Modélisation des matériaux et structures composites soumis à des sollicitations de type chocs hydrodynamiques

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Par

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Intitulée :

Modélisation des matériaux et structures composites soumis à des sollicitations de type chocs hydrodynamiques.

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Sigles/abréviations

ADSE	Aéroélasticité et Dynamique des Structures Expérimentales
ALE	Arbitraire Lagrange Euler
ANR	Agence Nationale de la Recherche
BEA	Bureau d'Enquêtes et d'Analyses
CCR	Centre Commun de Recherche
CEA	Commissariat à l'Energie Atomique
CEG	Centre d'Etudes de Gramat
CEO	Comité d'Evaluation et d'Orientation
CMO	Composite à Matrice Organique
CNRS	Centre National de la Recherche Scientifique
CPER	Contrat de Plan (ou de Projet) Etat Région
CSB	Comité Scientifique de Branche
CRD	Conception et Résistance Dynamique
DADS	Département Aéroélasticité et Dynamique des Structures
DCV	Direction de la Commercialisation et de la Valorisation
DGA	Délégation Générale pour l'Armement
DGA-TA	DGA Techniques Aéronautiques
DGAC	Direction Générale de l'Aviation Civile
DIRCOM	Direction de la Communication
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMSC	Département Matériaux et Structures Composites
DMSE	Département Mécanique du Solide et de l'Endommagement
DMSM	Département Matériaux et Structures Métalliques
DRET	Direction des Recherches et Etudes Techniques
DRH	Direction des Ressources Humaines
DRSC	Dynamique Rapide des Structures et Collisions
DSG	Direction Scientifique Générale
DTG	Direction Technique Générale
EC	EUROCOPTER
EDA	European Defence Agency
EDF	Electricité De France
EF	Eléments Finis
ENSAE	Ecole Nationale Supérieure de l'Aéronautique et de l'Espace
ENSAIT	Ecole Nationale Supérieure des Arts et Industries Textiles
ENSIAME	Ecole Nationale Supérieure en Informatique, Automatique, Mécanique, Energétique et Electronique
EPIC	Etablissement Public à Caractère Industriel et Commercial
EUCLID	Accord cadre de coopération européenne dans le domaine de la défense
FP	Framework Programme
FUI	Fond Unique Interministériel
GARTEUR	Group for Aeronautical Research and Technology in Europe
ICAM	Institut Catholique des Arts et Métiers
IMFL	Institut de Mécanique des Fluides de Lille
INSA	Institut National des Sciences Appliquées
ISEN	Institut Supérieure d'Electronique du Nord
JSO	Journées Stratégiques ONERA

LAMIH	Laboratoire d'Automatique, de Mécanique et d'Informatique Industrielles et Humaines
MAS	MAtériaux et Structures
MR	Maître de Recherche
MSAE	Modélisation et Simulation en Aéroélasticité
MSDS	Modélisation et Simulation en Dynamique des Structures
ONERA	Office Nationale d'Etudes et de Recherches Aérospatiales
PEA	Programme d'Etudes Amont
PRF	Projet de Recherche Fédérateur
RCS	Résistance et Conception des Structures
RG	Ressources Générales
SPAé	Service des Programmes Aéronautiques
SPH	Smooth Particle Hydrodynamics
UE	Union Européenne
UR	Unité de Recherche
UVHC	Université de Valenciennes et du Hainaut-Cambrésis
XFEM	Méthode aux éléments-finis étendus

Résumé

La pénétration d'un projectile – éventuellement balistique - à grande vitesse/haute énergie, et l'occurrence d'un coup de bélier dans un réservoir, représentent une éventualité qu'il est souvent légitime, sinon toujours nécessaire, de considérer en sécurité aéronautique. Pour ce protéger d'une telle éventualité, le durcissement structural à l'impact via l'intégration de blindages est une solution ultime, qui n'est – dans l'aéronautique – que rarement acceptable pour des raisons évidentes de pénalité de masse. La réduction de la vulnérabilité devient alors indissociable d'un exercice délicat d'optimisation de la résistance de la structure au regard de sa masse, ce qui nécessite donc de modéliser précisément l'occurrence d'un tel coup de bélier, sa sévérité et ses conséquences sur la structure. Ceci est d'autant plus vrai et difficile qu'on s'intéresse - depuis plusieurs décennies déjà en aéronautique - à des structures composites à renfort de fibres de carbone, qu'on sait être particulièrement fragiles aux chocs, et à des projectiles balistiques réels différant notablement de projectiles sphériques rigides, académiques. Les situations étudiées depuis les années 1980 à l'ONERA-Lille concernent en effet des impacts de balles ou d'éclats réels (simples ou multiples : gerbes) perforants et subsoniques p/r à la célérité des ondes dans le liquide.

Pour résumer la problématique traitée dans ce mémoire : après pénétration du réservoir, l'éclat ou la munition animée d'une vitesse proche d'un km/s est brutalement freiné(e) par le liquide contenu dans la structure. La force de traînée qui lui est opposée par le fluide varie violemment en fonction de l'évolution du profil traînant du projectile, en particulier lorsqu'il est déstabilisé et se retourne dans le fluide. Cette énergie cinétique est brutalement transférée au liquide, et il y a création d'un choc hydrodynamique puis d'une cavité (on est en présence d'un mélange fluide multiphasique air, vapeur, liquide) dans le sillage du projectile. Après une première onde de choc hydrodynamique potentiellement destructrice, l'expansion à peine plus lente de la cavité dans le liquide (quasiment incompressible) peut se traduire par des déformations non négligeables de la structure pouvant aboutir à des ruptures catastrophiques des matériaux ou des assemblages structuraux, le coup de grâce étant éventuellement porté lors de l'effondrement final de la cavité.

Le mémoire présenté à l'occasion de cette candidature à l'obtention d'une Habilitation à Diriger des Recherches retrace l'ensemble des travaux de recherche que j'ai été amené à réaliser et surtout à encadrer depuis le début des années 1990 concernant cette problématique de la *modélisation des matériaux et structures composites soumis à des sollicitations de type chocs hydrodynamiques,* en particulier sur les sujets de la caractérisation et de la modélisation, d'une part, du comportement et de la rupture dynamique des matériaux composites à matrice organique et, d'autre part, des interactions fluide/structures et des chocs hydrodynamiques consécutifs aux impacts balistiques dans des réservoirs aéronautiques.

Mots-clés : simulation numérique, caractérisation expérimentale, aéronef, réservoir, composite, coup de bélier, choc, hydrodynamique

Abstract

The impact of high speed/high energy projectiles – possibly ballistic ones – and the occurrence of an hydraulic ram (HRAM) event in fuel tanks, constitutes a threat which is often legitimized if not always compulsory to consider for aircraft safety. To prevent from such an eventuality, the impact hardening through armouring the structure is an ultimate solution which is hardly acceptable in aeronautics for obvious mass penalty reasons. The reduction of fuel tanks vulnerability then turns to become not separable from a difficult exercise of optimisation of the strength of the structure with respect to its mass. This objective requires to be able to accurately model the hydraulic ram event, its severity and consequences in terms of damaging the fuel tank structure. It is all the more important, first, as carbon fibres reinforced plastic (CFRP) composite structures are being massively introduced in aeronautics for tens of years, and one knows well that they exhibit brittle behaviours under impacts. Second, because complex ballistic projectiles can be concerned, the damaging effects of which can greatly differ from those of rigid (spherical) academic ones. Indeed, the scenarios which are being studied at ONERA-Lille since the 80's are related to real single ballistic bullets or multiple fragments impacts that cannot be prevented from perforating the fuel tank structures, in the present studied case at subsonic velocities compared to the sound speed in the considered solids or liquids.

To summarize the research which is addressed in the present thesis : after it has perforated the structure, the 1 km/s ammunition or fragment is brutally decelerated by the fuel in the tank. The drag force which is opposing its motion quickly varies together with the projectile drag coefficient, especially because it becomes unstable and tumbles trough the fluid. The kinetic energy of the projectile is transferred to the liquid medium, with an hydrodynamic shock being first generated, followed by the development of a possibly multi-phasic (air, vapour) gas cavity in the wake of the moving impactor. After the initial and possibly already damaging hydrodynamic shock wave has passed, the slightly slower growth of a large cavity in the (almost incompressible) fuel leads to an important dynamic deformation of the structure that can possibly turn into catastrophic failure of the structural materials or assemblies, with a final deathblow – if necessary - possibly arising at the very final collapse of this cavity.

The following works, which are here reported to candidate to the *Habilitation à Diriger des Recherches* grade of the University of Valenciennes, summarize some research that I was personally brought in performing or supervising at ONERA-Lille on the *modelling of composite materials and structures under hydrodynamic shock loads* since the beginning of the 90's. It focuses more specifically on the question of the characterisation and modelling of, on the one hand, the non-linear dynamic behaviour and rupture of organic resin based composites and, on the other hand, fluid/structure interactions and hydrodynamic shocks during ballistic impacts in aeronautical fuel tank structures.

Keywords: numerical simulation, experimental characterisation, aircraft, fuel tank, composite, hydraulic ram, shock, hydrodynamics

Chapitre 1

Curriculum Vitae Etendu

Eric Deletombe, né le 20 septembre 1964 à Marchiennes (59), de nationalité française. Maître de Recherche et Ingénieur Spécialiste à l'*Office National d'Etudes et de Recherches Aérospatiales* (ONERA), dans l'Unité de Recherche *Conception et Résistance Dynamique* (CRD) du Département *Aéroélasticité et Dynamique des Structures* (DADS).

L'ONERA est le principal acteur français de la recherche appliquée dans le domaine de l'aéronautique et du spatial. Il regroupe 1750 personnes dont plus de la moitié sont des scientifiques. L'ONERA est un EPIC placé sous la tutelle du Ministère de la Défense. Il se subdivise en quatre branches scientifiques, elles-mêmes organisées en dix-sept Départements.

La Branche Matériaux et Structures regroupe les Départements «Matériaux et Structures Métalliques» (DMSM), «Matériaux et Structures Composites» (DMSC), «Aéroélasticité et Dynamique des Structures» (DADS). Le Département DADS est composé de quatre Unités de Recherche : «Aéroélasticité et Dynamique des Structures Expérimentales» (ADSE), «Modélisation et Simulation AEroélastique» (MSAE), «Modélisation et Simulation en Dynamique des Structures» (MSDS), «Conception et Résistance Dynamique des structures» (CRD). Cette dernière unité, à laquelle je suis rattaché, est localisée sur le centre de l'ONERA-Lille. Comme l'intitulé des unités de recherche le laisse entendre, les activités de recherche menées dans le Département DADS (et l'UR CRD) sont de natures théoriques, numériques et expérimentales.

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Titres universitaires et diplômes

1989 Diplômes de Spécialisation Informatique et de Mastère en Systèmes Informatiques de l'Ecole Nationale Supérieure de l'Aéronautique et de l'Espace (ENSAE, Toulouse).

1988 Diplôme d'Ingénieur de l'Ecole Nationale Supérieure de l'Aéronautique et de l'Espace (ENSAE, Toulouse).

1982 Diplôme du Baccalauréat série C (Lycée Louis Pasteur, Somain, mention AB).

Responsabilités scientifiques et techniques

Je suis responsable ONERA de Projets d'Etudes et de Recherches pluriannuels - actuellement : *BaTolUS* (Agence Européenne de Défense, 2010-2013), *TSD* (Projet de Recherche Fédérateur

ONERA, 2010-2013), *CISIT* (Contrat Projet Etat-Région, 20007-2013) dans lequel s'inscrit un projet de recherche collaboratif financé sur Ressources propres ONERA et adossé depuis 2004 au Laboratoire Commun ONERA/CNRS/UVHC *Dynamique des Structures et Collisions* - et suis en charge de contrats/d'actions d'expertise auprès de la Délégation Générale de l'Armement (DGA). Un rappel de mes activités d'Ingénieur d'étude et de recherche depuis mon arrivée à l'ONERA en Décembre 1990, est dressé ci-après.

Expertises et contrats d'études et de recherche nationaux

FUI (2013-2016), Optimisation EF et qualification expérimentale au crash d'un démonstrateur de réservoir souple d'aéronef,
DGA-TA (2012-2014), Modélisation - Référentiel technique pour la spécification des arrimages dans les avions de transports en situation de crash,
SPAé (2001-02), Modélisation et Simulation EF (3D) - Coup de bélier hydrodynamique dans les réservoirs d'avions de transport futurs,
BEA (2001), Simulation EF – Diagnostic de l'accident du Concorde,
DGA (1998-02), Modélisation et Simulation EF - Réponse dynamique des structures de véhicules blindés aux impacts missiles,
SPAé (1997-99), Modélisation et Simulation EF (2D) - Coup de bélier hydrodynamique dans les réservoirs d'avions de transport futurs,
SPAé (1996-98), Essai, Modélisation et Simulation EF - Crash des hélicoptères composites (collaboration ONERA/DLR),
EC (1995-99), Modélisation et Simulation EF - Impact de volatiles sur verrière d'hélicoptères composites,
DRET (1994-96), Essai, Modélisation et Simulation EF - Développement de lois de comportement dynamique 3D pour les matériaux composites CMO,
EC (1992-93), Modélisation et Simulation EF - Crash d'absorbeurs composites pour hélicoptères.
DGAC (1990-97), Modélisation et Simulation EF - Crash d'avions de ligne à fuselage métallique (collaboration AIRBUS).

Contrats de recherche en collaboration internationale

EDA *BaTolUS* (2010-2013), Développement de méthodes d'optimisation par calcul EF de structures de réservoirs composites d'aéronefs au coup de bélier consécutif à l'impact balistique,
EUCLID *RTP3.32* (2004-2007), Essais et Simulations EF - Coup de bélier hydrodynamique dans les réservoirs d'avions d'armes composites,
EU FP5 *CRAHVI* (2001-2004), Essais et Simulation EF - Amerrissage et impacts grandes vitesses sur structures d'avions de ligne,
EU FP4 *SEAWORTH* (1998-2001), Essais et Simulation EF - Chocs hydrodynamiques (tossage) sur vaisseaux grande vitesse,
EU FP4 *CRASURV* (1997-2000), Essais, Modélisation et Simulation EF - Crash d'avions de ligne (fuselage composite),
EU FP3 *TIM-CRASH* (1992-1996), Essais et Simulation EF - Crash d'avions de ligne (fuselage métallique).
ONERA/DLR Joint Team Crashworthiness of Composite Helicopters (1996-2004), Caractérisation et modélisation dynamique des capacités d'absorption d'énergie des matériaux composites à matrice organiques.

Carrière professionnelle

2010-13 Chargé de Mission Scientifique auprès du Directeur du Département *Aéroélasticité et Dynamique des Structures* (DADS) de l'Office National d'Etudes et de Recherches Aérospatiales.

2004-13 Co-Président du Laboratoire Commun ONERA/CNRS/UVHC *Dynamique Rapide Des Structures et Collisions (DRSC).*

2008-09 Chef de l'Unité de Recherche *Conception et Résistance Dynamique* (CRD) du Département d'*Aéroélasticité et Dynamique des Structures* (DADS) de l'ONERA.

1999-07 Chef de l'Unité de Recherche *Résistance et Conception des Structures* (RCS) du Département de *Mécanique du Solide et de l'Endommagement* (DMSE) de l'ONERA.

1999 Nomination Maître de Recherches (MR1) ONERA.

1991-98 Ingénieur de Recherche dans la Division de *Mécanique des Structures* de l'Institut de Mécanique des Fluides de Lille (IMFL, ONERA-Lille).

1989-90 Scientifique du contingent à la Division *Robotique* de la Direction des Recherches, Etudes et Techniques de l'armement (DGA/DRET)

Activités de recherche

Ma première contribution de recherche au cours de ces années aura été de formuler le périmètre et le positionnement scientifiques de mon Unité de Recherche sur la thématique *Dynamique Rapide*, thématique qui était encore juste émergente – au moins en aéronautique civile - lors de mon embauche à l'ONERA (Décembre 1990). Les objectifs visés par ces recherches sont aujourd'hui déclinés, d'une part, en termes d'amélioration de la *survivabilité* des passagers (crash sur sols durs [RE-73] et mous, amerrissage [RE-9]) donc de sécurité dans le domaine basse vitesse [CI-17, CN-12] et, d'autre part, en termes de réduction de la *vulnérabilité* des structures (impacts balistiques [CI-16], de grêle [RI-16] ou de débris, chocs à l'oiseau [RI-4, CI-2, RE-13, RE-17, RE-39], chocs hydrodynamiques, explosions internes ou externes [RI-17, CI-14]) donc d'amélioration de la tenue structurale dans le domaine des plus grandes vitesses. Les axes de recherche identifiés furent ainsi subdivisés en quatre thématiques principales : (1) le développement d'outils et de méthodes numériques efficientes, par calcul éléments finis, pour l'analyse structurale de problèmes structuraux de grande complexité/ dimensions, (2) le développement et la validation de modèles mécaniques de comportement, d'endommagement et de rupture dynamiques pour les matériaux et les assemblages, (3) le développement de solutions spécifiques pour la modélisation précise des menaces, des chargements dynamiques et des impacteurs, et (4) le développement de protocoles expérimentaux spécifiques pour l'observation, la mesure, l'identification et la caractérisation dynamique des phénomènes dynamiques considérés et des modèles associés [CI-13, CN-9]. Par rapport aux recherches réalisées dans d'autres Départements ou Unités de Recherche de l'ONERA, ce périmètre scientifique adressait finalement des questions spécifiques relatives à la compréhension et la prédiction de la réponse transitoire temporelle (et non vibratoire) des matériaux et des structures sous chargements dynamiques, dans le domaine des grands déplacements et des grandes déformations (en particulier, non linéaires), en régime d'initiation et de propagation étendue de la rupture, pour une large gamme de vitesses de sollicitation (10^{-3} s^{-1}/10^{+3} s^{-1}) [CN-10, CN-11].

A titre plus personnel, mon activité de recherche des vingt dernières années s'est naturellement inscrite dans ce schéma. Mes travaux de recherche furent et sont toujours financés principalement sur Programmes d'Etudes Amont (PEA) de la DGA et ressources générales ONERA (RG). Ils ont été plus particulièrement – mais pas uniquement - concentrés sur la question de la modélisation des matériaux et structures composites, soumis en particulier à des sollicitations de type *chocs hydrodynamiques*, sujet que j'ai retenu pour présenter mon dossier d'Habilitation à Diriger des Recherches. Plus particulièrement, dès les années 80, l'ONERA s'était intéressé expérimentalement au sujet de la réponse dynamique des structures composites à l'impact balistique, pour les besoins du programme RAFALE. Les questions posées concernaient également l'étude expérimentale de la vulnérabilité de caissons réservoirs composites au coup de bélier hydraulique consécutif à ces impacts balistiques (campagnes d'essais de tirs de calibre 7.2 mm et 12.7 mm). Au cours des années 90, la problématique se reposa dans le cadre du programme ATF (Avion de Transport Futur, aujourd'hui A400M) et, les capacités informatiques ayant gagné en puissance, je fus chargé de mener des recherches orientées, cette fois, sur la modélisation et la simulation par éléments finis de la résistance des réservoirs d'avions militaires à une menace de type « coup de bélier » [RE-10, RE-12, RE-16]. Ces études se sont poursuivies dans les années 2000 avec DASSAULT-AVIATION et EADS (programme du successeur du RAFALE), en combinant cette fois aspects expérimentaux (l'UR disposant de nouveaux moyens technologiques particulièrement performants – caméra ultra rapide CORDIN 400 000 im/s) et numériques, dans le cadre du programme EUCLID RTP3.32 [RE-7, RE-8]. Pour la décennie en cours, ce sont cette fois les structures de projets de drones composites que j'étudie, par exemple dans le cadre du projet EDA BaTolUS dont je suis le responsable ONERA [RE-2, RE-4]. Ce programme pose cette fois la question de l'optimisation numérique de la conception des structures composites [RE-25], relativement à ce type de menace [RE-1].

En guise d'introduction rapide à la présentation de mes travaux de recherche, il est utile de rappeler que le durcissement structural à l'impact balistique via l'intégration de blindages est une solution ultime [RN-5, CI-16], mais qu'elle n'est – dans l'aéronautique – que rarement acceptable pour des raisons évidentes de pénalité de masse. La difficulté doit donc être contournée [RE-6]. La pénétration du projectile balistique, et l'occurrence du coup de bélier dans le réservoir, représentent une éventualité qu'il est légitime, sinon nécessaire, de considérer. La réduction de la vulnérabilité devient alors indissociable d'un exercice délicat d'optimisation de la masse de la structure, ce qui nécessite donc de modéliser précisément l'occurrence du coup de bélier, sa sévérité et ses conséquences sur la structure. Ceci est d'autant plus vrai et difficile qu'on s'intéresse plutôt en aéronautique à des structures composites à renfort de fibres de carbone qu'on sait être particulièrement fragiles aux chocs, et à des projectiles réels différant notablement de projectiles sphériques rigides, académiques. Les agressions que j'ai été amené à considérer concernaient en effet des impacts de balles ou d'éclats réels (simples ou multiples : gerbes) perforants et subsoniques p/r à la célérité des ondes dans le liquide. En résumant la problématique, après pénétration du réservoir, l'éclat ou la munition est brutalement freiné(e) par le liquide contenu dans le réservoir. La force de traînée qui lui est opposée par le fluide varie violemment en fonction de l'évolution du profil traînant du projectile. Cette énergie cinétique est brutalement transférée au fluide, et il y a création d'un choc hydrodynamique puis d'une cavité (on est en présence d'un mélange fluide multiphasique air, vapeur, liquide) dans le sillage du projectile. Après la première onde de choc hydrodynamique potentiellement destructrice, l'expansion plus lente de la cavité peut se traduire par des déformations non négligeables de la structure, pouvant aboutir à des ruptures catastrophiques des matériaux ou des assemblages structuraux.

Modélisation des chargements hydrodynamiques

En 1995, les capacités des outils de simulation étaient beaucoup plus restreintes qu'aujourd'hui, et je fus amené à proposer une méthodologie de simulation EF reposant sur l'utilisation de codes explicites lagrangien de dynamique rapide pour étudier la première phase du chargement (le choc hydrodynamique), en considérant un fluide monophasique (liquide uniquement). Pour contourner les écueils rencontrés avec ce type de modélisation (instabilités numériques, explosion des temps de calcul avec les déformations de maillage lorsque le projectile se retourne dans le fluide), je proposais de modéliser un projectile équivalent de forme conique (provoquant un écoulement plus « sympathique »), piloté en ouverture pour simuler l'évolution du coefficient de traînée du projectile réel et produire le choc hydrodynamique correspondant. La principale difficulté résidait alors dans la mesure expérimentale de ce coefficient de traînée. Les essais de calibre 12,7 mm, réalisés à l'époque au CEG de la DGA sur des caissons d'un mètre de profondeur, ne fournirent que trois clichés RX qui me renseignèrent sur les positions et orientations du projectile en trois instants seulement du tir, et je dus ré-estimer la cinématique du projectile par une méthode numérique inverse [CI-13, RN-1]. Cette première recherche fut à l'origine d'un grand nombre de questionnements, qui aboutirent à plusieurs travaux de recherche, en particulier au travers de deux thèses que je co-encadrais, *Contribution au développement des méthodes numériques de traitement des interactions corps durs/corps mous - Application au crash, aux collisions ou aux chocs* [RI-3, CN-2], [Portemont, 2003], et *Contribution à la validation des méthodes numériques pour les problèmes dynamiques couplés fluide-structure* [RI-2] [Haboussa, 2008], sous la Direction du LAMIH de l'Université de Valenciennes. Les travaux adressaient en premier lieu la question de la mesure des champs de pression hydrodynamiques par des capteurs traditionnels (en résumé, le capteur de pression est lui-même une structure soumise à un impact hydrodynamique, et la mesure n'est plus forcément objective), et celle de la validation par rapport à de telles mesures des outils et modèles numériques utilisés pour traiter les interactions fluide/structure et simuler les chargements de type hydrodynamiques. Il faut noter que les méthodes numériques avaient fortement évolué depuis 1995, les approches ALE et SPH ayant augmenté entre temps le champ des possibilités. L'ONERA avait par ailleurs étudié dans les années 80 des techniques de visualisation grande vitesse, qui permettaient (à l'aide de systèmes de chronoloupes à étincelles) d'acquérir des photographies à grande cadence (supérieure au million d'images par seconde) de la propagation du choc et de l'expansion de la cavité dans le sillage des projectiles. L'indice de l'eau variant fortement avec le niveau de pression, on observait des ombres (d'où la dénomination d'ombroscopie) qui étaient assimilées à une empreinte 2D instantanée de la cavité créée dans le sillage du projectile. En supposant que la position du projectile pouvait être estimée correspondre à la "pointe" de l'ombre, il était possible – à l'aide des clichés (le nombre d'images était limité à 24, ce qui est mieux que 3) - de mesurer la vitesse du projectile donc l'évolution de son coefficient de traînée. Convaincu au terme des thèses précédentes que des mesures de pression dynamique ponctuelles étaient insuffisantes pour notre besoin de compréhension et de modélisation de ce phénomène de coup de bélier (en particulier pour les phases d'expansion puis d'écroulement de la cavité pouvant s'étaler sur des dizaines de millisecondes), et impressionné par les nouvelles capacités des technologies d'imagerie numérique rapide (nous avions acquis une caméra ultra-rapide 400 000 im/s), j'ai proposé de réaliser des essais de tirs et de mettre en oeuvre à cette occasion des visualisations numériques du phénomène, dans une piscine vitrée de l'ONERA pour m'affranchir au mieux des conditions aux limites structurales et me focaliser sur l'interaction projectile/fluide. Les nouvelles caméras numériques constituent un moyen « satellite » plus léger et intéressant (outils de traitement numériques) que le système de chronoloupes, et elles avaient déjà été mises en œuvre avec succès dans le cadre de plusieurs études. Les résultats obtenus s'avérèrent particulièrement intéressants [RI-1, CI-1], et ces résultats expérimentaux servent aujourd'hui de référence pour nos réflexions théoriques [CN-1], et le développement et la validation des outils numériques [RE-48]. En termes de simulation numérique, l'un des principaux défis identifiés aujourd'hui concerne la capacité à réaliser des simulations numériques 3D de la pénétration du projectile dans le fluide qui soient robustes, précises et efficaces en terme de CPU, c'est-à-dire permettant de couvrir toute la durée du phénomène maintenant observée (10-30 ms) : une collaboration avec le LaMCoS de l'INSA-Lyon a ainsi été initiée pour améliorer les méthodes SPH dans le code EUROPLEXUS, dans le cadre d'une thèse EDF/INSA-Lyon, *Modélisation par la méthode SPH de l'impact d'un réservoir rempli de liquide* [Maurel, 2008]. D'autres recherches se poursuivent, qui s'intéressent au développement de modèles fluides multiphasiques plus physiques (Thèse ONERA-DGA en cours de Thomas Fourest, 2012-2015, en collaboration avec l'ENSTA-Brest), et de modélisations mécaniques équivalentes [RE-2, RE-5, RE-48] pour traiter la réponse structurale globale des réservoirs soumis à ce type de chargements.

Comportement et rupture des matériaux composites à matrice organique

Mes travaux sur la modélisation du comportement, de l'endommagement et de la rupture dynamique des matériaux composites à matrice organique ont débuté dès 1992 [RE-36]. En effet, pour répondre à l'évolution prévisible des normes de sécurité, EUROCOPTER avait mis en place un programme de recherche sur le développement de longerons sous-plancher et de bas de cadre composites CMO, destinés à amortir par absorption d'énergie la sévérité des chocs rencontrés lors des crashs hélicoptères. Les éléments de poutres étudiées avaient des âmes de profil sinusoïdal ou trapézoïdal, constituées de stratifiés de tissus et d'unidirectionnels de divers matériaux composites à renfort de fibres de carbone et de kevlar. Je fus donc amené à évaluer à l'époque les fonctionnalités composites d'un code du commerce explicite de dynamique rapide, sans grand succès. Il fut donc décidé d'approfondir cette problématique dans le cadre d'études DRET (dès 1994), les premières recherches concernant alors la caractérisation et la modélisation des comportements dynamiques des matériaux composites CMO à renforts de fibres de carbone T300/914. Je formulais à cette époque les principes élémentaires d'un premier modèle générique de comportement et de rupture 3D dynamique pour les matériaux composites CMO, à l'échelle mésoscopique du pli, et en opérait une première implémentation (sous forme d'une loi utilisateur pour un code du commerce) [RI-7, RE-27, RE-28]. Les principes généraux du modèle développé visaient à pouvoir représenter un matériau 3D orthotrope dissymétrique (différence traction/compression), renforcé ou non dans chacune des directions d'orthotropie, pouvant développer un comportement non-linéaire dans les trois directions matérielles, en traction et en compression, et dans les trois plans de cisaillement. Un critère de type Tsaï-Wu était proposé pour décrire l'enveloppe de comportement élastique, et l'évolution des modules tangents était pilotée par les énergies de déformation non-linéaire cumulées au cours du chargement monotone dans chacune des directions matérielles. Le modèle permettait d'exhiber une dépendance à la vitesse de sollicitation au travers du critère d'élasticité qui était rendu dépendant de la vitesse de déformation totale. Chaque direction et sens de sollicitation était traité avec des variables internes propres, pour permettre de représenter des variations de comportement allant de l'élastique-fragile au non-linéaire dépendant de la vitesse, selon la direction matérielle et le signe de la sollicitation (intéressant pour le kevlar par exemple). La rupture était traitée par association de plusieurs critères de type mécanique : par contraintes ultimes, par critère élastique-fragile de type Tsaï-Wu (avec dépendance de la rupture à la vitesse de sollicitation), ou par endommagement cumulé (dans ce cas associé à un seuil d'initiation de l'endommagement en déformation non-linéaire, et une variable d'endommagement adoucissante. Le modèle s'avéra finalement plutôt onéreux en termes de coûts de calcul, mais il permettait de représenter empiriquement presque tous les types de comportements observés à l'époque expérimentalement. Il n'avait pas été formulé thermodynamiquement. Parallèlement à cet exercice de modélisation, j'initiais des réflexions sur la caractérisation du délaminage (essai ARCAN), ou du comportement dynamique en compression des composites (sur éprouvettes « diabolos » rectangulaires ou cylindriques) [RE-33/…/35]. Ces recherches et développements furent poursuivis à partir de 1996 à l'occasion de divers travaux de thèse ou de post-doctorat dirigés par le LAMIH de l'UVHC [CN-3], et d'un projet de recherche mené en collaboration avec le DLR-Stuttgart [RI-7, CI-4, CI-5, RE-18, RE-24, RE-30, RE-32]. Divers matériaux furent étudiés à ces occasions, composites à renforts de fibres de verre, de kevlar, d'aramide, et de carbone. Le modèle que j'avais proposé fut adapté en 1998, et implémenté en 2D pour des éléments de coque dans un code du commerce, à l'occasion du programme EU BRPR-CT96-0207 CRASURV [RE-26, RE-29, RE-31]. Il est aujourd'hui disponible dans la librairie du code, et régulièrement utilisé pour les études industrielles qui nous sont confiées, avec plus de succès que l'étude originelle de 1992 (par exemple pour l'étude du crash de l'hélicoptère TIGRE). Ces recherches se poursuivent aujourd'hui en particulier dans le cadre du PRF Transition Statique-Dynamique [RE-19/…/23] dont je suis responsable pour le DADS, et d'une thèse *Modélisation dynamique avancée des matériaux composites CMO pour l'étude de la transition statique-dynamique* [RI-5], [Berthe, 2013] que je co-encadre actuellement, sous la Direction de l'Ecole Centrale de Lille.

Mécanique des assemblages

J'avais clairement identifié l'importance de la question de la modélisation des assemblages rivetés dès les premières études de simulation numérique qui m'avaient été confiées au début des années 90 (études DGAC [RE-46, RE-47] et EU TIM-CRASH [RE-44, RE-45]), et qui concernaient le crash de tronçons de fuselage métallique d'avions commerciaux. Ce fut le sujet de la première thèse que je co-encadrais à l'ONERA, sous la Direction du LAMIH de l'Université de Valenciennes, *Caractérisation numérique et expérimentale des assemblages rivetés sous sollicitation dynamique* [RI-9/…/15, RN-2, RN-3, RE-40/…/43], [Langrand, 1998], qui visait au développement de super-éléments de liaisons (rivets) non-linéaires et en rupture, et étudiait la possibilité d'en opérer une caractérisation virtuelle par calcul fins par éléments finis (les plans d'expérience expérimentaux des liaisons rivetées, vu leur extrême variété, s'avérant rapidement hors de prix). A cette occasion, le protocole ARCAN fut détourné de son objet premier pour tester ces éléments de liaison ponctuelle. L'importance de la bonne prise en compte de ces assemblages est aujourd'hui reconnue par tous, les protocoles de type ARCAN se sont généralisés y compris dans l'industrie, et de nombreux programmes de recherche s'intéressent encore aujourd'hui à ce sujet (point de soudure par friction-malaxage, point de soudure polymères, etc). Ce thème de la mécanique des assemblages en dynamique rapide fut un des thèmes fondateurs du Laboratoire Commun DRSC, et les coopérations avec le LAMIH sur ce sujet ont été poursuivies depuis cette époque au travers de plusieurs autres thèses, en particulier sur le sujet du développement de super-éléments de coques perforées, [RI-8, CI-7/…/11, CN-4/…/7], e.g. *Contribution au développement d'un élément de type coque fragilisée, pour la prise en compte des phénomènes de fragilisation structurale liés aux techniques de rivetage*, [Patronelli, 2001]. Cet axe de recherche se poursuit encore aujourd'hui (Thèse ONERA-Région de Claire Hennuyer, 2011-2014). C'est à l'occasion des différents programmes évoqués dans le paragraphe précédent, et à partir de 1998 – dans un premier temps pour des études industrielles de crash (crash TIGRE, EU CRASURV) - que l'étude du comportement et de la ruine dynamique des assemblages composites rivetés fut abordée dans l'UR. Le sujet fut ensuite étudié en 2004, dans le cadre du programme EUCLID RTP3.32 qui s'intéressait à la simulation du coup de bélier hydrodynamique dans les réservoirs d'avions d'armes, qui mis en évidence que les assemblages structuraux constituaient le maillon faible structural pour ce type de sollicitation et de structures. Dans le cadre de ce projet, furent en particulier développés des protocoles expérimentaux de type ARCAN, permettant de caractériser des critères de rupture des assemblages composites rivetés sous sollicitations mixtes I-II [RE-37, RE-38]. La thématique de l'étude et de la modélisation du comportement dynamique des assemblages composites rivetés fit par ailleurs l'objet d'une thèse que je co-encadrais, sous la Direction du LAMIH de l'Université de Valenciennes, *Dynamique de la ruine des assemblages composites par liaisons rivetées au crash et à l'impact – Simulations* *expérimentales et numériques pour l'étude et le développement de modèles de comportement et de rupture par matage des liaisons* [RI-6, RN-2], [Postec, 2006], et continue d'être étudiée dans l'UR (PRF TSD, ANR VULCOMP II). Elle se complexifie et se diversifie néanmoins aujourd'hui, avec la généralisation du recours aux assemblages par collage ou collage/rivetage (Thèse ONERA-Région de Vincent Joudon, 2011-2014).

Autres thèmes de recherche

Parallèlement à ces travaux de recherche, et en tant qu'ingénieur de recherche ONERA et responsable d'UR, j'ai été amené à m'intéresser à divers sujets connexes à mes thèmes de recherche personnels. Ces activités ont largement nourri et enrichi mes réflexions et connaissances sur les sujets précédemment évoqués. Sans être exhaustif, j'en citerais quelques-uns qu'il me semble important de mentionner, puisqu'ils me donnèrent l'occasion de co-encadrer d'autres travaux de thèse.

Bien que n'étant pas expérimentateur de métier, j'ai eu l'occasion de suivre et débattre avec mes collègues de nombreux travaux de recherche de nature expérimentale. J'ai ainsi co-encadré, sous la Direction du LAMIH de l'Université de Valenciennes, la thèse *Moyens d'essais et de caractérisation de lois de comportement matérielles en dynamique moyennes vitesses* [CI-15], [Haugou, 2003], dont l'objectif visait au développement et à la mise en place dans le laboratoire de notre premier système de caractérisation dynamique des matériaux aux Barres de Hopkinson.

J'ai également eu l'occasion d'initier puis de suivre un certain nombre de travaux de nature prospective concernant les *Méthodes Numériques* applicables à nos problématiques, et j'évoquerai pour exemple la méthode des éléments finis étendus (XFEM), et la thèse *Méthode des éléments-Finis étendus en Espace et en Temps – Application à la propagation dynamique de fissures* [Réthoré 2005] que j'ai eu le plaisir de co-encadrer sous la Direction du LaMCoS de L'INSA-Lyon.

Enfin, et pour sortir du périmètre de la *Dynamique Rapide*, j'aimerais évoquer les recherches menées au sein de l'UR dans le domaine de la conception mécanique (appliqué à l'étude de nouveaux concepts structuraux d'aéronefs), persuadé que je suis du fort potentiel scientifique et technologique de cette discipline, en mentionnant par exemple la thèse *Contribution au développement d'une méthode d'homogénéisation des composites à fibres actives – Application à la torsion active de pales d'hélicoptères* [Lenglet, 2003], que j'ai eu le plaisir de co-encadrer sous la Direction de l'ISEN.

La liste des publications et rapports communiquée en annexe permettra de compléter ces quelques mentions.

Activités de promotion de la recherche

Collaborations nationales et internationales

Collaboration avec le Commissariat à l'Energie Atomique (CEA) et le Centre Commun de Recherche de l'Union Européenne – CCR ISPRA), Consortium « *EUROPLEXUS* », depuis 2008.

Collaboration ONERA/ IFSTTAR/CNRS/ CREPIM/VALUTECH/CRITTM2A UVHC/USTL/UA/ ECL/EMD, Contrat de Projet Etat-Région « *Campus International pour la Sécurité et l'Intermodalité dans les Transports (CISIT*) », depuis 2007.

Collaboration avec le CNRS et l'Université de Valenciennes et du Hainaut-Cambrésis, Convention de Laboratoire Commun « *Dynamique Rapide des Structures et Collisions (DRSC)* », entre le LAMIH et le DADS, depuis 2004.

Collaboration avec le CNRS et le Groupe SAFRAN, Consortium « *Méthodes Avancées en Ingénierie Mécanique* » (MAIA/MM3), depuis 2003.

Collaboration ONERA/DLR, responsable du Joint Team « *Composite Helicopter Crashworthiness* » de 1996 à 2003, puis de projets commun de recherhe « Aicraft VulneraBILITY », de 2004 à 2011.

Associations, fédérations et réseaux thématiques

Adhérent et membre (3AF Sénior) de *l'Association Aéronautique et Astronautique de France*, membre actif de la Commission Structures, depuis 2008.

Adhérent au *Groupe Français de Mécanique des Matériaux*, MECAMAT.

Membre de la *Fédération Francilienne de Mécanique* (F2M), depuis 2008.

Membre du Groupe d'Intérêt « Impact » de *l'European Aeronautics Science Network* (EASN) depuis 2003, et adhérent EASN depuis 2010.

Organisation de conférences, séminaires et journées scientifiques

Conférence Internationale « *Dynamic behaviour of structures and materials, interaction and friction* », membre du Comité International, ENIM, Metz, 2011.

Commission Essais de l'Association Aéronautique et Aérospatiale Française (3AF), co-organisateur de la journée technique « *Essais en Dynamique Rapide* », ONERA, Lille, 2010.

Entretiens de Toulouse, organisateur de la session « *Structures - Réponse dynamique des structures à l'impact et au crash* », avec l'UVHC/LAMIH et EUROCOPTER, ISAE, 2009.

Comité Consultatif sur les Recherches en Soudage (CCRS), co-organisateur d'une journée scientifique de la Commission Rupture, ONERA, Lille, 2006.

Groupe de Travail MécaDymat, co-organisateur d'une journée scientifique « *Mécanique et Dynamique des Matériaux* », ONERA, Lille, 2003.

Conférence Internationale, « *International Crash and Design Symposium* », membre du Comité Scientifique, UVHC, Valenciennes, 2003.

Journées Scientifiques ONERA, co-organisateur d'une journée « Matériaux et assemblages », ONERA, Châtillon, 2001.

Participation à la manifestation de la Fête de la Science 2000, au travers de l'élaboration puis la présentation d'une animation interactive intitulée « Matériaux métallique, un univers solide et opaque », Lille, 2000.

Activités et responsabilités d'intérêt collectif

Embauché à l'ONERA en décembre 1990 comme Ingénieur de Recherche, je me suis intéressé dans un premier temps à la modélisation du comportement au crash des structures métalliques aéronautiques. L'activité de recherche sur la thématique Dynamique Rapide augmenta au cours des années 90, en combinant des problématiques expérimentales et numériques, et je devins l'animateur d'un groupe de 5 ingénieurs de recherche et 4 techniciens sur cette thématique. Nommé Chef d'Unité de Recherche en 1999, et officiant jusqu'en 2009, j'ai poursuivi cette mission d'animation, de coordination scientifique et technique, et de représentation des quelques 20 collègues ingénieurs et techniciens de l'Unité de Recherche *Résistance et Conception des Structures* (renommée *Conception et Résistance Dynamique*, en 2008). Avec ces responsabilités, d'autres thématiques – et celle de la Conception Mécanique en particulier – sont entrées dans mon champ d'expertise.

En tant que Responsable d'Unité de Recherche à l'ONERA, j'ai été amené à assurer des missions d'intérêt général d'animation (en organisant régulièrement les réunions d'information, en jouant le rôle de relais de la Direction auprès du personnel et vice-versa), d'évaluation annuelle des personnels de l'Unité de Recherche, de planification des moyens (équipements informatiques et petits équipements de laboratoire) et des plans de charge à cours et à moyen terme (donc d'embauches), de suivi de l'avancement des travaux contractuels (ce qui consistait d'abord et avant tout à détecter d'éventuelles dérives, à en identifier l'origine, à résoudre les problèmes techniques - en convenant de la réorganisation des ressources et en réorientant les travaux si nécessaires), et de communication interne et externe de l'Office (en collaboration avec la Direction de la Communication). En tant que Co-président du Laboratoire Commun DRSC, j'ai assumé des responsabilités de pilotage et d'animation scientifique, de défense du bilan de l'activité devant le Conseil Scientifique et le Conseil d'Orientation du Laboratoire, et de mise en oeuvre de ses recommandations.

Dans le domaine scientifique, j'étais responsable de proposition d'orientations scientifiques et de programme de recherche annuel de l'UR, de la définition de ses plans d'investissement à court et moyen terme (plans quinquennaux et projets d'investissements scientifiques à long terme, en collaboration avec la Direction Technique Générale), de la planification de ses budgets d'accompagnement de la Recherche (missions, conférences, formation), et de la politique de rayonnement scientifique de l'UR (communications et publications). J'ai participé à la définition des axes directeurs de la recherche du Département DMSE au sein de la Branche MAS (sous la tutelle des Directeurs de Recherche et de la Direction Scientifique Générale de l'ONERA) ; j'ai préparé, rédigé et négocié des projets pluriannuels de recherche avec nos partenaires régionaux, nationaux et internationaux (contrat de plan état-région, protocoles d'accord et de collaboration scientifiques, programmes de recherche EU, etc.) ; j'ai participé à l'expertise, auprès des Directions de Programme de l'ONERA, des niveaux de compétences d'équipes concurrentes ou complémentaires de celle de l'UR au niveau national et international, afin d'établir la politique d'intégration de l'Office dans l'Europe de la Recherche.

Dans le domaine des relations humaines, j'ai été impliqué dans la gestion des ressources humaines de l'UR (en collaboration avec la DRH), dans la recherche de la meilleure adéquation possible entre la politique globale de l'Office en la matière, et les besoins de l'UR. J'ai par ailleurs effectué un mandat de Délégué du personnel, et ai participé à un Groupe de travail de la DRH sur l'élaboration de la charte doctorale de l'ONERA.

