INSTITUT CLÉMENT ADER

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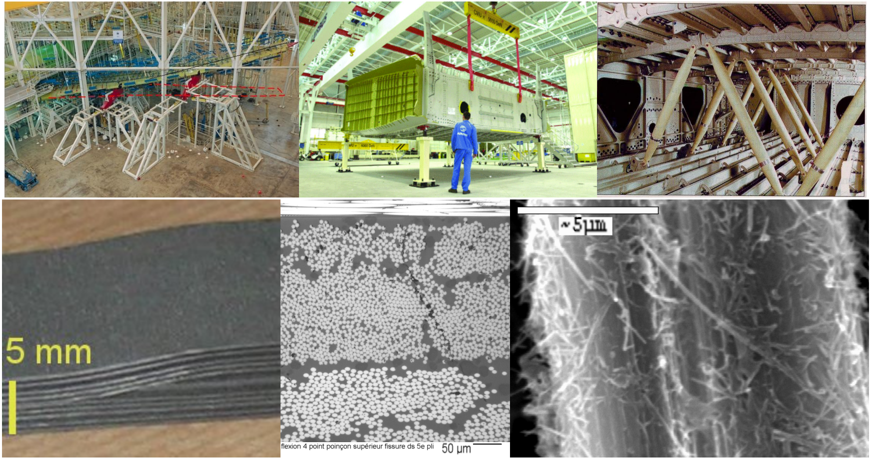
Suivi de l'endommagement dans les composites par stéréo-corrélation d'images

J.-N. Périé, J.-C. Passieux

Institut Clément Ader (ICA), Université de Toulouse, CNRS/INSA/Mines Albi/UT3/ISAE, Toulouse, France

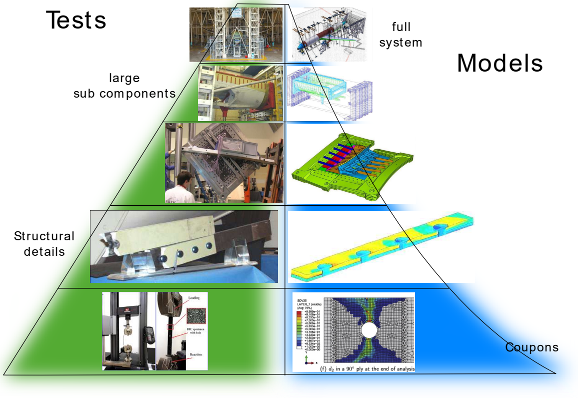
Context



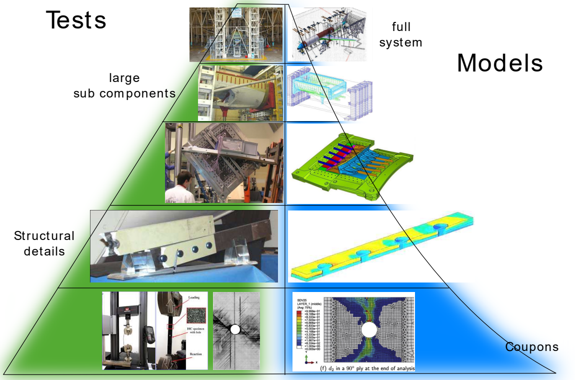
[Riccardis2006]

- Complex architecture, variabilities, defects, effect of manufacturing, etc.
  $\rightarrow$ **the assessment and prediction of their behaviour is still a real challenge**

Context


Tests
full
system
Models
large
sub components
Structural
details
Coupons

Context



→ **More predictive** models

→ **Images can be used to build more realistic models**

Context

→ **X-ray μ Computed Tomography can now provive a valuable insight at various scales**

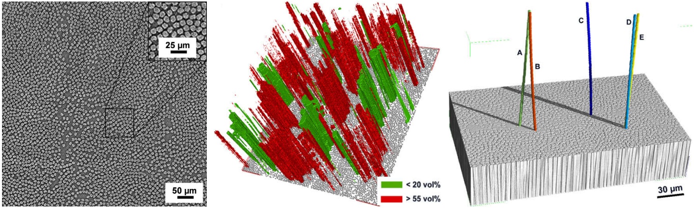


Figure: Fiber volume content and fiber orientation [Requena2009]

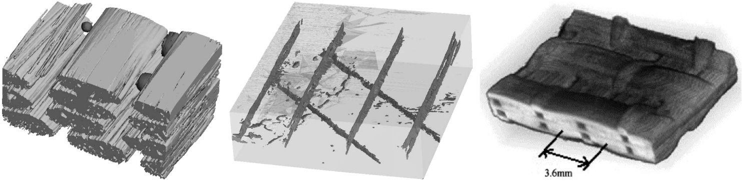
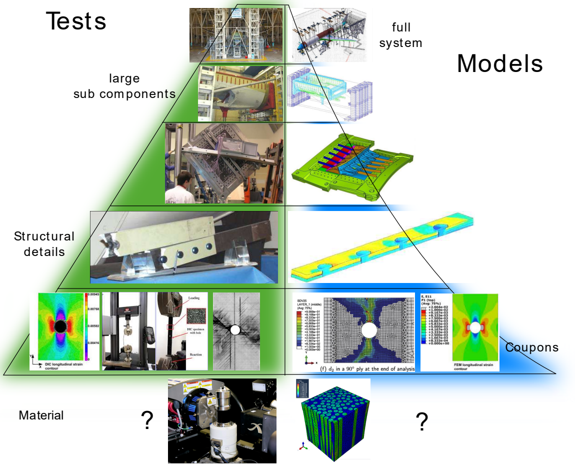


Figure: Defects and damages [Schilling2005] Geometry [Desplentere2005]

Context



→ More predictive models

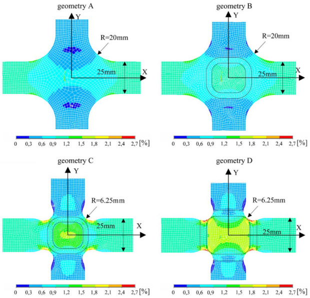
→ Images can be used to propose more realistic models

→ **More complex** and **well instrumented** experiments

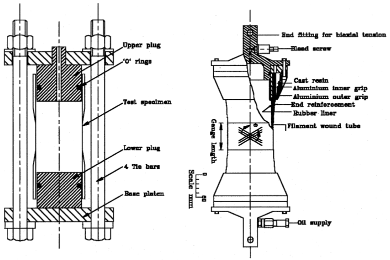
→ **DIC, stereo DIC and DVC can be used to measure kinematical fields**

Context

More representative structure subjected to a multiaxial (and non-proportional) loading



[Smits et al. 08]



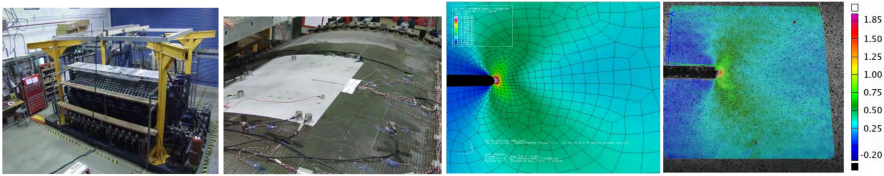
[Soden et al. 02]

