UNIVERSITÉ DE BRETAGNE-SUD

NUMERICAL STUDY OF DYNAMIC RELAXATION METHODS AND CONTRIBUTION TO THE MODELLING OF INFLATABLE LIFEJACKETS

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December 7, 2011

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INTRODUCTION

Background

Objectives

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INTRODUCTION

Background

Objectives

Introduction - Form-finding (I)

- **Form-finding of membrane structures**
  - <u>Structural membranes</u>: façades, stadiums' covers, …

Introduction - Form finding (and II)

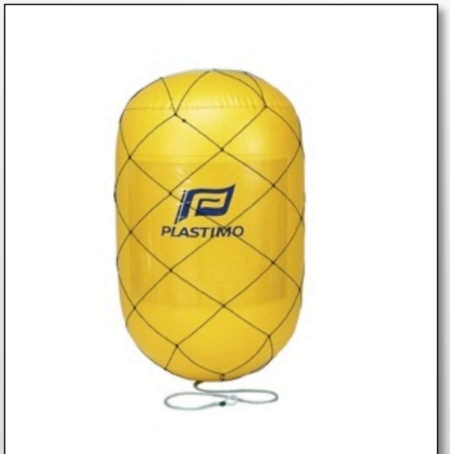
- Inflatable structures: modules for the ISS, temporary hangars, Tensairity® structures, emergency sealing of pipes, …

2008

2011

Background

- ***Plastimo*** ➔ Form-finding of **inflatable buoys, liferafts, lifejackets, …**



- **Complexity → Need for fast and efficient calculations**

Form-finding → DYNAMIC RELAXATION METHODS (Civil engineering)

Background and objectives

Dynamic Relaxation (DR) → [Troufflard]* → Form-finding of INFLATABLE STRUCTURES

Created a tool currently used by Plastimo:

- Form-finding of **inflatable lifejackets**
- A particular DR method: Dynamic Relaxation with Kinetic Damping
- A single particular type of finite elements: triangular elements

QUESTION:

Is it the best DR method to use?
Can we do better?

<u>PhD Dissertation:</u> "Etude numérique et expérimentale des structures gonflables: application aux gilets de sauvetage" (2011)

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INTRODUCTION

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MAIN OBJECTIVES

- **<u>FIRST OBJECTIVE</u>:** Systematic study of DR methods and comparison
  - ***Generalization*** of the method used by J. Troufflard
  - Which one is the ***best*** (inflatable structures) ?

- **<u>SECOND OBJECTIVE</u>:** Contribution to the creation of a simulation tool

Currently: Tests on a pool Lack of repeatability	⇨	**Simulation tool:** Application of DR methods Parameterized mannequin and water *Tendencies*

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NUMERICAL STUDY OF DYNAMIC RELAXATION METHODS

Introduction to Dynamic Relaxation

DR method with KD: new proposals

Comparison of several DR methods

Introduction to Dynamic Relaxation

DR method with KD: new proposals

Comparison of several DR methods

Form-finding of inflatable structures: dynamic relaxation

FEM (membrane)

Implicit algorithms

Numerical instabilities (lack of stiffness, wrinkles)

SOLUTION

Explicit algorithms

- ✔ No matrix inversion
- ✔ Solution
- ✗ Stability
- ✗ Large number of time steps

DYNAMIC RELAXATION

*"The method relies on a discretized continuum in which **the mass of the structure is assumed to be concentrated at the nodes** on the surface. The system of concentrated masses **oscillates about the equilibrium position** under the influence of out-of-balance forces. With time, it **comes to rest under the influence of "damping""*** [W.J. Lewis, "Tension Structures", 2003]

<u>OBJECTIVE: Final equilibrium position of the structure for a given load</u>

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Dynamic Relaxation: damping

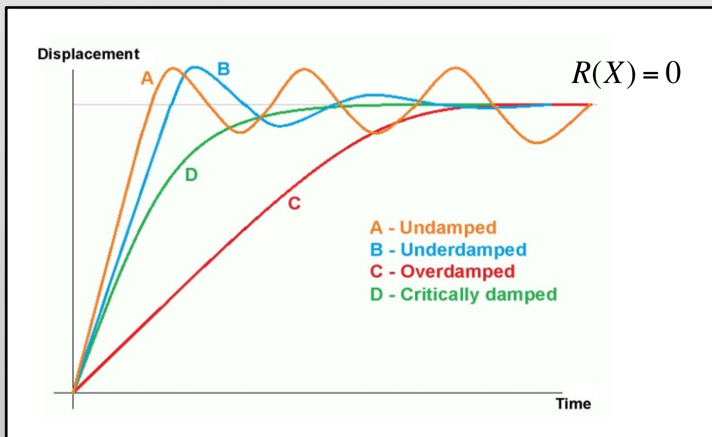
Objective:

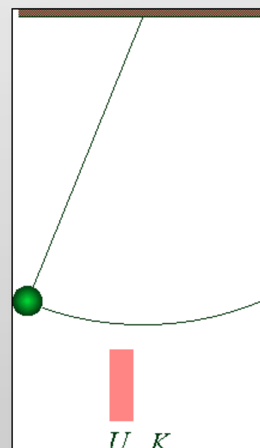
$$R(X) = 0$$

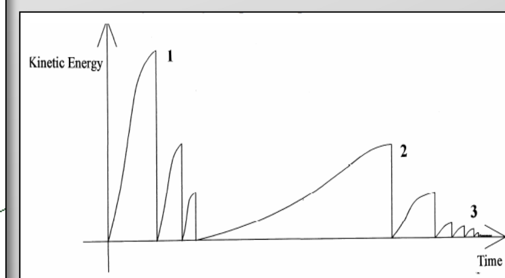
Methodology →

$$[M_i]\ddot{X}_i + [C_i]\dot{X}_i + R(X_i) = 0$$

Viscous damping [Underwood, 1983]	Kinetic damping [Barnes, 1988]
Movement damped by *introducing an artificial viscosity*	Movement damped *by resetting velocities to zero* at each kinetic energy peak







<u>Aim:</u> try to find the optimum *c* ↔ <u>Aim:</u> try to reach fast kinetic energy peaks

DR methods

DR with viscous damping → Mass matrix formulation & Damping coefficient

$$M\ddot{X} + cM\dot{X} + R(X) = 0$$

Guarantee stability and good convergence (fixed time step)

[Underwood, 1983]

General reference method: **oDR**

DR with kinetic damping → Mass matrix formulation →

$$M\ddot{X} + R(X,\dot{X}) = 0$$

[Barnes, 1988]
Cable structures

[Han-Lee, 2003]
Membrane structures

Limited to a particular element and behavior
Can we extend the method?

Contributions to DR method

- Two main contributions are made in this work:

1. Within *DR method with kinetic damping*: **Two new proposals of formulation for the mass matrix** are presented (*).
    - Objective: Extent the applicability to any kind of finite element and non-linear behaviour.

2. **Comparison of several DR methods** with viscous and kinetic damping in the case of large displacements of membrane structures (**).
    - Objective: Help deciding whether a damping method is better than the other in a particular case (membrane inflatable structures).

(*) J. Rodriguez, G. Rio, J.M. Cadou, J. Troufflard, *"Numerical study of dynamic relaxation with kinetic damping applied to inflatable fabric structures with extensions for 3D solid element and non-linear behavior"*. **Thin-Walled Structures**, vol. 49, no. 11, pp. 1468-1474 (2011).

(**) J. Rodriguez, G. Rio, J.M. Cadou, "Comparison of several dynamic relaxation methods in the case of large displacements of membrane structures" (Submitted to **Mechanics Research Communications**)

Introduction to Dynamic Relaxation

DR method with KD: new proposals

Comparison of several DR methods

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Proposal 1 (KDR1)*

DR with KD:

$$M\ddot{X} + R(X,\dot{X}) = 0$$

[Barnes, 1988] → CFD

$$m_i = \lambda \frac{\Delta t^2}{2} S_i$$

(Cable elements)

[TrouffIard, 2007]:

$$S_i = \sum_e \frac{ep}{4}\left(\frac{E}{1-\nu^2} + \sigma_x + \sigma_y + \sigma_{xy}\right)$$

New proposal, KDR1:

$$S_i = \sum_e \frac{ep}{4}\left(\alpha K + \beta\mu + \gamma\frac{I_\sigma}{3} + \frac{\theta}{2}\sigma_{mises}\right)$$

- Parameters α, β, γ and θ allow to control the influence of each part
- Extended applicability

* J. Rodriguez, G. Rio, J.M. Cadou, J. Troufflard, *"Numerical study of dynamic relaxation with kinetic damping applied to inflatable fabric structures with extensions for 3D solid element and non-linear behavior"*. **Thin-Walled Structures**, vol. 49, no. 11, pp. 1468-1474 (2011).

Proposal 2 (KDR)*

$$M\ddot{X} + R(X,\dot{X}) = 0$$

- Based on the work of [Underwood, 1983]: Gerschgorin's theorem

$$m_i = \lambda \frac{1}{2} \max_{k=1}^{3}\left(\rho_{3(i-1)+k}\right) \quad \text{where} \quad \rho_i \le \sum_j \left|K_{ij}\right|$$

At least one stiffness matrix must be calculated

Enough with the calculated mass matrix at the beginning

Maximum along 3 axes (to avoid null values)

* J. Rodriguez, G. Rio, J.M. Cadou, J. Troufflard, *"Numerical study of dynamic relaxation with kinetic damping applied to inflatable fabric structures with extensions for 3D solid element and non-linear behavior"*. **Thin-Walled Structures**, vol. 49, no. 11, pp. 1468-1474 (2011).

Parameter λ and stability

$$[M_i]\ddot{X}_i + [C_i]\dot{X}_i + R(X_i) = 0$$

Usually in DR → $\Delta t = 1$

Stability managed with [M] and [C]

Proposal 1, KDR1: $m_i = \lambda \frac{\Delta t^2}{2} S_i$

[Barnes, 1988]: Mass matrix is **fictitious**
→ λ « corrects » acting on time step

Proposal 2, KDR: $m_i = \lambda \frac{\Delta t}{2} \max_{k=1}^{3}\left(\rho_{3(i-1)+k}\right)$ $\rho_i \leq \sum_j |K_{ij}|$

[Underwood, 1983]: $m_i \geq \frac{(\Delta t)^2}{4} \sum_j |K_{ij}|$

$$\lambda \frac{1}{2} = \frac{(1)^2}{4} \Rightarrow \lambda = 0.5$$

λ adjusts the time step

Testing the new proposals

FE software

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HEREZH++ *:

- C++ **ACADEMIC** FINITE ELEMENTS SOFTWARE:
  - Implicit and explicit time schemes
  - 1D, 2D and 3D elements
  - Complex behaviors (e.g. elasto-hysteresis for shape memory alloys)
  - **Possibility of implementing and developing new ideas**

GMSH **:

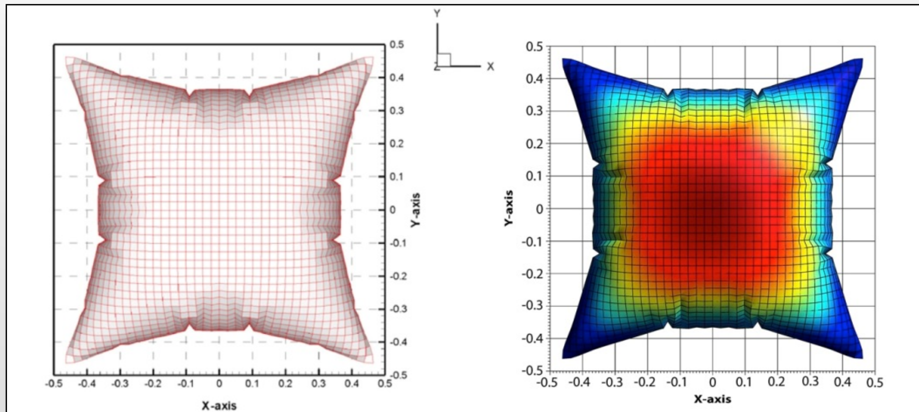
- SOFTWARE FOR MESHING AND POST-PROCESSING

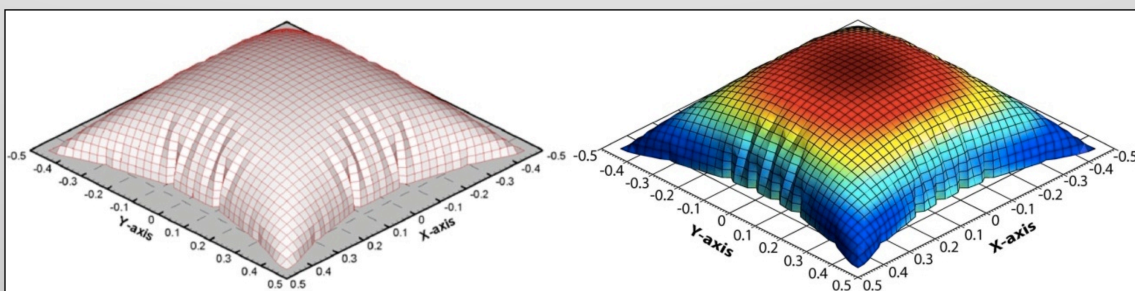
(*) G. Rio, Herezh++: FEM software for large transformations in solids. Laboratoire d'ingénierie des matériaux de Bretagne (UEB-UBS, France). APP (Agence pour la Protection des Programmes) - Certification IDDN.FR.010.0106078.000.R.P. 2006.035.20600; 2011

(**) http://geuz.org/gmsh

Validation of implementation

- Classical test [*Wu-Ting, 2008*]*: **rectangular membrane** inflation (250x250mm). Validation results:

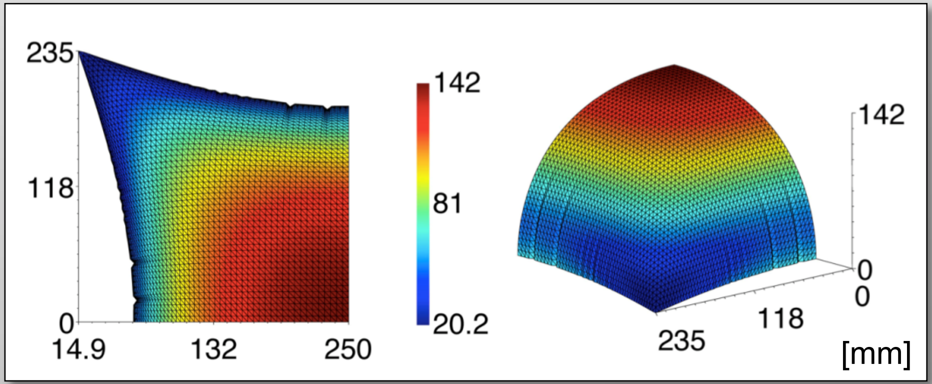




* T. Wu and E. Ting, "Large deflection analysis of 3D membrane structures by a 4-node quadrilateral intrinsic element". Thin-Walled Structures, vol. 46, no. 3, pp. 261-275 (2008).