Je suis actuellement (depuis 2010) *Chargé de Mission Scientifique* auprès du Directeur du Département *Aéroélasticité et Dynamique des Structures* (DADS). A ce titre, et aux côtés des Chefs d'Unités de Recherche, j'assiste le Directeur pour ce qui relève du pilotage et du rayonnement scientifiques du Département (par exemple en validant les projets de publication des chercheurs du département, en préparant le rapport annuel d'activités), et contribue annuellement à la préparation et à la tenue des Comités d'Evaluation et d'Orientation (CEO) du Département DADS, ainsi qu'aux réflexions menées à l'occasion des Journées Stratégiques ONERA de la Branche *Matériaux et Structures* (JSO). Nommé représentant du Département DADS au Comité Scientifique de la Branche *Matériaux et Structures* de l'ONERA, composée – en plus du DADS - des Départements *Matériaux et Structures Métalliques*, et *Matériaux et Structures Composites*, je suis enfin chargé – pour le DADS - d'assister le Directeur Scientifique de Branche MAS dans certaines de ses réflexions et missions (dont l'animation scientifique). A ce titre, je suis par exemple amené à participer annuellement à la sélection des dossiers de thèse proposés dans la Branche, et à l'évaluation des travaux des doctorants de 3ème année (un prix est décerné chaque année).

Par ailleurs, je suis chargé de développer les collaborations du Département DADS avec le monde académique, et suis en particulier Co-président du Laboratoire Commun CNRS/ONERA/UVHC/ *Dynamique Rapide des Structures et Collisions* (DRSC), créé en 2004 avec le LAMIH de l'Université de Valenciennes et du Hainaut-Cambrésis. Je suis également le représentant de l'ONERA au Comité Stratégique du consortium des utilisateurs et développeurs du Code de calcul explicite EUROPLEXUS (UE CCR, CEA, EDF, ONERA, LMS-SAMTECH). En tant que Thématicien du Département DADS pour la *Dynamique Rapide*, je suis enfin le correspondant de la Direction de la Commercialisation et de la Valorisation (DCV) de l'ONERA, qui me consulte à ce titre pour prospecter, favoriser et concrétiser de nouvelles opportunités de recherches contractuelles (e.g. ANR, FUI, UE) dans ce domaine scientifique.

Activités d'encadrement de la recherche

Thèses co-encadrées (quotité*)

Les doctorants co-encadrés (excepté J. Réthoré, qui a passé 50% de sa thèse au LaMCoS de l'INSA-Lyon) étaient accueillis à l'ONERA pour leur thèse, et placés officiellement sous la responsabilité d'un (ou plusieurs) ingénieurs(s) de recherche. Pour une partie des thèses listées ci-dessous, j'étais le responsable attitré (quotité de 1), mais pour d'autres, le responsable ONERA était un des collègues de l'Unité de Recherche que je dirigeais, mais j'assurais un suivi prononcé des travaux (quotité de ½).

Modélisation des chocs hydrodynamiques (3)

(1/2) Thomas Fourest, Advanced modeling of coupled fluid/structure hydrodynamics for vulnerability analysis – Application to the Hydrodynamic Ram in fuel tanks, University of Brest (ENSTA), 2015 (en cours).

(1/2) Grégory Haboussa, Contribution à la validation des méthodes numériques pour les problèmes dynamiques couplés fluide-structure, Université de Valenciennes et du Hainaut-Cambrésis, LAMIH, 2008.

(1) Gérald Portemont, Contribution au développement des méthodes numériques de traitement des interactions corps durs/corps mous - Application au crash, aux collisions ou aux chocs, Université de Valenciennes et du Hainaut-Cambrésis, LAMIH, 2003.

Comportement et rupture des matériaux composites à matrice organique (3)

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Foreword

One of the major goals of the French Aeronautics and Space Research Centre is to perform targeted Research in the Aeronautics and Space fields, for military and civil use. In order to perform a valuable targeted Research, it is essential to be involved in the Research effort. It is also necessary to detect the new emerging knowledge, offering a great potential for the aimed applications. Finally, in a context of generalised economic competition, it is also essential to be able to quantify – and thus prove – the progress that such new technologies can bring, as soon as possible in the development process. And that, always keeping in mind the necessity to produce Research results, readable and easily assimilated and used by the industry.

ONERA is interested in Material sciences (which concern data and models), in the « technological» Research (which concerns elaborated products), and in Applied Mathematics (which generate tools necessary to understand, solve and design aeronautical structures). The Research performed here is dedicated to these objectives, one of its goals being to enable the improvement of aeronautics and space structures against extreme aggressions. The illustrated case in the present research deals with the hydraulic ram phenomenon in composite tanks in case of ballistic impacts. Our concern here is to increase the structural strength, not for a purpose of durability but in terms of mechanical resistance against extreme solicitations, which is linked to the understanding and prediction (by numerical computation) of the behaviour (in dynamics) and the failure of composite materials, assemblies and structures, following high energy/high speed ballistic impacts in fuel tanks.

For particular applications (military, civil transportation, space) and for performance reasons, various material properties are sought (with different priorities according to the final product). For example, high performance metals and composites are widely used in different products of the civil aircraft industry (as well as in the military one). More and more aircraft components – including wings - are made of fibre reinforced composite materials because of high stiffness, strength and low weight. The composites structures can be made of carbon, aramid, glass fibres, etc, embedded into a polymer matrix. In some case, for equivalent energy absorption, composite components can be 50% lighter than steel components. In the present case, the resistance of aircraft composite fuel tanks to ballistic impacts has to be improved. One part of the solution is to increase the material characteristics. Another one is to develop theories and models which will enable the manufacturer to numerically design and optimise its structures regarding extreme load conditions. This means that the development and modelling of the materials must be done together with considering the structural problem as a whole, meaning: taking the general environment and the studied threat into account.

One of the preferred scientific techniques used to perform the analysis and the modelling of physical behaviours consists in the simulation of the studied phenomenon. This simulation can be experimental or numerical. One essential step of the proposed research thus concerns the development of theories and validation of numerical simulation tools. But this step definitely relies on the production of reference experimental results which deal with the different scales of material, assemblies and structural behaviour.

Chapter 2

Modelling of the dynamic behaviour of composite materials and structures

Synthesis of Research (1992-2013)

Introduction

ONERA is interested in material sciences (which concern products and models). The use of composite materials in the transportation industries is increasing every year, mainly to reduce vehicle weight. Lighter structures allow greater autonomy and reduced greenhouse gas emission. More and more aircraft components – including wings hence fuel tanks - are made of fibre reinforced composite materials because of high stiffness, strength and low weight. More than 50% of the A350 Airbus aircraft is made of composites, while for the A320 the figure was closer to 10%. Most of the aeronautic composites are carbon fibres reinforced plastic (CFRP) materials. But some structures can be partly made of aramid or glass fibres embedded in a polymer matrix. These composites, when used for structural applications, are subject to various kinds of loading during the airplane life, from creep during parking, to dynamic impacts during flight such as bird or ice ones. Compared to metallic materials, CFRPs are known to exhibit an increased brittleness when dynamic impacts are considered. On the other side, for equivalent energy absorption, aramid or Kevlar composite components can sometimes be 50% lighter than steel components. This means that the dependence of the composite materials behaviour to the solicitation speed must be characterised and taken into account in the design of structures.

In 1992, ONERA was contracted by EUROCOPTER for a F.E. modelling study of the crash energy absorption capability of organic composite sine-wave beam elements of the underfloor structure of the TIGRE helicopter. In the aeronautical field, the only aircraft which is compelled today to crash certification is the military helicopter. To pass certification, specific structural parts are designed and set in the underfloor part of the rotorcraft, in order to absorb the kinetic energy during crash events, to limit the acceleration levels transmitted to the crew and preserve the integrity of the primary structure. A commercial FE code (RADIOSS) was used for the exercise: the energy absorbers were modelled using a mesoscale description of the composite laminate (which included carbon and aramid reinforced plastic plies), with a static nonlinear orthotropic behaviour being taken into account. The conclusion came straightforwardly: the selected F.E. code (and probably any of the others) and CMO models could not succeed in correlating the tests results provided by EUROCOPTER [RE-36]. At that time, two fundamental questions raised: the first one was about the experimental characterisation of strain-rate influence on the non-linear behaviour and failure of the constitutive materials. The second one was about the formulation and development of strain-rate dependent mesoscale models for composite laminates simulations.

The topic of the presented research deals with the prediction of hydraulic ram effects in aircraft composite integrated fuel tanks in case of ballistic impacts. The concern here is to increase the structural strength, not for a purpose of durability but in terms of mechanical resistance against extreme solicitations. This is linked to the understanding and prediction (by numerical computation) of the dynamic behaviour and failure of composite materials, assemblies and structures. Indeed, in 1995, ONERA was contracted by the French DGA to study this topic in the frame of the development of the future Military Transport Aircraft (Avion de Transport Futur), meaning the actual A400M. The issue was then to decide whether metallic or composite wings, hence integrated fuel tanks, should be proposed: the problem was the well-known brittleness of carbon fibres reinforced plastic materials with respect to dynamic loads, with an identified risk that a composite design could possibly dramatically fail in case of hydrodynamic ram loads consecutive to ballistic impacts [RE-16]. The main research outcome was the improvement of the composite design in terms of damage resistance (high energy involved) and not damage tolerance (low energy involved, less than 140 J according to the norms). The main point to reach such an objective concerned the development of numerical models that would enable the manufacturers to design and optimise their composite wings/fuel tanks considering this very high velocity load case (impacts about 1000 m/s, compared to 10 m/s for crash situations). This also meant that the selection of improved materials could not be done without considering the representative structural problem as a whole : so, and because of their numerical efficiency for structural simulations, mesoscopic models were preferred to simulate the composite structures behaviours.

Any finite element numerical simulation of the structural response of composite structures (here fuel tanks) during high-speed dynamic events (here HRAM) requires first to characterise the materials dynamic behaviour in the full range of solicitation speeds which take place during the aggression. Clearly, when very high speed and energetic solicitations are studied, the question of the dependence of the CMO material behaviour and failure (including delamination) does not only stand in terms of strain rate, but also in terms of temperature (as it is also for metallic materials for high strain rates, see the Johnson-Cook model). The dynamic effects influence the different phases (linear and non-linear) of the material response. Many progresses were still to be made concerning the understanding of these effects. For materials that are not or not much strain-rate dependent, the modelling and characterisation of the behaviour under a quasi-static loading can be enough to perform numerical impact simulations. For strain-rate dependent materials, one cannot bypass the dynamic tests to characterise and identify the most appropriate models in the strain and strain-rate ranges of interest. The first following paragraph deals with the question of testing these CMO composite materials dynamically, which is a quite different and very difficult problem compared to metallic materials.

The second part of the works that are presented in this chapter concerns mesoscale models that have been studied at ONERA from the beginning of the 90's to represent the composite CMO dynamic behaviour from the low strain viscoelastic phase, up to the final rupture, via the damage development at intermediate strains. This research started with the development of a semi-empirical model on the basis of inelastic work considerations (the purpose of the design being to best dissipate the initial kinetic energy of an impactor). The last – more recent and still in progress – part of the presented work is dealing with more physically based models. Considering all these models, the main future research issue would be to propose a unified frame for the description of creep, static, fatigue and low to high-speed dynamic composite material behaviours.

Dynamic testing of CMO composite materials

The first point of course is to determine whether a given composite material has to be considered strain-rate dependent or not. The question is not so simple, since among all the works performed at ONERA [RI-18], [RE-27], [RE-30], [RE-32], it has been observed that the composite laminates as a whole did not always exhibit a clear and simple dynamic dependent response, when it was proved that the constitutive plies behaviour did. As mesoscopic modelling was targeted (and possibly links with the microscopic scale), it was decided from the beginning to introduce – then characterise - dynamic effects in the non-linear behaviour models of the constitutive plies of composite laminates [RE-33], [RE-86]. Then, it was necessary to properly identify these dynamic models parameters, which turned to be another serious difficulty.

Concerning experimentation, one must first say that scatter in results, which depends on various non-deterministic parameters (defects in materials, process quality, initial damage, etc), considerably increases when one considers dynamic events and rupture. Many other poorly-known or ill-quantified parameters might also play a significant role on the dynamic test results (e.g. bad-alignment of specimens, sliding of the specimen between grips, etc), that would then simply lead to erroneous test understanding and exploitation, if not cared of and/or taken into account for the modelling exercise. So, it is of utmost importance to precisely identify and control all these parameters, what can only be assessed after having systematically performed a sufficient number of tests. Such tests being destructive, the related costs are expensive (one must also consider that for research needs, the instrumentation and the results exploitation are heavy and expensive processes).

As previously said, fully physically justified models of the dynamic behaviour of materials are generally not implemented in the industrial numerical tools. Phenomenological and empirical models are usually found, which raise a validity problem when used beyond the range of solicitation that was covered by the experimental tests for their identification purpose. During an impact solicitation, a large structure will experiment a very large range of strains and strain rates (possibly very high levels at the impact point and time, and possibly very low levels far from this point and time). To obtain mechanical tests for all these strain rates, from static to dynamic cases, different testing machines have to be used. The main reason of that is that it is not possible to design a single testing machine of such mechanical capabilities that are required by the targeted tests so easily. For instance, on-the-shelf static testing device can easily be found with high capabilities in terms of effort (ONERA possesses a 30 T static tension/compression machine) and size of specimens (normalised static specimens are quite large to satisfy the Saint Venant principle). But finding hydraulic machines that can still develop such efforts dynamically is almost impossible: ONERA had to design its dynamic testing machine by itself, thirty years ago, to get a 5 T-10 m/s dynamic jack. Today, one can more easily find commercial conventional testing machines for strain rates lower than 0.1 s^{-1}, servo-hydraulic machines for strain rates between 0.1 to 100 s^{-1} and Split Hopkinson pressure bars (SHPB) for strain rates from 500 to 10^4 s^{-1}, which can be used to test metallic materials [CI-15]. The current development of composite (especially high modulus and high-toughness CFRP) materials with higher mechanical characteristics is bringing the difficulty back in the test laboratories (esp. when 3D interlock, braided, etc, composite materials are studied).

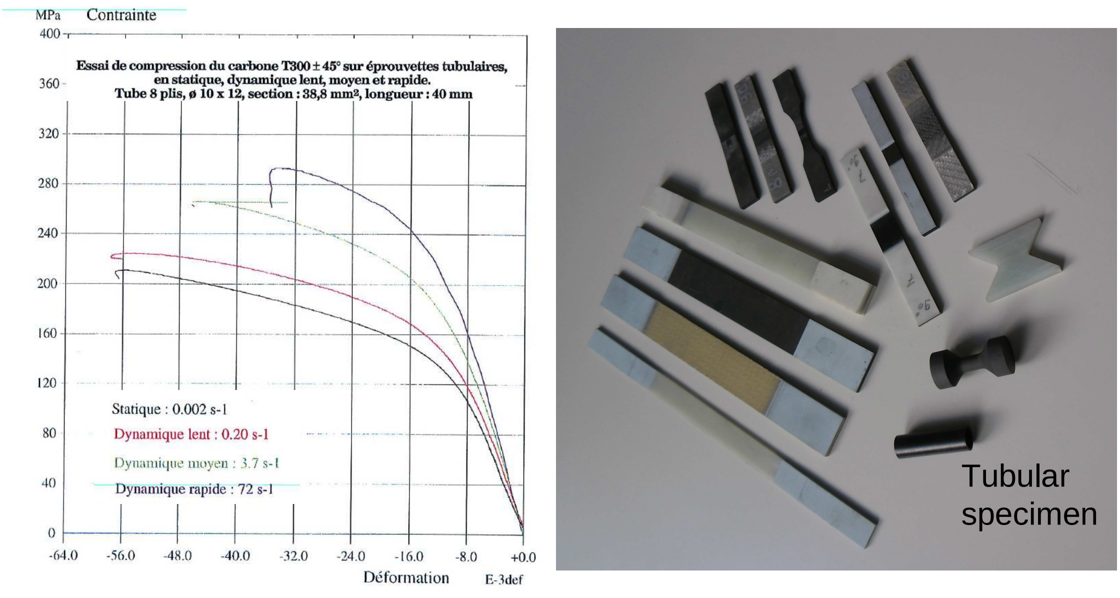
In general, the dynamic material specimens must have smaller dimensions than the static ones, in order to fit with the dynamic test machines lower capabilities in terms of effort. Then, the characterisation of the dynamic behaviour of the materials on a full strain rate range which requires creep, quasi-static and dynamic tests (necessarily realised on various testing machines), cannot be performed without a risk of inconsistency appearing on the test results, due to the change of testing machine, and variation of the geometry of the samples from one machine to another. The question of having a representative elementary volume of material is the first point that limits the possible minimum thickness of the specimens in particular. But edge or shape effects can also come into account when the material specimen response is studied. This risk is increased when composite materials, including CFRP ones, are studied, since this kind of materials is known to naturally exhibit scale effects. For instance, research work on similitude has shown that the composite material mechanical parameters generally vary when less or more that tree constitutive plies are studied. Also Delsart [Delsart, 1999] found a difference of 15% on a CFRP shear modulus between different specimen geometries with different width/free length ratio, tested on the same testing device. Rosen himself – when he proposed his well-known and now standardised composite shear modulus characterisation protocol - warned the user community about possible important geometry and scale effects on the nonlinear response of his specimen. So, the use of various testing devices is classically associated to the use of various sample geometries. When normalised test samples are used on conventional static testing machine, shorter samples are used on dynamic jacks and SHB testing devices that each test laboratory can design as it thinks better. Lots of work have been done at ONERA in the 90's to study different dynamic specimens geometry [RE-33], [RE-86] to be tested on its 5 T/ 10 m/s hydraulic jack : flat rectangular material coupons, 2D and 3D dog-bones specimens, cylindrical tubes were first studied for metallic materials. Concerning composites materials, specimens with added tabs, and dog-bones Diabolo cylindrical ones, were also sometimes used for tension or compression dynamic tests respectively.

The first part of the presented experimental works was performed in the 90's. It concerned this kind of relative characterisation of strain rate effects on composite material behaviours, using a single test machine and various specimen geometries. In parallel, many other connex and complex phenomena have been experimentally sudied in dynamics, such as the influence of the environment temperature on the material behaviour, or structural (understand macroscale) aspects such as delamination, scale effects, and assembly. The second and more recent part of the works concerned the development of specific test protocols using Split Hopkinson Bars, and improvement of tests on Hydraulic jacks, with a particular concern being given to ensuring the consistency of test results coming from different testing machines and specimen geometries.

Development of specific experimental protocols and composite test specimens for the characterisation of composite CMO non-linear behaviour and rupture [RE-33] RE-34] [RE-35]

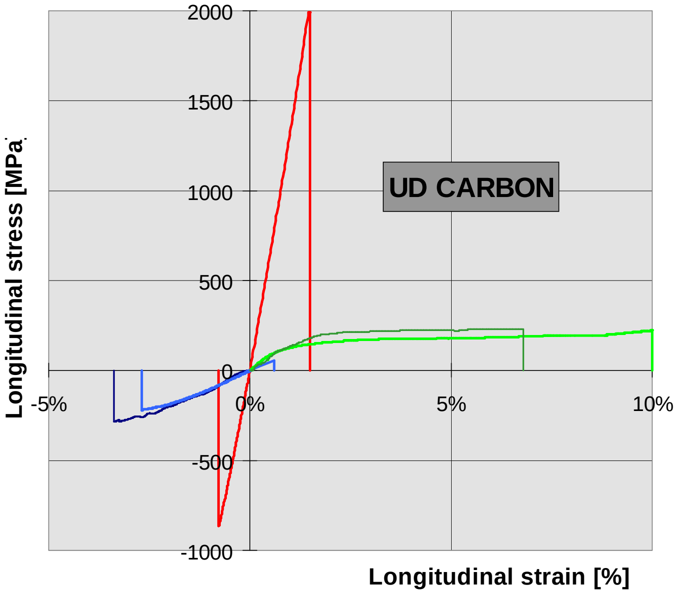
The first research works (the tested material was the T300/914 tape material) aimed at the dynamic characterisation of materials under uniaxial traction and compression loading conditions, with the use of the ONERA dynamic hydraulic jack. The main characteristics of this testing device are: maximal displacement speed of 10 m/s, 50 KN load capacity, and 250 mm of displacement range. Working with small dimensions coupons (effective length of 20 mm and section of 20 mm^2), the objective was to reach strain rates up to 500 s^{-1}, and failure for high-strength materials (carbon fibres UDs). For this kind of tests, no standard is available neither for the specimen geometry or the testing machines: it is always a question of compromise. Compared to static tests, specific strain gauges were almost systematically used: it is almost impossible to get the specimens strain simply from the load actuator displacement measures (because of the specimens stiffness which is not negligible compared to the test machine one since the more heavy the load actuator, the more difficult to reach higher velocities). Small dimensions and wide strain range (20%) gauges are necessary to get a grip on the high local nonlinear behaviour, with high frequency band not to modify the dynamic data at full speeds.

The dynamic tests immediately raised major difficulties: the goal was to perform tests at a constant and imposed strain rate, it was thus necessary to transfer to the jack enough power to achieve that. Then, in compression, once the coupon breaks, the jack must be stopped before it damages the load piezoelectric cell. That could only be achieved by increasing the coupons length hence decreasing the strain rate levels in specimens. Moreover in compression, it is essential to work with sufficiently important sections, to avoid the buckling mechanism, which is not a material phenomenon but a structural one. As the coupons strength increases with the section, the maximum loading capacity of the testing device was rapidly reached. For the tensile tests, two other problems appeared. The first one concerns the need to grip the coupon (unlike the compression tests where the coupon could simply lay on the plate). Gripping the coupon introduces tri-axial stress state close to the auto-clamping jaws. Then it became essential to increase the complexity of the composite coupons geometry to avoid failure problems in the jaws (addition of tapes, machining of the effective length part of the specimen, etc). Moreover, the gripping/clamping system introduces clearance, mass and specific dynamic contribution. All that contributed to the appearance of mechanical noise, which gets more and more penalising as the loading rate increases (natural frequencies, etc). Finally, and after lots of works have been done to improve each of these points, composite materials were hardly characterised up to 50 s^{-1} in tension along the fibres directions, with very different geometries being used for uniaxial tension and compression tests. Note that the elastic strain rate is considered here, in the linear domain, since no non-linearity usually develops in the elastic-brittle fibres direction. When the materials shear behaviour was investigated, strain rates could largely increase in the nonlinear domain, compared to the linear elastic one.



Dynamic test results on tubular specimens of T300/914 (left) and example of various composite specimen geometries (right)

At low speed, the behaviour of the T300/914 carbon/epoxy UD composite material was elastic brittle in tension and compression along the fibre directions. When standard specimens (flat or tubular) were used for compression, the maximum stress fell down to less than half the tension value. The difference of behaviour between tension and compression has been reported to almost disappear once specimens with anti-buckling guides were used to prevent buckling instabilities: another way to deal with these instabilities was to use thicker specimens. This was the reason why ONERA studied Diabolo shape specimens. These specimens had to be machined out from thick composite plates and the machining difficulty and cost was so high that this specimen geometry was eventually abandoned. In the transverse direction, the maximum stress and strain were much higher in compression than in tension (more than 450%). This was due to the fact that the failure mechanism is very sensitive to the load direction (fibre/matrix debonding in tension). The tension behaviour was linear elastic brittle and the compression one clearly non-linear though it was not checked then if it came from plastic and/or damage mechanisms by cycling the quasi-static tests. For +/-45 laminates, the static behaviour was highly non-linear in both tension and compression. Again, it was not studied if the non-linearity came from plastic and/or damage mechanisms. Under dynamic loads, the behaviour for carbon/epoxy UD proved to remain elastic brittle in tension and compression along the fibres direction, with a noticeable but small difference between tension and compression. The scatter in failure stress/strain was important and did not permit to exhibit any strain rate influence that was not expected anyway. For the transverse (in compression) and shear directions, the material behaviour kept the same general trends than in static, but with their characteristics being very sensitive to the strain rates (between 10^{-3} s^{-1} up to 50 s^{-1}).

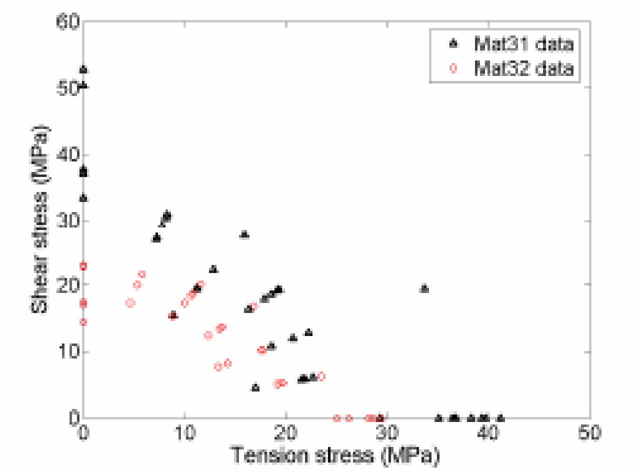


Dynamic test results on a carbon/epoxy UD tape material (red in the fibre direction, blue in the transverse direction, and green in the in-plane shear direction)

The characterisation of out-of-plane and through-the-thickness material properties raised great difficulties. Indeed, it would have been necessary to manufacture very thick composite plates to be able to machine test specimens to study the materials out of-plane tension, compression and shear properties. The only attempt that was made in the early 90's concerned the unidirectional T300/914 material, for which 20 mm long Diabolo shaped specimens were machined out from very thick plates to test the compression behaviour in the fibre and transverse direction, to compare them with test results obtained with other specimens geometries (flat, tubes, etc). Some attempts were made in the Research Unit in the late 2000's to use the Arcan test protocol [Arcan, 1987] to characterise the out-of-plane behaviour of a glass E/epoxy UD composite material under static conditions, together with the study of rupture and delamination criteria, that were reported in [Gning, 2006].

E_{11}^t	E_{11}^c	E_{22}^t	E_{22}^c	G_{12}	ν_{12}	ν_{23}
45.4 GPa	43.4 GPa	10.9 GPa	10.1 GPa	4.4 GPa	0.297	0.3

	Shear Modulus (GPa)	Strength (MPa)	Failure Strain (%)
Mat31	3.9 (10%)	42.3 (21%)	2.81 (53%)
Mat32	3.8 (8%)	18.9 (21%)	0.52 (10%)

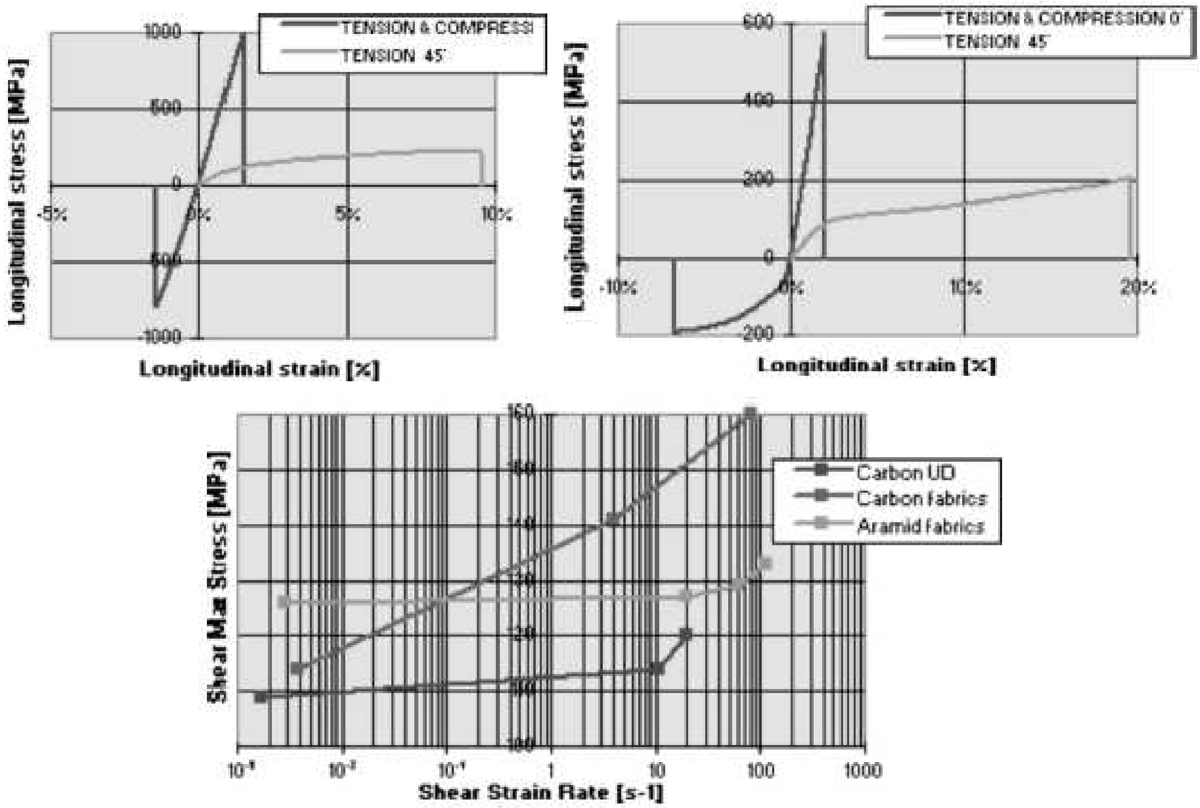


Elastic moduli and biaxial fracture envelope of glass E/epoxy material obtained with Arcan test protocol

If necessary, for unidirectional materials, an isotropic transverse assumption was generally proposed to be made, the material behaviour being supposed to be the same in the tension, compression and shear directions which involve a transverse resin direction (σ_{22}, σ_{33}, τ_{12}, τ_{31}, and even for τ_{32} which is more questionable). For composite fabrics, this kind of assumption can clearly not be made. Since thin composite structures modelled with shell elements, hence plane stress states problems which do not need through-the-thickness material behaviour to be known ($\sigma_{33} = \tau_{23} = \tau_{31} = 0.$), were studied, the testing of thick specimens was finally abandoned due to expensive manufacturing and machining costs. Note that existing specific static normalised protocols to characterise the out-of-plane shear behaviour of composite materials (τ_{23}, τ_{31}), have only been implemented in the laboratory very recently, because thicker and thicker composite pieces, and 3D composite materials, are being introduced in the aircraft structures today.

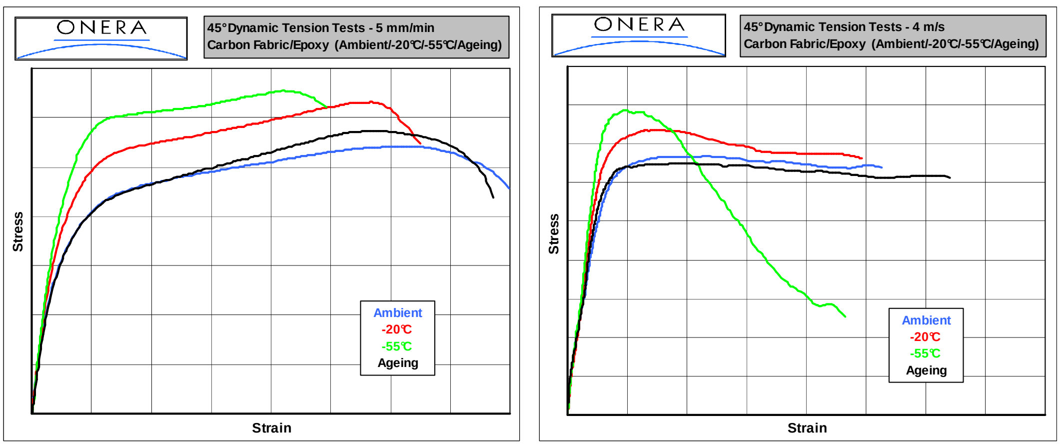
Analysis of the dynamic behaviour for a large variety of different CMO materials and first evidence of temperature effects [RE-27] [RE-30] [RE-32]

In the following years, in the frame of an international cooperation (ONERA/DLR and FP7) which concerned the composite aircraft and rotorcraft crashworthiness, many other composite materials have been tested up to the hydraulic jack speed limit, which included both thermosets [RE-29], [RE-31], [RE-32], [RE-92] : UD carbon/epoxy, carbon and aramid fabric/epoxy, and thermoplastics : carbon and aramid fabric/PEI. The tests that ONERA-Lille performed with this dynamic facility were tension and compression tests on 0°, 90° and +/-45° [Rosen, 1972] specimens. According to the tested material, assumptions were sometimes made to reduce the number of tests: for instance the behaviour of balanced fabrics in the warp and weft directions were often assumed to be the same, and only checked in static. The force level was measured thanks to a piezoelectric cell, which made it possible to get the conventional stress evolution. Displacement of the main crosshead could be directly measured, but strain gauges were systematically glued on the specimens to get accurate values enough to draw the material stress versus strain behaviour, measure the Poisson coefficients and get the rational stress/strain curves. Maximum strains were possibly given when the limit of the strain gauges had not been reached. Yield stresses were also defined when the behaviour turned to be non-linear enough to define a 0.2% strain limit value. Compared to carbon fabric/epoxy materials, the behaviour of the aramid/epoxy fabrics was different in tension compared to compression along the fibres direction: it looks elastic-brittle in tension, and highly non-linear (elastic-plastic?) and highly sensitive to the strain rate (between 10^{-3} s^{-1} and 50 s^{-1}) in compression. In shear, the maximum strain level was higher (almost 20%) than for carbon/epoxy materials, with always a highly nonlinear and strain rate dependent behaviour.



Comparison of carbon/epoxy (upper left) and aramid/epoxy (upper right) fabrics behaviour, and maximum shear stress strain rate dependence (bottom)

The dependence of the carbon/epoxy materials behaviour to the temperature was also investigated, together with the strain rate. The mechanical tests were realised in a cryogenic caisson, and the temperature was decreased down to about -100°C (using liquid azote). The tests results clearly shown an important influence of these two parameters onto the non-linear behaviour of the material, especially when the shear response was studied.



Combined influence of temperature and strain rate on
the behaviour of an organic composite material

These temperature effects are more deeply studied today, as it will be presented in next paragraphs.

In the end, few experimental points are necessary to identify a linear or logarithmic strain rate dependent model. For physical or phenomenological models based on thermodynamic / mechanistic formulations, several points at selected strain rates could be enough. But a continuous and consistent characterisation over the strain range is absolutely necessary for the identification of empirical models, which are the most widespread ones in commercial explicit FE codes. This necessity is all the more obvious if more complex and piecewise strain rate dependent behaviours are concerned. During this first research, the existence of scale and shape effects on small size coupons or different shapes was clearly confirmed. So, ONERA decided to conduct a dedicated experimental research, with one of its goal being the search of at least partial overlapping between the different ranges available thanks to the various testing devices (static machine and dynamic jack, Hopkinson bars, etc), to validate the continuity (and thus the coherence and validity) of the tests results obtained with very different experimental means and exploitation protocols.

The first step to reach this goal, consisted in performing quasi-static tests with normalised test specimens (at a quasi-static speed of 5 mm/min) on ONERA 10 T static machine, and in comparing test results with those obtained with specific dynamic geometries on the ONERA high-speed jack (at the same rate of 5 mm/mn). Then, a new testing device for the ONERA high-velocity jack has been developed to alleviate problems of vibrations (a Titanium test rig was manufactured, and a piezoelectric load cell with higher dynamic characteristics was set up), which permitted (together with the use of more accurate filtering techniques) to increase the exploitable speed range of the machine for at least 4 constitutive CFRP plies specimens in tension (from 1 m/s in 1995 up to 4 m/s today), then reaching $100s^{-1}$ strain rates properly. In parallel, Split Hopkinson Bars systems were specifically designed to reach the lowest strain rate range as possible: one of the main difficulty in the use of Hopkinson bars appears when one wants to characterise materials for large strains (higher than 10%), which leads – for low velocities - to increase the bars length (to avoid the use of deconvolution tools to solve problems of superposition of reflected waves). The use of extensometric techniques (gauges first, then optical extensometry) instead of the original SHB theory (which imposes very small specimen dimensions in compression) was proposed to characterise the stress/strain tensile behaviour of CMO from longer specimens. The overlapping of test data between these SHB test rig and the hydraulic jack was demonstrated (the same specimen being used for both) between 300 and 400 s^{-1} (for XES steel and 2024 aluminium) [CI-15], [Haugou, 2003], which was still far from the $100s^{-1}$ highest strain rates obtained with the hydraulic jack.

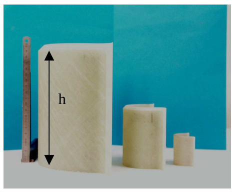
ONERA High-velocity jack (left) and Split Hopkinson bars (right)

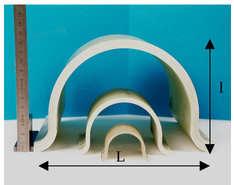
To increase the strain rate range with the hydraulic jack up to 300 s^{-1}, several solutions were proposed: first, the use of bi-stage specimen shapes, with a larger part of the specimen keeping in the material elastic strain range, and a strain gauge glued there to measure le load instead of using the piezoelectric cell. The problem was then again a question of the experimental cost, since the machining of composite specimens is not easy, and the machining quality issue is important to reduce scatter in the dynamic test results. On the other hand, the SHB system proved to be difficult to use to test composite materials, and several years of developments were still necessary to reach the initial objective in terms of exploiting the SHB strain rate range capability for composites [Portemont, 2011].

Scale effects and similitude analysis of the dynamic response of composite structures [RI-18] [CN-14] [CN-03]

During the same period, some research was performed which concerned scale effects in composite materials and scaling rules for composite structures [CN-3], [CN-12]. Indeed, similitude or scale reduction techniques were and will still be a major stake for industrials in the field of structural testing, as long as virtual testing will not be completely validated. Then, a study dealing with the evaluation of different ply arrangement techniques has been done on omega structures at different scales, and crash tests performed at different velocities. In the studied scaling method, the material was the same for all the scaled specimens, and a Cauchy geometric similitude was applied on the dimensional parameters of the selected omega structure. The Cauchy similitude also implied the conservation of the impact speed.

	Prototype	Model
Displacement	δ	$\beta\delta$
Load	F	β^2F
Energy	Ec	β^3Ec

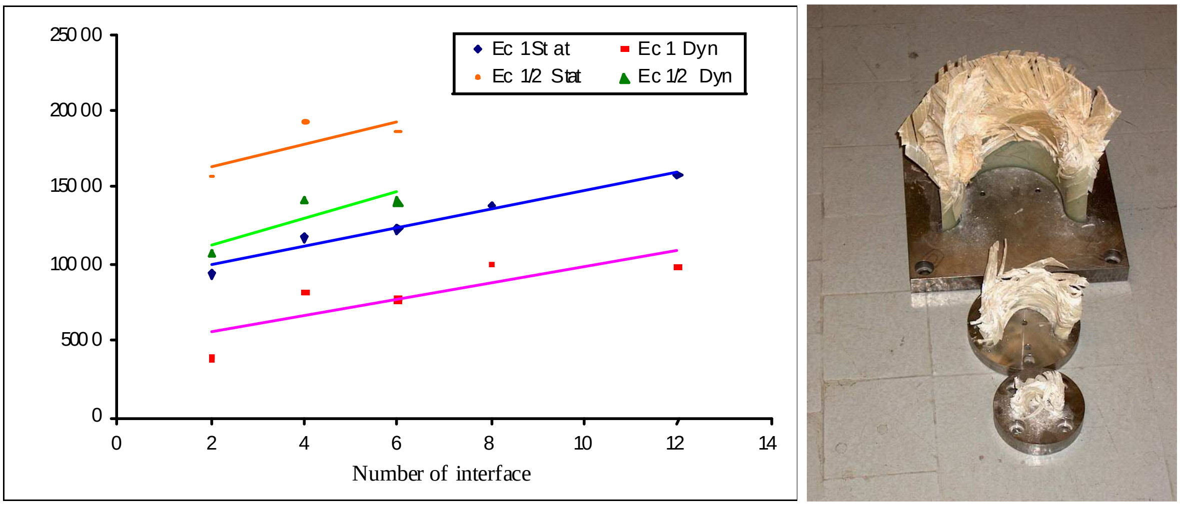




Cauchy relations for the displacement, strength and energy absorption

All the omega specimens were made up of an E/epoxy glass material that had been previously characterised in the test lab, under static, dynamic (accordingly to the previously described protocols) and cyclic mechanical loads (since the Ladevèze damage model was used for the simulation part of the work) [Ladevèze, 1991, 2002], [Rozycki, 2000], [Dormégnie, 2001]. The most interesting results were obtained with the +/-45° laminate whose main advantage was to feature a more stable compression load plateau. This campaign showed the little influence of the loading speed on the crush response of the omega specimens (from 5 mm/mn up to 4 m/s), while the E/epoxy glass material dynamic characterization at the ply mesoscale level had shown opposite results. This kind of results had already been observed in previous helicopter crashworthiness studies. When some difference appeared, it was explained by the higher amount of debris remaining at the contact between the impactor and the structure in static (in dynamics, debris are projected away from the contact surface, thus reducing significantly the effort). The second important conclusion of this work concerned the dependence of the amount of dissipated energy during the omega specimens crushing, and the number of interfaces in the stacking sequences (which varies from 2 to 14 interfaces when the full scale was studied): for instance all the stacking sequences between the $[+45_4 / -45_4]_s$ and the $[+45 / -45 / +45 / -45 / +45 / -45 / +45 / -45]_s$ laminates were tested.

In the case of the omega specimens with the maximum number of interfaces (2 interfaces for scale 1/4, 6 for scale 1/2 and 14 for scale 1), the energy and effort were nearly the same considering the scaling parameters, as long as the rupture mode is the same. The main rupture mode observed in the tests performed consisted in a peeling mode where plies progressively and symmetrically split, on both sides of the middle-plan of the structure.



Evolution of the static and dynamic energy absorption according to the number of interfaces for the 1/2 and 1 scale omega specimens (left) and pictures of the specimens (right)

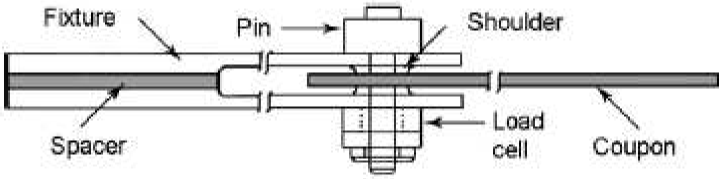
The last but very important conclusion of this work was that it would be clearly necessary to properly characterise and model the interfaces delamination mechanisms, to predict composite laminates response and energy absorption capabilities under static or dynamic conditions, and that previous research works had to be continued [Walrick, 1999].

Influence of CMO stacking sequence on the dynamic bearing strength of composite riveted assemblies [RI-06] [RN-02]

When considering the design of aeronautical structures in terms of crash and impact resistance, riveted joints should fulfill a double role. They are first vital for maintaining the structural integrity of the structure, but they could also contribute to the energy absorption thanks to specific failure modes. The very first research works on this subject in the Research Unit concerned metallic structures [RI-12] [R1-13] [Langrand, 1998], which are still continued today as presented in many details in [Langrand, 2010].

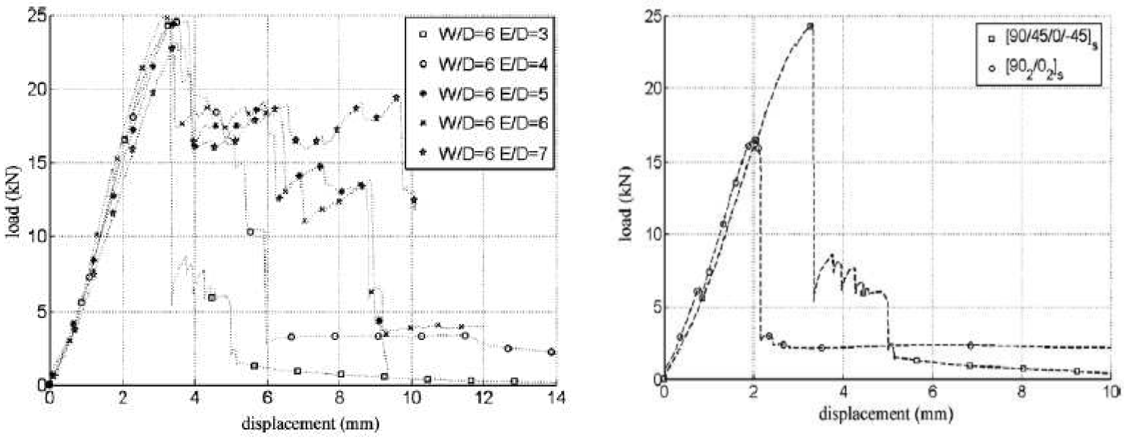
For composite structures a dedicated research was also done that concerned the specific bearing failure mode of composite riveted joints, which is characterized by a stable progression of the rivet through the composite laminate and therefore leads to notable energy dissipation [Postec, 2006]. It has been demonstrated in several works that the improvement of composite fuel tank structures with respect to HRAM loads would depend on the riveted connections capabilities to withstand these hydrodynamic loads [RE-6], [RE-38]. Though many studies concerned bearing failure mode, most of them mainly focused on the initiation of failure (few data were available on the propagation phase of the bearing failure, which sustains the absorbed energy) or targeted at evaluating the influence of geometrical parameters (width and edge margin, with respect to the rivet diameter). Notably, as it has been seen previously, the influence of a specific parameter of composite laminates – namely the number of inter-ply interfaces – already known as playing an important role in the behavior of composite energy absorption components, had never been studied. The proposed works therefore aimed at experimentally studying the influence of the loading speed and the number of interfaces on the bearing properties, i.e. the energy absorption capacities, of riveted composite joints and at analyzing the failure mechanisms involved in bearing processes.

