Liege University– Faculty of Applied Sciences
Department ArGEnCo
Structural Engineering Sector

Development and implementation of a methodology for hybrid fire testing applied to concrete structures with elastic boundary conditions

by

Ana SAUCA

Outline of the Presentation

Introduction

Theoretical developments

Numerical analysis of the case study

Experimental studies

Conclusions and future work

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Introduction

How a structure behaves when exposed to fire?

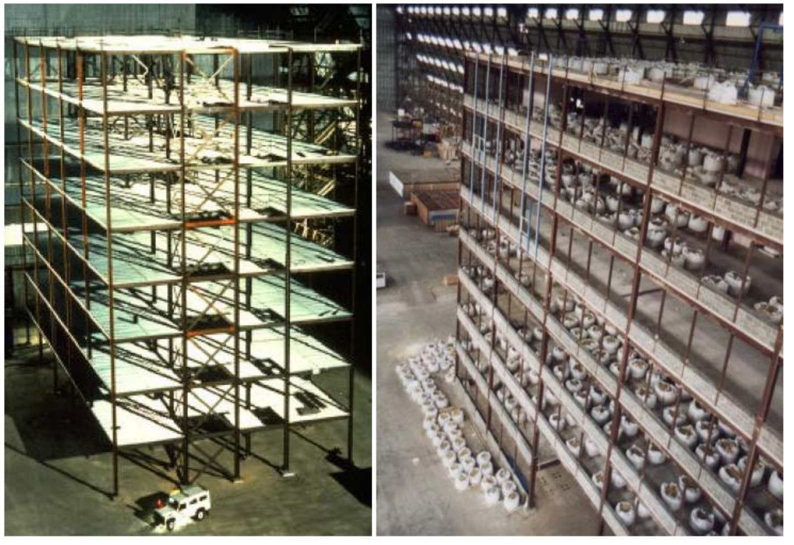
(TFRI, 2007)

Individual testing

- Individual structural elements
- Unreal boundary conditions

Full scale testing

- Real boundary conditions
- Expensive approach



(Cardington test)

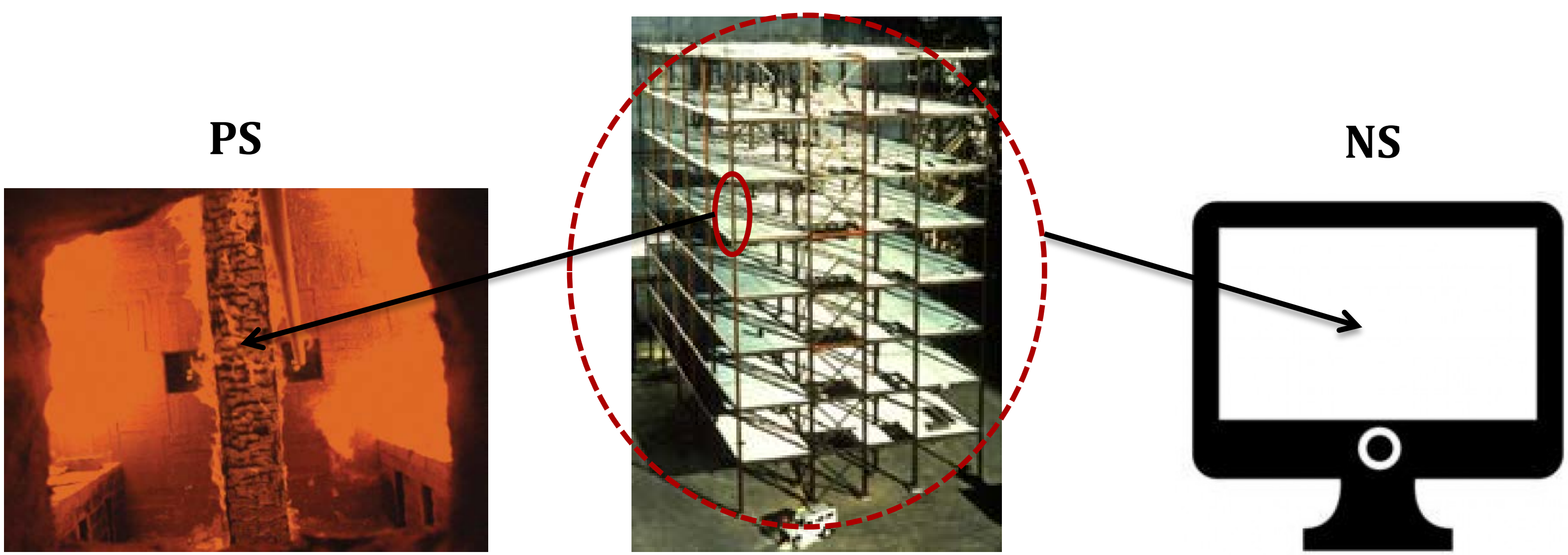
Introduction

Hybrid fire testing (HFT)

- Testing individual structural elements
- Accounting for the effect of the surrounding
- Substructures:

  Physical substructure (PS) tested in the furnace

  Numerical substructure (NS) modelled aside

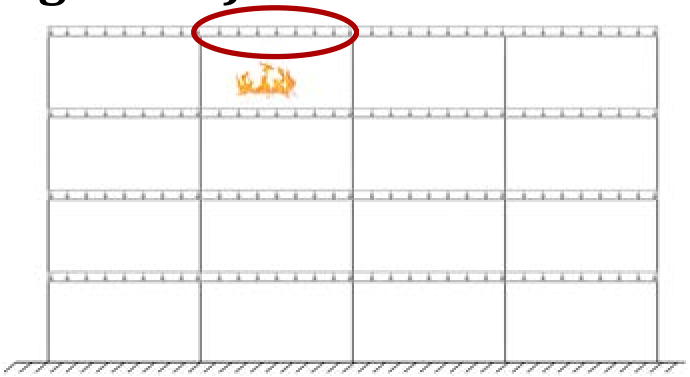


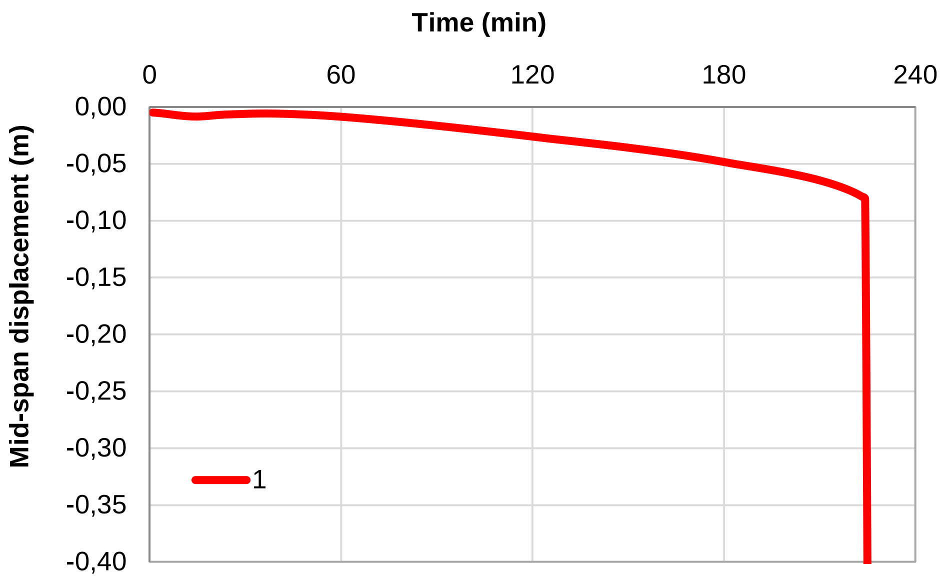
(TFRI, 2007) *(Cardington test)*

Boundary Conditions in Fire Tests

Configurations of the beam (moment resisting frame)

1. Full scale test



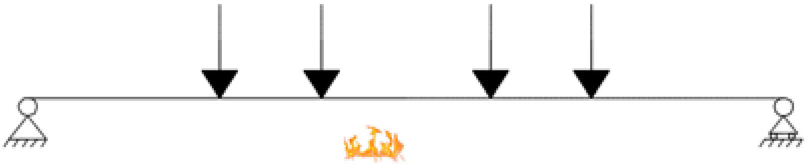


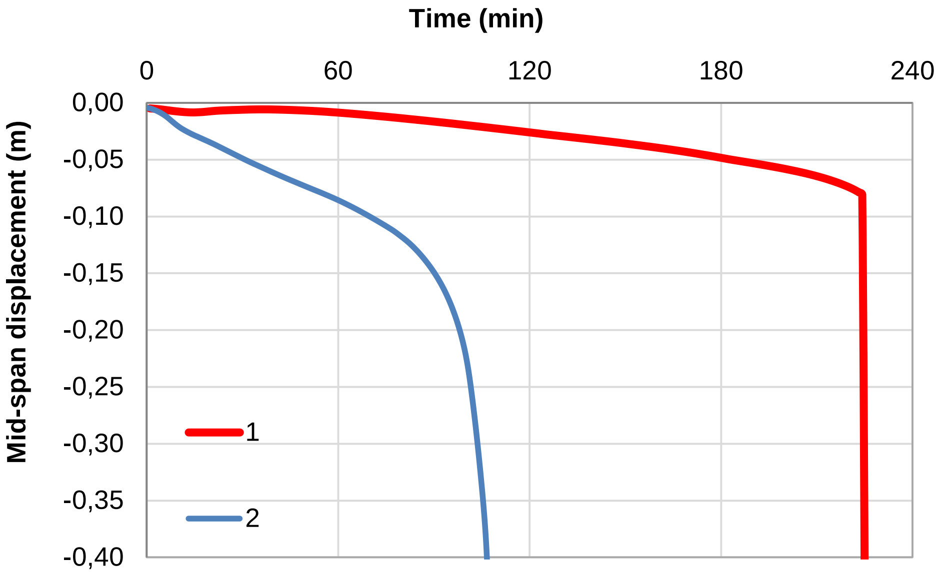
Boundary Conditions in Fire Tests

Configurations of the beam (moment resisting frame)

1. Full scale test

2. Simply supported test





Boundary Conditions in Fire Tests

Configurations of the beam (moment resisting frame)

1. Full scale test

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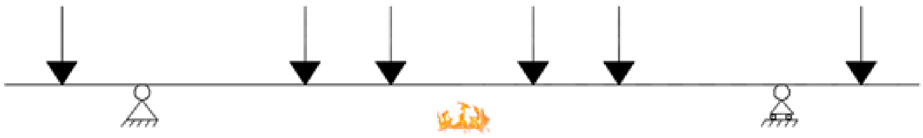
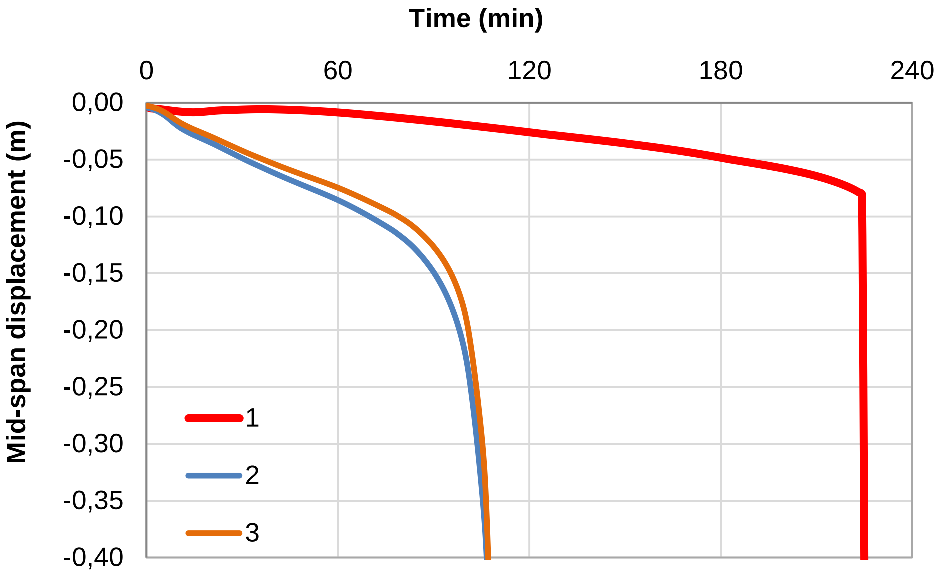


3. Simply supported test (moment on the supports induced)



Boundary Conditions in Fire Tests

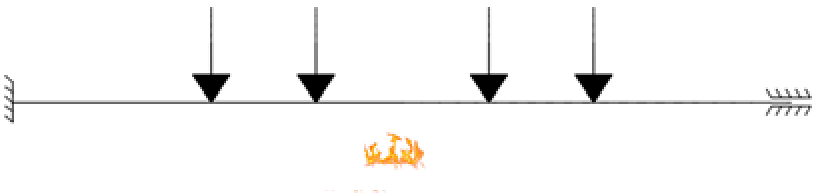
Configurations of the beam (moment resisting frame)

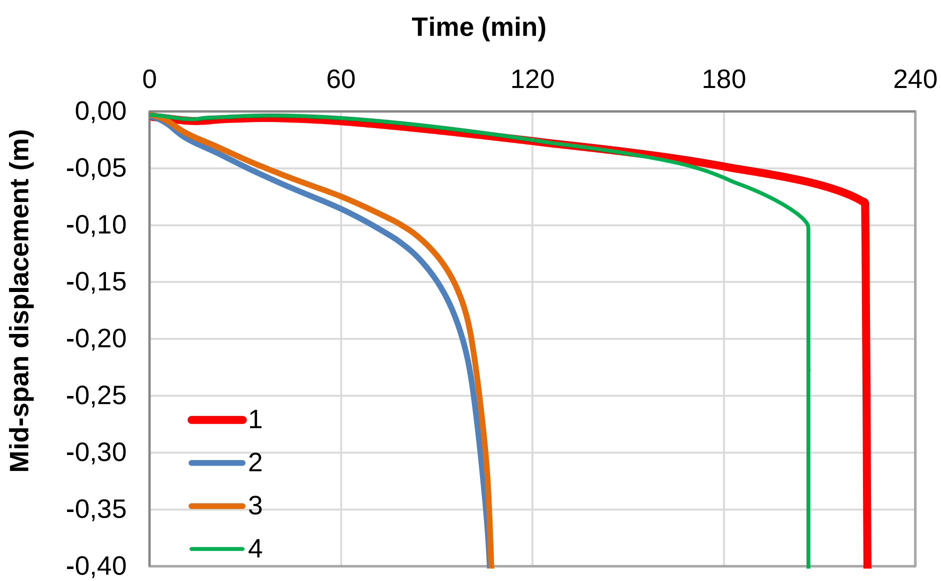
1. Full scale test

2. Simply supported test

3. Simply supported test (moment on the supports induced)

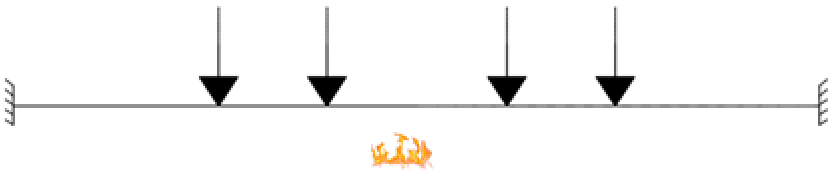
4. Fixed rotations test (free thermal expansion)





Boundary Conditions in Fire Tests

Configurations of the beam (moment resisting frame)



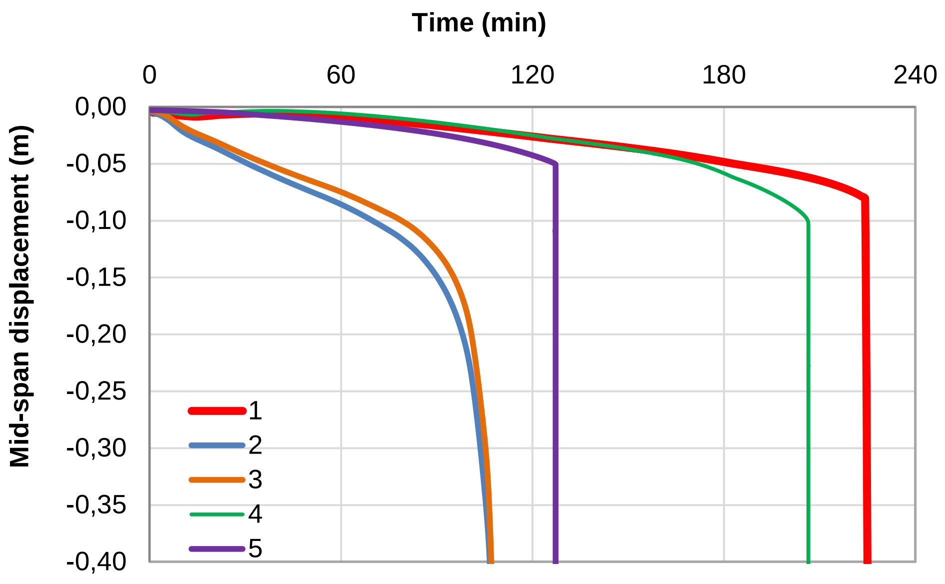
1. Full scale test

2. Simply supported

3. Simply supported test (moment on the supports induced)

4. Fixed rotations test (free thermal expansion)

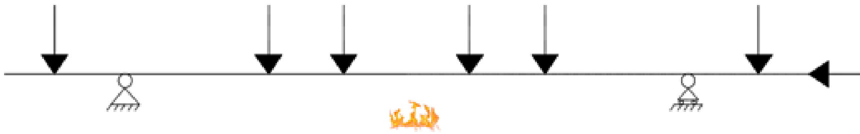
5. Fixed rotations test (blocked thermal expansion)

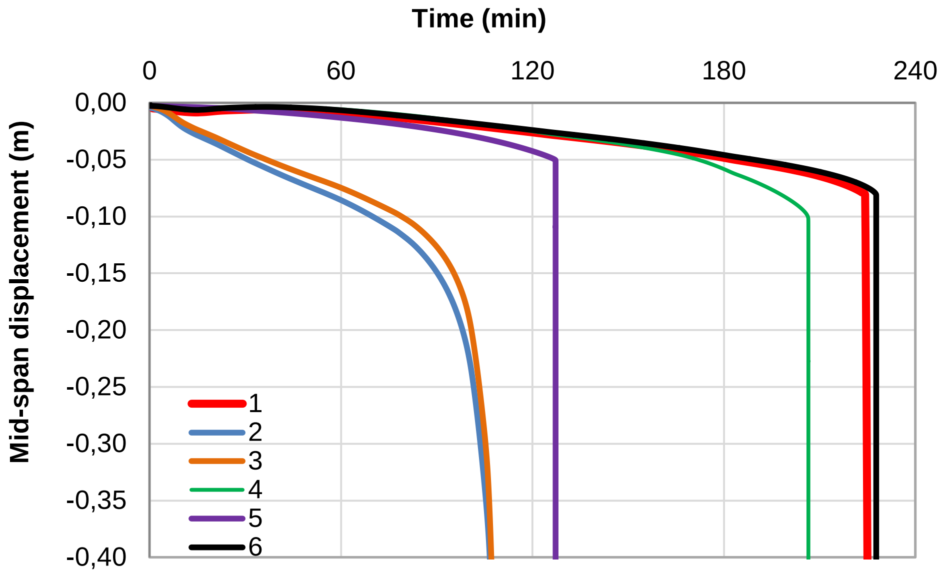


Boundary Conditions in Fire Tests

Configurations of the beam (moment resisting frame)