Case studies: 1/8 of an air bag (I)

- The calculation parameters used in Herezh++ were:
  - **Convergence criterion**: Same than a static case (balance of generalized internal and external forces). Precision: 10^{-3}
  - In the case of KDR1: α=β= 0.9 and γ=θ= 1
  - **Material properties**: technic textile employed in lifejackets (TEXTANE)
    - *Young modulus*: 125 MPa ; *Poisson's ratio*: 0,41
    - *Thickness*: 0,27mm ; *Density*: 10e-9 ton/mm3
  - **Load**: P=0.015 MPa (150 g, order of magnitude of inflatable lifejackets)



Case studies: 1/8 of an air bag (and II)

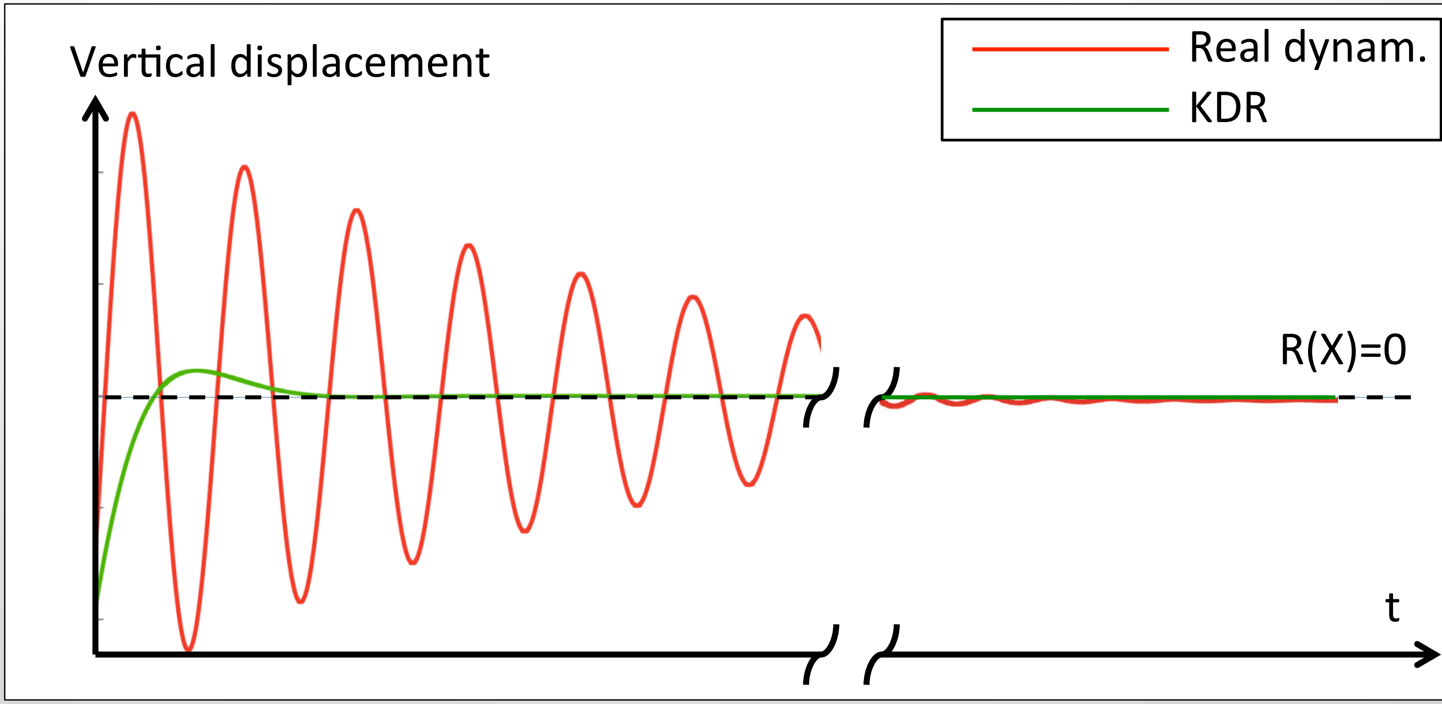
- Number of iterations and calculation times*:

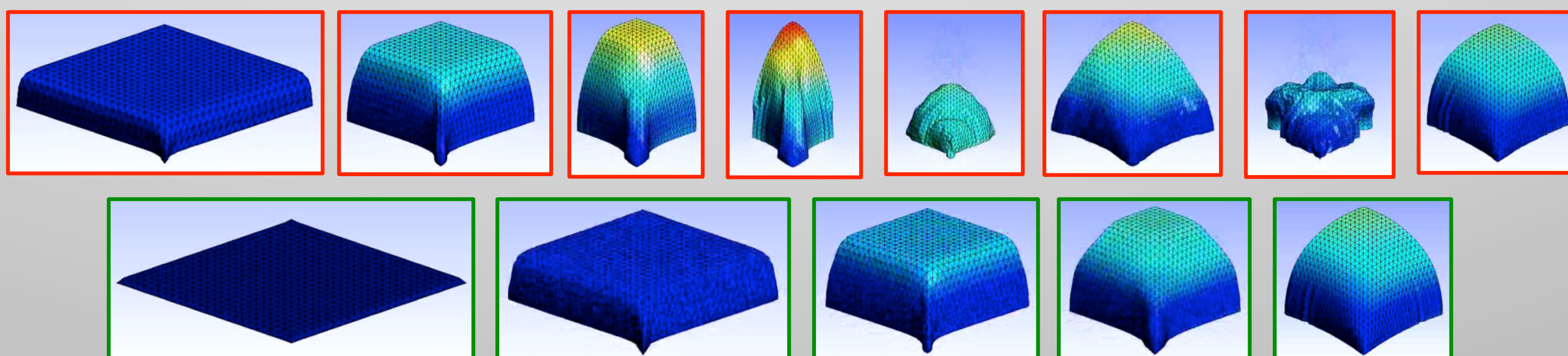
Mesh	Number of iterations and calculation times (s)					
	Proposal 1 (KDR1)			Proposal 2 (KDR)		
	λ	Iterations	Time (s)	λ	Iterations	Time (s)
TL1 (2028 dof)	10	546	14.1	0.6	565	13.8
TL2 (7803 dof)	10	923	101.5	0.7	1081	111.8
TQ1 (7803 dof)	13	1128	118.4	0.6	1185	119.8
TQ2 (30603 dof)	14	2158	943.3	0.7	2358	970.1
RL1 (2028 dof)	6	422	23.7	0.5	423	22.6
RL2 (7803 dof)	6	671	150.4	0.6	841	183.9
RQ1 (7803 dof)	10	1015	159.8	0.5	970	148.8
RQ2 (30603 dof)	9	1688	1085.6	0.5	1889	1552.1

T: Triangular elements	**R:** Rectangular elements
L: Linear interpolation	**Q:** Quadratic interpolation
1: 25x25 elements mesh	**2:** 50x50 elements mesh

* Calculations made on an Apple computer (Processor 2x2.93 GHz Quad-Core Intel Xeon, Memory: 16 GB 1066 MHz DDR3) with just one processor

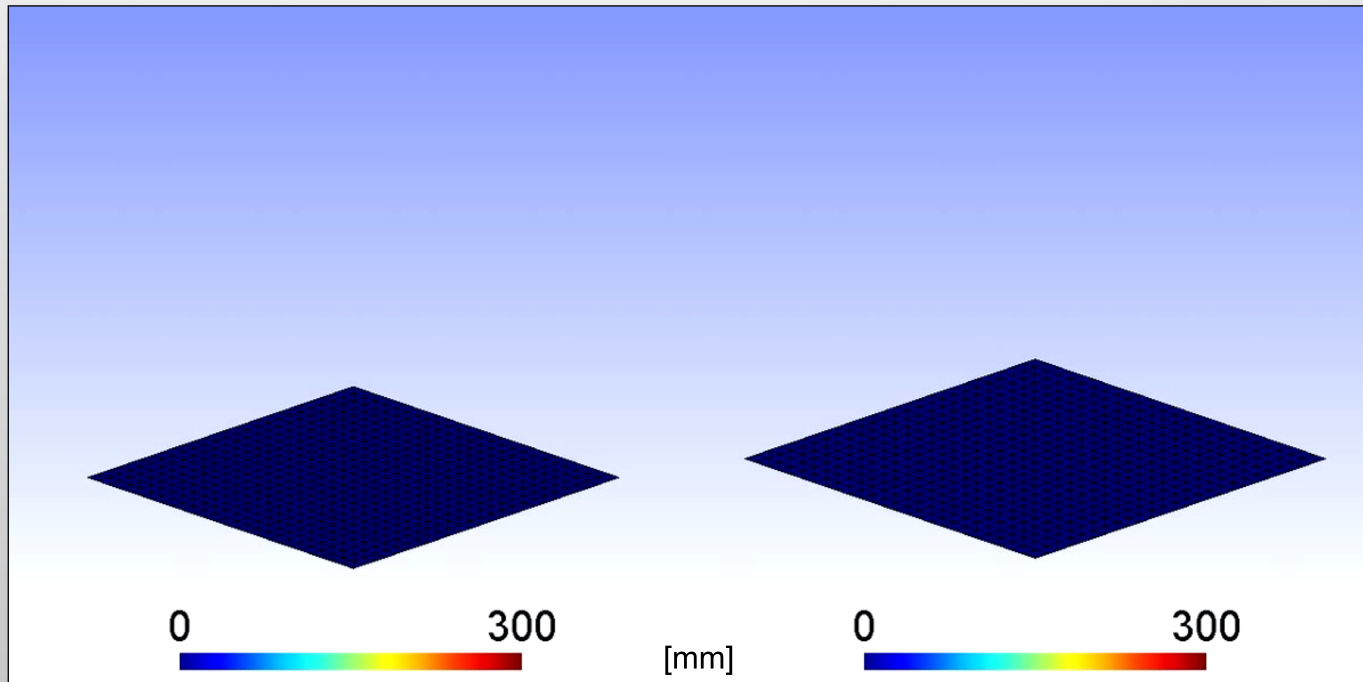
Comparison real dynamics vs KDR (I)



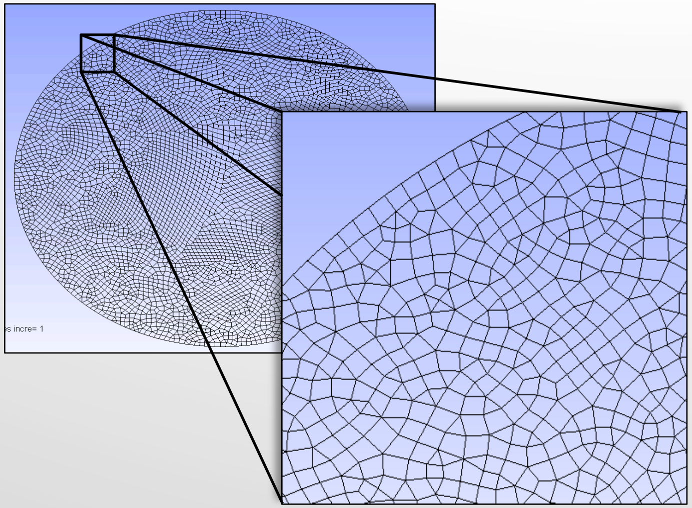


Comparison real dynamics vs KDR (and II)

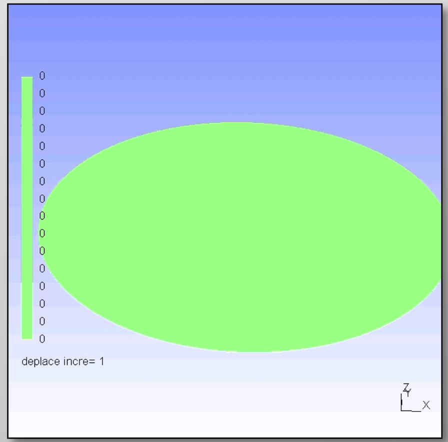
TL1	
Real dynamics Low artificial damping	KDR (Proposal 2)



Case studies: circular mesh



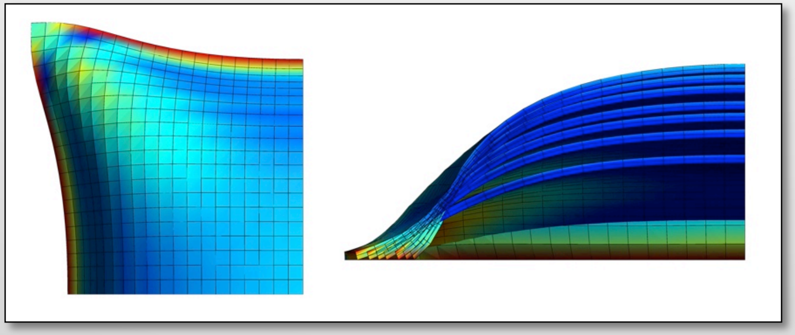
Inflation of a circular mesh composed of a mix of triangular and rectangular elements

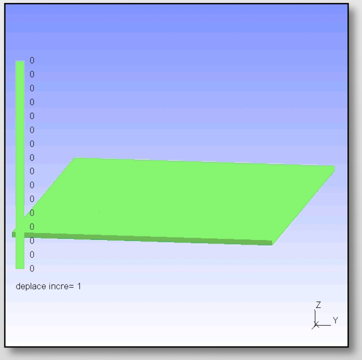


Mesh	Calculation times (s) and number of iterations					
	Proposal 1 (KDR1)			Proposal 2 (KDR)		
	λ	Iterations	Time (s)	λ	Iterations	Time (s)
17856 dof	10	2096	1068.3	0.4	1322	616.745

Case studies: 3D elems., complex law, incremental loading

- **3D quadratic hexahedral** finite elements
- Material: Vitton elastomer* (assembly of an additive **hyperelastic** stress and stress **hysteresis**).
- **Incremental** calculation (10 increments)





Mesh	λ	Incr. 1	Incr. 2	Incr. 3	Incr. 4	Incr. 5	Incr. 6	Incr. 7	Incr. 8	Incr. 9	Incr. 10
3969	3	32020	8470	6540	4730	2830	2910	970	2590	910	690

* Vandenbroucke A, Laurent H, Hocine N, Rio G. A hyperelasto-visco-hysteresis model for an elastomeric behavior: Experimental and numerical investigations. Computational Materials Science 2010;48:495-503.