An experimental protocol was then proposed based on the ASTM D591 standard procedure dedicated to the analysis of bearing properties of polymer matrix laminates reinforced by high-modulus fibers. Within the presented works, a double shear configuration was selected: it was made of two metallic fixtures machined in a heat-treated steel (Marval 1800 Mpa) material and linked by a bolted pin (fastener), which permitted to load the composite coupon. The fixtures and composite coupons were in contact through two cylindrical shoulders directly machined on the fixtures (diameter 13 mm). A load cell, which the load pin passes through, was placed on the external side of one fixture in order to control and record the evolution during the test of the clamping force applied to the specimen. An initial fastener torque of 3 Nm was thus imposed, in agreement with the specifications of the ASTM procedure. With respect to the norm, specimens consist in flat, constant rectangular cross-section coupons, with a center-line hole located near one end.



Presentation of the adapted ASTM protocol to test bearing failure of composite laminates

The protocol was used to the study of the previously described and characterized glass E/Epoxy material. After preliminary tests, according to the different studied laminates, modifications of the experimental protocol had to be considered to get the expected bearing failure mode, through a variation of the margin distance E and the width W of the specimens, reported to the hole diameter D. It was observed that an increase of the E/D ratio (E/D = 5 or E/D = 6), compared to the initial ASTM specification (E/D = 3), led to the apparition of the bearing mode, when an E/D = 3 ration was often synonym of net failure mode.

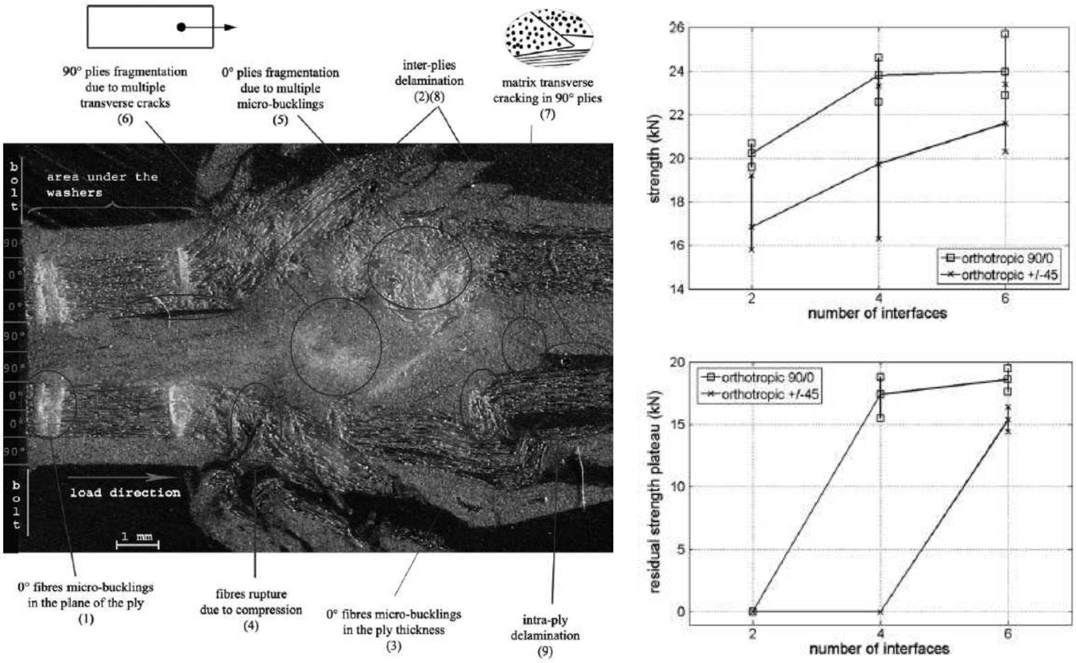


Influence of specimen geometry on the specimen response for a quasi-isotropic laminate with a maximum plateau for W/D = 6 and E/D = 3 (left) and net failure of other laminates with W/D = 6 and E/D = 3 (right)

To analyze the influence of the number of inter-ply interfaces on the bearing behavior of the composite laminates, six symmetrical orthotropic laminates made of eight pre-impregnated plies were defined, constituted either of (90/0) or of (±45) orientations. For both cases, the change of some plies position in the laminate thickness permitted to modify the number of interfaces, from two to six. Consequently, specimens were 5.3 mm thick, which slightly exceeds the ASTM specification. The drilling of the specimens was carried out with a standard ''Brad & Spur'' 6 mm carburized drill, which was reported to give the best results. This drilling constitutes a delicate operation which can, in addition to heat increase, cause delamination and damages. The drill rotation and advance velocities, which strongly influence the degree of development of potential damage mechanisms, were carefully defined in order to minimize possible damages.

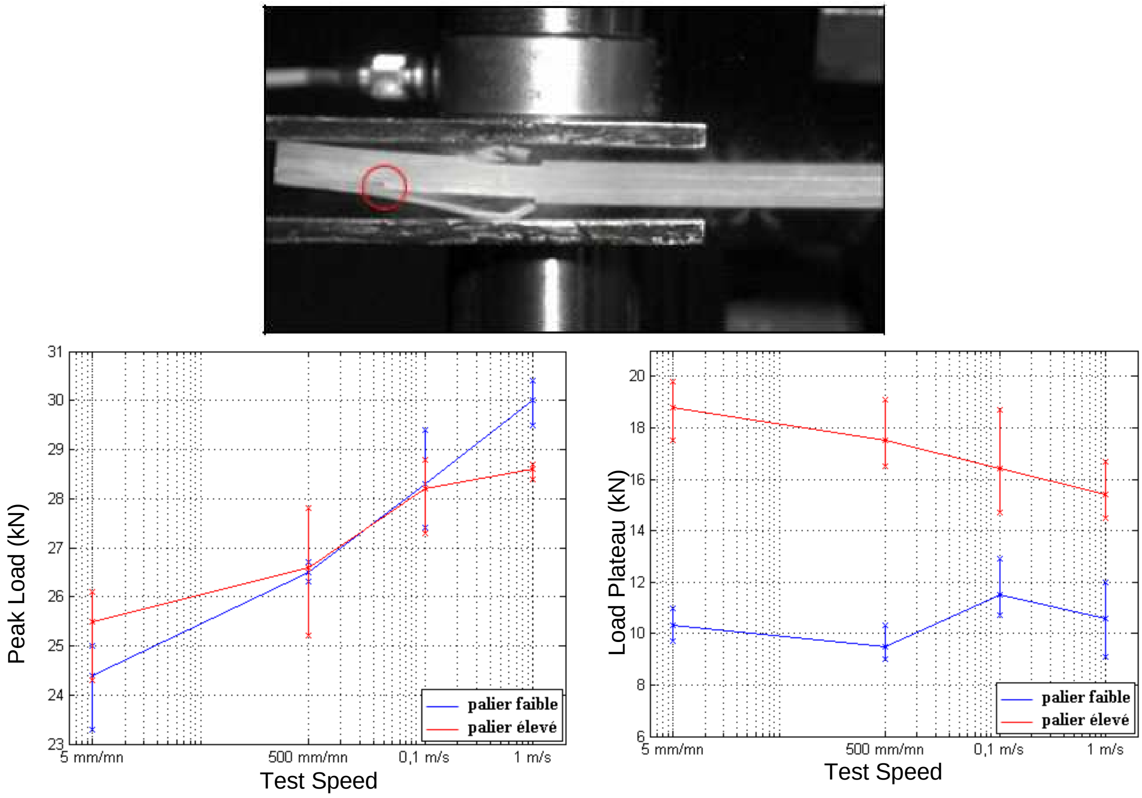
Static and dynamic tests were performed on the already mentioned hydraulic static machine and hydraulic jack. Four data were measured, two efforts and two displacements. The first effort was the load sustained by the specimen and measured by the piezoelectric load cells. The second effort was the clamping force. The global cross-head displacement was measured by means of standard mechanical extensometers. An optical extensometer was also used to measure the local displacement between two black/white targets, one located on the fixture of the ASTM rig and the other painted on the specimen, at the hole neighborhood.

Taking into account the low number of plies and the nature of the studied material, the external observation of the specimen after testing can give relevant information on the development of some rupture mechanisms, such as delamination. To look in further details failure phenomena and due to the impossibility to visualize in situ the rupture process during the testing, some specimens were additionally cut-out through their thickness, post-mortem, for microscopic observations. To avoid material losses and local modifications during the cutting, specimens were preliminary molded in a colored resin, sufficiently fluid to infiltrate the cracks by capillarity effect. The microscopic visualizations showed the high complexity of the failure mechanisms involved in the bearing process, including fragmentation, micro-buckling and delamination.



Failure mechanisms for $[(90/0)_s]_2$ laminate (left) and synthesis of evolution of peak and plateau loads according to number of interfaces for 90°/0° and +/-45° laminates (right)

Concerning the influence of the test speed on the test results, only the quasi-isotropic laminate with a maximum number of interfaces was studied. The test results could be decided in two sets according to the plateau level: one set of specimens developed a high plateau level together with a symmetric failure progression, when the second set developed a low plateau level with a dissymmetric failure mode with bending of the specimens. Whatever the plateau level, the test speed clearly influenced the maximum peak load before the bearing failure mode (20% increase on the 5 mm/mn to 1 m/s speed range), when its influence on the load plateau is less pronounced.



Dissymmetric failure mode with low plateau level (top) - Influence of test speed on the peak and plateau loads for the quasi-isotropic laminate with six interfaces (bottom)

Despite the natural dispersion of rupture test results when composites are studied, the significant number of tests permitted to draw general conclusions with good confidence. The influence of the number of inter-ply interfaces on the fracture mode was clearly highlighted. According to the tested laminate, an increase of this interface number permits to pass from a brutal rupture mode to a progressive rupture in bearing. One could identify a critical number of interfaces necessary to obtain bearing, this parameters being proved to be dependent on the tested laminate (four for the (90/0) laminate and six for the (±45) laminate). For the selected geometrical dimensions (E/D and W/D), the increase in the number of interfaces permits to decrease the stress concentrations imposed to each interface, by generating a more homogeneous stress distribution in the thickness of the specimen. The global resistance of the laminate increases and the force level necessary to initiate bearing is more likely to be reached – before a brutal rupture – with higher number of interfaces.

Also these test results confirmed the conclusions that were drawn from the scaled omega specimens tests under crash conditions: the influence of the test speed on the failure mode and the associated dissipated energy was clearly much less than the influence of the number of interfaces. All these results finally demonstrated again the importance of correctly characterizing and modeling delamination in composite laminates when their static and dynamic strength and energy dissipation capabilities are investigated. The characterization and modeling of composite delamination is being studied in the Research Unit since the 90's, but will not be presented in the present report.

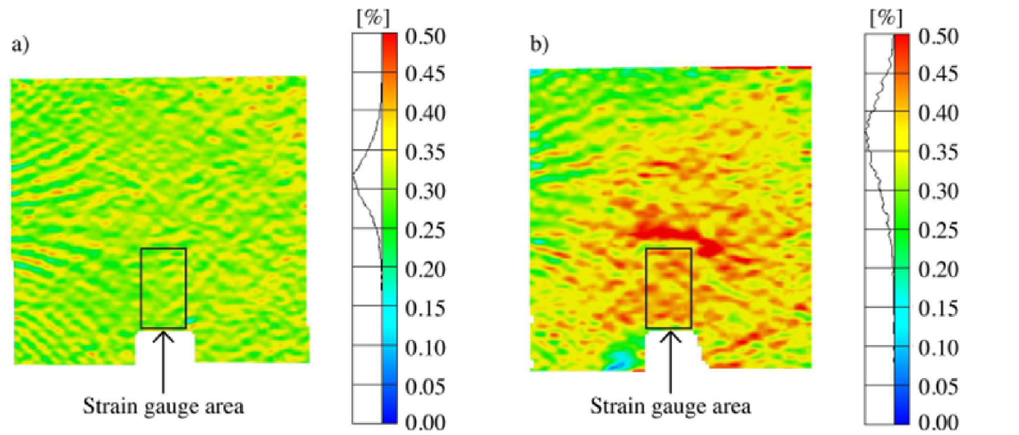
Evidence of strain rate dependence of the viscoelastic behaviour of CMO – Towards a pre-normalisation of tensile test protocols [RI-19] [CI-24] [CN-15]

The last research work that is presented in this chapter has been started more recently. The main reason of that being the increase of computer power and the increased capabilities of test instrumentations, which makes it more and more possible to characterise and validate physically based models for which the modern numerical simulations. Several aspects of the dynamic behaviour of composites were neglected up to now, because they were difficult to study, and of less importance compared to others when empirical models were considered. When physical models are expected, each piece of behaviour is of equal importance. In the previous test campaigns, several aspects were noticed such as the influence of the test speed on the elastic behaviour of the composite materials, or the temperature effect on the non-linear behaviour of these materials. In the frame of an ONERA self-funded research project, "Projet de Recherche Fédérateur Transition Statique-Dynamique" [RE-19], [RE-23], [RE-83], and in Berthe's PhD work [RI-19], the question of unifying static and dynamic models that were previously separately developed by different research teams was raised. The challenge is to develop physically based models that could be used to study the damage tolerance of composite structures from impact (meaning dynamic loads), to residual strength analysis (including creep), with the same material models. It was then decided to study all the composites behaviour aspects under the dynamic frame, which raised new difficulties: for instance, the measure of the viscoelastic response of composite materials, at very small strains, brings new experimental difficulties when dynamic testing is concerned.

The purpose of the present research was to perform extensive dynamic experimental characterization of a T700GC/M21 UD ply material in order to use it for the identification procedure of a broad strain rate range viscoelastic mesoscopic model. The identification of such models requires tests at many different strain rates in order to be applicable for any dynamic, static and creep loadings. To obtain various strain rates, various testing machines are classically used with consequently various sample geometries. This can induce inconsistencies in the identified material mechanical parameters, for instance, and first of all for the various composite material moduli.

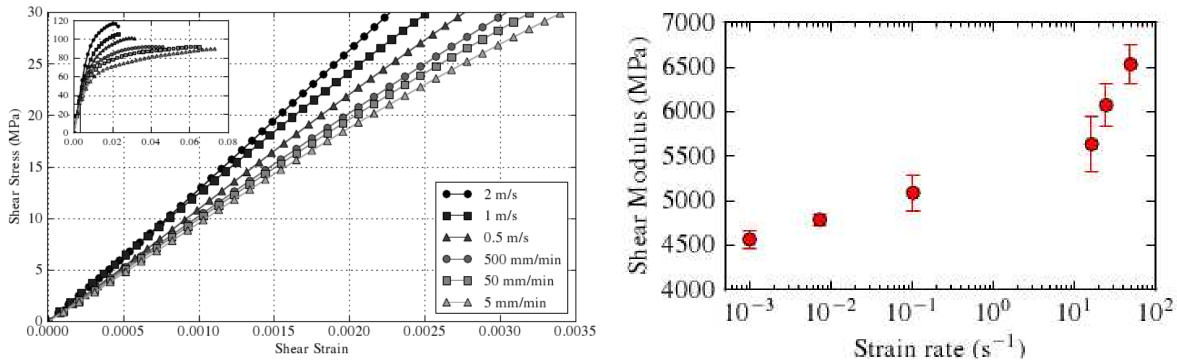
In the present research, the characterisation of the static and dynamic elastic properties of T700GC/M21 UD material was investigated. The study was focussed on stacking sequences that were expected to present rate-dependencies: $[(\pm 45°)_p]_s$ and $[90°]_m$. To obtain relevant dynamic experimental curves that can be used directly together with static and creep tests for identification purposes, the composite specimen geometry had to be optimised in order to avoid the scale and shape effects already mentioned in the previous paragraphs. The validation of final geometries relied, on the one hand, on the use of Stereo Digital Image Correlation (S-DIC) techniques (such as used in [Lecomte, 2009]) to check the homogeneity of strain field when small composite specimens are used and, on the other hand, on the comparison of controlled strain rate tests results with imposed speed test results performed with the ONERA hydraulic jack. The point is here to ensure consistency of test results from creep to dynamic loadings. In this study focussed on the evaluation of the elastic properties of a CFRP material at various strain rates, dynamic tests were performed with the ONERA hydraulic jack only (no Split Hopkinson Pressure Bars). A long geometry with normalised dimensions and a short geometry with specific dimensions for dynamic tests were studied. It can be noticed that in plane dimensions and thickness of the specimens were modified to compare creep/static and dynamic responses. It was assumed that thickness effects are of second-order importance with regard to the measurement of viscoelastic properties (4 to 8 plies specimens are studied respectively for dynamic and static tests). To validate the dynamic specimen geometry, Rosen $[(\pm 45°)_p]_s$ specimens were used to measure the shear modulus G_{12} [Rosen, 1972]

Full field measurement techniques (a Stereo Digital Image Correlation system) were used to qualitatively and quantitatively compare the strain fields of the normalised and short specimens geometry, during quasi-static tests performed on the same testing device. The elastic properties were obtained using strain gauges. The S-DIC analysis was performed with the Aramis 6.1 (GOM) software. The same Region Of Interest (ROI) was used for the different geometries. It was a 35mm x 28mm rectangular ROI, 1 pixel corresponding approximately to a 21µm x 21µm surface. As the precision of the measured displacements with the Aramis software has been previously checked to be about 1/30 pixel, the measurements precision was about 0.7 µm. A Zone Of Interest (ZOI) of 24 pixels and a distance between the centres of two successive ZOI of 12 pixels were taken for correlation computations. These values lead to good compromise between spatial resolution and uncertainty. The average strain rates in the linear part of the response were about the same 10^{-4} s^{-1} order of magnitude for the short and the long specimen geometries. The strain field on the long specimen was quite homogeneous (s_d = 0.043% where s_d is the standard deviation) whereas it varied more (s_d = 0.152%) for the initial short specimen. This non homogeneous strain revealed by the strain field analysis explained for instance the difference observed in the past by Delsart in the evaluation of composite shear modulus G_{12}. A geometrical criterion on the length/width ratio was then defined and validated (using S-DIC) in order to obtain dynamic short geometry specimens with a homogeneous strain in the specimen section: the free length of the specimen has to be at least twice its width. Then, the strain fields were far more homogeneous (s_d = 0.039%) in the section where the strain gauge is set. Using this geometry and the normalised one, tests with a controlled strain rate of $\dot{\varepsilon} = 5.10^{-4}$ s^{-1} were performed with a static testing machine. A difference of 5% only was then found on the shear modulus value (to be compared with the 20% for the initial short geometry), which was in agreement with the dispersion values that can be found in the literature (that can be attributed to classical dispersion in hand-made laminate composite, etc). The same kind of tests were performed on the $[90°]_m$ laminate, and the same conclusions were drawn : the controlled strain rate tests and the S-DIC tests proved that an appropriate improved short geometry could be used in a consistent way to measure viscoelastic effects on a large strain rate range, from quasi-static to dynamic test speeds.



Strain field analysis on normalised specimen geometry (left) compared to the dynamic short geometry before optimisation

Then the strain rate influence on the viscoelastic behaviour of the T700GC/M21 material using the previously validated short geometries was studied. Dynamic tests were performed with the ONERA hydraulic jack. The loading speed during the tests was evaluated with a laser transducer (Keyence LC2450 with a precision of ±8µm). The improved short geometry of the $[(\pm 45°)_p]_s$ laminates was tested at 6 different speeds: 2 m/s, 1 m/s, 0.5 m/s, 500 mm/min, 50 mm/min and 5 mm/min. For each speed, at least three tests were performed in order to check repeatability. In terms of strain rates, these speeds led to average strain rates in the elastic part of the behaviour ranging from $1.10^{-3}\ s^{-1}$ up to $88\ s^{-1}$. Clearly, the apparent shear modulus increased by 30% from an average value of 4565 MPa ± 2.1% for the 5 mm/min tests to 6528 MPa ± 2.7% for the 2 m/s tests (evaluation of the secant modulus between ε_l =0.05% and ε_l =0.25% as in the static normative procedure). A much smaller influence was observed on the $[90°]_m$ laminate.



Dynamic test results in shear on T700GC/M21 (left) and evolution of the apparent shear modulus (right)

Finally, this research completely confirmed the previous results obtained on other CFRP composite materials (e.g. G839/M18), with an important influence of the strain rate being observed on their apparent shear modulus, and an accurate test protocol being validated to properly identify this effect from creep to dynamic loadings.

Synthesis and Conclusions

Concerning my contribution to the research field of the dynamic testing of CMO composite materials, it began in the 90's, mainly by defining then supervising many works that were done in the ONERA-Lille test laboratory. Specific experimental protocols and composite test specimens had then to be defined, set up and evaluated to characterise the CMO materials non-linear behaviour and rupture: many of them have been finally abandoned, sometimes after many years of unfruitful attempts. Others have just started, because of new technologies being now available to improve the test possibilities : if one has to be mentioned, the use of dynamic optical extensometers and digital cameras (together with image correlation techniques) have been generalised to enrich, increase confidence and assess most of the test protocols which are based on standard medium speed hydraulic jacks. These technologies are now being implemented for high velocity Split Hopkinson Bars apparatus or even gas gun tests with a promising success. Thermal (including DMA) analysis is also being performed, and evidence of the influence of temperature on the behaviour of CMO materials has been properly demonstrated and measured. All these protocols have been applied to study many CMO tape or fabrics materials which exhibit very different dynamic responses (glass, carbon, Kevlar, aramid, etc), without the ONERA database being exhaustive of course. But new lightweight CMO materials are already raising new challenges, for instance 3D reinforced interlocks, braided, stitched composites, etc, which challenge the test means capabilities for sure. Others have not yet being even considered at all (bio-materials, etc). Last, many complex phenomena have been studied experimentally in dynamics, such as scale effects, importance of interlaminar interfaces, broad dependence on strain rate and temperature, with a much better understanding and knowledge of them being reached today compared to the 90's: time has come to study the influence of dynamic loadings onto the damage evolution in CMO materials, that will require to get more insight (tomography starts to be used in situ for static analysis), at different stages of loading (which is a true difficulty when dynamic tests are considered) to possibly feed multi-scale physical analysis and improve understanding of these very complex materials.

Mesoscale dynamic modelling of CMO composite materials and structures

Introduction

Commercial explicit codes with dynamic dependent material models had been developed since the 80's, to first deal with the analysis of crash and impacts responses of metallic structures. These codes met a huge success in the automotive industry. Viscoplastic models were proposed to deal with medium and high dynamic situations, for instance with plastic strain rate and temperature dependence being considered (e.g. Jonhson-Cook model). The foundation for these studies was the prediction of the dissipated energy in the material deformation process, since the question was to predict how and how much of the initial kinetic of an impactor or the structure itself would be accommodated during crash or impact events. Failure modelling was not the first priority since the dissipated energy in the rupture initiation/propagation was of second order compared to the strain energy : but its occurrence having a huge influence on the global ruin scenarios, engineering rupture criteria together with erosion techniques were used that were judged to be enough as long as the mesh discretisation was thin enough.

The development of composite material models in the explicit codes in the early 90's also aimed at better predicting the dynamic strength and energy absorption capability of composite structures during dynamic events. At the mesoscale level, the composite laminates were considered as a stack of several layers of possibly different materials, each one having an orthotropic behaviour, with different material law parameters, different orthotropic angles and different thicknesses. The interface between the different layers was not explicitly described, its failure being mainly modelled through the degradation of the material strength according to the thickness direction. Compared to the dynamic tests results that were presented in the previous paragraphs, these models suffered from heavy limitations and deficiencies : the inability to take into account dissymmetric behaviours (in traction vs compression) in the orthotropic directions of the plies, the unavailability of strain-rate or temperature dependence, and the lacks of proper modelling of the laminates failure mechanisms (delamination of course - which was proven to have an important influence on the laminate global response – but also fibre breakage, fibre/matrix debonding, etc).

Besides, the numerical simulation of these situations relies on the resolution of mechanical waves propagation equations in the solids (to catch shockwave effects), which means that a very small discretisation of time has to be used, which explains that explicit resolution schemes were traditionally preferred, instead of implicit ones, to study highly dynamic events. Even when explicit schemes are used, the complexity of the non-linear phenomena that must be taken into account (behaviour, rupture, contacts and friction, etc) restrain the use of very complex models such as those which can be found for static analysis and implicit schemes. For numerical cost reasons, specific non-linear dynamic material models are then proposed, that can be simplified versions of physically or phenomenologically based static models, but can also sometimes just be empirical (but very efficient) purely dynamic models. The research works for the past 20 years mainly dealt – for the former models - with the introduction of improved descriptions of the damage evolution on the basis of material tenacity considerations, without taking into account any strain rate dependence (except for the viscoelastic effects that were originally introduced for creep analysis need). For the latter models, the strain-rate dependence was introduced in the material behaviour and rupture criteria by

ONERA, on the basis of energetic considerations (such as viscoplastic deformation work), or damage delay effects.

The presented research then started in the early 90's, with some works that aimed at the development of a 3D semi-empirical orthotropic dissymmetric and strain rate dependent material model which assimilated, on the one hand, non-linearity – when it appeared - with plastic mechanisms and, on the other hand, softening and rupture to ultimate damage development. The ONERA 3D model for organic matrix composite materials was first implemented as a user-law in the finite element code RADIOSS (ALTAIR). Then it was slightly modified in the frame of the EU BRPR-CT96-0207 CRASURV (1998) and implemented by the RADIOSS code developer for $2D^{1/2}$ applications (shell elements).

Other enhanced composite material models appeared in explicit codes during this period. The most well-known one is the Ladevèze model [Ladevèze, 1991, 2002], which relies on a more phenomenological (and thermodynamically founded) description of the composite material behaviours based on the damage theory. This model was for instance characterised and evaluated in Dormégnie's work that concerned the possible application of scale reduction techniques to crash energy absorbers, in glass E/epoxy omega components (see previous paragraph). But no strain rate was available in the Ladevèze model version at that time, neither sophisticated interface models as those proposed by Allix [Allix, 1987].

The ONERA $2D^{1/2}$ and 3D semi-empirical models are still being used today [RE-19], [RE-83]. It has been recently implemented in the EUROPLEXUS research code, for comparison purposes with more physically based (non-linear viscoelastic damage model, ONERA Progressive Failure Model – OPFM) 3D composite material models, in the frame of the ONERA self-funded research project "Projet de Recherche Fédérateur Transition Statique Dynamique" that is mentioned in the last paragraph [RE-19], [RE-23], [RE-83].

Modelling of the non-linear dynamic behaviour and rupture of CMO composite materials – General principles [CI-23] [RE-28]

According to the test results presented in the previous paragraphs, the model that was proposed to be developed in the early 90's was a 3D anisotropic nonlinear model. The model was directly formulated in the composite materials orthotropic directions. Ruling out the temperature that was not yet of interest in these studies, the observable variables could have been either the stress tensor σ (related to the Gibbs free enthalpy) or the strain tensor ε (related to the Helmholtz free energy). Though this should theoretically lead to equivalent results, the choice between these 2 variables greatly influences the way formal expressions are described so that inversion from one formulation to the other quickly becomes impossible. Though the stress formulation has the advantage of simplifying the parameters identification (since most usual tests provide uniaxial stress states), the strain formulation was preferred because the strain is a true observable variable and because its implementation is straightforward in FE codes that provides the strain state at each resolution step.

Elastic stress increments are calculated thanks to a standard orthotropic compliance operator where linear elastic Young - E_{ii} - and shear - G_i - moduli can be identified from uniaxial tests. In order to take into account the experimentally observed differences between tension and compression, tension and compression young moduli were differentiated (the shear behaviour was assumed to be symmetric in tension and compression):

$$[\varepsilon] = [Z^t][\langle\sigma\rangle^+] + [Z^c][\langle\sigma\rangle^-]$$

Assuming symmetry of the compliance operators, and symmetry of Poisson effect in tension and compression, the compliance operators can finally be fully defined with 12 elastic material characteristics : 6 tension and compression young moduli : E_{11}^t, E_{11}^c, E_{22}^t, E_{22}^c, E_{33}^t, E_{33}^c , 3 shear moduli : G_{23}, G_{31}, G_{12} and 3 Poisson coefficients : ν_{23}, ν_{31}, ν_{12}.

In their original work [Tsaï, 1971] Tsaï and Wu developed a new criterion to describe the failure envelope of elastic-brittle composite materials or laminates. As already proposed in the existing composite model in the RADIOSS code, it was decided to use this criterion to define the yield envelope that delimits the elastic limit, over which non-linear mechanisms (be it damage or plasticity) start to develop. In the standard Tsaï-Wu formulation, 3 coupling parameters F_{12}, F_{23} and F_{31} are introduced to characterise coupling effects between the 3 principal material directions. In the present case, possible other coupling effects were introduced between principal and shear directions: F_{15} to model coupling effects that would yield micro-buckling mechanisms, F_{34}/F_{35} to model coupling effects on delamination initiation, and F_{24}/F_{26} to represent coupling effects that would yield fibre debonding mechanisms. As shear tension and compression responses are assumed to be equivalent, the introduction of the parameters requires the use of absolute values in the coupling terms involving shear stresses. The yield criterion is then written:

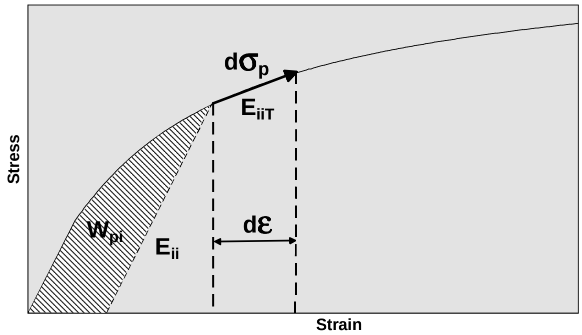
$$F([\sigma]) - 1 = 0$$

With: $F([\sigma]) = \sum_{i=1,3} F_i\sigma_i + \sum_{i=1,6} F_{ii}\sigma_i^2 + \sum_{\substack{i=1,3\\k=4,6\\j\neq k}} (F_{ik}\sigma_i|\sigma_k| + F_{ij}\sigma_i\sigma_j)$

and: $F_{ii} = \frac{1}{\sigma_{iy}^t.\sigma_{iy}^c}$, $F_i = \frac{1}{\sigma_{iy}^t} - \frac{1}{\sigma_{iy}^c}$, σ_{iy}^t and σ_{iy}^c the tension and compression yield stresses in direction i. The main difficulty here is to identify the F_{ij} parameters: traditionally it is suggested to take $F_{ij} = \alpha\sqrt{F_{ii}F_{jj}}$ with 0<α<1, which requires identifying a single α value from tests. A specific static tri-axial machine the capacity of which is 40 tons had been designed several years before the present research to perform combined compression/tension/shear tests on materials, to measure the damage sensitivity of composites under multi-axial loads and to identify the Tsaï-Wu coefficient F_{12} (as a failure criterion) [Paluch, 1994]. The Arcan test protocol was also proposed to identify the delamination parameters, but with poor success.

The experimental studies clearly showed that the nonlinear behaviour which is traditionally associated to damage effects and/or plastic mechanisms at micro-scale level in organic composite materials greatly differs from one material direction to another. Phenomenologically, different effects are usually observed that should be related to the material constituent that pilot them: damage in the fibre reinforced directions is associated to rupture of filaments (in tension) or micro-buckling (in compression), when damage in the shear or transverse (incl. out-of-plane) directions are traditionally associated to micro-cracks development, fibre/matrix debonding, and delamination, that mostly take place in the matrix constituent. It can also be observed that the nonlinear effect depends on the load, in traction or compression, except for the shear response which often appeared to be quite symmetric. As the proposed composite orthotropic material law was written in the material directions, it was then decided to have the nonlinear effects described according to a number of evolution functions of tangent moduli, equal to the number of material and load directions. Once the elastic criterion is exceeded, the stress increment is calculated from the strain increment thanks to a tangent compliance operator:

$$[d\sigma] = [Z_T]^{-1}[d\varepsilon]$$



Contrary to the elastic compliance operator, the tangent one was defined as a «full» operator (which means for instance that coupling coefficients such as Z_{T1112} are not null, i.e. a variation of σ_{12} involves a variation of ε_{11}).

$$[Z_T] = \begin{bmatrix} \frac{1}{E_{11T}} & \frac{-\nu_{21T}}{E_{22T}} & \frac{-\nu_{31T}}{E_{33T}} & \frac{-\nu_{41T}}{G_{4T}} & \frac{-\nu_{51T}}{G_{5T}} & \frac{-\nu_{61T}}{G_{6T}} \\ \frac{-\nu_{12T}}{E_{11T}} & \frac{1}{E_{22T}} & \frac{-\nu_{32T}}{E_{33T}} & \frac{-\nu_{42T}}{G_{4T}} & \frac{-\nu_{52T}}{G_{5T}} & \frac{-\nu_{62T}}{G_{6T}} \\ \frac{-\nu_{13T}}{E_{11T}} & \frac{-\nu_{23T}}{E_{22T}} & \frac{1}{E_{33T}} & \frac{-\nu_{43T}}{G_{4T}} & \frac{-\nu_{53T}}{G_{5T}} & \frac{-\nu_{63T}}{G_{6T}} \\ \frac{-\nu_{14T}}{E_{11T}} & \frac{-\nu_{24T}}{E_{22T}} & \frac{-\nu_{34T}}{E_{33T}} & \frac{1}{G_{4T}} & \frac{-\nu_{54T}}{G_{5T}} & \frac{-\nu_{64T}}{G_{6T}} \\ \frac{-\nu_{15T}}{E_{11T}} & \frac{-\nu_{25T}}{E_{22T}} & \frac{-\nu_{35T}}{E_{33T}} & \frac{-\nu_{45T}}{G_{4T}} & \frac{1}{G_{5T}} & \frac{-\nu_{65T}}{G_{6T}} \\ \frac{-\nu_{16T}}{E_{11T}} & \frac{-\nu_{26T}}{E_{22T}} & \frac{-\nu_{36T}}{E_{33T}} & \frac{-\nu_{46T}}{G_{4T}} & \frac{-\nu_{56T}}{G_{5T}} & \frac{1}{G_{6T}} \end{bmatrix}$$

where:

- E_{iiT} and G_{kT}, respectively the principal and shear tangent moduli, are non-linear functions depending on the inelastic work in the direction i/k, W_i / W_k :

  $E_{iiT} = E_{ii}.\left(1 - B_i\left[W_i\right]^{n_i}\right)$ for i=1,3 with E_{ii} : elastic modulus

  $G_{kT} = G_k.\left(1 - B_k\left[W_k\right]^{n_k}\right)$ for k=4,6 with G_k : elastic shear modulus

  The nonlinear coefficients B and n are identified for each direction (1-6) from uniaxial static tests,

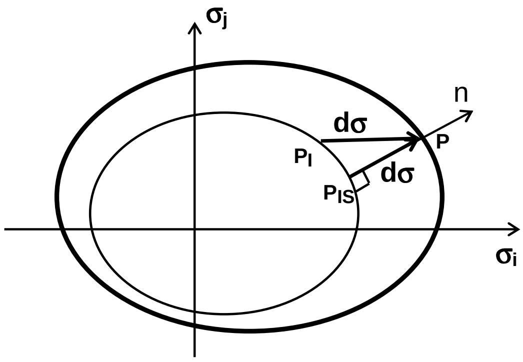
- ν_T are nonlinear Poisson coefficients that are calculated using some sort of normality rule (the nonlinear stress increment direction is normal to the criterion). Then :

$$\nu_{ijT} = \nu_{ij}.\frac{E_{iiT}}{E_{ii}} + \left(\frac{E_{iiT}}{E_{ii}} - 1\right).\frac{n_j}{n_i}$$

where ν_{ij} are the elastic Poisson coefficients, and n_j, n_i the components of the normal vector to the Tsaï-Wu criterion,

- then a somehow consistency rule (we assume that we keep on the yield envelope) is used to update the yield criterion, that relies on the introduction of two internal variables, a scalar variable R that would represent the envelope growth (if any), and a tensor variable $[X]$ that would represent a translation of the envelope in the stress space. The yield criterion is now written as :

$$F([\sigma]-[X])+R-1=0$$



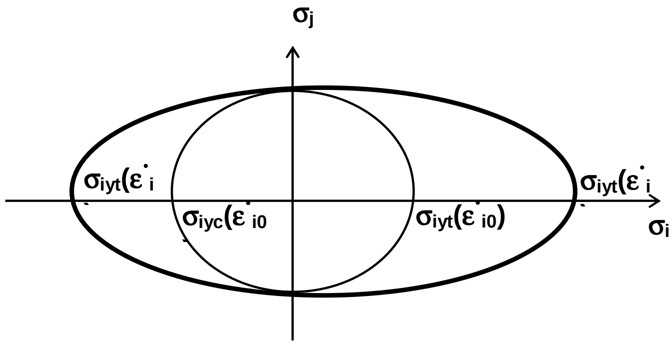
A strain rate dependence of the composite materials behaviour had been observed in several cases (almost every time when their shear behaviour was considered, but also sometimes for the fibre tension/compression for instance when aramid materials were studied). Experiments have also shown that dynamic effects are not only very different from one material, and one direction, to another, but also that this influence in one direction could be very different ratios according to the considered characteristics (Young modulus, yield stress, rupture values). Representing these various influences would have required introducing a great number of parameters, the identification of which would have been a real difficulty. A simplified strain rate dependent model was then proposed.

First, considering the total energy dissipation (for crash or impact analysis) as the main data to predict, it was decided to implement dynamic effects not on the Young moduli, but on the non-linear parts of the composite material law. Second, it was often experimentally observed, that the yield and rupture stresses evolve the same way (increase or decrease) – if not in the same amplitude - under dynamic conditions: the introduction of a dynamic dependence of the yield stresses, will influence the rupture. This is achieved through the introduction of C_i and (i=1,6) parameters in a logarithm function that penalises the F_{ii} coefficients of the Tsaï-Wu criterion:

As a strain rate dependence of the material behaviour had been observed in several cases (almost every time for the shear behaviour, but also sometimes along the fibre directions for instance when aramid materials were studied), the elastic yield envelope was modified to exhibit a strain rate dependence through the F_{ii} parameters (influence on the volume of the criterion), as a logarithmic function:

$$F_{ii}/F_{ii}^{0}=1+C_i Ln(\dot{\varepsilon}_i/\dot{\varepsilon}_{i0})$$

where $\dot{\varepsilon}_i$ and $\dot{\varepsilon}_{i0}$ refer to current and threshold total strain rates, and F_{ii}^0 is the static value of the Tsaï-Wu criterion when $\dot{\varepsilon}_i < \dot{\varepsilon}_{i0}$. Because of the introduction of different parameters for each direction, dynamic effects are uncoupled.



Last but not least, the modelling of rupture was based on a multi-criteria description, which made it possible to mix a large variety of rules according to each material and load direction:

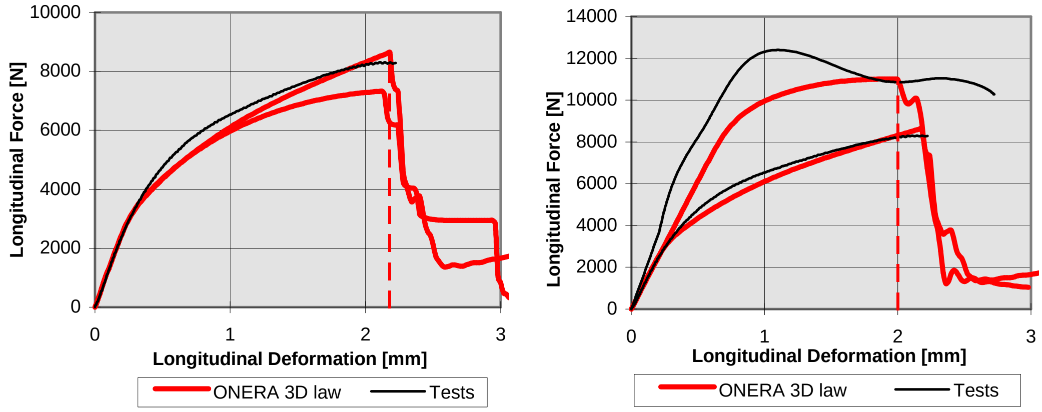
- standard ultimate stresses or strains can be defined for each stress/strain direction, different values can be given in tension and in compression,
- maximum symmetric allowable values for (nonlinear) dissipated energies can be defined for each direction, instead of an ultimate stress/strain criterion (e.g. for shear ultimate rupture/decohesion),
- or the Tsaï-Wu envelope can be used simply as a rupture criterion instead of as a yield criterion.

For this simple empirical model, conventional stress/strain curves were enough to be extrapolated from tests, to get complete sets of materials data, using simple hypothesis and on-the-shelf optimisation tools. Numerical and mathematical validations with single elements were done for all directions and various tested materials. Eventually, the developed material law proved to be able to reproduce a large variety of complex anisotropic composite behaviours.

Validation of ONERA 3D CMO orthotropic non-linear material model with respect to composite test specimens and dummy energy absorbers [RI-07] [CI-04] [CI-05]

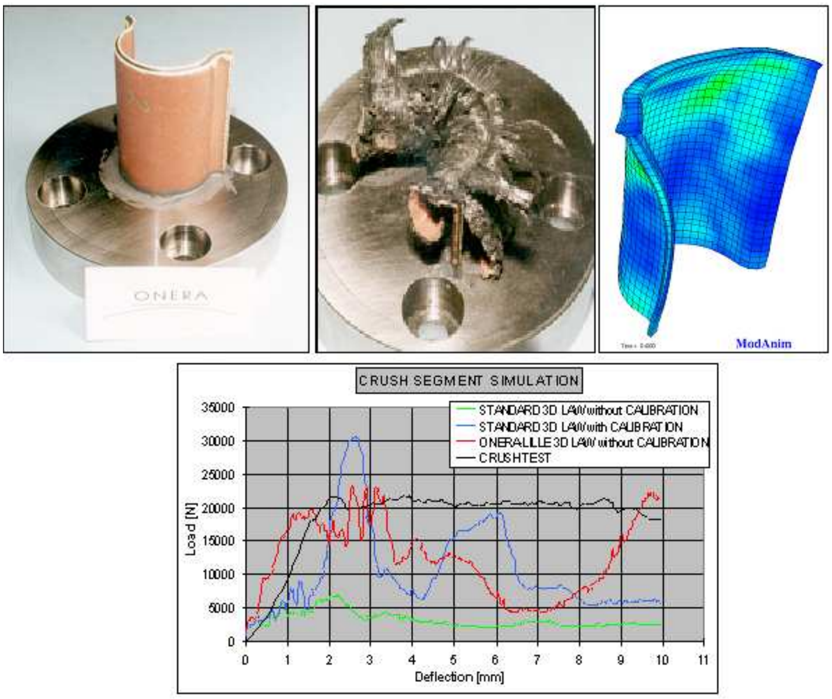
The first case of application of the previously described material model concerned medium speed dynamic events, and crashworthiness of composite helicopters. New aircraft and helicopter structural designs are including more and more organic composite materials due to their high mechanical characteristics and mass specific energy absorption capability compared to metals. Their design is a real challenge due to the very complex failure behaviour of composites. As a consequence the development of composite energy absorbing structures needs large test programmes to prove the different design variants, which increases the design costs. Within a German/French research co-operation on rotorcraft technologies, ONERA and DLR have been co-operating for many years in order to investigate and improve the general understanding and know-how in FE modelling of crashworthy composite components under low velocity impacts [RE-27], [RE-30], [RE-32].

The ONERA contribution in the cooperation mainly consisted in the identification and use of its previously described composite material law, to simulate the crash behaviour of small half-tubular components. Part of the work has been dedicated to the mechanical static and dynamic characterisation of polymer composite ply materials and laminates used in sub-floor components such as sine-wave or cruciform beams (see previous paragraphs). Three thermoset composite materials have been statically and dynamically tested by ONERA for strain rates between 10^{-5} s^{-1} and 100 s^{-1} with hydraulic machines: a unidirectional (UD) carbon, a carbon fabric, and an aramid fabric, all reinforced with epoxy resins. Once completed, the database has been used as input data for numerical simulation purposes. Basic numerical validations have been performed which proved that the complex orthotropic behaviour of the different tested composites could be accurately modelled with the identified sets of materials parameters.



