Analyse d'assemblages boulonnés par corrélation d'images

J. de Crevoisier, T. Cazes

L. Champaney, N. Swiergiel (AIRBUS), F. Hild

école normale supérieure paris-saclay

université PARIS-SACLAY

LMT

cnrs dépasser les frontières

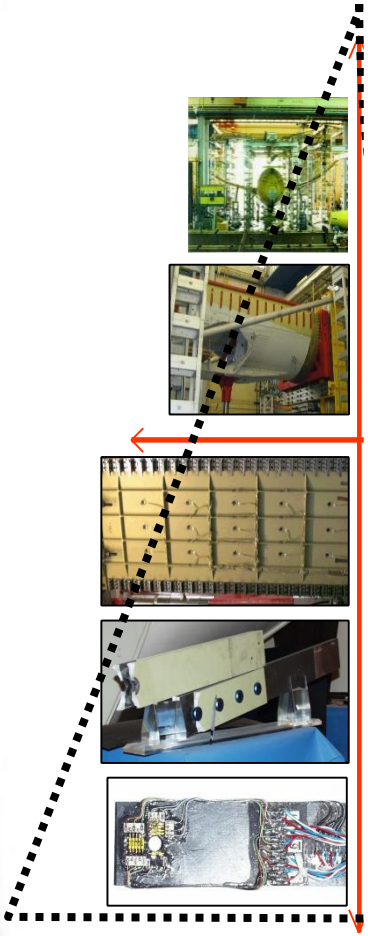
3 M Bolts in Assemblies*

- Reliable control of bonding of composites / maintenance?
- Many parameters influence assembly to transfer load, or to dissipate energy
- Sizing based on finding most loaded bolt
- New experimental tools: image correlation

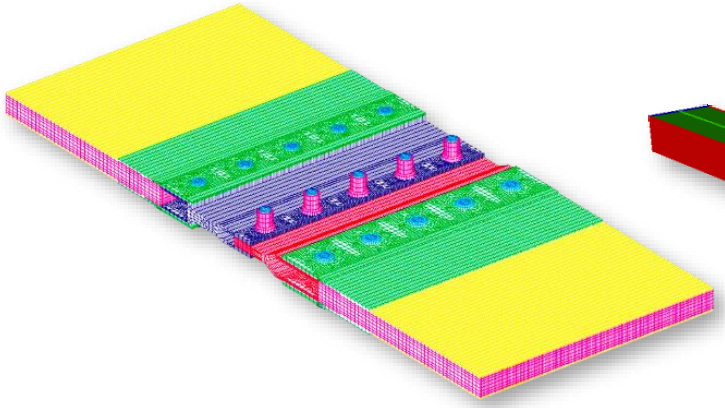
*[https://lejournal.cnrs.fr/videos/la-si-delicate-physique-des-trous]

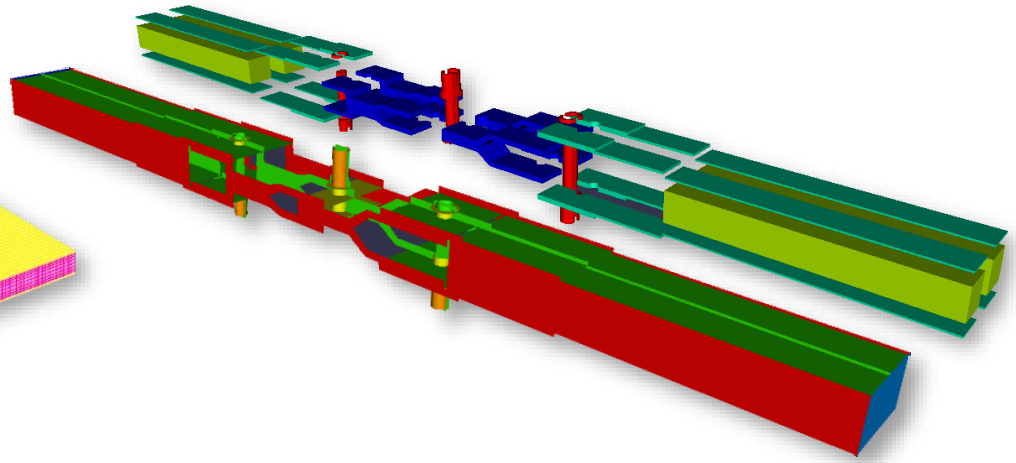
Test Pyramid

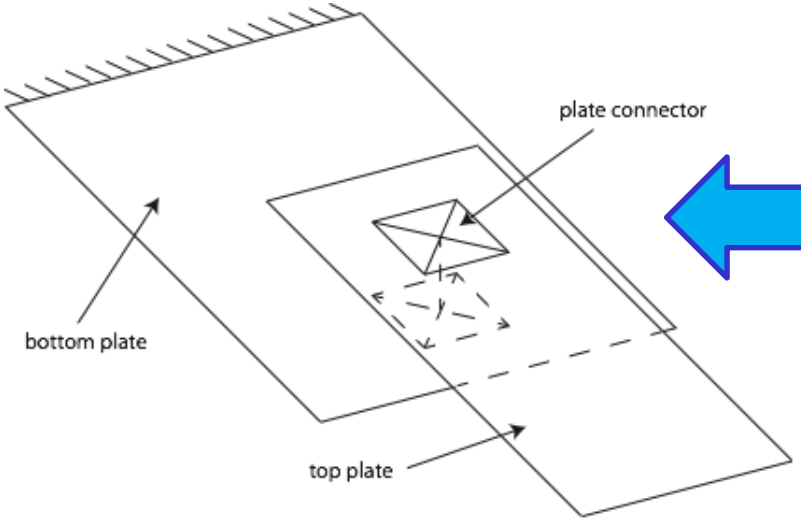
AIRBUS

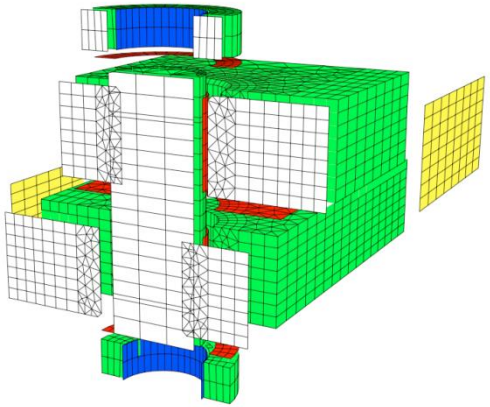


Multiscale Modeling of Bolted Assemblies



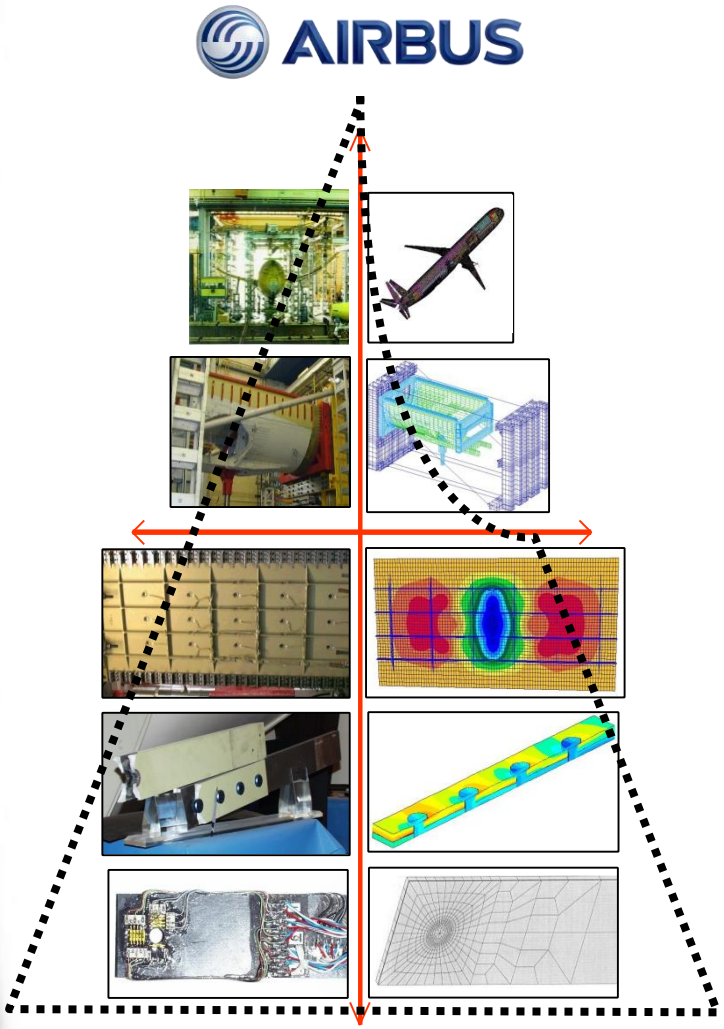




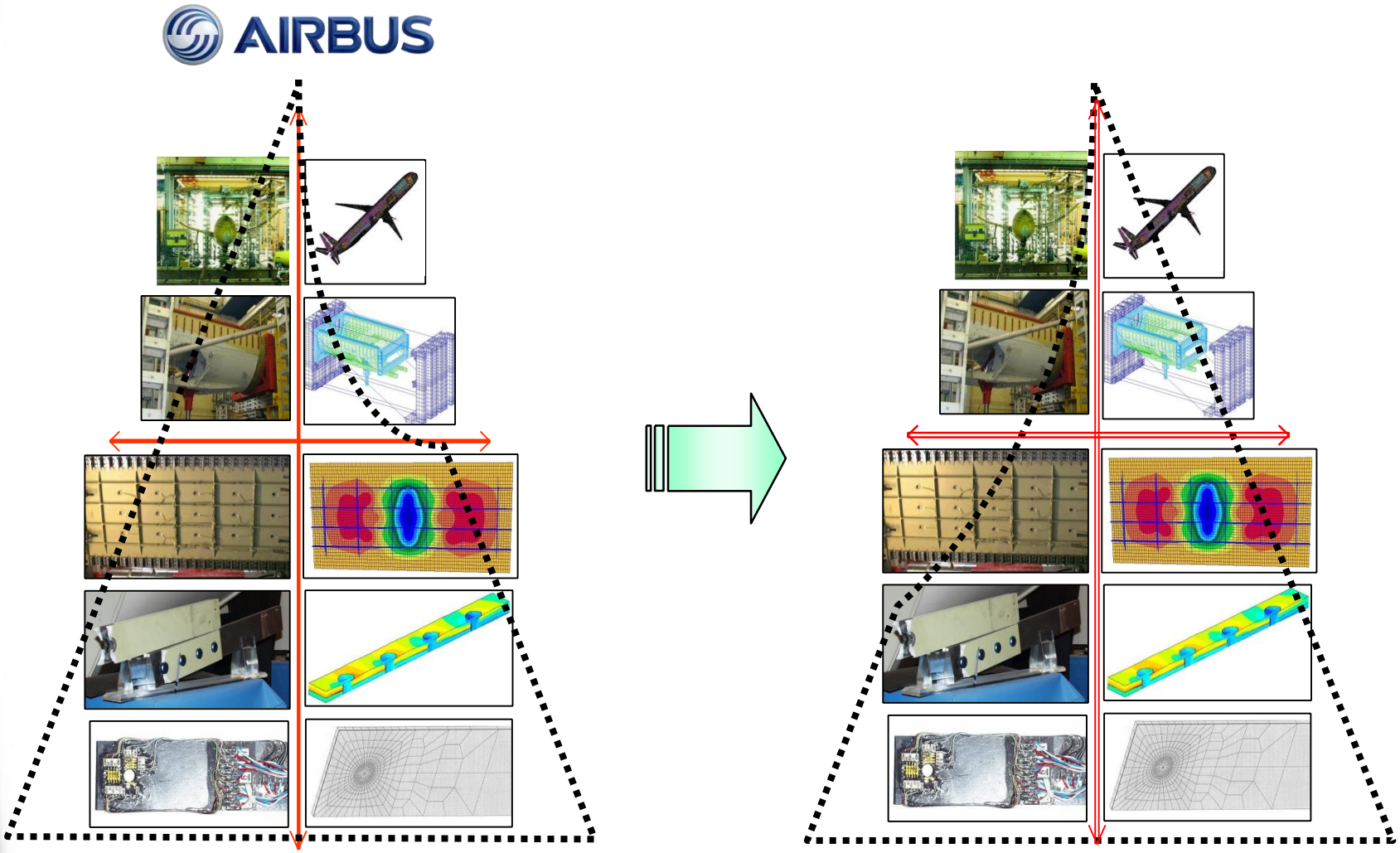


[Guguin *et al*., 2016, *Adv. Model. and Simul. in Eng*. Sci. 3(16) pp. 1-18]

Test and Simulation Pyramid

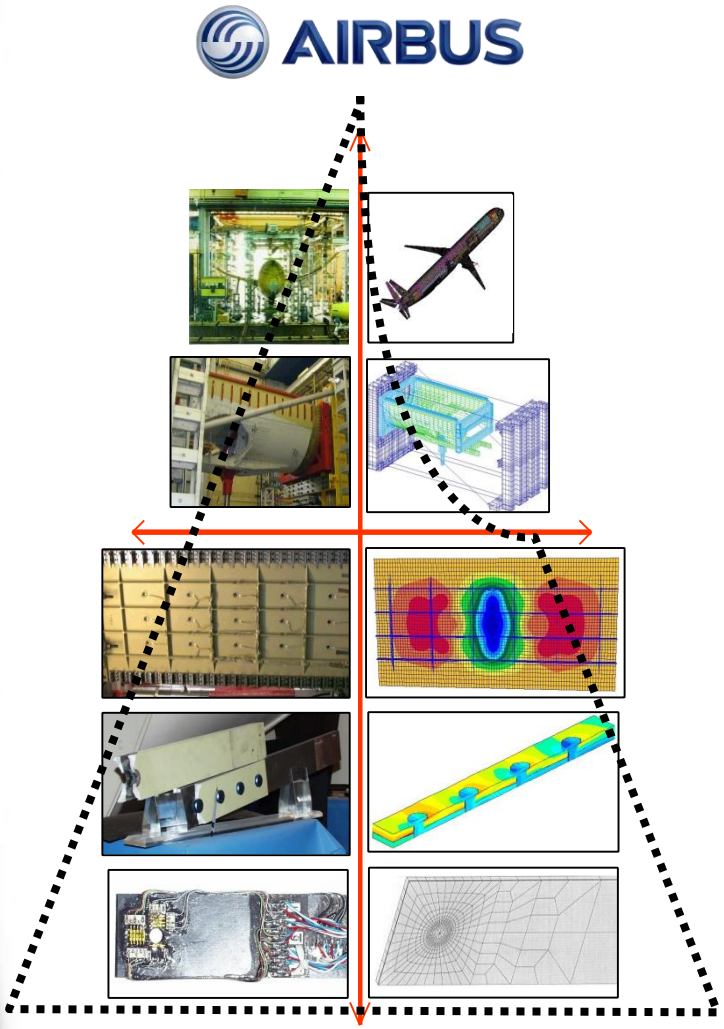


Toward Virtual Tests?