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Conclusion for new proposals

1 type of finite element	→	**Any** type of element
1 material behaviour	→	**Generalized** to a more global behaviour
1 loading type	→	Possibility of **incremental** calculations

Introduction to Dynamic Relaxation

DR method with KD: new proposals

Comparison of several DR methods

Comparison of different DR methods

DR with kinetic damping → Successfully generalized and validated → KDR1 / KDR

DR with kinetic damping now works for a general case
Is it better than other existing DR methods?

DR with viscous damping → Mass matrix formulation & Damping coefficient

Different proposals of DR with VD implemented

DR with viscous damping: implemented formulations

- **Mass matrix formulation:**

Based on [Underwood, 1983]

$$m_i = \lambda \frac{1}{2} \max_{k=1}^{3} \left(\rho_{3(i-1)+k} \right)$$

Based on [Rezaiee-Pajand, 2011]

$$m_{ii} = max \left[\frac{(\Delta t)^2}{2} K_{ii}, \frac{(\Delta t)^2}{4} \sum_j |K_{ij}| \right]$$

- **Damping coefficient:**

  - [Underwood, 1983]: $c = 2\omega_0$
  - [Rezaiee-Pajand, 2011]: $c = \sqrt{4\omega_0^2 - \omega_0^4}$
  - [Qiang, 1988]: $c = 2\sqrt{\frac{\omega_0}{1+\omega_0}}$

oDR

mDR

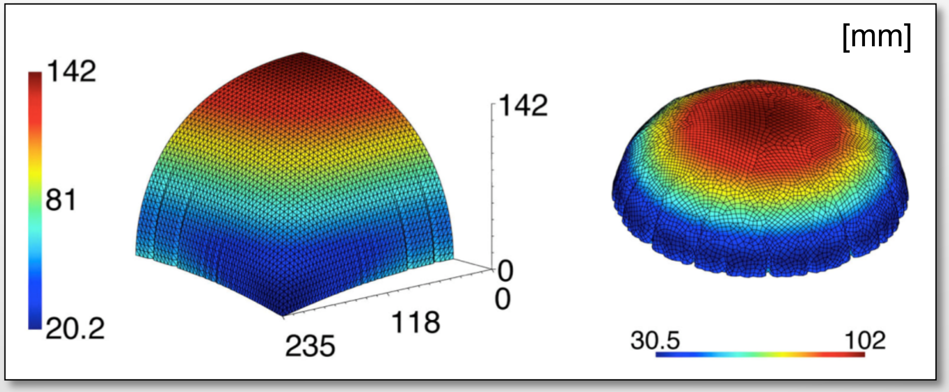
mdDR

uqDR

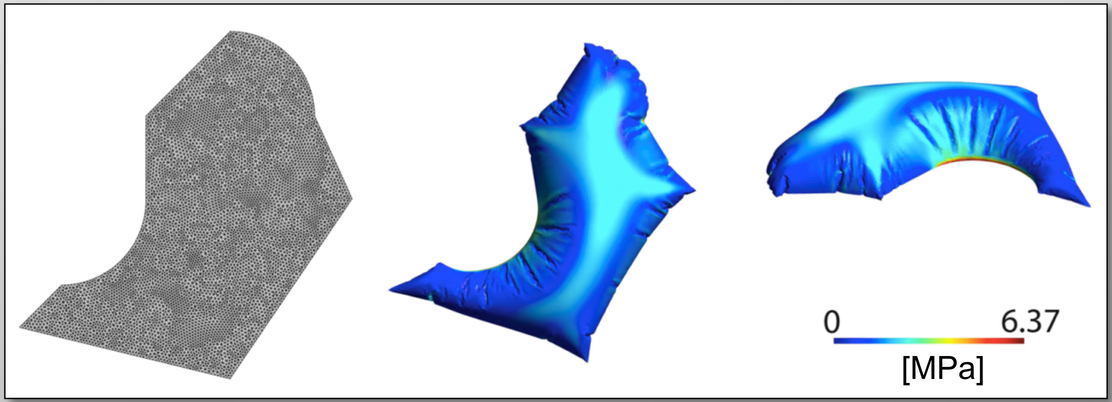
pqDR

Case studies

- Inflation of squared and circular air bags (same properties than previously)

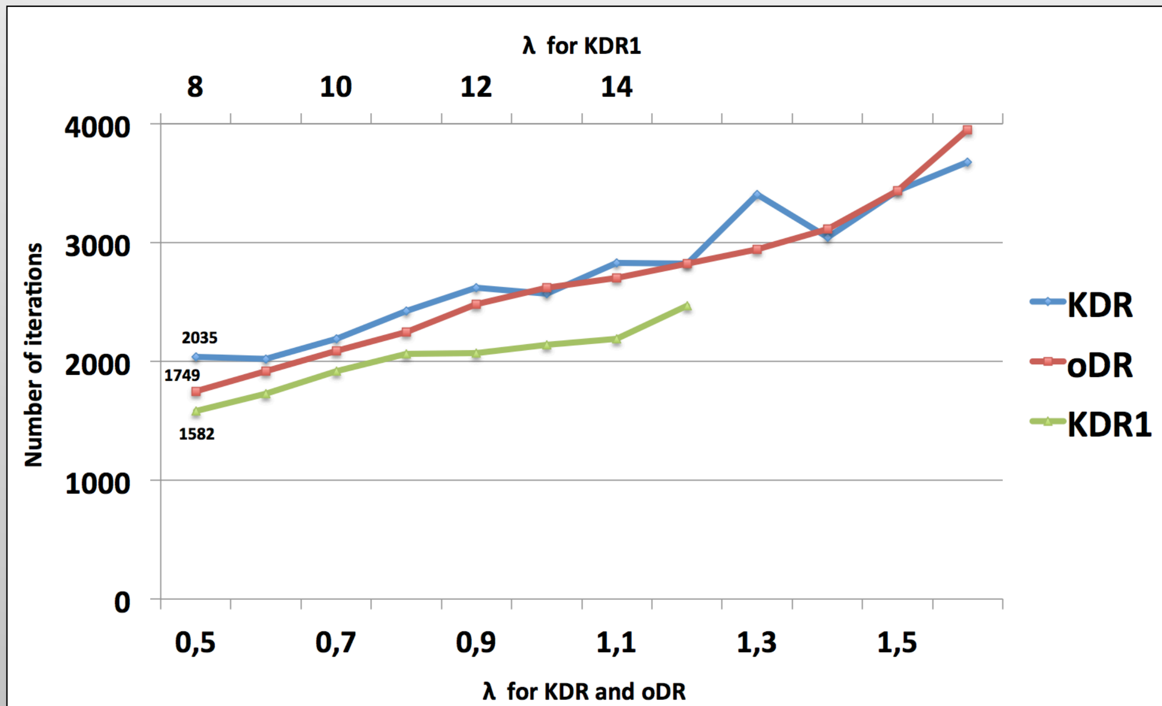


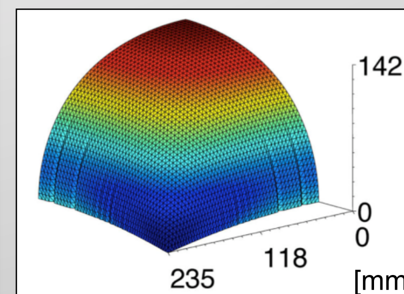
- Inflation of a random non-smooth shape



Case studies: some results – RQ2

	DR method \ λ =	5	6	7	8	9	10	11	12	13	14	15	
RQ2	KDR1	div	div	div	1582	1729	1915	2066	2068	2139	2189	2467	
	DR method \ λ =	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	2
	KDR	2035	2021	2189	2425	2622	2572	2829	2822	3403	3047	3436	3677
	oDR, mDR, mdDR	1749	1918	2088	2249	2478	2620	2705	2825	2940	3114	3436	3948
	uqDR, pqDR	div	div	div	>15k	>15k	>15k	>15k	>15k	>15k	>15k	>15k	>15k

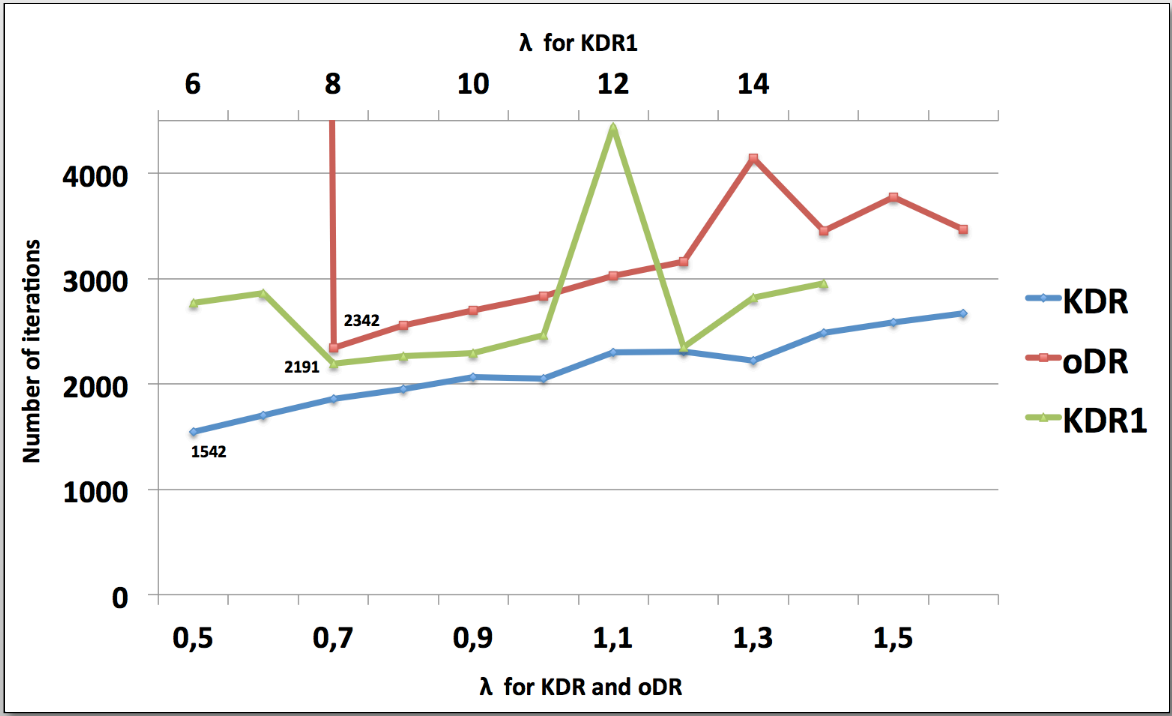


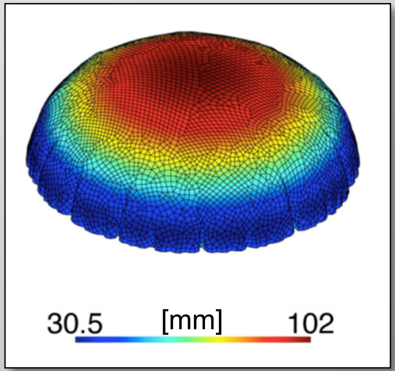


Case studies: some results – Circular mesh

CIR	DR method \ λ =	5	6	7	8	9	10	11	12	13	14	15
	KDR1	div	2767	2860	2191	2262	2291	2466	4445	2353	2819	2956

CIR	DR method \ λ =	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	2
	KDR	**1542**	1703	1857	1953	2068	2053	2300	2306	2220	2487	2585	2673
	oDR, mDR, mdDR	div	div	2342	2553	2700	2835	3023	3163	4144	3451	3772	3468
	uqDR, pqDR	div	div	div	11105	12105	13070	14012	14936	13720	14490	>15k	>15k





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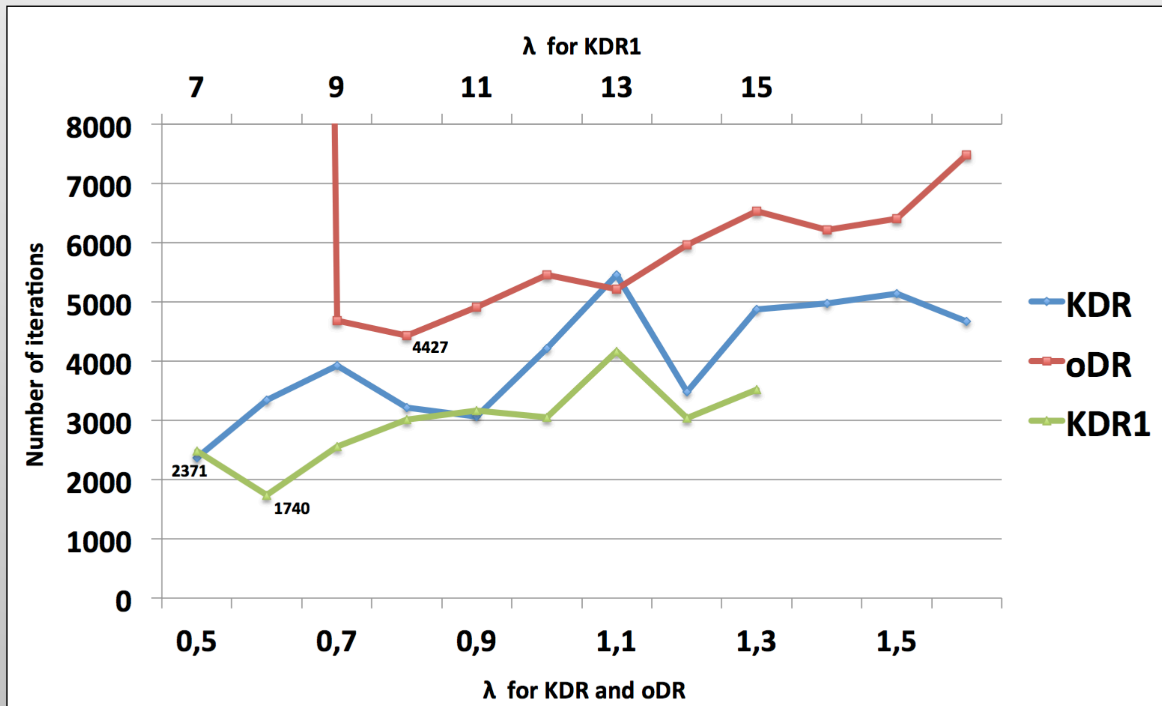
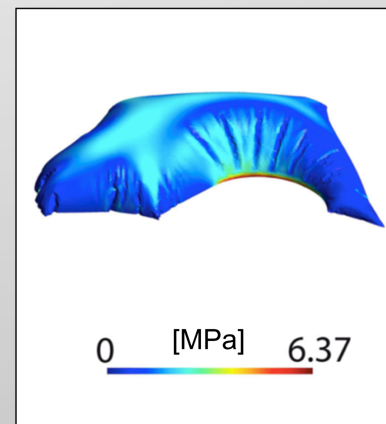
Case studies: some results – Benchmark