Simulation of tests specimens and comparison with static (left) and dynamic (right) results Carbon fabric/epoxy material in shear (+/-45° Rosen test)

Then more complex simulations have been undertaken to compare with the crash components test results. Hybrid segment crush specimens were made by DLR and dynamically tested at ONERA. These hybrid half-tube specimens were made of a carbon/aramid/epoxy lay-up (A45, A45, C45, C0, C0, C45, A45, A45), where A45 is a +/-45° aramid fabric ply, C45 is a +/-45° carbon fabric ply, and C0 a 0° unidirectional carbon ply, the ply angle being given with respect to the segment axis. Simulations have been performed with an FE 3D model (brick elements) containing the correct segment geometry (including chamfer to trigger the crushing behaviour at the top of the segment) and laminate.



Comparison of crash test result on hybrid (aramid/carbon) segment and 3D simulations different with different composite mesoscale material laws

Using a standard 3D material law without calibration led to very poor agreement with the test results. The comparison could be improved by replacing the UD carbon elastic brittle behaviour along the fibres direction by an elastic-plastic model without rupture, which was not physically representative. The 3D ONERA material model enabled to reach a better agreement without calibrating the material parameters that were identified from coupon tests. This success was nevertheless at the expense of an increased computing cost (80 CPU hours instead of 4 CPU hours). Though the agreement has been improved with the material law developments, the simulation still eventually diverged from the test results after few millimetres have crushed. The reason is that a global buckling mode appeared and prevented the progressive plies separation and crushing failure mode from developing (the peeling mode was well initiated thanks to the modelling of the trigger, but its propagation was stopped).

Eventually, the numerical simulations proved that the modelling of the orthotropic dynamic behaviour of composites could be improved using enhanced material laws. However, the dynamic CRD ONERA empirical model already turned to be quite expensive in terms of computing times, and not very suitable for crash simulations on larger structures. The computers power has greatly increased since this study, and computer clusters are now available at reasonable prices. In more recent works [RE-83], a comparison have been made between the numerical efficiency of this ONERA model (implemented in EUROPLEXUS) with more phenomenologically based ones (OPFM and ODMS static models): the studied case was the impact on composite plates, and the 3D models were enriched with the inter-laminar interfaces being modelled using modern Cohesive Zone Elements (the same CZM were used, that highly contribute to the increase of the numerical costs). Note that the OPFM model is not implemented directly in EUROPLEXUS, but plugged to the code through a specific functionality that explains the high system CPU costs compared with the other models.

	OPFM (Z€PX)	ODMS (€PX)	CRD (€PX)
Numerical efficiency			

Initial time step (ms)	$2{,}4.10^{-5}$	$2{,}4.10^{-5}$	$5{,}9.10^{-6}$
Calculation times (5 ms impact case)	25 days	2 days	4 days
Computer efficiency			
User CPU time (%)	25	90	85
System CPU time (%)	75	10	15
Required Memory (Gio)	> 30	3,5	3,5

Comparison of numerical efficiency of different 3D composite material models in EUROPLEXUS

Implementation of ONERA material model in explicit codes for $2D^{1/2}$ analysis of aeronautical structures [CI-27]

In the frame of the European research project 'CRASURV – Design for Crash Survivability', which was focused on the use of composite materials in transport aircraft fuselage structures with improved energy absorption capabilities, the ONERA 3D composite model was slightly adapted and implemented by the RADIOSS code developer, for $2D^{1/2}$ applications (shell elements). The objective of the project was to numerically design a composite fuselage barrel (A320 size) with respect to crashworthiness, which meant two objectives: preserve the structural integrity of the composite cabin and floor structure, and reduce passengers accelerations down to a 20g survivable level by dissipating the initial crash kinetic energy in composite crash absorbers that were set in the underfloor part of the fuselage structure.

The composite laminate is modelled using thin shell finite elements that represent a stack of several layers, each having an orthotropic behaviour. Each layer is in plane stress state. The yield criterion is given by Tsai and Wu [Tsaï, 1971] for a plane stress state:

$$F([\sigma]) = \sum_{i=1,2} F_i \sigma_i + \sum_{i=1,2,4} F_{ii} \sigma_i^2 + \sum_{i=1,j=2} (F_{ij} \sigma_i \sigma_j)$$

$$F_i = \frac{1}{\sigma_{iy}^t} - \frac{1}{\sigma_{iy}^c}, i = 1,2 \qquad F_{ii} = \frac{1}{\sigma_{iy}^t . \sigma_{iy}^c}, i = 1,2,4 \qquad F_{12} = -\sqrt{F_{11} F_{22}}$$

If the criterion value is less than 1, the behaviour is elastic, otherwise the behaviour is non-linear. The yield stresses are given by a nonlinear function of the inelastic work and of the rate of inelastic work:

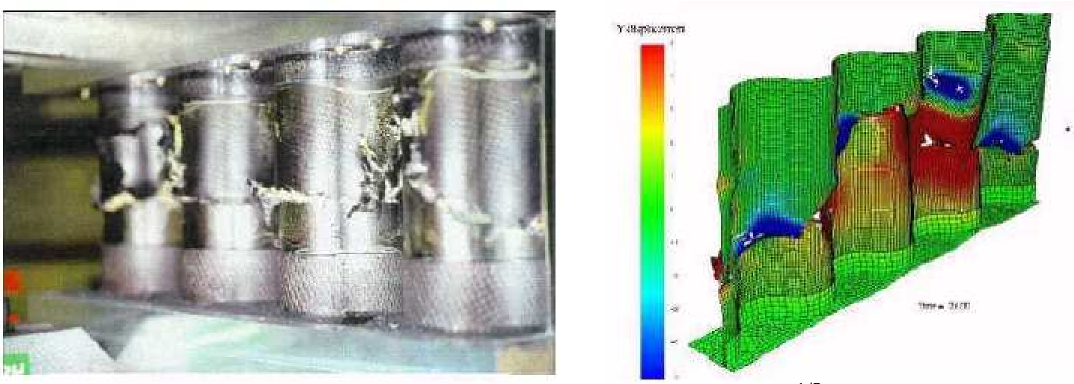
$$\sigma_{iy}^\alpha = \sigma_{i0}^\alpha (1 + b_i^\alpha W_a^{n_i^\alpha})(1 + c_i^\alpha \ln \frac{\dot{W}_a}{\dot{W}_0})$$

where $\alpha = c, t$ (for compression and tension) and i=1,2,4.

A specific procedure has been defined to identify the material law parameters from static and dynamic tests results. The test results were provided by another partner, which used Hopkinson Bars to get carbon UD (T300/914) and fabrics (G803/914, G803/1454) mechanical characteristics up to 500 s^{-1}.

Tensile failure can occur in orthotropic directions if a maximum tensile strain ε_t is reached. Then the tensile stress falls to zero for a maximum strain ε_m. The material softening between ε_t and ε_m is modelled with a damage model. Excessive inelastic compression and shear strains are prevented thanks to a threshold criterion on inelastic work $W_a^{max} \geq W_a$.

The material parameters had to be calibrated to correlate the numerical simulation results with a 500 mm/mn test done on sine-wave beam crushing component alone. In the tested case, the trigger mechanism did not function correctly, which was also obtained with the calibrated FE simulation (initiation of failure not located in the lower/triggering part of the web).

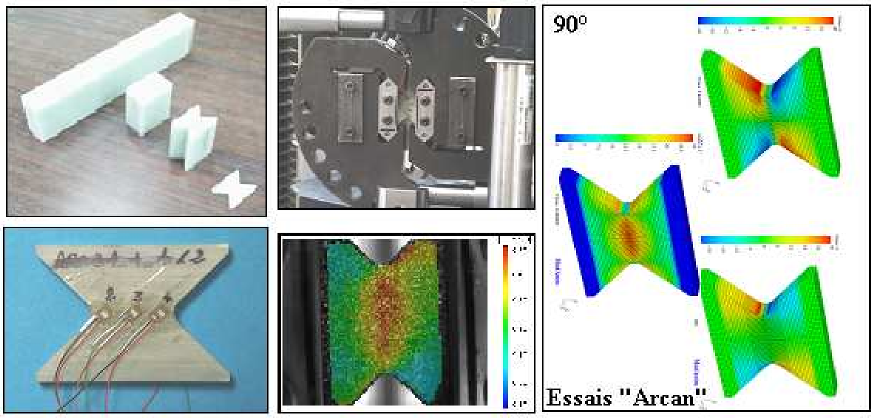


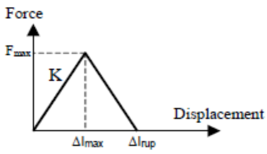
Comparison of crush test and calibrated FE simulation using the $2D^{1/2}$ dynamic material model for composite laminates

ONERA was involved in the post-test simulation of the sub-cargo floor structure [RE-26]. Then, the full barrel composite structure was numerically designed using the previously calibrated material model, including the crash energy absorbers, to satisfy the crash requirements. Finally, the barrel was manufactured and tested: the integrity of the composite fuselage frames and passenger floorbeam was effectively preserved, but the crash absorbers did not operate at all, because of an early rupture of the sub-cargo floorbeam in a riveted assembly zone, resulting in passenger acceleration levels that exceeded 50g. The final conclusion was that more effort should be put on the modelling of the composite riveted assemblies under dynamic loadings (see Postec's PhD works).

Dynamic modelling of delamination in CMO materials using discrete cohesive zone models [Delsart, 2005]

As it was previously said, the ONERA 3D material model proposed a simplified representation of delamination effects through the degradation of the material strength along the through-the-thickness direction. It was clearly noticed that the influence of delamination on the dynamic strength and energy absorption capability of composite laminates was very important in many cases. The simple representation of delamination effects in continuum mechanics based 3D mesoscale models would then not be accurate enough to capture such an important influence. Discrete cohesive zone models were then also studied in the Research Unit, together with the attempts of characterising delamination with the Arcan test procedure [Delsart, 2005], [Postec, 2006]. The first studies relied on the combined use of the ONERA 3D material model to model glass E/epoxy plies butterfly specimens, together with traction/separation laws (linear springs between mesh nodes) being calibrated from the Arcan tests results.



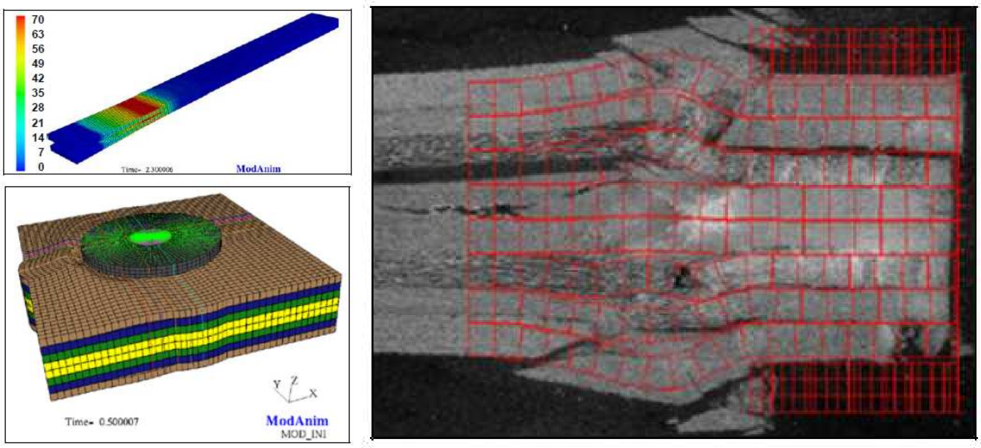


Mode I			Mode II		
K	F_{max}	Δl_{max}	K	F_{max}	Δl_{max}
66057	4,33	6,6E-05	26640	4,6	1,7E-04

FE simulations of glass E/epoxy Arcan tests results under a variety of failure modes mixture (top), and calibrated traction/separation laws for failure modes I and II (bottom)

Then, these material and discrete cohesive zone models were used by Postec to simulate his test campaign results, which concerned the study of the bearing failure or glass E/epoxy laminates (see previous experimental paragraphs). DCN tests were also performed during this work to validate the traction-separation law that had been calibrated with Arcan test results.

These results were used to model and simulate the bearing response of Postec's composite riveted joints. Though the numerical failure pattern did pretty well correlate the test result, the failure load was poorly predicted, and traction/separation laws should again have to be calibrated to improve correlation.



Qualitative comparison between Postec's test results and FE suimulation with ONERA 3D composite material model and discrete cohesive zone models

These conclusions explain why current works are still in progress in the Research Unit (in the frame of the ONERA self-funded project "Projet de Recherche Fédérateur Transition Statique Dynamique", and in Joudon's PhD Work.) to deal with the dynamic characterisation and development of improved Cohesive Zone Elements in the EUROPLEXUS code [RE-19], [RE-23], [RE-83].

Development and validation of a multi-spectral viscoelastic model for creep to high speed dynamic response of CMO materials [RI-05] [CI-21] [CI-22]

We have previously seen, when crash and impacts situations are considered, that many organic matrix composite materials, such as the G939/M18 carbon fibers reinforced plastic fabric, exhibit a change in the shear behavior according to the strain rate. Specific empirical models have been previously proposed to take this effect into account, without suffering to high CPU costs penalty, and model composite materials nonlinear and dynamic behaviors at the mesoscale level in a laminate description. Because of the increase of the modern computer capabilities, the issue of developing more physically based composite material models is becoming less and less questionable. Compared to the research that was previously proposed, a more physical modeling necessary starts with the modeling of dynamic effects on the shear modulus, G_{12}, which was neglected up to now for simplicity (then CPU cost) reasons. Concerning this particular point, a lot of work exists that concern the modeling of the creep phenomenon, which also relies on time-dependent considerations (see LMT Cachan or ONERA models).

Clearly, ONERA identified a new research issue that would be to achieve a unified vision of the various existing dynamic models, covering the various dynamic loading types (from creep to impacts). The aim of the presented work, that was performed in the frame of the ONERA in-house "Projet Fédérateur de Recherche (PRF) Transition Statique Dynamique" (2010-2013), an in Berthe's PhD works [Berthe, 2013] [RI-05], is to develop an improved viscoelastic formulation, that could apply to dynamic, static and creep loadings [RE-19], [RE-23], [RE-83]. It is based on the ONERA progressive failure (OPFM) model, because the description of this viscoelastic model is based on a temporal spectrum formulation which appears easier to identify (than the Schapery model or other integral models based on known relaxation and creep functions, [Schapery, 1966]) from available dynamic experimental data.

The ONERA progressive failure model is a mesoscopic model, based on knowledge of the ply behavior. As the purpose of this research is to model the mechanical response of organic matrix composite materials over a broad strain rate range, a focus on the variation of CFRP tangent shear modulus G_{12} is first made, since it is well-known to be rate-dependent. The viscoelastic spectral model from [Maire, 1992, 1997] is used, where the viscoelastic behavior of the ply, in the local basis, can be written as:

$$\sigma = C^0 : (\varepsilon - \varepsilon^{ve})$$

where σ is the Cauchy stress, C_0 the elastic tensor, ε the total strain and ε^{ve} the viscous strain.

With the spectral formulation (which can be seen as a generalization of rheological viscoelastic models, with an important number of springs and dashpots), the total viscous strain results from the sum of elementary viscous mechanisms ξ_i, associated with a relaxation time τ_i and a weight μ_i:

$$\dot{\varepsilon}^{ve} = g(\sigma)\sum_i \dot{\xi}_i \qquad \dot{\xi}_i = \frac{1}{\tau_i}(\mu_i g(\sigma) S^R : \sigma - \xi_i) \qquad g(\sigma) = 1 + \gamma\left(\sqrt{{}^t\sigma : S^R : \sigma}\right)^n$$

with g(σ) a non-linear function (necessary to describe the usually observed non-linearity of viscous effects according to the stress level), and S^R the viscous compliance.

The set of elementary viscous mechanism is modeled thanks to a Gaussian envelope (representing a spectrum of viscous mechanisms), the weight of the viscous mechanisms being a function of their relaxation times. Theoretically, the larger the number of considered viscous mechanisms, the more representative the model (practically in the following cases, the spectrum was discretized by 200 elementary viscous mechanisms, which proved to be enough after a convergence study). Then, the identification of two parameters from tests (n_c the mean of the Gaussian spectrum, and n_0 the standard deviation), is enough to define the Gaussian envelope:

$$\tau_i = \exp(i) \qquad \mu_i = \frac{\overline{\mu_i}}{\sum_i \overline{\mu_i}} \qquad \overline{\mu_i} = \frac{1}{n_0\sqrt{\pi}} \exp\left(-\left(\frac{i-n_c}{n_0}\right)^2\right)$$

The temporal spectrum parameters (n_c and n_0) define the range of strain rates in which the behavior will turn to be time-dependent.

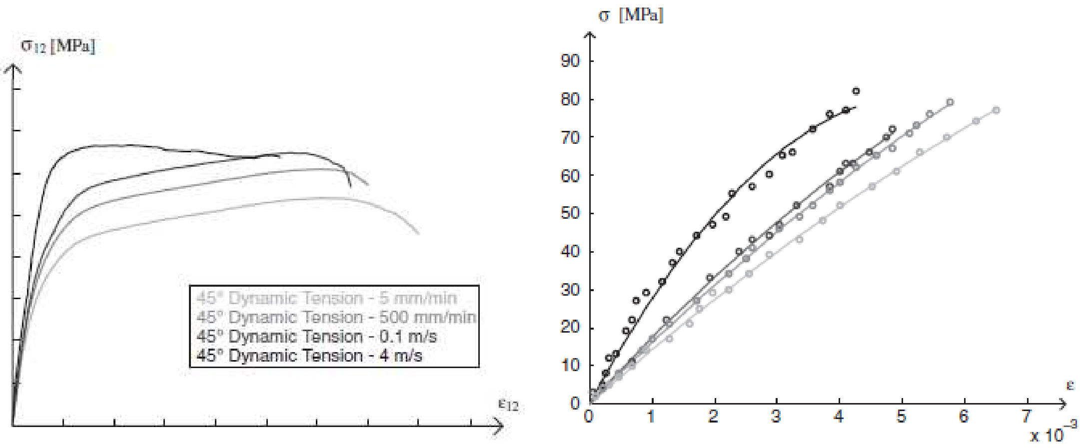
In order to simplify the identification question, the viscous compliance is taken as a function of the elastic compliance S_0. In the present case where carbon fibers reinforced composite materials were studied, viscous effects are assumed to only develop in the shear direction (G939/M18 case), or possibly also in the transverse one if UD tape materials are considered (T700/M21 case).

$$S^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \beta_{22} S_{22}^0 & 0 \\ 0 & 0 & \beta_{66} S_{66}^0 \end{pmatrix}$$

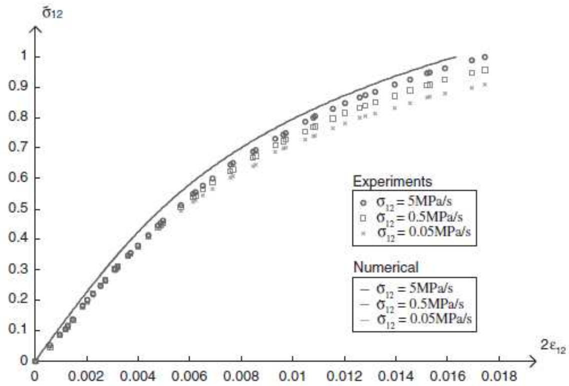
This viscoelastic model only needs two tests to identify all viscous parameters (n_c, n_0, β_{22}, β_{66}, γ and n): a multiple step creep test on a +/-45° laminate (for fabrics) and a single creep test on a 90° laminate (for UD tape).

As carbon fibers are not rate-dependent, the G939/M18 woven ply which was first studied, is not rate-dependent in the fiber and transverse directions. Thus, viscosity in the transverse direction has been neglected (β_{22}=0). Note also that only small stress levels are considered in the following, in order to identify the viscoelastic behavior of the ply, before any damage appears.

Classically, Maire's model is identified with very low strain rate tests [Maire 1992]. Thus, the identified value of G_{12} is less than the apparent shear modulus observed in high strain rate mechanical tests. With such a model, if the strain rate is too high compared to (n_c, n_0), no viscous mechanisms are activated and the apparent behavior is purely elastic. If the strain rate is very low, all viscous mechanisms are activated, the apparent behavior is the asymptotic viscous behavior. The value of the purely elastic asymptote corresponds to G_{12}. The viscous asymptote will depend on the value of β_{66}. Finally, the non-linear shape of the curve is linked to γ and n. In order to be predictive in a large range of dynamic rates, the G12 value has to be identified with the highest possible speed test, which would give the higher tangent modulus. So to be suitable for dynamic tests as well as for static or creep tests, the model has to be identified on tests that include high strain rate ones: this viscoelastic model, identified on dynamic tests only, was proved not to be suitable for static tests. Conversely, static parameters only are not suitable to represent dynamic tests.

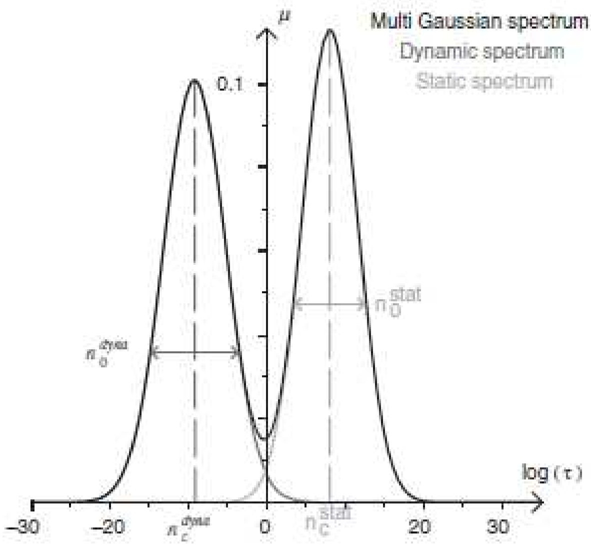


G939/M18 +/-45° dynamic test results (left) and corresponding identified viscoelastic model from 10^{-3} s^{-1} to 100 s^{-1} (right)



Comparison of normalised G939/M18 +/-45° quasi-static test results (from literature) with the non-linear (viscous) asymptote of the viscoelastic model identified with the dynamic test results

The proposed solution was to superimpose a dynamic Gaussian spectrum (n_{dyna}^{c} and n_{dyna}^{0}), identified on dynamic data, and a static Gaussian spectrum (n_{stat}^{c} and n_{stat}^{0}), identified on static data, all the other viscous parameters being unique [CI-21], [CI-22].



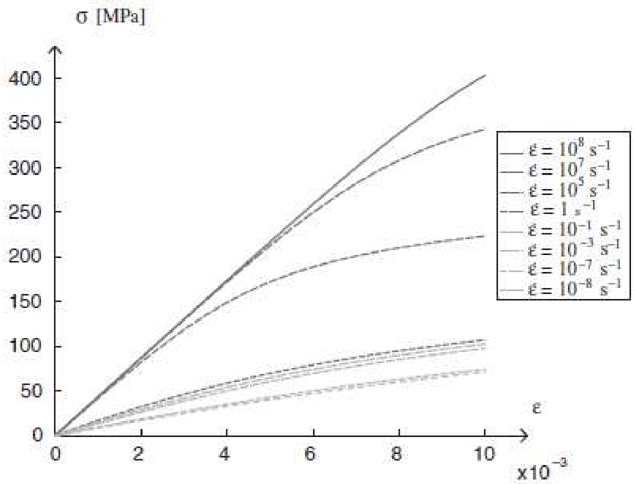
Berthe's multi-spectrum proposal for CMO viscoelastic modeling

The following equations only have then to be re-written in order to take account of this superimposition:

$$\mu_i = \frac{\overline{\mu_i}^{quick}}{\sum_i \overline{\mu_i}^{quick}} + \frac{\overline{\mu_i}^{slow}}{\sum_i \overline{\mu_i}^{slow}} \qquad \overline{\mu_i}^{k} = \frac{1}{n_0^k \sqrt{\pi}} \exp\left(-\left(\frac{i - n_c^k}{n_0^k} \right)^2 \right)$$

The main result of this new formulation is to introduce two sets of asymptotes for the viscoelastic behavior. To illustrate the capability of the improved multi-spectrum model, a theoretical set of parameters is obtained for G939/M18, which concatenates standard literature values (for the static spectrum) and dynamic spectrum parameters identified from the ONERA dynamic shear test results.

G_{12}	n_0^{dyna}	n_c^{dyna}	n_0^{stat}	n_c^{stat}	γ	n	β_{66}
15,800 MPa	5.6	−9.25	5	8	0.8	2.5	3.2



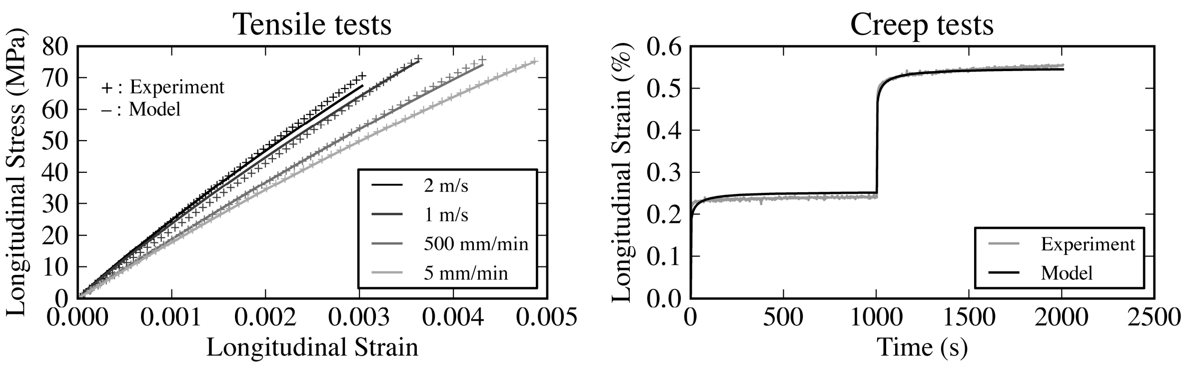
Theoretical viscoelastic behavior of G839/M18 from creep to high speed dynamic loadings

The multispectral model with this set of parameters exhibits a broad dependence between 10^{-8} s^{-1} and 10^{+8} s^{+1}, which means from creep to high strain rate dynamic tests. In fact, the dynamic part of the spectrum defines two asymptotes: purely elastic and viscous, the latter one becoming the upper asymptote of the static part of the spectrum.

The characterisation of strain rate-dependent mesoscopic elastic properties of T700GC/M21 UD ply material has then been performed by Berthe [RI-19]. The test results exhibited a 30% increase of the shear modulus on the $\dot{\varepsilon} \in [10^{-3}\ s^{-1}; 100\ s^{-1}]$ strain rate range, and a low dependence of the transverse modulus on the same strain rate interval. These experimental results have then been used to identify the previously described viscoelastic model, which proved then to be applicable for dynamic, static and creep loadings, as long as enough care is taken to make sure that the different tests results used for identification are consistent. In the identification procedure, 8 parameters have to be found: G_{12}, n_c^{quick}, n_0^{quick}, n_c^{slow}, n_0^{slow}, β_{66}, γ and n. Apart from the dynamic tensile tests that have been previously described, creep test results were proposed to be used to get the slowest viscous phenomena accurately identified. The parameters of the model were identified with three different sets of experimental curves. In the viscoelastic model identification process, only small stress levels are considered (σ closed to 70 MPa) in order to avoid any risk of damage appearing (or accept a very limited amount of damage). Clearly, the multi-spectrum model, once identified using both the dynamic tests and creep tests data which are consistent together, proved to be very representative for dynamic and creep tests altogether. The comparison was much poorer when a mono-spectrum model identified with all the tests, or a multi-spectrum model identified only with static or dynamic tests results, were used.

G_{12}	n_c^{quick}	n_0^{quick}	n_c^{slow}	n_0^{slow}	β_{66}	γ	n
11287 MPa	-11.04	5.08	3.3	2.53	1.17	0.91	2.06

	2 m/s	1 m/s	500 mm/min	5 mm/min	Creep
Mean(Error)	3.36 %	6.56 %	1.09 %	0.78 %	2.73 %
Max(Error)	15.41 %	25 %	5 %	1.47 %	25.5 %



Example of Berthe's model set of parameters for T700GC/M21 CMO material (top) and comparisons with dynamic and creep test results (bottom)

The research is being continued at the present time, with the characterisation of the CMO material behaviour dependence to the temperature (Berthe and Joudon's PhD works). Different DMA test campaigns have already been realised on the M21 epoxy resin, on the one hand, and on the T700GC/M21 composite material on the other hand. Mechanical dynamic tests have also been done on the T700GC/M21 material at ambient, -40°C and -100°C temperature. The test results did confirm this temperature dependence, and are currently being exploited in order to model – for the viscoelastic part of the composite material behaviour – the time-temperature equivalence that is a well-known principle for polymers: the increase of tests speed leads to the evolution of the characteristic transition temperatures of the M21 resin, and influences the resin – hence the whole composite - material behaviour.

Synthesis and conclusion

Considering the question of the mesoscale dynamic modelling of CMO composite materials, my first contribution to the research was to propose a generic empirical 3D material frame to represent the non-linear dynamic behaviour and rupture of these materials at the ply level, whatever their nature. Indeed very different responses were experimentally observed when considering carbon (almost elastic-brittle in the fibres direction), glass (more non-linear in compression along the fibres directions), or Kevlar/aramid (highly non-linear in most material or load directions), all of these materials also heriting a highly non-linear behaviour in shear from their organic resin phase. It was all the more necessary since a mixture of these materials was already used by the industry when confronted to dynamic strength requirements. Once implemented, the ability to identify the 3D material model and its relevance had to be addressed at the mesoscale level, and validated at the macroscale level against dynamic tests on small composite dummies. It did prove to better – if not perfectly – behave than the existing models, but at the expense of CPU costs. This report led to the model implementation for multi-layered shell elements for its use in $2D^{1/2}$ structural analysis of aeronautical structures (such as composite fuel tanks subject to HRAM dynamic loads, very recently). Besides, and even though the question was long known, research on the dynamic modelling of delamination in composite CMO laminates started at ONERA-Lille at little later, when it was demonstrated that the rough approach that consisted in representing delamination by the sole transverse degradation of the mechanical properties in our 3D model was not satisfactory enough. Discrete cohesive zone models were first used, but the current research is now dealing with general (surface) cohesive zone models, the main research trend again being the introduction of dynamic or temperature effects in these models. Recently again, it was decided to increase the modelling research scope to the dynamic elastic behaviour of the CMO materials: it had been disregarded from the 90's because energy dissipation in the composite non-linear behaviour was our first concern. But when high velocity and high energy impacts are considered, the elastic stiffness, the overall redistribution of loads in large composite structure (and joints), and the organisation of local damage into global ruin mode have to be accurately predicted. A multi-spectral viscoelastic model for creep to high speed dynamics of CMO materials has then been developed and assessed, then justified and generalised by introducing a general time-temperature equivalence principle. Coming next are the modelling of the visco-damage (strain rate and temperature dependence of the damage evolution laws), including delamination, the study of 3D composite reinforced materials, and the foundation of phenomenologically and thermomechanically based multiscale models.

Conclusions and perspectives on the characterisation and modelling of composite materials and structures

The research that was presented in this chapter concerned the question of the experimental characterisation and numerical modelling of CMO composite materials, under dynamic solicitations. It started – as far as I am concerned - 20 years ago, in the frame or several military research projects which addressed two main issues: the crashworthiness of composite helicopters, and the improvement of the damage resistance of composite integrated fuel tanks with respect to hydrodynamic ram events. Microscale models had been proposed, which relied on the theoretical characterisation of the resin and fibres constituent, but such models quickly found some limits as soon as the nonlinear behaviour under large stresses and strains was studied: among the questions, stood the problem of the modelling of the resin/fibre interphase that depends on the manufacturing process and cannot easily be studied but at the mesoscale level. This interphase material would clearly control the compression, micro-buckling, etc, behaviour of the composite material. Also, the dynamic characterisation of small fibres or resin samples only was not an easy challenge.

So a continuum mechanics mesoscale modelling was targeted from the beginning: it was decided to study the non-linear composite behaviour at the constitutive ply level. Because of scale effects, and to work on representative elementary volume, the composite specimens have to be made of several (some authors say at least three) elementary plies of the same orientation, which rapidly lead to practical limitations with regard to the test means, due to the high strength and stiffness of CFRP materials. In 1994, I was entrusted some research work on these topics, in the frame of French DGA/DRET research contracts. The first studies concerned the characterisation and modelling of the dynamic behaviour of T300/914 carbon fibres reinforced plastic (organic resin) material. I formulated basic principles for a generic composite material model at mesoscopic scale, and implemented them in a user-routine to be plugged to a commercial FE code (RADIOSS) [RI-7, RE-27, RE-28]. The basic idea behind the model was to be able to represent any 3D orthotropic asymmetric (difference between tension and compression) composite material, with or without reinforcement of any type along any of the 3 orthotropic directions, meaning that different possibly non-linear and strain rate dependant behaviours could develop in all material directions, in tension, compression or shear. A Tsaï-Wu criterion was selected to describe the elastic envelope, over which the evolutions of tangent moduli in the material directions were piloted by internal variables which were inelastic internal (deformation) energies. The strain rate dependency was introduced by having the Tsaï-Wu elastic envelope parameters being functions of the total strain rate. Each orthotropic and load direction was attributed specific variables and parameters, in order to make it possible to describe different behaviours as elastic-brittle or no-linear dynamic dependent ones according to each direction of the material or load sign. Carbon and Kevlar fibre reinforcements, tape or fabrics, 2D or 3D composite materials were potentially eligible to be modelled by this kind of generic empirical behaviour law. Rupture was addressed by implementing a set of possible criteria : a multi-axial elastic-brittle criterion (the elastic strain rate dependent Tsaï-Wu envelope being also the rupture envelope), or uniaxial ultimate stresses, or a cumulated damage criterion (the onset of the softening damage being associated to a non-linear strain threshold, and its evolution law being identified from experimental total dissipated energy considerations). The 3D model was eventually quite expensive to be computed, but it could describe almost all kinds of behaviours that had been experimentally observed in the lab. No thermodynamical foundation was proposed to further validate the proposed empirical model. This model was adapted in 1998, and implemented for $2D^{1/2}$ finite element analysis (multi-layered shell elements) in the RADIOSS explicit crash code, in the frame of the EU BRPR-CT96-0207 CRASURV project [RE-26, RE-29, RE-31]. It is available today in the open Radioss library, and often used for the industrial studies that ONERA is contracted for (e.g. EDA BaTolUS project which concern the FE optimisation of composite UAVs fuel tanks subject to hydraulic ram loadings).

In parallel to this modelling exercise, several works were initiated in the lab in which I participated, that concerned the experimental characterisation of composites delamination (using ARCAN specimens), or of the dynamic behaviour of reinforced fibres composite under compression (dog bones specimens) [RE-33/…/35]. These research works were continued after 1996, in particular through PhD or Post-Doctorate works that were supervised by the LAMIH of the University of Valenciennes [CN-3], and in the frame of a French-German ONERA-DLR research project [RI-7, CI-4, CI-5, RE-18, RE-24, RE-30, RE-32]. Various materials were then studied such as glass, Kevlar, aramid and carbon fibre composites, with thermoset or thermoplastic resins. As often, the experimental work could not be dissociated from the modelling world: if the damage based phenomenological nonlinear behaviour of CMO composites was already known, the experimental characterisation of such models was heavy and difficult even under static conditions. This explains why our choice was to prefer simpler empirical models as a start, the dissymmetric and orthotropic nature of which already leading anyway to huge test campaign: tension, compression and shear loadings were to be studied, according to the different material directions, with different test speeds and test temperatures, etc. The increased scatter in composite test results compared to metallic materials, the influence of the material manufacturing process, but also of the specimens machining process, were supplementary traps added to the basic challenge of testing the materials at representative speeds with respect to the studied structural cases (crash, bird strike, ballistic impacts, hydraulic ram, etc), without any established normative protocols. A very expensive and laborious research work was ahead of us. The expertise that has been built up in the ONERA test laboratory throughout these years of research constitutes a rare investment, and a relevant one if one considers the large increase of use of these composite materials in the aeronautical structures in the recent years. Various test means are available from quasi-static machines up to Split Hopkinson Bars, and hydraulic jacks that can be used to consistently cover strain rates ranging from 10^{-3} s^{-1} to 1000 s^{-1}, making it possible to address quite a large variety of structural dynamic problems.

But new challenges already arise, with the normalisation of material dynamic testing being probably on the rail, with the development of new generation 3D composite materials, and modern computers that have now the power to handle with more physically based multiscale models [Laurin, 2005, 2007], [Trovalet, 2008]. Considering this multiscale objective, and the homogenised continuum mechanics field that is the general frame of the present research, the main breakthrough today very certainly concerns the future use of field measurement techniques, whether it comes from in-situ situ tomography techniques applied for fatigue or quasi-static analysis, or stereo digital image correlation techniques that start to be used at very high speeds, or thermal cameras that already reveal amazing results. These powerful experimental and numerical technologies will make it possible to study, validate and identify models of unmatched complexity till now.

At short term, the present research will focus on the characterisation and modelling of temperature and time/strain rate dependence of damage models in composite CMO materials (including the topic of Cohesive Zone Models for delamination, with Joudon's PhD works which have started in 2011). In the frame of an ONERA/DGA PhD work proposal, Berthe's viscoelastic bi-spectral model is proposed to be enriched with the state of the art OPFM damage and rupture models, for instance such as:

$$S = S^0 + \Delta S^m \qquad \Delta S = \sum_i d_i H_i \qquad \dot{d}_i = \frac{1}{\varsigma_i}(d_i^{nr} - d_i)$$

with ΔS is the variation of the softness tensor, H_i are damage effect tensors according to the material directions, and ζ_i a characteristic time associated to a delayed damage effect, with the damage evolution law being formulated with standard thermodynamic considerations. Then the time/temperature equivalence principle will be challenged together with cyclic tests in order to study the question of the existence of visco-damage effects, and analyse and predict the time/strain rate influence on damage models.

Another PhD work (CIFRE SAFRAN), will start soon to study the dynamic behaviour of 3D interlock composite materials for turbomachines applications. A collaboration between ONERA, ALTAIR and the University of Mumbay (IIT) is under discussion, the subject of which concerns the microscale analysis and foundation of composite mesoscale dynamic models. Last, the long lasting partnership with the University of Valenciennes (LAMIH) on CMO composite material modelling will continue, for automotive applications.

The second axis of work will concern applied mathematics issues: the previous proposed models will be implemented in the EUROPLEXUS explicit code (the owners of this code are the French CEA and the EU CCR, ONERA being co-developer), with the main challenge being the optimisation of their resolution efficiency in terms of accuracy vs CPU costs. If one targets an industrial application (such as structural optimisation of composite fuel tanks structures against HRAM threats), it is indeed very important to keep the numerical costs of the non-linear models as low as possible which means avoid any useless modelling or algorithmic complexity. This kind of implementation exercise in an explicit solver will also be used to perform heavy virtual analysis, and define multiscale modelling strategies, for instance to study contact and friction mechanics at the damage microscale level, that might be of importance since one can expect that viscous and thermal effects might come from this mechanics.

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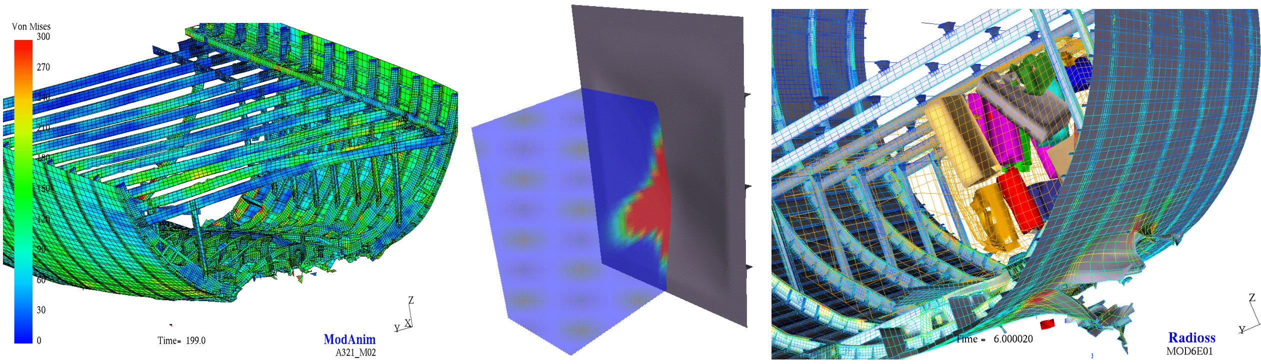
Chapter 3

Characterisation and numerical simulation of hydraulic ram in fuel tanks

Synthesis of research (1995-2013)

Introduction

Various Fluid/structure Interaction problems (HRAM, Bird Strikes, Ditching, Explosions) have been studied for many years at ONERA/DADS, first experimentally [Petitniot, 1983] then using simulation codes [Santini, 1998] [RE-17]. Different formulations (Lagrangian, Arbitrary Lagrange Euler, Coupled Euler Lagrange and Smooth Particle Hydrodynamics) and equations of state (e.g. viscous hydrodynamic, bi-phase liquid/gas) were available in the numerical tools and have then been evaluated since the 90's [Randles, 1996] [CI-02]. For the solid domain, a lagrangian F.E. model of the structure is generally used. Concerning the fluid domain, the Arbitrary Lagrange/Euler (ALE) formulation is preferred to be used to model the fluid medium [Donea, 1983, 2004] [Souli, 2000]. More recently, a Coupled Euler Lagrangian (CEL) formulation was implemented in the Computational Structural Mechanics explicit commercial codes, where non conform solid mesh can be completely bathed into the fluid one, so there are no common nodes and less mesh constraints to be imposed between the solid and fluid domains. The method for coupling the fluid and the structure is generally based on the use of specific interfaces between structure elements and fluid nodes, which compute interaction forces. The interfaces stop the flow propagation of the fluid media and transmit the pressure load to the solid domain.



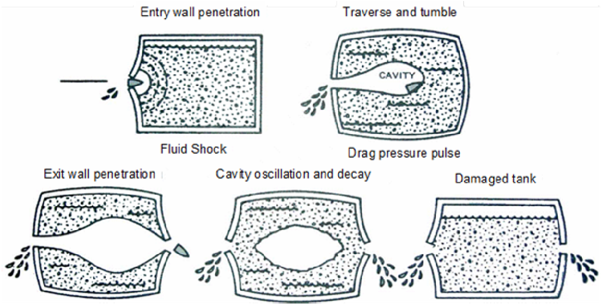
Examples of Ditching, Bird Strike and Explosion FSI Simulations

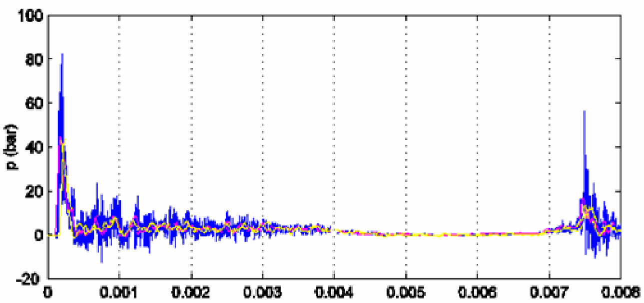
The different formulations (e.g. lagrangian, ALE and SPH) and equations of state (e.g. viscous hydrodynamic, bi-phase liquid/gas) have long been investigated at ONERA-Lille [RE-17] [Ortiz, 2004] [Delsart, 2010]. The F.E. results have been compared to experimental data when available (concerning bird strikes, many test results exist on rigid, metallic, composite and transparency panels), in terms of dimensionless pressure vs. time diagrams, Hugoniot and stagnation pressures, etc. In the end, when no calibration is operated, and as long as no penetration occurs, the Lagrangian, ALE and CEL formulation (as they are implemented in the RADIOSS code) proved to be appropriate or not - according to the considered hydrodynamic studied case. When rupture occurs (which is often our studied case), the interface should be deactivated in order that the fluid might flow through the broken structure, which might raise important numerical difficulties: that is mainly why Smooth Particle Hydrodynamics methods were also investigated.