1. Full scale test
2. Simply supported test
3. Simply supported test (moment on the supports induced)
4. Fixed rotations test (free thermal expansion)
5. Fixed rotations test (blocked thermal expansion)
6. HFT





Challenges of HFT

Errors → modeling errors, experimental errors

Derive proper methods

In real HFT, the delay in communication is crucial

Development of a general methodology (not site dependent)

Research Objectives

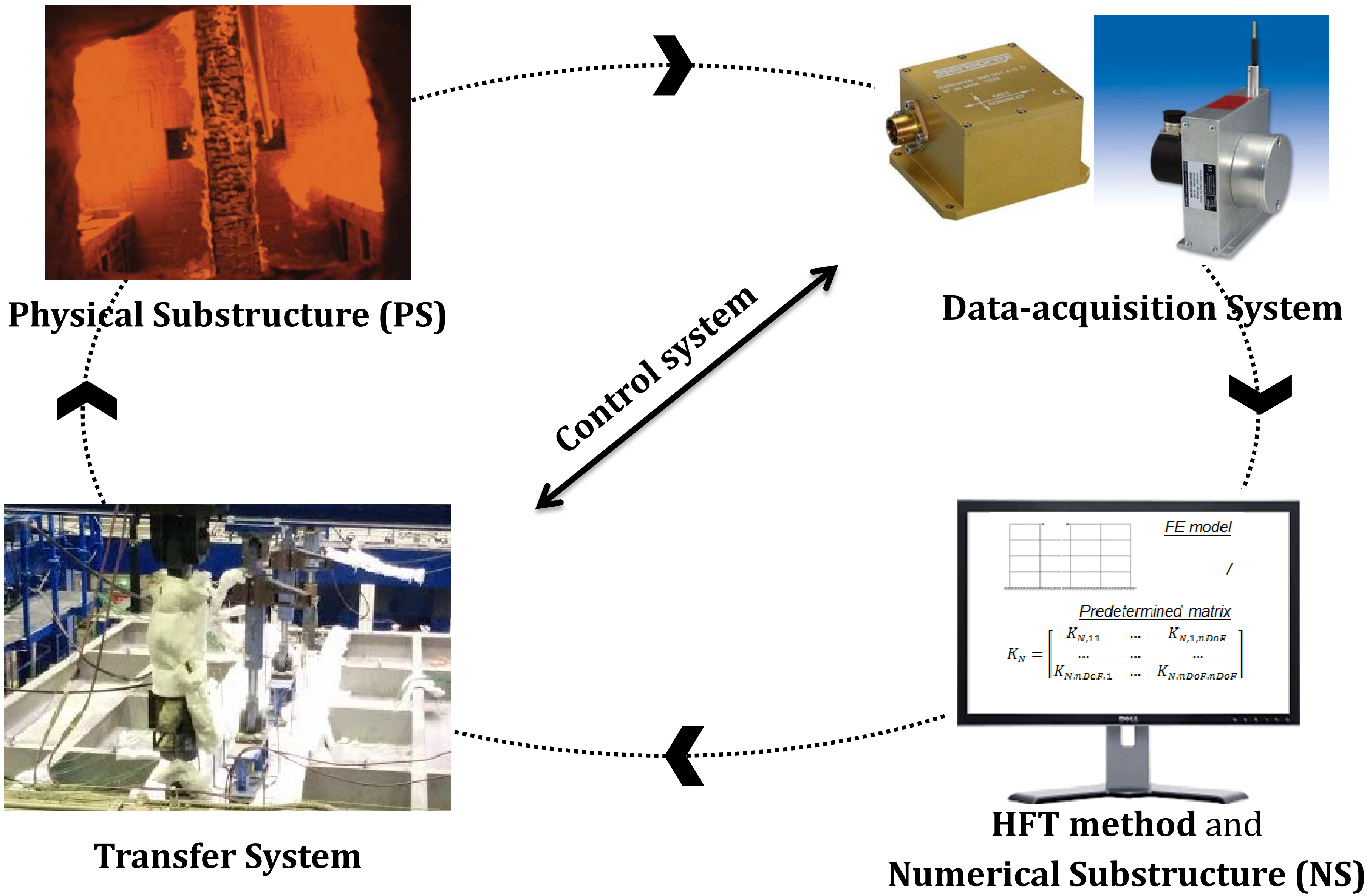
Review the concept in fire field

Development of a new method for HFT

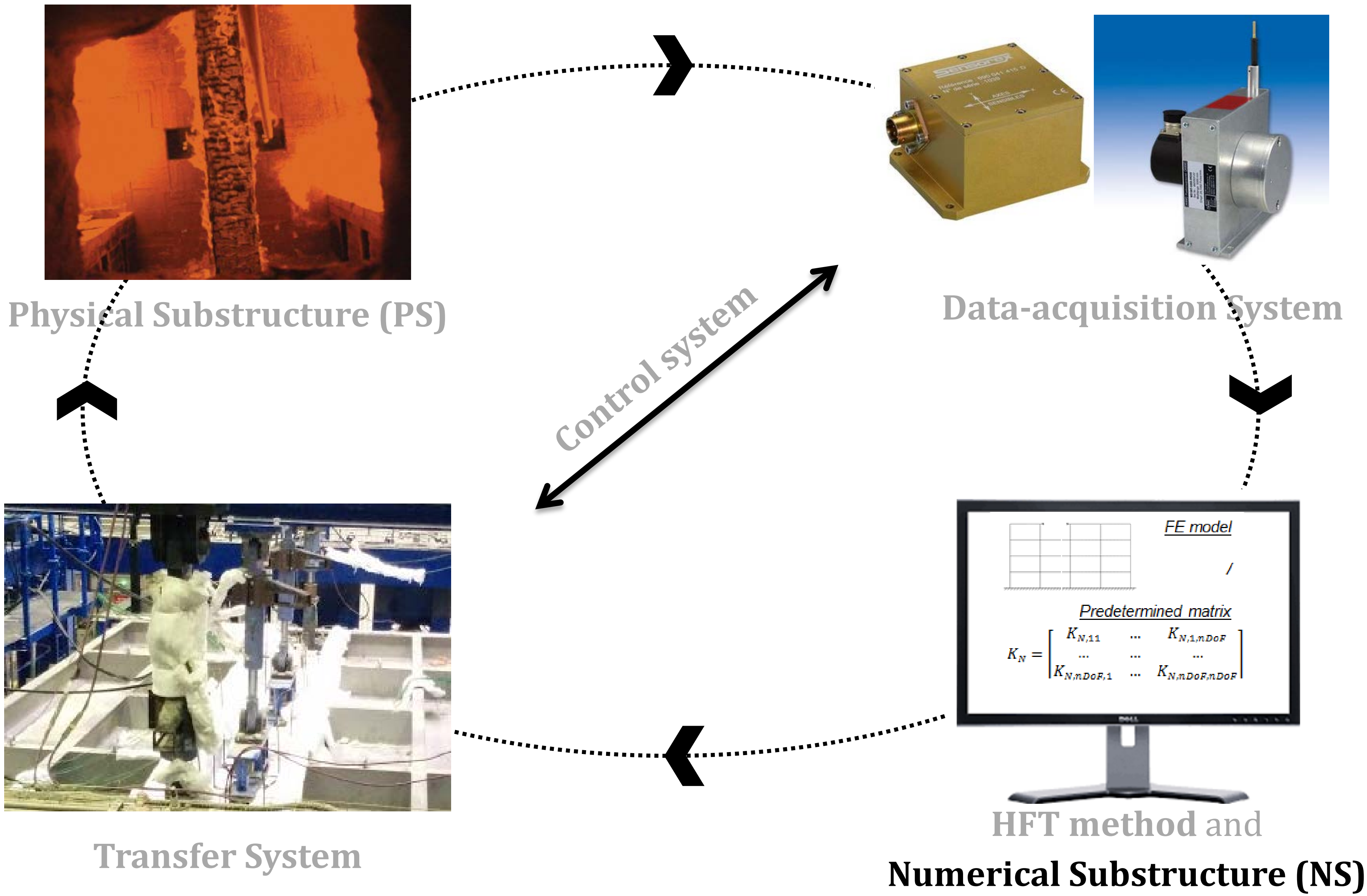
Method implementation in CERIB fire testing facility

Experimental validation

Control Process



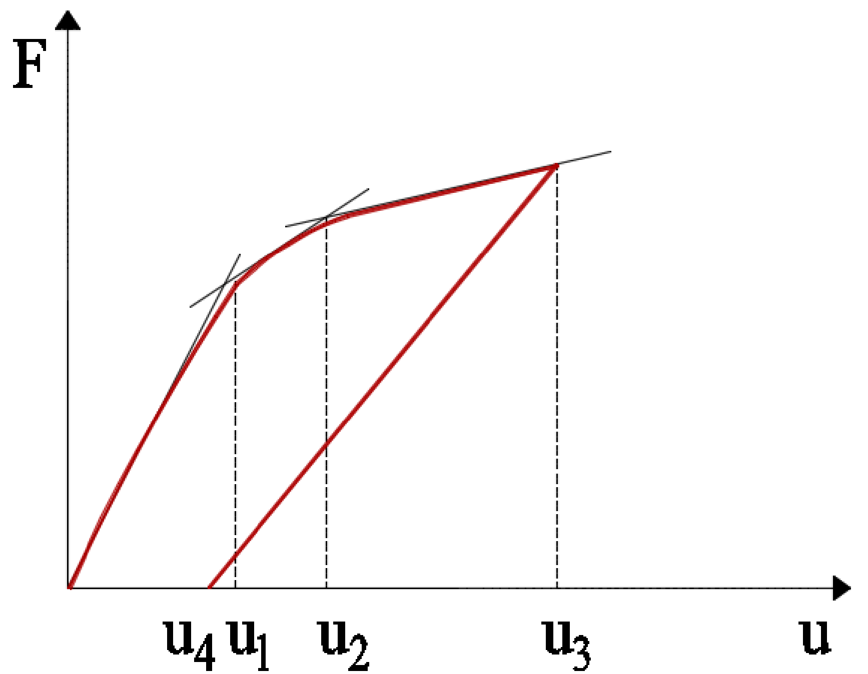
Control Process



The Representation of the NS

Finite element model (FEM) for elevated temperatures

Predetermined matrix for ambient temperatures



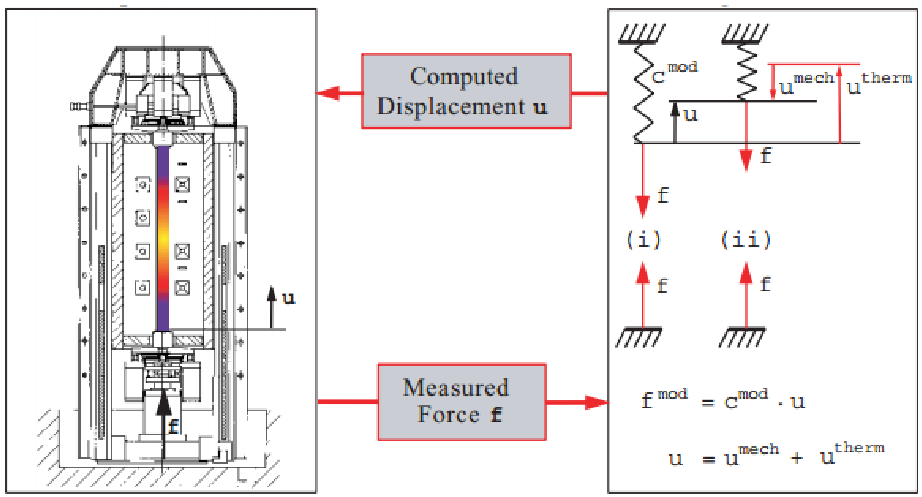
(Predetermined matrix → multi-linear)

Seismic vs. Fire Field

Criteria	Seismic field	Fire field
Type of tests	Slow tests possible	Real time needed*
Solved equation	Dynamic equation needed	Static equations possible
Size of the PS	Small scale possible	Real scale needed*
Transfer system and *data-acquisition system*	Ambient temperature	Elevated temperatures

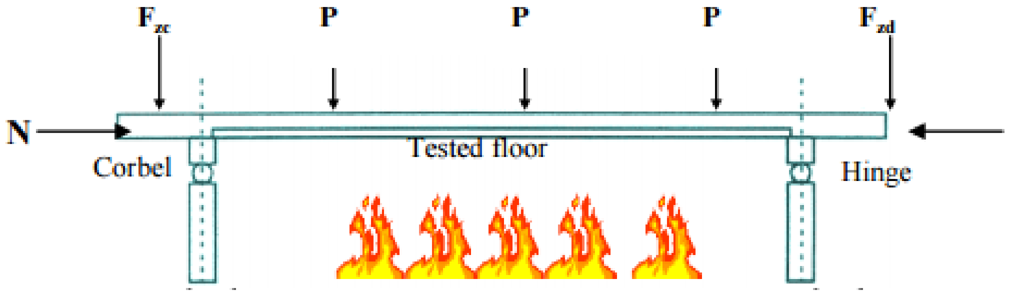
* Except for specific elements

State of the Art in the Fire Field



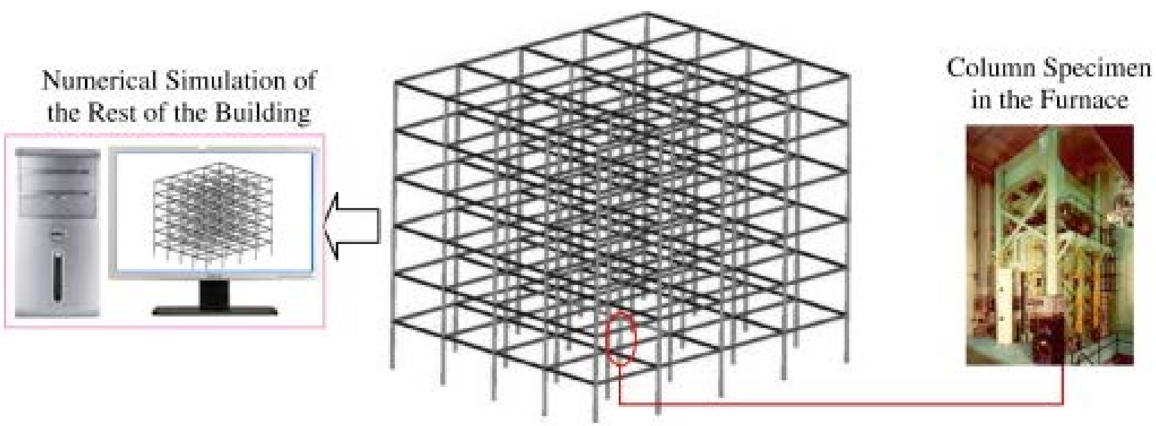
Korzen (1999)

- 1 DoF
- NS → constant stiffness



Robert (2008)

- 3 DoFs
- NS → constant stiffness

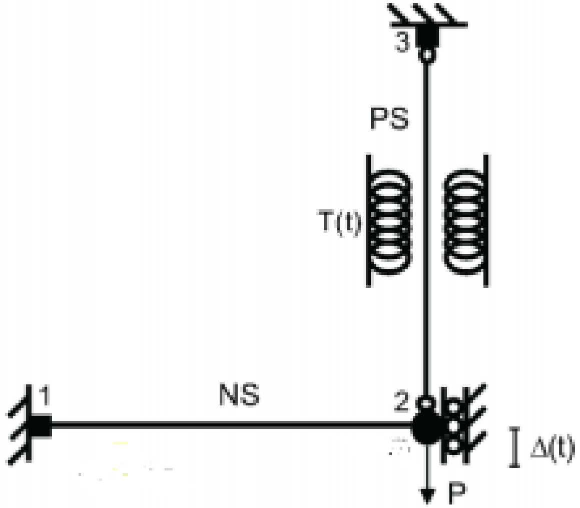


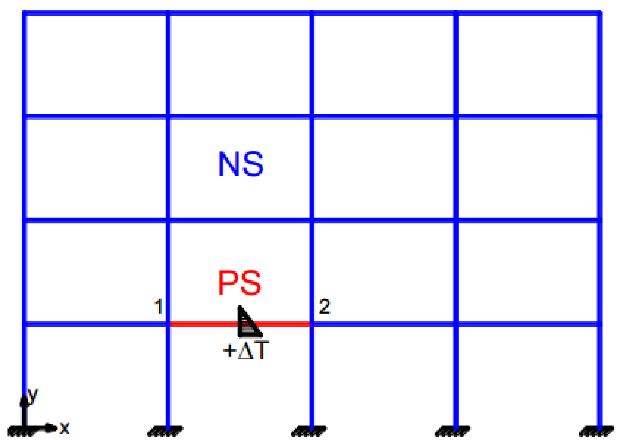
Mostafaei (2013)