- Many specimens can be (easily?) manufactured and tested
- Loading is partly known (some components of the reactions) and may be used in a simulation/experiment dialog

- The specimen and the loading may not be representative of actual applications

Context

Representative structure subjected to realistic loadings

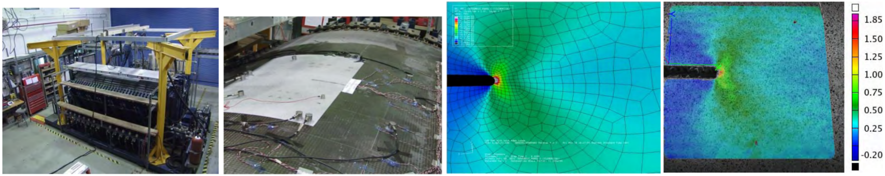


[Leone et al. 08]

- Full scale specimens
  → **Actual geometry**, material defects, residual stresses, etc.?
- Test bench is very specific
  → **Actual boundary conditions and loading?**

Context

Representative structure subjected to realistic loadings

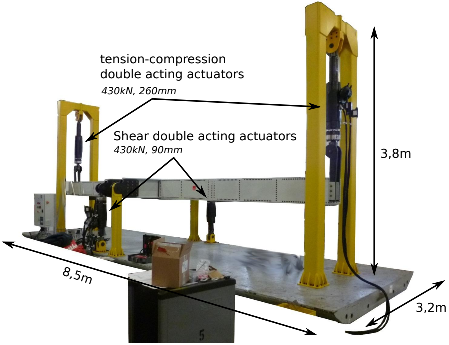


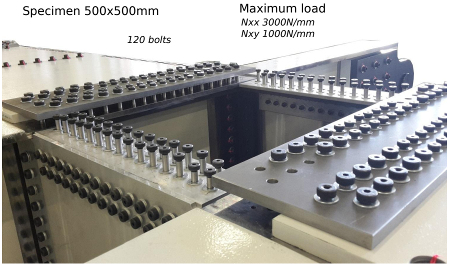
[Leone et al. 08]

- Full scale specimens
  → **Actual geometry**, material defects, residual stresses, etc.?
- Test bench is very specific
  → **Actual boundary conditions and loading?**
- Digital Image Correlation is now widely used in such contexts to provide 3D information
  → **Quantitative comparison of measured and simulated data?**
  → **Small strains in comparison with "standard" DIC measurement uncertainties!**

Context

- **VERTEX Project** (Funding: ANR-12-RMNP-0001 - More information: web site)
  "**Modelling** and **experimental validation** of composite structures under **complex loadings**"
  - Partners: Airbus Group, Holo3, LMS Samtech Samcef
    ICA [Bouvet et al. 09] , LMT [Ladeveze et al. 05] , ONERA [Huchette et al. 06]
  - Our work package: **Stereo DIC instrumentation and control**





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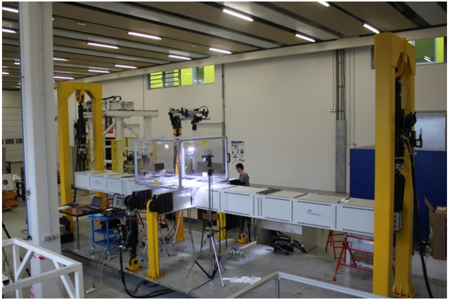

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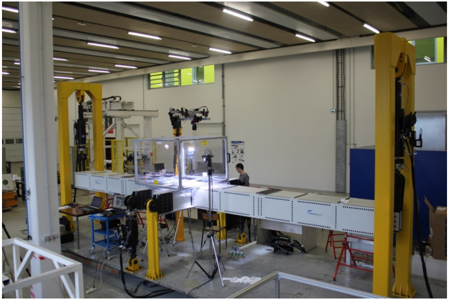
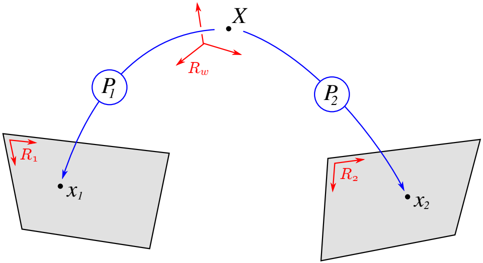


- Non-conventional testing machine
  - nonlinear transfer function (some parts of the machine may undergo plastification)
  - **Experiment**: how to control of the device to follow the **complex loading**?
  - **Validation**: Unknown (hyperstatic) loading conditions at the **FE model**'s boundary

Classic SDIC

- **Key features of the classical approach** [Hartley 04,Sutton et al. 09]
  - **nonlinear camera models** $\mathbf{x}_c = \mathbf{P}_c(\mathbf{X}, \mathbf{p}_c)$



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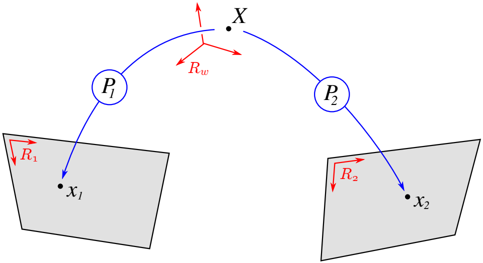
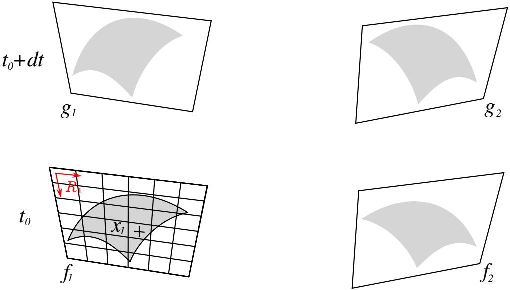


  - **Calibration of the camera parameters** $\mathbf{p}_c$ [Lorusso et al. 97,Garcia and Orteu 01]
    - **intrinsic** (focal length, image center, distorsions) (considered offline)
    - **extrinsic** (translations, rotations) (considered unknown)

Classic SDIC

- **Displacement measurement with the classical approach**



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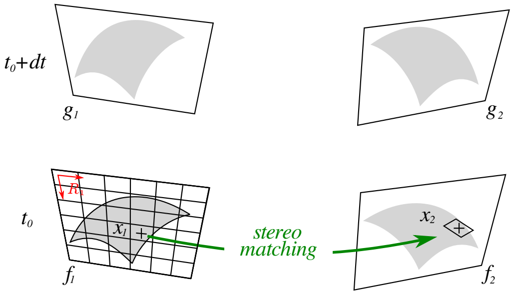

  - **stereo matching** between reference images

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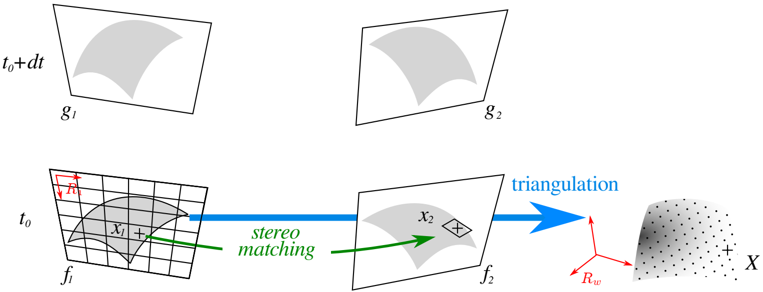