In 1995, ONERA was contracted by the French DGA to study the topic of the prediction of hydraulic ram effects in aircraft composite integrated fuel tanks in case of ballistic impacts, in the frame of the development of the future Military Transport Aircraft (Avion de Transport Futur), meaning the actual A400M. A neat perforation of military aircraft tanks by ballistic projectiles induces a slow leakage of fuel which might allow the aircraft to return, but the eventuality of global damage to the tank, of major and rapid loss of the whole fuel, of a weakening of the structural strength hence destruction of the aircraft, have to be examined and prevented. So the design of fuel tanks with a reduced vulnerability with respect to hydrodynamic ram events (HRAM) was a long-time studied problem in the Defence aircraft industry: when hit by a high speed / high energy ballistic projectile, aircraft tanks can suffer from a catastrophic failure mode consecutively - not to the direct impact of the ammunition onto the structure - but to the hydrodynamic loads that the crossing of the ammunition trough the liquid medium creates.

When a solid target is hit (e.g. entry wall of container) a pressure shock wave is almost systematically generated in the solid medium, which is partly transmitted to the fluid system. The quantification of this first shock pulse is not easy to reach since it depends on the local interaction between the projectile and the solid materials (nonlinear, possibly thermal, damage and rupture behaviours), and also possibly on structural parameters (geometry, boundary conditions, etc). Anyway, this very first impact load often proves not to be the most threatening one in terms of fuel tank vulnerability. The hydraulic ram (HRAM) denomination traditionally concerns phenomena that occur after that the first solid wall of a fluid tank has been perforated. It refers to high amplitude dynamic overpressure-depression discontinuities (shocks) transiting in the liquid and reflecting on the structures boundaries. The amplitude and duration of the very initial shock pulse depend on the impactor characteristics (material, size): when a rigid projectile hits a liquid medium, a hemispherical shock wave is often reported to be generated [Varas, 2009] [Lecysyn, 2010] which radiates from the impact point into the fluid, with various formulae for the shock pressure being given, e.g. in [Borg and Cogar, 2007]. The shock pressure in impacted elastic mediums is used to be calculated as $p_s = \rho c v$, with p_s the peak pressure, v the particle velocity, ρ the impacted medium density, and c the impacted medium sound velocity. In fact, in the case of a direct impact of a solid onto water, the induced shock wave intensity depends on the projectile geometry and orientation with respect to the fluid surface: normal impact of sharp projectile would almost generate no initial shock wave, when flat projectiles impacts would cause high pressure pulses according to the previous equations. These very brief pressure peaks are very difficult to measure and, again, are not the more dreadful if considering subsonic impact cases.

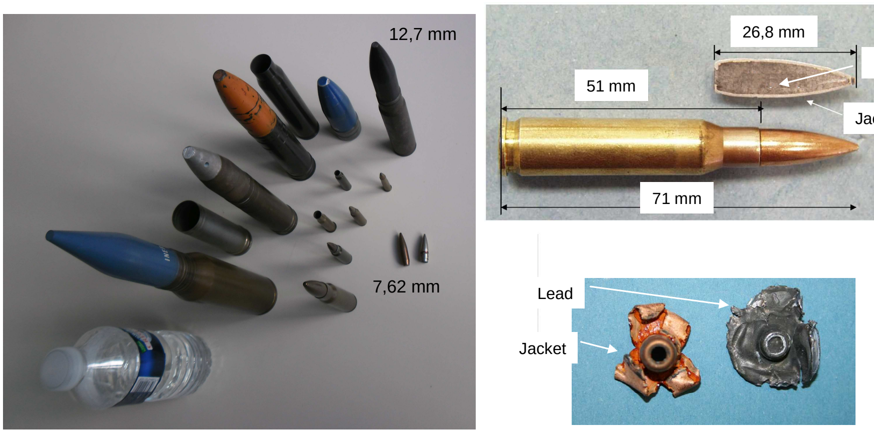
The HRAM phenomenon which is studied in the present research occurs because the projectile is brutally slowed down or even stopped by the encountered drag forces in the fluid, its kinetic energy being dynamically transferred to the fluid during the process. A second pressure pulse is then generated, than can be more easily observed that the previous one, followed by a longer but lower pressure pulse that accompanies the development of a cavity/wake behind the projectile. Last, after the projectile has stopped or exited from the tank, the cavity/wake collapses which can create a second mechanical shock which can be deadly for the structure if it has already been seriously damaged during the previous load phases [Ankeney, 1977].





Description of HRAM event (left) and Pressure time history (bar/ms) recorded in a dummy test experiment.

The first part of the presented research is dedicated to experimental works that aimed at improving the understanding and the measuring of hydrodynamic behaviours in fluid mediums during high velocity impact situations. Pressure measurements, of course, are the basic experimental data to be used to address theoretical issues, and validate numerical simulations. But their use is not straightforward for non hydrodynamicists, and great care must be taken when designing experiments. Then, as high velocity phenomena that the eyes cannot catch are here of interest, the use of high speed imagery techniques has always been the key for understanding HRAM events: high speed digital video cameras have become today the ultimate experimental mean to study high velocity impacts situations, including when fluid/structure interactions are concerned.



Various balistic projectile calibers (left) and fragmented 7,62 mm projectile due to impact and hydrodynamic drag during water entry (right)

The second part of this chapter deals with numerical simulations again. The computing capabilities of FE explicit dynamic codes (e.g. RADIOSS) to deal with hydrodynamic fluid/structure interaction problems at full structure scale were of course to be assessed in the 90's, the main question being the theoretical validity of the fluid models (equations of state, need of multi-material or multi-phasic fluid behaviour) and the stability of the numerical resolution schemes when hard/soft mediums interactions, very high velocities and large mesh deformations were involved (both for Lagrangian and ALE formulations). Engineering and pragmatic approaches had nevertheless to be proposed to cope with numerical costs limitations, sometimes at the expense of the physical foundation of the models. The constant increase of modern computers power logically brought back these physical and mathematical questions wide open, which are still current research axis at ONERA.

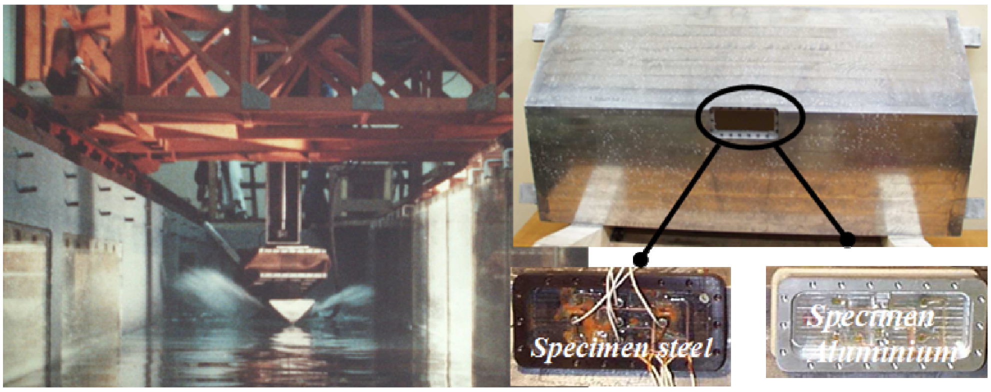
Experimental characterisation of Hydrodynamic RAM events

Theoretical results [Von Karman, 1929], [Wagner, 1931], [Okada, 2000], are available to compare and validate numerical tools with respect to global cinematic responses of structures subject to hydrodynamic loads, but the validation of the tools in terms of predicting the local mechanical fields (that could lead to local deformation and rupture of structure skins) could not be reach that way [RE-9]. The validation of numerical methodologies and tools is then based on the simulation of experimental tests of an increasing level of complexity. When accidental situations are considered, the tests are destructive by nature, which means that the experimental exercise may be very expensive (usually, the final validation step is limited to a single test configuration). The interest of the numerical tools, once validated, is that the simulations are much less expensive than the experimental tests. The problem is that the generality/validity of the tool must be demonstrated. The only way to do so is to prove that it relies on physical and not empirical models and equations, and that the numerical resolution scheme does not influence the simulation results. So, it is essential to evaluate the validity domain of the numerical codes to derive simulation methodologies. For that purpose, it is important to build up a parametric test campaign and database, with all the parameters under control, to be able to compare the model with a number of different proper and as simple test cases as possible.

Then, this necessary experimental research work was splitted into several steps. The measurement of local transient hydrodynamic parietal pressures was first focussed on, first with the question of the validity (and objectivity) and accuracy of pressure measurements obtained with standard on-the-shelf transducers. Specific test rigs and experiments had to be set up for that purpose. The research results finally led us to change our test protocols, and use other kinds of pressure transducers in the hydraulic ram tests which are of interest in the present report. Considering then the characterisation of hydraulic ram during representative high speed ballistic tests, specific firing experiments were proposed which relied on the qualification and use of very high speed digital cameras (up to 400 000 fr/s) to record the HRAM phenomenology, and measure other data together with local transient pressures that was previously mentioned. Finally this experimental work permitted to get academic results of great interest for the evaluation and improvement of numerical simulation tools.

Objectivity of local dynamic pressure measurement for the validation of structural numerical simulations

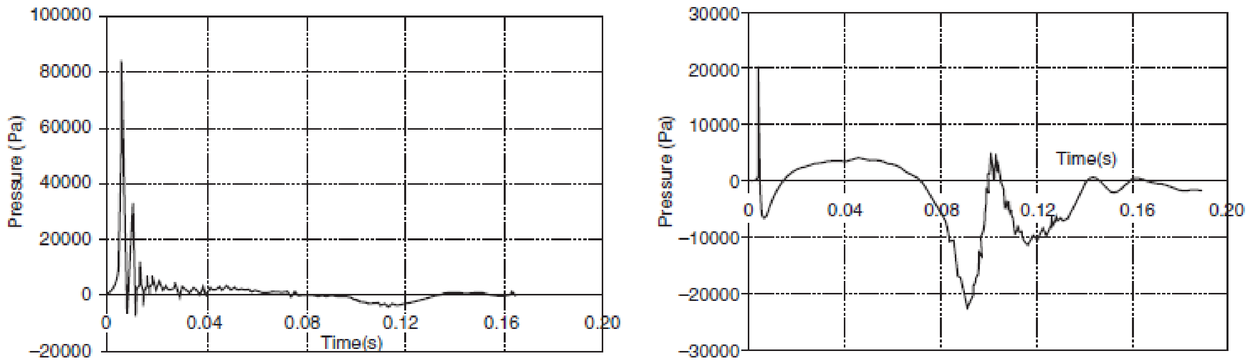
For instance, elementary impacts tests on water had been carried out at ONERA in the frame of an EU Project (SEAWORTH BRPR-CT97-0464) [Le Roy, 1999] [RE-14], [RE-15] [RE-93] [RE-94] that dealt with impacts of structures on water (ditching, slamming). These laboratory test cases were expected to be basic generic cases of interest to validate the numerical tools in terms of local mechanical measurements - even if the laboratory structures differed from the real ones, their scale or their design being different - assuming that if the numerical results correlate well with the laboratory test results, the numerical tool would be validated and could be used straightforwardly to model any real structures and hydrodynamic configurations (including precisely defined qualification and certification tests).



Hydrodynamic pool (left) and dihedral geometry and metallic flexible specimens (right)

The laboratory tests consisted in hydrodynamic impacts of rigid frames (rigid 130° dihedral and flat impactor geometry) set on an hydraulic jack, the maximum vertical speed of which was 2 m/s, itself mounted on a trolley the maximal longitudinal speed of which was 20 m/s. The impacts were studied on a calm lake in the ONERA 20m x 2m x 2m pool, at different speeds. The rigid shapes were instrumented with ENDEVCO accelerometers, KULITE XTC-76A-190M flush pressure sensors (In this field, the "flush" transducers are the most frequently used because they bring some protection against possible floating dusts), and equipped with small flexible metallic specimens with strain gauges. The dimensions were designed in such a way that it was possible to consider that 3D boundary effects on the local measured data were negligible during the impact events. The idea was to vary the plate material (steel, aluminum) and thickness (0.5, 1, 2, 8 mm), the angle and velocity of impacts, to build up enough of an experimental database to make it possible to validate different eulerian or lagrangian simulation tools in terms of prediction of local data.

The local measurements of the fluid pressure levels were more difficult to handle with than the acceleration and strain ones. For the case of the flat panel impacts, the responses of the different pressure transducers were almost identical, indicating a fairly uniform pressure on the surface of the panels. The test not being destructive, it was possible to reproduce them to evaluate the natural discrepancy. Generally speaking, the pressure measurements were quite repetitive. For the dihedral case, whatever the configurations (angle, speed, etc), the results exhibited larger oscillations and sometimes negative relative pressure (absolute) values, with great difficulty to obtain repetitive tests results. In the end, these tests on "elementary" structures did not prove to be as simple as one might have thought.



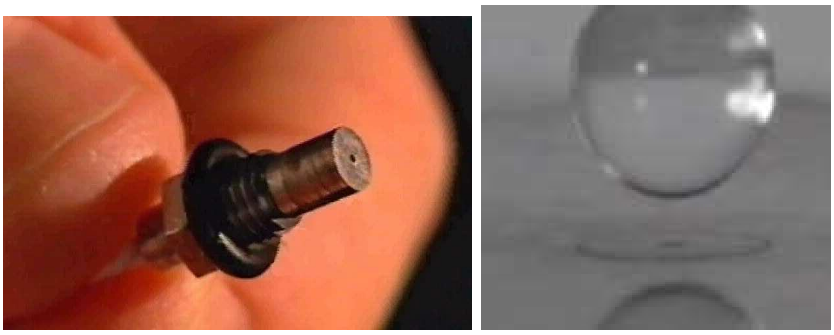
Impact of flat frame (left, 1 m/s), and dihedral frame (right, 2 m/s)

On the one hand, some of the recorded pressure data, measured with piezo-resistive transducers, were discarded from the database because they were clearly erroneous (hardly understandable and explainable: oscillations, depression). On the other hand, large discrepancies were pointed out between the test and numerical simulation results, none of the numerical methods being able to reach a satisfying correlation with the test results in terms of pressure, strain or acceleration levels. The question of adequacy between the test configuration and the numerical models naturally raised: influence of 3D effects, validity of fluid Equation of State (viscosity, cavitation), and complexity of the fluid/structure interaction (laminar or turbulent layer). So the idea naturally came that simpler experiments than those previously described should be considered if one wants to validate the fundamentals of the different codes. A bibliographic review was started to find basic reference fluid/structure interaction test cases to be used for code validation, but no proper data was found in the literature. It was then decided to define such a reference test case, and to build up an experimental database to be used by the scientific and research community. A simple experiment could have consisted in the impact of water droplets on circular flexible plates. The correlation data would be the deformation of the plate, a very well-known material being selected for the considered specimen. This kind of test should be easy to perform, and it should be very repetitive. High speed video cameras could be used to measure the droplet shape and impact velocity. This case would have the advantage to be symmetric, which means that first 2D parametric simulations could be done to improve the numerical and test procedures. Then 3D models would be derived to completely assess the tool capabilities.

But another important question came to our mind then, that address the relevance of research laboratory tests (like the SEAWORTH ones): they are often equipped with many instruments that could make the locally measured data quite different from what should be with the bare real structures, which would raise the question of the objectivity of the measured data, if the measurement sensors were not themselves modeled in the numerical simulations. For instance, the KULITE transducers have been selected because of their specific flush design: a small hole is made in a flush skin, to let the water enter a cavity in which the measuring deformable membrane is set. This flush design enables one to get rid of geometrical singularities which could locally modify the flow and the pressure level at the transducer location. At equilibrium, the same pressure is assumed to stand at the surface of the specimen and in the transducer. But during dynamic events, the influence of the transducer design on the pressure measurements was not clear. Of course, the same question also stands when bird strike [RI-4], [RE-13], [RE-17] or HRAM [RE-10], [RE-11], [RE-12], [RE-16] problems are studied. In the end, the fundamental question of the meaning of the pressure value delivered by the transducer - compared with the numerical one or with the one which would be supported by the structure without a transducer – should always raise.

Analysis of KULITE pressure sensor measurements under water impacts [CI-26]

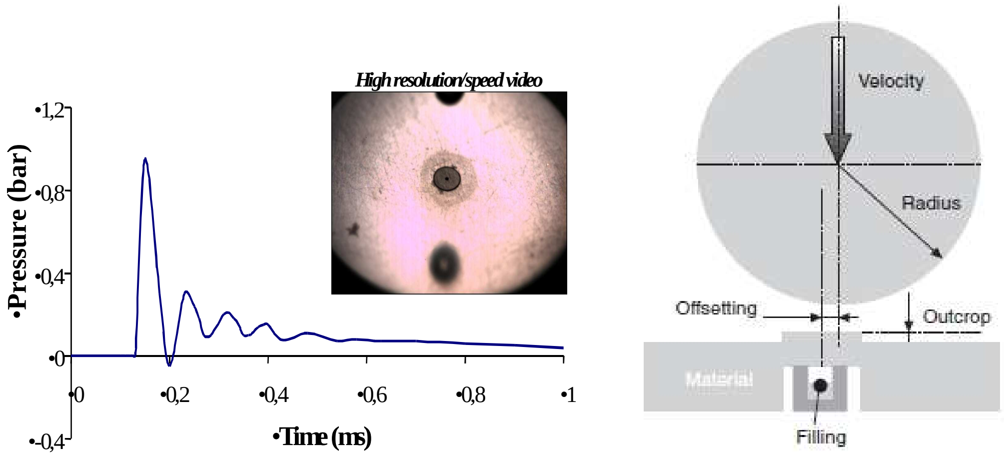
As a consequence I proposed to study the pressure transducer as a test specimen in a PhD work [CI-26] [CN-02], no bias being introduced in the fluid/structure interaction study since the tested structure would be the measuring device. Experimentally, a pressure transducers works by translating the electric signal that comes from an extensometric strain gauge (diaphragm) into a pressure value. The very flexible diaphragm part of the pressure transducer has a small dimension compared with the whole structure, which is considered to be rigid. As long as the strain gauge works in its linear domain, it is possible to use a linear transfer function between the pressure and the electric voltage thanks to an experimental static calibration procedure which consists in applying two different pressure levels, and to measure the corresponding electric signal once the equilibrium is reached. Theoretically, a dynamic calibration procedure (based on shock tubes experiments) should be applied to calibrate the dynamic transfer function of transducers for dynamically applications. The experimental test case that was proposed to be studied concerned the impact of water droplets on pressure transducers, hence the study of the fluid flow and associated dynamic deformation of the diaphragm, with of course the air presence having an influence on the process.



Picture of the KULITE cavity pressure transducer (left) and proposed hydrodynamic test case (right)

The previously described KULITE cavity transducer was selected to be studied. Indeed, these transducers have high natural frequencies, which is very interesting for the targeted dynamic applications. It delivers the relative pressure with respect to the atmospheric one (open backwards to atmosphere). The diaphragm is located inside the transducer external rigid envelope, with a hole being machined at the top to have the outside pressure acting inside the envelope onto the flexible membrane. For corrosive fluids, the diaphragm is made of a semi conductive silicon material into which the gauge is directly machined since the optimal sensor capacity is obtained after a judicious choice of the mono-crystal diaphragm shape, and the position and geometry of the gauge in the crystal. The overall diameter of the transducer head is about 3.7 mm, the diameter of the water port is 0.5 mm, and the inside cavity at the bottom of which the diaphragm is placed, is 0.8 mm diameter by 1 mm depth.

Tests were then performed to measure the dynamic pressure during controlled impacts of water droplets on the KULITE transducer. Though a particular effort had been made to propose as simple an experiment as possible, some difficulties and questions soon appeared anyway.

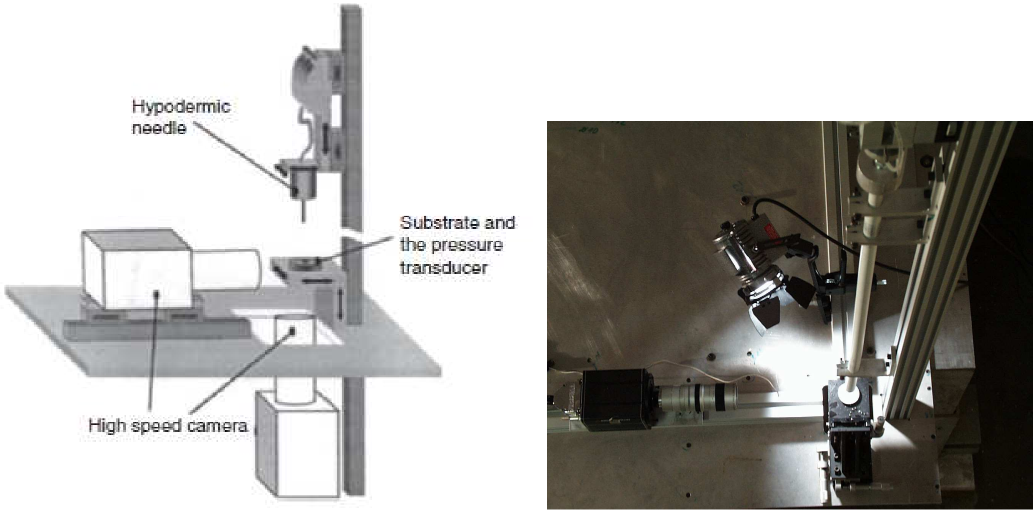


Results of water droplet impact (left) and example of sources of uncertainty (right)

The natural frequency of the pressure transducer is about 500 kHz according to the provider (which is assumed to be the diaphragm first natural frequency). The test results were filtered on a 23 kHz basis which came from the data acquisition system. Some of the experimental water droplet impact results exhibited an 11 kHz frequency component. As an elastic pressure wave would propagate and reflect inside a 4 mm diameter (0.035 g and 33.5 mm^3) water droplet within 2.5 µs during the impact, an approximately 180 kHz pressure wave would appear. The pressure wave which would propagate and reflect inside the 1mm deep transducer air cavity (0.5 mm^3) would be at least 150 kHz. So, only an added mass of water effect which would naturally decrease the diaphragm natural frequency, could then explain the appearance of this 11 kHz frequency: it means that some water entered the rigid envelope during some tests (at highest impact velocities). The use of blotter paper to dry the transducer after the tests demonstrated that water actually came into the transducer. A FFT analysis was also realized, to quantify the added mass effect. The dynamic range of application of this kind of transducer – and its dynamic calibration - should then be considered according to these considerations.

Development of specific test rig and protocol to study the response of pressure transducers during water impacts [RI-03]

So, an experimental set-up was designed and built up to measure the impact pressure and to film the behavior of water droplets falling onto a KULITE cavity pressure transducer [Portemont, 2002, 2003]. The water droplets were generated by a hypodermic needle. Different needles were used to vary the droplet diameter between 3 and 5 mm (the transducer diameter being 3.7 mm). The temperature of the tested liquid was controlled by a very thin thermocouple element which was inserted inside the needle. To keep the water droplet and transducer revolution axis aligned, a very rigid and accurate (two axis) device was designed. Droplets could be released from a varying height of up to 2 m to obtain impact velocities ranging from 0.5 to 5 m/s. A 40 mm diameter Plexiglas tube was raised around the fall trajectory to prevent any air motion from modifying the water droplet trajectory.



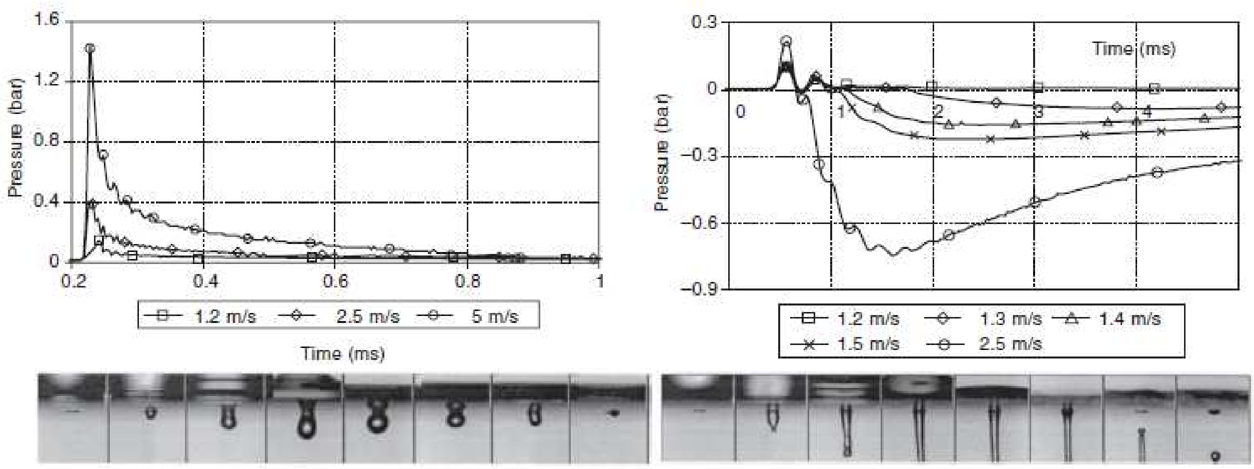
Schemes of the test apparatus (left) and test parameters (right)

The pressure transducer was screwed onto a substrate which was fixed onto the rigid support through of a linear stage (three axes) which makes it possible to accurately position it with respect to the vertical fall axis. Before any test, the pressure transducer and the substrate were replaced by a Plexiglas plate in order to check that the water droplet impact point was well centered, by filming the impact from below the support. The falling water droplet crossed a laser beam which triggered the high-speed video and the data acquisition system (Nicolet 10 MHz, connected to the Vishay 9210 amplifier). During the impact, it was then possible to associate levels of pressure with pictures of the water droplet deformation and flow (which depended on the substrate material). The high-speed camera (Visario) was set at a 10000 frames per second (10µs for the shutter) rate, equipped with a 105 mm lens (Nikkor). The pictures obtained with the high-speed camera were post-treated to measure the initial conditions of the impact (shape, diameter and velocity of the water droplet). The error was around 50 µm (which corresponds to a relative error of approximately 4.0 % of the real diameter) on the water droplet position, and 0.04 m/s on its velocity. It was possible to modify the nature of the fluid (here only distilled water was used), the position of the sensor (offset with respect to the impact point, outcrop, etc), or the nature of the substrate (material, roughness, thickness of the plate, etc).

The first tests were carried out with distilled water, because its properties are perfectly known. Though a very accurate and specific apparatus has been purchased (medical material) to drop the water, and a plastic tube barrier has been designed to prevent any air gust to influence the droplet trajectory, the pressure measurements showed a large discrepancy of results which could be explained once high speed videos have been operated: random trajectories were observed (due to aerodynamic instabilities - according to Weber, Reynolds, Bond coefficients – when the velocity of the droplet increased [Lesser, 1981, 1983]), that led up to 2 mm scatter on the impact position at 5 m/s. Fortunately, has the experiment is very cheap, tests could have been repeated as many times as necessary to get exploitable results. Finally, many parameters were investigated such as the water droplet size, the impact speed (depending on the drop height), the water density (salt added), the initial presence of water inside the transducer envelope or not, plus a number of others.

The first part of the study consisted in evaluating the influence of the sensor (position, cavity, etc), of possible capillary effects (substrate material), as well as the influence of the water droplet velocity and shape on the measured impact pressure. To evaluate the experimental scatter, three tests were carried out for each configuration. A strong influence of the velocity, offset and cavity filling ratio was observed.

The main point which is discussed hereafter is that two different kinds of pressure responses (which depended on the initial air/ water filling ratio of the rigid envelope) were observed. When the transducer cavity was initially filled with water, the pressure curve shape remained the same for velocities varying from 1.2 and 5 m/s (limit of the experimental device). A first peak pressure was followed by a progressive slope until the stagnation pressure (P_e = 0.03 Bar). Whatever the velocity, the duration of the pressure response is about one millisecond (τ = 1 ms). The maximal pressure depends on the impact velocity, whereas the stagnation pressure remains the same. When the transducer cavity was initially filled with, the pressure curve changed completely. A small positive pressure peak was always followed by a higher negative pressure peak which slowly fainted (τ = 120 ms). The negative pressure peak increases with the impact velocity. From 2.5 m/s up to 5 m/s the negative pressure peak remained the same, around– 0.8 bars. The high-speed videos showed that when the velocity increased (> 1.2 m/s), an air bubble of increasing size appeared at the transducer hole.



Comparison of impact test results: cavity initially filled of water (1 ms, top left) and initially filled with air (4 ms, top right) - and dummy test at 1,2 m/s (bottom left) and 2,5 m/s (bottom right)

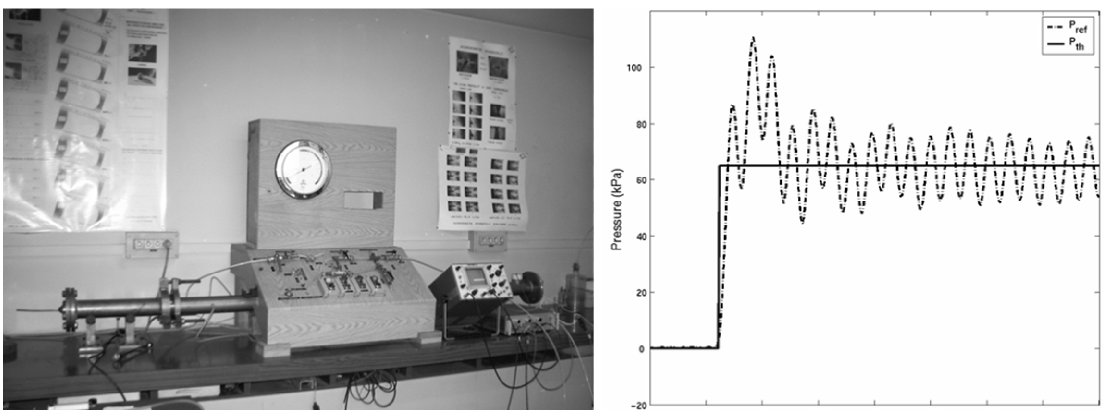
To understand the pressure measurements when the cavity was empty, another dummy experiment was done on the basis of a small perforated plate, the dimensions of which were the same as the transducer ones. For velocities less than 1.2 m/s, the water did not fall through the perforated plate: a single small droplet being generated but remaining attached to the plate, oscillating in and out, and eventually going back out of the specimen due to capillary and superficial tension effects. The oscillation frequency was about the same frequency 3.5 KHz than the one measured with the pressure transducer. For increased velocity, the inertial effects eventually became predominant, till a water droplet passed through the perforation. The negative pressure measurement was then explained physically, and confirmed by numerical thermo-elastic simulations and other tests where the temperature of the water and/or gauge was modified: it corresponded to a thermal effect when (cold) water enters the cavity and falls onto the membrane, and spreads over the hot point where the silicon gauge is set.

The explanation for the erroneous SEAWORTH test results has been finally found, and an important recommendation was made concerning the use of piezo-resistive strain gauges, when used for hydrodynamic tests on cold liquids. The research results were communicated to the KULITE company which designed improved pressure transducers afterwards, and to partner test laboratories to change or at least care about their hydrodynamic testing protocols.

Correction of pressure measurements during water impacts to get objective hydrodynamic parietal pressure [RI-02]

The important variable to size structures with respect to hydrodynamic events is the dynamic parietal pressure that the structure will be subjected to. However, the pressure profiles recorded in experimental tests to validate the numerical design tools do not always correspond to the parietal pressure because they integrate the dynamic response of the measurement device. Thus, the database cannot be exploited directly to validate numerical methods because the comparison would be between an experiment in which the phenomenon is modified by the presence of a transducer and a simulation in which no transducer is present: evaluations of dynamic pressures that structures undergo at the moment of an impact with a fluid can be biased. In the example studied here, the potential bias comes from the measurement method. To examine this potential bias, Portemont conducted a laboratory study into the case of water drop impact on a pressure transducer. The transducer chosen for the experiment was a relative transducer whose measurement element (an elastic silicon membrane) was protected from any possible dust and debris by an access chamber. This type of transducer was recommended for studying hydrodynamic impact at intermediate speeds. Portemont's experiments highlighted a noticeable measurement perturbation coming from the experimental configuration, notably the initial presence or absence of water inside the transducer chamber

The academic objective of the present research [Haboussa, 2005, 2008] [RI-02] was to study the methodological feasibility of a method for processing the experimental responses that will allow the pressure measured along a structure wall (parietal pressure) to be corrected of the influence of the transducer. This correction would allow the results of numerical simulations to be compared directly with an appropriate experimental reference (in our case, the dynamic pressure truly exerted on the wall of the modeled structure). The dynamic calibration of a transducer with a shock tube typically permits the validity range of the results (rising time and dynamic balancing time) to be defined, and the gauge factors needed to exploit the electrical signals experimentally to be determined [Lavergne, 1978] [Sudan, 1981].



ONERA Shock tube apparatus (left) and comparison of the theoretical pressure step and reference measured one (right)

This calibration process was proposed to be used to quantify the dynamic interference of the transducer on the pressure measurements: once the imposed theoretical dynamic pressure profile and the real signal delivered (with the linear static gauge factor) are known, the transfer function linking the two signals can be formalized. The knowledge of this transfer function then allows the pressure measurements to be corrected inversely of the influence of the transducer, to get the value of the dynamic parietal pressure exerted on the structure during impact. With the goal of proposing and validating an appropriate method for processing the dynamic pressure responses delivered by the studied transducer, Portemont's KULITE transducer was studied (with exactly the same electronic acquisition system, used at 10 MHz sampling frequency, which means that the same electronic conversion coefficient can be applied for both the present test results and Portemont's ones) in the present research, in order that Portemont's results can be used for application case.

The pressure transducer placed at the bottom of the low-pressure compartment, as was the reference transducer. The cavity transducer, object of the calibration phase, was thus subjected to a theoretical P_5-P_1 pressure step. The dimensions of the shock tube used in the present experiments generated a plateau time long enough to permit the dynamic calibration procedure to be performed correctly. The real input pressure measured by the reference pressure transducer was different enough from the theoretical perfect P5-P1 ramp in the shock tube to justify its use as the input pressure to be compared to the KULITE measurement. Also, two additional pressure transducers were placed at different points in the low-pressure compartment of the shock-tube to measure the real speed of the shock wave and its real Mach number M_{sh}. This experimental value, which proved to be different from the theoretical value, would be necessary to calculate the future transfer function.

Very soon, it appeared that the measured response differed from the P_5-P_1 input, which pointed out that the studied pressure transducer had a real influence on the output data, notably when water was introduced in the KULITE transducer cavity. The influence of the transducer on the output data (measurement) could be described as modifications of the frequency spectrum, amplitude and phase of the measured signal, compared to the input signal. So the test results were transposed into the frequency domain using a discrete Fourier transform.

Subscript $_{ref}$ refers to the dimensions and measurements of the reference pressure step P5-P1, subscript $_s$ refers to the dimensions and measurements of the cavity transducer during the shock tube tests, and subscript $_d$ refers to the dimensions and measurements of the cavity transducer during the drop impact tests.

$$\forall k \in [0 : N-1] : \begin{cases} F(p_{ref}(k)) = \sum_{n=0}^{N-1} p_{ref}(n) e^{-2i\pi k \frac{n}{N}} \\ F(p_s(k)) = \sum_{n=0}^{N-1} p_s(n) e^{-2i\pi k \frac{n}{N}} \\ F(p_d(k)) = \sum_{n=0}^{N-1} p_d(n) e^{-2i\pi k \frac{n}{N}} \end{cases}$$

Correcting the measurements of the cavity transducer subjected to drop impact in the frequency space is, in the end, a matter of performing the following operation in the Fourier space, where the exponent ^{corr} corresponds to the corrected measurement:

$$\forall k \in [0:N-1],\ F(p_d^{corr}(k)) = \frac{A_d(k)A_{ref}(k)}{A_s(k)} e^{i(\Phi_d(k)-\Phi_{ref}(k)+\Phi_s(k))}$$

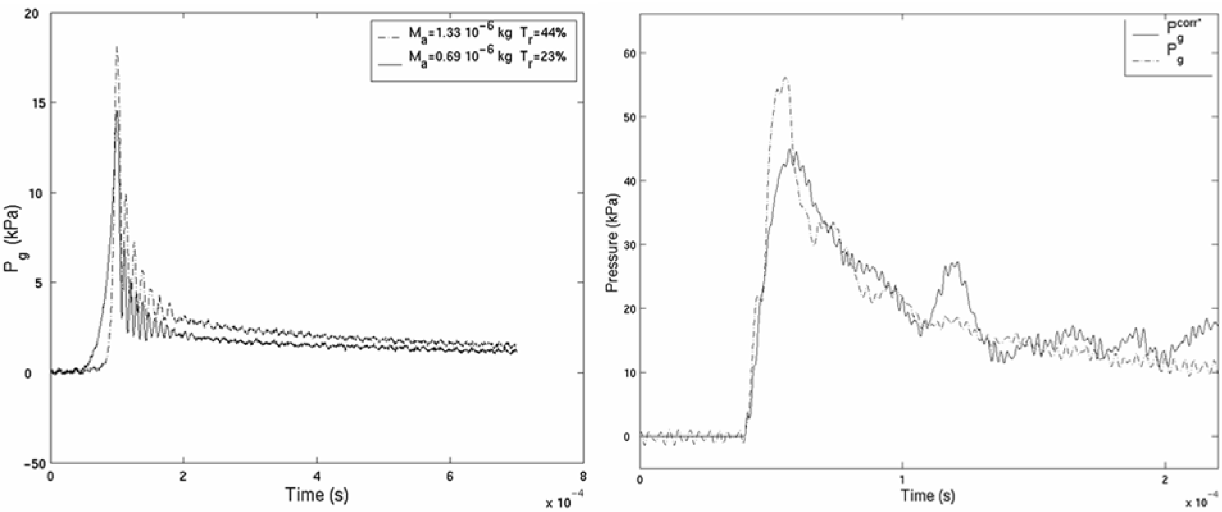
Thus, returning to the temporal space, the transducer transfer function H_N is obtained:

$$\forall n \in [0:N-1],\ p_d(t_n) \rightarrow \frac{1}{N}\sum_{k=0}^{N-1} F(p_d^{corr}(k)) e^{2i\pi k \frac{t_n}{t_N+\Delta t}}$$

Applying this transfer function to the pressure signal measured by the transducer during water drop impact thus gives the corrected real pressure:

$$H^*: p_g(t) \rightarrow p_g^{corr^*}(t) \approx p_{real}(t)$$

The principal problem in implementing the proposed experimental protocol then laid in the determination of the amount of water that was introduced in the transducer cavity, in the present tests and in Portemont's ones. Indeed, Portemont systematically performed several tests with the same test parameters: all other factors being equal, his results revealed differences that were, in the end, attributed to differences in the cavity filling ratio. An analytical model and methodology had to be developed, as described in [Haboussa, 2008], to sort this information out of the database results. Once the spectral analysis of Portemont's experiments had been made to determine the effective filling ratios for his tests, dynamic calibration tests were performed on the cavity transducer in the shock tube, with the same filling rates. Note that another possible source of deviation appeared than, since the membrane burst in the shock tube was not a perfectly repetitive process. Portemont's test results for each impact speed, drop diameter, and any other parameter of his experiments, were then post-treated to get the value of the parietal pressure that would apply in the same case on a structure wall without the presence of the pressure transducer.



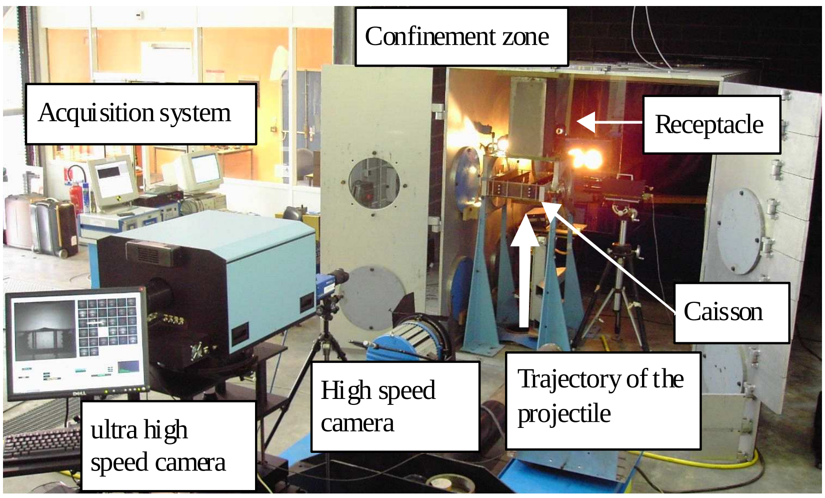
Comparison of pressure results with different identified filling ratios (left) and of corrected parietal versus raw KULITE pressures (right) from Portemont's tests.

In order to assess the interest and to check the robustness of the method, two different transfer functions which corresponded, on the one hand, to two very different filling ratios and, on the second hand, to two slightly different filling ratios, were applied on Portemont's results. The obtained parietal pressure profiles were very different in the first case and very similar in the second case, showing both the benefits of taking the filling ratio into account, and the robustness of the method. In order to quantify a little further the effect of the pressure correction in terms of severity of a hydrodynamic fluid/structure interaction, two key data were extracted from the tests: the pressure peak, and the pressure impulse. Concerning the pressure peak, the parietal pressure systematically exhibited a lesser maximum that the original cavity transducer one. The higher the cavity filling ratio, the more significant the overpressure peak measured with the cavity transducer. The raw pressure was generally 20% higher than the parietal pressure which would then be conservative in terms of static structural sizing. The raw pressure impulse was generally 5% lower than the parietal impact pulse, and was then not conservative in terms of transmitted energy for dynamic structural sizing but not significant knowing the scatter of results.

Characterisation of hydraulic ram phenomenology during representative high speed ballistic tests [CI-01]

A specific firing test rig was developed at ONERA in the frame of the EUCLID RTP3.32 research project that dealt with the improvement of military aircraft fuel tanks against HRAM. The weapon used was the PARKER HALE 308 Winchester gun of 7.62 mm NATO caliber that had already been used in the past 80's to perform experimental studied. This gun was proposed to be used as a generic research mean to study HRAM problems, since it required less security/safety accreditations to be used than 12,7 mm or more powerful ammunitions, but was nevertheless representative of realistic military threats. The gun was set vertical in the basement of the ONERA test laboratory, which makes it possible to shoot structures that are located above in the lab, with representative configurations. A 9.3 grams and 28.6 mm long bullet is used, with a 870 m/s speed at the exit of the muzzle (subsonic speed with respect to liquid sound speed i.e. 1500 m/s), that corresponds to a 3520 J energy. The standard bullet is made of a 0.60 mm CuZn20 Tombac jacket, with a lead core inside.

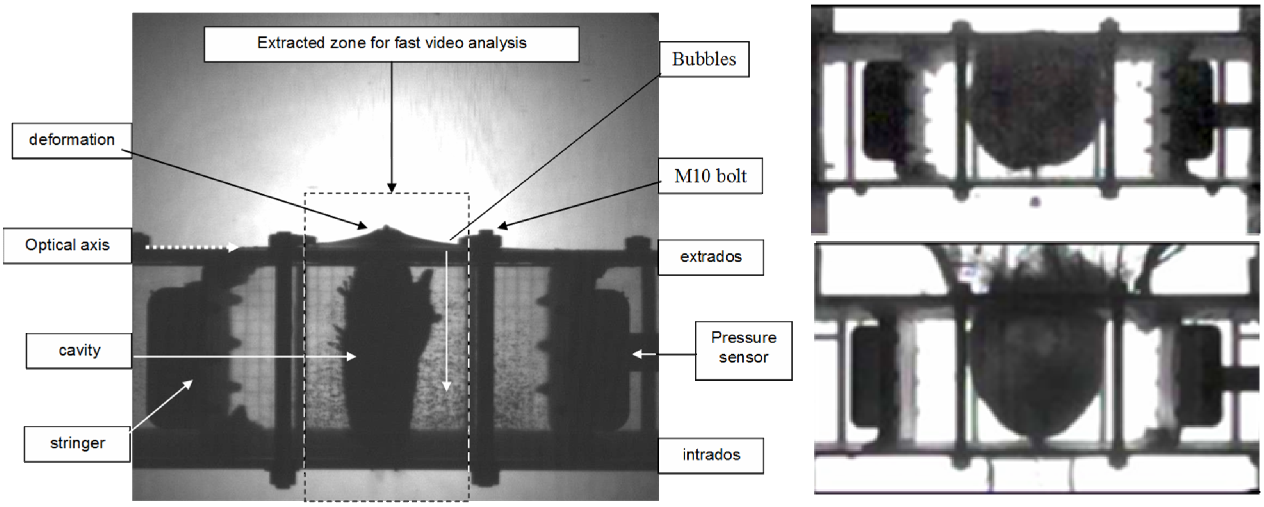
The bullet speed just before impact is recorded with an optical (laser) barrier, with a precision of about one microsecond and one tenth of millimeter, hence a limited 0.42% relative error on the speed of the projectile. The optical barrier is also used to trigger the acquisition system and the high speed cameras, with the same TTL signal in order to have a common reference time for all the dynamic data. The tested structures may be equipped and instrumented with strain gauges, accelerometers, and pressure sensors. KISTLERTM piezoelectric pressure transducers were for instance used, than have an effective range of 100 MPa, linearity better than 0.5% of the full scale and an eigen frequency of 150 kHz.