- 1 DoF
- NS → software SAFIR

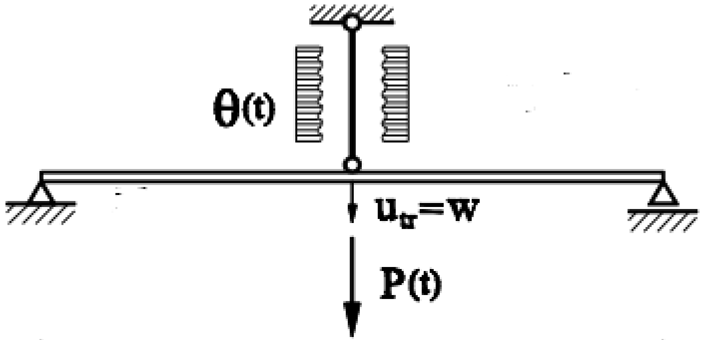
State of the Art in the Fire Field

Whyte et al. (2016)
- 1 DoF
- NS → FEM





Schulthess et al. (2016)
- 1 DoF
- NS → FEM



Tondini et al. (2016)
- 2 DoF
- numerical validation

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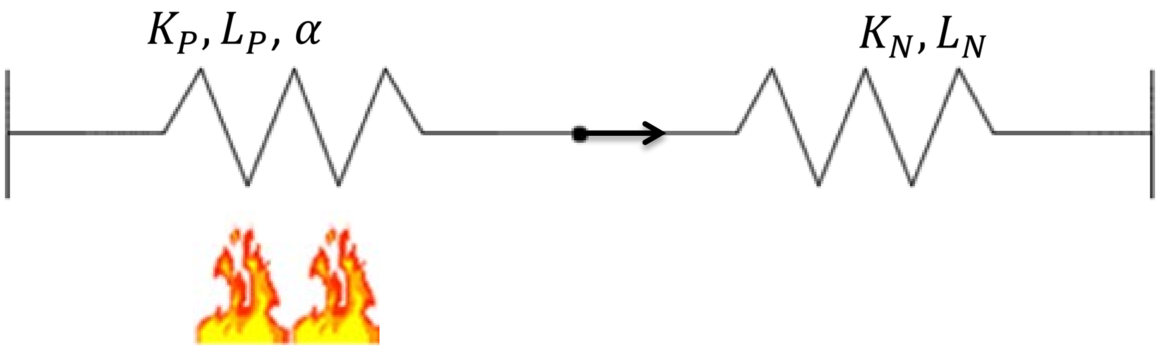
First Generation Method (FGM)

R: the stiffness ratio $R = \frac{K_N}{K_P}$

Complete structure



Physical Substructure *Numerical Substructure*

1. Read $F_P(t_n)$ **and** $F_N(t_n)$

2. Compute $du(t_n) = -(K_N)^{-1}[F_P(t_n) - F_N(t_n)]$

3. Impose $u(t_n) = u(t_{n-1}) + du(t_n)$

First Generation Method (FGM)

Displacement Control Procedure

$$u(t_n) = \frac{1}{R} \cdot \alpha \cdot L_P \cdot \sum_{i=0}^{n-1} \left[\left(-\frac{1}{R} \right)^i \cdot T(t_{n-i}) \right]$$

Force Control Procedure

$$F(t_n) = K_N \cdot \alpha \cdot L_P \cdot \sum_{i=0}^{n-1} \left[(-R)^i \cdot T(t_{n-i}) \right]$$

FGM is conditionally stable: $R = \frac{K_N}{K_P}$

- R > 1 request a displacement control procedure
- R < 1 request a force control procedure

Analysis First Generation Method

Analysis of the previous tests

Test	Method	R
Korzen	FCP	R<1 ✓
Mostafaei	FCP	R<1 ✓
Robert	FCP	0.167 (R<1) ✓ 0.756 (R<1) ✓

- Correct choice for **ambient conditions !**

Observations

- R varies during the test (K_P degradation: heating, spalling, …)
- Multiple DoFs (requesting different procedures)

Conclusions

- Need of a **new method**

Theoretical Background of the New Method

Finite Element Tearing and Interconnecting method (FETI)

- Method developed for numerical analysis
- Uses the vector of Lagrange multiplier (interface forces)
- In the computation of the Lagrange multiplier the stiffness of the PS is considered
- FETI method can be applied in the context of HFT

The stiffness of the PS needs to be accounted during the HFT

Theoretical Formulation

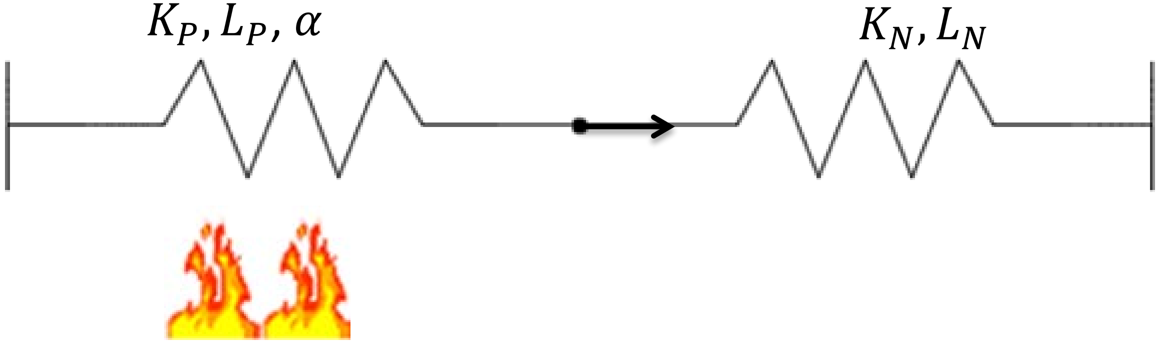
New method (Second generation method)

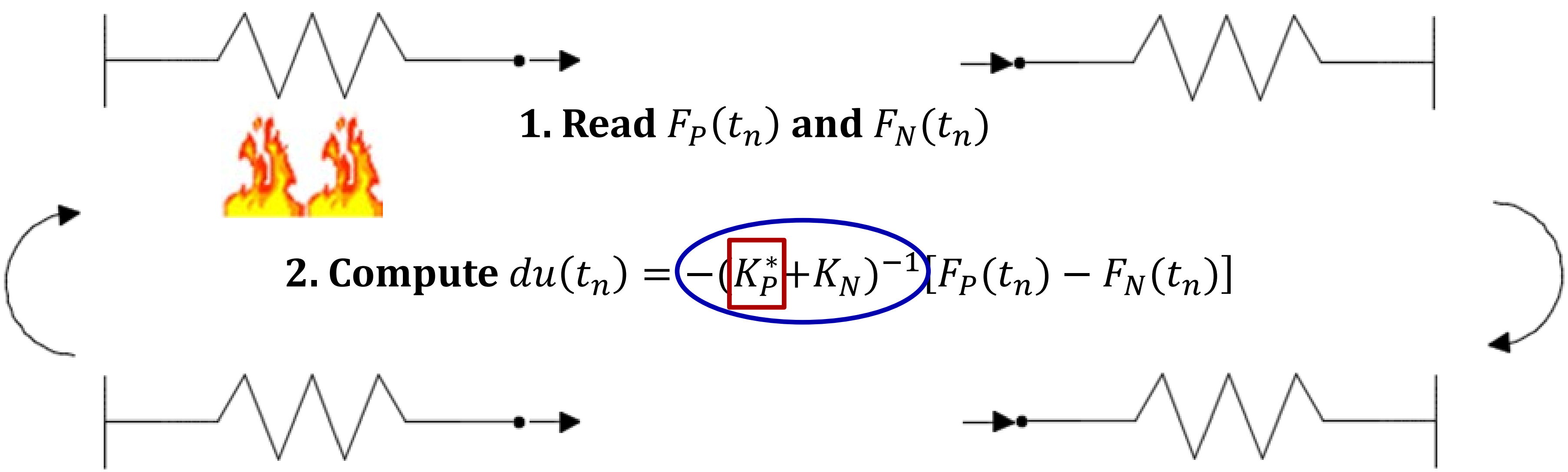
- Displacement control $(K_N + K_P)^{-1}$
- Force control $(\frac{1}{K_N} + \frac{1}{K_P})^{-1}$

First generation method

- Displacement control ${K_N}^{-1}$
- Force control K_N

New Method in DCP





1. Read $F_P(t_n)$ **and** $F_N(t_n)$

2. Compute $du(t_n) = -(K_P^* + K_N)^{-1}[F_P(t_n) - F_N(t_n)]$

3. Impose $u(t_n) = u(t_{n-1}) + du(t_n)$

New Method

Objectives of the new method:

A) Stability

B) Equilibrium and compatibility

C) Reproduction of the exact solution
(same response as in the complete structure)

A) Stability (DCP)

Computed displacement (new method)

$$u(t_n) = \frac{K_P}{K_N + {K_P}^*} \cdot \alpha \cdot L_P \cdot T(t_n)$$

versus

Computed displacement (first generation method)

$$u(t_n) = \frac{1}{R} \cdot \alpha \cdot L_P \cdot \sum_{i=0}^{n-1} \left[\left(-\frac{1}{R} \right)^i \cdot T(t_{n-i}) \right]$$

B) Equilibrium and Compatibility (DCP)

Compatibility: the same displacements imposed on the PS and NS

Equilibrium: verified at the time $t_n + \Delta t_P$

$$\Delta F(t_n + \Delta t_P) = F_P(t_n + \Delta t_P) + F_N(t_n + \Delta t_P)$$
$$= -K_P \cdot \alpha \cdot L_P \cdot \underbrace{\left(T(t_n + \Delta t_P) - \frac{K_N + K_P}{K_N + {K_P}^*} \cdot T(t_n) \right)}$$

$$\Delta F(t_n + \Delta t_P) \cong 0$$

Observations:

$$\Delta t_P \cong 0$$

$${K_P}^* \cong K_P$$

C) Reproduction of the Exact Solution (DCP)

Exact solution

$$u(t_n) = \frac{\mathrm{E}_P \cdot A_P}{K_N + K_P} \cdot \alpha \cdot T(t_n)$$

HFT solution

$$u(t_n) = \frac{K_P}{K_N + {K_P}^*} \cdot \alpha \cdot L_P \cdot T(t_n)$$

Equal because

$$\mathrm{E}_P A_P = K_P L_P$$

New Method

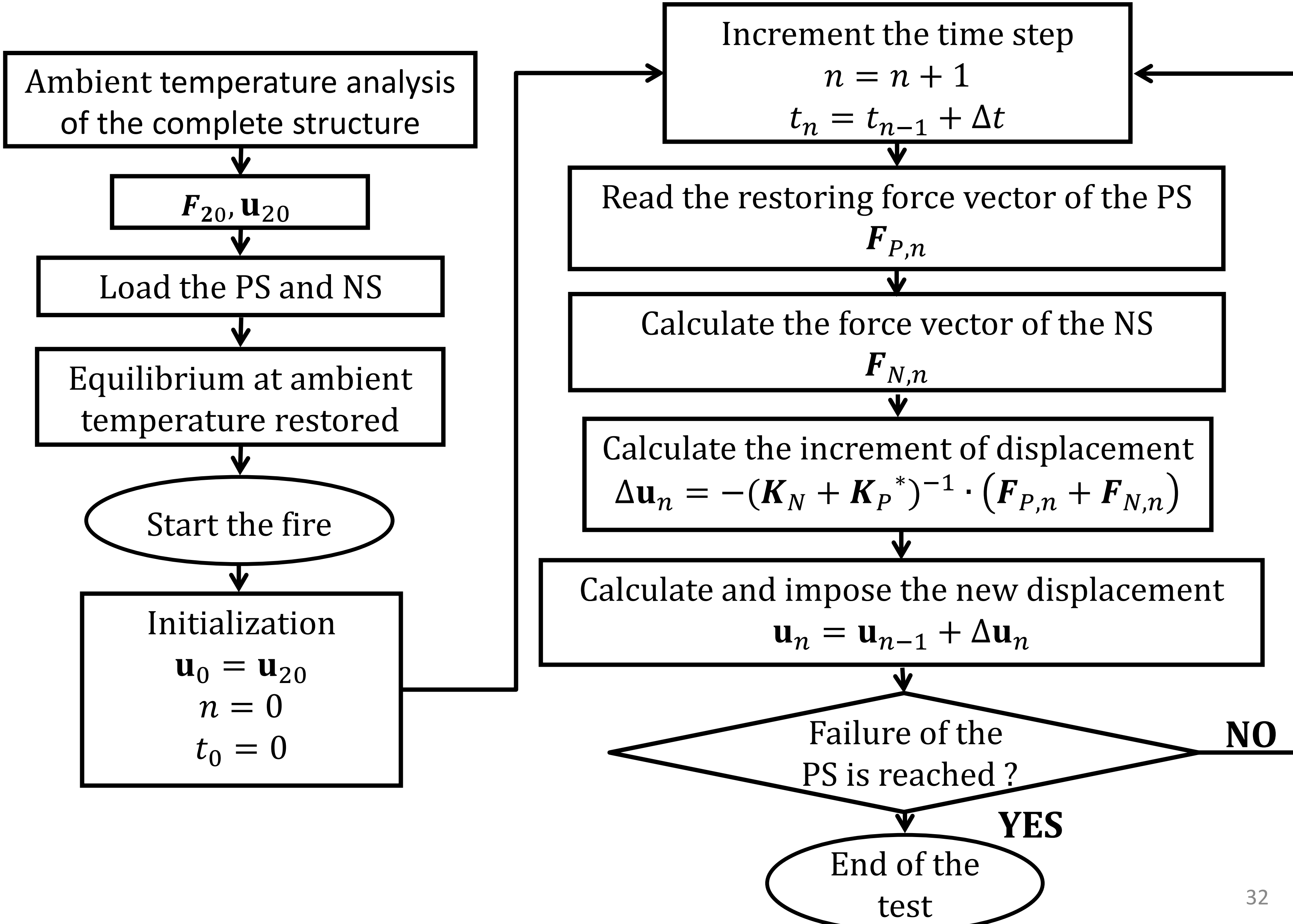
Inspired from FETI

Unconditionally stable on R

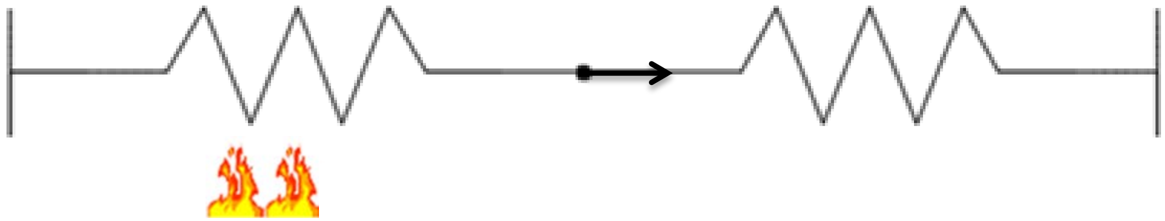
Interface equilibrium and compatibility ensured
(for proper values of $\Delta \boldsymbol{t_P}$ and $\boldsymbol{K_P^*}$)

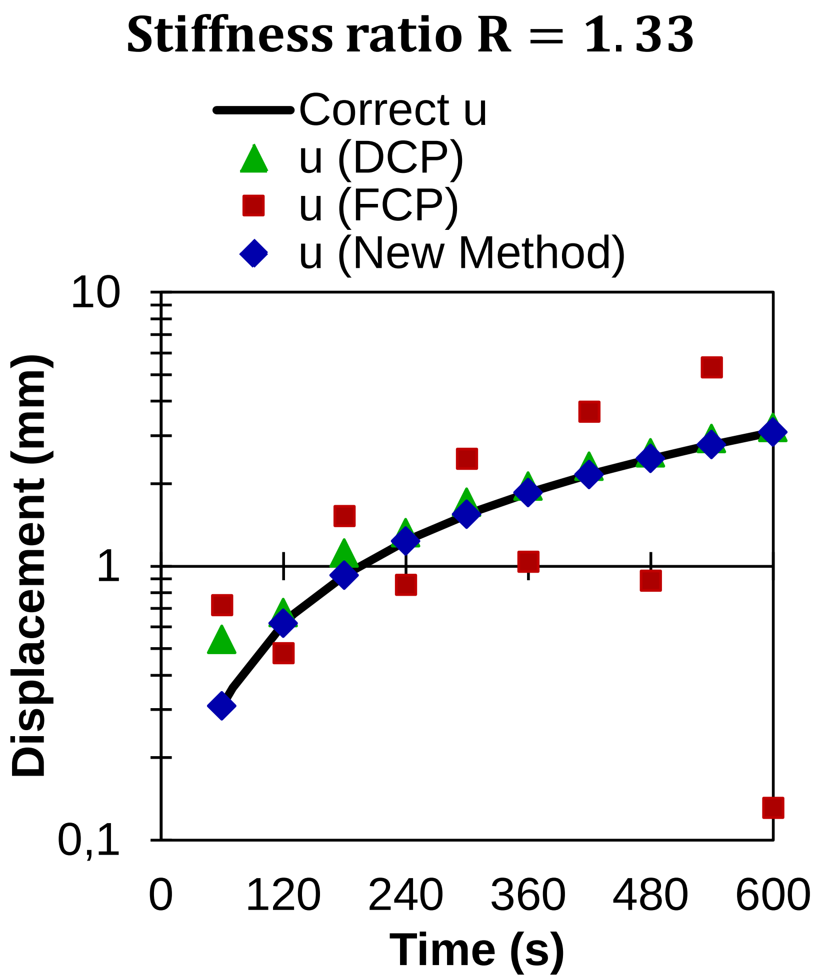
The exact solution is reproduced
(for proper values of $\Delta \boldsymbol{t_P}$ and $\boldsymbol{K_P^*}$)

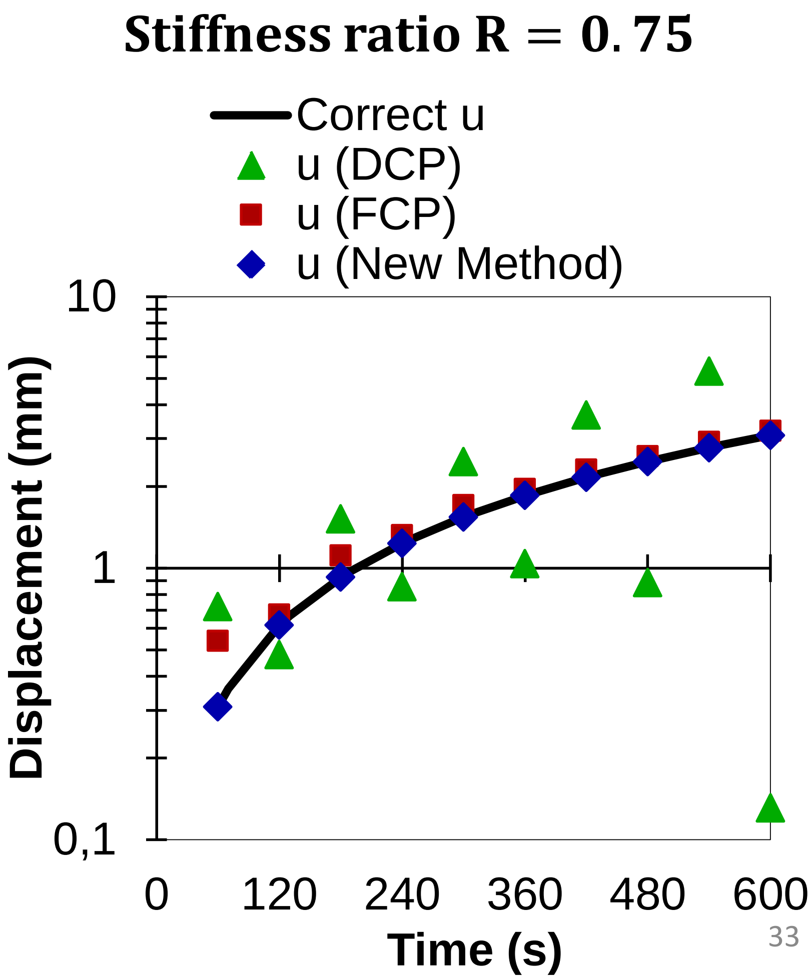
New Method


Ambient temperature analysis of the complete structure
$\boldsymbol{F}_{20}, \mathbf{u}_{20}$
Load the PS and NS
Equilibrium at ambient temperature restored
Start the fire
Initialization
$\mathbf{u}_0 = \mathbf{u}_{20}$
$n = 0$
$t_0 = 0$
Increment the time step
$n = n + 1$
$t_n = t_{n-1} + \Delta t$
Read the restoring force vector of the PS
$\boldsymbol{F}_{P,n}$
Calculate the force vector of the NS
$\boldsymbol{F}_{N,n}$
Calculate the increment of displacement
$\Delta \mathbf{u}_n = -(\boldsymbol{K}_N + \boldsymbol{K}_P{}^*)^{-1} \cdot (\boldsymbol{F}_{P,n} + \boldsymbol{F}_{N,n})$
Calculate and impose the new displacement
$\mathbf{u}_n = \mathbf{u}_{n-1} + \Delta \mathbf{u}_n$
Failure of the PS is reached ?
NO
YES
End of the test