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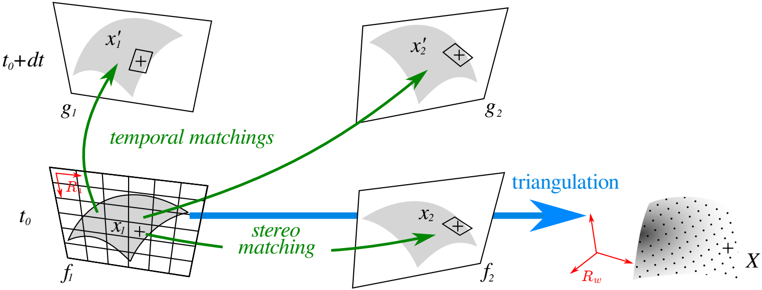

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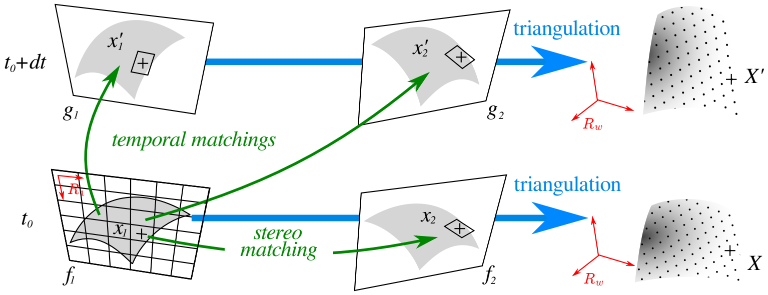

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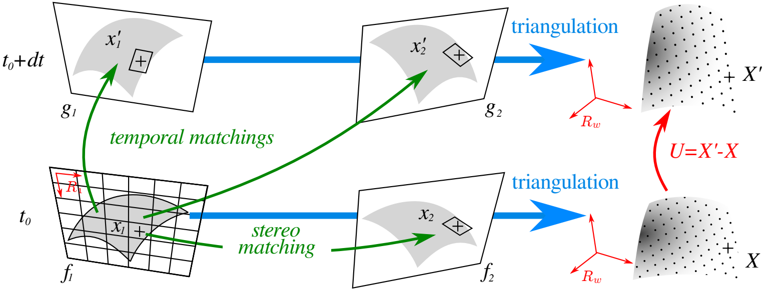

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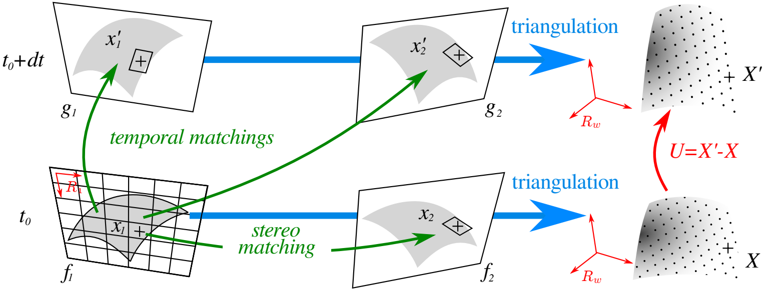

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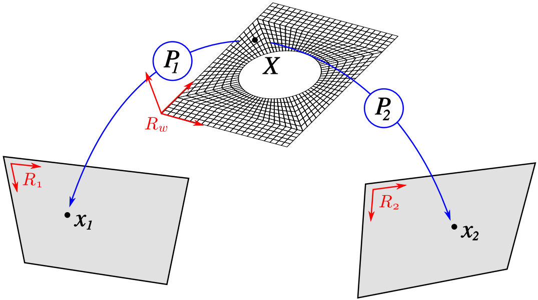
  - **displacement estimation**

- **Limitations**:
  - Dissymmetric **master-slave** formulation
  - Works in the **image coordinate system**, unit: pixel
  - Displacement **U not** the solution of **a unique optimization process**

- **Displacement measurement** [Pierré et al. 17]



[Pierré et al. 17] **Pierré, Passieux and Périé (2017)**. Finite Element Stereo Digital Image Correlation: framework and mechanical regularization. *Experimental Mechanics*. 53(7)443-456.

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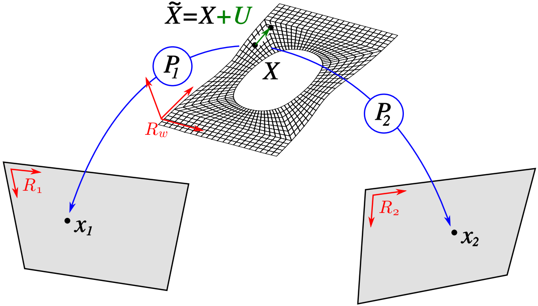

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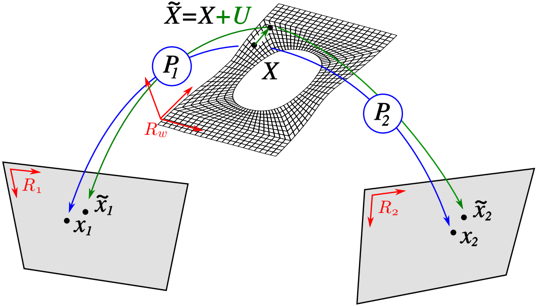

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FE-SDIC

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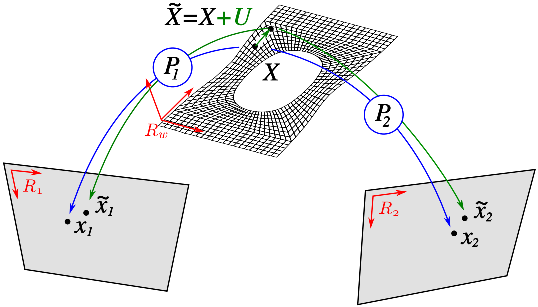

Matching + Triangulation on the 3D displacement **U**:

$$\mathbf{U}^{\star} = \arg\min_{\mathbf{U}} \sum_{c} \int_{\Omega} \Big[f_c(\underbrace{\mathbf{P}_c(\mathbf{X})}_{\mathbf{x}_c}) - g_c(\mathbf{P}_c(\underbrace{\mathbf{X} + \mathbf{U}(\mathbf{X})}_{\widetilde{\mathbf{x}}_c})) \Big]^2 d\mathbf{X}$$

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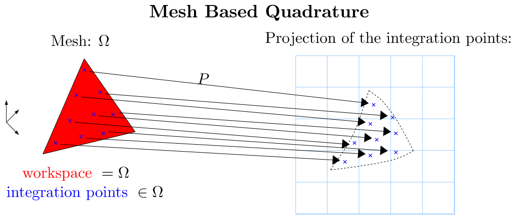
Quadrature [Pierré et al. 16]

- Need to define a quadrature rule in the world coordinate system.