*[Mahé *et al.*, 2005, *7e CNCS*]
[Structures et tremblements, 2005, *J. CNRS*, 184]
[Barbaux, 2011, *Journées UPSTI*]

Bolted Assemblies?

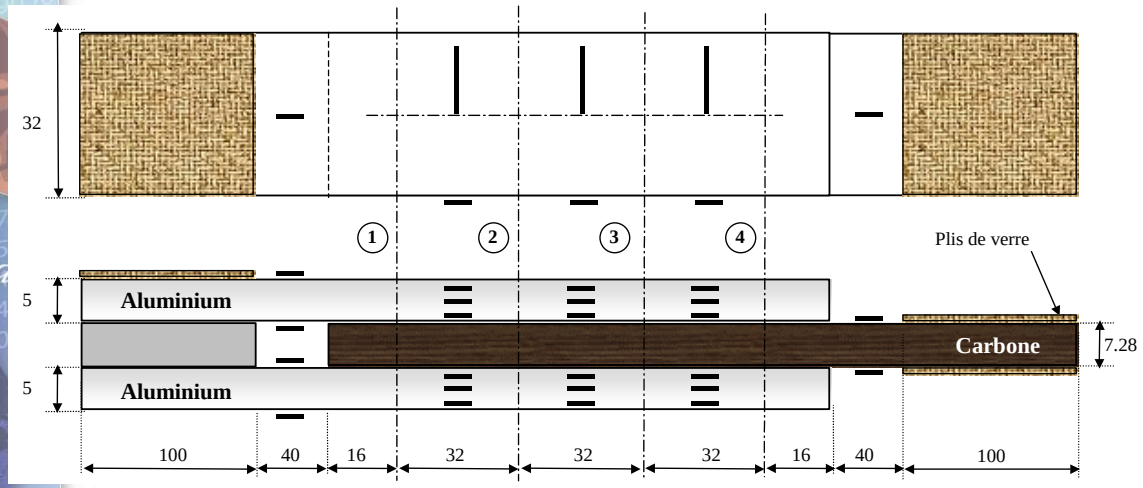


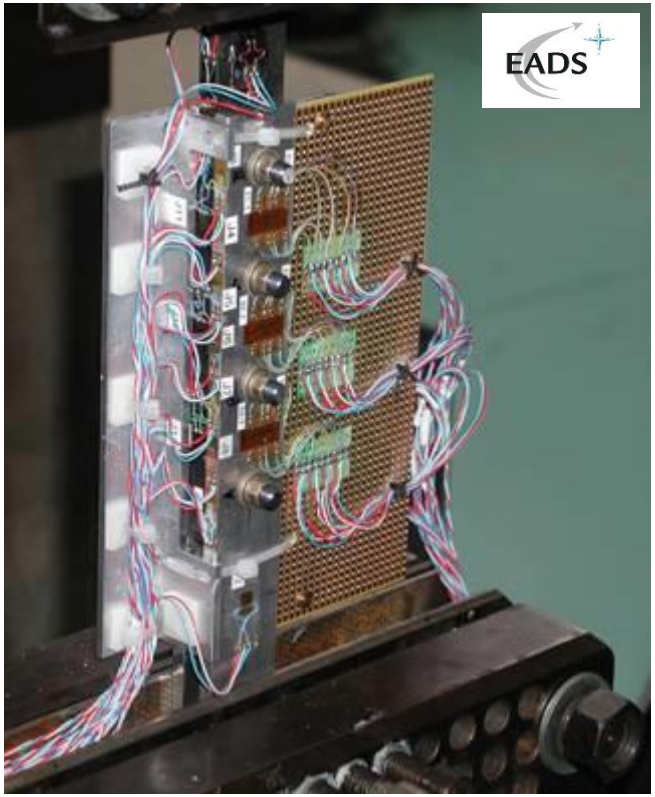
Challenges:
Mechanical stresses + thermal stresses (difference between coefficients of thermal expansion) + assembly stresses

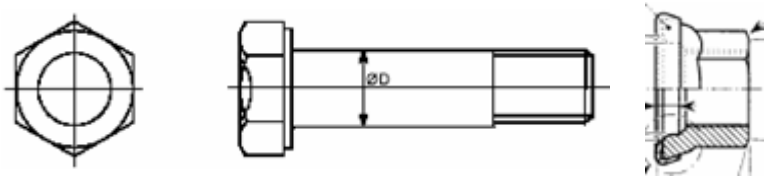
→ **Improved understanding of load transfers during the life cycle of an aircraft for optimized sizing**

Background

Case study: Standard method

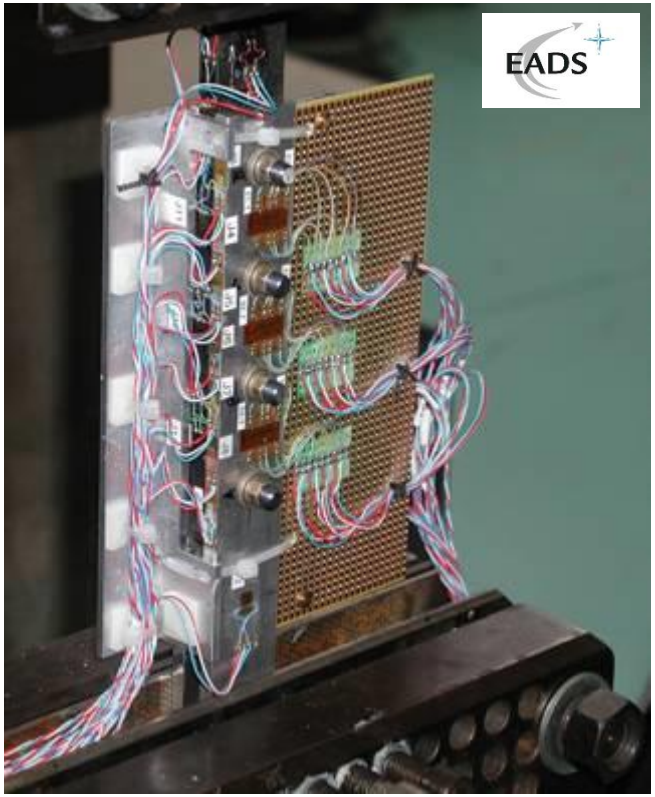






Challenges

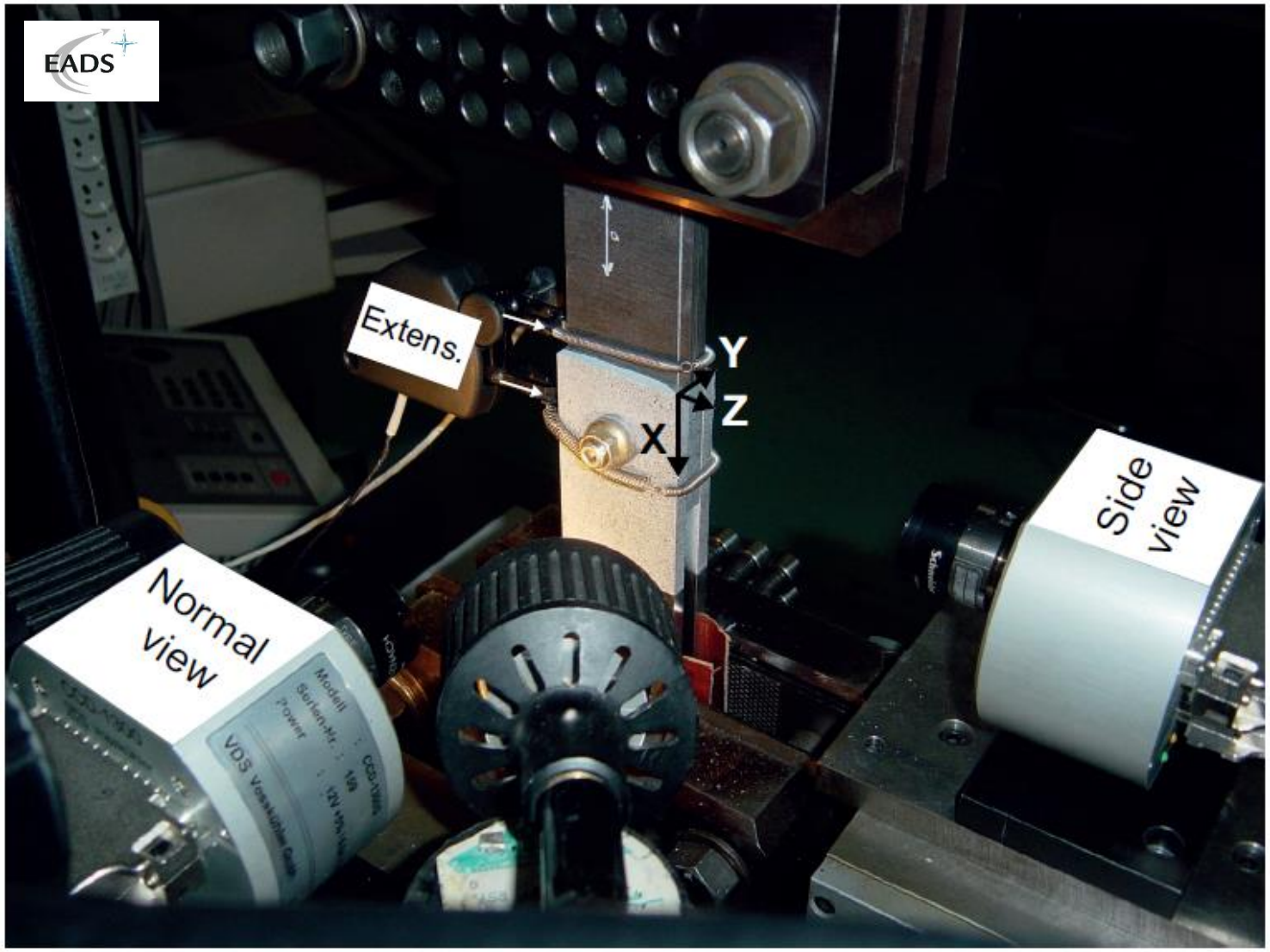
- Discriminate and quantify load transfer modes
- Minimize instrumentation cost
- Reliability of measurements
- Identification of characteristic parameters (e.g., rigidity, coefficient of friction)
- Comparisons between test and computation



Outline

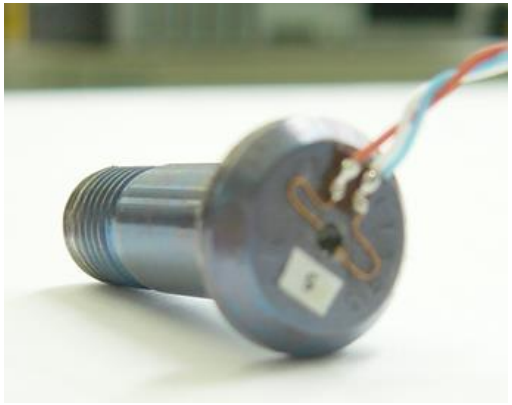
- Introduction
- **Double lap joint w/ single bolt (fatigue)**
- Load transfer in 4-bolt assembly
- Conclusion & perspectives