Numerical Example 1 DoF Linear System







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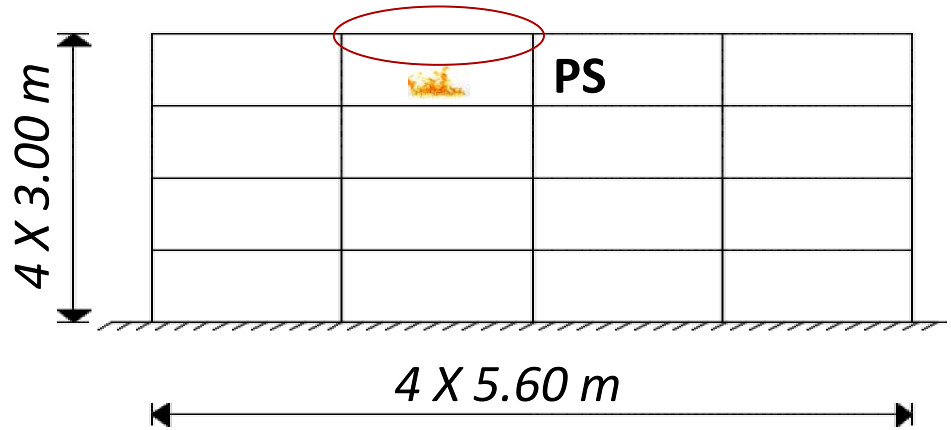
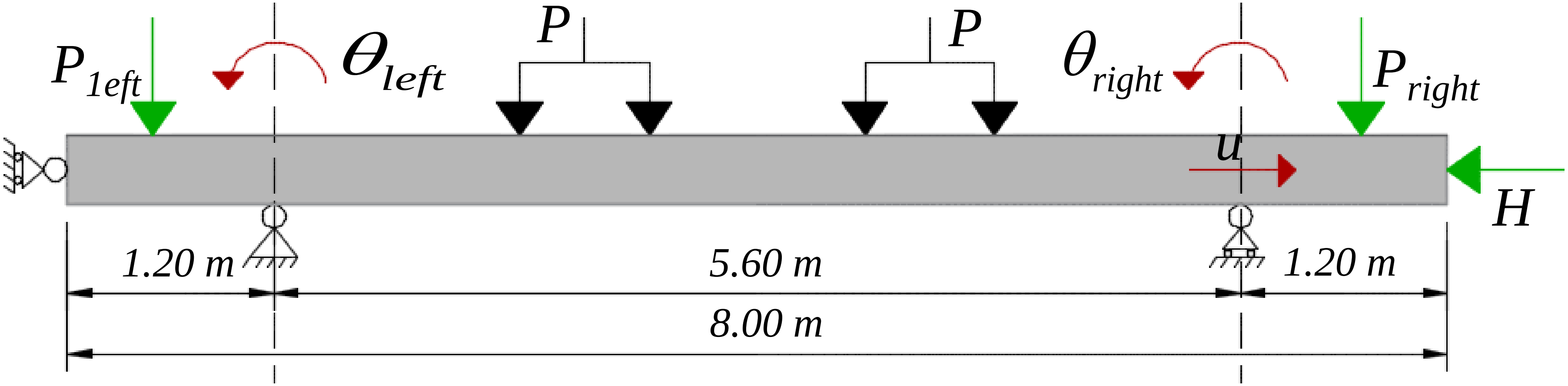
Description of the Case Study



Configuration of the PS



NS defined by the elastic predetermined matrix

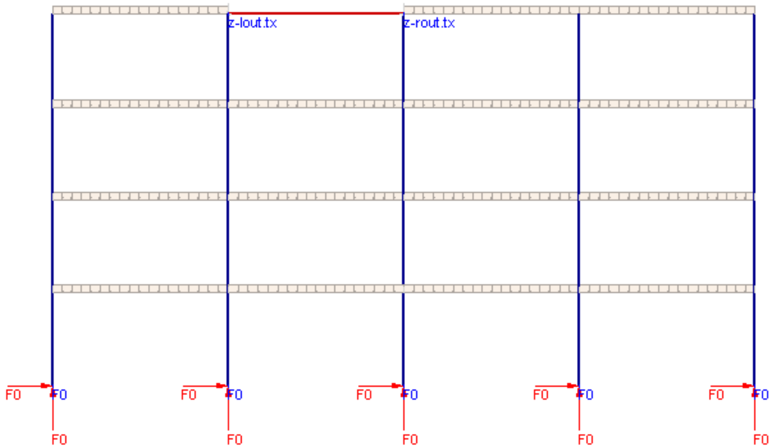
$$\boldsymbol{K}_N = \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix}$$

Predetermined Matrix vs. Initial Tangent Stiffness Matrix

Predetermined matrix of the NS

- Computed in SAFIR, tangent to the loaded stage

$$\boldsymbol{K}_N = 10^6 \begin{bmatrix} 11 & -12 & 8 \\ -12 & 65 & -9 \\ 8 & -9 & 64 \end{bmatrix}$$



Stiffness Matrix of the PS

- Computed in SAFIR, tangent to the loaded stage

$$\mathbf{K}_P{}^* = 10^6 \begin{bmatrix} 479 & 0 & 0 \\ 0 & 26 & 13 \\ 0 & 13 & 26 \end{bmatrix}$$

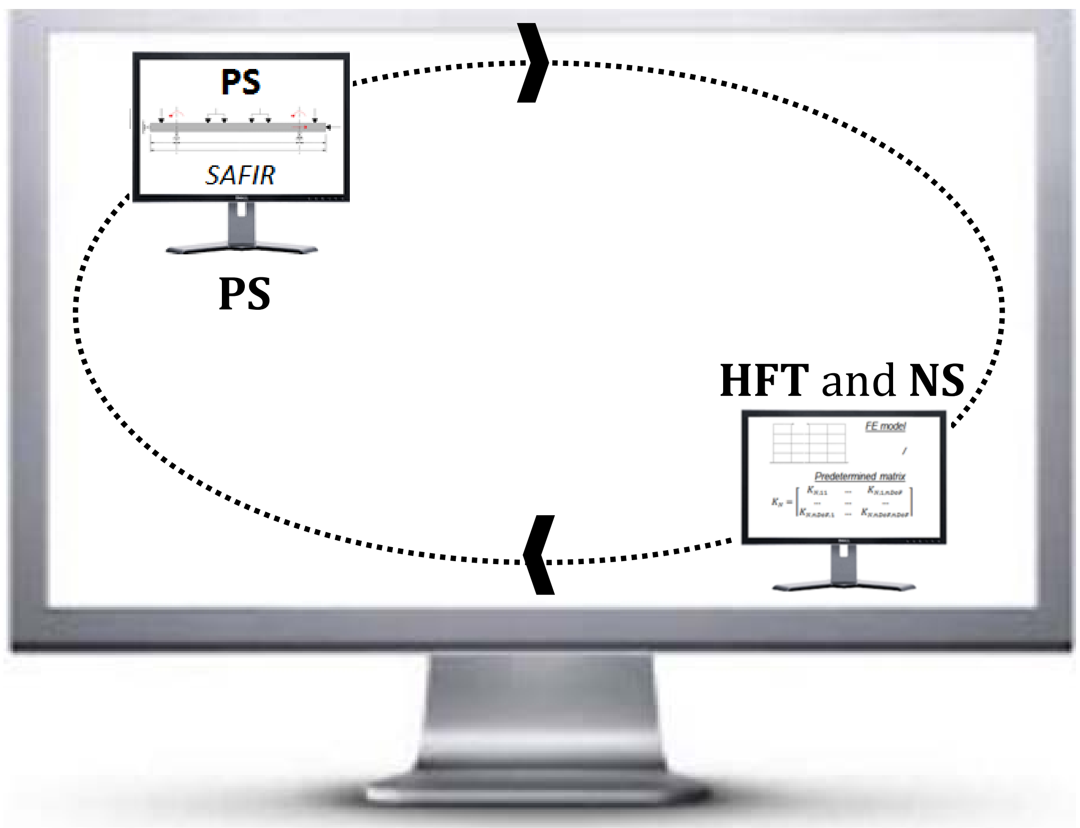
Virtual HFT

PS modeled in the FE software (SAFIR)

NS constant predetermined matrix defined before the HFT

Communication: manually, Matlab, **new subroutine SAFIR**

Advantage: proper selection of the Δt and K_P*



Virtual HFT of the New Method (DCP)

Procedure: Displacement control

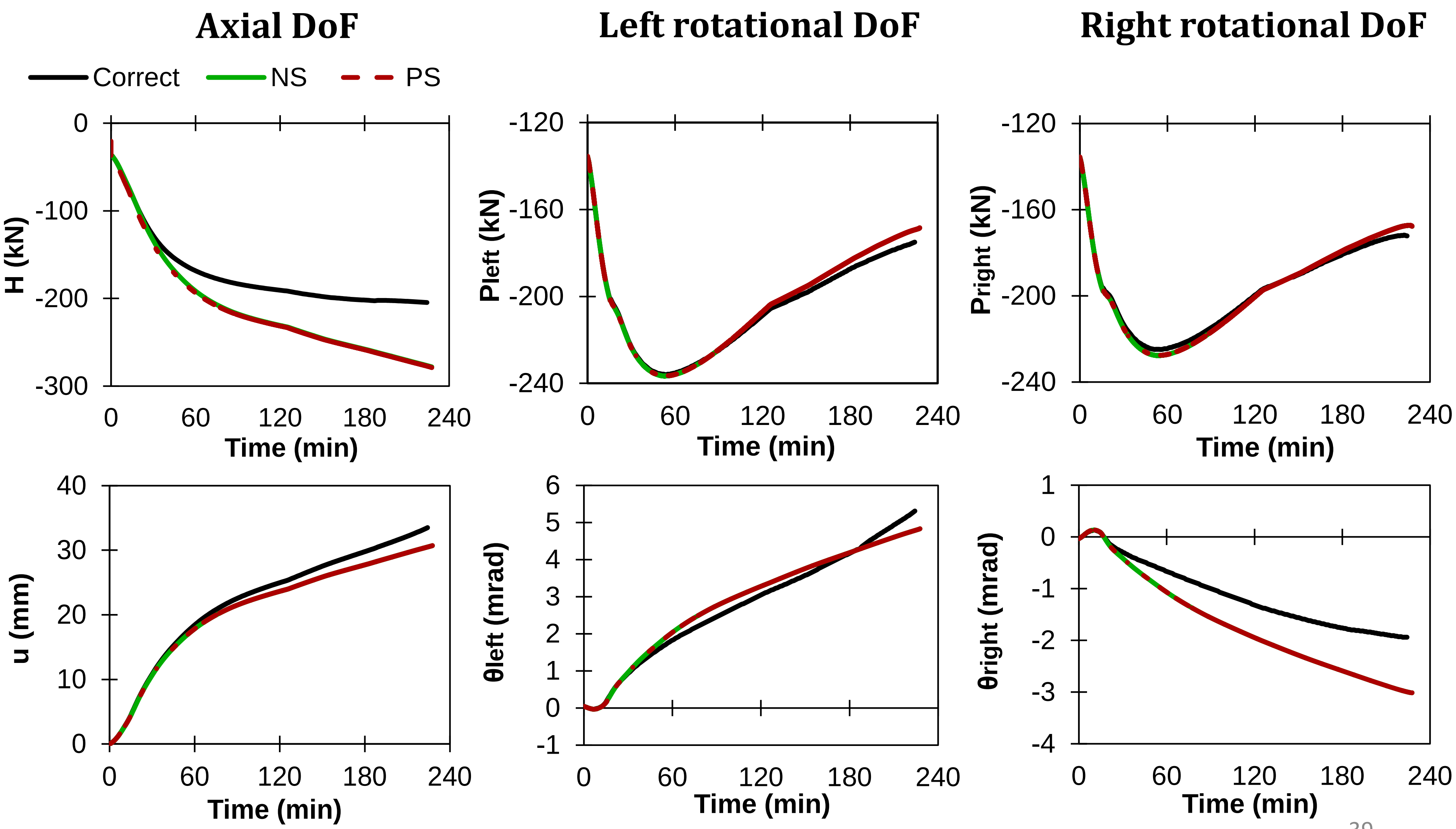
NS: constant predetermined matrix defined before the HFT

Parametric study: Δt and $K_P{}^*$

Case	Time step	The PS's stiffness
Case 1	$\Delta t = 1\ s$	$K_P^* = 1.50 K_{P0n}$
Case 2	$\Delta t = 10\ s$	
Case 3	$\Delta t = 30\ s$	
Case 4	$\Delta t = 60\ s$	
Case 5	$\Delta t = 5\ min$	
Case 6	$\Delta t = 10\ min$	
Case 7	$\Delta t = 1\ s$	$K_P^* = 5 K_{P0n}$
Case 8		$K_P^* = 10 K_{P0n}$
Case 9		$K_P^* = 50 K_{P0n}$
Case 10		$K_P^* = 0.50 K_{P0n}$

Virtual HFT of the New Method (DCP)

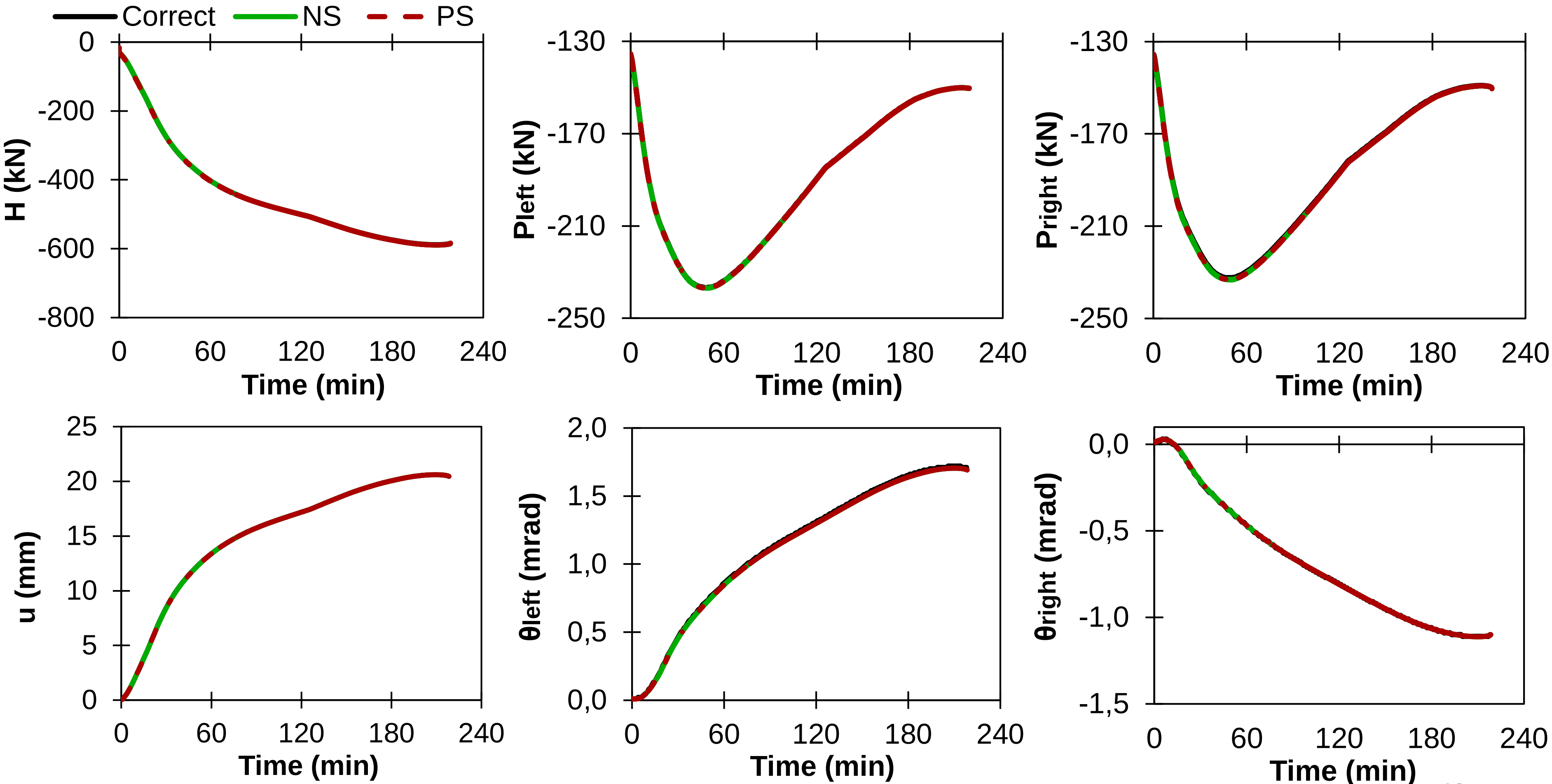
Case 1 ($\Delta t = 1\ s; K_P^* = 1.50K_P$)



Virtual HFT of the New Method (DCP)