Description of the ONERA 7,62 mm firing test installation and instrumentation

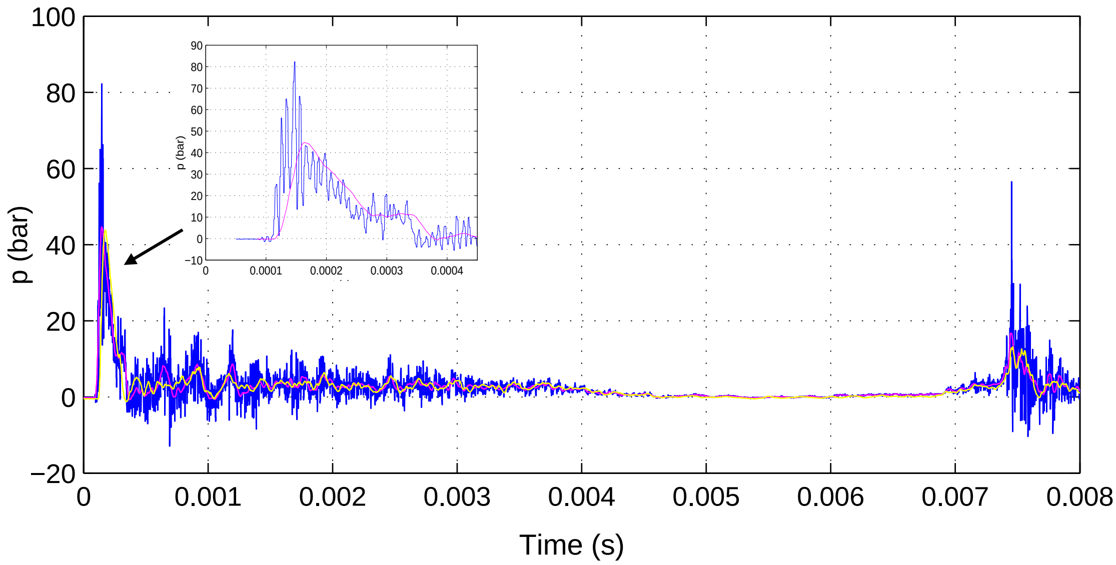
The improvement of knowledge was largely expected to come from high speed digital visualizations [Shi, 2009], possibly to get a grip on the initial configuration of the projectile (speed, incidence), to visualize the pressure waves and the cavity inside the fluid, to spot the position of the projectile inside the cavity, to evaluate the deformation of the exit wall, and to follow the trajectory of the projectile after exit. Two types of high speed cameras were implemented. The first one was a CORDIN ultra high speed digital camera: its maximum possible frame rate is 400.10^{+3} fps, with 32 pictures only (rotating prism based technology). That means that a 0.1 ms phenomenon (or an 85 mm spatial displacement for an 850 m/s moving target) can be captured at full rate if correctly triggered. With a 1024x1024 pixels to cover a 150 mmx150 mm window, the resolution is almost 0.15 mm/pix (no light intensifier is needed, which improves the resolution). Last, the storage of some pictures before the trigger signal arrives is made possible thanks to pre-triggering. The second camera was a VISARIO high speed digital camera (with a zoom) in order to observe/measure the cavity geometry evolution during the HRAM event. The time scale (≈ 10 ms) being not the same as for the projectile kinematics (< 1 ms), the VISARIO resolution can be reduced to 512 * 196 pixels in order to still catch HRAM video at a 10 000 fps rate, at the expense of quality. Two xenon (to avoid heating the structure) flash projectors of strong power (2*1500 W) were used to provide sufficient light to reduce the exposure time to a minimum value (2.5 microseconds for the CORDIN camera) in order to limit the blurs on the pictures due to the displacement of the projectile.

The firing test rig was then used to perform ballistic impacts on metallic and composites plates (of equivalent static resistance), and metallic and composite dummy tank structures. Results were compared to [Townsend, 2003] for a qualitative point of view (a different ballistic projectile was used). The HRAM event, as far as the fluid only was concerned (pressure profile, cavity expansion, etc), was not influenced by the material that constitutes the fuel tanks. But the composite material damage and failure behaviors were much more complex, then probably more difficult to properly model than the well-established plastic metallic ones.



Description of HRAM test (left) and failure mode of a metallic dummy tank (top right and composite dummy tank (bottom right)

For the synchronous acquisition and recording of the data, a NICOLET Multipro multi-channel transient analyzer was used (1 Mega-samples per second, with 12-bit resolution), together with the FAMOS software environment. Flush pressure transducers were used according to the knowledge gained from the previous research. They were set inside the dummy caissons (not on its walls). The measured pressure always presented the same general profile: a first high pressure peak which corresponds to the very rapid tumbling of the ammunition (0,2 ms). Then a lower pressure response is observed during the cavity growing phase (3,5 s), with a final very short burst of pressure (0,2 ms) being recoded late when the cavity completely collapses (see figure below).



Pressure time history in a composite EADS-IWF dummy caisson subject to a realistic 7,62mm induced ballistic HRAM

Interpretation of hydraulic ram test results according to different types and size of fuel tanks [RI-01] [CN-01]

The scientific literature on HRAM effects in liquid tanks, be it numerical and/or experimental, proved to be very limited, except for US technical reports and conferences proceedings, with only few journal papers on this specific subject being referenced. The present research concerned an experimental effort which aimed at comparing two hydraulic ram events throughout their different steps up to the final collapse of the cavity. The specificity of this research compared with the literature was that it concerned no spherical rigid impactors, but a NATO 7.62 mm bullet with its real geometry and material definitions, which induces tumbling mechanisms and variable drag coefficient when penetrating the liquid. The other point of this research was to study two very different configurations (almost infinite and confined cases), where many other authors tested a single structure with partially different test configurations with respect to filling ratio, bullet velocity or bullet type.

In addition to the different tests that were performed in the EUCLID RTP3.32 project, the idea was to perform a 7.62 mm firing test in the ONERA hydrodynamic pool (see SEAWORTH paragraph). We decided to concentrate on digital image analysis to measure the cavity geometry during its growth and collapse phases. The originality of the work consists in the fact that – compared with other works such as [Lee, 1997] [Nishida, 2006] – the phenomenon was studied up to tens of milliseconds in this very large pool for theoretical analysis of the bullet/liquid interactions only, and compared with tests on dummy fuel tanks to consider influence of boundary conditions on the cavity characteristics (geometry, dynamics).

The knowledge of the projectile kinematics $v(t)$, $\gamma(t)$ gives access to the drag coefficient $C_D(t)$ and to the evolution law of the velocity decay coefficient $\beta(t)$ as introduced in [Ankeney, 1977]. This is very interesting if one wants to model the HRAM event using equivalent projectile and pressure models like Deletombe et al. [CI-3], [CI-28] :

$$\beta(t) = \rho A C_D(t)/2m = -\gamma(t)/\, v(t)^2$$

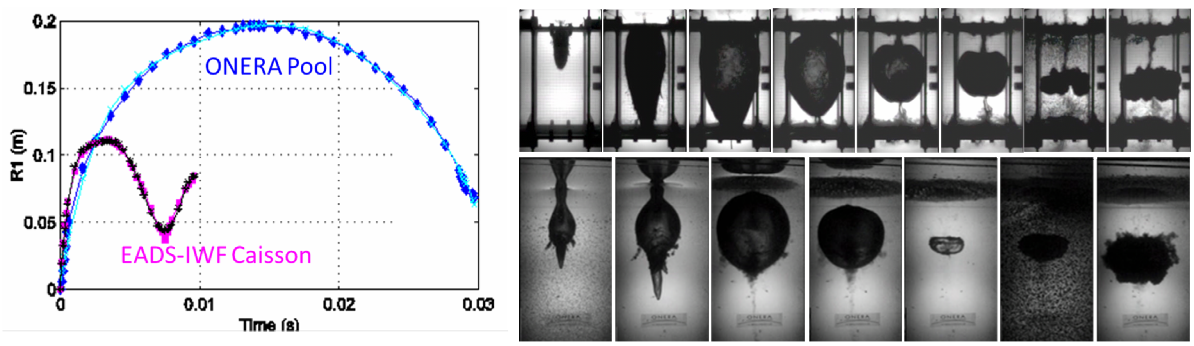
The higher the velocity decay coefficient, the shorter the projectile energy is transferred to the fluid, which can produce severe shock waves. Then the difficulty was to get continuous and accurate enough information about the bullet displacement in order to derive its velocity and acceleration, and then calculate the drag coefficient. In real structures, it is obviously not possible to reach this information unless using X-ray scans to follow the high density metallic projectile position through the lightweight structure that contains the liquid as it was done in [Valèze, 1997]. The problem then was the number of X-ray cameras (then measurement points) that can be set up along the bullet trajectory. If the assumption is made that the structure geometry and stiffness have almost no influence on the projectile/liquid interaction that will determine this drag coefficient, it appears easier to use transparent structures or no structure at all (no entry wall) and high speed cameras to catch the projectile displacements. Such an assumption had to be assessed, which was the main objective of the present work. However, past experiments showed that the change in the multiphase fluid system optical indexes with the pressure and density makes such a tracking of the projectile very difficult. Indeed whatever the camera resolution and light exposition, the projectile wake and gas cavity (mixture of air and liquid vapour) which surrounds the subsonic projectile creates optical shades [Settles, 2001] that makes locating the projectile almost uncertain. Regardless, if one assumes that the projectile is located at the very front of the moving optical shade, an estimation of the projectile position can be reached.

In the case of a pointy 7,2 mm ammunition impact, no important initial pressure shock wave was expected to happen when firing a dummy fuel tank or in the ONERA pool. The main phenomenon of interest then concerned the projectile tumbling kinematics: such a projectile is designed to have a stable behaviour in air, but when it penetrates a liquid medium, its stability is lost (together with the development of very complex fluid/structure interaction mechanisms such as supercavitation, rarefaction waves on free surfaces, etc). As it tumbles, its drag coefficient suddenly increases, which generate a high pressure pulse (the projectile can be seen as a moving pressure source). In case of a rigid projectile, this pressure pulse amplitude and duration could theoretically be directly related to its shape and tumbling kinematics, through its drag coefficient evolution. Unfortunately, it has just been seen that the tumbling kinematics and shape of the 7,62 mm ammunition in the present tests could not be easily observed because of optical effects. A direct measurement of the pressure should then be implemented if one wants to get this mechanical data, with all the difficulties that such a measurement could raise (see previous paragraphs).

Anyway, the comparison of the cavity shape and dynamics was expected to give enough information to quantify confinement effects according to the type and dimensions of the fired container (dummy tank or pool), and to permit the validation of numerical tools. Also, these tests were expected to help in understanding whether cavitation effects should also be considered or not in HRAM simulation studies. Cavitation locally appears in a liquid system when the thermodynamic pressure and temperature conditions are such that part of the liquid phase changes into vapour (no void permitted). At 10^{+5} Pa atmospheric pressure, the vaporization temperature of water is known to be 100°C. At ambient 17°C temperature, the vaporization pressure of water is about 2.10^{+3} Pa. Cavitation is often mentioned when hydrodynamic problems are considered [Knapp, 1970] [Lecysyn, 2010]. Water vapour can also appear because of high temperature increase of the soft bullet during its brutal deformation and even tearing process. It is then important to consider the volume of air which is trapped in the wake of the projectile: without air, the total volume of the cavity would be filled with water vapour.

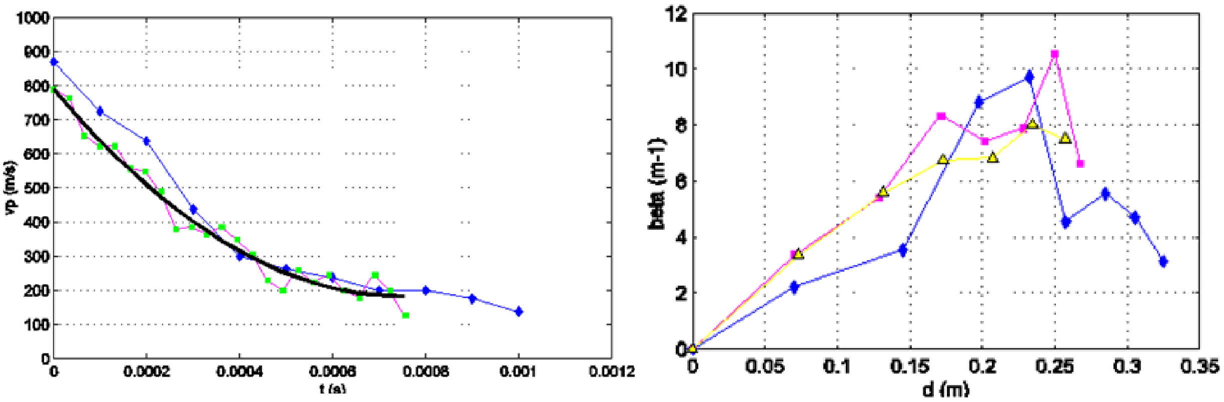
Most of the few papers that deal with HRAM effect in tanks are related to metallic structures [Schwer, 1988] [Borg, 2001] [Varas, 2008]. The here-studied EADS-IWF CFRP composite caisson was a rectangular box of 312 mm in height, 540 mm in width and 657 mm in depth. It was made of two 6.24 mm thick composite skins, the upper one with two composite stiffeners. The front and rear sides of the box consisted of 50 mm thick PMMA walls, in order to illuminate and film the bullet trajectory and cavity geometry evolution during the test. The right and left walls were made of 40 mm steel material. Everything was bolted together within a metallic rigid frame. The composite caisson was shot from below. Then to study the projectile motion and the cavity evolution free from any structural interaction, several tests were performed in a large liquid container. The dimensions of the ONERA hydrodynamic pool are 1.5m (in depth) x 1.5m (in width) x 20 m (in length). The firing installation was set up above the pool. So, these firing tests were vertical and from above. The only instrumentation that was set up for this test consisted of the VISARIO high speed camera, placed at the lateral side of the hydrodynamic pool to record the cavity evolution during tens of milliseconds.

The projectile turned to be partially destroyed, whatever the test configuration, meaning that the only interaction of the projectile with the fluid was enough to tear it into fragments. From the more heavily instrumented experiment on EADS-IWF caisson test (ultra-high speed camera), it was possible to confirm the generation of a small spherical shock wave in the fluid when the bullet impacted the container entry wall and water. The overall HRAM event lasted about 8 ms, with a first 0.25 ms long pressure burst measured by the pressure transducers around 0.15 ms, and a second one of approximately the same length arising later at 7.5 ms (see figure at the beginning of the chapter). The synchronised association of high speed videos and pressure measurements permitted to demonstrate that the first pressure burst corresponded to the penetration and immediate tumbling of the 7,62 mm in the tank, and the second one corresponded to the final collapse of the cavity (with a cloud of small cavitation bubbles suddenly appearing and disappearing on the PMMA windows). The lower pressure signal which was measured between 0.25 and 8 ms corresponded to the growth and collapsing phases of the cavity. The radius, radius growth rate and volume of the cavity bubble have been estimated using the VISARIO camera digital pictures. From the test in the ONERA pool, with the same ammunition, the same initial velocity and impact angle, it was possible to record the same chronology of events, but for the duration of the HRAM which was 30 ms long instead of 7,5 ms, and the maximal radius of the cavity which was about 20 cm instead of about 11 cm.



Evolution of the cavity average radius (left) for the 7,62 mm firing test and VISARIO pictures of tests in EADS-IWF caisson (top right) and in ONERA Pool (bottom right)

The tip of the cavity shade can be tracked thanks to the video pictures: it was assumed to be the position of the projectile nose also. Then the speed and acceleration of the 7,62 mm ammunition could be post-treated and compared between the Pool and the EADS-IWF caisson. Accounting for scatter in initial velocities and impact angles, it was possible to confirm from these tests that the confinement effects have no influence on the 7,62mm tumbling kinematics: the velocity decay coefficient was almost the same whatever the tests, be it in the pool, in a composite or metallic caisson. The about 3 kJ kinetic energy of the bullet was almost fully transferred to the fluid within less than 1 ms in all cases, when the HRAM total event lasted between 8 to 30 ms according to the test case. Compared with other literature results where the projectile was a rigid sphere with a well-known constant drag coefficient, high variations of the drag and velocity decay coefficients of the 7,62 mm ammunition were calculated during the drag phase.



Evolution of the 7,62 mm velocity (left) and velocity decay coefficient (right) for different firing test in ONERA pool (in blue) and EADS-IWF metallic and composite caissons (other colours)

It could also be seen at the very end of the videos in the pool that some air had been trapped in the projectile wake. Beside the physical understanding and proper modelling of the HRAM cavity growth and collapse, however it works, the liquid quantity that was transformed into vapour (and back to liquid) was expected to be small: so if an incompressible liquid assumption is made, the conservation of mass and volume of the liquid implies that the liquid medium would exactly expand in the same proportion than the gas bubble. If the fuel tank is fully filled of fuel, then the structure would not have only to stand the initial peak pressure, but also to deform as much as this internal volume of fluid increases. Then, as it was clearly pointed out that the cavity characteristics were clearly dependent on the container geometry and stiffness, the numerical sizing of fuel tanks against such HRAM threats would in the end clearly require fully and accurate coupled fluid/structure interaction methods to be used. The complete numerical simulation of the containers response and failure under such HRAM conditions would then rely on the use of complex coupled fluid-structure models, with a need in segregating thermodynamic parameters of influence for the multiphase fluid to be handled and validated against experimental data.

Synthesis and conclusions

When the numerical prediction of hydraulic loads induced damage in aeronautical structures was addressed in the 90's, our first concern was the definition of experimental protocols to validate coupled fluid/structure interaction simulations. The measurement of local transient hydrodynamic parietal pressures was focussed on, since local pressure may be responsible for local rupture of the materials and structures when highly dynamic loadings are considered. It also seemed a simpler and more relevant data to be measured, when the use of accelerometers and strain gauges was also tried, in particular to directly validate the fluid (often water) modelling. Very soon, this objective was confronted to unexpected difficulties, first with the question of the validity, then of the objectivity of the pressure measurement being raised. Several research works started then to further analyse the dynamic response of pressure transducers subject to hydrodynamic impacts. Specific test rigs and experiments were set up (drop test or shock tube). The research results explained why some data from standard transducers could sometimes be completely wrong and misleading. More basically, with the studied standard transducers, the research also pointed out that a 10 to 20% difference generally stands between the raw pressure measurement and the true parietal pressure on the structure, if no dynamic correction is made. These conclusions finally led us to change our test protocols, and use another kind of pressure transducers in the hydraulic ram tests of interest in the present report.

Considering now the characterisation of hydraulic ram during representative high speed ballistic tests, specific 7,62 mm firing experiments were set up, which relied on the qualification and use of very high speed digital cameras (up to 400 000 fr/s) to record the HRAM phenomenology, and measure other data together with local transient pressures that was previously mentioned: mainly the size, geometry and evolution of the cavity in the wake of the projectile according to its trajectory were studied, and compared for different kinds of containers. It was confirmed that the projectile kinematics hardly depended on the containers characteristics, if large enough. The cavity dimension and dynamics on the contrary was proved to be very dependent of the containers characteristics, because of various seclusion effects. Last but not least, specific tests were done in ONERA-Lille very large pool, that permit to get academic results of great interest for the numerical simulations evaluation which will be presented in the next paragraph.

Numerical simulation of Hydrodynamic RAM in fuel tanks

The hydraulic ram problem refers historically to overpressure-depression discontinuities (shocks) transiting in liquids and reflecting on solid boundaries, creating very dynamic and high amplitude loads. If the shock level is high enough, the structure can be damaged: acoustic codes/equations were sometimes used to simply model HRAM effect on structures, because under incompressible fluid assumptions, no fluid motion is considered, and all the energy (which would be deposited into the fluid by the projectile) would transit through the fluid as acoustic pressure waves, and interact with the structure. But many experiments (see previous chapter) proved that the acoustic loads are not the only ones that have to be considered in these cases: the wake and cavity formation behind the ballistic projectile have to be taken into account, which depend on numerous and complex initial conditions (e.g. impact velocity), transient conditions (e.g. projectile deformation/tumbling), and boundary conditions (e.g. size of container, etc). Numerical works were first done by [Kimsey, 1980]. Then, because of the large increase in computer power and of many improvements in simulation codes, numerical works have grown for the past 20 years that aimed at simulating full 3-D complex fluid-structure coupled HRAM events.

In the 90's, there were already several ways to deal numerically with the prediction of the fluid/structure hydrodynamic interactions with numerical codes:

- By using eulerian CFD (Computational Fluid Dynamics) explicit codes to study the flow around rigid shapes or boundaries, by solving Navier-Stockes (NS) equations and taking into account biphasic media, viscosity, laminar or turbulent flows,
- By using lagrangian CSM (Computational Structural Mechanics) explicit codes, to study transient shock waves in solids (and fluid under solid approximations), by solving the propagation wave equations,
- By coupling previous fluid and solid codes, to get an accurate modeling of both media, at the expense of numerical difficulties and costs,
- Some of the explicit CSM codes were able to deal with mixed fluid/solid formulations such as the Arbitrary Lagrange Euler (ALE) or Smooth Particle Hydrodynamics

(SPH)/Lagrangian ones that could improve the fluid representation for non-turbulent unrotational flows, around deformable structures.

But most of these research works have been performed to challenge the FE tools numerical efficiency in simulating HRAM events only during the first instants of time [Varas, 2009, 2012] [Artero-Guerrero, 2012], for academic undeformable projectiles [Disimile, 2009], hence with several physical issues being poorly addressed (fluid compressibility and viscosity, cavitation in presence of air, containers geometry and characteristics, etc). The analytical models [Held, 1995] [Lecysyn, 2009] hardly correlated with the experimental results when real and representative situations such as the ones that ONERA is studying were considered. For that purpose, several research axes have been investigated in order to study the bullet/liquid interactions during the impact/tumbling/fragmenting phases, to model the cavity evolution from growth to final collapse and burst, and to discriminate and draw conclusions concerning the contribution to structural damage from different aspects/phases of HRAM events.

The first research topic that is presented hereafter relates to the resolution of the local interactions between the fluid and the unstable projectile, the tumbling, the deformation and even the fragmentation of the latter (duration of the phenomenon is about some tenth of milliseconds), until final stop or perforation of the tank. Few works exist, since the great majority of the literature relates to academic, possibly unstable projectiles which do not deform, the prediction of the hydrodynamic drag coefficient being then easily treated by fluid mechanics equations only. Provided that one can afford a suitably fine (thus very fine) grid and that CPU costs are not counted for, some methods have been developed since the 90's that theoretically make it possible today to address strong fluid/structure coupling for the resolution of the behavior of the deformable projectile and the fluid flow around it. Other methods have been developped that rely on problem simplicications to get affordable CPU costs and avoid numerical difficulties. Almost all of these methods have been studied by ONERA, each of them having advantages or disadvantages according to the studied coupled fluid/structure problem (bird-strike, ditching, hydrodynamic ram, etc) [RI-04] [CI-02] [CN-13], the main problem being that they often include numerical parameters to control the stability of simulations to the detriment of the direct physical justification of the results.

The second research topic relates to the modeling of the complex hydrodynamic phenomena that develop in the fluid in the wake of the projectile (until a few tens of milliseconds, as previously highlighted), and this until the collapse and burst of the cavity and the generation of a second peak of pressure. This subject is the most difficult to treat, and the major scientific difficulties identified to date for this point relate, first, to the physical modeling of the multiphase fluid environment (equations of state, viscosity, phase change, cavitation, etc) for the prediction of the generation and growth of the cavity in the wake of the projectile and, second, to the numerical formulation needed to make the simulation of the dynamic behavior of the cavity possible until its collapse [Saurel, 2009], the preference being here rather given to finite volumes [Leconte, 2011].

Finally the third and last point (which will not be detailled in the present report) relates to the treatment of the interactions between the fluid and the structural body in rupture or simply in large deformations, over several periods of the modal response of the tank. Concerning the structure, the challenge concerns the modeling of the dynamic behavior, of the damage and of the ruin of the tank material (see first chapter). Concerning the fluid, a specific difficulty concerns the numerical simulation of the flow and ejection of the fluid out of the tank in case of large rupture: this is an important point according to the content of the tank (fire, chemical risk, etc) [Combescure, 2009] [Maurel, 2009].

As a conclusion, one has seen that different methods can be favored today according to the aspect of the HRAM problem on which one's attention is focused, but none of them seems capable of treating all aspects of the full HRAM event. Hence research is still needed to get these methods more powerful, robust and physically-based, which also requires adequate experimental data for understanding, identification or validation purposes.

Development of equivalent projectile models for strongly coupled and fully lagrangian explicit 2D FE simulations of HRAM phenomenology [RN-01] [CI-03]

During transportation missions of airborne troops towards militarily non assured areas, snipers with « light » weapons can shoot the aircraft during its taking-off or landing, which constitutes a real threat for the tanks. In particular, there exists a rare but particularly destroying scenario, where the projectile generates in the tank, under certain circumstances, a catastrophic damage due to a so-called "hydraulic ram phenomenon", possibly leading to a so large damage that there is a risk of fire or rapid loss of all the fuel. Such a scenario becomes more and more likely to happen if one considers the generalization of peace missions, and is less and less acceptable. This threat had to be taken into account for the design of military transport aircraft (A400M). Knowing the costs of experimental campaigns, and aware of the long term development of numerical simulation methods as substitution tools, the SPAé/ST/STA launched in 1997 a collaborative research project, gathering Airbus (Aérospatiale at this time), the DCE (Centre d'Etudes de Gramat), and ONERA. The ultimate goal was to develop and validate numerical methods for the prediction of the structural behavior of aircraft tank structures with respect to this threat. The development of a numerical FE methodology, and its application to the simulation of a 12,7 mm firing test (considered as a particularly serious threat) on a metallic ATR42 tank caisson, were contracted to ONERA. The tests for the methodological developments were carried out by the Centre d'Etudes de Gramat (CEG) on dummy metallic structures [Valèze, 1997].

This type of ammunition, weighting a few tens of grams and with a velocity ranging up to about 1000 m/s, has an initial kinetic energy of about 10 kJ. Generally it was admitted that a negligible part of this energy is dissipated when traversing the entry wall (intrados) of the wing, whether it was metallic or composite. On its trajectory, the projectile would find a space more or less filled with liquid, and internal walls. The ram pressure phenomenon occurs when there is enough liquid on the trajectory of the ammunition. In this case, after having penetrated the tank, the ammunition is slowed down and even stopped by the fluid (for concerned subsonic velocities, of about 800 m/s, 70 cm of liquid are sufficient to « stop » the projectile [Valèze, 1997]. On a mechanical level, a drag force is opposed to the projectile by the fluid, related to initial kinematical (velocity) and geometric (shape, incidence, etc) parameters of the projectile, and related to initial kinematics (velocity) and behavior (density, compressibility, viscosity, etc) of the fluid. In this process, the kinetic energy of the ammunition is transferred to the liquid at the immediate vicinity of the trajectory. The energy transfer from the ammunition to the fluid generates a cavity that grows dynamically in the wake of the projectile. The higher the energy transferred, the larger the cavity volume. The tumbling kinematics of the projectile controls the energy rate transfer, then the size and shape of the cavity.

On the assumption that the fluid is incompressible, it must then find elsewhere a space where to expand. Either the tank is partially filled with air, at the immediate proximity of the trajectory, and the fluid can find there some place there, or it is not, and the elastic structure must then adapt to deform for it. In concrete terms, the more the projectile is stopped roughly and near an external wall, the more the structure is driven to adapt (that is to say to deform) locally. So, if there is no free space close enough to the cavity, the penetration of the projectile in the tank can lead to important, even disastrous, rupture.

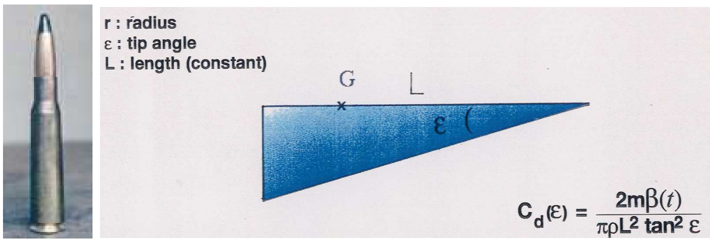
The projectile (stable in the air) becomes unstable in the fluid and tumbles more or less roughly, depending on the initial configuration. During this tumbling, the drag coefficient of the projectile changes dynamically, going through minimums and maximums depending on the section of the resistant profile presented to the fluid. If the projectile strikes the tank and the fluid in an ideal unstable equilibrium configuration (so with a null incidence angle), the dynamic of this tumbling motion will be weak, even non-existent. But the ammunition usually has an incidence angle (angle between its axis and the direction of its velocity, and is also spinning). Moreover the incidence of the projectile (related to its trajectory) is not so important than its so-called obliqueness angle between the projectile and its velocity in the reference fluid (combination of the velocity of the projectile with the one of the aircraft). The tumbling motion turns out to be particularly complex if a complete description is of interest, what was not the case in the present research, where only a maximum conservative envelope was studied. In the same mind, the work did not aim at modeling and predicting the structure rupture, but just at assessing its global mechanical loading.

The CSM explicit codes used to study the dynamic behavior of structures solve the propagation equations of mechanical waves in continuous media. They calculate the state variables of continuum media, mainly strains and stresses, according to behavior material laws that can be associated to thermodynamic equations of state (e.g. relating volume, pressure and velocity for a fluid medium). If the lagrangian description is generally used for the solid domain, the eulerian description usually prevails in fluid mechanics. A more general description, the Arbitrary Lagrange Euler (ALE one) which is a mixture of the lagrangian and eulerian ones, was often reported to be more adapted to the resolution of this kind of coupled fluid/structure problem, but more expensive in terms of CPU costs. It was also not exempt of numerical difficulties. Concerning the calculation costs, the lagrangian description was by far the most attractive, but on one condition: indeed with such an approach, the difficulty consists in not reaching so large mesh deformations in the fluid that the elementary time step of the calculation does not decrease in such proportions that the resolution becomes unstable or simply unreachable. Actually, for explicit F.E. calculation codes of structures, the stability is conditioned by a time step condition proportional in first approximation to the size of the smallest element of the mesh. Then, the number of calculation cycles necessary to solve an event of a given duration is all the more important that one of the elements of the model becomes small.

The basic idea proposed by ONERA consisted in modeling the ammunition by an equivalent conical projectile. The interest to use a regular sharp shape of this type was to get a much smoother flow of the fluid around the projectile, and to get rid of numerical difficulties that were expected to develop in a real modeling of the tumbling ammunition, which was clearly confirmed later when accurate simulation of the 3D kinematics of various ammunitions was attempted by ONERA. The geometry of the conic projectile would be controlled to change with time, and to represent the instantaneous value of the drag coefficient of a tumbling projectile. Indeed the value of the drag coefficient of such a cone is given by abacuses according to its radius. With such a smooth flow, it was expected to be able to model the fluid with a lagrangian formulation without numerical difficulties, then improving the validity of the results in terms of calculated transient hydrodynamic pressure levels, and highly reducing the simulation costs (3D simulations of fuel tank structure and fluid were targeted from the beginning). A difficulty to model the fluid medium lied in the ability to represent the separation of the flow around the projectile, or more precisely to numerically process the evolution of the topology of the medium. In our case, the ammunition was supposed to have a rectilinear trajectory, the knowledge of the orientation of the trajectory and of the point of impact of the projectile was then enough to know the separation line. The fluid medium was discretized with two separate half-space meshes, both side of the separation line, that the conic projectile would push aside without any fluid cell being passed through (the resistance in traction of the liquid being null, the pre-existence of this separation line induces a priori only a negligible energetic bias in the calculation).

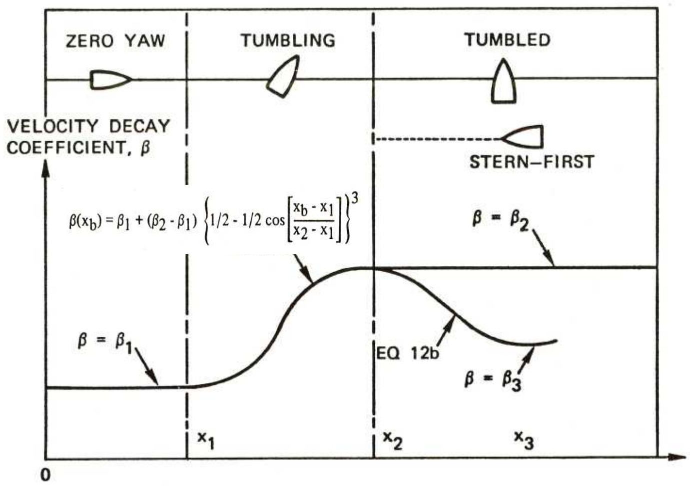
The equivalent projectile would be endowed with the same velocity than the real projectile. The drag coefficient and velocity and their evolution with time being identical, the pressure field induced into the fluid and then the structural resultant loadings onto the fuel tank structure were expected to be equivalent in first approximation. The difficulty for ONERA consisted then in determining the evolution profile of the drag coefficient of the real 12,7 mm ammunition, which depends not only on the geometry of the ammunition (which was known), but also on initial kinematical conditions (velocities, initial obliqueness, etc) which were quite random. The length of the projectile being considered constant, the evolution of the drag coefficient and then of the geometry of the cone is simply described by functions imposing a radial velocity of its opening. The method needs to know the real kinematics [V(t), γ(t)] of the ammunition in the fluid, which determines the instantaneous drag coefficient of the projectile :

$$C_D(t) = \frac{2m\beta(t)}{\rho A_0(t)} \qquad C_D(t) = \frac{2m\beta(t)}{\pi\rho L(t)^2 \tan^2 \varepsilon(t)} \qquad \gamma = -\beta V^2$$



Picture of the 7,62 mm ammunition (left) and simplified 2D axisymmetric trinagular model of the bullet (right)

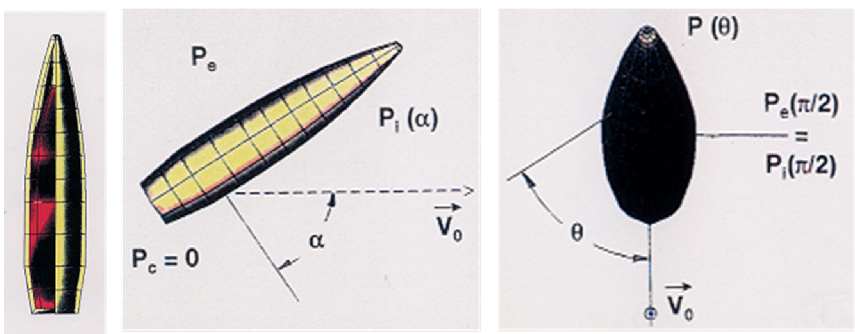
One possibility consisted naturally in trying to obtain this [V(t), γ(t)] kinematics numerically, by modeling the fluid/structure interaction between the highly deformable ammunition and the fluid. This topic is still a research one today, and it was abandoned in 1995's because of unsolved numerical difficulties. To determine the equivalent model, a second solution would have consisted in measuring experimentally this kinematics. Actually, only X-ray imaging technique, operated by CEG Gramat, permitted to observe precisely the course and attitude of a 12,7 mm ammunition in dummy metallic tank structures. But the size of X-ray cameras limited the possible pictures to a maximum number of 4 along the whole trajectory of the ammunition: hence only two or three velocities, and one or two accelerations, could be extrapolated which was not enough to compute a dynamic drag function of time. The CEG results were nevertheless used to validate an inverse numerical method of determination of the drag coefficient dynamics, using a general mathematical form of the drag coefficient given by [Ankeney, 1977] (see figure below).



Evolution of drag coefficient during the tumbling phase [Ankeney, 1977]

A FE model of the 12,7 mm ammunition was then proposed, with a parametric analytical pressure field being applied on it instead of modeling the fluid:

$$P_i^n = C^n\left[P_0 + f(t)P_1\cos\theta\sin\alpha + \left(1 - f(t)\right)P_2\right]$$
$$P_e^n = C^n\left[P_0 + \left(1 - f(t)\right)P_2\left(1 - \cos(\pi - \theta)\right)\right]$$
$$with : \theta \in [0,\pi], \alpha \in [-\pi/2, \pi/2]$$
$$and : \theta_e \geq \pi/2, \theta_i \leq \pi/2$$
$$and : f(t) = f_1 + (1 - f_1)\left[\frac{1 - \cos\left(\frac{\pi(t - t_1)}{t_2 - t_1}\right)}{2}\right]^N$$



FE model of the 12,7 mm projectile and description of applied pressure field main characteristics (for inverse identification)

The parameters of the analytical pressure model were identified using an optimization tool and the FE simulations, to minimize the error between the set of information that were collected from the CEG test results. This set of data consisted in angles and positions of the center of gravity of the ammunition on the X-ray pictures, and the corresponding times (8 sets of data were available from tests).

P_0	P_1	P_2	f_1	N	Ω_0	t_1	t_2
Pa	Pa	Pa			rad/s	s	s
1.00E+08	7.50E+08	-2.00E+07	3.10E-02	1.95	1.37E+03	0	5.32E-04

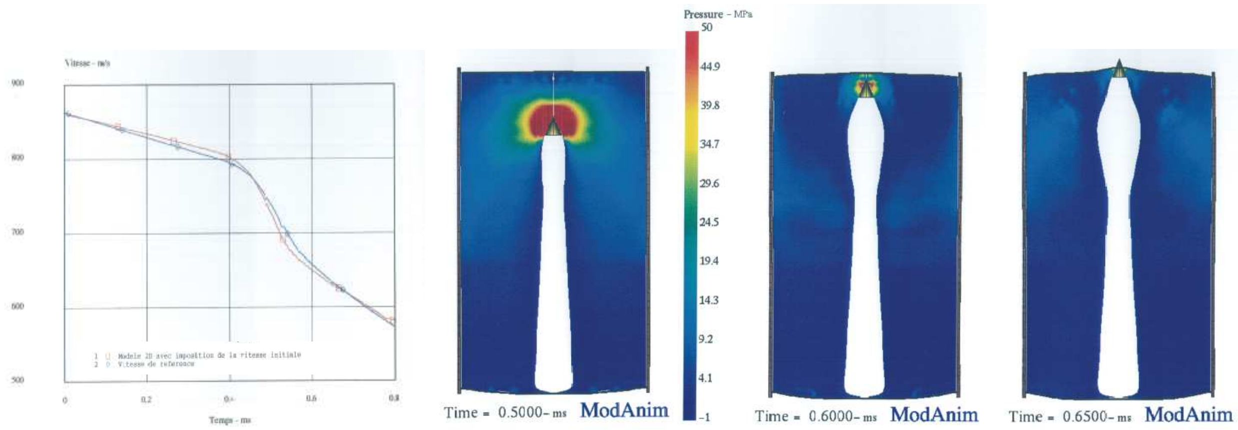
	t=1.8e-4 s		t=5.e-4 s		t=6.e-4 s	
	α	X_G	α	X_G	α	X_G
	°	m	°	m	°	m
Test n°4	7.9	0.117	49.7	0.381	90.0	0.458
Kin. Model	8.0	0.119	49.6	0.382	90.0	0.457
Deviation %	-1.3	-1.2	0.2	-0.3	0.0	0.2

Identified parameters of pressure function and comparison between cinematic model of the projectile and CEG test

Then, the velocity and acceleration of the virtual 12,7 mm were extracted from the FE simulation, and the velocity decay coefficient calculated according to its theoretical formula $\gamma = -\beta V^2$, which then permitted to calculate the corresponding opening angle of the equivalent conic projectile $\varepsilon(t)$:

$$\tan^2 \varepsilon(t) = \frac{2m\beta(t)}{\pi\rho L(t)^2 C_D(t)}$$

Axisymmetric 2D simulations of the CEG 12,7 mm firing tests on dummy metallic tanks were then performed to evaluate the hydrodynamic pressure loads that would have applied onto the structure. The projectile mass and forward initial velocity was the experimental ones, and the projectile shape hence drag evolution was controlled by imposing lateral nodes displacement to triangular projectile nodes.



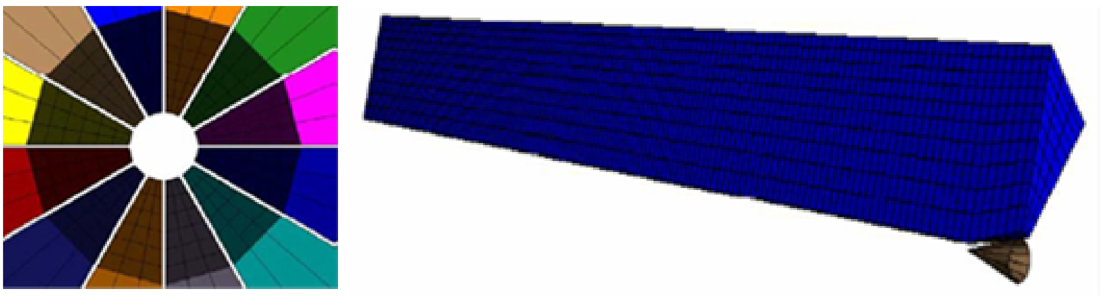
Comparison of the equivalent projectile kinematics due to the drag force in the FE lagrangian water mesh compared to the reference identified ones (left) and pressure analysis (right)

As no pressure transducers or strain gauges had been used in the CEG tests on metallic parallelepipedic caissons, the obtained values could only be interpreted to give general orders of magnitude (having axisymmetric assumption in mind) for pressures in the fluid, and stresses and strains in the structure. The other objectives of the work were also finally reached: no numerical instabilities developed in the 2D simulations, and the CPU costs were very low. The main perspective at the end of this methodological work concerned the 3D extension of this methodology, as described in next paragraph.

3D FE lagrangian simulation of HRAM in a metallic fuel tank structures [CI-25]

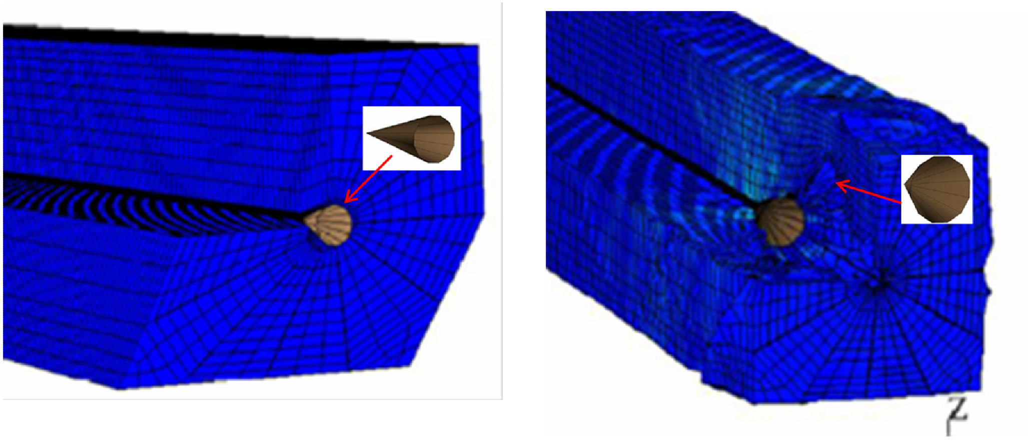
The second phase of the SPAé/ST/STA research launched in 1997 concerned the application of the numerical method proposed by ONERA to the simulation of a 12,7 mm firing test on a metallic ATR42 fuel tank structure. The tests were carried out by the Centre d'Etudes de Gramat, on a real structure supplied by Airbus S.A. [Moréno, 2000]. Once the validity of the methodology had been established in 2D, the next step consisted in implementing it in 3D, and in applying it to the simulation of the hydrodynamic ram pressure in a real aircraft tank structure. An aluminum ATR42 tank FE model was developed that contained about 33 500 shell elements and 35 000 volume elements. The standard material laws were respectively an elasto-plastic model for the metallic parts and a hydrodynamic viscous law (as the one presented in the previous paragraph) for the water.