Experimental Protocol

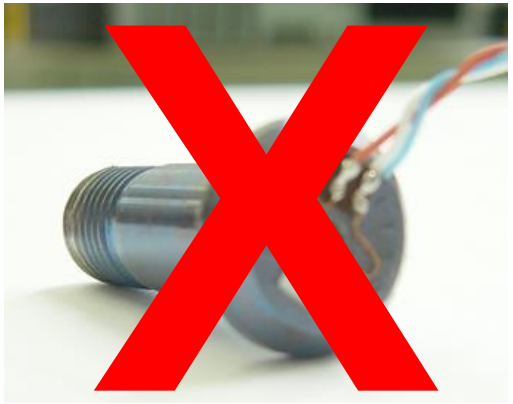


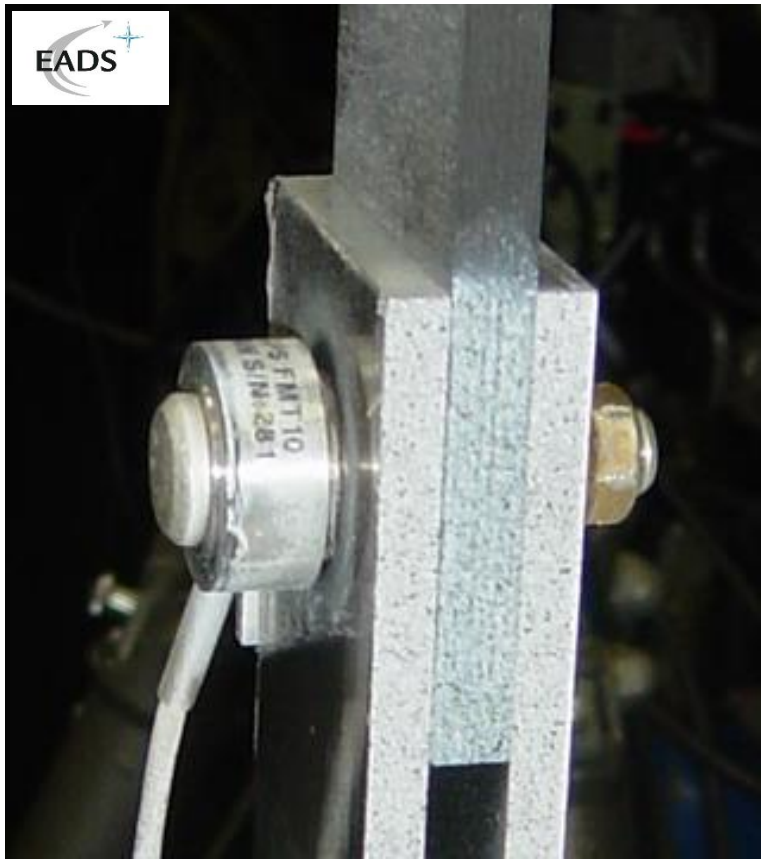
[de Crevoisier *et al*., 2012, *Exp. Mech.* 52 (6), pp.561-572]

Bolt Load Cell



Bolt Load Cell





Studied Assemblies

Hybrid assembly (DLS):

- 2 Al alloy plates (2024)
- 1 carbon / epoxy composite plate (32 plies)

3 configurations:

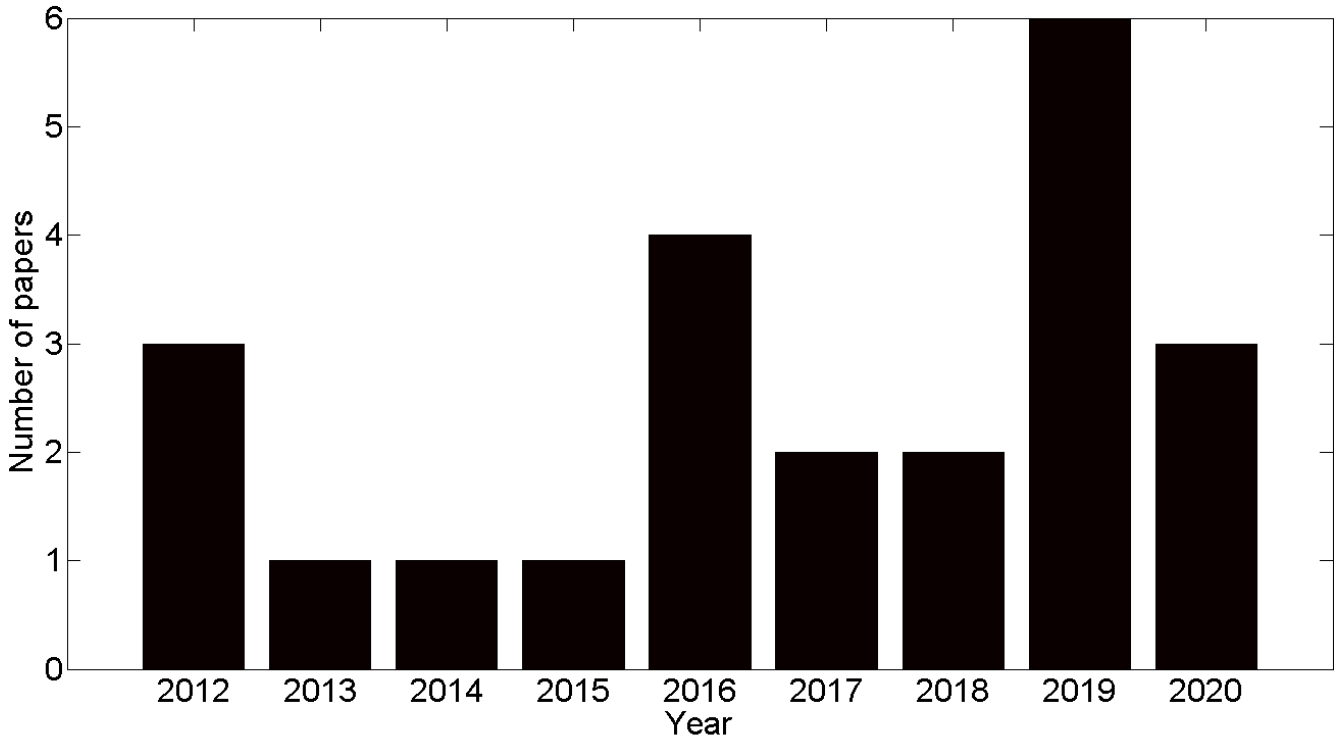
- Reference
- Severe (sandblasted)
- Reduced bolt tension (30%)

2 methods (DIC):

- Discrete
- 2D fields

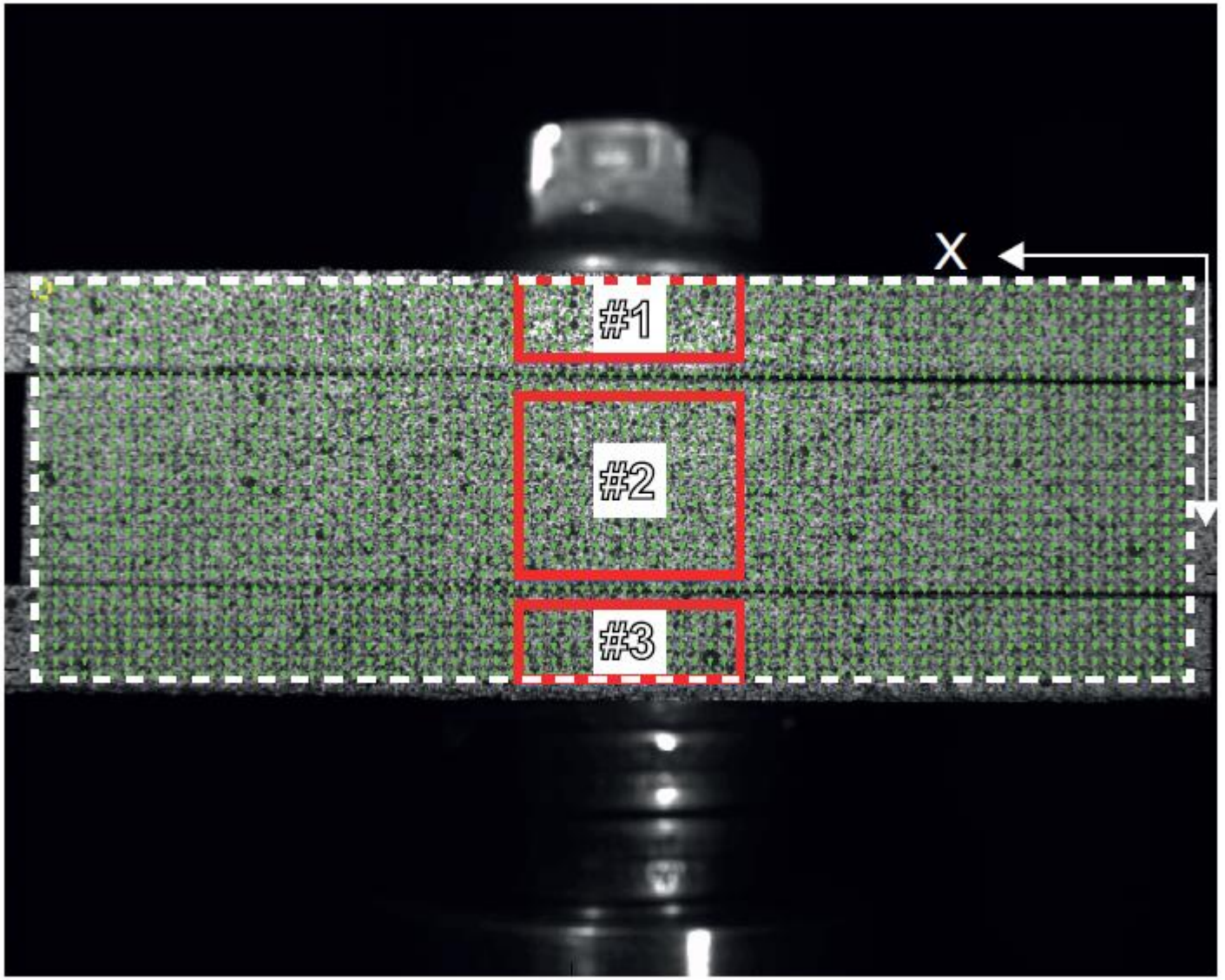
How Classical?

Topic*: “digital image correlation” & “friction coefficient”

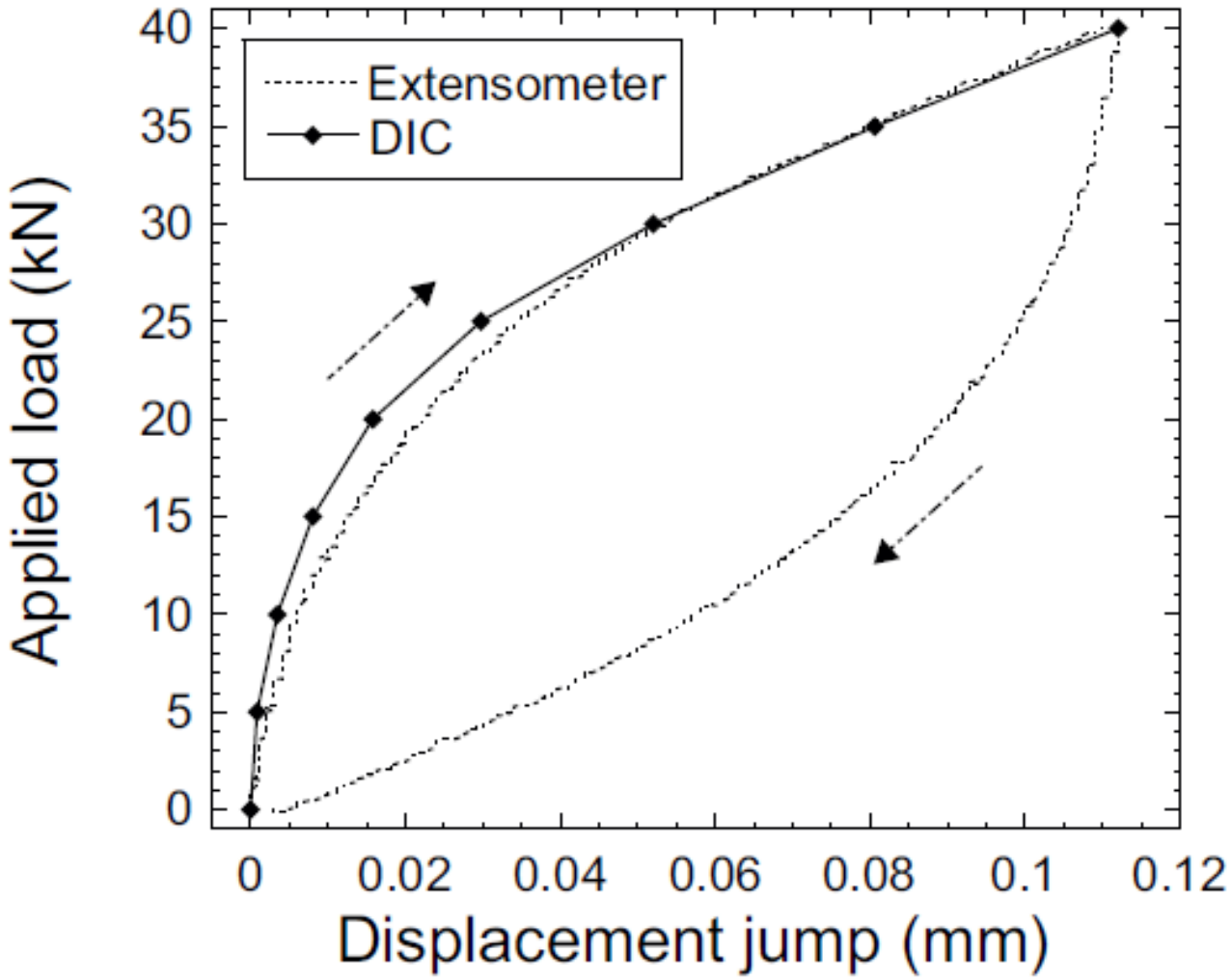


*[*Web of Science*, accessed on January 21, 2021]