Case with elastic NS

Axial DoF | Left rotational DoF | Right rotational DoF

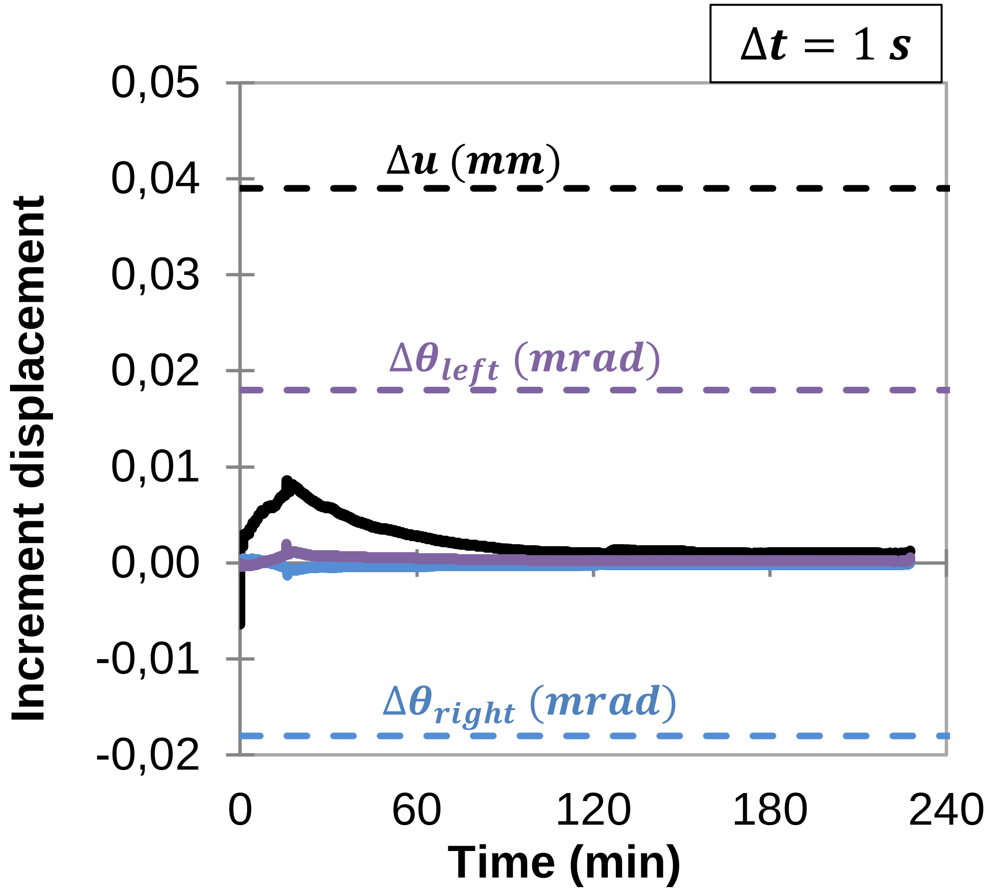


Virtual HFT of the New Method (DCP)

Increment of displacement

Resolution transducer: **0.039 mm**

Resolution inclinometer: **0.018 mrad**



Virtual HFT of the New Method (DCP)

Equilibrium and compatibility can be achieved

- **Small values of** $\Delta \mathbf{t}$ needed
- **Too Small** $\Delta \boldsymbol{t}$ might induce incremental displacements smaller than the **resolution of the transducers**

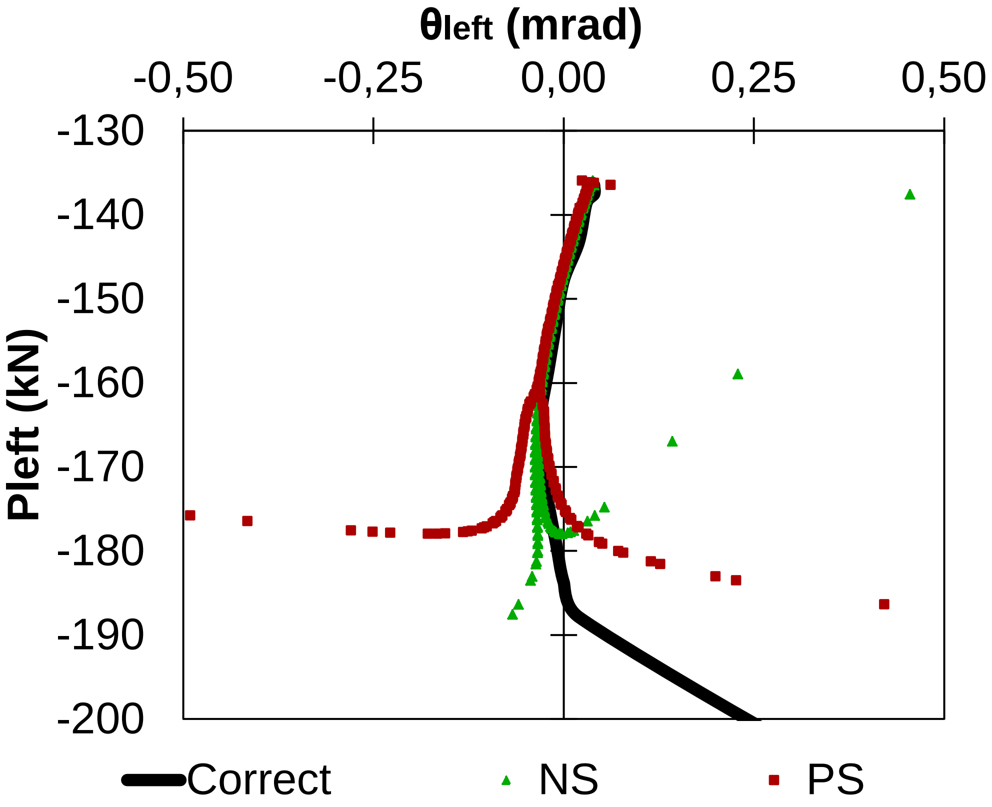
Increase of $\boldsymbol{K_P^*}$ influences negatively the equilibrium and compatibility

Decrease of $\boldsymbol{K_P^*}$ induces instability

Constant $\boldsymbol{K_{\mathrm{N}}}$ induces slight divergence from the correct solution

Virtual HFT of the New Method (FCP)

Force Control Procedure



The stiffness of the PS → ill conditioned

Applied **load can be larger than the limit load**

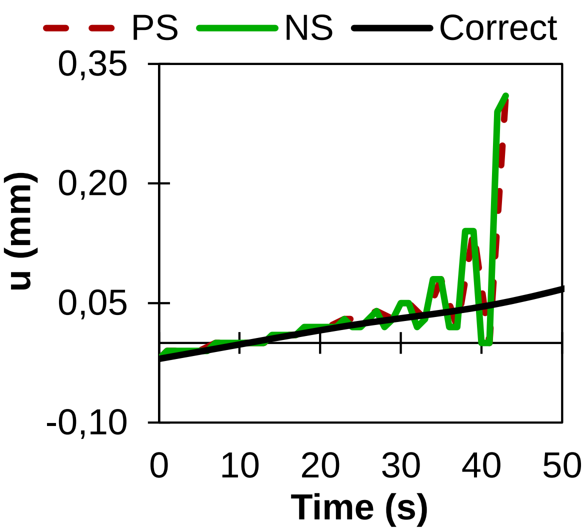
Virtual HFT of the First Generation Method

Procedure: Force Control

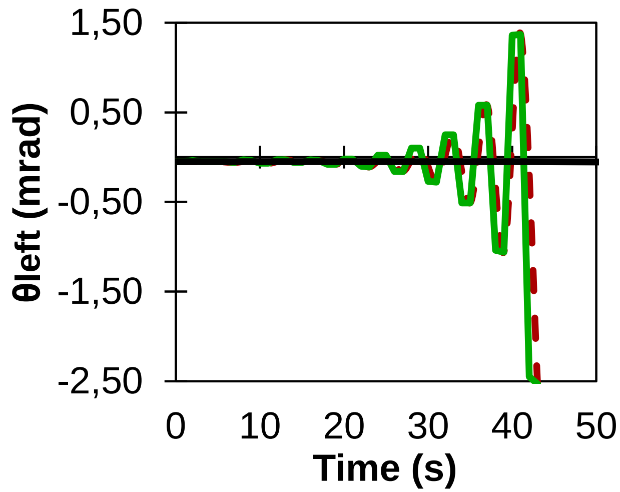
Stiffness ratio:

$$R = 0.20 \text{ (horizontal displacement)} \quad \rightarrow \text{FCP}$$
$$R = 2.53 \text{ (rotation left)} \quad \rightarrow \text{DCP}$$
$$R = 2.48 \text{ (rotation right)} \quad \rightarrow \text{DCP}$$

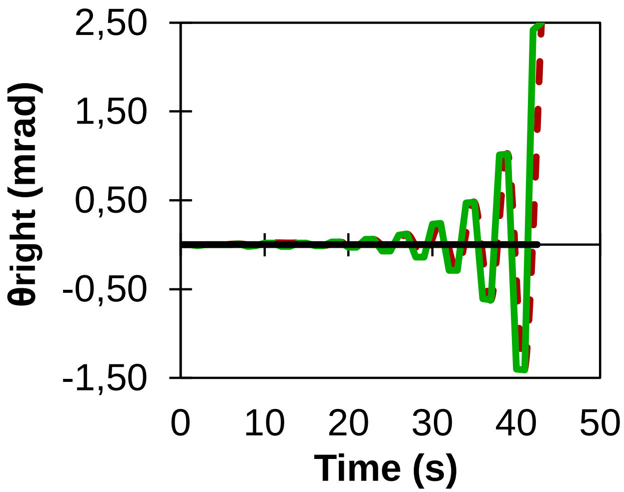
Axial DoF



Left rotational DoF



Right rotational DoF



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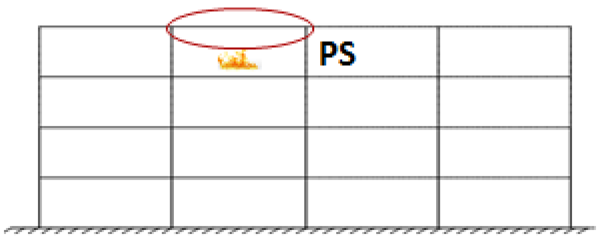
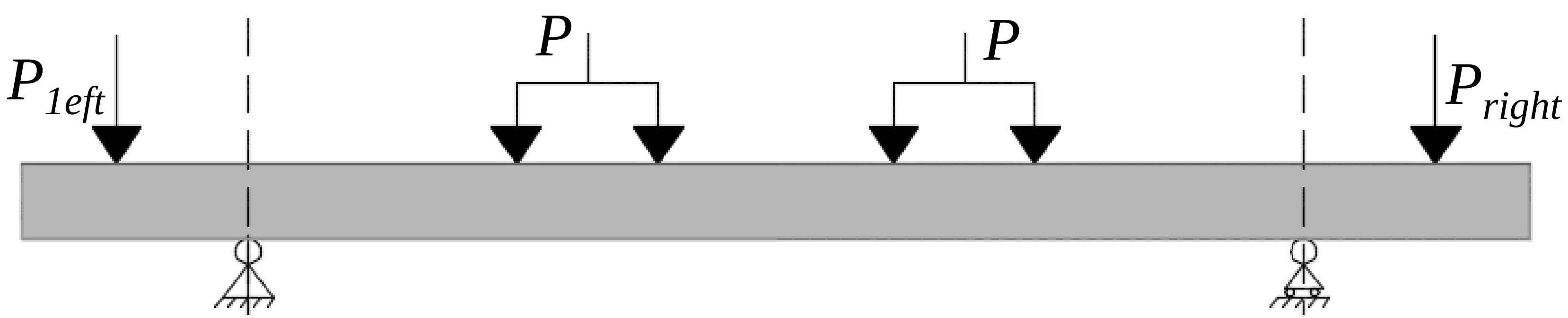
Tests

Tests performed in CERIB

- **Test 1** (standard test)

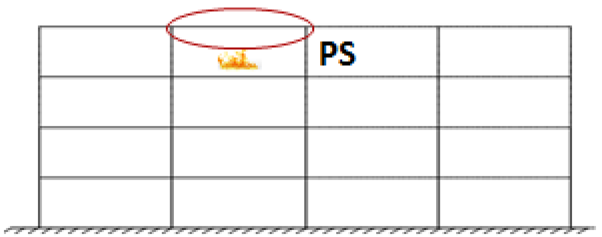


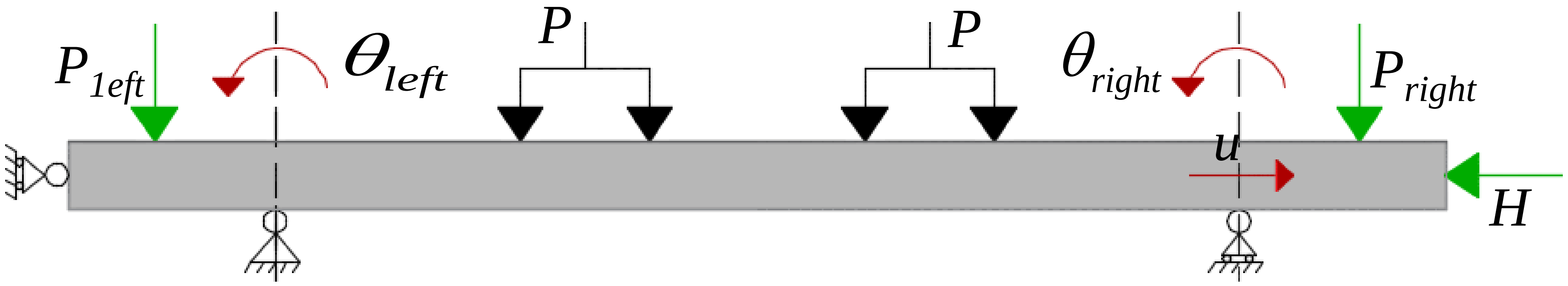


Tests

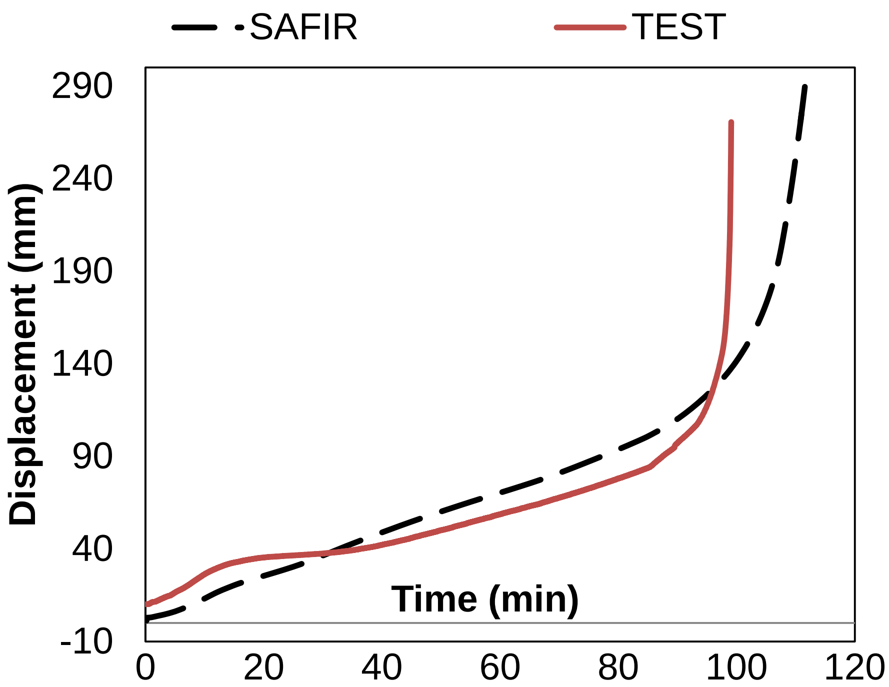
Tests performed in CERIB

- **Test 1** (standard test)
- **Test 2** (hybrid fire test)
- **Test 3** (hybrid fire test)





Test 1


SAFIR
TEST
Displacement (mm)
Time (min)
290
240
190
140
90
40
-10
0
20
40
60
80
100
120

Responsibilities

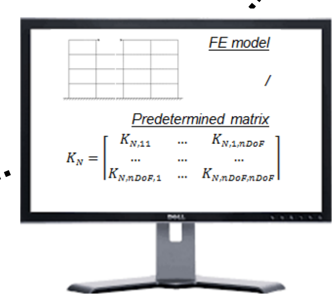
PS
CERIB

DAS
CERIB

Control system
External company

Transfer System
CERIB

External company



NS and **HFT method**
ULg

Test 2

Steps:

- Load the beam

  Stage 1: load P/2

  Stage 2: in addition apply interface displacements

  Stage 3: In addition apply P

- Restore equilibrium at ambient temperature (Stage 4)
- Start the fire

First Observations of the Test 2

Multiple Errors were identified in the code of the **control system**:

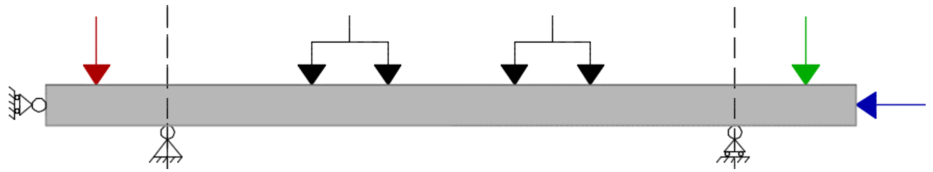
- Unit system (*m* versus *mm*)
- Force increasing to infinity
- …