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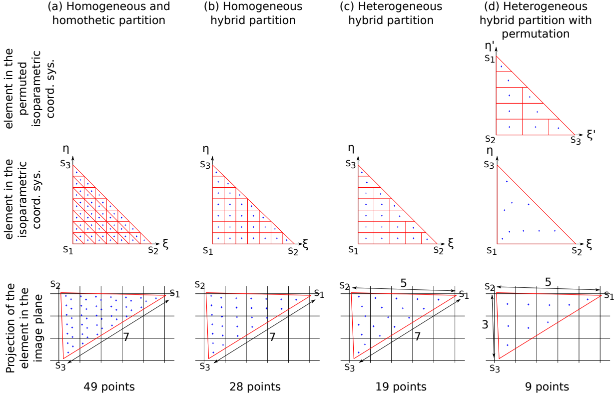

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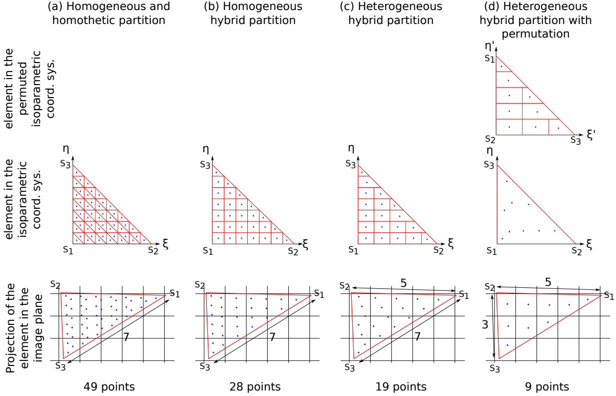

→Proved to be optimal and also relevant for 2D-DIC...

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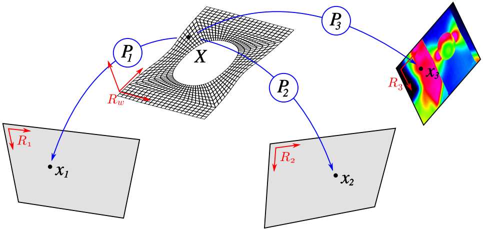
FE-SDIC

- Advantages of using finite elements in SDIC:
  - No master-slave structure: no constraints on the number of camera
  - Works in the **CAD coordinate system**, units: m
  - Convenient for the user (link with analysis, validation, identification...)
  - 3D surface displacement reduced to a **unique optimisation problem**
  - Space-time regularization [Passieux et al. 18]
  - **General framework for data fusion** (IR camera [Charbal et al. 16] , acoustic emissions...)



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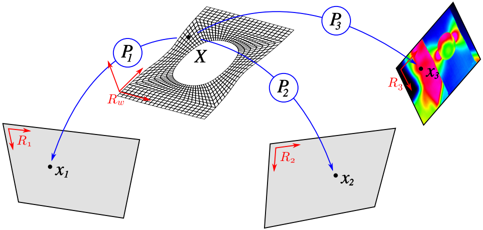
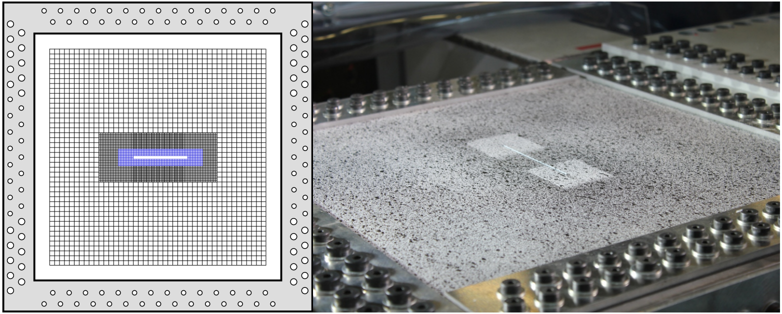


- **Today's presentation**.
  1. Applied to multiscale/multiview measurements [Serra et al. 2017]
  2. Mechanical regularization [Pierré et al. 17, Serra et al. part I 2017]
  3. Identification of kinematic boundary conditions [Serra et al. part I 2017]
  4. Towards validation of composite structures [Serra et al. part II 2017]

1. Multiscale/multiview measurements (Application to Vertex)

Proposed Stereo FE-DIC

Application within the context of structural testing



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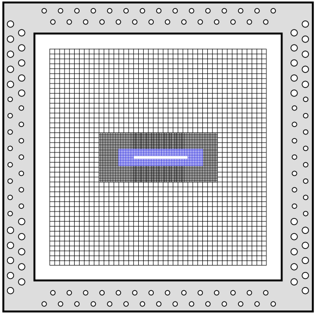

- The proposed framework can handle as many cameras as needed

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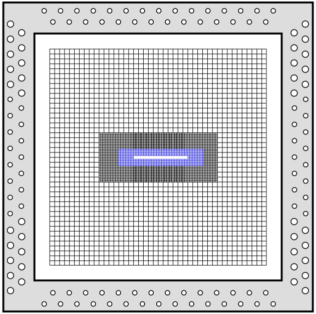

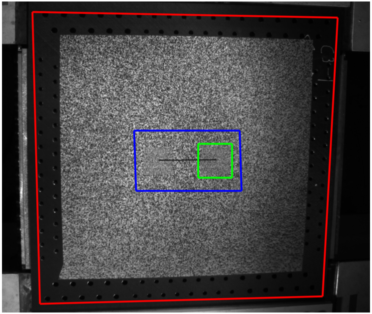

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  →**Allows using actual simulation meshes for Stereo FE DIC measurements**

  →**A suitable speckle is synthetised and printed onto the surface**

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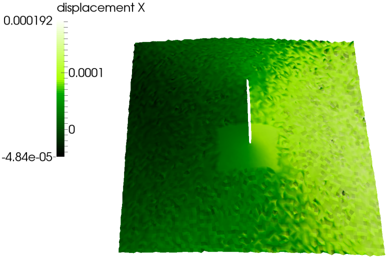

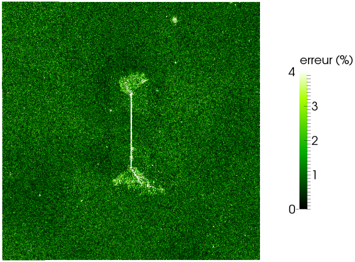

- The proposed framework can handle as many cameras as needed
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  →**Multiscale measurements**
- Gray level residual map reveals cracks

Proposed Stereo FE-DIC

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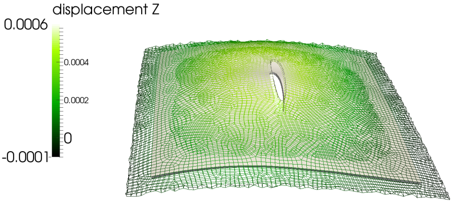