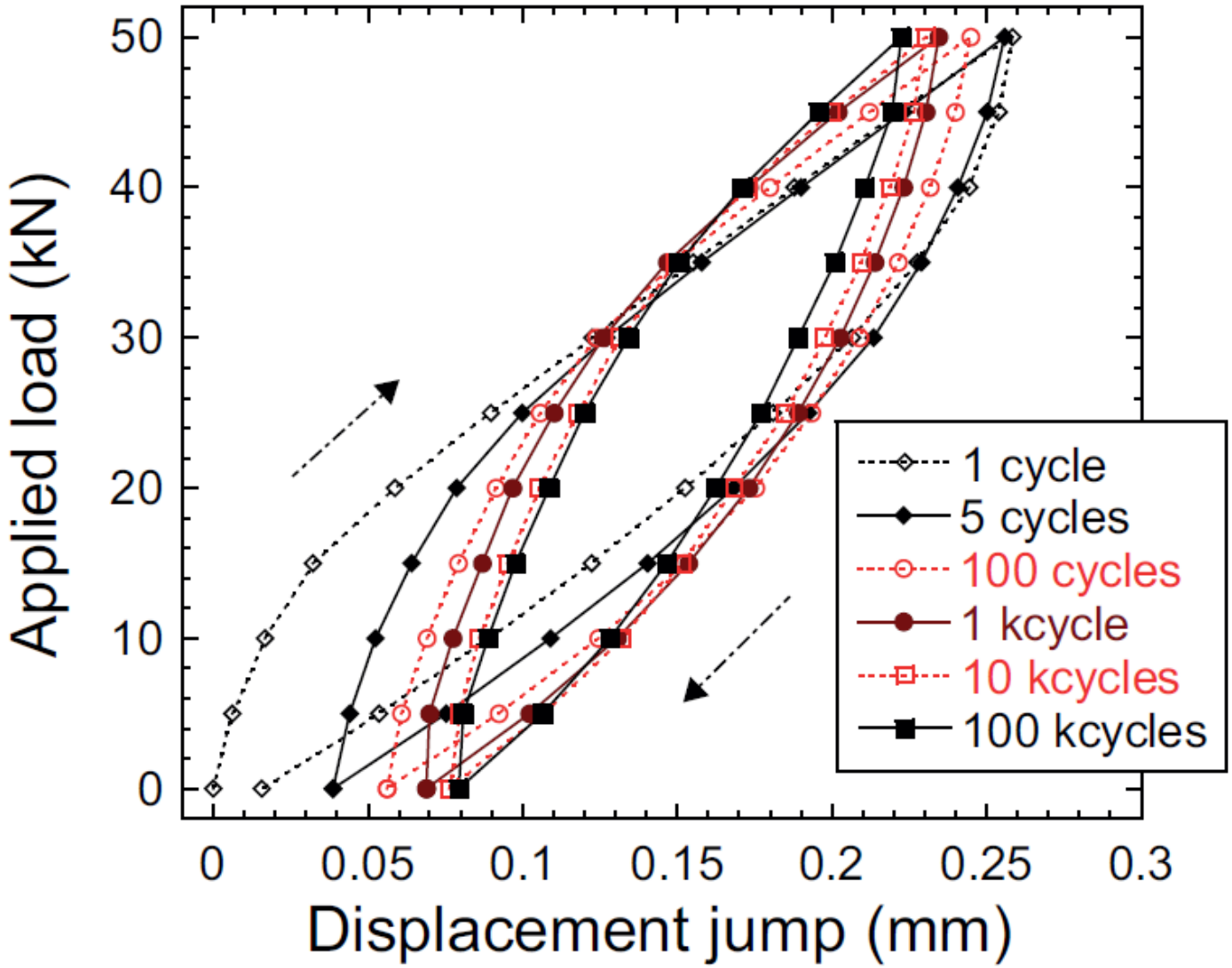
Analysis of Edge



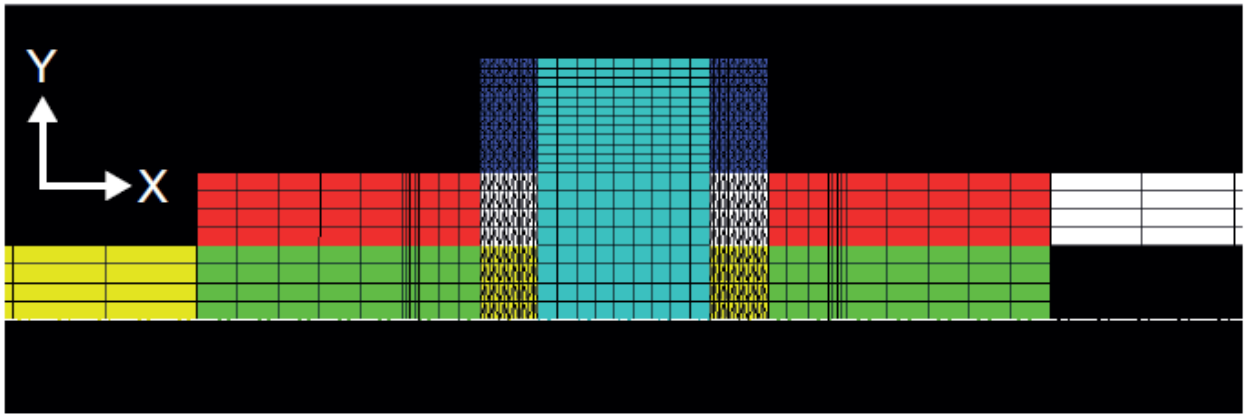
Comparison w/ extensometer
First cycle

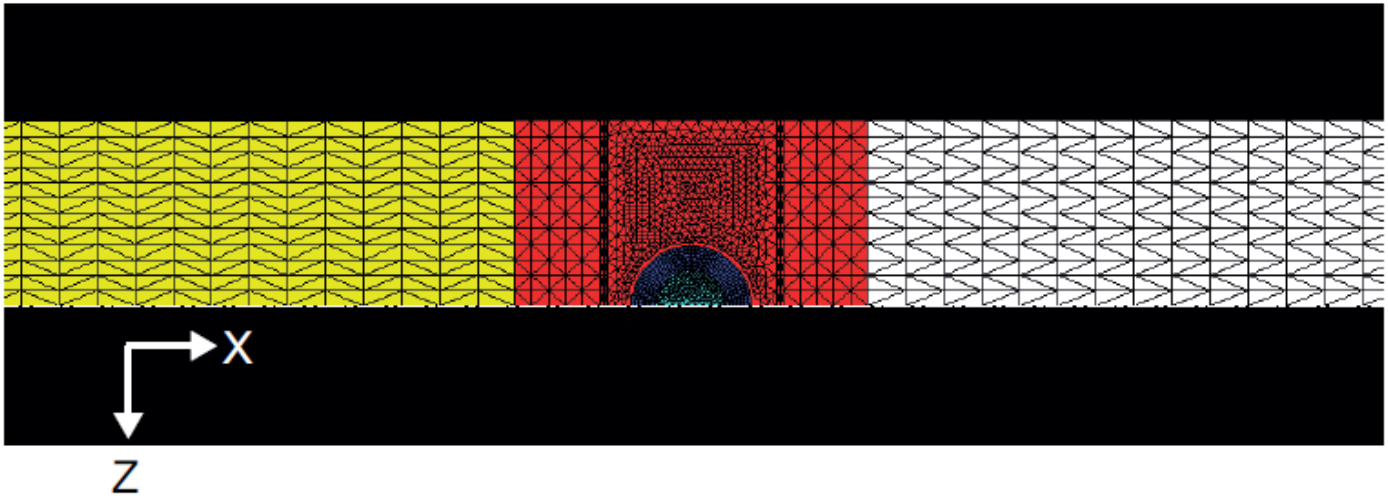


Changes w/ Number of Cycles



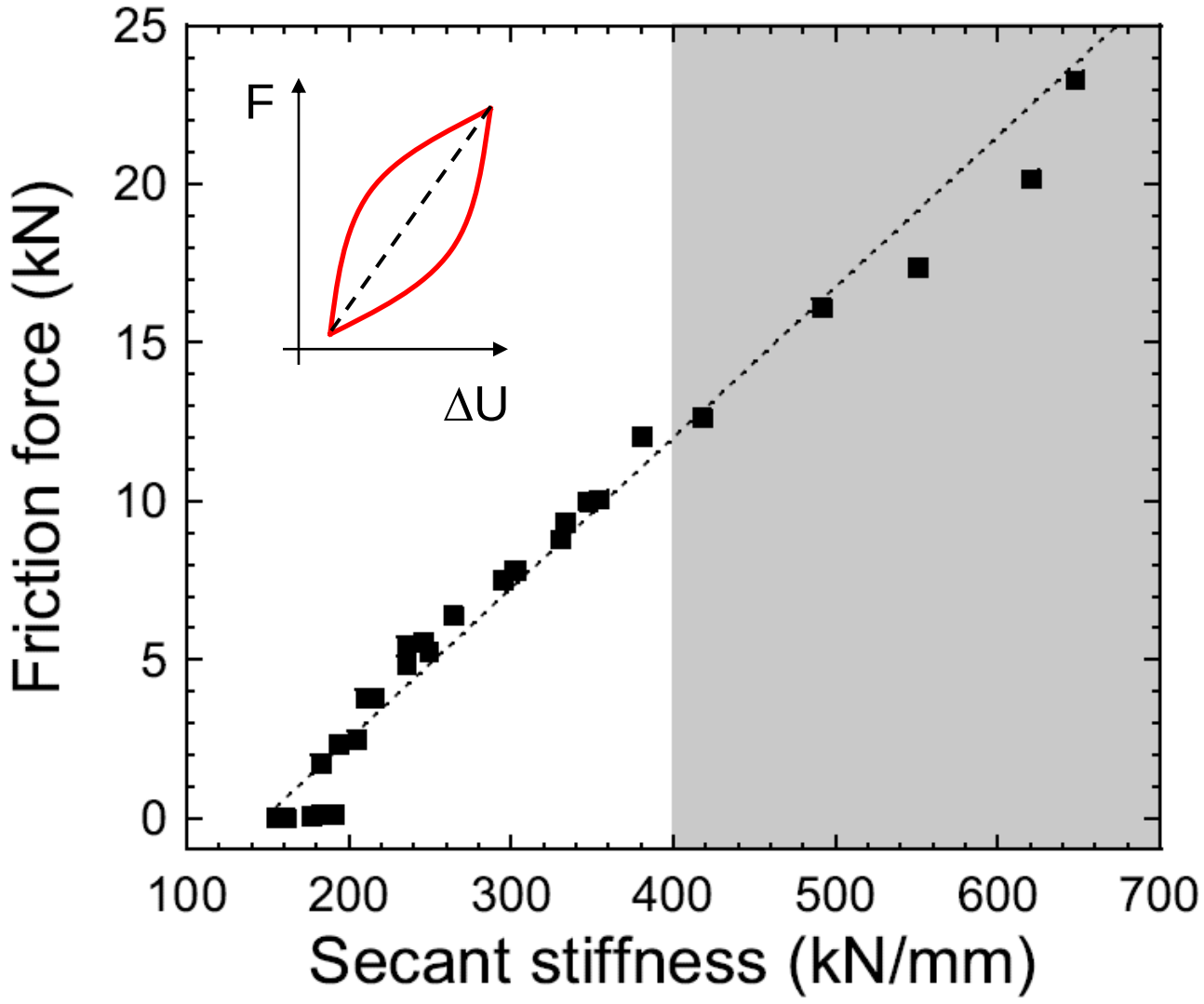
Numerical Model (Cofast*)
Constant Gap + 3D Friction + Symmetry



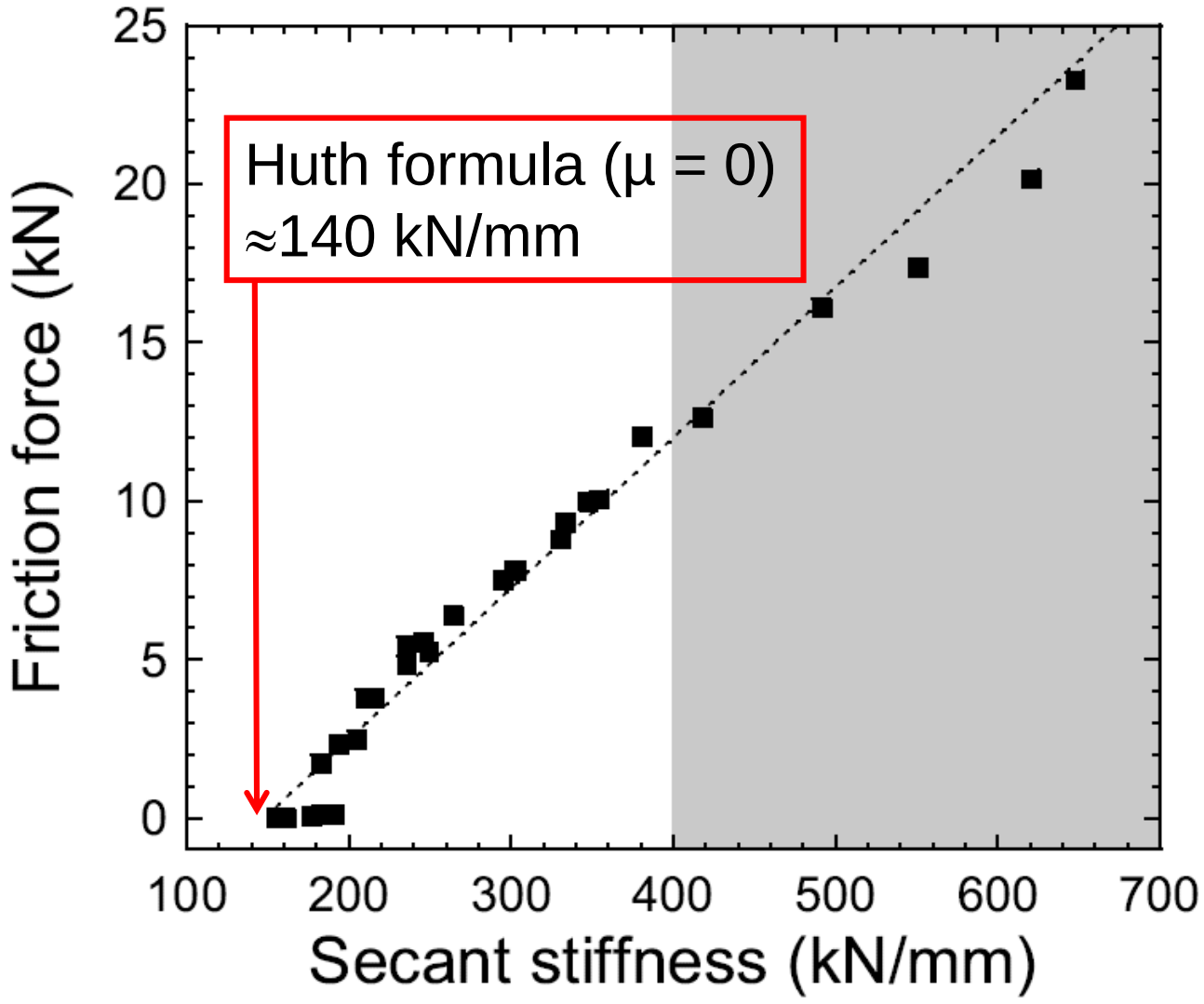


*[Champaney *et al*., 2008, *Comput. Mech*. 42 pp. 305-315]