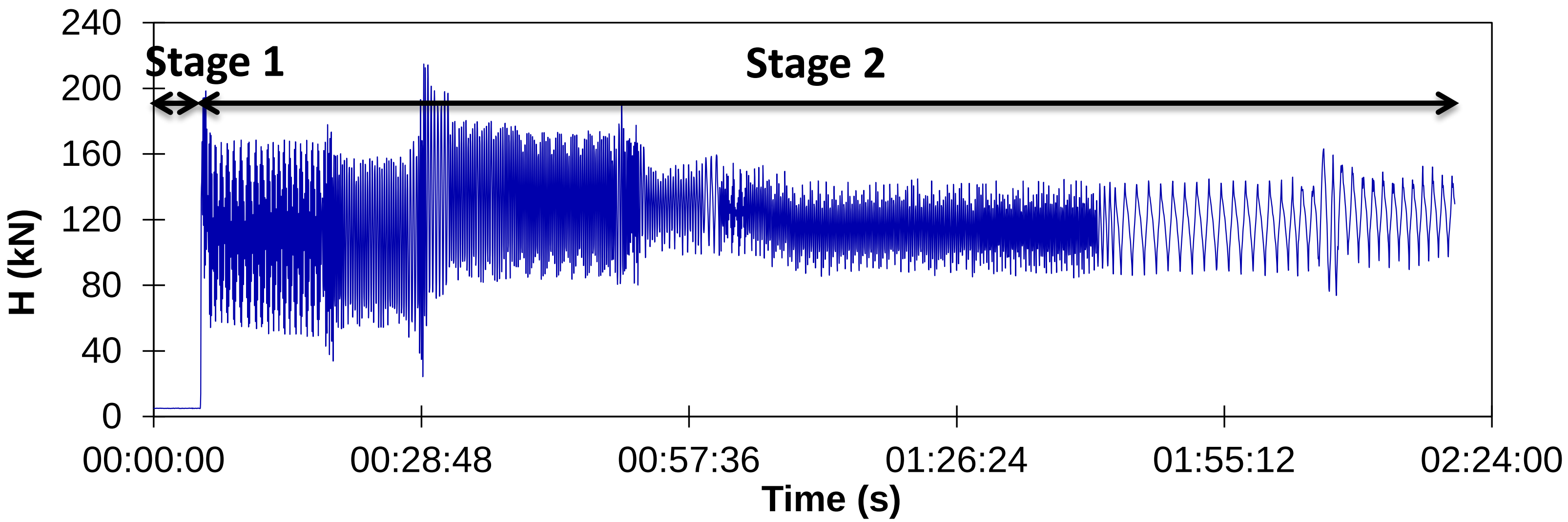
→ Impossibility to impose the target displacements

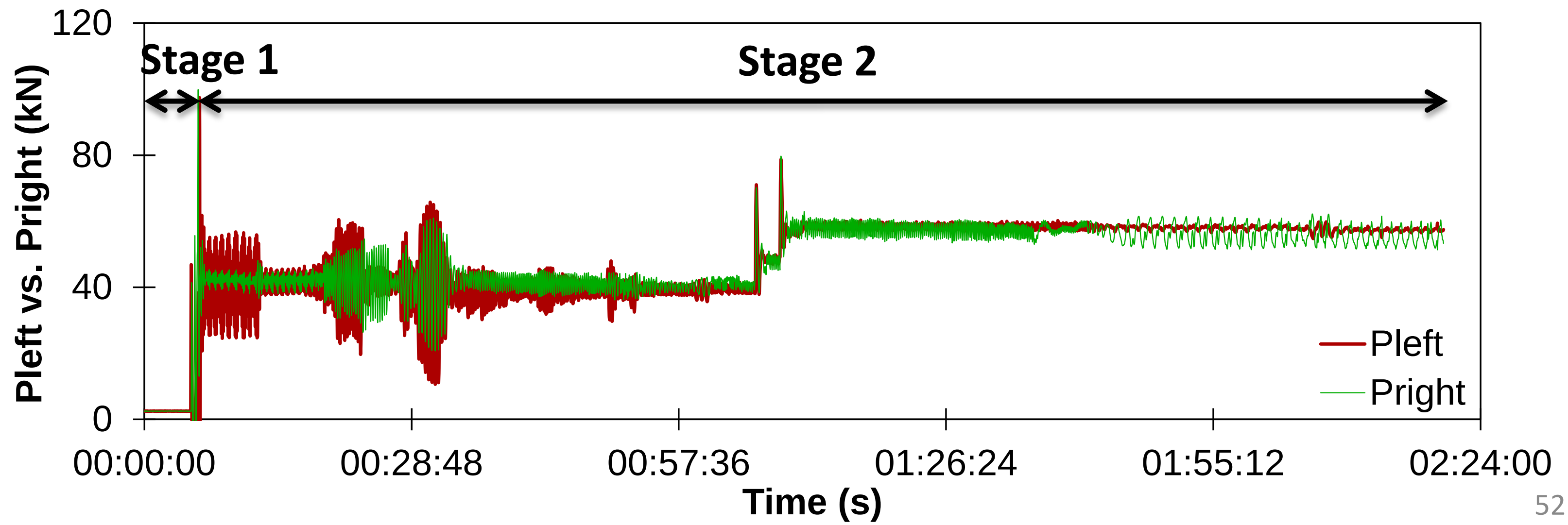
Test 2

Stage 1: load P/2

Stage 2: load interface displacements



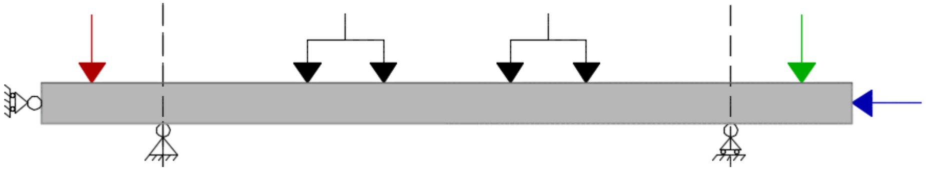


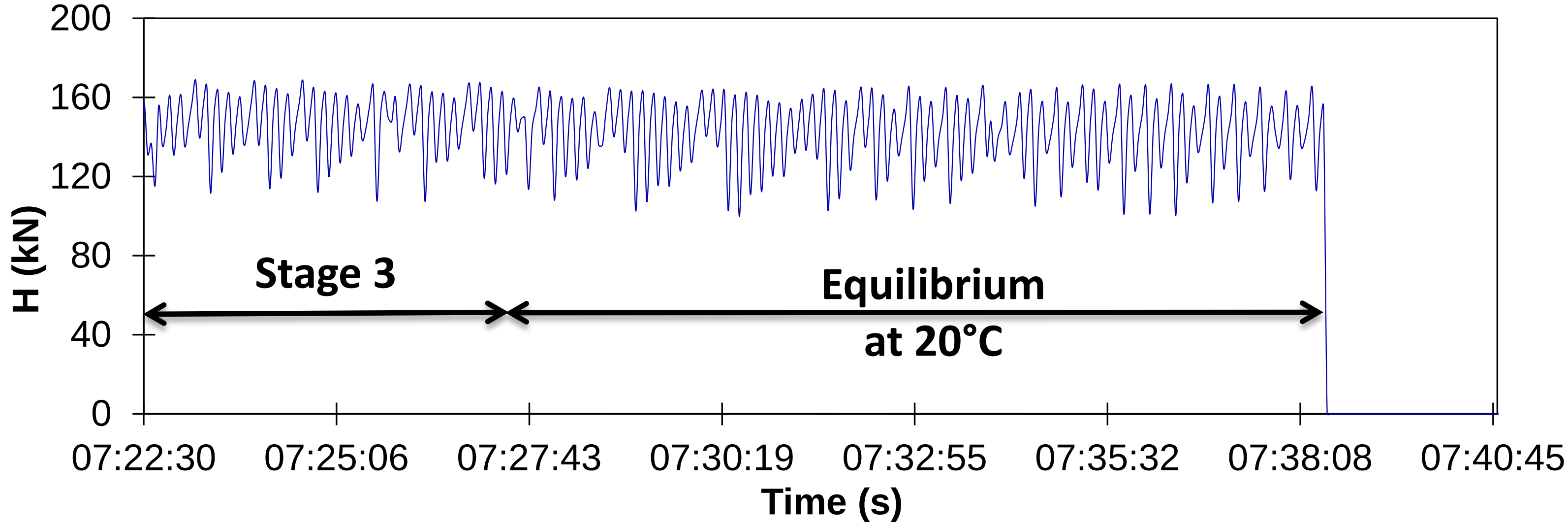


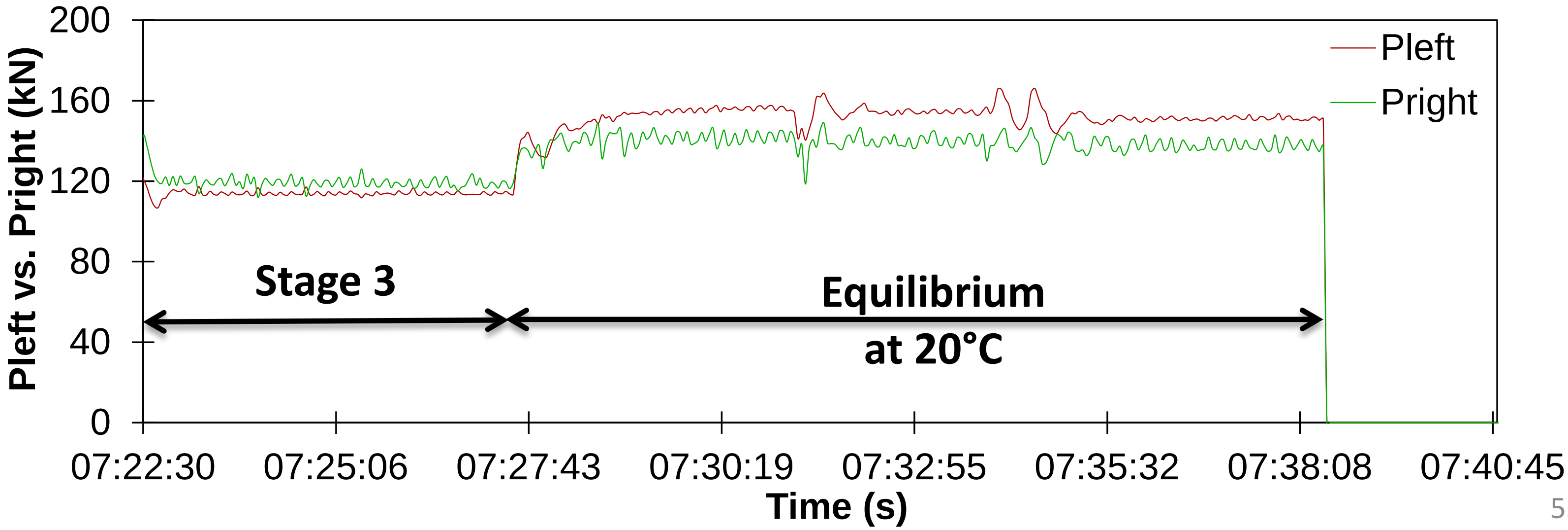
Test 2

Stage 3: load P

Stage 4: equilibrium at 20°C







Test 2

Observations when restoring the equilibrium at 20°C

- No changes are registered in the horizontal actuator
- The behavior is different compared with the one expected → the beam is unloaded for reflection

Next Operations of the Test 2

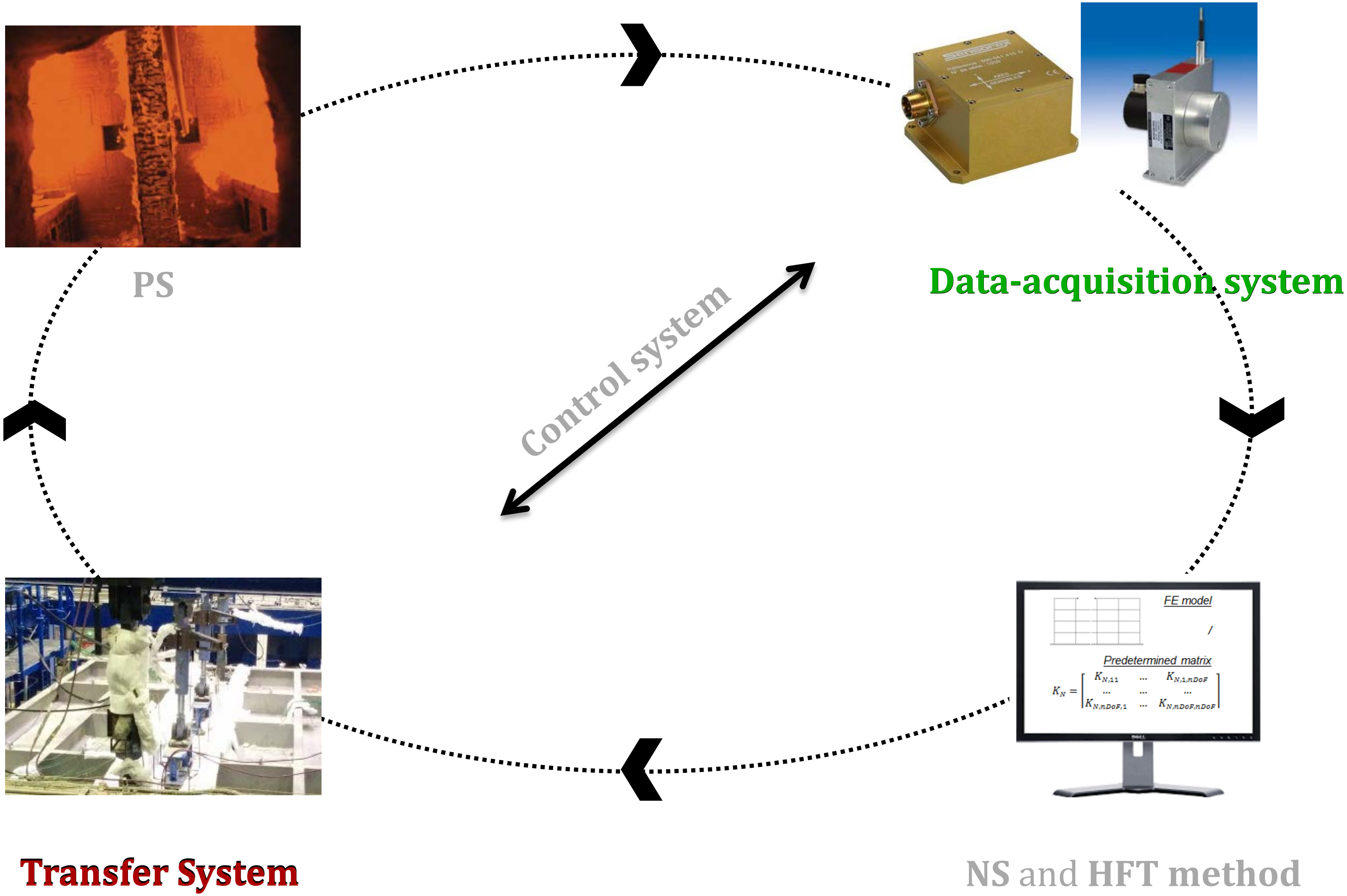
The loading and the restore of the equilibrium are repeated several times

Meanwhile, more corrections of the code are done in the control system

The behavior does not improve (instability occurred at one stage)

For safety reasons → the **test was canceled (before the fire exposure)**

Post-analysis of the Test 2



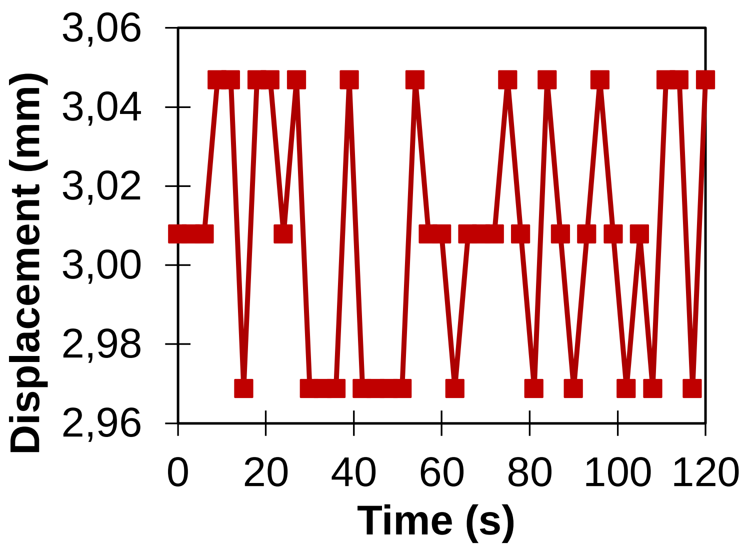
Lessons Learned from the Test 2

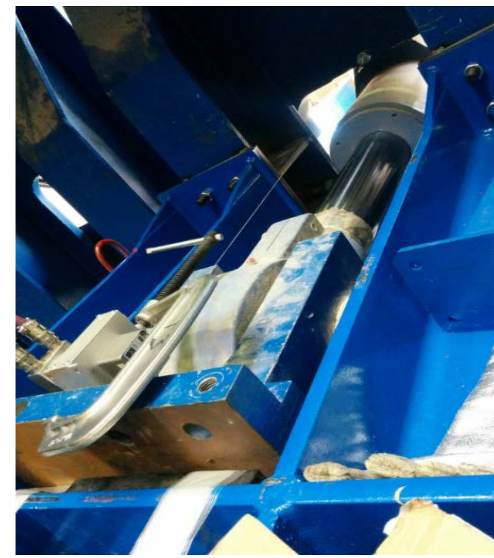
The **resolution** of the **data acquisition system (DAS)** → produces spikes in the response of the system

Data-acquisition System

Resolution of the DAS

Test actuator with the transducer





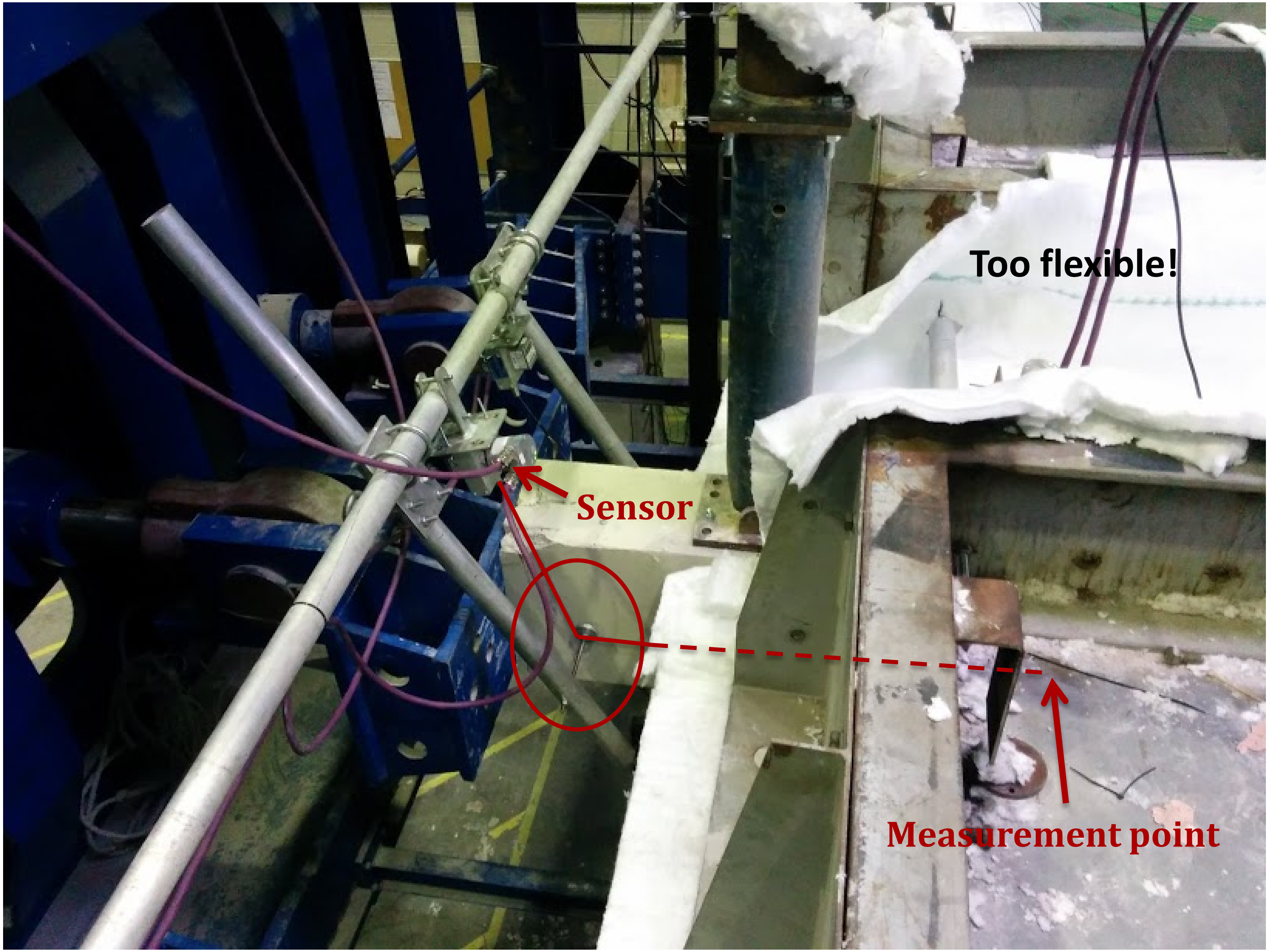
Resolution 0.039 mm → variation of force of 2 tons !