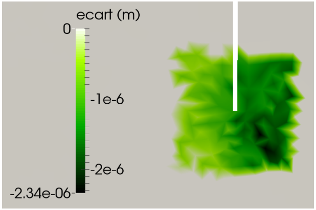

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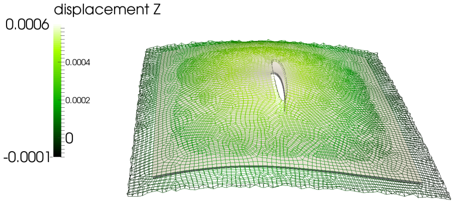
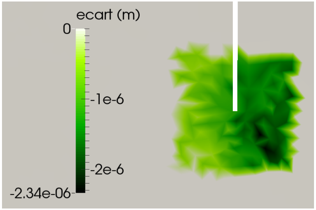
- Gray level residual map reveals cracks
- Stereo FE-DIC makes simulation/experiment dialog much easier

Proposed Stereo FE-DIC

Application within the context of structural testing





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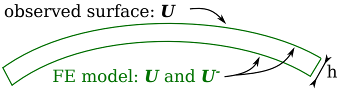
- **BCs? ← mechanical regularisation of FE stereo measurements**

2. Mechanical Regularization

Proposed Stereo FE-DIC: Mechanical regularised

Displacement measurement with mechanical regularisation

- Solid Shell model :



$$\begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} U_x \\ U_y \\ U_z \\ U_x^- \\ U_y^- \\ U_z^- \end{bmatrix}$$

Proposed Stereo FE-DIC: Mechanical regularised

Displacement measurement with mechanical regularisation

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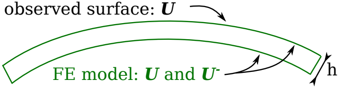

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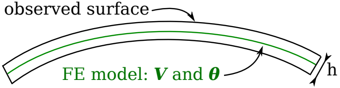
- Plate/Shell model :

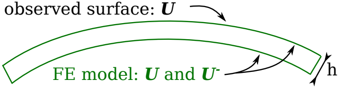


$$\begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & \frac{h}{2} & 0 \\ 0 & 1 & 0 & 0 & \frac{h}{2} \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \\ \theta_x \\ \theta_y \end{bmatrix}$$

Proposed Stereo FE-DIC: Mechanical regularised

Displacement measurement with mechanical regularisation

- Solid Shell model :



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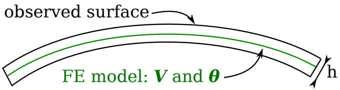

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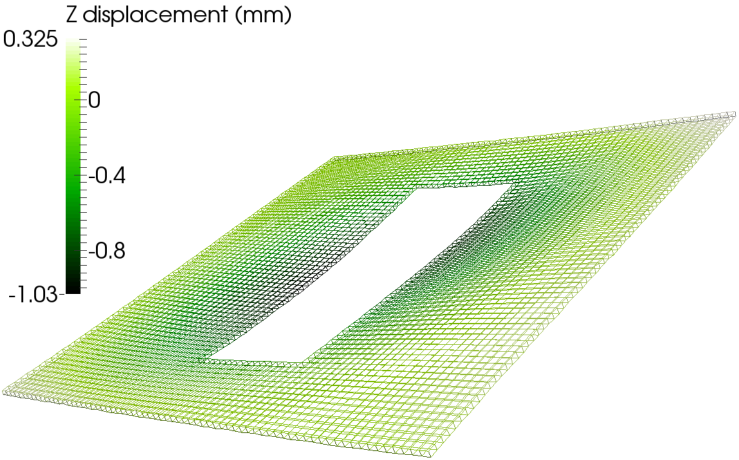
- Regularised DIC formulation [Rethore, Roux, Hild 08] [Leclerc et al. 10]

$$\mathbf{V}^\star = \arg\min_{\mathbf{V}} \sum_c \int_\Omega \Big[f_c(\mathbf{P}_c(\mathbf{X})) - g_c(\mathbf{P}_c(\mathbf{X} + \Pi\mathbf{V}(\mathbf{X})) \Big]^2 d\mathbf{X} + \lambda_k \|\overline{\mathbf{K}}\mathbf{V}\|_2^2 + \lambda_T \|\mathbf{T}\mathbf{V}\|_2^2$$

Example

Measurement of mechanically consistent BC during a shear test



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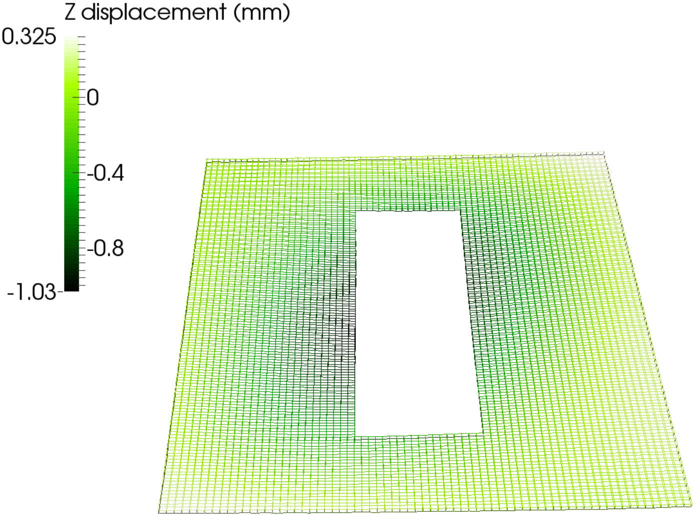

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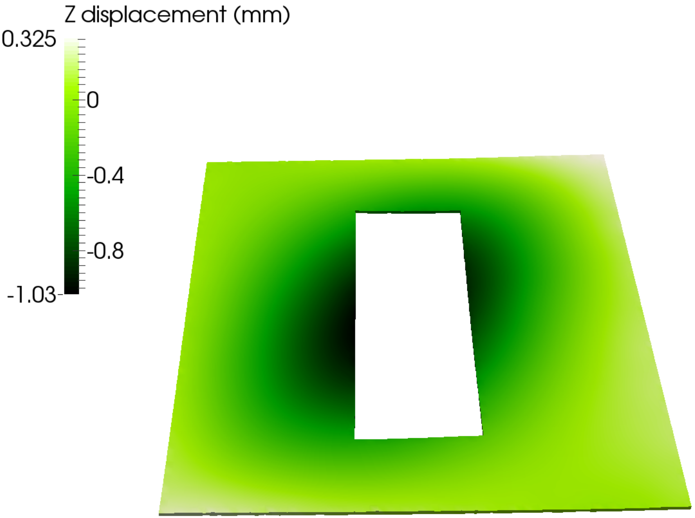