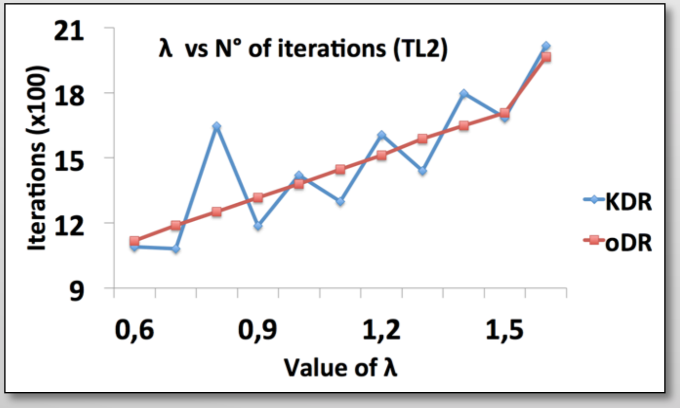
	DR method \ λ =	5	6	7	8	9	10	11	12	13	14	15	
BEN	KDR1	div	div	2481	**1740**	2556	3010	3164	3049	4170	3035	3514	
	DR method \ λ =	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	2
	KDR	2371	3338	3922	3212	3062	4212	5449	3482	4875	4978	5134	4675
	oDR, mDR, mdDR	div	div	4685	4427	4911	5458	5217	5962	6535	6208	6409	7483
	uqDR, pqDR	div	div	div	>15k	>15k	>15k	>15k	>15k	>15k	>15k	>15k	>15k

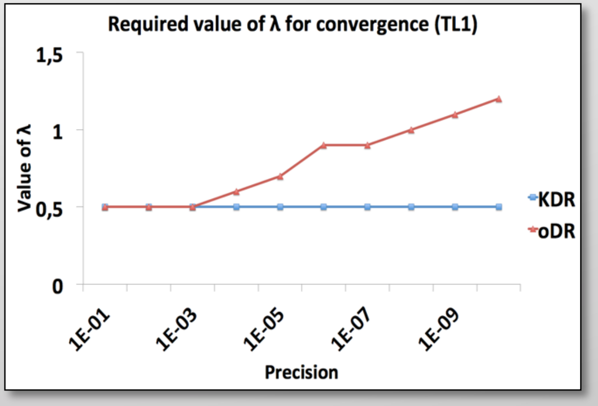




Comparison: main conclusions

- DR with VD and KD → Similar
- Importance of damping coefficient, 'c'
- Underwood $\equiv$ Rezaiee-Pajand
- Importance of λ





- DR with KD appears to be more efficient for complex meshes (non-smooth) or very unstable situations (incremental calculations)

3

CONTRIBUTION TO THE MODELLING OF INFLATABLE LIFEJACKETS

3D optical measurement

Creation of a human body model

Inflatable lifejackets and contact mechanics

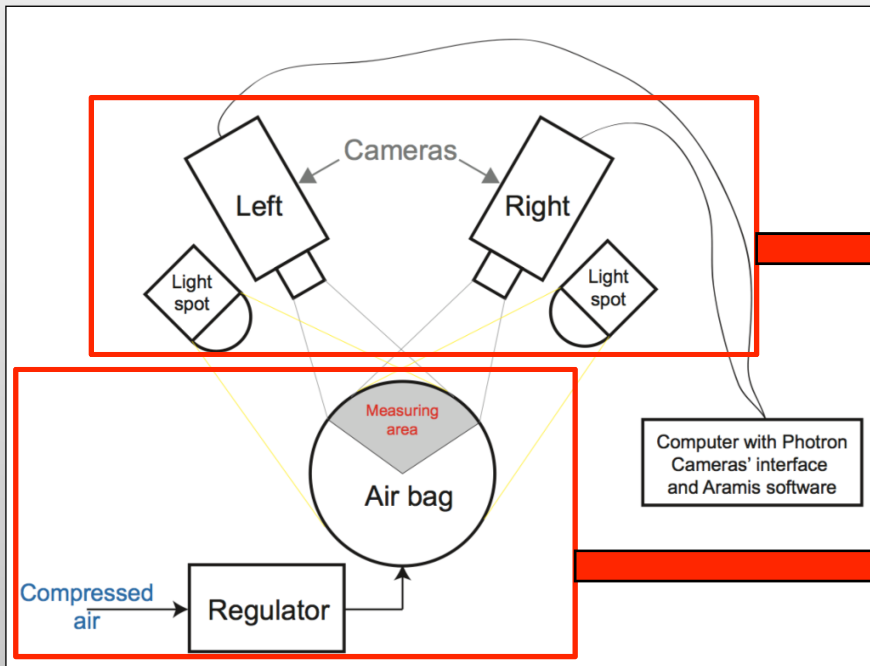
3D optical measurement

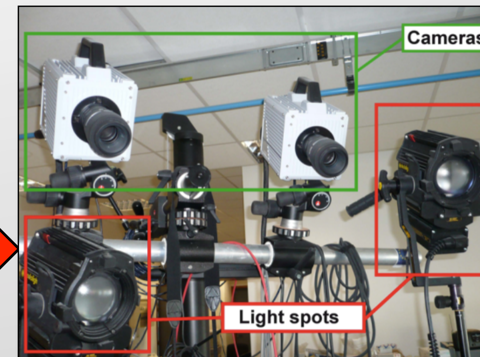
Creation of a human body model

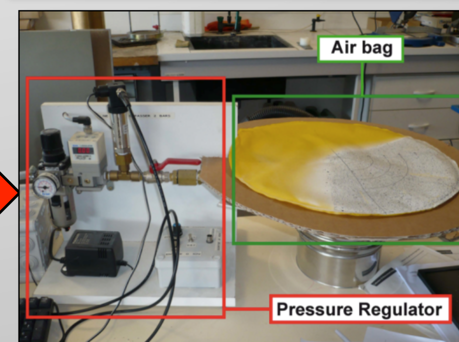
Inflatable lifejackets and contact mechanics

Objective and setup

DR methods allow to simulate inflatable structures → **How close are we to reality ?**

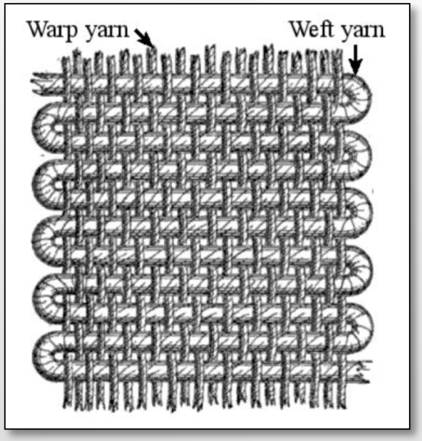


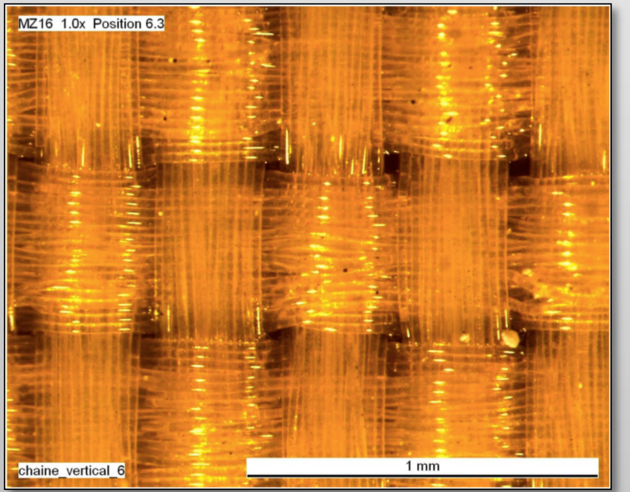


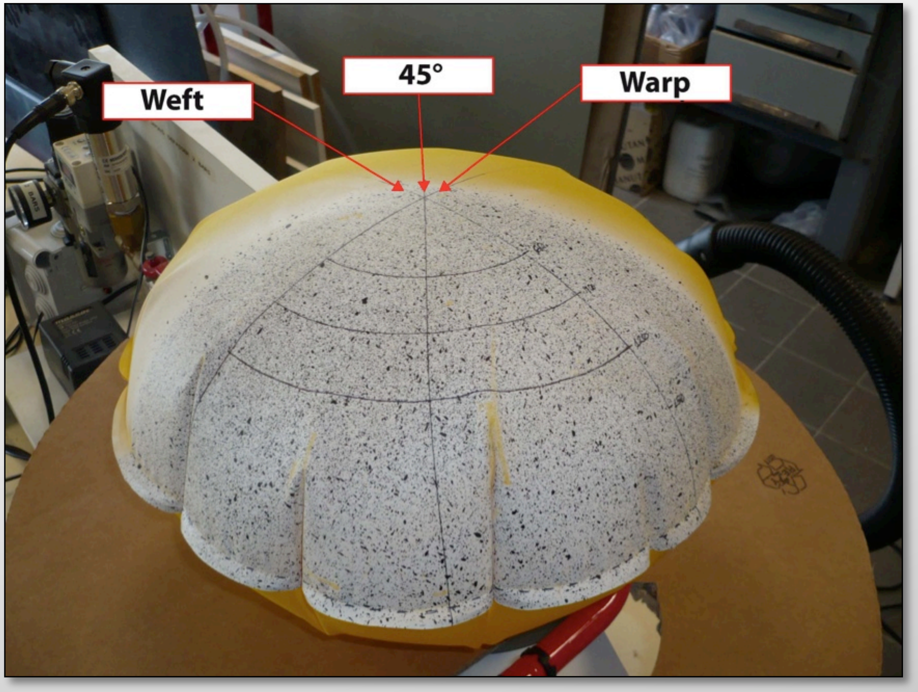


Sample preparation

- Material: technic textile → fabric weaving

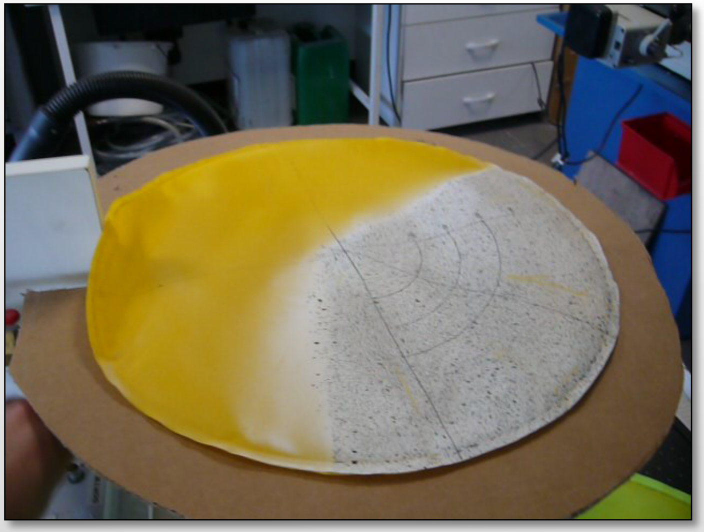


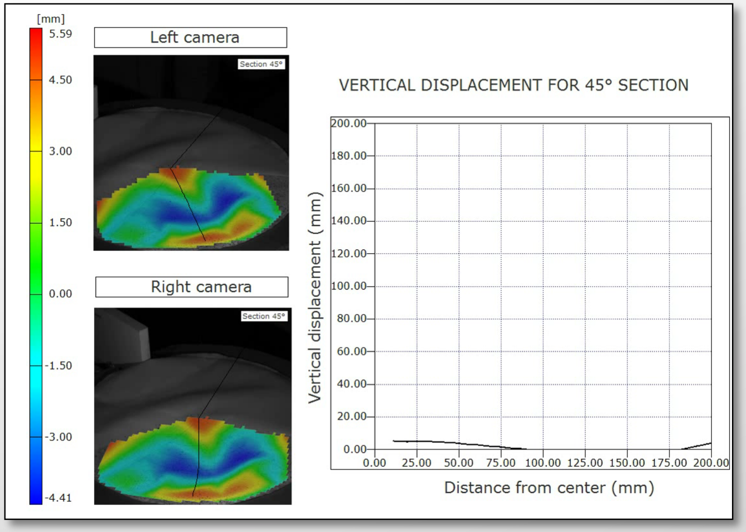




Small sollicitations → Isotropic ?