Lessons Learned from the Test 2

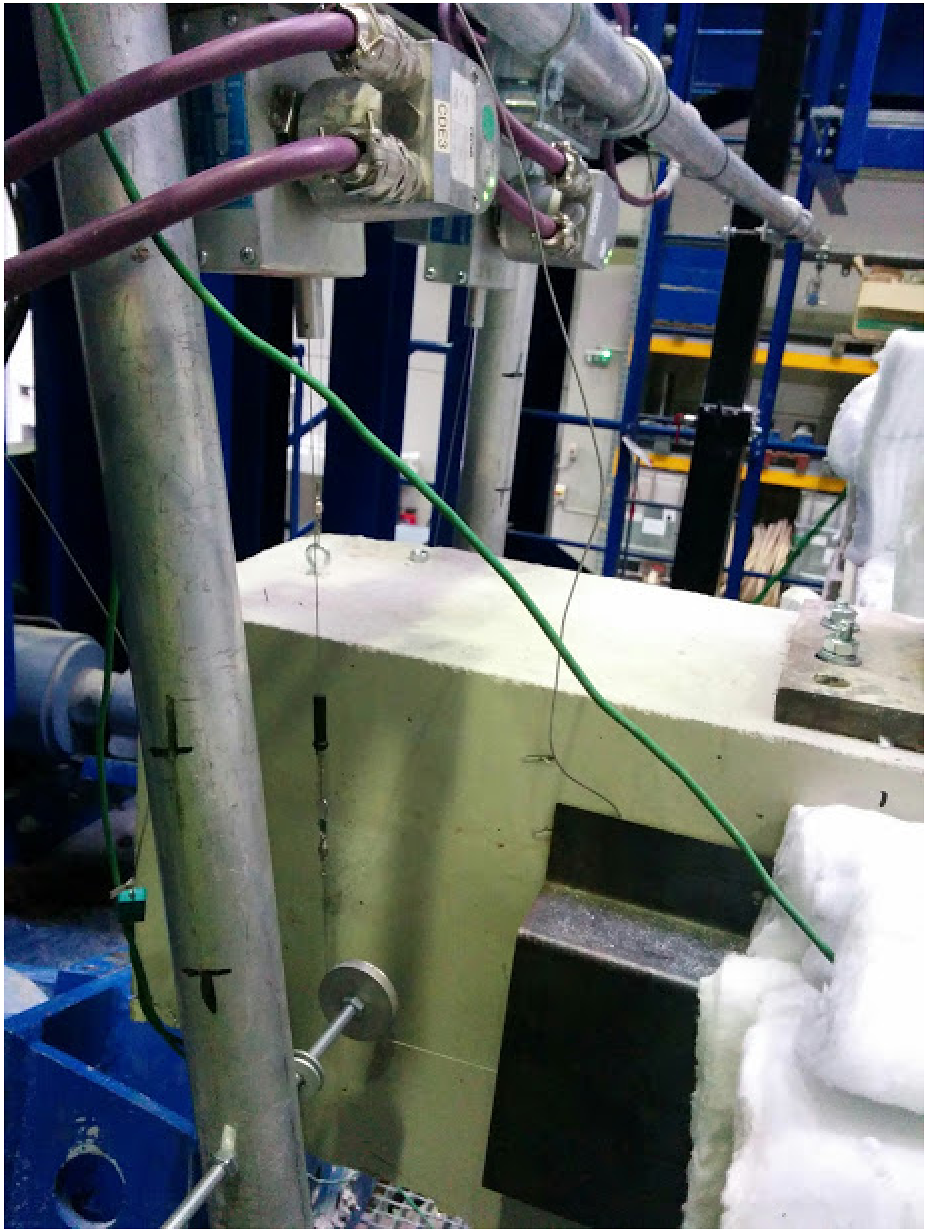
The **resolution** of the **data acquisition system (DAS)** → produces spikes in the response of the system

The **supports** of the **DAS** were too flexible → increased the spikes in the readings

Supports of the Data-acquisition System



Supports of the Data-acquisition System



Too flexible!

Lessons Learned from the Test 2

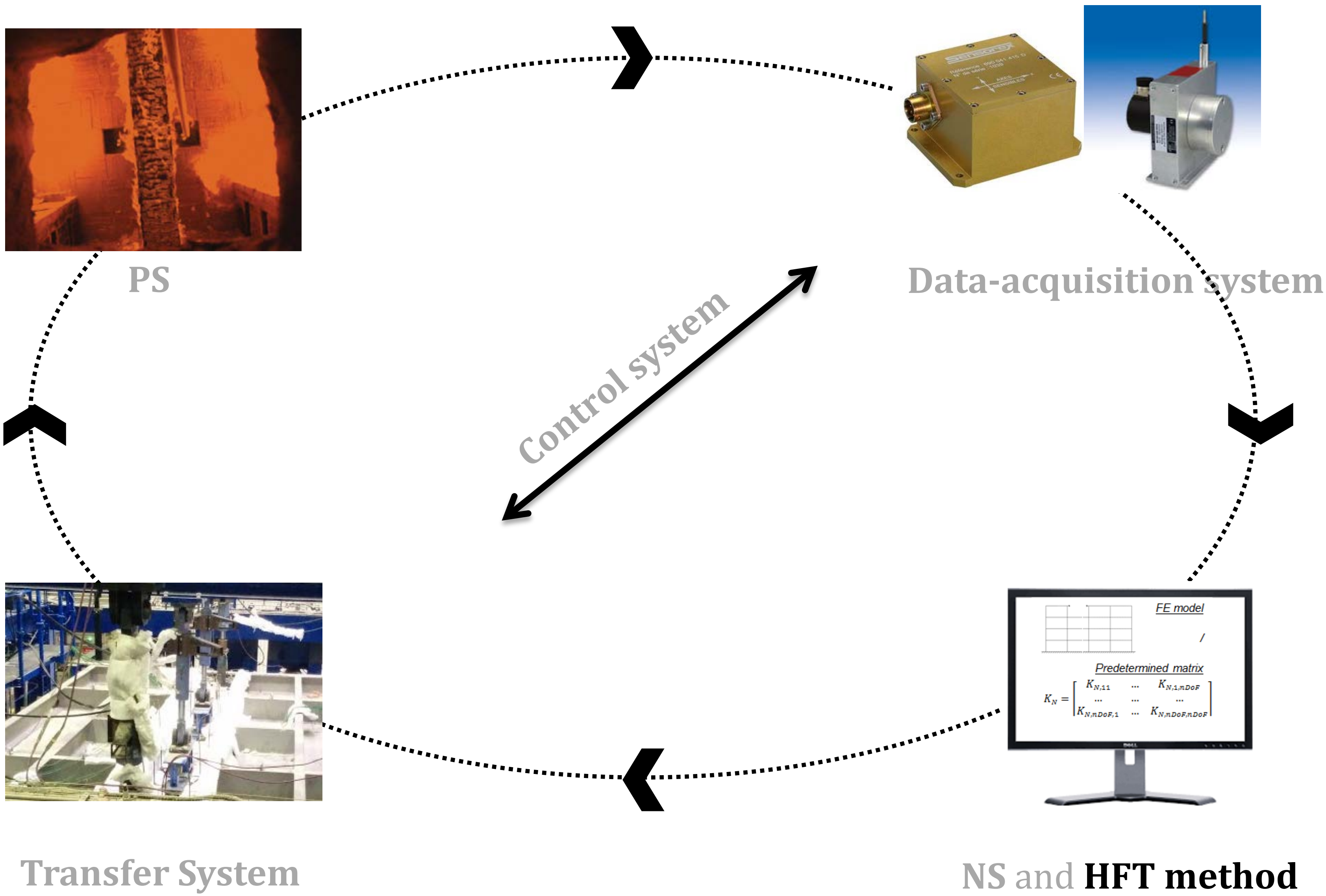
The **resolution** of the **data-acquisition system (DAS)** → produces spikes in the response of the system

The **supports** of the **DAS** were too flexible → increased the spikes in the readings

The **force** in the horizontal **jack** was less than 10% of the capacity

More appropriate **jacks** could be used

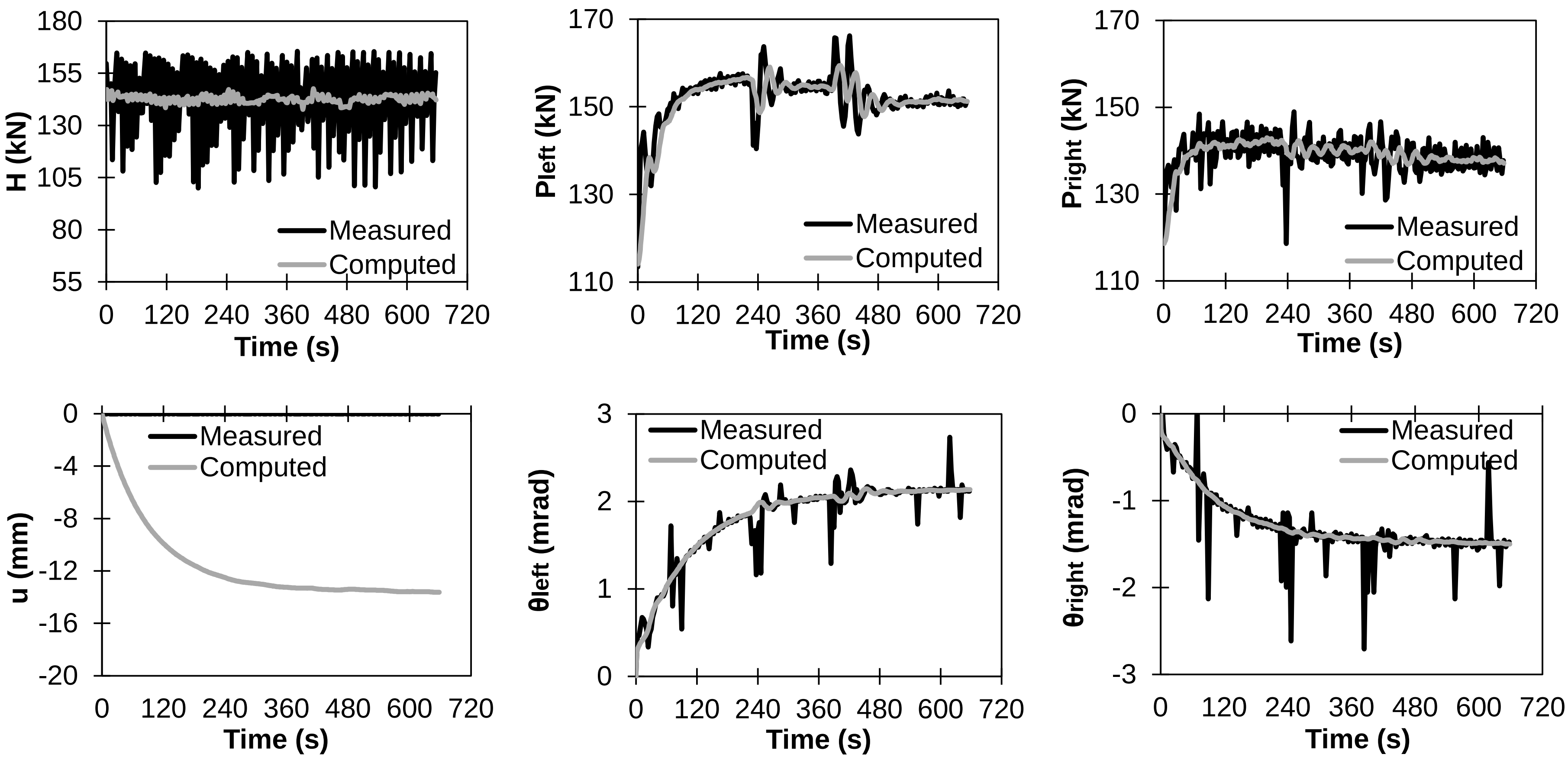
Control Process



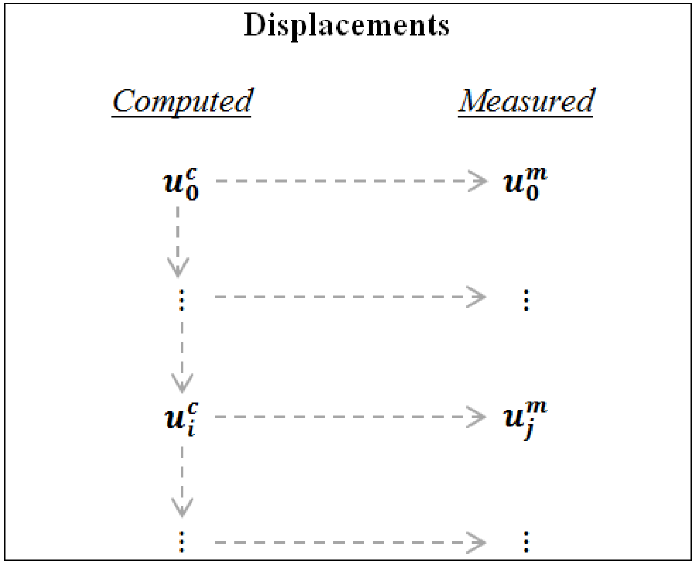
Equilibrium at Ambient Temperature

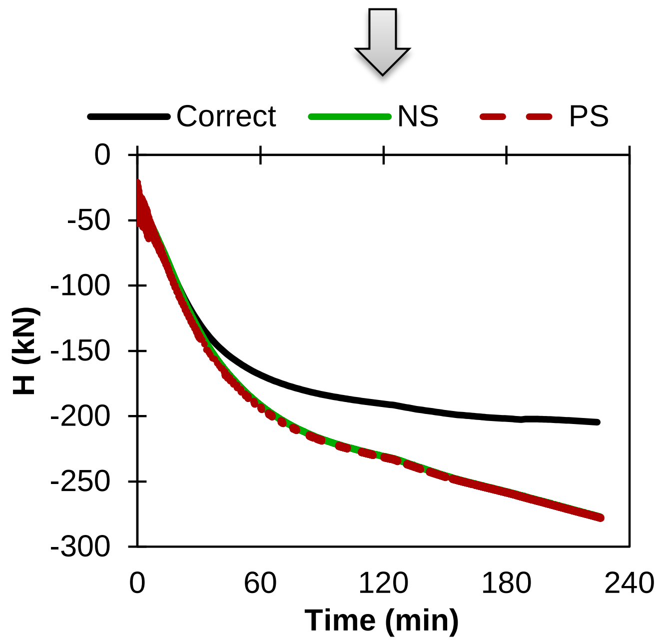
Measured versus computed values

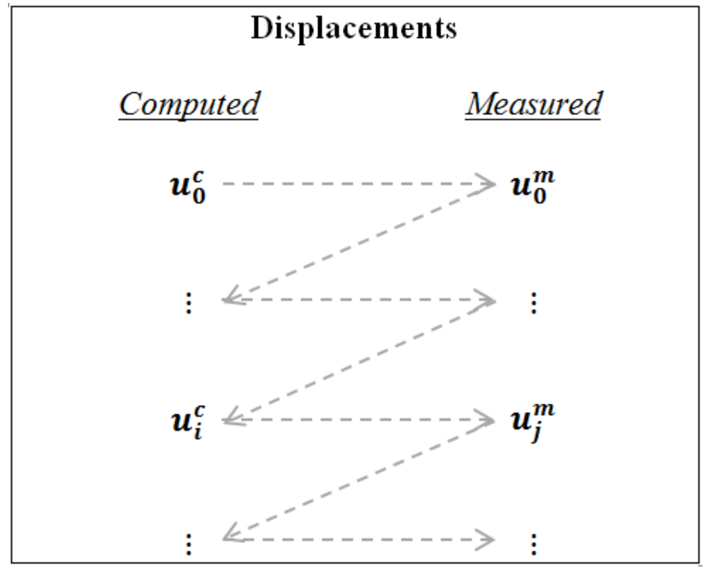
Axial DoF | Left rotational DoF | Right rotational DoF