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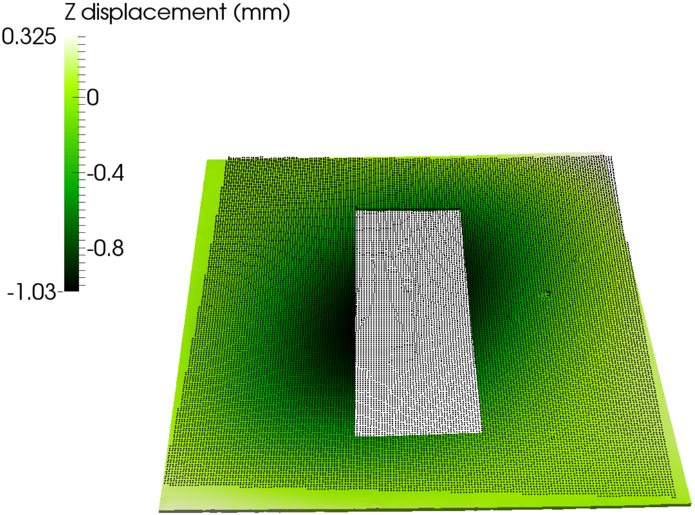

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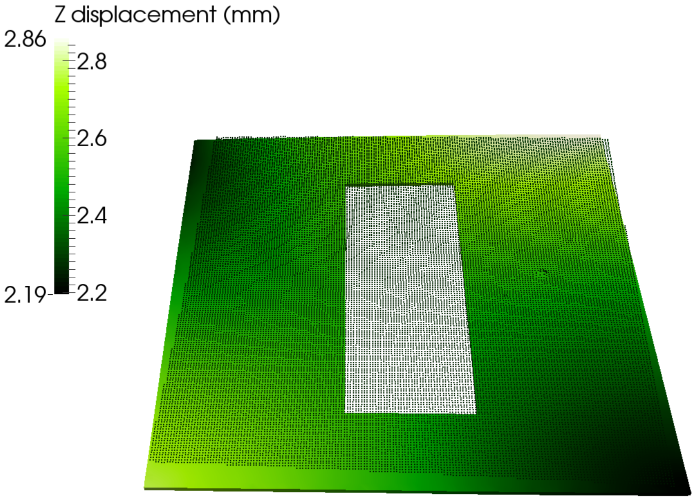

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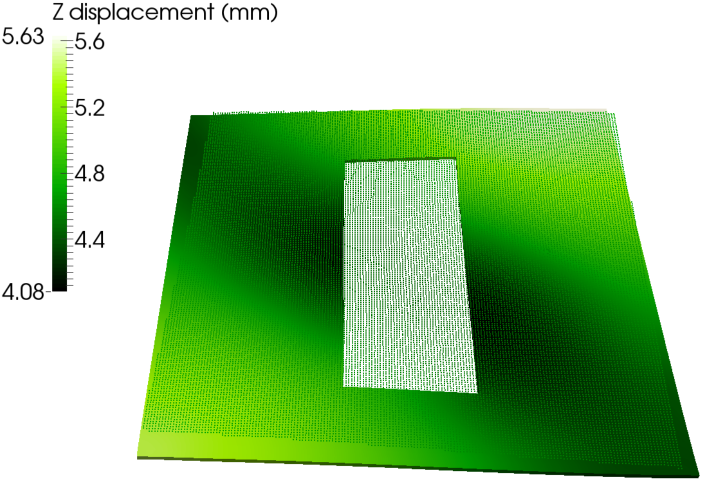

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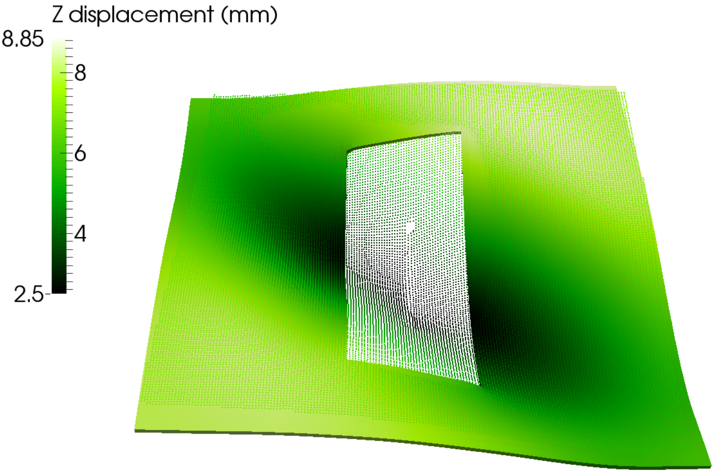

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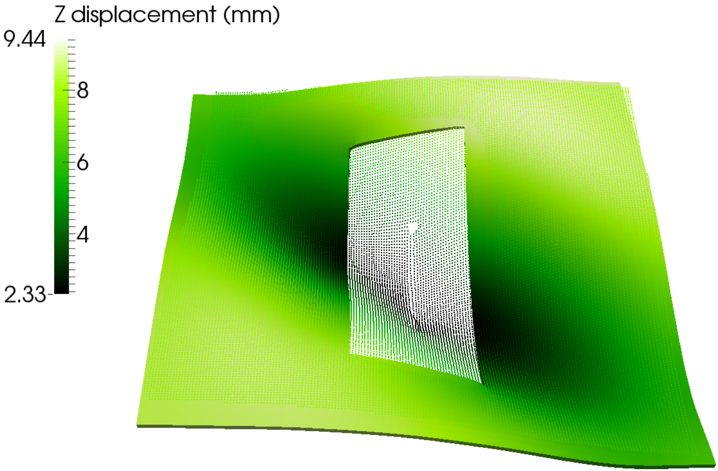

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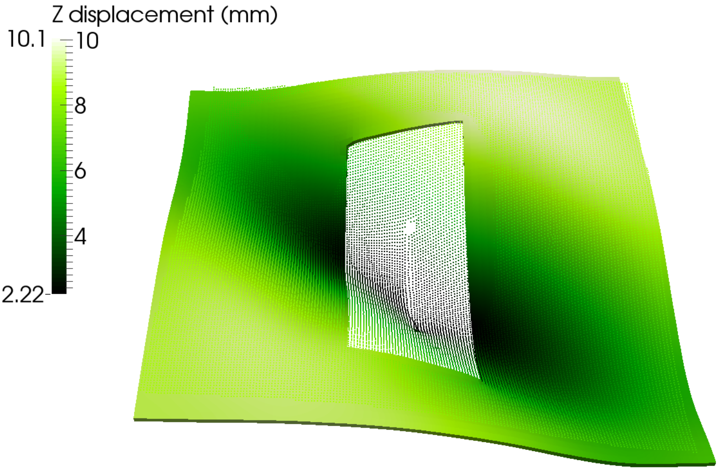

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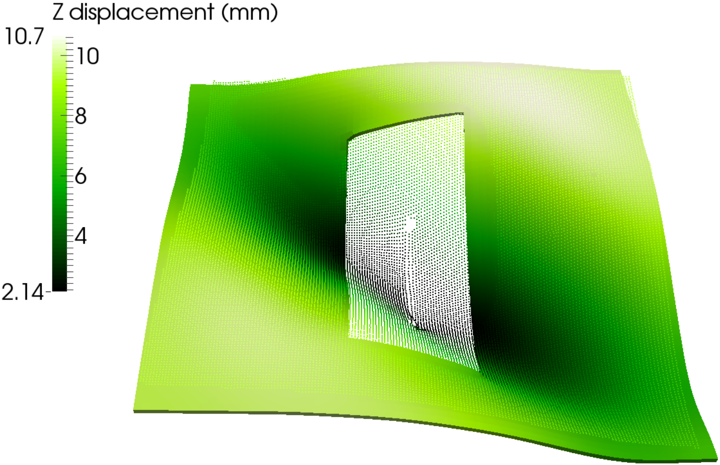