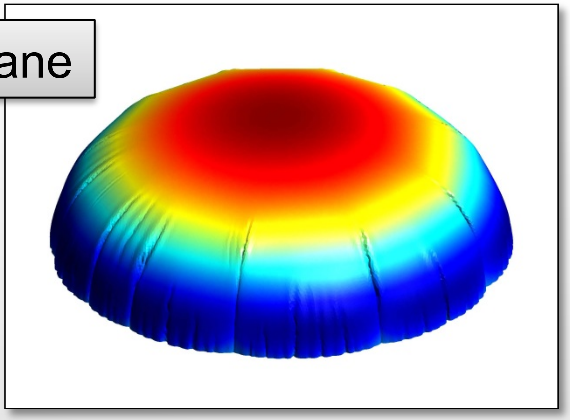
Measuring

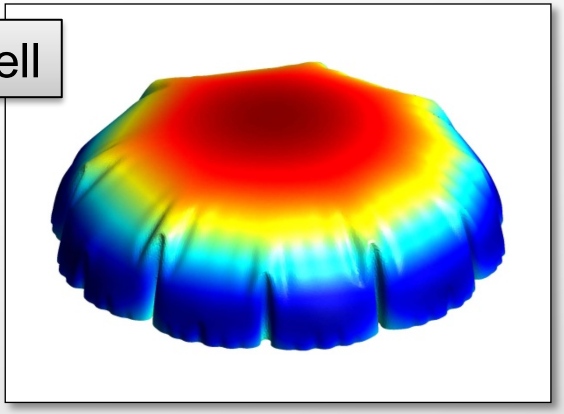




- **Difficulties:** Unable to fix a global frame: rigid body motion, wrinkles,…
- **EXPLOITABLE**: Global displacements and general allure

Numerical simulation: Shell elements*





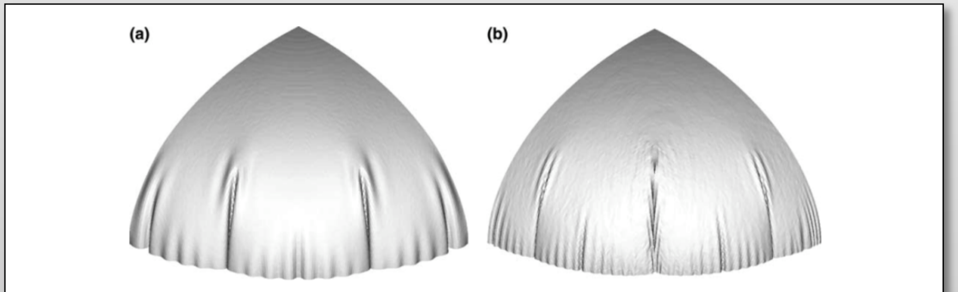
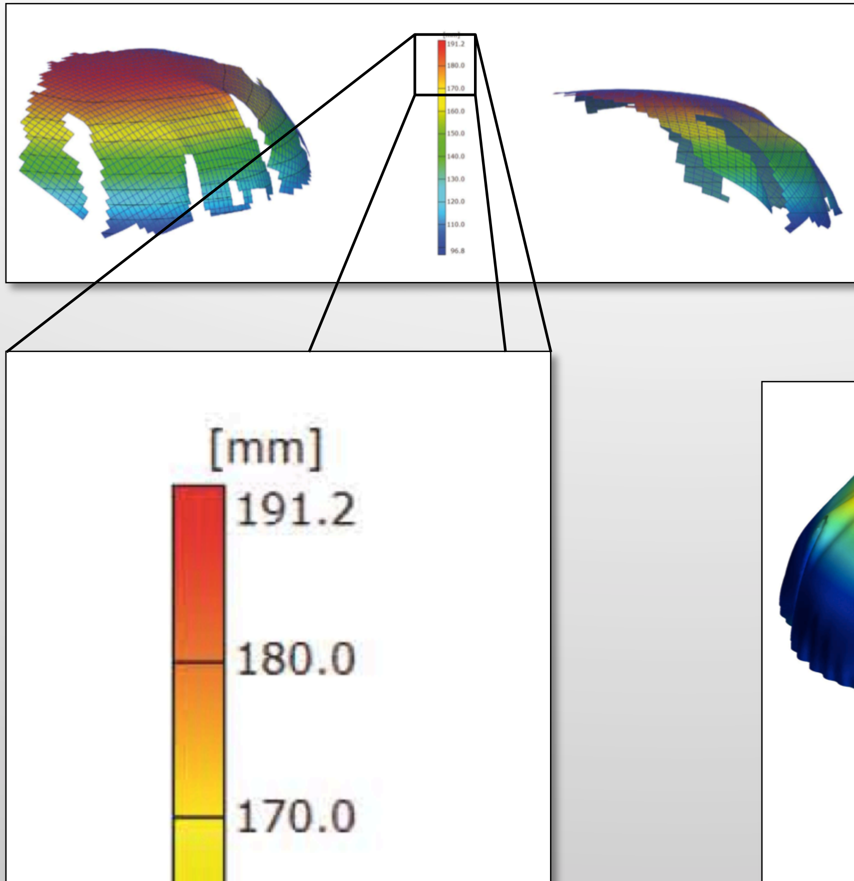


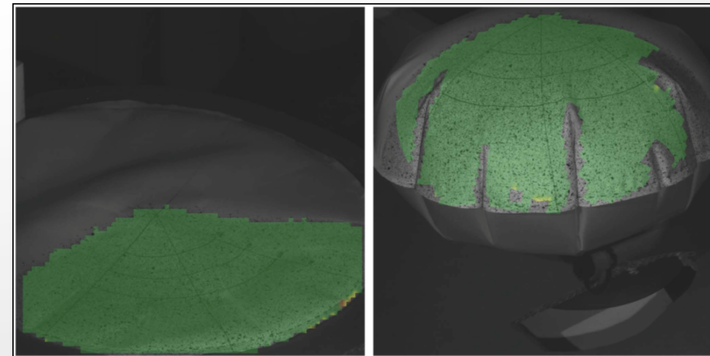
Fig. 19. Inflation of a circular airbag. Deformed configurations for final pressure: (a) bending formulation; (b) membrane formulation.

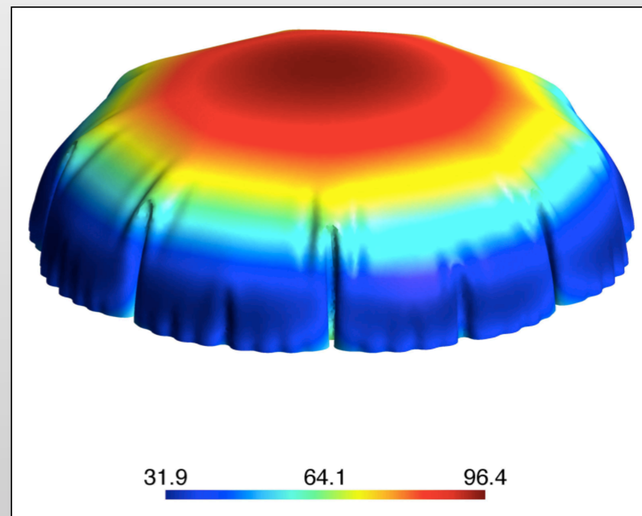
E. Oñate and F. Flores, *“Advances in the formulation of the rotation-free basic shell triangle*”. Computer Methods in Applied Mechanics and Engineering, vol. 194, no. 21-24, pp. 2406-2443 (2005)

* H. Laurent and G. Rio, “Formulation of a thin shell finite element with continuity c and convected material frame notion”. Computational Mechanics, vol. 27, no. 3, pp. 218-232 (2001). ISSN 0178-7675.

Comparison (I)



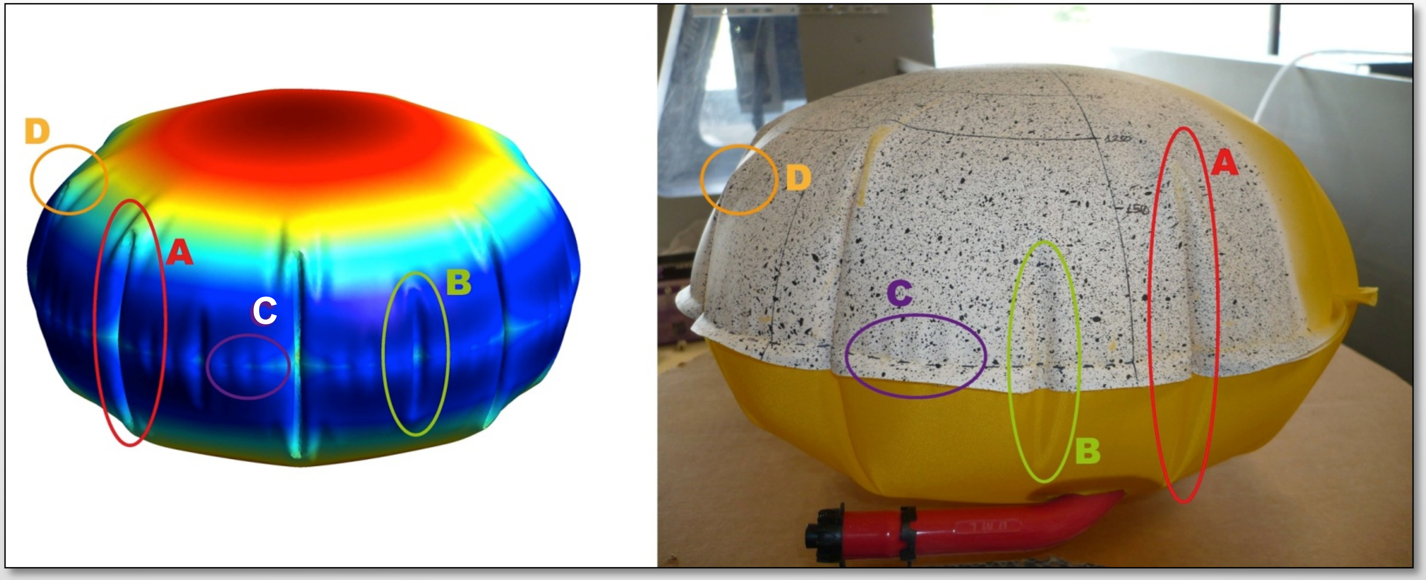


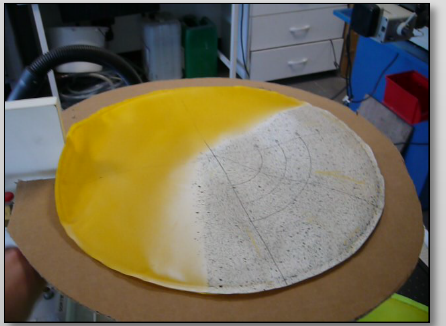


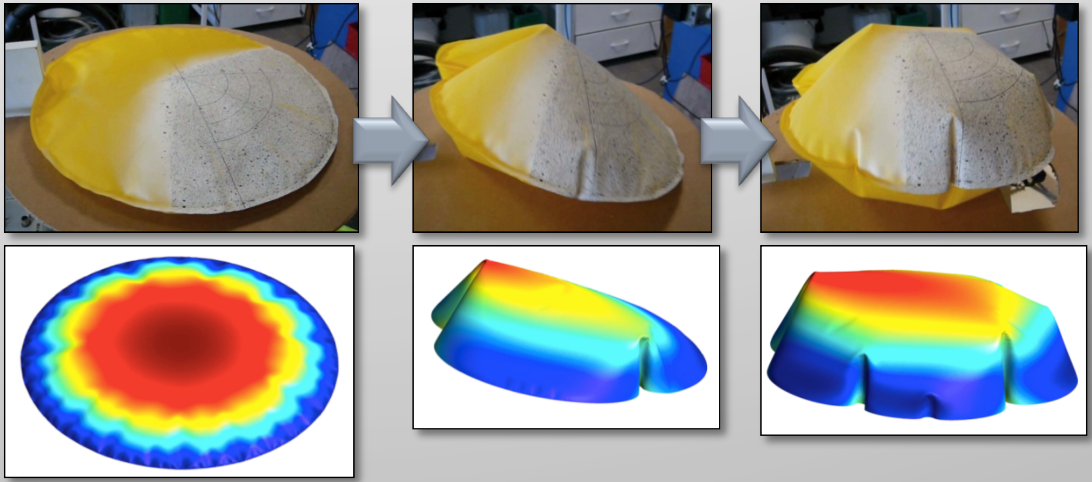
191.2 mm

96.4 x 2 = 192.8 mm

Comparison (and II)







3

CONTRIBUTION TO THE MODELLING OF INFLATABLE LIFEJACKETS

3D optical measurement

Creation of a human body model

Inflatable lifejackets and contact mechanics

Objective

Aim: To create a **parameterized model** of a human body that will serve as a **support** to obtain its **interaction with an inflatable lifejacket**

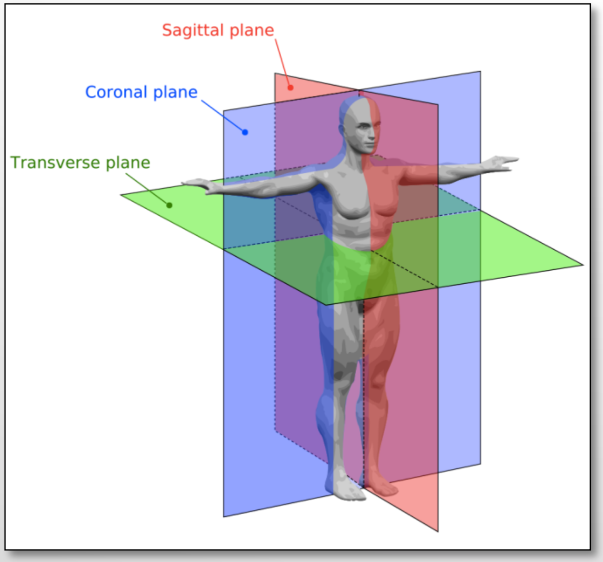
WHAT THIS IS ABOUT:

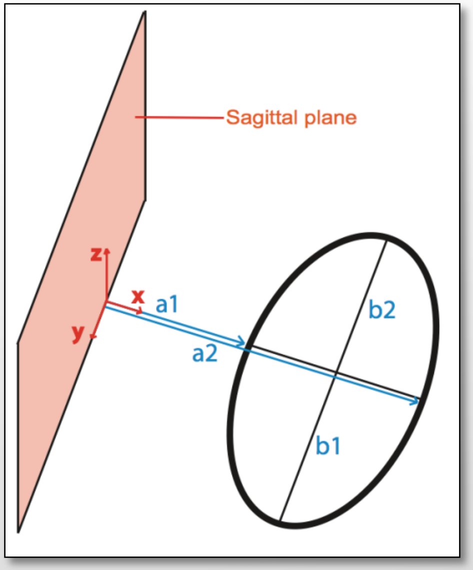
- Human-shaped FE model
- Fully parameterized (any human morphology)
- Amount of elements as small as possible

WHAT THIS IS **NOT** ABOUT:

- Human model with a precise and very realistic allure
- Precise modelling of all body parts and/or skeleton and internal organs
- Study of kinematics