To implement the previously described HRAM simulation methodology, it was necessary to mesh the 3D geometry of the conic projectile (12 equal facets representing angular sections of 30°). A direct 3D generalisation of a continuous lagrangian fluid mesh around the 3D conic projectile was not a difficulty, but the numerical lagrangian resolution turned out to be a very tricky exercise. Again, because the trajectory of the projectile being supposed to be known (rectilinear, in first approximation), a numerical artifice was proposed that consisted in imposing to the fluid mesh topological constraints that prevented contact detection and resolution to rapidly become a problem: the fluid mesh was itself divided in 12 angular 30° sections that corresponded to the projectile's. The fluid sections were separated by virtual (contact) barriers to force the fluid mesh to have a smooth outward radial flow with respect to the facets of the cone.



3D modelling methodology and constraints imposed on the fluid mesh

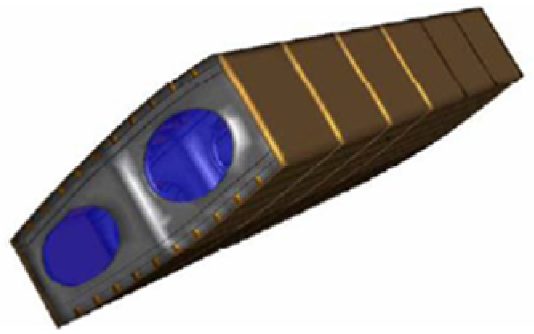
Finally, a fluid « cartridge » of 100 mm sides was generated around and along the future trajectory of the projectile. This part of the future model contained (cone, virtual barriers, fluid mesh, etc) about 55 000 volume elements. Contact interfaces were implemented to impose a proper fluid flow. A 45 g added mass and 900 m/s initial velocity were imposed to the cone to obtain a representative initial impact configuration. Imposed radial velocity functions are defined with respect to time on the nodes of the conic projectile in order to monitor its opening and get a representative drag coefficient compared to the one identified during the first part of the research.



Simulation of the conic projectile penetration in the fluid mesh, and of the numerical cavity expansion related to its maximum opening during the tumbling phase.

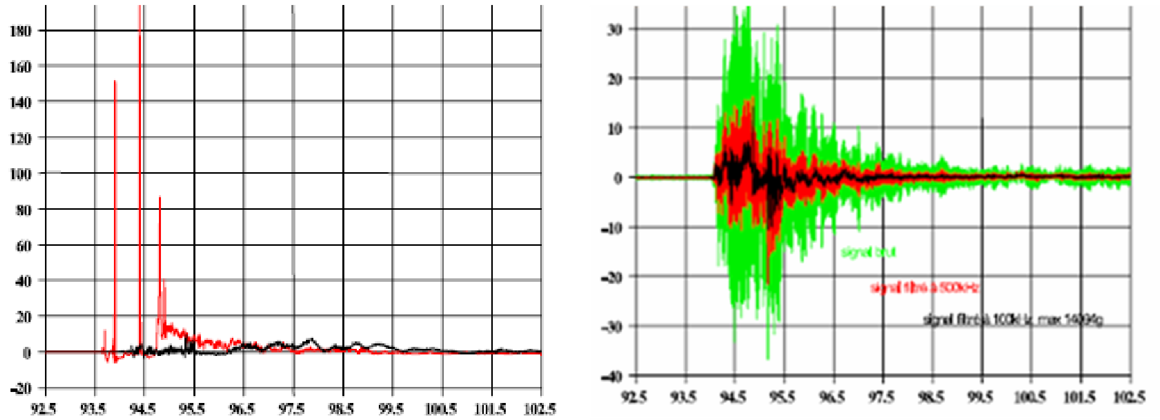
During the penetration of the projectile, the fluid elements were submitted to a radial compression that brought their dimension (and the time step) to decrease by an important, but acceptable factor (the stability condition – i.e. elementary time step - was controlled not by the elements size, but by the contact resolution). It was then possible to obtain a « nice » deformation of the lagrangian mesh around the equivalent conical projectile. The validity of the simulation was assessed by conservation of the mass and total energy (3.3% error only) of the model, the lack of hourglass energy, etc. The FE simulation run for a 0.6278 ms time event, which was split in 147 900 calculation cycles (the time step fell from 1.44 10^{-4} ms down to 1.29 10^{-6} ms), then a negative volume appeared (fluid volume element) that stopped the simulation.

A comparison with the experimental results [Moréno, 2000] – in the case of a tank structure full of water - was done to evaluate the validity of the modeling methodology.



Picture of the ATR42 3D FE model (structure and fluid mesh) to simulate CEG 12,7 mm HRAM experimental test

The ATR42 tank was equipped during the tests, with two accelerometers (one on the intrados and the other on the extrados of the fuel tank), several pressure sensors, and strain gauges. The acceleration test results were filtered down to 100 kHz (black curve). The HRAM main event stood between 94.0 and 97.5 ms, and lasted about 3.5 ms which is more than the 0.625 ms FE simulation duration. Only the intrados measurements could then be really compared to the simulation results, with a recorded peak pressure about 145 bars during the first 0.625 ms, a maximum filtered acceleration about 35 mm/ms^2, the strain maximum level was about 10^{-3}.



CEG pressure (left, in bars) and acceleration –right, in mm/ms^2) 12.7 mm test results on the ATR42 aluminium tank structure

In the simulation, the maximum recorded pressure was about 500 bars in the vicinity of the projectile. The maximum simulated acceleration value was about 40 mm/ms^2 but still increasing at time 0.625 ms. The strain level was not really exploitable. In the end, the numerical temporal and mechanical magnitudes were qualitatively representative of the measured orders of magnitudes but the comparisons were not very demonstrative, the main conclusion being that it would be necessary to improve the numerical methods in order to reach a 3.5 ms (or at least 1.75 ms) long event to validate any numerical methodology properly. Also, it was difficult to take the initial obliquity of the projectile into account in this equivalent modeling method.

The research which followed this study (whatever the formulation used, be it ALE, SPH or CEL) was then, and is still focused on these two objectives.

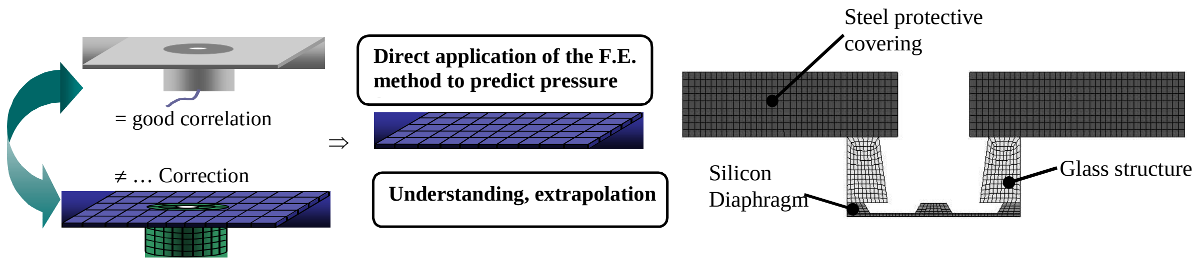
Evaluation of SPH lagrangian formulation for strongly coupled hydrodynamic fluid/structure interaction modeling in explicit FE codes [CI-01] [CI-26]

In the research that followed, new modelling techniques and new capabilities of F.E. simulation tools were studied, that would be stable enough to make the HRAM simulation reachable on such a 3.5 ms duration. In particular, the Smoothed Particle Hydrodynamics (SPH) started to be available in the explicit FE codes of interest. The SPH formulation is a meshless Lagrangian approach which presents a straightforward compatibility with the CSM analysis F.E. codes and could then easily be implemented in these codes. SPH methods make use of particles representing a continuous material/fluid medium. The particles are free from any finite element formulation, but interact with each other thanks to interpolation functions, using the same material laws or fluid equations of state that those used for the lagrangian or ALE finite elements (see previous paragraphs). The integral approximation of a scalar function f (for example, the displacement field) in space Ω is written as:

$$\prod f(x) = \int_{\Omega} f(y) W(x-y,h)\, dy$$

where W is an approximation kernel, responding to specific criteria, h is the smoothing length of this kernel, representative of the extension of the zone of influence of the particles in the calculation of the approximation of the function. More information about this formulation can be found in [ref], but the advantages of the SPH methods are the possibility of bearing with large deformations (no mesh), and fluid flow through a broken structure. Fluid/structure interactions are addressed by using contact interfaces, as it is done with lagrangian finite elements. Their disadvantages are the calculation costs (a large number of particles is often required to get enough accuracy, larger than the number of finite elements that would be used to discretize the same problem), and the absence – compared to ALE formulations - of bi-material or biphasic mediums.

The aim of the research work was to assess the theoretical and numerical limitations of this SPH technique regarding hydrodynamic simulations. As previously mentioned, the EU SEAWORTH difficulties and results (1998-2001) initiated the idea to use the pressure transducers themselves as validation specimens to assess coupled fluid/structure numerical models. The first case study was the one proposed in Portemont's PhD work [Portemont, 2004], which concerned water droplet impacts onto a pressure transducer. The simulations were performed with the explicit code RADIOSS. The aim of this work was to model a KULITE (with its silicon diaphragm, glass structure and steel protective envelope) pressure transducer response to water droplet impacts. The diaphragm elastic material characteristics and 3D geometry (after a transducer had been sacrificed, the geometry was observed not to be axisymmetric) were known.



Validation of FE tools with respect to the fluid/structure interaction problem, based on the modeling of the KULITE pressure transducer as a test specimen

The behavior model used for the fluid modeling is based on viscous hydrodynamic law principles. The considered law is specifically designed to model biphasic media (liquid and gas). The equation of state and relation between the deviatoric stress and the strain rate tensors which are used to describe the fluid were:

$$S_{ij} = 2\eta \dot{e}_{ij} \qquad \Delta p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu)E_n \qquad \mu = \frac{\rho}{\rho_0} - 1$$

where σ_{ij} is the deviatoric stress tensor, η is the dynamic viscosity, $\dot{e}_{ij}$ is the deviatoric strain rate tensor, ρ is the reference density, ρ_0 is the initial density, and E_n is the energy per unit volume.

For the air:

$$C_0 = C_1 = C_2 = C_3 = 0 \text{ (perfect gas hypothesis)},$$

$$C_4 = C_5 = \gamma - 1 = 0{,}4$$

$$E_{n0} = \frac{p_0}{\gamma - 1}$$

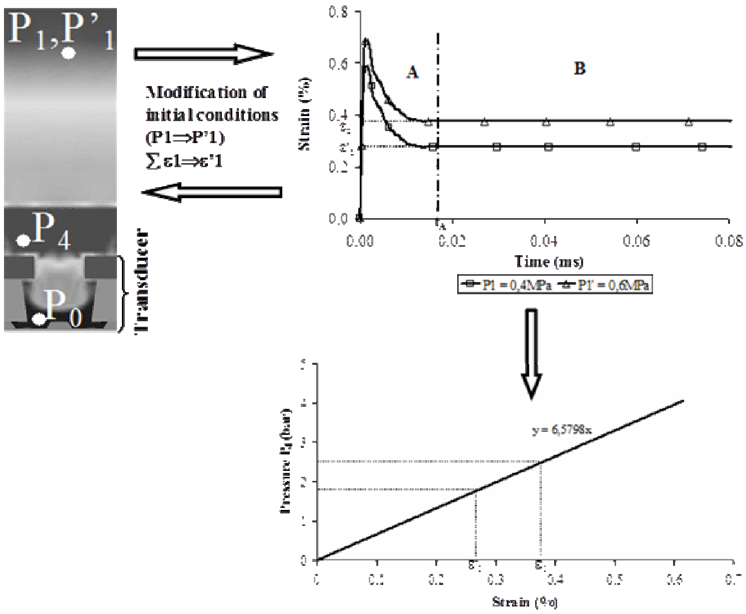
For the water:

$$C_0 = C_2 = C_3 = C_4 = C_5 = E_0 = 0$$

$$C_1 = \rho_0 . c^2 = 2250$$

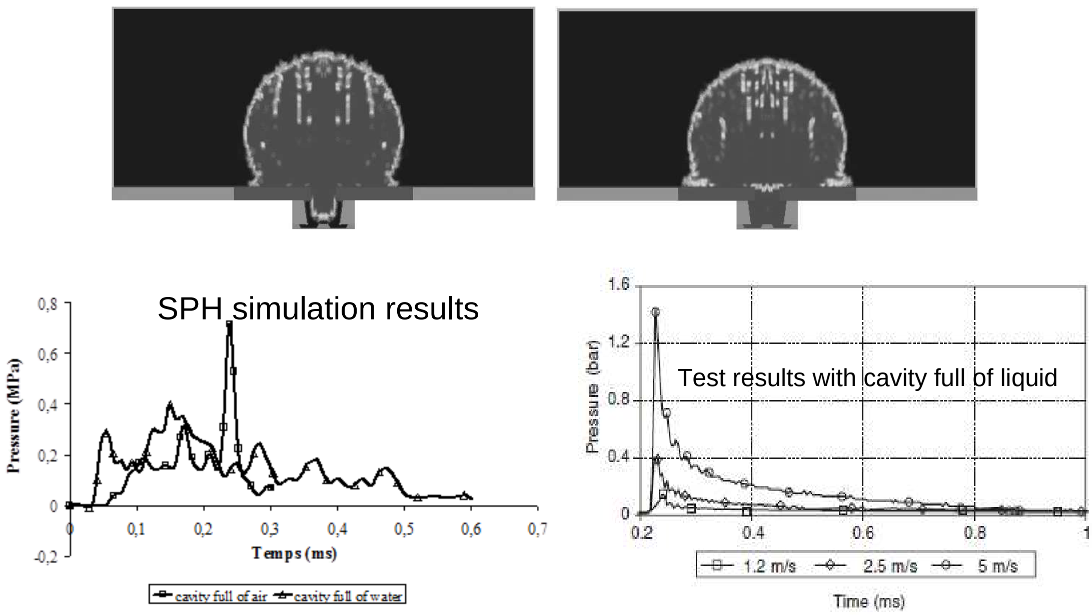
where c is the sound speed in water.

As it has to be done experimentally, the first step of the numerical works consisted in calibrating the numerical sensor (in its linear domain) on the principle of shock tubes tests, than can be virtually simulated. The numerical results are filtered at the same cut-off as the experimental acquisition system frequency.



Principle of dynamic numerical calibration of the transducer

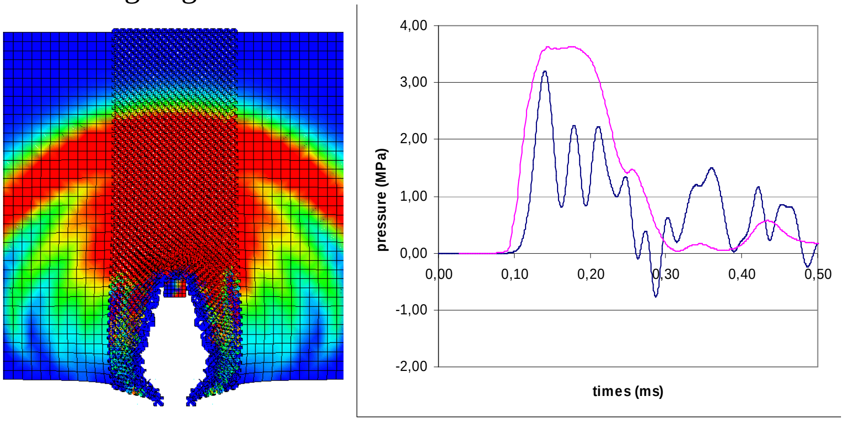
Once the numerical sensor has been calibrated, it was possible to get the virtual pressure from the numerical diaphragm deformations, for any water droplet impact simulations that were realized with the explicit code RADIOSS.



3D SPH simulations of a water droplet impact with a transducer rigid envelope initially filled with air (top left) and filled with water (top right), and corresponding virtual pressure results (bottom)

Though the SPH discretisation was very high (hence the CPU costs quite expensive), the order of magnitude of the measured pressure could only be roughly predicted, and not the experimental pressure profile: many other parameters that were proved to influence these laboratory test results were not taken into account.

Anyway, it was decided to challenge the SPH formulation for much higher impact speed simulations, and hydraulic ram problematic [Thevenet, 2009] [CI-01]. In the following work, as the SPH method is a time consuming method, only the central part of the fluid domain, which is supposed to interact directly with the projectile, was discretized with particles, the rest of the fluid being still modelled with lagrangian finite elements.



SPH / LAG simulation of a 7,62 mm HRAM event (EUCLID RTP3.32 research project) in a dummy tank structure

Finally, simulation and experimental (see EUCLID RTP3.32 in the experimental paragraphs) pressure results were compared with some success as far as the first millisecond was studied, but it was still impossible to run the FE simulations up to the expected 3.5 ms which corresponded to the maximum size of the cavity (then maximum deformation of the composite fuel tank) during the test.

After that work and since very interesting experimental results had been obtained in the ONERA-Lille pool, other theoretical questions raised which temporary re-oriented our research efforts.

Analysis of HRAM energy partition between acoustic, kinetic and possibly cavitation mechanisms in liquid mediums [CN-01]

The objective of the present work was to discriminate what has to be modelled to estimate the induced level of HRAM damage in a tank structure, assess its residual strength, and possibly improve its design. In the field of dynamic strength of structures, it is usually considered that the main point to care about is the transferred energy (rate) that the targeted structure has to cope with. For instance, the structure adaptation might be kinetic (fragments projection), by heat or by irreversible solid deformation, damage and rupture. The studied mechanical system in which energy conservation principle is applied is made of different "sub-systems" (projectile, cavity bubble, liquid medium, and solid structure). For each sub-system, different physical phenomena are involved, and ranked, according to the energy amount they would dissipate, store and release during the HRAM event. Some of them could be evaluated from the available test data (EUCLID RTP3.32 research project), but others – especially concerning the fluid system - could not. So this research work focused on general theoretical considerations, with a coarse energy evaluation exercise being done on the open mechanical system constituted by: the cavity bubble, the liquid mass, and the solid structure. A number of assumptions were made to deal with unknown quantities, hopefully in a conservative way with respect to the ultimate goal of the study, study their influence on the damage of the structure. For instance, it was assumed that the dissipated energy in the ammunition deformation process can be neglected in what follows, in a conservative way.

The amount of transferred energy that is considered in the present study was about 3000 J (800 m/s of a 7,62 mm 9 g bullet). The dummy tank dimensions (fully filled with water) were about 300 mm in height (direction of the bullet trajectory), 550 mm in width and 650 mm in depth. The cavity bubble developed long after the initial pressure pulse (shock wave) has vanished. It was considered that the kinetic and potential (gravity) energy of the water vapour in the cavity are negligible compared to its latent energy (energy stored in physico-chemical change), any calorific energy created during the HRAM process will never reverse back into a mechanical energy that could notably load the fuel tank structure (temperature was then assumed to be constant and ambient in the cavity during the HRAM process, no viscous energy is dissipated in the liquid vapour. So the main energy to be considered for the cavity bubble should correspond to the latent heat. An important question was about its amount (in fact, some air is entrapped in the wake of the bullet, and the gas is an air/water vapour mixture). If we consider that the cavity is only full of water vapour (pure cavitation phenomenon), then the latent heat is the amount of energy stored (and released later) by water during its change of state without changing of temperature, meaning a phase transition:

$$Q = \rho_C V_C L_v$$

where Q is the amount of energy stored (and released) during the water phase change, VC the volume of the cavitation bubble (measured thanks to high speed videos), ρ_C the vapour density, and L_v the specific latent heat of vapour. The parameters values would depend on the unknown thermodynamic state of the vapour in the cavitation bubble (different possible values are given hereafter for the thermodynamic coefficients).

P	**T**	**ρ_c**	**L_v**	**C_v**
Pa	**°C**	**kg/m3**	**J/kg**	**J/kg**
2,00E+03	290,67	0.015	2,46E+06	1,86E+03
1,00E+05	372,79	0.590	2,26E+06	2,03E+03
3,00E+06	507	15.009	1,79E+06	3,41E+03

Main characteristics of water vapour at different ambient pressures

The latent heat evolution was calculated assuming an isothermal cavitation process in the liquid, under 1 Patm, 293 K conditions, and :

$$P_{sat} = P_0 e^{\frac{ML_v}{R}\left(\frac{1}{T_0}-\frac{1}{T}\right)} = 0.0204 \text{ Patm}$$

with T_0 =373 K, M = 0,018 kg/mol, L_v = 2,455×10^{+6} J/kg, R = 8,31447 J/K/mol, P_0 = 10^{+5} Pa.

This latent energy would be stored (no dissipation assumed) then released during the 8 ms long process (observed time of collapse of the cavity bubble in the EUCLID RTP3.32 test), according to the following time-history which has been established from the high speed videos (blue curve). The maximum latent energy under isothermal assumptions only reach about 200 J (0,02 Patm), which could probably be neglected compared to the initial 3000 J energy, in a conservative sizing approach.

Concerning the liquid medium (here water, see [Nagayama, 202]), it was assumed that that its temperature was constant, and that it behave as a non-viscous fluid (no energy dissipated). The potential (gravity) energy rise (part of the water was moved upward) was small compared to other components. The water mass and volume were supposed to be constant (incompressible fluid, few grams of vapour mass). Its main energy would then consist in kinetic and acoustic contributions. A number of simplifications or assumptions were made (sometimes because of unknown quantities) to evaluate, on the one hand, the purely acoustic energy (compressible liquid) and, on the second hand, the kinetic energy (cavity expansion, uncompressible hypothesis) in the liquid medium (water). Two kinds of experimental data were available, that concern first the assumed spherical pressure shock wave (to derive acoustic energy), and the cavity bubble expansion velocity (to derive liquid velocity fields, then momentum and kinetic energy under uncompressible hypothesis).

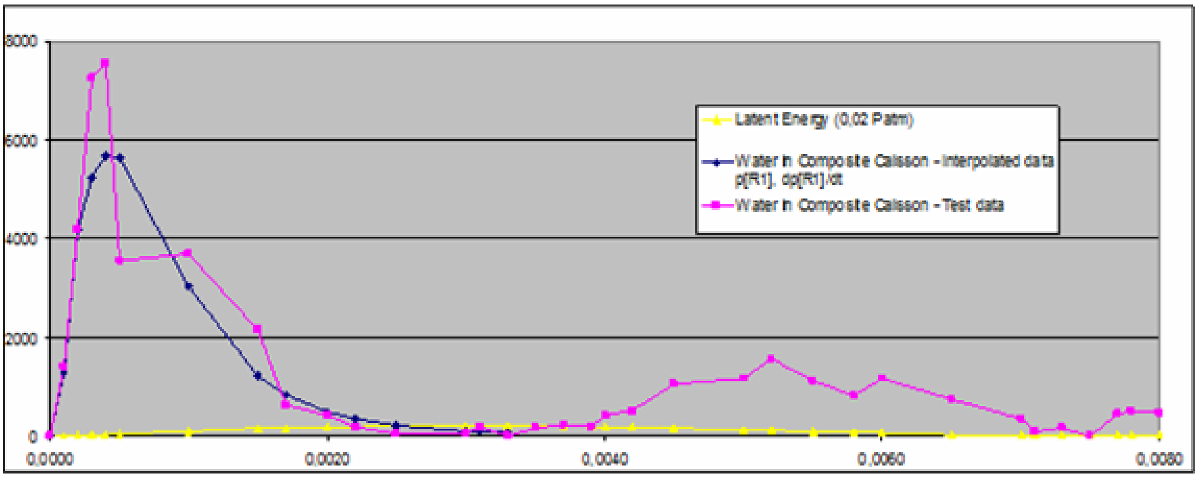
For a compressible fluid, a pressure wave induces a density change in the liquid medium (hence and optical indices change) which also means that the fluid particles concentrate thus move when the transient pressure pulse comes through. In an adiabatic process, the acoustic energy corresponds to the internal energy stored in a volume element V when the initial pressure P_0 increases to pa = P_0 + p. For a perfect fluid, the internal energy (small perturbations hypothesis) that is transported by pressure waves is known to be made of two components: a kinetic and a purely acoustic one:

$$I = \iiint_V \rho u^2 + \frac{p_a^2}{2\rho c^2} dV \text{, with: } p_a = c^2(\rho - \rho_0)$$

with p_a the acoustic pressure, u the fluid velocity, c the sound celerity, and ρ the fluid density (initial and actual values). A spherical pressure wave was considered, radiating from the impact point of the bullet on the tank wall, and inducing an approximated triangular p(t) pulse shape, that could be correlated in space p(r), knowing the sound celerity and the 0,2 m position of the pressure gage from the impact point (see previous experimental paragraph, EUCLID RTP3.32 test results). The purely acoustic energy could then be coarsely evaluated from a 5 MPa peak / 0.150 ms long pressure pulse, to be about 100 J, which can probably be also neglected in first approximation or in a conservative sizing exercise.

To consider the kinetic component, note that – under compressible assumption - an increase of water density for an average 2,5 MPa pressure peak (about 0,1% of its initial density), with about 0,3 m^3 volume (then 300 kg) of water being concerned by the pressure pulse, would mean that a 3 m/s average fluid velocity increase (in the half-spherical water ring that comes through the pressure gauge) would be enough to "store" the remaining 2700 J of the bullet initial kinetic energy once the latent heat and purely acoustic energy have been taken out. It was not possible to measure the fluid velocity field with the experimental techniques that were available for the EUCLID RTP3.32 test. Nevertheless, this point proves to be of first importance, since this kinetic energy would act onto the structural wall, thanks to the momentum principle.

The water kinetic energy component could be analysed through the 0.125 m radius / 10 ms cavitation bubble growth and collapse that could coarsely be measured thanks to the high speed videos. Assuming a spherical volume of uncompressible water with a gas bubble of known growing radius inside, the equivalent kinetic energy could be easily calculated and interpolated by a polynomial function.



Coarse comparison of latent heat and water kinetic energy (Joules) evolutions during the 8 ms long 7,62 mm EUCLID RTP3.32 HRAM test

The kinetic energy in the fluid largely overpassed the initial kinetic energy of the bullet at the beginning of the penetration phase, which could be easily attributed to experimental errors on the cavity bubble radius measurements at the very beginning of the test. Once the cavity bubble dimension turns to be more measurable (around 0,5 ms) the energy amount fell back around the initial kinetic energy of the bullet (which was at that time almost integrally transferred to the system).

The main point that could be concluded from this coarse analysis was that about half the initial kinetic energy was probably stored as elastic energy in the structure, since it was released to the water medium as kinetic energy during the cavity collapse phase. This 2000 J remaining energy will then have to be dissipated by the system long after the initial pressure peak or even the maximum cavity size has occurred. Again, these results demonstrate the importance of modelling much more than the very first millisecond of the HRAM event to study the fuel tank structural response and possible damage with respect to HRAM situations.

Study of HRAM in fuel tanks induced by pure cavitation phenomenon [CI-19]

The problem of HRAM in fuel tanks is quite complex and is still not very well modelled, all the more as experimental observation, analysis and validation remain difficult to obtain. The concerned physics, when non academic high-speed deformable projectiles are considered, depends on so many and highly non-linear aspects (fluid, material, geometrical, etc), that no expert predictions or decisions can be made concerning the outcome of such HRAM scenarios without the help of costly numerical simulations. But the fluid-structure coupling (especially with the deformable projectile) generally leads to numerical instabilities. HRAM includes several phases, each one having its own time scale as presented in the previous paragraphs. The purpose of the present work was to identify the most or least determinant ones that have to be considered or disregarded when designing structural aircraft fuel tanks, in order to possibly simplify the needs for modelling.

After the initial shock wave phase, as the subsonic projectile moves forward and tumbles through the liquid, it is submitted to high drag pressures that quickly slow it down. Its kinetic energy decreases and is transferred to the fluid as liquid kinetic energy, mechanical energy (pressure) and possibly latent heat (cavitation): indeed, a gas cavity develops in the wake of the projectile, the constituent of which can be a mixture of air and liquid vapour. Some air at atmospheric pressure is entrapped in the wake of the projectile and, if the pressure level that establishes in the cavity behind the projectile decreases down - but not less - to the liquid saturation pressure, vapour is also generated. The cavity first grows then collapses which means that the vapour phase – if any - turns back into liquid phase and possibly retrieves the stored latent energy to the mechanical system. The objective of the present numerical exercise was to model the process of such a latent energy being stored in the fluid medium (creation of liquid vapour), and later released back into fluid mechanical and kinetic energy, to evaluate the importance of taking this cavitation phenomenon into account to design HRAM resistant structures [ref]. For that very specific purpose, and to maximise the cavitation amount, no air was considered in the present modelling exercise. Also, no projectile impact in water was modelled (then no acoustic shock), because of the well-known difficulties that such a strategy would bring: the liquid cavitation process was here solely produced by using a moving heat energy source that progressively creates water vapour in the liquid medium. The objective was to reach a 10 to 30 ms long simulation (like those described in the experimental paragraphs), with a biphasic law with change of state being used for the liquid. As energy quantities are concerned, having an energy conservative formulation was preferred not to dissipate them numerically, and it was then decided to use a Finite Volume method instead of e Finite element ones.

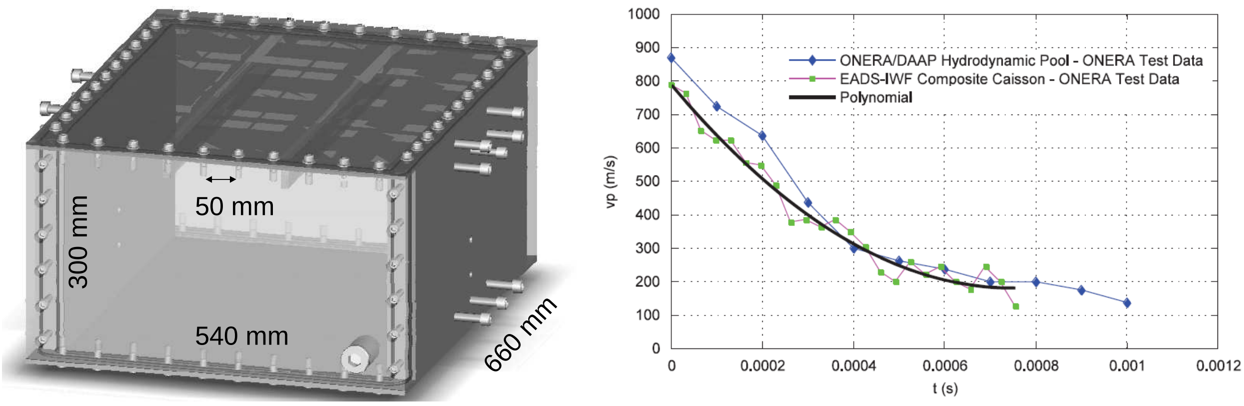
So, in the present research, the EUROPLEXUS explicit (central-difference scheme) research code was challenged to solve the very dynamic expansion and collapse of cavities like the ones observed when ballistic impacts are studied. EUROPLEXUS is designed to accurately solve fast dynamic problems for coupled fluid/solid systems, and includes both finite element and volume element formulations to solve solid lagrangian and fluid eulerian interaction problems. EUROPLEXUS is a computer code being jointly developed since 1999 by the French CEA and EC JRC Ispra. It stems from CEA's CASTEM-PLEXUS and the previous CEAEC joint product PLEXIS-3C. ONERA is member of the developing partners of this code since 2008, for aeronautical applications. Geometric (large displacements and rotations, large strains), and material (plasticity, viscoplasticity, etc) non-linearities are fully taken into account. The code provides 1-D, 2-D or 3-D solid (continua, shells or beams) and fluid elements, with fluid/structure interaction functionalities being also implemented. Numerous element types and a comprehensive library of E.O.S and material laws for fluids, solids and special media (e.g. impedances) are available. Three main descriptions frameworks are available in the code: the Lagrangian description (including Smooth Particle Hydrodynamics) which is well suited for the structural domain, the Eulerian description for purely fluid problems, and the Arbitrary Lagrangian Eulerian (A.L.E.) description which is typically used in fluid-structure interaction problems. For numerical analysis, the Finite Volume Method (F.V.) can be used to solve partial differential equations, like the finite element method (F.E.), where approximations of integrals are made. The F.E. method uses a variational formulation of the equations (or weak form) while the F.V. method is based on the direct form of the equations (strong form), that makes Navier-Stokes conservation equations solving possible. Finally, one has to solve the partial differential equations on a spatial discretization of the studied domain. The A.L.E. method [ref] allows an intermediate description of the studied domain to be used, that stands between purely Lagrangian mesh and purely Eulerian grid and makes the F.V. formulation applicable. It allows to handle fluid-structure interactions with deformation of the fluid mesh that can adapt to the structural one, what a purely eulerian one would not succeed in.

EUROPLEXUS allows handling water and its vapour as a homogeneous mixture together with its F.V. formulation. Beside the biphasic mixture law, EUROPLEXUS provides E.O.S. to model water change of state, which includes the latent energy in the energy balance for higher accuracy. As water and its vapour are treated as a homogenous mixture, the tension energy of the gas-liquid interface is not considered though it is known to be an important quantity for the understanding of the physics of equilibrium and motion of bubbles in a quasi-static frame. In the present case, it is assumed that the tension energy can be neglected since it would be small compared to the latent energy in the cavity (the ratio between the tension energy and the latent energy of the bubble is proportional to R^{-1}, the inverse of the radius of the bubble, and we are studying large cavities here). The following considerations were also taken to model the problem:

- the water is in equilibrium, i.e. same pressure and same temperature for water and vapour within a fluid volume,
- the initial conditions of the biphasic material in sub-domains are given by an initial pressure, an initial temperature, and an initial mass title (ratio between the mass of vapour and the mass of water),
- a time dependent specific energy is injected in the material along the theoretical projectile trajectory (at successive sources location),
- a quite high numerical damping coefficient is used to increase the stability of the code by filtering high frequencies, at the expenses of amount of numerically dissipated energy.

The physical properties of water were tabulated from the well-known (P,T) diagram that describes the low-temperature, the saturation curve, the high-temperature and the hypercritic domains, which is used to determine the title of the water (above 800 °C) [ref]. This description greatly influences the complexity of the computations, since, for each time step, for each element, the algorithm must explore this diagram to determine the state of the water in the fluid volume element. In the present case, the [0, 6000] °C temperature and [7.10^{-3}, 3.10^{+4}] bar pressure intervals for the (P,T) diagram were split in 80 intervals for the low temperature domain, 150 intervals for the saturation curve, 150 intervals for the high temperature domain, and 180 intervals for the hypercritic domain.

The idea was to model a full cavitation process that would develop along the projectile trajectory, and then to study the expansion and collapsing of the created vapour bubble. As a starting point, it was considered that the vapour production (latent energy) was proportional to the loss of kinetic energy of the 7,62 mm projectile as recorded in [ref]. In the presented simulation, a 300x460x540 mm3 Au2024 T321 metallic dummy tank with 6 mm thick aluminium top and bottom skins was modelled (EUCLID RTP3.32 project). The transparent windows are made of 50 mm thick elastic PMMA material. The aluminium material is modelled using a perfect elasto-plastic material model with a Von Mises criterion. The F.V-FE mesh is volumic for both the fluid and the structure domains, with a conform mesh being used to improve stability and prevent having to solve F/S interactions. Finally, the mesh is about 130 000 finite elements and 575000 finite volumes large.



Presentation of the experimental case and test results (7.62 mm projectile velocities)

From these tests, a power loss W(t) could be calculated at position d(t), at time t, along the projectile trajectory which was traduced by a lineic energy being delivered at position z, at time t(z), and led to formulate an energy injection function as a continuum of synchronised sources. The continuous model was then discretized for the numerical study, with N sources of coordinate z_i, defined at regular intervals corresponding to the (1x1x5 mm3) F.V. elements of the mesh along the projectile trajectory. Finally, sources S_i were activated at time $t_i=t(z_i)$ and the injected energy $f_i = f(t_i) = f(z_i)$ was computed so that an energy $k\Delta E_{ci}$ is delivered to the fluid, with:

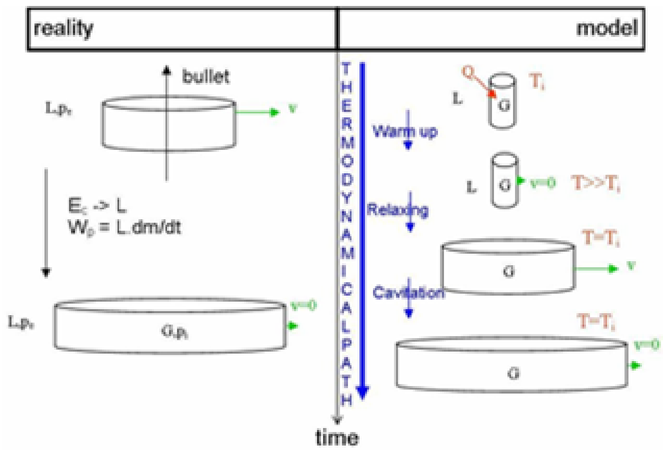
$$\Delta E_{ci} = \frac{E_{ci+1} - E_{i-1}}{2}$$

with E_i being the interpolated kinetic energy of the bullet at positions z_i. To avoid load discontinuities that can always generate numerical artefacts, the f_i injection functions are given a triangular shape between t_{i-1} and t_{i+1}, and a f_i^{max} maximum amplitude, that gives the expected $k\Delta E_{ci}$ injected energy once integrated. In the later numerical study, k=1 is taken, which means that the initial 3kJ kinetic energy of the 7,62 mm projectile is injected in the numerical model.

The only available energy injection method in EUROPLEXUS consists in direct injection of energy in the model, as heat that increases the specific enthalpy h of water in the F.V. source S_i (latent heat is a particular form of enthalpy for water). It initiates local ebullition then cavitation, as reported in [ref]. In the real case, the bullet induces a radial displacement of the water. Because of the depression, water is vaporized. If one writes the energy balance at the interface between water and vapour, neglecting compression of water and viscous forces, the following equation is obtained:

$$W_p = L \cdot \dot{m}$$

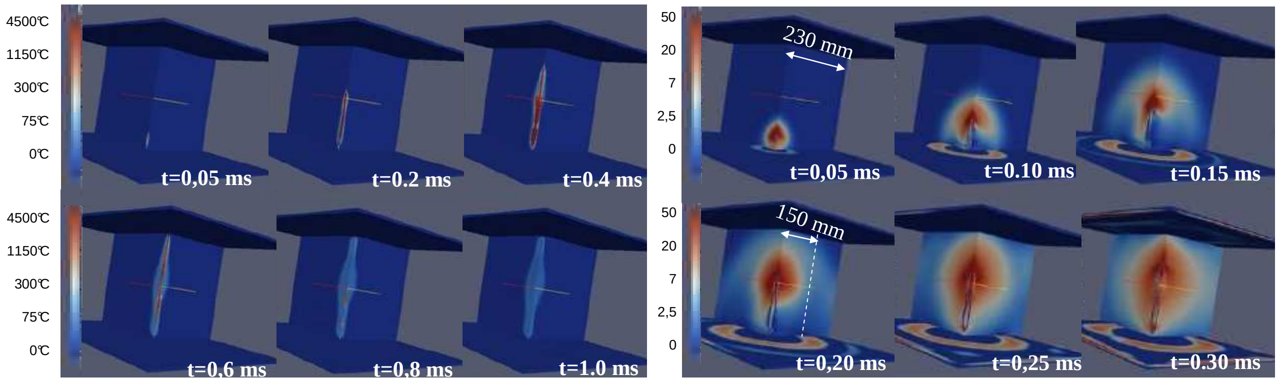
where W_p denotes the work of the pressure forces, L is the latent heat of the vapour, and $\dot{m}$ the quantity of water which is vaporized at the interface. No variation of temperature in vapour phase needs to be considered (at saturation pressure and temperature in the test). By integrating the above equation, a conversion mechanism of projectile kinetic energy into vapour latent heat is modelled (see below). During the collapse of the cavity, the contrary phenomenon occurs.



Presentation of the modelling philosophy

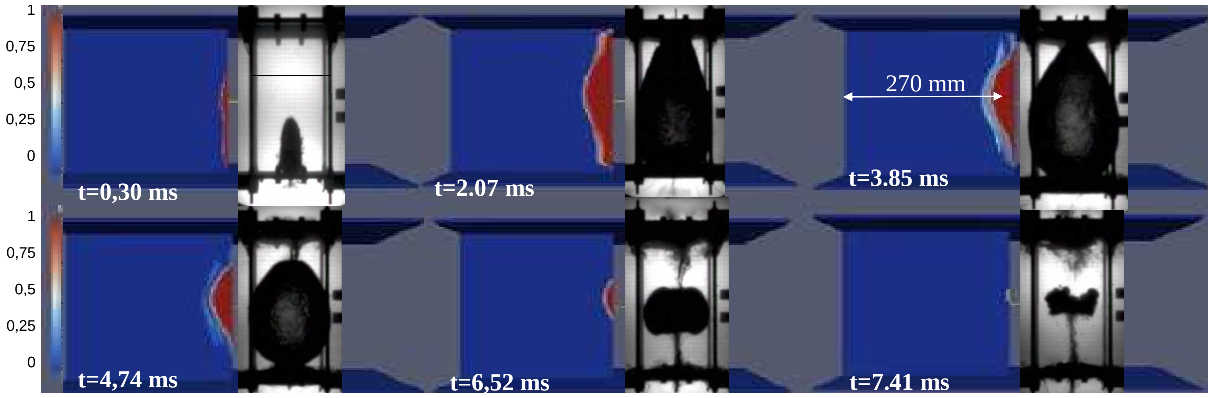
By heating the sources volume, the water is vaporised and overheated. The vapour then relaxes (in an anisotropic way) which produces kinetic energy of the surrounding water. An adiabatic assumption was made, that no heat transfer would take place between the vapour created in the F.V. sources and the water in the surrounding elements: no vaporization of water is made possible but the one initially present in the F.V. sources. Then, the energy used to warm the water up to 100°C and vaporize it in the F.V. sources becomes smaller as the volume of the sources decreases, and most of the injected energy is then used to warm up the vapour and convert into mechanical effects (cavity expansion and fluid pressure) during its adiabatic relaxation.

The maximum temperature value during the loading phase of one source was about few hundreds degrees. As shown in the following figure, this temperature increased in some of the FV sources up to few thousands degrees (e.g. between 0,05 ms and 0,25 ms) after the injection phase: this could be explained because of convection process in the vapour cavity. Then, the temperature of the vapour decreased rapidly: after one millisecond, it was down to 60 °C, and 30°C after eight milliseconds, which is far below the saturation temperature at 1 bar. The maximum peak pressure at t=0,2 ms and 5 cm from the shot line in the simulations was recorded about 5 bars (see following figure), then largely (one order of magnitude) below the 50 bars measured in the corresponding test. This was explained because the mechanical shock between the projectile and water was not modelled in this simplified exercise.



Evolution of the temperature (left, in °C) and pressure (right, in bars)
during the energy injection phase

After the energy injection phase, the fluid kinetic energy was enough to induce cavity expansion with its own cavitation production, long after all the sources have been shut. A new equilibrium was finally reached, before the cavity started to collapse after several milliseconds, in satisfactory good agreement with what was observed during tests. The lifetime of the cavity was 7,41 ms in the simulation, which correlated well with the 7,5 ms one observed in the EUCLID RTP3.32 test. But the obtained size and shape of the cavity in the numerical simulations turned to be a little different from the experimental ones: the maximum radius of the cavity is about 60 mm in the simulation where it was 75 mm in the box experiments. This was probably due to the previously described convection process that very quickly homogenizes the internal energy in the vapour phase: the expansion of the vapour cavity between 1 ms and 8 ms should be governed by mechanical cavitation dynamics, but the heat convection keeps the corresponding sources active when these should be "shut": the cavity keeps on expending in areas by thermal effects where and when it should only be by mechanical ones.



Comparison (vapour volume title) of the spatial dynamic expansion and collapse of a heat generated numerical cavity with the 7,62 mm ballistic test ones

As a conclusion, the 10 ms growth and collapse kinematics of a cavitated-like water vapour bubble proved to be possible with the EUROPLEXUS code, with a satisfactory CPU time (5 days to simulate the 8 ms full collapse of the cavity). If the geometry and the dynamics of the 3 kJ injected-heat bubble were close enough to the 3 kJ ballistic generated one, the peak mechanical loadings that would apply onto the structure walls were largely underestimated (due to the absence of modelling of the projectile impact), and more correspond to the mean pressure measured during this kind of test. The perspective of this research is, first, to improve the numerical model with a possible second gas being considered in the mixture law to consider the influence of the air trapped in the projectile wake on the cavity characteristics.