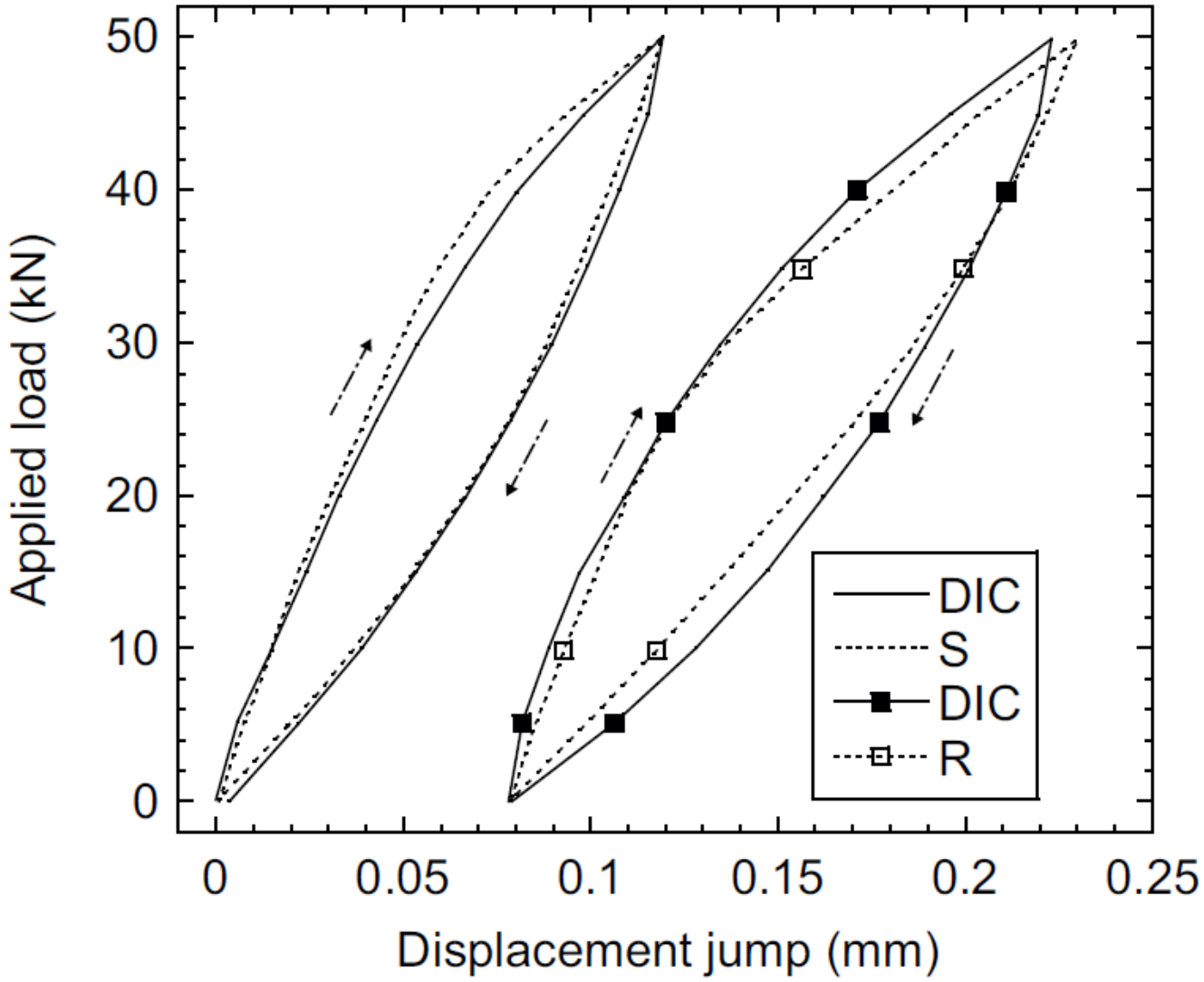
Secant Stiffness (Simulation): Good Indicator



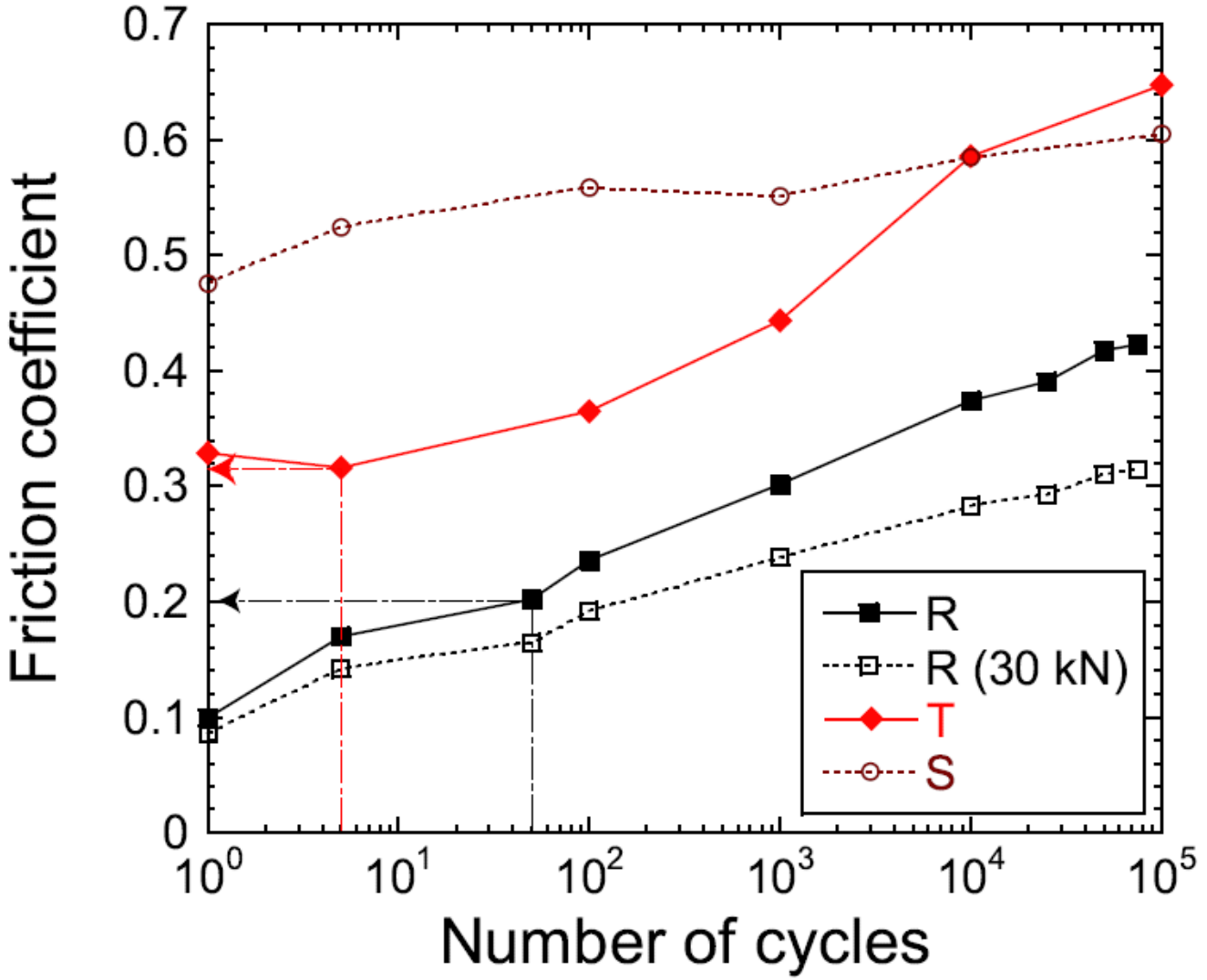
Secant Stiffness (Simulation): Good Indicator



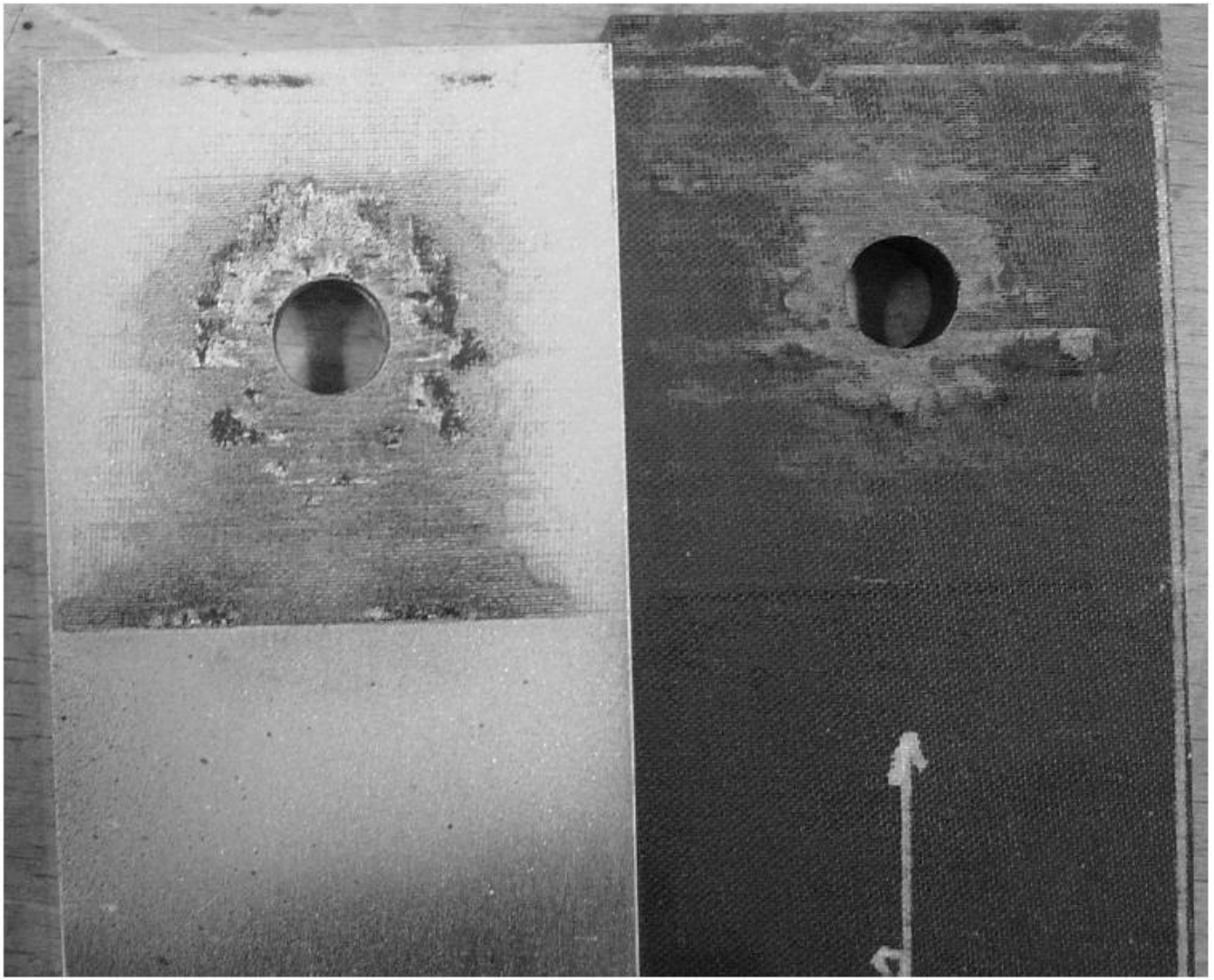
Identification Results



Identification of Friction Coefficient (vs. Number of Cycles)



Post-mortem Observations (T)