Methodology

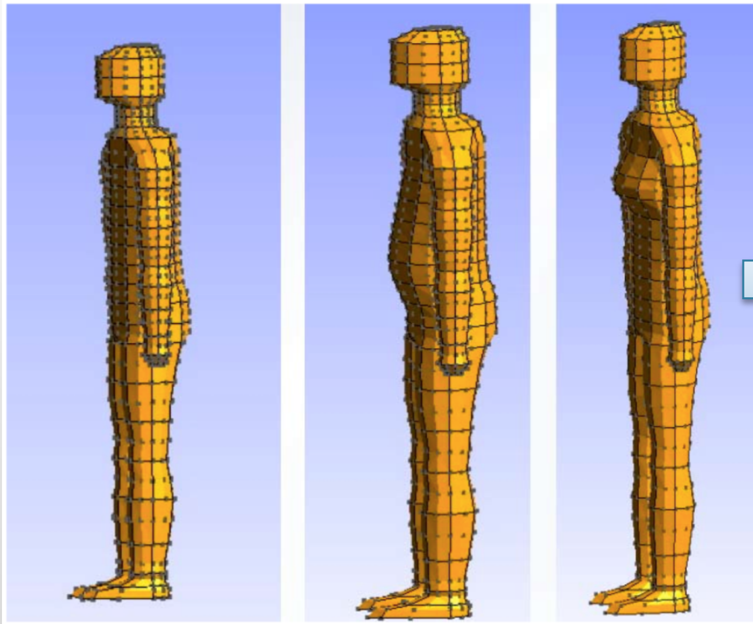




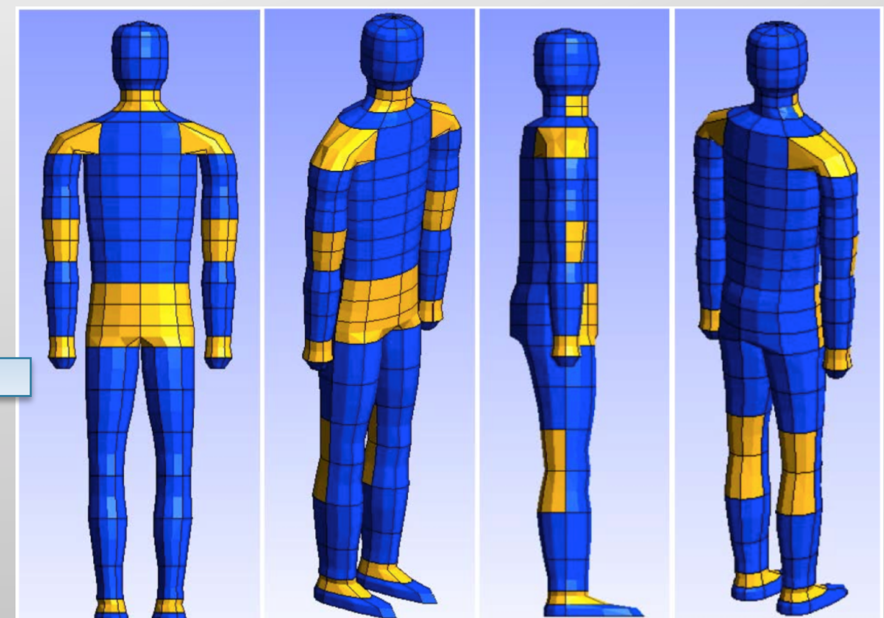
[Troufflard, 2004]

- Mesh in Gmsh format
- Mesh coded and generated in C++
- 156 Quadratic Hexahedra (27 nodes)
- Eventually linear hexahedral elements after transformation with Gmsh

Modelled mannequin



Virtually any shape
5 parameters to define



Possibility of defining the joints' behaviour separately

3D optical measurement

Creation of a human body model

Inflatable lifejackets and contact mechanics

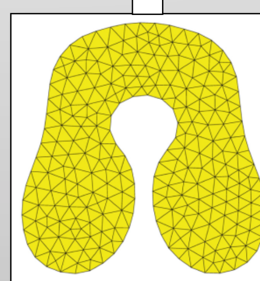
Industrial application of DR methods

Difficulties:

- Complex shape
- Large displacements
- Short time
- (Contact with the person)

Provided profile → Mesh generation → Numerical simulation (DR)

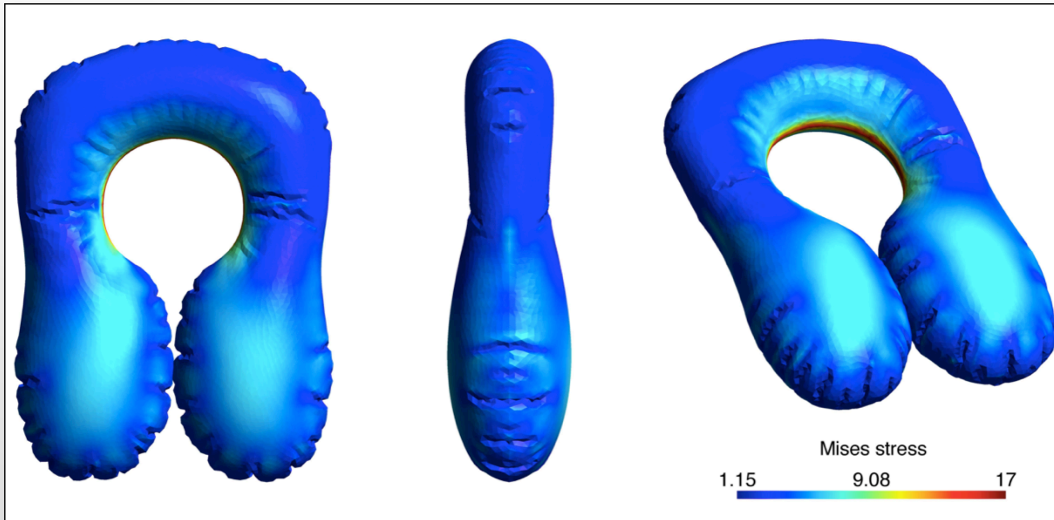
PLASTIMO



Perl [Troufflard]

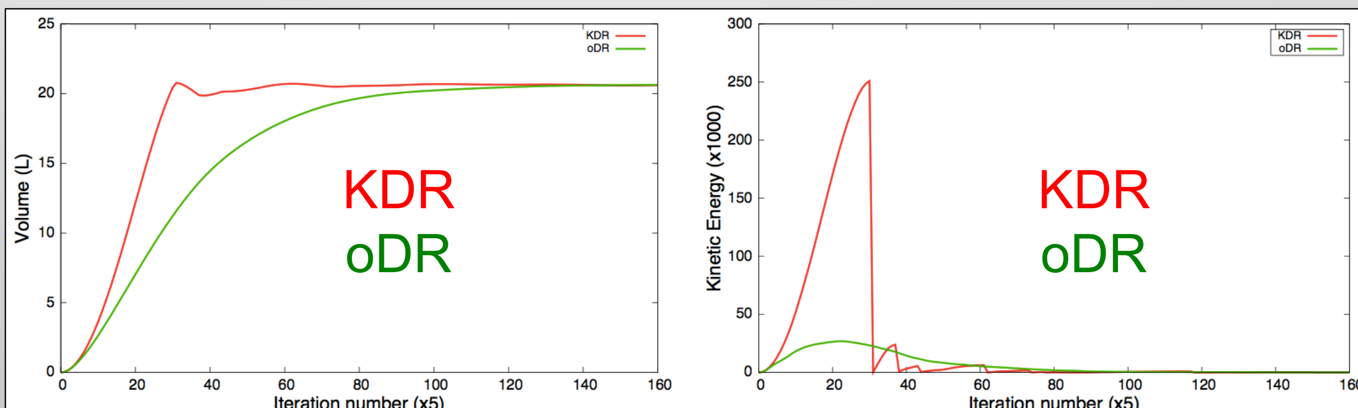
Herezh++
Gmsh

Numerical simulation



Calculation parameters:

- E = 125 MPa
- ν = 0.41
- ρ = 10^{-9} ton/mm^3
- Thickness = 0.27 mm
- Load: P = 0.015 Mpa
- Dynamic Relaxation
- Precision 10^{-3}



30 000 dof; ~5 min calculation (2.93 GHz, 16 GB RAM)

Lifejacket-mannequin interaction

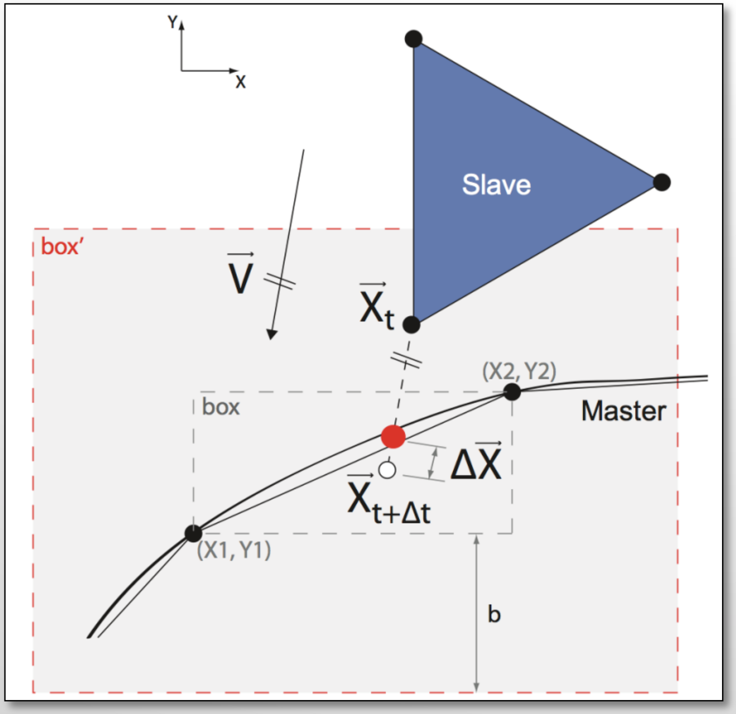
All the presented DR methods can be applied to the simulation of inflation of a lifejacket

NEXT STEP

Can we use DR to study the interaction lifejacket-mannequin?

CONTACT MECHANICS

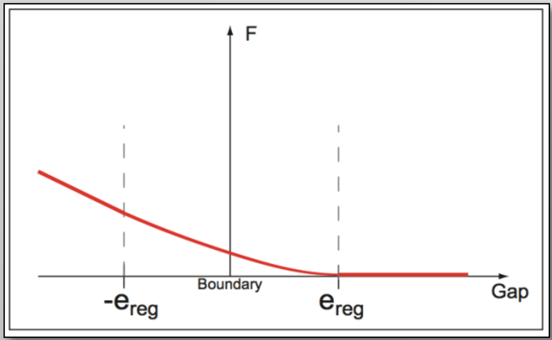
How contact is implemented in Herezh++



- **Penalty method**:

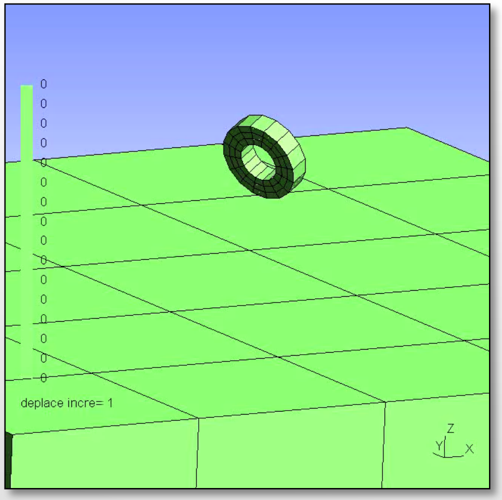
$$\vec{F} = -\alpha \cdot \beta \cdot \Delta x$$

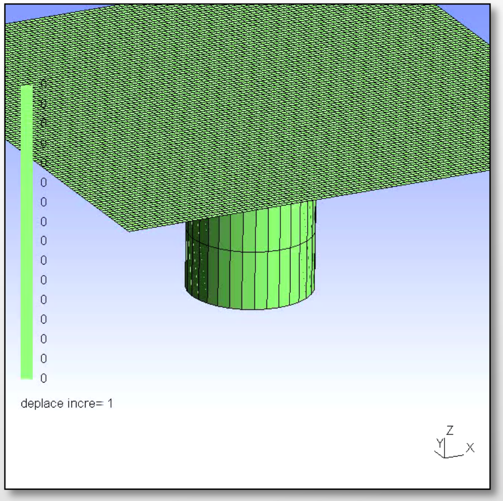
- (αβ) is the penalty parameter
  - α is accesible to user
  - β depends on behavior of contacting bodies (harder of softer)

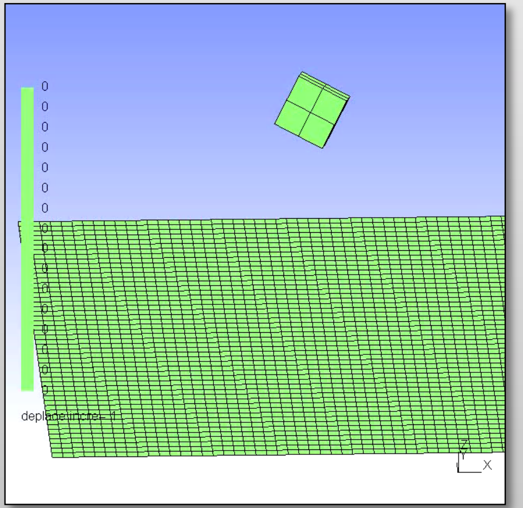


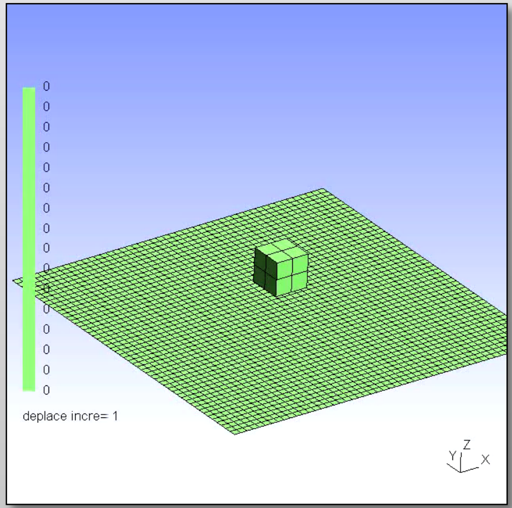
- When $e > e_{reg}$ ➔ $\beta = 0$
- When $-e_{reg} \leq e \leq e_{reg}$ ➔ $\beta = \beta_{base}(e-e_{reg})^2/e_{reg}^2$
- When $e < -e_{reg}$ ➔ $\beta = \beta_{base}$

Validation tests (I)