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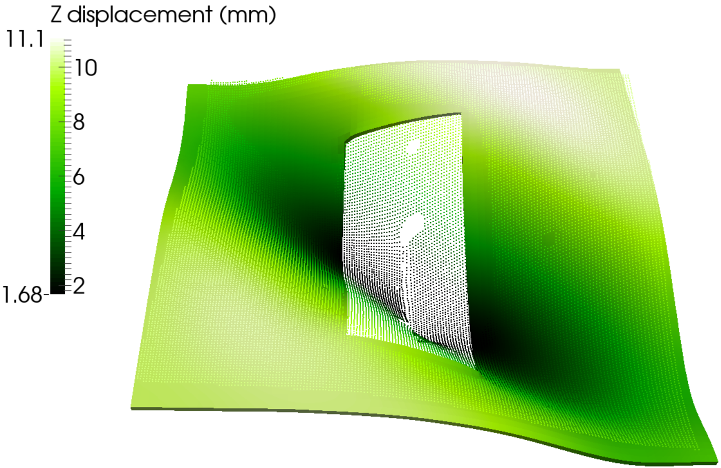
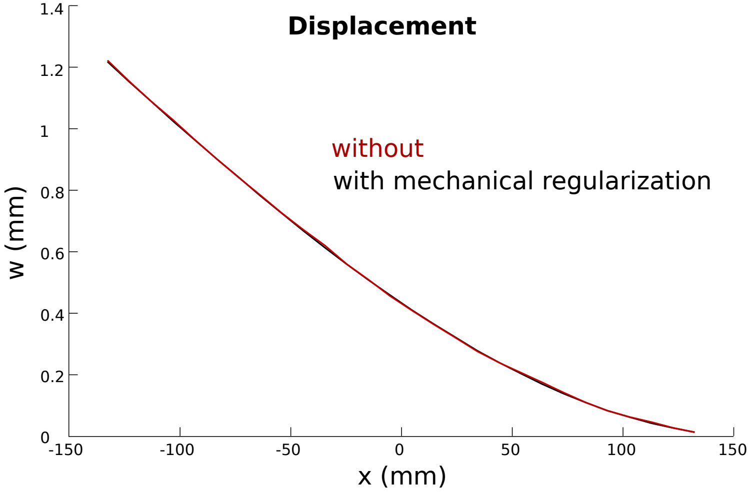


Examples

- **Illustration on a simple test case of a plate in bending**



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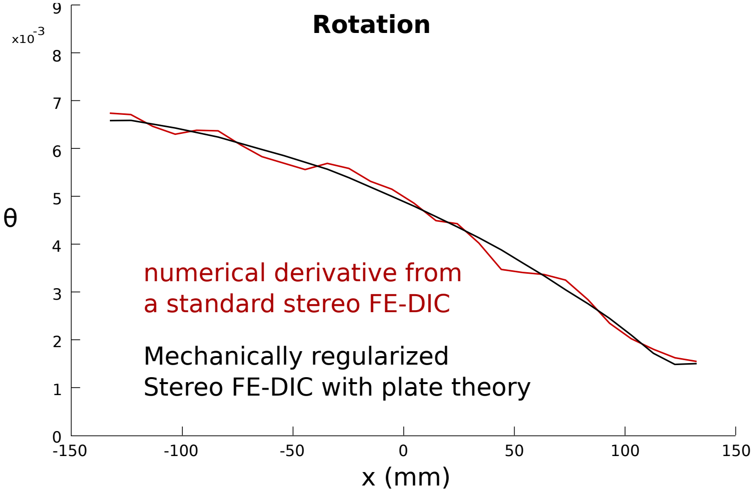
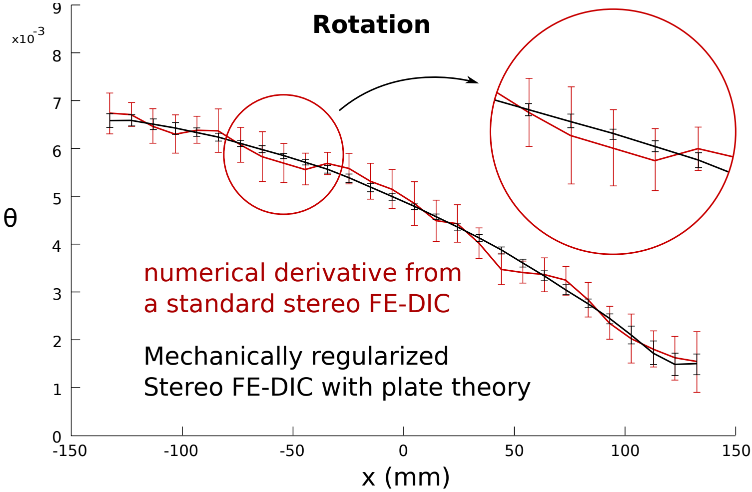


- Illustration on a simple test case of a plate in bending



3. Identification of Boundary Conditions in Stereo DIC (Application to Vertex)

Identification of boundary conditions

- Assume that we have a reliable constitutive model far from the central notch.

$$\mathbf{Kq} = \mathbf{f}$$

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$$\mathbf{K}\mathbf{q} = \mathbf{f}$$

- renumber the dofs:

$$\begin{pmatrix} \mathbf{K}_{ii} & \mathbf{K}_{ib} \\ \mathbf{K}_{bi} & \mathbf{K}_{bb} \end{pmatrix} \begin{pmatrix} \mathbf{q}_i \\ \mathbf{q}_b \end{pmatrix} = \begin{pmatrix} 0 \\ \mathbf{f}_b \end{pmatrix} \quad \Rightarrow \quad \mathbf{q}_i = -\mathbf{K}_{ii}^{-1}\mathbf{K}_{ib}\mathbf{q}_b$$

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- building an operator:

$$\mathbf{q} = \mathbf{L}\ \mathbf{q}_b \quad \text{with} \quad \mathbf{L} = \begin{pmatrix} -\mathbf{K}_{ii}^{-1}\mathbf{K}_{ib} \\ \mathbf{I} \end{pmatrix}$$

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- Resolution of the DIC problem in projection on this basis

$$\mathbf{V}_b^\star = \underset{\mathbf{V}_b}{\arg\min} \sum_c \int_\Omega \left[f_c(\mathbf{P}_c(\mathbf{X})) - g_c(\mathbf{P}_c(\mathbf{X} + \Pi\mathbf{L}\,\mathbf{V}_b) \right]^2 d\mathbf{X}$$