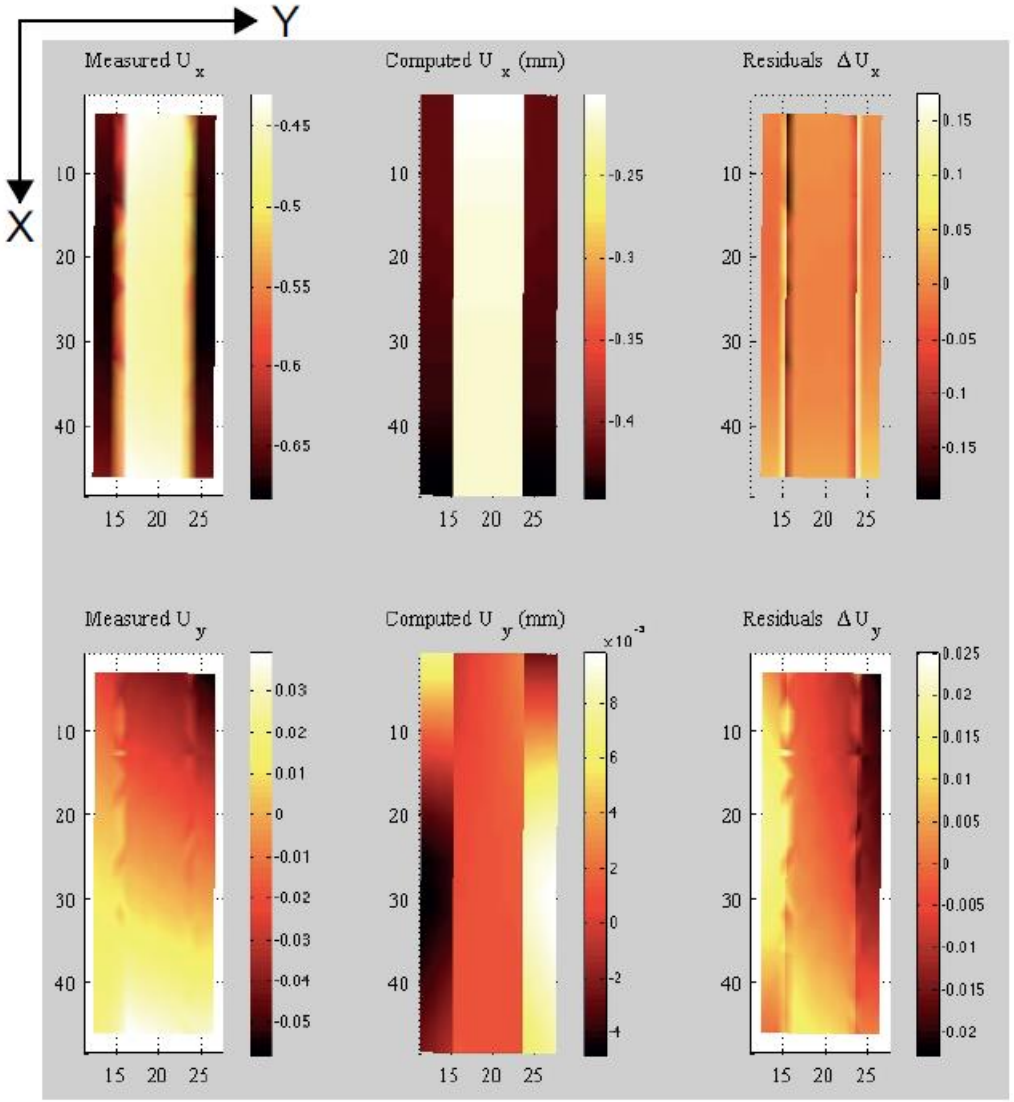


Full-Field Validation

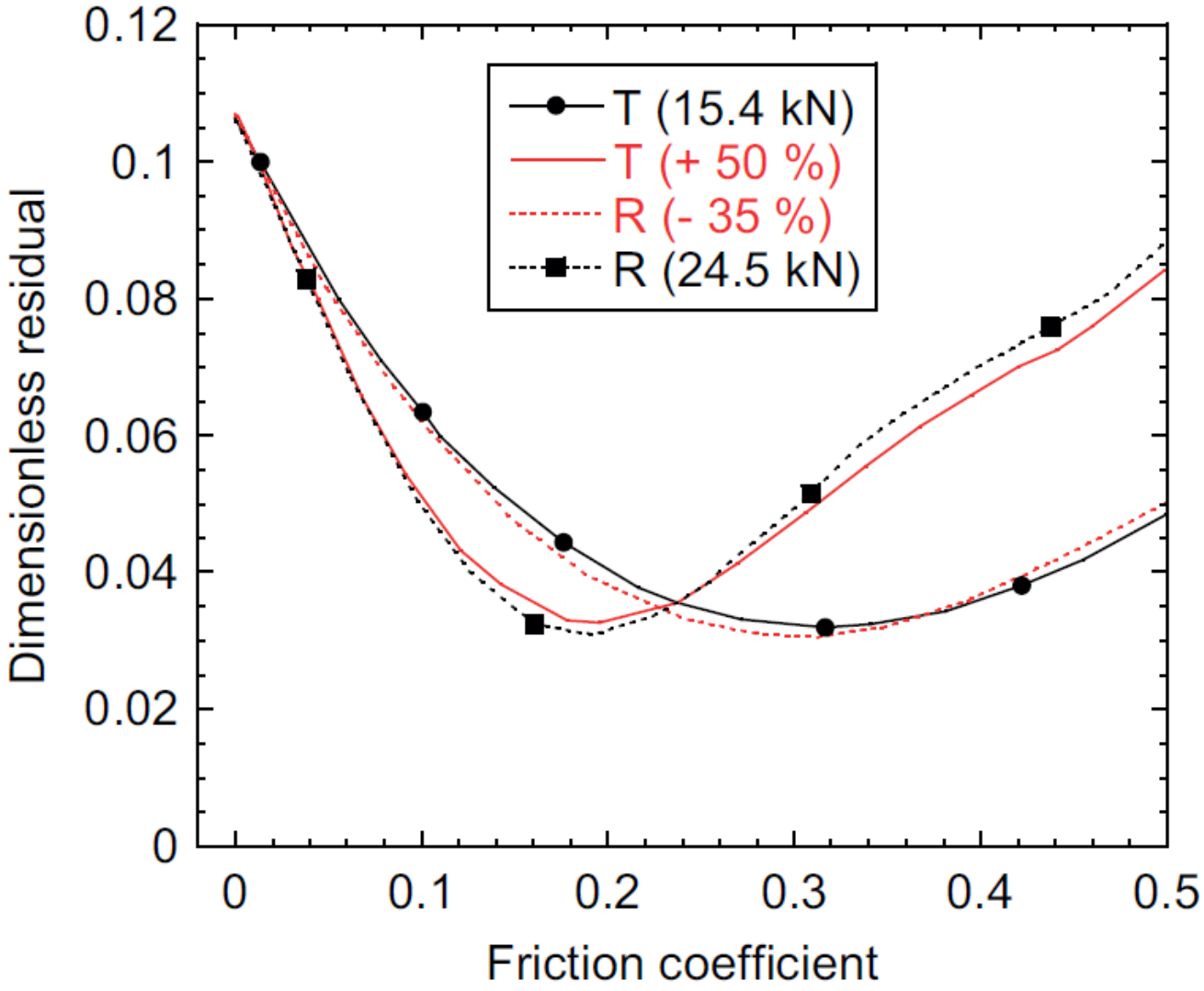
- Measured field $\underline{\mathbf{u}}_{meas}(\underline{\mathbf{x}})$
- Computed field $\underline{\mathbf{u}}_{comp}(\underline{\mathbf{x}})$
- Rigid body motions $\underline{\mathbf{u}}_{rbm}(\underline{\mathbf{x}}) = \underline{\mathbf{u}}_0 + \underline{\boldsymbol{\omega}} \times \underline{\mathbf{x}}$
- Validation residuals

$$\rho = \min_{f,\underline{\mathbf{u}}_0,\underline{\boldsymbol{\omega}}} \sum_i \left(\underline{\mathbf{u}}_{meas}(\underline{\mathbf{x}}_i) - \underline{\mathbf{u}}_{comp}(\underline{\mathbf{x}}_i) - \underline{\mathbf{u}}_0 - \underline{\boldsymbol{\omega}} \times \underline{\mathbf{x}}_i \right)^2$$

Full-Field Validation



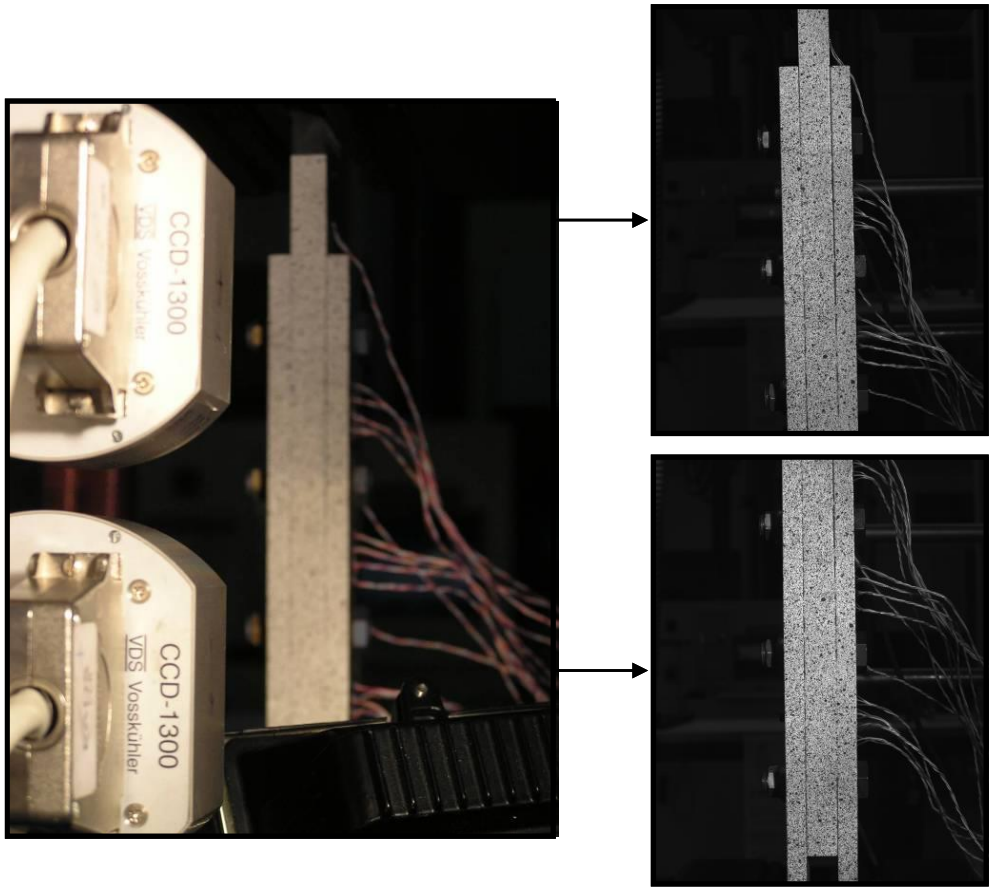
Full-Field Validation

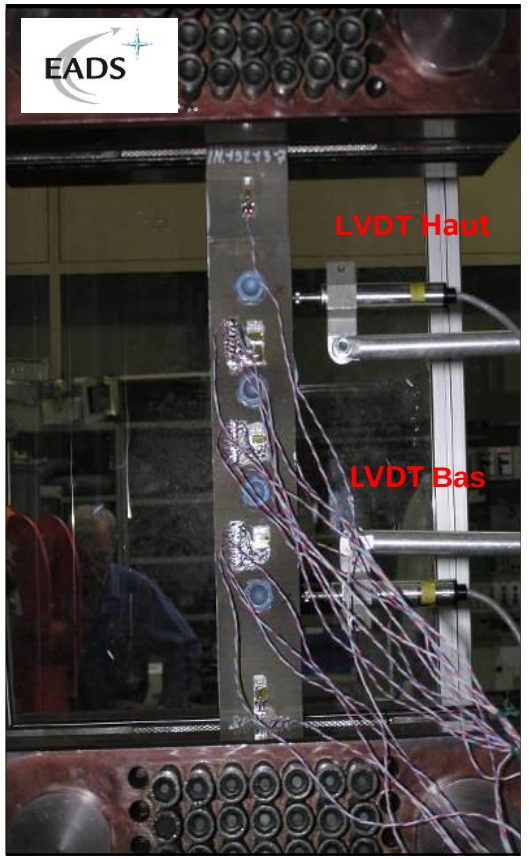


Outline

- Introduction
- Double lap joint w/ single bolt
- **Load transfer in 4-bolt assembly**
- Conclusion & perspectives

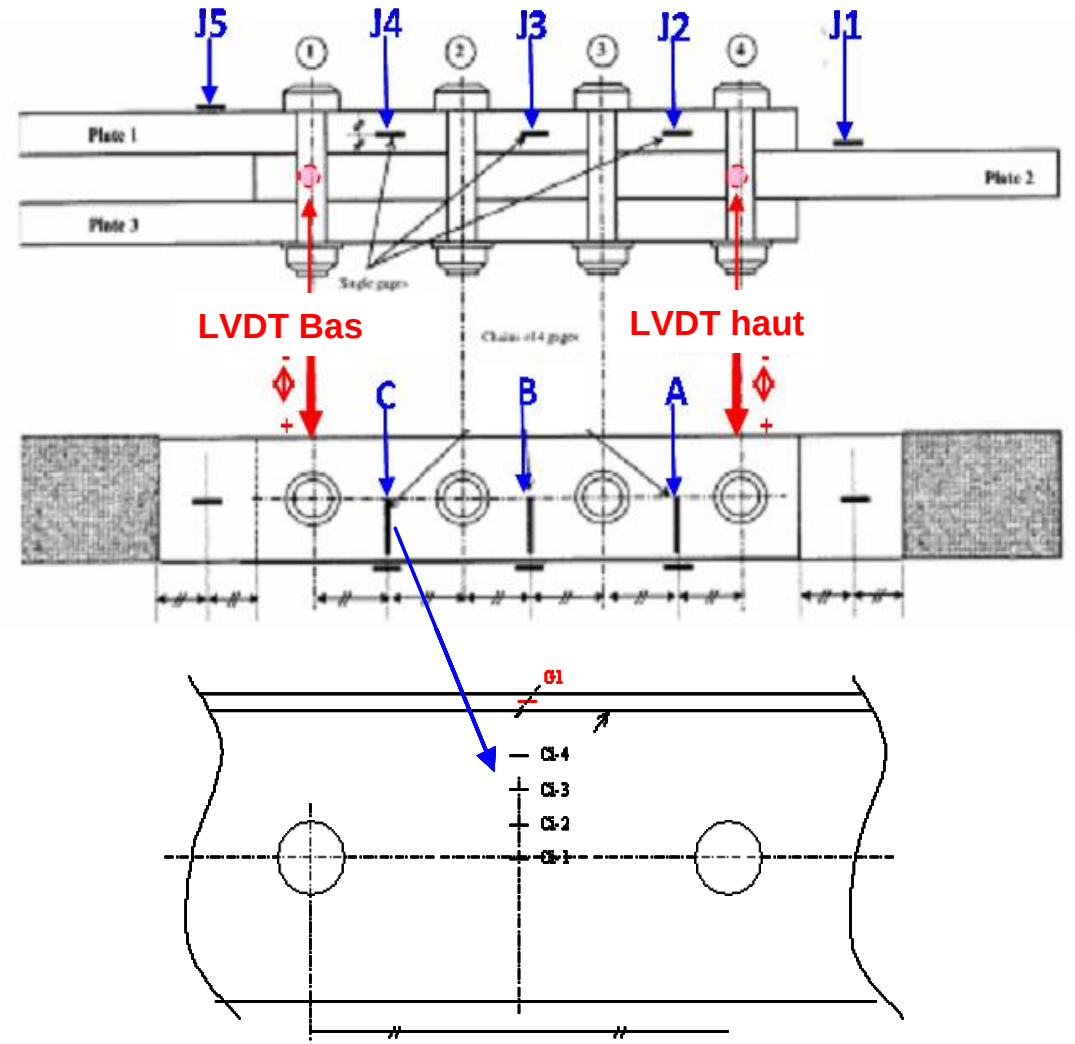
Extension to Multiple Fastening





[Cazes, 2009, *Internal report,* EADS]