Validation tests (and II): Dynamic Relaxation

Introduction

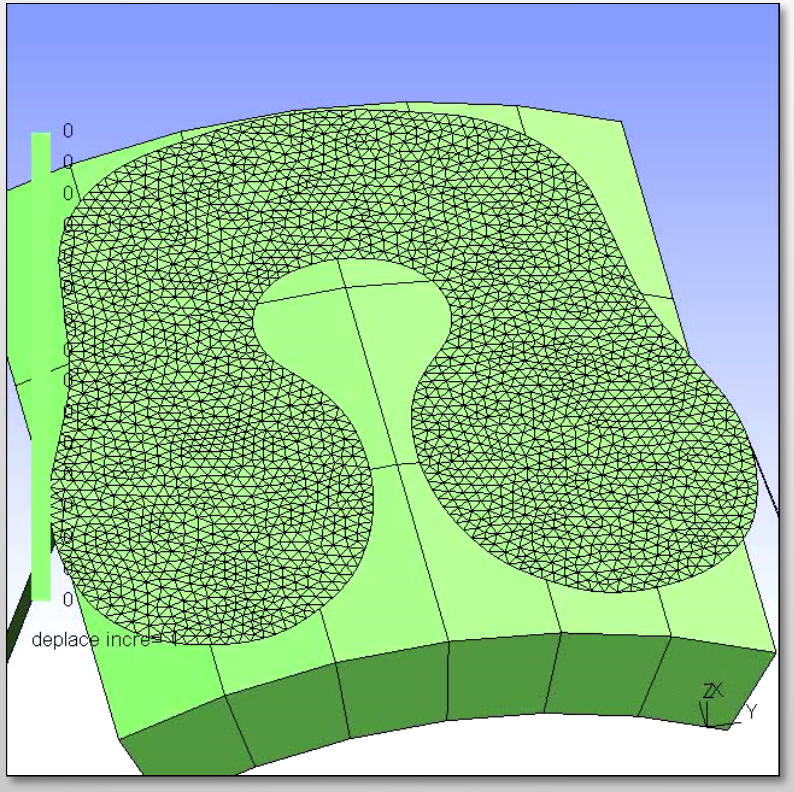
Outline

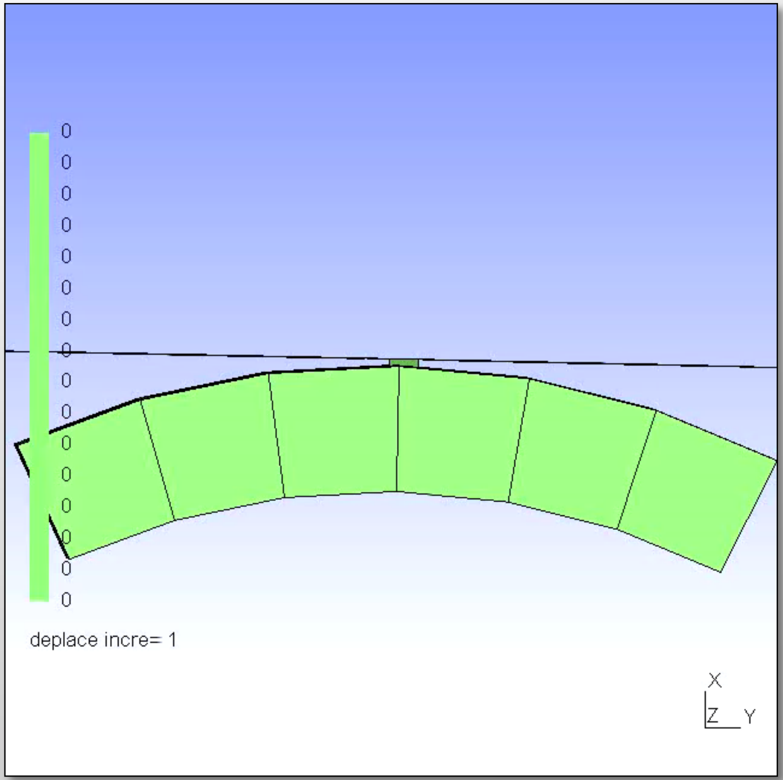
Dynamic
Relaxation

Application
to lifejackets

Conclusions
Perspectives

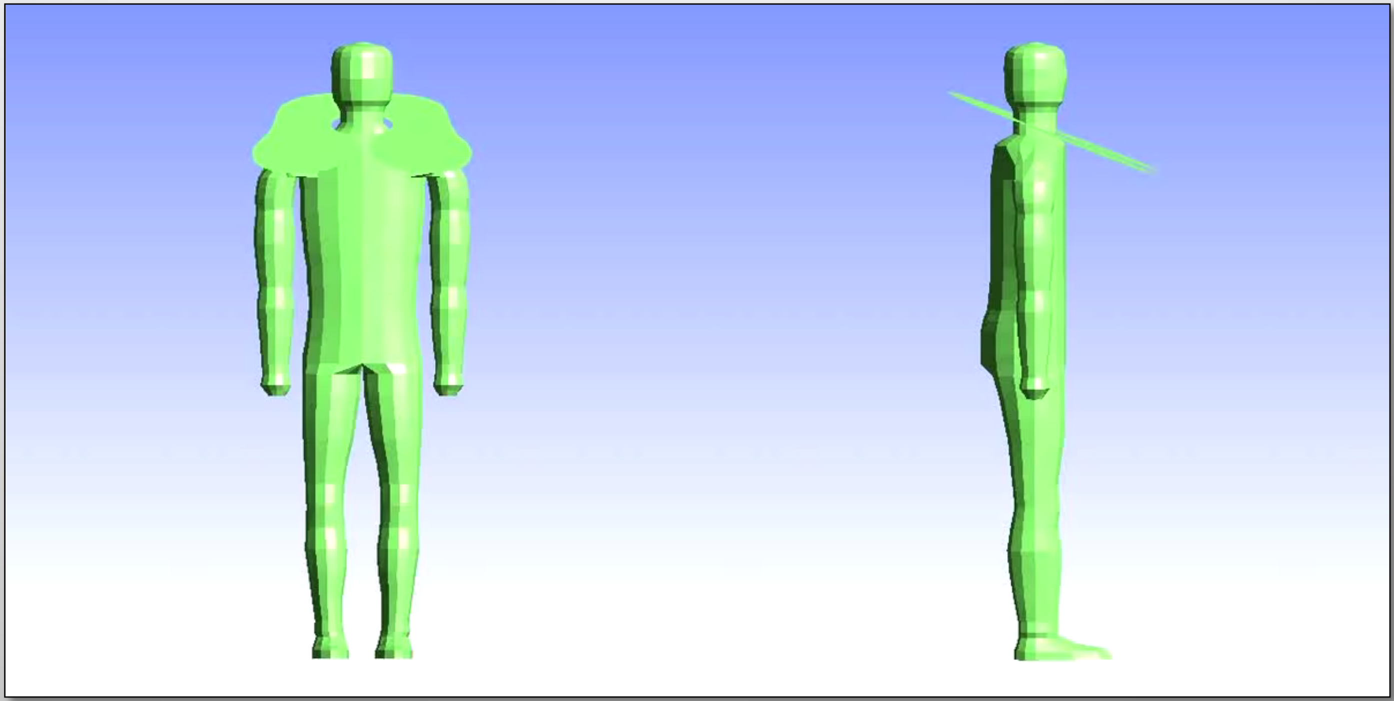
Lifejacket attached to a rigid cylindrical surface (**Dynamic Relaxation**):



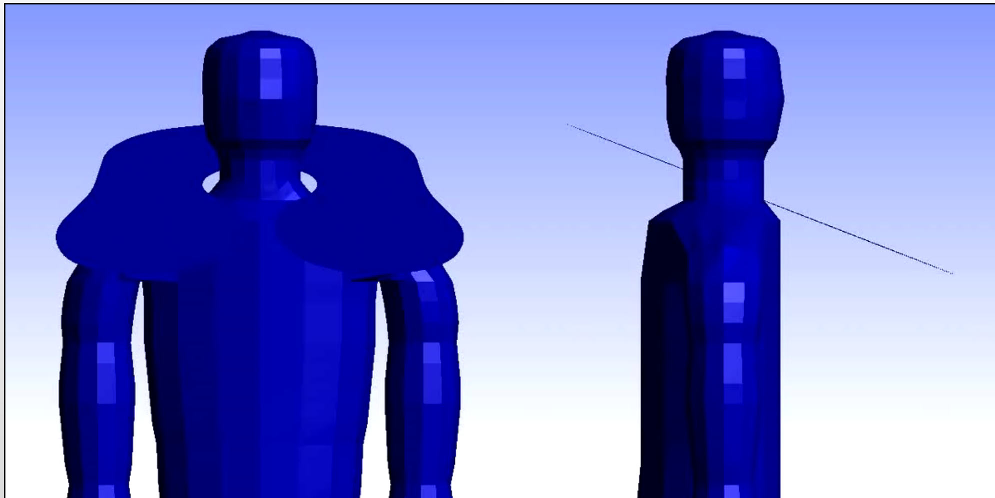


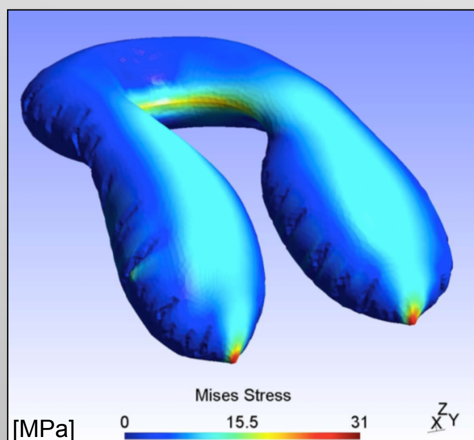
Mannequin wearing the lifejacket

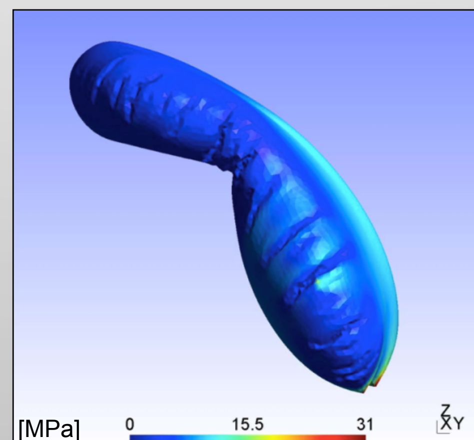
- Simulation in 3 steps:
  1) Lifejacket falls freely on the mannequin until a still position
  2) Lifejacket is virtually attached to the body (fixing some nodes)
  3) Lifejacket is inflated by applying an internal pressure

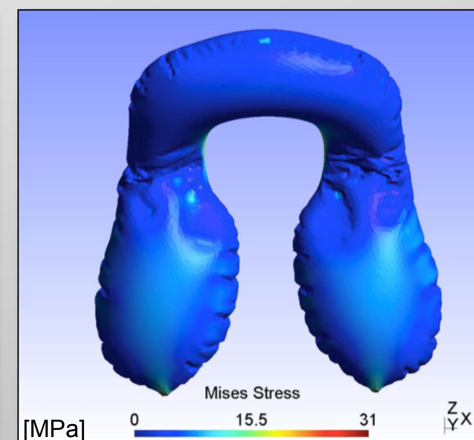


Final result (I)



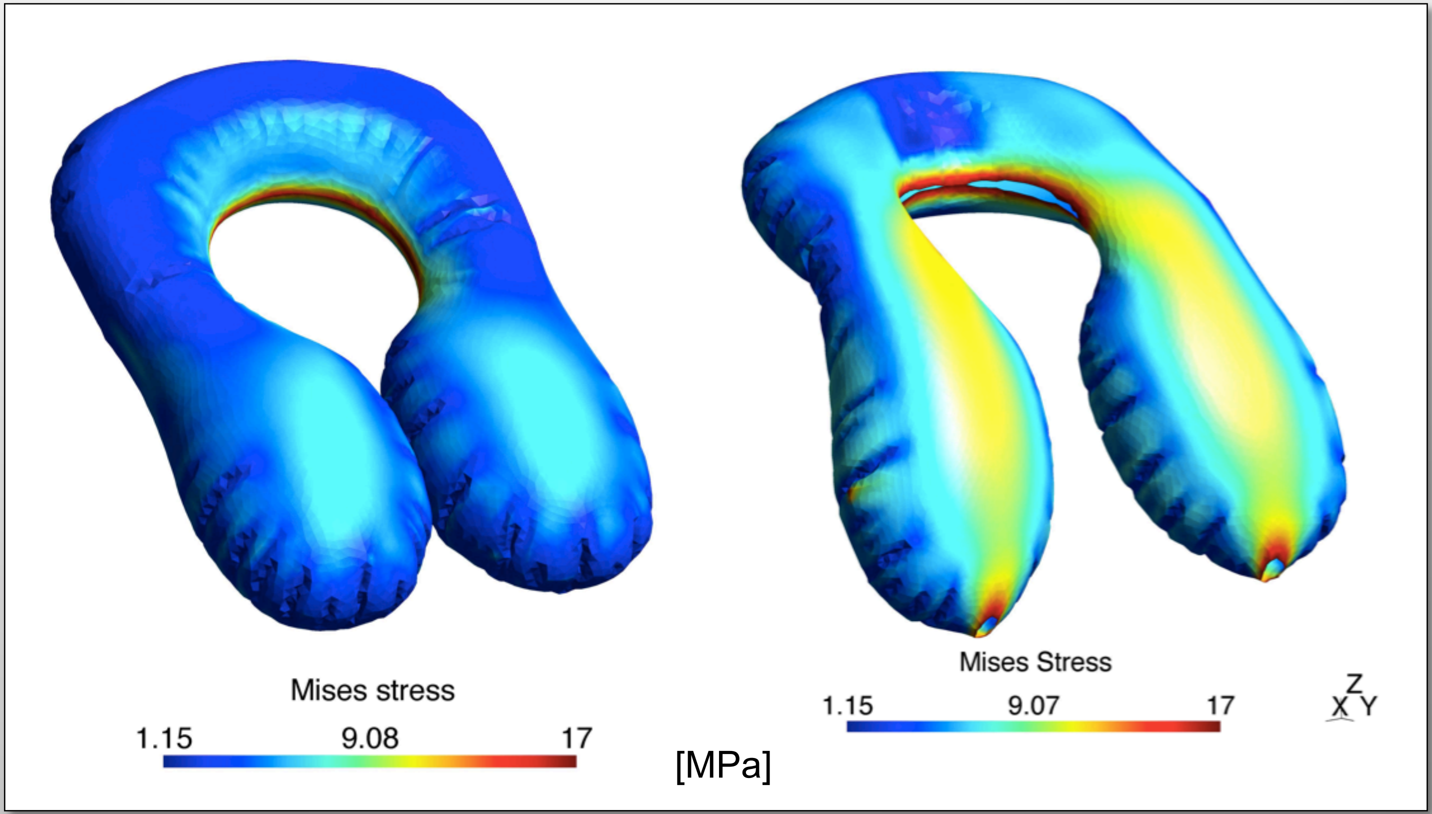






Final result (and II)

- Applicability of **DR along with contact mechanics** has been proved
- **Industrial interest**: different behaviour when the lifejacket is worn by a person.