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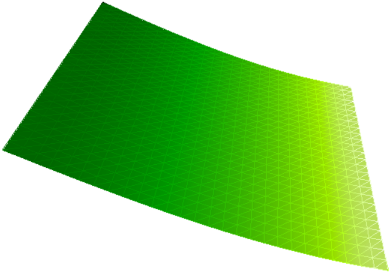
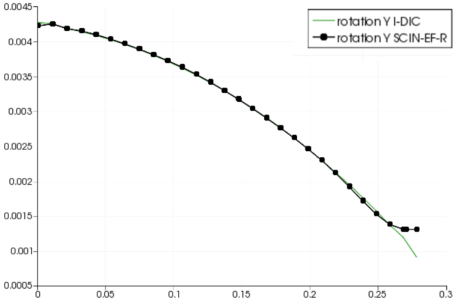
- Resolution of the DIC problem in projection on this basis

$$\left(\mathbf{L}^T \mathbf{M}_{sdic} \mathbf{L}\right)\ \mathbf{q}_b = \mathbf{L}^T \mathbf{b}$$

Identification of boundary conditions





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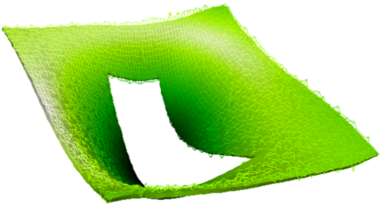
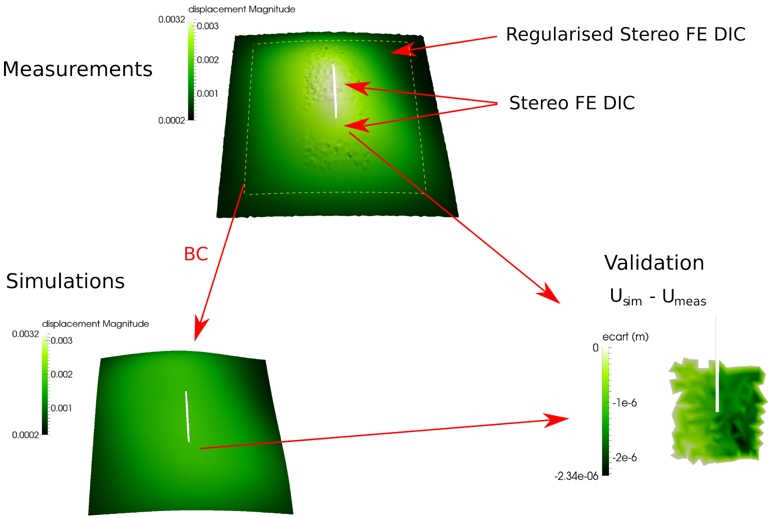


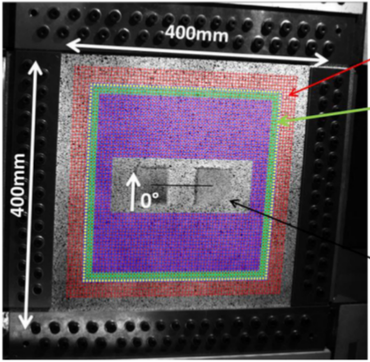
4. Toward validation of non-linear models at the structural scale

Principle of validation



Example of DPM

- ICA's Discrete Ply Model [Bouvet et al, 09, Serra et al. 17]



Zone (350×350mm^2) far from bolted area where DIC is applied

Zone (300×300mm^2) modeled by Abaqus with boundary conditions provided by FE-DIC
In-plane and out-of-plane displacement imposed on a band of three elements

Zone not modeled by FE-SDIC (only DPM)

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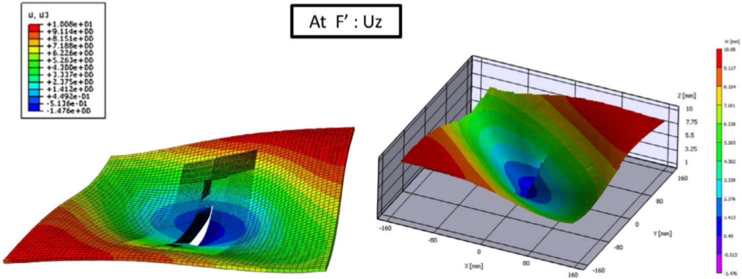
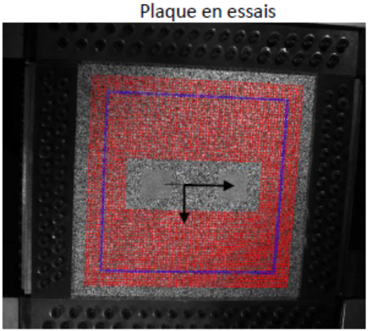
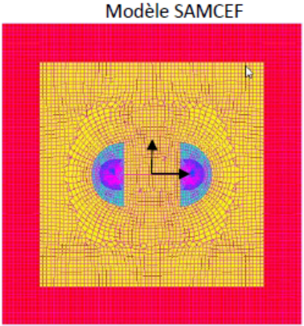


Example of Damage Mesomodel

- Samtech implementation of LMT's Damage mesomodel [Lubineau and Ladevèze 08] [Courtesy of SIEMENS]





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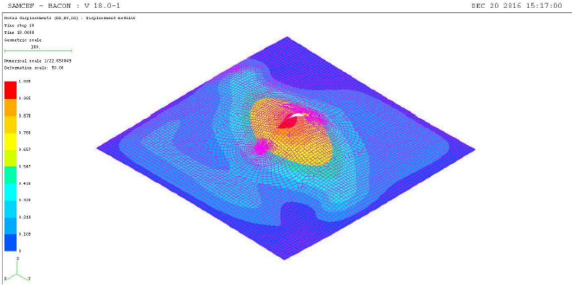
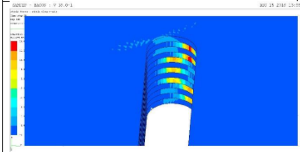
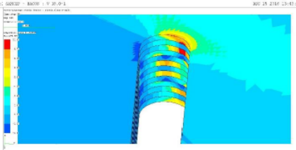


Déformation selon X en simple traction cisaillement C32 . Pli 10 et pli 12 à (tous deux à -45°)	Déformation selon Y en simple traction cisaillement C32 Pli 11 et pli 13 (tous deux à 45°)
	

Conclusions

Advantages of a formulation in the world coordinate system (FE-SDIC)

- A **convenient framework** for dialog with FE simulation (validation, identification)
- No master-slave structure: No restriction on the **number and the type of cameras**
- Possibility to incorporate the **knowledge of a model** (regularization, BC identification...)
- Open the way for **space-time formulations**
- A good formalism to incorporate **heterogeneous sensors**

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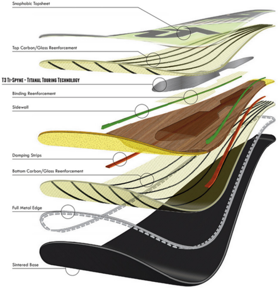
Perspectives

- Identification of elastic parameters of the models (loading assessment)
- Better consideration of **test history**
- **Validation** of non-linear FE models
- Possible **update** of constitutive parameters
- A **free FE-DIC Python library** available

Thank You


Snophobic Topsheet
Top Carbon/Glass Reenforcement
T3 Ti-Spyne - Titanal Touring Technology
Binding Reenforcement
Sidewall
Damping Strips
Bottom Carbon/Glass Reenforcement
Full Metal Edge
Sintered Base