Second, a full 3D FV simulation of a high-speed penetrating projectile in the tank is to be performed, in order to assess the combined mechanical and thermodynamic modelling capabilities of the EUROPLEXUS code with respect to a representative HRAM ballistic event. Research works are currently in progress [Fourest, 2015] [CN-13] to determine and improve the capability of the EUROPLEXUS CEL solver together with an multi-material (air and water) fluid law to simulate the growth and collapse of cavities created by ballistic impacts in water filled tanks.

Synthesis and conclusions

My research activities concerning the numerical simulation of Hydrodynamic RAM in aeronautical fuel tanks started in 1995. Different fully coupled numerical solutions to solve hydrodynamic fluid/structure interactions had already been developed from the 80's, such as general (and commercial) FE codes or more specific ones (such as hydrocodes) which relied on Lagrangian, Arbitrary Euler-Lagrange, Particle hydrodynamics or even Coupled Euler-Lagrange formulations. None of them was able to accurately predict high speed ballistic induced HRAM events in fuel tanks from the ballistic impact to the final catastrophic failure long after that the projectile has passed trough or been stopped in the fuel tank, and the induced cavity has totally collapsed. The computer powers was not as powerful as today, and the question of the numerical CPU costs was a real problem to study representative complex 3D fuel tank structures : I first proposed to rely on purely lagrangian simulations (more efficient, not diffusive, etc), the main drawback being that the fluid lagrangian mesh in the studied case developed excessive deformation around the projectile during its tumbling phase, with the computations failing due to numerical instabilities or defeating time steps. To counter these difficulties, I propose to use standard explicit codes, and an equivalent simplified projectile model of smoothly varying shape (conic one) the radius of which being forced to reproduce the same drag coefficient that the one of true projectiles. The proposal was first addressed in an axisymmetric frame, and then extended for 3D configurations, with interesting results being obtained. But such a method required data to get the true projectile drag coefficient evolution law: such data were only available from difficult and expensive test campaigns, or using accurate 3D fluid/structure interaction modelling of the interactions between the highly deformable projectile and the fluid, again. For this purpose, and because ALE simulations also often suffered from unavoidable numerical instabilities, it was decided to challenge the Smooth Particle Hydrodynamics lagrangian method to predict the projectiles kinematics in the fluid. A major question when such numerical solutions are developed, concerns the validation of the simulations with respect to simple enough but representative reference test results: even then, the comparisons often fail and raise their lot of questions, due to the high complexity of the physics which is involved in the hydraulic ram phenomenology. The SPH formulation nevertheless proved to bring some improvements compared to the other ones, and many authors – as we - are now using it to study this problem, at least when simplified dummy tanks are concerned. Now that this numerical formulation has been agreed to be promising enough, the research has been focussing on improving the physics in the fluid EOS and behaviour models: compressible (vs purely acoustic), viscous (vs non dissipative), and cavitating (vs monophasic) aspects had to be regarded. It was first proposed to do so by considering and analysing general energy conservation principles, and by producing academic numerical exercises. Our understanding and knowledge is improving, but many research works will still be needed before the high speed ballistics induced HRAM vulnerability of fuel tanks structures can be claimed to be accurately predicted.

Conclusions and perspectives on the characterisation and numerical simulation of Hydraulic RAM in fuel tanks

The specificity of the present research compared with papers in the open literature which are studying hydraulic ram in fuel tanks, is that most of them consider constant projectile shape and associated drag coefficients, and only the very first stage of the HRAM process (less than 1 ms) until the projectile exits the structures. The present works relate to firing tests performed in fuel tank containers, using deformable projectiles which tumble and can be torn apart during the fuel penetration process, and address the total HRAM duration, until the final collapse of the wake/cavity long after the projectile has stopped or passed through the structure.

In terms of experimental knowledge, the first presented works concerned the improvement of pressure measurement techniques and protocols, mainly to increase the confidence level for indirect validation of numerical simulations, especially in terms of local pressure field (to better predict local rupture). The generalisation of high speed imaging techniques also brought huge new information for the understanding of the various phenomena involved in the considered HRAM scenarios, and raised many new questions. The research also pointed out a number of lacks in the physical characterisation of these phenomena (e.g. temperature, pressure and velocity fields), which turn in the end in questioning the use of complex physical models and equations of state that are used in fear of missing some important parameter. For the fuel or substitute liquid [Fourest, 2015]: what about compressibility, viscosity, cavitation (with change of state) effects? For the fluid system: what about the need of multiphase (liquid, vapour) and multi-material (air, vapour) behaviour laws? If full scale tests will still clearly be needed until numerical simulations have definitely proved their capabilities, small and medium scale laboratory tests are still missing that would pave the way for maturation of these numerical tools and models: a number of research works – that were not all reported here – have been and will continue to be realised to this goal. Among the planned ones: (1) testing of simple fuel tank dummy structures, associated with particle image velocimetry techniques to get insight in the transient velocities in the liquid during ballistic test, (2) development of dynamic tests to characterise the fuel or substitute fuel EOS, including cavitation, this list being of course not exhaustive.

Concerning the numerical aspects, huge progress has been made since the 80's, thanks to the admirable increase of the computers power and massive parallelisation of the computing tools. If the Smooth Particle Hydrodynamics formulation was established to possibly be the only candidate to succeed in modelling HRAM, new Coupled Euler Lagrange are generalizing and competing with the lagrangian particle approaches. But many mathematical difficulties and possible traps still remain on the path because of the true complexity of the underlining non-linear physics in HRAM phenomena: efficient and robust ad-hoc resolution schemes, and not only nice formulation frames, will be needed before we succeed in predicting the final burst of pressure at ultimate collapse of the fluid cavity in the fuel tank. That is the main reason why ONERA joined in 2008 the Consortium of development of the EUROPLEXUS research code (CEA and EU JRC-ISPRA dynamic explicit FE code): most of the ingredients that we expect to be of importance for our future research works are already available in the code (Finite Elements and Volumes, SPH-ALE and CEL formulations, complex fluid EOS, etc), with full access to the code sources.

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Application, conclusions and perspectives of the research

Optimisation of a composite fuel tank structure with respect to HRAM dynamic loads

Reducing vulnerability of aeronautical structures to dynamic threats can be achieved through improved configuration, damage tolerance and damage resistance. Damage resistance is mostly a question of materials and structural design. Because of their high mechanical performances and low weight, the use of lightweight composite materials, e.g. Glass or Carbon Fiber Reinforced Plastic, is then of great interest. Advanced nonlinear numerical design is then required to come out with the best compromise between damage resistance capability and final weight of the structures, and the design or optimization (a key and long lasting research topic for composites [RN-08]) of composite tanks with a reduced vulnerability – meaning here acceptable rupture level – with respect to HRAM turns to become a challenging numerical problem, because both the prediction of the composite dynamic behavior and rupture, and the modeling of the hydrodynamic loads that are produced during HRAM events, are challenging issues for the research community as previously described in chapters 2 and 3.

Examples of composite pieces: from raw fabric CFRP (bottom right) to impacted sandwich part (top left)

With the development of Unmanned Aircraft Vehicles (UAVs) for civil and defense applications, the HRAM vulnerability issue raised again. Indeed, to increase UAVs operational capabilities, each possible/relevant volume should be used as a fuel tank, which leads to design parts of both wings and center fuselage as possible structural fuel tanks. The increase of payload for such UAVs is a key issue. The use of lightweight composite materials is then all the more recommended here, with not only the design but the optimization of the composite tanks with a reduced vulnerability with respect to HRAM turning to become a very essential question. This very ambitious objective was challenged thanks to the knowledge and research results that were described in the previous chapters: in the frame of an European Defense Agency (EDA) research project (BaTolUS, 2010-2013), ONERA is currently involved in the numerical design, optimization and validation against ballistic tests of a French National Variant (FNV) of an UAV center fuselage fuel tank demonstrator. For that purpose, the most important part of the work was dedicated to propose, set up and assess an efficient numerical optimization methodology and strategy that can be used to support the improvement of the French damage resistant fuselage design. We will see how the previously described research works were determinant to reach such an ambitious objective.

The optimization methodology which has been proposed aims at helping engineers to find a UAV design of lowest mass, that meets the static design requirements, and is still able to return after having been hit by a ballistic projectile (7,62 mm or 12,7 mm caliber). ALTAIR's commercial HyperStudy optimizer and Radioss FE crash code are used in the following work.

Definition of equivalent hydrodynamic loads for HRAM events [TBPS] [RE-02] [RE-03] [RE-04]

The BaTolUS project is dealing with the question of the optimization of composite fuel tanks with respect to Hydraulic Ram dynamic loads generated by non-academic highly deformable ammunitions (e.g. 7,62 m, 12,7 mm), which is an originality of the research compared to other works where academic and almost rigid spherical projectiles were studied. Part of the numerical difficulty concerns the modeling of the hydrodynamic transient loads that apply onto the structure in such non-academic cases (tumbling, deformation or even fragmentation of the projectile). Indeed, since optimization is concerned, then accurate loads should be accounted for instead of general ones. Considering that no complete 3D fluid/structure interaction simulations can be used in numerical optimization loops, because of difficulties, deficiencies and unacceptable CPU costs of a complex modeling of the tank structure full of liquid (like previously discussed CLE or SPH modeling), ONERA proposed to develop CSM simulations relying on calibrated dynamic temporal load functions (pressure field) directly applied to the finite elements of the model of the structure. Such a simplified transcription of the hydrodynamic loads would enable one to get rid of the modeling of the ballistic projectile and fuel in the tank (and related CPU costs).

So, an uncoupled scheme has been proposed by ONERA, to get rid of that specific difficulty. First, the characteristics of a simplified equivalent burst pressure source were determined to approximate the initial pressure burst that is often reported in the literature and ONERA experiments to be generated by the tumbling kinematics of the studied non-academic projectiles. Indeed, transient pressure time-histories of the same generic kind have often been recorded close enough to the projectile (before any reflection from the structure boundaries occurs and combines with the initial pulse), but far enough from the projectile with respect to its dimensions, in order to formulate the corresponding hydrodynamic load modeling problem as a spherical propagation wave problem from a punctual source. Knowing the burst source characteristics, a specific treatment could be applied to transport the pressure time-history from the source position to each point of the structure with respect to the distance. No fluid damping effect was taken into account, and an acoustic energy conservation principle was used to calculate the pressure peak value to be applied to the structure walls according to the distance. Second, and because the dimensions of the considered fuel tank structure were small enough, the longer (several milliseconds) half sine-wave pressure load which corresponds to the cavity expansion phase in the wake of the bullet was equally added to all the previous transient pressure functions to act as an average dynamic pressure acting globally on the structure. A dynamic pressure field (mapping of hundreds or thousands of pressure functions, depending on the FE mesh size of the structure) could then be automatically generated, that did not need to be re-computed during the structural FE explicit simulations.

Determination of the simplified HRAM dynamic pressure loads

In this research work, the characteristics of a generic 7,62 mm source have been first determined from an experimental 7,62 mm firing test that was performed in the frame of the EUCLID RTP3.32 research project [TBPS]. The generic burst pressure profile was modeled as a triangular shape function of few 1/10th of millisecond duration. To represent wave propagation and transient effects of the shock wave, the occurring time of the applied pressure functions change according to the distance of each concerned finite element of the structure FE model from the pressure source, and the pressure amplitude varies according to this distance and the following acoustic energy conservation principle:

$$I = \iiint_V \left(\frac{\rho u^2}{2} + \frac{p^2}{2\rho c^2}\right) dV,$$

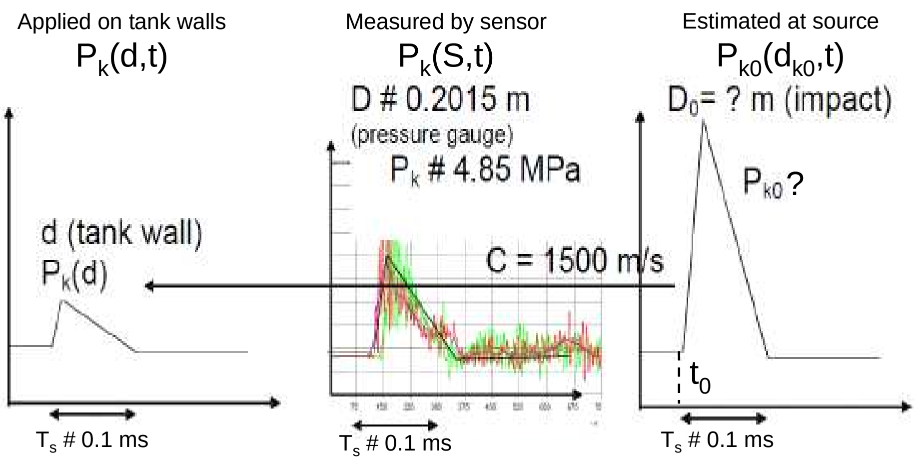
Or:

$$I = \iiint_V \frac{p^2}{2\rho c^2} dV = \frac{1}{2\rho c^2} \int_{-\theta_0}^{+\theta_0} \int_0^{\pi} \int_0^{d_0+0.0625} p^2 \; r^2 \sin\phi dr d\phi d\theta$$

if the kinetic part is disregarded (incompressible assumption). The main assumption made was that the concerned liquid volume changes from a growing purely spherical one to a moving spherical ring of constant width. Then the final equation to get the pressure peak according to the distance was (since the pressure profile duration is assumed to be the same whatever the distance because of incompressible assumption):

$$P_k(d)^2 \; V(d) = P_{k0}^{\;2} \; V(0) = P_k(S)^2 \; V(S)$$

where $P_k(d)$ is the peak pressure value at distance d from the impact point, $P_k(S)$ is the peak pressure value at pressure sensor location, P_{k0} is the peak pressure value at source location, V(d) is a spherical ring volume concerned with pressure profile $P_k(d)$, V(S) is a spherical ring volume concerned with pressure profile $P_k(S)$, and V(0) is a purely spherical volume concerned with pressure profile $P_{k0}(0)$ at source point.



Estimated transient burst pressure loads onto fuel tank structure walls

P_{k0} was assumed to be the initial drag pressure of the bullet: $P_{k0} = \frac{1}{2}\rho \, v_0^2$, where ρ is the density of the fluid, and v_0 the initial velocity of the projectile when hitting the fluid. The source location (inside the tank, distant from the entry wall according to shot line), was assumed to be the barycentre of the kinetic energy release rate, that could be calculated thanks to the high speed videos that gave access to the projectile speed evolution:

$$X_G = \frac{1}{2\alpha}\frac{\left[1-(1+2\alpha X_F)e^{-2\alpha X_F}\right]}{\left[1-e^{-2\alpha X_F}\right]}$$

where X_G is the source abscissa, α is the velocity decay coefficient (here, 0.005 from ONERA 80's reports), and X_F is the abscissa where the kinetic energy release rate of the bullet is 90% (from EUCLID-RTP3.32 tests on dummy tanks).

Concerning the definition of the mean dynamic pressure that was observed during the cavity growth which was measured using digital videos in the reference tests, a simple half-period of a sinusoidal function was retained:

$$p_m(t) = P_{\max}\sin(\omega t) \quad P_{\max} = \overline{p}\, c(K)$$

where P_{max} is the maximum (relative) pressure during cavity expansion phase, ω is the pulsation i.e. 2π/T, and T corresponds to 20 wave propagation/reflection times along the larger structure dimension. T can be calculated from max(h, l, L) and the sound speed in the fluid, where (h, l ,L) are overall dimensions of the tank. The influence of the stiffness of the structure on the average pressure level is introduced by c(K), and determined from test results. The average pressure value $\overline{p}$ is determined through an incoherent summation of the drag pressure wave (decreasing with distance r) over the length L of the shot line:

$$\overline{p} = \frac{1}{L}\int_0^L \frac{1}{2}\rho.(v_0.e^{-\alpha.x})^2\,\frac{R}{r}dx = -\frac{R}{4r\alpha L}\rho.v_0^2\left[e^{-2\alpha.x}\right]_0^L = \frac{R}{4r\alpha L}\rho.v_0^2\left[1-e^{-2\alpha.L}\right]$$

where x is the abscissa along the shot line, L is the length of the shot line, v_0 is the initial velocity of the projectile, r is the smaller distance between shot line and side walls, and R is a characteristic length of the projectile.

The final pressure load that is applied on the fuel tank structure according to the distance to the pressure source location is finally:

$$P_w(d,t) = p_k(d,t) + p_m(t)$$

Calibration of the simplified HRAM dynamic pressure loads

In case of a rigid structure, the total burst pressure that should be applied onto the structure walls would amount twice the dynamic incident transient value in the fluid, because of full positive reflection principle. Assuming that the pressure measured by the flush transducers in the tests were dynamic (and not static) pressures, a conservative (x2) effect was taken into account in the basic definition of the hydrodynamic burst load functions to be applied onto the structure walls. On the other hand, the structures are not perfectly rigid: to consider the role of the acoustic impedance of the structure walls, another correction factor on the sole burst part of the load functions should be introduced. For the present research, a single global calibration factor has been considered (reflection factors should theoretically depend on local stiffness). This calibration factor was finally optimized by equaling the external forces work compared to the initial kinetic energy of the projectile, which gave a x0,57 value (x2 x0,57 = x1,14 # 1), which sounds like the measured pressure in the test was indeed a "static" pressure (and not a purely dynamic one), and that the structure stiffness was almost rigid with respect to wave reflection effects.

The methodology of determination of the generic source and associated equivalent hydrodynamic load field has been validated considering the EUCLID RTP3.32 structural test results that was studied in [Charles, 2012], in terms of local strains and structure walls displacements of the metallic dummy fuel tank. Knowing that a quite coarse $2D^{1/2}$ structure model was used, and that the impact of the ammunition on the structure was not modeled, the numerical validation was quite satisfying, the magnitudes and temporal scales of the test and simulation results being of the same orders of magnitude for both the upper skin displacement (measured by optical extensometer), and the lower and upper skins deformations (measured by strain gauges), even if one could have hoped that the form of the temporal curves better fit with each other.

Numerical optimization strategy and methodology [CI-20]

The following work started with the formulation of the "vulnerability" minimization problem, in terms of constraint(s) and objective function(s). The general philosophy had to be formulated, taking care of general considerations about FE modeling to get acceptable CPU costs. The HyperStudy software offers different resolution algorithms to solve an optimization problem. Two different methods can be used: a mono-objective method or a multi-objective one. In terms of multi-objective methods, Hyper-Study proposes two algorithms: a Multi-Objective Genetic Algorithm (MOGA) or a Gradient Based Multi-objective Method for Optimization (GMMO). The multi-objective algorithms have been tried, but were given up (and will not be discussed in the present report) because they turned to be far too time-consuming. The other algorithm that HyperStudy offers (GMMO) is then used in the present work: it is a gradient based one, which relies on the Adaptive Response Surface Method (ARSM). Its principle consists in searching the direction (in the space of design variables) which gives the higher slope, that is to say the direction for which the objective function of the minimization problem decreases the fastest. GMMO produces a solution by exploring the Pareto-front of the problem. It consists in sampling the surface response of the objective function for a set of points in the design variables space. HyperStudy then approximates this surface using quadratic polynomials, based on the mobile least square method, to propose an optimal set of value for the design variables, then iterates until a convergence criterion is satisfied. Concerning the HyperStudy optimization strategy, the initial model is first analyzed through a sensitivity study on each parameter (design variable), with respect to the objective function and constraints. Then a first set of polynomial coefficients are determined for the objective function (OF) approximation, that best satisfy the constraints of the problem. The approximated optimum design is searched mathematically, and this approximate optimum design is analyzed: stopping criteria are checked, and the optimization process ends when/if adequate conditions are met. In the present study, the design variables (DV), i.e. the variables (or parameters) of the FE model that will vary during the optimization process, were the thicknesses of the different metallic components of a generic UAV fuel tank structure.

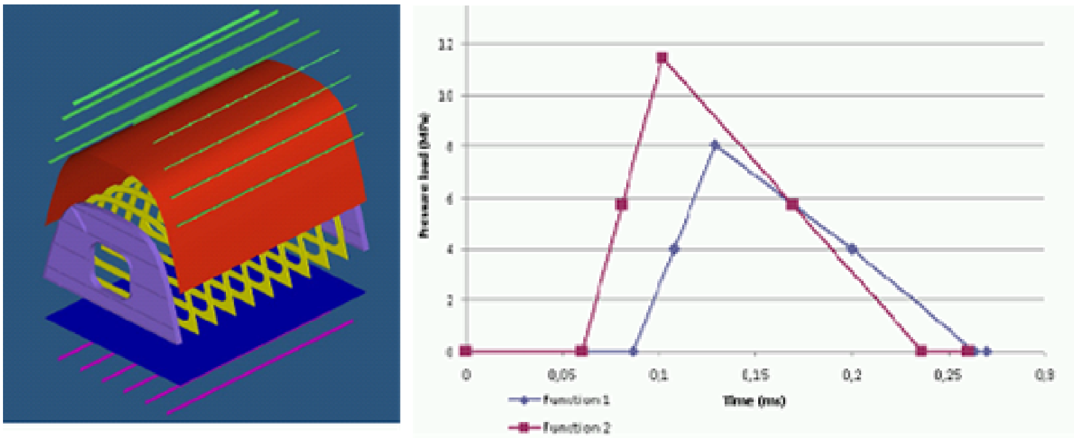
Now, the purpose of the design optimization is theoretically to satisfy the static design requirements, and minimize both the mass of the structure (in aeronautics, it is a priority), and the vulnerability of the fuel tank against HRAM threats: this means a multi-objective process, that was first tried but had to be abandoned because of CPU costs. Moreover, "reducing the vulnerability of the structure would be translated in expert words as "avoiding a defeating fuselage rupture". This qualitative objective is very difficult to formulate mathematically, and a simpler and clearly more conservative one has been preferred: "avoid any rupture in the structure, except at impact and perforation point", which sounds more like a constraint than an objective function. Then a mono-objective problem remained, mass minimization, with a conservative constraint on rupture. An objective function that maximizes the specific energy of the complete fuel tank (considered as an "absorbing structure") was preferred:

indeed, in crashworthiness studies, when impact energy has to be dissipated by absorbers, a particular "specific energy" capability is always used to discriminate between various solutions. This specific energy corresponds to the ratio [dissipated energy]/[mass] in the studied absorbing components. As metallic structures were considered in the present methodological case, the dissipated energy to be considered would be the plastic energy. The optimal solution in terms of vulnerability would in the end present a maximum [plastic energy]/[mass] ratio, and satisfy the imposed constraints (e.g. static performances – minimum components thickness - of the structure, and no-rupture condition). Since the thinner the components, the higher their plastic deformation and the lower their weight, this objective function was consistent with the mass reduction objective.

Because of numerical cost reasons (time, size of result files, complexity and cost of the OF evaluation), another solution was proposed for practical reasons: it was decided to approximate the total plastic energy by the total internal energy in the structure. Indeed this total internal energy (single data) and the FE model mass are systematically available in RADIOSS simulations output files. But this internal energy corresponds to plastic energy only after elastic energy has been damped: this is artificially obtained after applying a relaxation step after the FE impact simulations. A "dynamic" relaxation (well-known for its better robustness) has been preferred instead of the "kinetic" one. This method is based on a traditional damping formulation that is based on the definition of an artificial viscosity. To fully address the question of the vulnerability of the fuselage tank structure, it was previously explained that a constraint on elements rupture had to be added. It was proposed to count the "ruptured" elements by searching the string "RUPTURE" in the minutes file of the FE simulations, to write down the number of apparitions of this string in a text file. This value would be checked as a constraint (should be equal to zero) of the optimization problem.

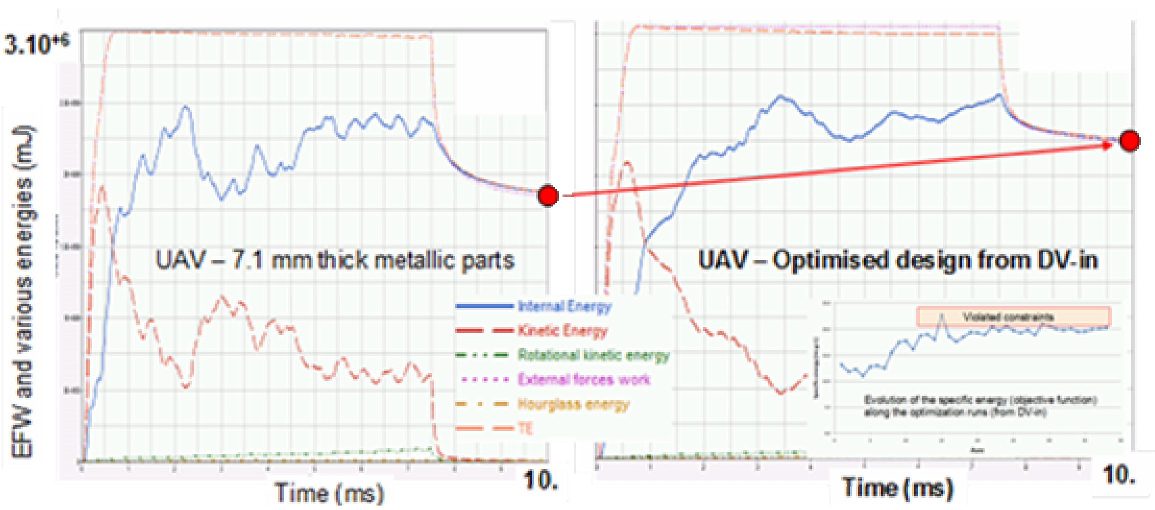
Other constraints were added to the optimal solution search. First, the satisfaction of the static requirements is formulated for the present methodological exercise by imposing that each final component thickness is larger than the initial one (since the static requirements have been used to define the initial solution). Second, as the HRAM transient pressure field supported by the structure is approximated by pressure load functions in the FE simulations (the fluid and bullet penetration are not modeled), and because this model has been derived from experimental results obtained on a given experimental configuration (7.62 mm impacts on previous military aircraft wing fuel tanks) and calibrated considering the FNV initial design, some care had to be taken to use it when the initial FNV FE model is changing during the optimization process. In particular, it is assumed here that the external forces work (EFW) of the structure when the equivalent loads are applied on it, cannot exceed (and should be almost equal) to the projectile initial kinetic energy which is transferred to the system (here about 3000 J). Any FNV design modification would then be consistently proposed to stand against the studied threat.

The application case that has been studied in the present work was a complete AU2024 aluminum UAV center fuselage fuel tank, made of different components: stringers, skin, bulkheads, frames, floor, and floor stringers. The liquid phase was not modeled, and no added mass was considered to take the liquid weight into account in the simulations (the corresponding static stress could be neglected compared to the hydrodynamic loads level). To start the design exercise, a single 7.1 mm thickness to all the components was proven to satisfy all the imposed constraints (larger than the 2 mm static design requirement, no rupture observed and EFW equal to 2995 J). The tank structure was modeled with 22630 shell elements. To represent projectile perforation, the element impacted by the projectile has been cancelled. In terms of material law, an elasto-plastic power model was used to define the components material: aluminum 2024-T351. The data file also includes contact interfaces between the different components, and boundary conditions (BC). To model the hydrodynamic loads on the structure (here 7.62 mm bullet vertical trajectory, from below and at center of the floor), pressure functions have been imposed on the skin, floor and bulkheads elements (not on frames, stringers, etc), according to the method described in the previous paragraph. To represent wave propagation and transient effects, the occurring time (and not only the pressure levels) changes according to distance of each concerned finite element from the pressure source (which is here 7 cm after the bullet perforation point through the floor). The maximum pressure applied on the closest element from the pressure source was here about 32.5 MPa.



Presentation of the fuel tank structure (left) and example of transient pressure functions to be applied on different shell elements (right)

It is important to note that the time window for the application of all of the pressure loads was less than 1 ms. Then, the HRAM event duration that was computed was 7.5 ms in order that the structure can reach a dynamic equilibrium after the transient load was over. Finally a 2.5 ms extra computing time was added to perform the relaxation step. Each RADIOSS run then simulated a 10 ms long dynamic structural response. Each single run took less than 4 min CPU time (on a 4-cores Xeon X5650 - 2.67 GHz, 64 bits – and Windows 7. OS, using a parallel version of the code). Concerning the optimization path starting from design variables that satisfy the imposed constraints (DV-in), it took 38 runs to get a converged solution. HyperStudy maximized the objective function while respecting the constraints, by modifying gradually all DVs: starting from 15,48 mJ/g (initial design), the specific energy reach 20,23 mJ/g (+31%) at the end of the process. HyperStudy obtained a set of thickness values for the components where floor was at the maximum possible value (9 mm). The main point here to mention is that the general trend was not the one that would be expected from a simple "homothetic" hardening of a standard static design.



Maximization of the internal energy after relaxation after the optimization process from initial design (left) to optimized design (right)

The data file also includes boundary conditions: it was decided that no clamping conditions should better be imposed at the boundaries of the structure because they would induce stress concentration (then increased components thickness to prevent rupture). More realistic boundary conditions were not easy to define, unless the full structure is modeled. Concerning the components assemblies, tied contact interfaces were used, that represent perfect and undamageable bonding conditions instead of riveted ones.

As specific energy maximization was concerned, the focus was made on the variation of plastic deformation after optimization of the structure. Between first and final run, the plastic strain level in the frames (where plastic energy is maximum) has been multiplied by 3.6, without reaching failure plastic strain. In the initial model (7.1 mm thick frames), the maximum plastic strain level was about 2%, where in the last run (2 mm thick frames), plastic strain reach 7.4%. When considering mass reduction, a decrease of 28% was obtained: starting from 140 kg, the final structure mass fell down to 111 kg.

Last point, the elapsed time required for the optimization process was 04h 24mn 05s, and the CPU time 02h24mn05s. It means that many different impact situations (velocity, location of impact point, etc) can be studied cheaply, or that the optimization exercise could be enlarged by including several – possibly ponderated - impact cases (the probability of the fuel tank being hit from any other side – except top - cannot be completely excluded) in the process.

As a conclusion the previous results proved that the optimization could be performed, and that it could be efficient enough in industrial terms (CPU times), and lead to recommendations that would not be straightforward for a "static design" expert. Even if the specific energy increase did not seem very impressive/ determinant regarding various solutions, the mass benefit was really interesting. For instance, an increase of 100 kg of the static design (from 2 mm to 7.1 mm thick metallic components) would be needed to coarsely satisfy the vulnerability constraints (as defined in the first part of the document): this penalty could be reduced to 40 kg by using the proposed optimization methodology.

But the final solution was clearly dependent on the initial point of the optimum research: it means that a more sophisticated strategy should be used to cover a larger solution space (e.g. genetic algorithms), and/or expert rules/extra-constraints should be added to restrain the field of possibilities (e.g. skin stringers thickness should be less than frames thickness, etc). The second point that should be improved concerns mainly the representativeness of the FE model of the structure, since the boundary conditions (ideally, the full aircraft should be modeled – at least at a coarse level - to get representative stiffness and avoid inappropriate stress concentration or relaxation at boundaries that would clearly change the fuel tank optimization results), fuel mass, and joints were not properly represented.

Conclusions and synthesis

The methodological formulation (in terms of constraints and objective function) of an HRAM vulnerability minimization problem, which is compatible with the use of standard fast dynamics FE structural analysis codes, has been proposed and evaluated against a metallic representative generic industrial case. For this purpose, equivalent hydrodynamic load functions had to be determined and assessed in order not to have to model the ballistic projectile and fluid in the fuel tank: these equivalent hydrodynamic loads were derived from the experimental results and knowledge gained after many years of research. Then, the specific energy of the fuel tank structure (i.e. the dissipated energy divided by its mass, as used to design energy absorbers) was considered to be the key driver in the proposed optimization philosophy. The final formulation of an HRAM vulnerability minimization problem proved to be compatible with the use of standard fast dynamics FE structural analysis codes (here using the HyperStudy and RADIOSS commercial softwares) and efficient enough in industrial terms (CPU times). It also means that many different impact situations (velocity, location of impact point, etc) can be studied cheaply, or that the optimization exercise could be enlarged by including several - possibly ponderated - impact cases (the probability of the fuel tank being hit from different sides should be considered) in the process. It also means, because the final solution can be dependent on the initial point research of the optimization process, that a more sophisticated (and costly) strategy could be used to cover a larger solution space (e.g. together with genetic algorithms).

This optimization philosophy is currently being reproduced for the optimization of a composite dummy tank (EUCLID RTP3.32 geometry). It means that a non-linear analysis is needed, that will be possible thanks to the use of non-linear composite material laws such as the one which was developed, and may now be properly characterized, as presented in the previously described research on composites CMO materials. As dynamic equivalent load cases are used instead of modeling the fluid response to the ballistic impact, the complexity of the numerical models will be related to the non-linear composite structures mainly. Hence, no volumic, but only 2D multi-layer shell elements will be used to reduce the CPU costs of the structural FE simulations, first with no delamination being modeled, to make the numerical optimization faster. For a composite structure optimization, the number of composite plies, together with the material type and orientation (the stacking sequence), are straightforward parameters to be considered. The optimization process would first consist in changing each layer thickness (all usual standard directions being included in the model). This variation should theoretically be discrete (multiple of the ply thickness), but continuous values should first be considered to discard possible orientations when the corresponding thickness would turn to be small enough. The previously described elastic-inelastic orthotropic composite law would be used to model the composite material behavior (T700GC/M21, which proved to be elastic brittle in tension and compression along the fibers and transverse material directions, and highly non-linear in shear).

Final conclusions and perspectives

The presented research is dedicated to the improvement of aeronautics and space structures against extreme aggressions. The illustrated case deals with the hydraulic ram phenomenon in fuel tanks in case of high speed/high energy ballistic impacts. Our concern here is to increase the mechanical resistance against hydraulic ram solicitations, which is linked to the better understanding and prediction (by numerical simulation) of both the dynamic behaviour and failure of materials, assemblies and structures, and the hydrodynamic response of liquids when fluid/structure interactions with high speed ballistic projectiles are considered. In the present case, the resistance of composite aircraft fuel tanks to ballistic impacts induced HRAM event has to be improved. One part of the solution is to increase the materials performances. Another one is to develop theories and models which will enable the manufacturer to numerically design and optimise its structures regarding these extreme loading conditions. This means that the development and modelling of the materials must be done together with considering the structural problem as a whole, meaning: taking the general environment and the studied hydrodynamic threat into account. So, the main goal of the presented research concerns the development of theories and the validation of numerical simulation tools to ultimately get rid of expensive experimental campaigns. But this step definitely relies first on the production of reference experimental results for validation, which properly deal with the different scales of material, assembly and structural behaviours. The present report hence concerned the question of the experimental characterisation and numerical modelling of CMO composite materials and structures behaviours, on the one hand, and of ballistic hydrodynamics, on the other hand.

Concerning composites, a mesoscale modelling strategy was proposed from the beginning, which would address the non-linear composite behaviour and rupture at the constitutive ply level. The basic principles for a generic composite material model were proposed and refined in parallel to the development of dynamic experimental protocols in the test laboratory (no established normative protocols still exist today for the dynamic characterisation of composite materials), on an empirical basis. The basic idea behind the model was to be able to represent – at the ply level - any 3D orthotropic asymmetric composite material, with or without reinforcement of any type along any of the 3 orthotropic directions, meaning that different possibly non-linear and strain rate dependent behaviours could develop in each material direction, in tension, compression or shear. Carbon, glass, aramid and Kevlar fibre reinforcements, thermoset or thermoplastic, tape or fabrics, 2D or 3D composite materials were dynamically characterised between 1994 and 2013, and some of them modelled with this empirical model with more or less success. No thermodynamic foundation was proposed to validate the empirical 3D model but it was adapted in 1998, and implemented for $2D^{1/2}$ finite element analysis (multi-layered shell elements) in the RADIOSS explicit crash code. It is available today in the open Radioss library, and often used in our industrial and research contracts, the later example being in the EDA BaTolUS project which concerns the FE optimisation of composite UAVs fuel tanks subject to hydraulic ram. But new challenges already arise, with the normalisation of material dynamic testing being probably on the rail, with the development of new generation 3D composite materials, and modern computers that have now the power to handle with more physically based multiscale models [Laurin, 2005, 2007], [Trovalet, 2008]. Considering this multiscale objective, and the homogenised continuum mechanics field that is the general frame of the present research, the main breakthrough tomorrow will very certainly concern the future use of field measurement techniques, be they tomography, image correlation, or thermal ones. These powerful experimental and numerical technologies will probably make it possible to develop, validate and identify models (and simulation tools) of unmatched complexity. At short term, we will focus on the characterisation and modelling of temperature and time/strain rate dependence of damage models in composite CMO materials (including the topic of Cohesive Zone Models for delamination). The second axis of work will concern applied numeric issues with the main challenge being the improvement of the lagrangian FE resolution strategies in terms of accuracy vs CPU costs (e.g. implicit-explicit coupling, non-local behaviour models, and numerical treatment of rupture).

Concerning transient hydrodynamics, the main originality of the present research was to address deformable non-academic projectiles (which tumble and can be torn apart during the fuel entry process), and study the total hydraulic ram event duration, until the final collapse of the wake/cavity long after the projectile has stopped or passed through the structure. Here again, the first step concerned the improvement of experimental techniques (incl. high speed cinematography) and protocols to improve the understanding of these HRAM phenomena (and point out some lacks in our current physical knowledge), and increase confidence in the test results that are still used for indirect validation of fluid/structure numerical simulations. The question of the influence/importance of compressibility, viscosity, and cavitation effects on the final hydrodynamic loads that the structures have to cope with, is still – but less - pending. The need of multiphase (liquid, vapour) and multi-material (air, vapour) behaviour laws is being checked. Concerning the numerical aspects, huge progress has been made since the 80's, thanks to the admirable increase of the computers power, and the improvement and massive parallelisation of the computing tools, with enhanced Smooth Particle

Hydrodynamics and Coupled Euler Lagrange formulations being now widespread. Mathematical difficulties will probably appear together with the increase of the EOS complexity which will be necessary to predict the complex HRAM non-linear physics, which explains the attention that we are currently paying to discriminate at short term which ones are really meaningful for real fuels. For that purpose, small and medium scale dynamic laboratory tests are still missing that would help the maturation of these numerical tools and models, and several research ideas have been recently proposed to be investigated. A second axis of work currently concerns a possible analogy with underwater explosions, since similarities have been pointed out between the HRAM cavities and explosive induced bubbles dynamics, the main identified difference being the confinement effects that have to be considered in our case.

All these research works would probably be worth another 20 years length of time.

Modélisation des matériaux et structures composites soumis à des sollicitations de type chocs hydrodynamiques

La pénétration d'un projectile – éventuellement balistique - à grande vitesse/haute énergie, et l'occurrence d'un coup de bélier dans un réservoir, représentent une éventualité qu'il est souvent légitime, sinon toujours nécessaire, de considérer en sécurité aéronautique. Pour se protéger d'une telle éventualité, le durcissement structural à l'impact via l'intégration de blindages est une solution ultime, qui n'est – dans l'aéronautique – que rarement acceptable pour des raisons évidentes de pénalité de masse. La réduction de la vulnérabilité devient alors indissociable d'un exercice délicat d'optimisation de la résistance de la structure au regard de sa masse, ce qui nécessite donc de modéliser précisément l'occurrence d'un tel coup de bélier, sa sévérité et ses conséquences sur la structure. Ceci est d'autant plus vrai et difficile qu'on s'intéresse - depuis plusieurs décennies déjà en aéronautique - à des structures composites à renfort de fibres de carbone, qu'on sait être particulièrement fragiles aux chocs, et à des projectiles balistiques réels différant notablement de projectiles sphériques rigides, académiques. Les situations étudiées depuis les années 1980 à l'ONERA-Lille concernent en effet des impacts de balles ou d'éclats réels (simples ou multiples : gerbes) perforants et subsoniques p/r à la célérité des ondes dans le liquide.

Pour résumer la problématique traitée dans ce mémoire : après pénétration du réservoir, l'éclat ou la munition animée d'une vitesse proche d'un km/s est brutalement freiné(e) par le liquide contenu dans la structure. La force de traînée qui lui est opposée par le fluide varie violemment en fonction de l'évolution du profil traînant du projectile, en particulier lorsqu'il est déstabilisé et se retourne dans le fluide. Cette énergie cinétique est brutalement transférée au liquide, et il y a création d'un choc hydrodynamique puis d'une cavité (on est en présence d'un mélange fluide multiphasique air, vapeur, liquide) dans le sillage du projectile. Après une première onde de choc hydrodynamique potentiellement destructrice, l'expansion à peine plus lente de la cavité dans le liquide (quasiment incompressible) peut se traduire par des déformations non négligeables de la structure pouvant aboutir à des ruptures catastrophiques des matériaux ou des assemblages structuraux, le coup de grâce étant éventuellement porté lors de l'effondrement final de la cavité.

Le mémoire présenté à l'occasion de cette candidature à l'obtention d'une Habilitation à Diriger des Recherches retrace l'ensemble des travaux de recherche que j'ai été amené à réaliser et surtout à encadrer depuis le début des années 1990 concernant cette problématique de la modélisation des matériaux et structures composites soumis à des sollicitations de type chocs hydrodynamiques, en particulier sur les sujets de la caractérisation et de la modélisation, d'une part, du comportement et de la rupture dynamique des matériaux composites à matrice organique et, d'autre part, des interactions fluide/structures et des chocs hydrodynamiques consécutifs aux impacts balistiques dans des réservoirs aéronautiques.

Mots-clés : SIMULATION NUMERIQUE ; CARACTERISATION EXPERIMENTALE ; AERONEF ; RESERVOIR ; COMPOSITE ; COUP DE BELIER ; CHOC ; HYDRODYNAMIQUE

Modelling of composites materials and structures under hydrodynamic ram loading

The impact of high speed/high energy projectiles – possibly ballistic ones – and the occurrence of an hydraulic ram (HRAM) event in fuel tanks, constitutes a threat which is often legitimized if not always compulsory to consider for aircraft safety. To prevent from such an eventuality, the impact hardening through armouring the structure is an ultimate solution which is hardly acceptable in aeronautics for obvious mass penalty reasons. The reduction of fuel tanks vulnerability then turns to become not separable from a difficult exercise of optimisation of the strength of the structure with respect to its mass. This objective requires to be able to accurately model the hydraulic ram event, its severity and consequences in terms of damaging the fuel tank structure. It is all the more important, first, as carbon fibres reinforced plastic (CFRP) composite structures are being massively introduced in aeronautics for tens of years, and one knows well that they exhibit brittle behaviours under impacts. Second, because complex ballistic projectiles can be concerned, the damaging effects of which can greatly differ from those of rigid (spherical) academic ones. Indeed, the scenarios which are being studied at ONERA-Lille since the 80's are related to real single ballistic bullets or multiple fragments impacts that cannot be prevented from perforating the fuel tank structures, in the present studied case at subsonic velocities compared to the sound speed in the considered solids or liquids.

To summarize the research which is addressed in the present thesis : after it has perforated the structure, the 1 km/s ammunition or fragment is brutally decelerated by the fuel in the tank. The drag force which is opposing its motion quickly varies together with the projectile drag coefficient, especially because it becomes unstable and tumbles trough the fluid. The kinetic energy of the projectile is transferred to the liquid medium, with an hydrodynamic shock being first generated, followed by the development of a possibly multi-phasic (air, vapour) gas cavity in the wake of the moving impactor. After the initial and possibly already damaging hydrodynamic shock wave has passed, the slightly slower growth of a large cavity in the (almost incompressible) fuel leads to an important dynamic deformation of the structure that can possibly turn into catastrophic failure of the structural materials or assemblies, with a final deathblow – if necessary - possibly arising at the very final collapse of this cavity.

The following works, which are here reported to candidate to the Habilitation à Diriger des Recherches grade of the University of Valenciennes, summarize some research that I was personally brought in performing or supervising at ONERA-Lille on the modelling of composite materials and structures under hydrodynamic shock loads since the beginning of the 90's. It focuses more specifically on the question of the characterisation and modelling of, on the one hand, the non-linear dynamic behaviour and rupture of organic resin based composites and, on the other hand, fluid/structure interactions and hydrodynamic shocks during ballistic impacts in aeronautical fuel tank structures.

Keywords : SIMULATION NUMERIQUE ; CARACTERISATION EXPERIMENTALE ; AERONEF ; RESERVOIR ; COMPOSITE ; COUP DE BELIER ; CHOC HYDRODYNAMIQUE

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