4

CONCLUSIONS AND PERSPECTIVES

General conclusions

Perspectives

General conclusions

Perspectives

Introduction

Outline

Dynamic Relaxation

Application to lifejackets

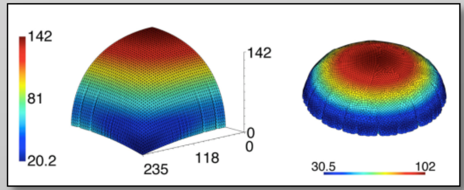
Conclusions Perspectives

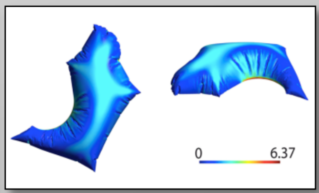
Conclusions (I)

- Exhaustive study on **Dynamic Relaxation**:
  - Presented two new proposals that extended applicability of DR with KD:

1 DR method →	**Several** DR methods
1 type of finite element →	**Any type** of finite element
1 law of behavior →	**Generalized** to a more global behavior
Restricted boundary conditions →	Proved its functioning with **contact**
1 loading type →	Possibility of **incremental** loading

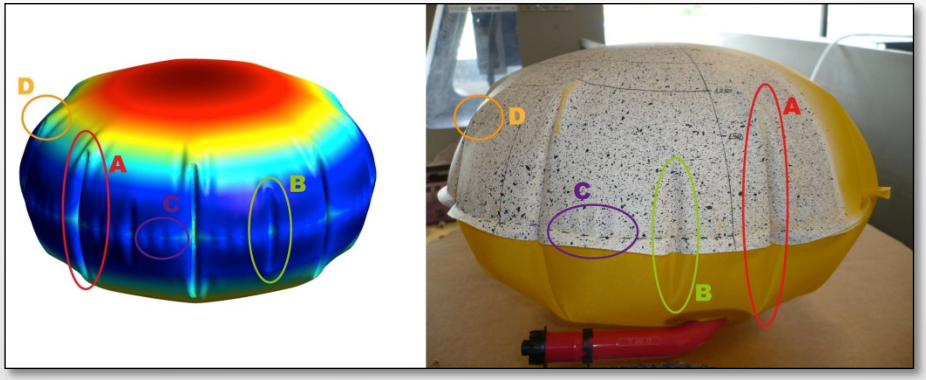
  - Comparison of several DR methods
  - Alternative to Newton's method?



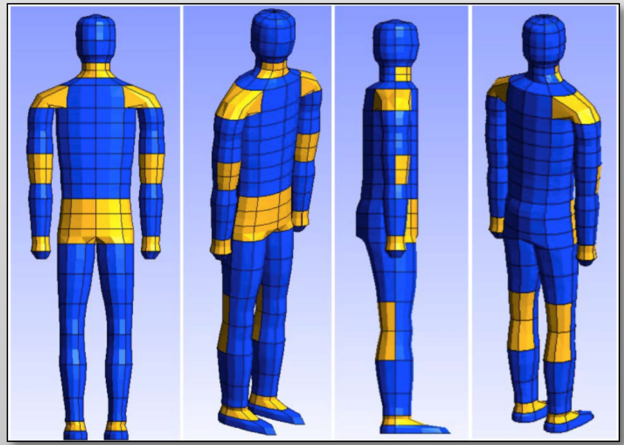


Conclusions (II)

- 3D optical measurement: **good agreement** with reality

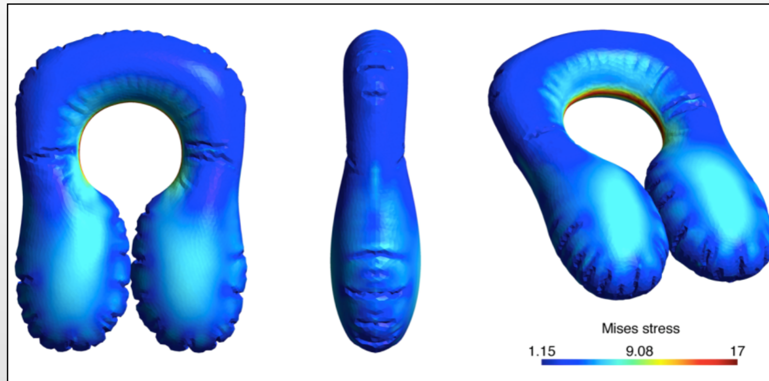


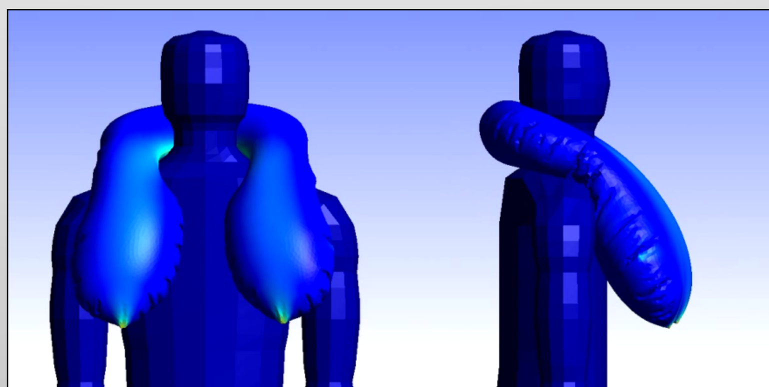
- Parameterized **human body model**



Conclusions (and III)

- **Application** of DR to **inflatable lifejackets** (incl. contact mechanics)



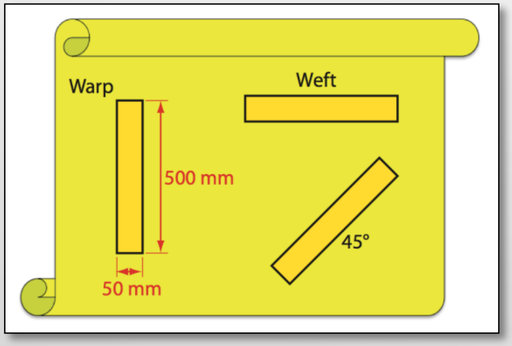


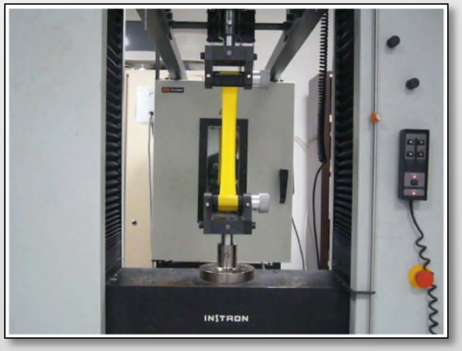
General conclusions

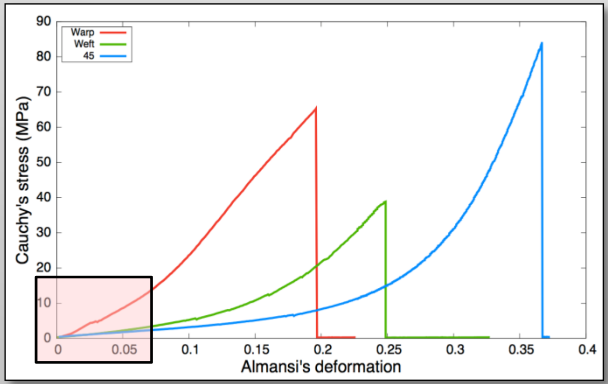
Perspectives

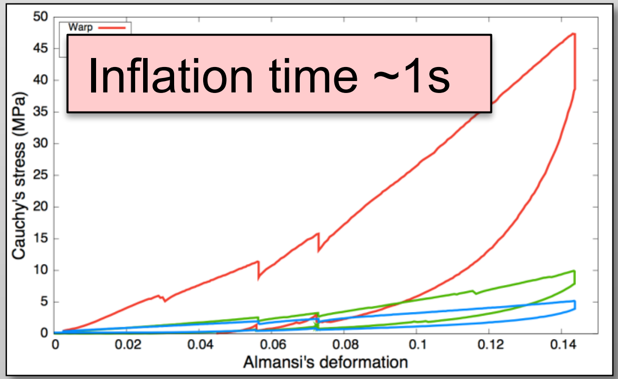
Academic perspectives (I)

- **Academic:**
  - Validation of DR proposals with more **complex behaviours** (plasticity)
  - Implementation of the complex **behaviour of technic textile** in the numerical simulations (tests at different temperatures?)



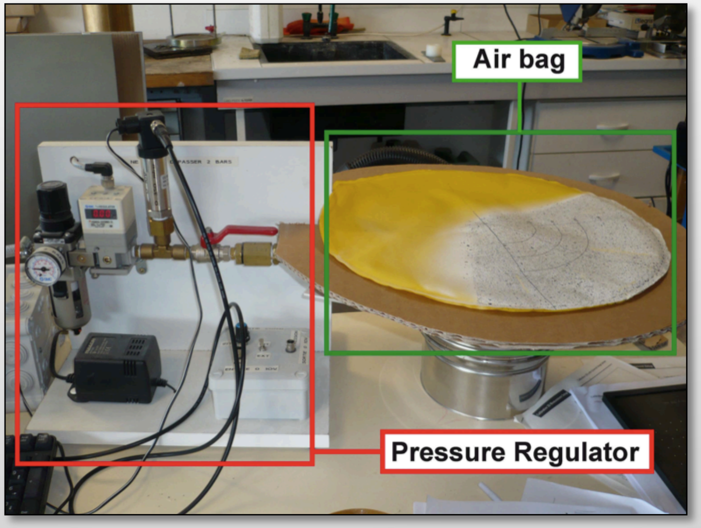






Academic perspectives (and II)

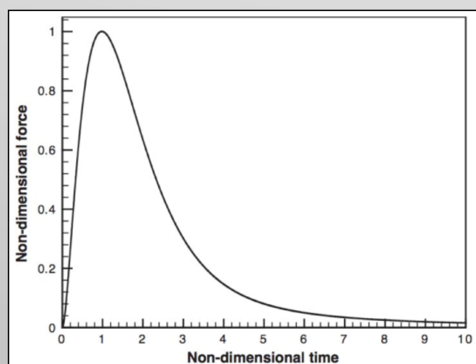
- **3D measuring**: appropriate support



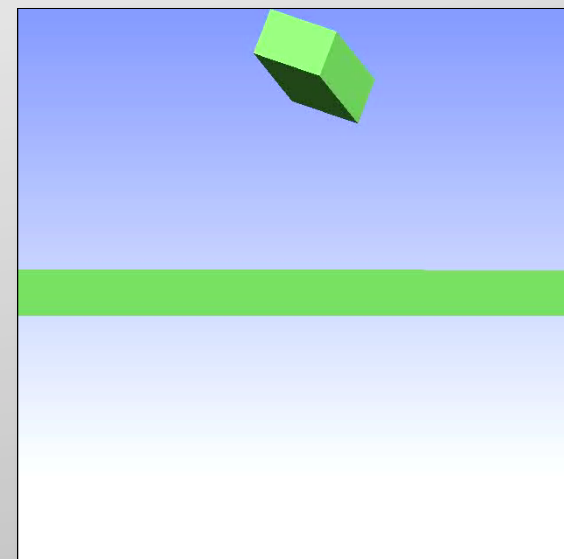
Industrial perspectives

- **Industrial**:
  - Water modelling
    - **<u>Aim</u>**: to simulate a behaviour not far from reality
    - Fast calculations → No fluid-structure coupling
    - Already implemented: *hydrostatic pressure* and *hydrodynamic forces*
    - New problem: water impact (important?)

Hydrostatic pressure + Hydrodynamic forces + ~~Water impact~~ ?

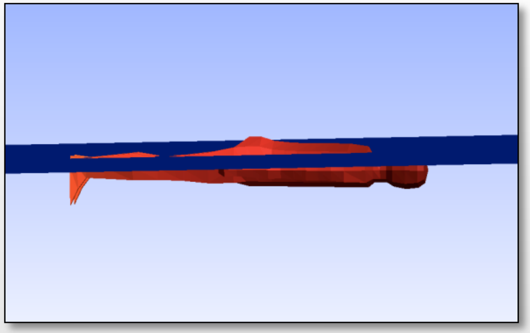


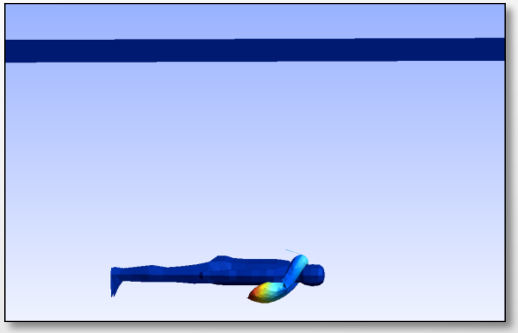
Analogy with *slamming*



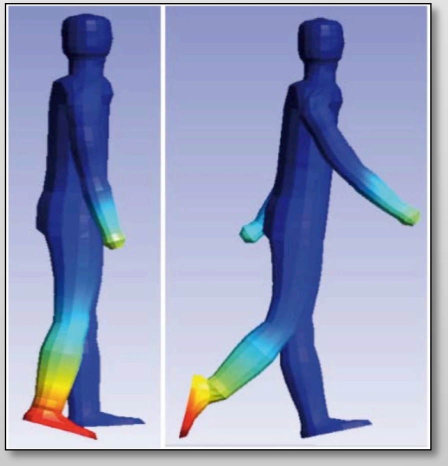
Industrial perspectives

- Simulation of mannequin inside water





- Improvement of the **mannequin** ?



- Lifejacket: validation of **self-contact**

THANK YOU

UNIVERSITÉ DE BRETAGNE-SUD

NUMERICAL STUDY OF DYNAMIC RELAXATION METHODS AND CONTRIBUTION TO THE MODELLING OF INFLATABLE LIFEJACKETS

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December 7, 2011

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