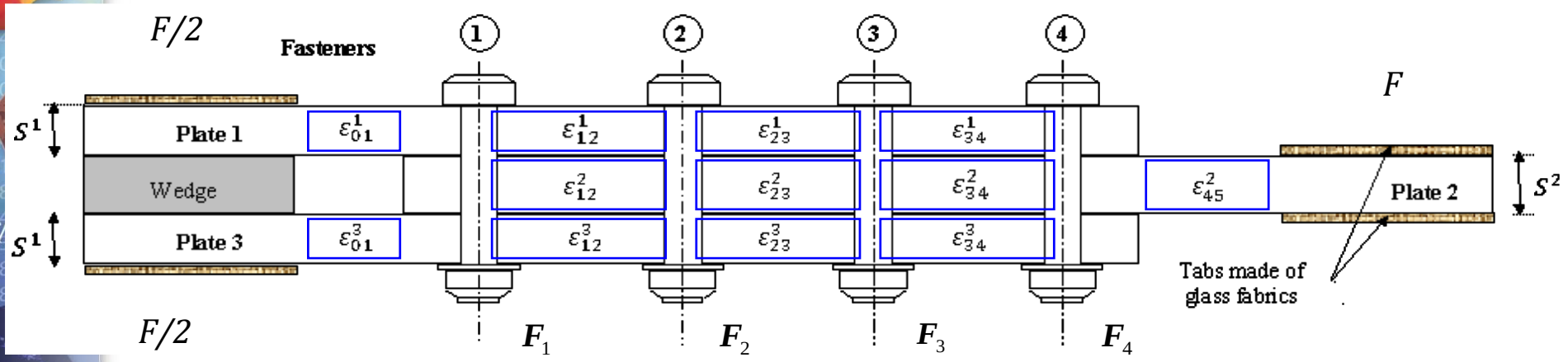
Strain Gauges



17 gauges :

- 14 on the face
- 3 on the edge

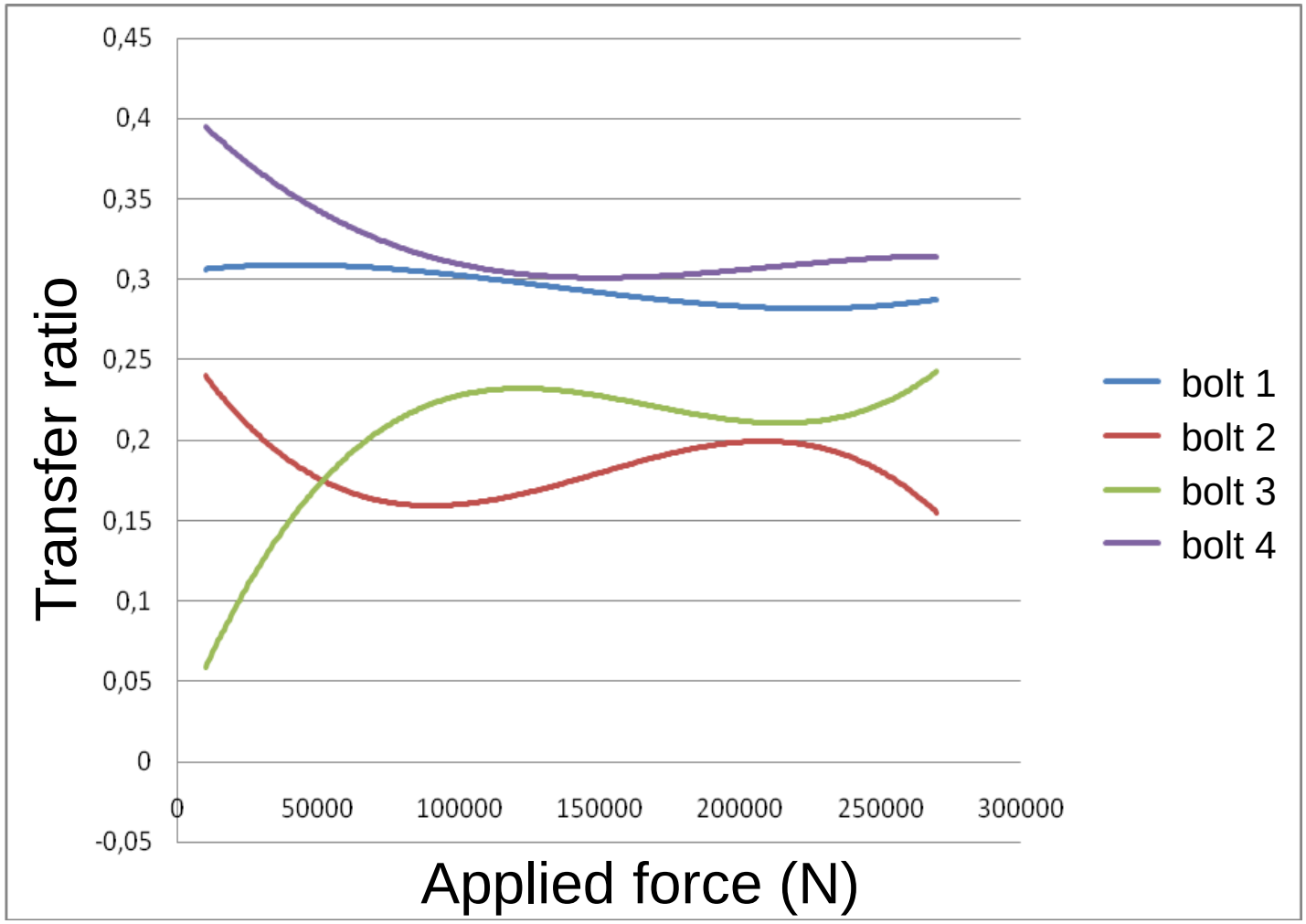
Transfer Ratio?



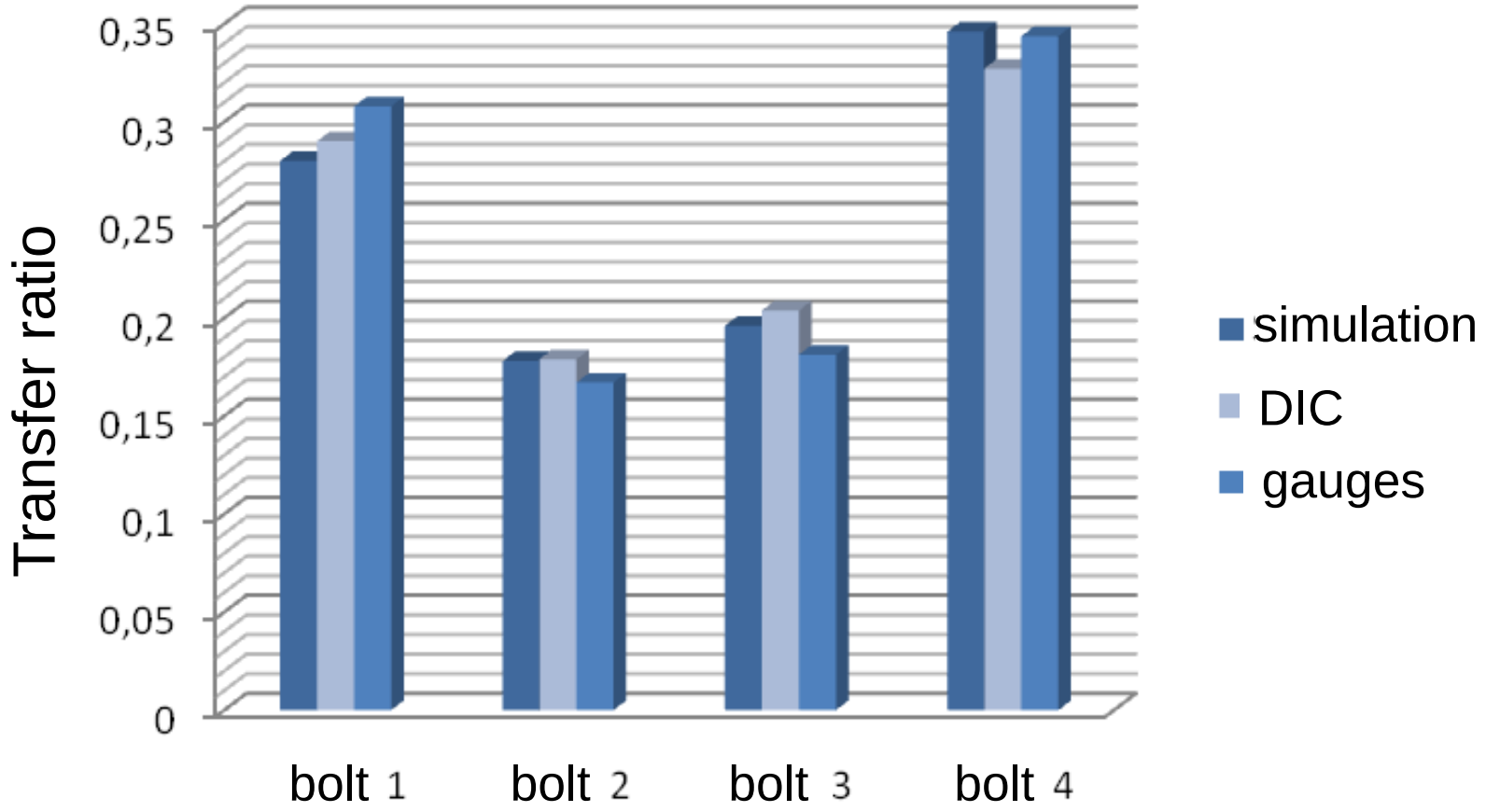
$$\begin{cases} F = E^1 S^1 (\varepsilon_{01}^1 + \varepsilon_{01}^3) \\ F - (F_1^1 + F_1^3) = E^1 S^1 (\varepsilon_{12}^1 + \varepsilon_{12}^3) \\ F - (F_1^1 + F_1^3 + F_2^1 + F_2^3) = E^1 S^1 (\varepsilon_{23}^1 + \varepsilon_{23}^3) \\ F - (F_1^1 + F_1^3 + F_2^1 + F_2^3 + F_3^1 + F_3^3) = E^1 S^1 (\varepsilon_{34}^1 + \varepsilon_{34}^3) \\ F = F_1 + F_2 + F_3 + F_4 \end{cases}$$

$$\begin{cases} F = E^2 S^2 \varepsilon_{45}^2 \\ F_1^2 + F_2^2 + F_3^2 = E^2 S^2 \varepsilon_{34}^2 \\ F_1^2 + F_2^2 = E^2 S^2 \varepsilon_{23}^2 \\ F_1^2 = E^2 S^2 \varepsilon_{12}^2 \\ F = F_1 + F_2 + F_3 + F_4 \end{cases}$$

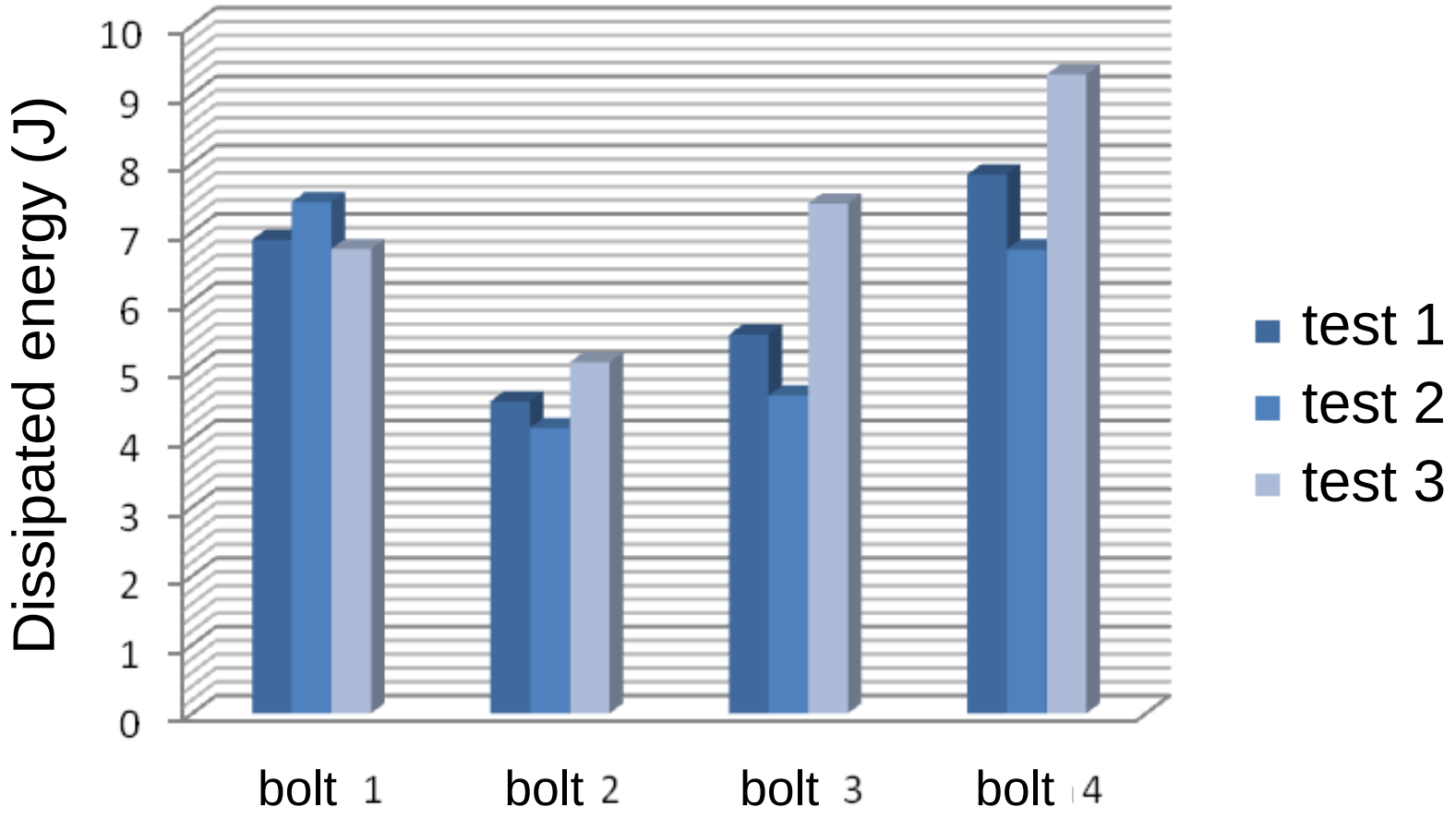
Transfer Ratio vs. Applied Force



Validation


Transfer ratio
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
bolt 1
bolt 2
bolt 3
bolt 4
simulation
DIC
gauges

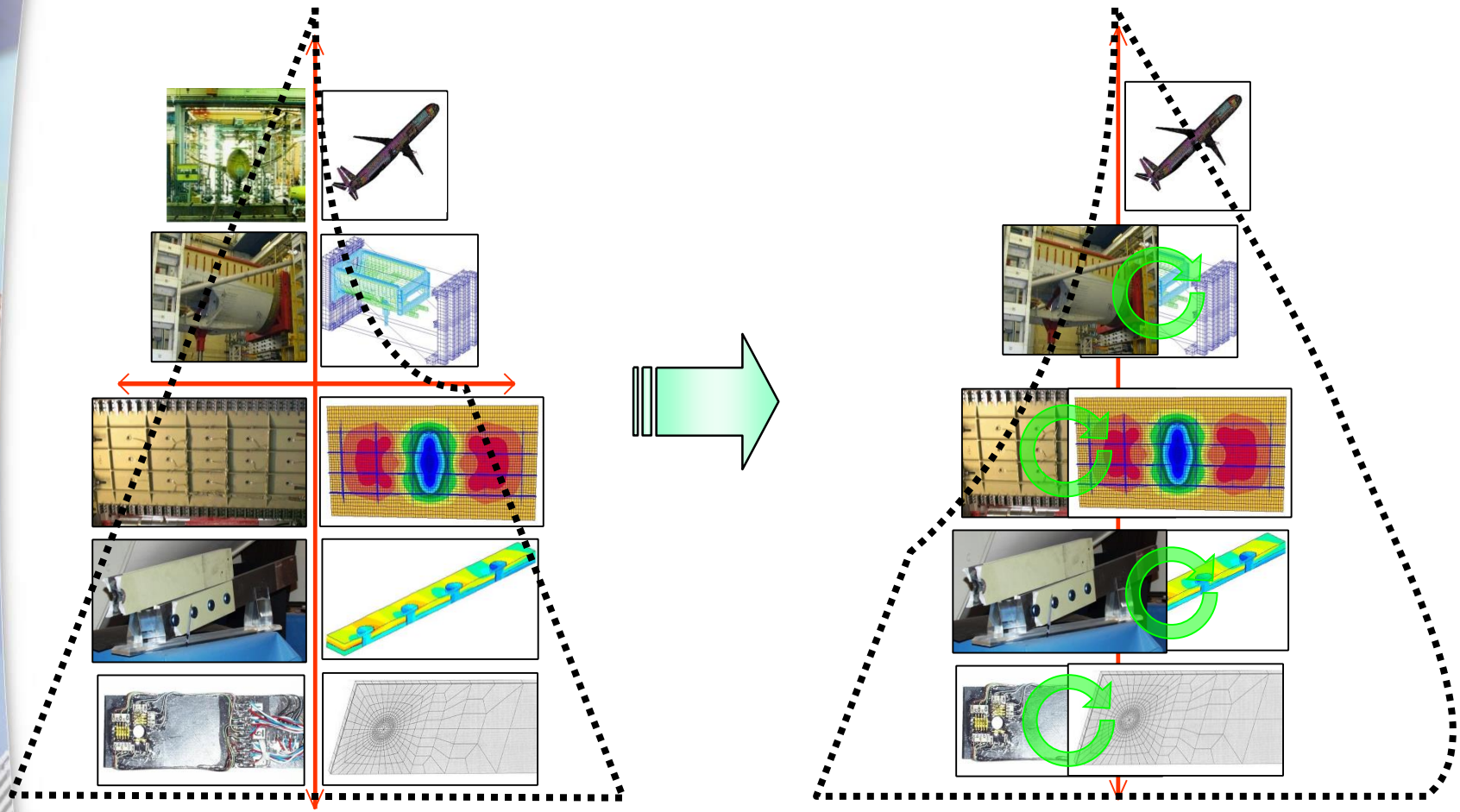
Dissipated Energy



Conclusion

- Improvement of experimental protocol
- In spite of difficult context and low image definition, DIC has shown its ability to provide quantitative information in analysis of single and multi-bolt assemblies
- Evolution of friction coefficient and transfer ratios
- Calculation of dissipated energy

Outlook

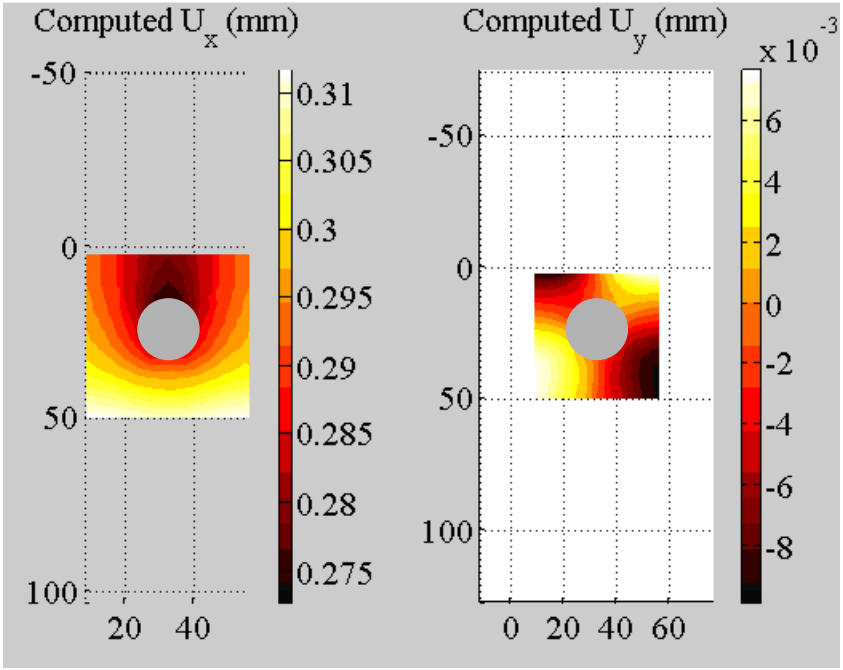


Test / simulation interactions

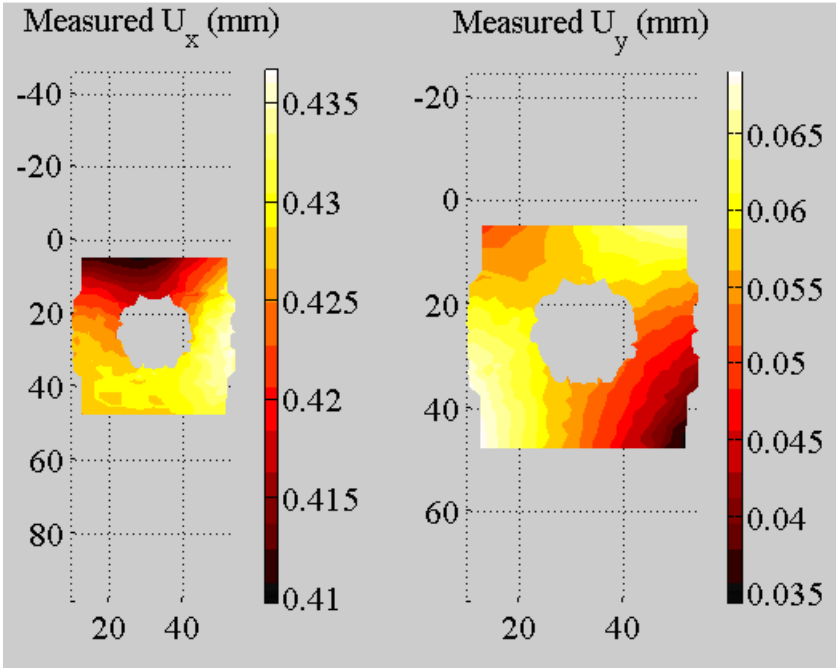
Merci de votre attention !

Computed / measured fields

COFAST*

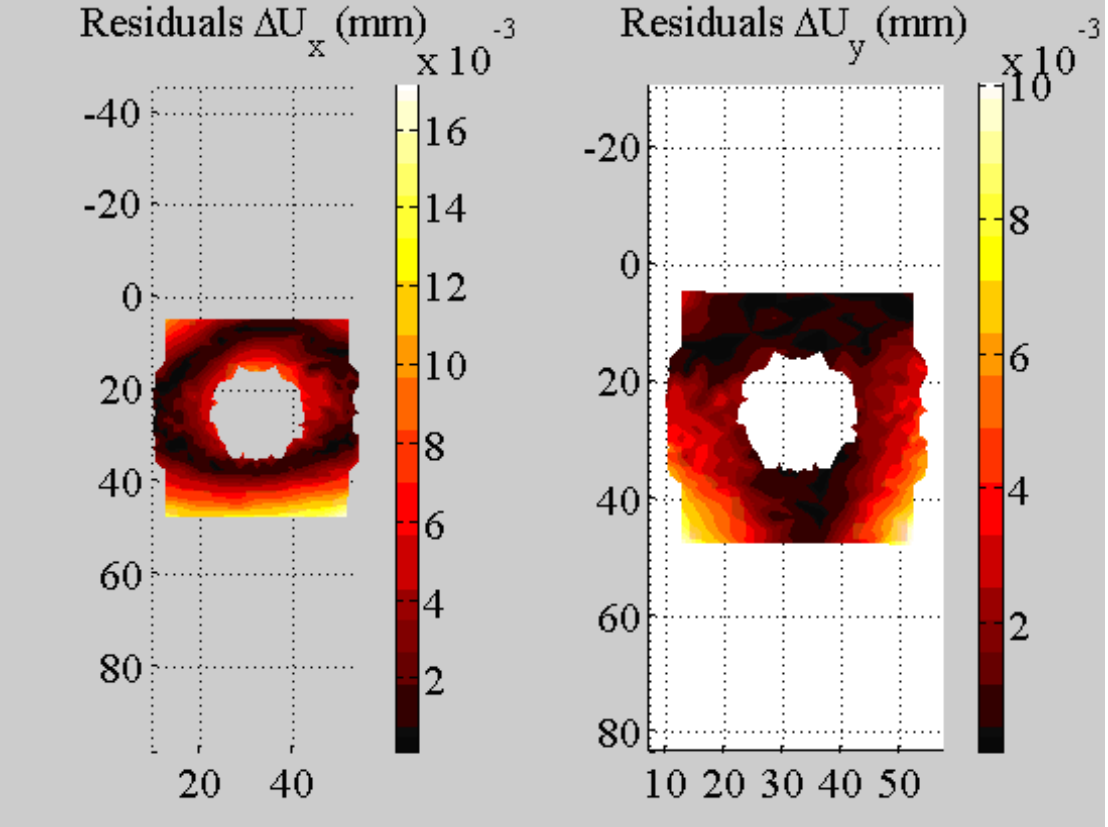


Q4-DIC**



*[Champaney *et al.*, 1999, *Comput. Struct.* 73 249-266]
**[Besnard *et al.*, 2006, *Exp. Mech.* 46 789-803]

Identification residual



Tf = 6000 N