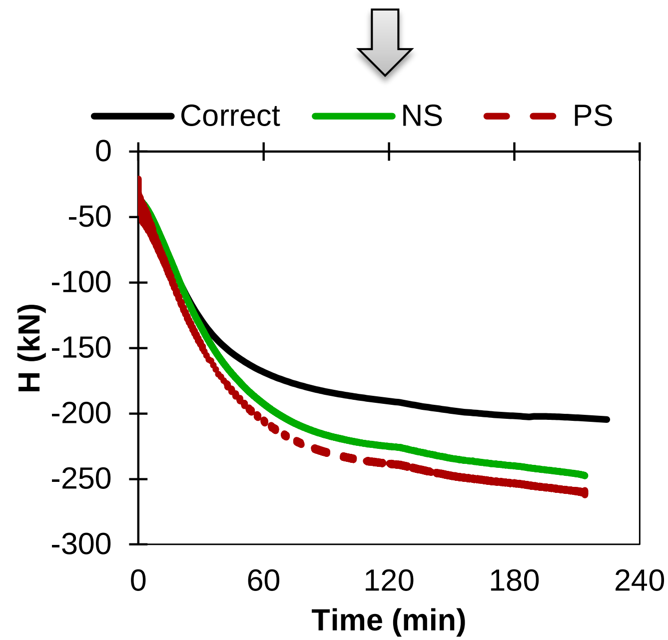


Equilibrium at Ambient Temperature









Conclusion of the Post-analysis of the Test 2

The **resolution of the DAS** can be improved

The **support system of the DAS** needs to be improved

The **horizontal jack** is not used at the maximum capacity

Errors observed in the **control system**

e.g. Impossibility to impose target displacements by the horizontal jack

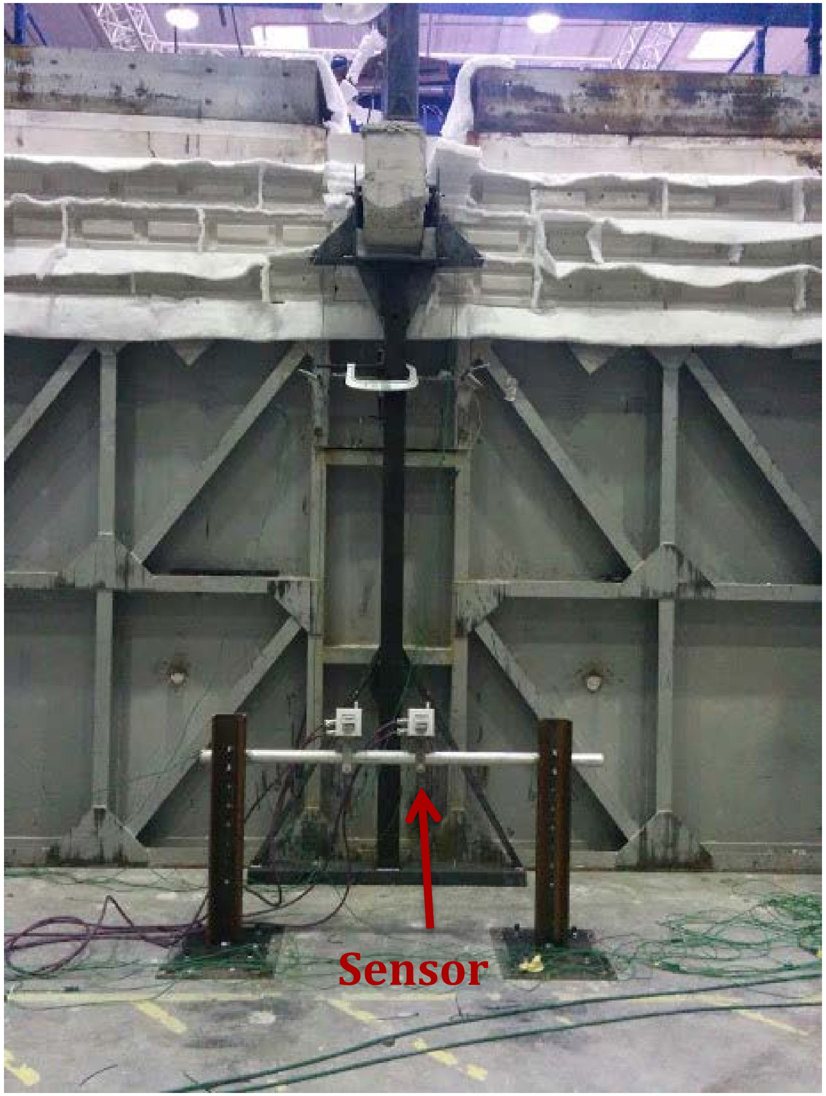
The restoring of the equilibrium at ambient temperature has been done fast without giving the possibility to observe the process in real time → perform the process step by step

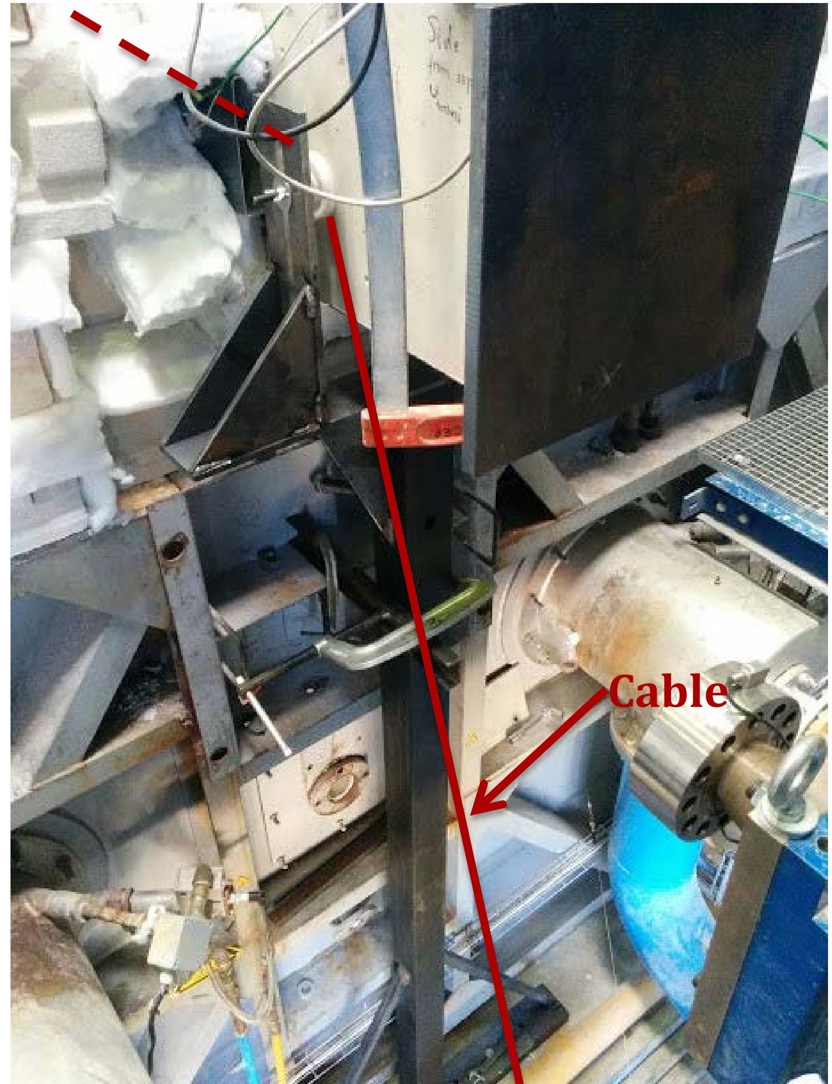
Improvements for the Test 3

The **resolution of the DAS →** did not change

The **support system of the DAS →** stiffer

Support System of DAS





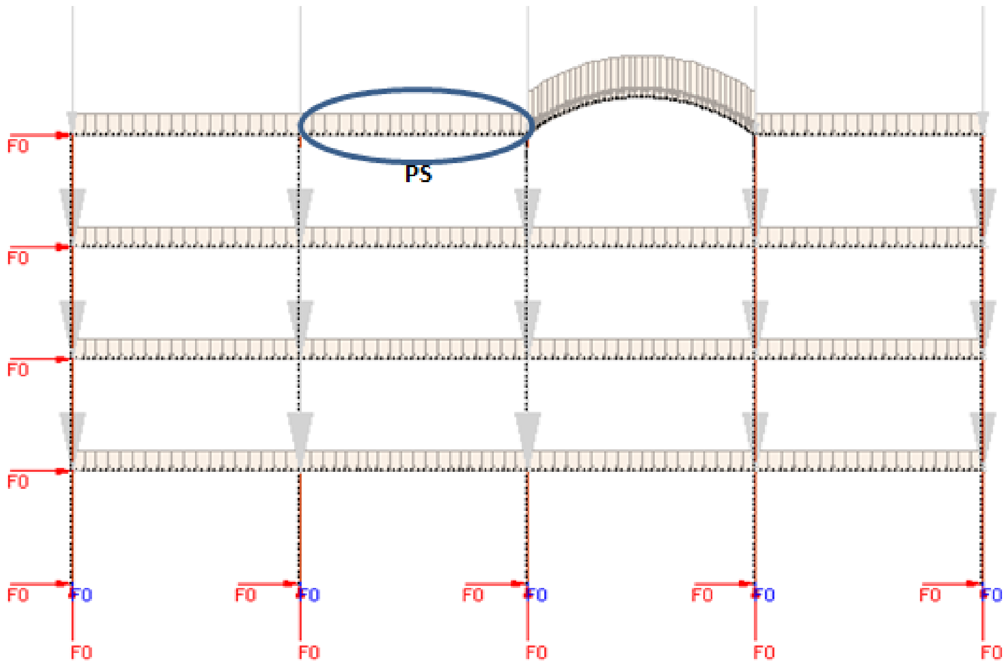
Improvements for the Test 3

The **resolution of the DAS** → did not change

The **support system of the DAS** → stiffer

The **configuration of the structure** was modified to increase the axial force

New Configuration of the Structure



The **axial force** 20°C: 37 kN →72 kN

Improvements for the Test 3

The **resolution of the DAS →** did not change

The **support system of the DAS →** stiffer

The **configuration of the structure** modified to increase the axial forces

The code of the control system was corrected

The code of the control system was **supposed to be corrected**

Realization of the Test 3

Stage 1 (Loading of the span) → OK

Stage 2 → again, errors in the control system were observed (control jacks pushing to infinite values)

Specimen unloaded to allow time to the operator for analysis

Operator was distracted and unwillingly activated the loading

Control jacks pushing to infinite values

Final Conclusion

One PS is still available

The external company was not available before February 2017

Test 1 → January 2016

Test 2 → June 2016

Test 3 → October 2016

No other hybrid fire test was decided to be performed

Post-analysis of the tests was done in the last stage of the thesis

Outline of the Presentation

Introduction

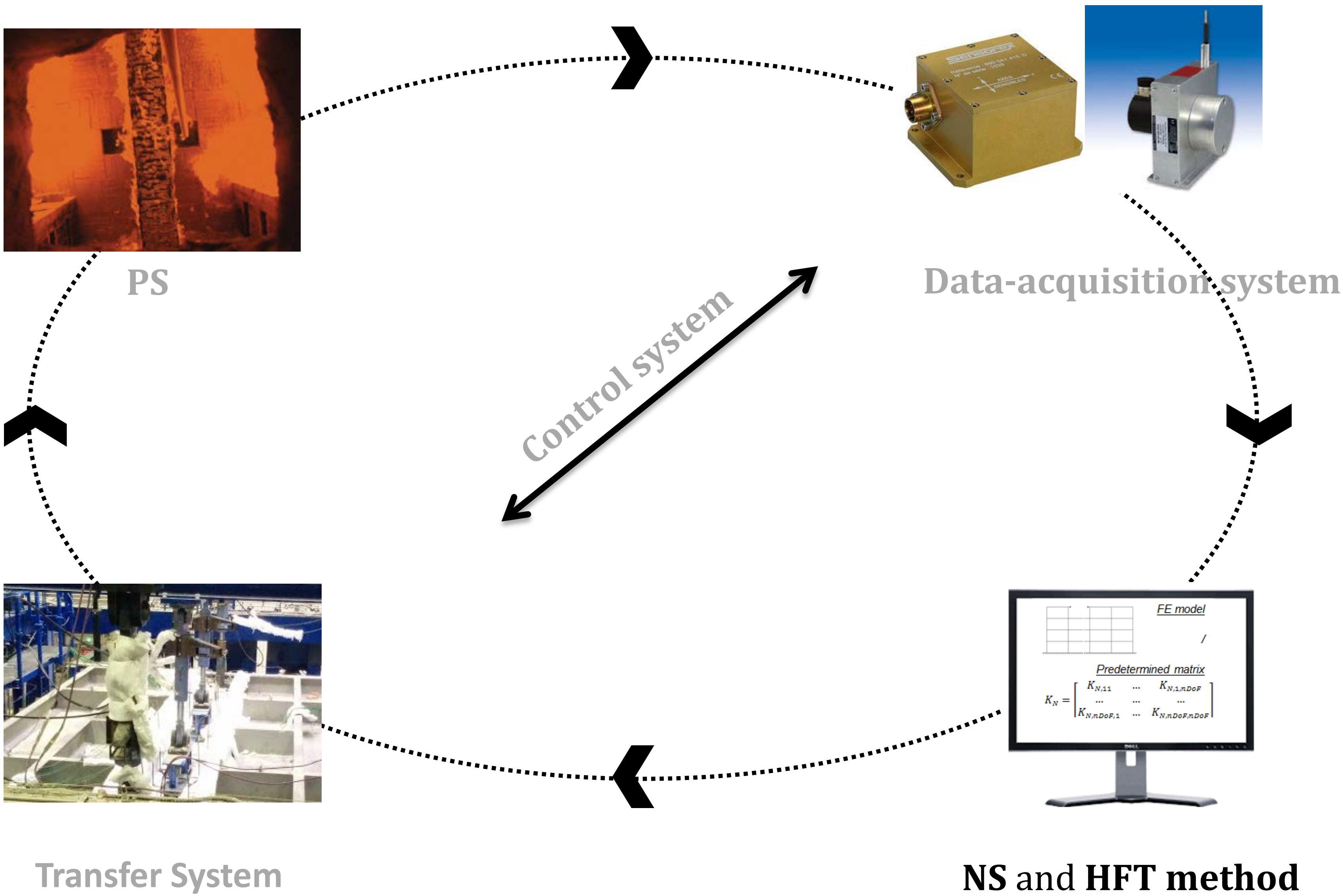
Theoretical developments

Numerical analysis of the case study

Experimental studies

Conclusions and future work

Control Process



Contributions and Conclusions

1. Numerical developments

SAFIR → new subroutine developed for virtual hybrid fire tests

- implemented for the case when the NS is described by the predetermined matrix

Contributions and Conclusions

2. HFT methodology

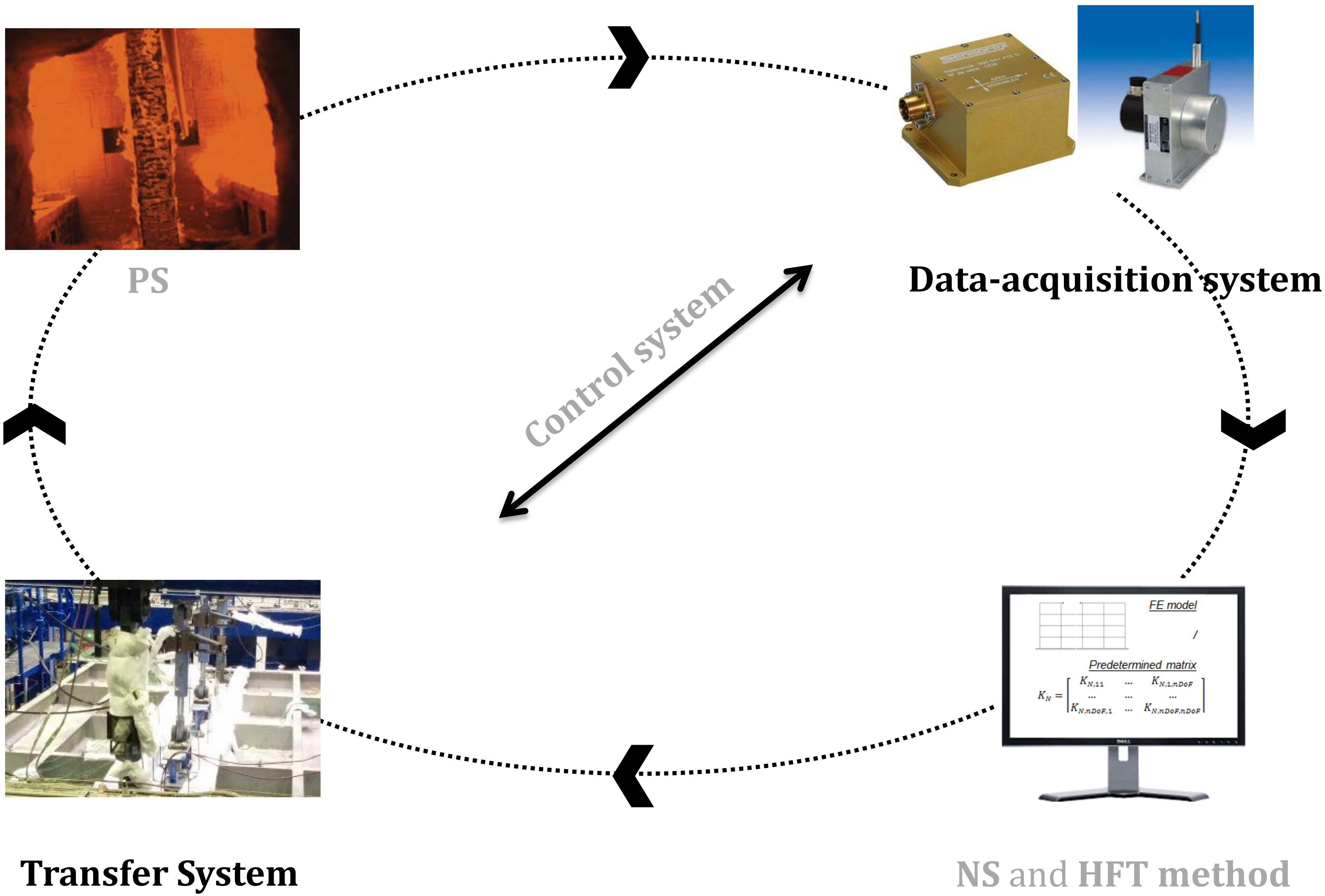
The first generation method → conditionally stable on R

- *Cause*: the stiffness of the PS is neglected

The new method → stable in the virtual environment

- *Cause*: the stiffness of the PS is considered
- *Displacement control procedure*: stable and applicable also in the last stage of the HFT
- *Force control procedure*: might be unstable
- Parametric analysis performed (time step, estimation of K_P)

Control Process



Contribution and Conclusions

3. Experimental work

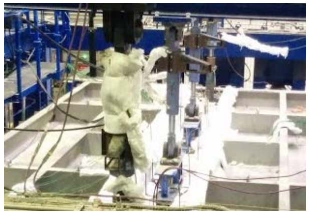
Hybrid fire tests could not be performed but lessons have been learned:

Data-acquisition system

- The *resolution* affects the accuracy of the results (e.g. on the equilibrium)
- *Support system* must be stiff enough

Transfer system

- The *capacity* must be selected in accordance with the load to be applied
- *Type of dual action actuators* might be improved



Future Work

HFT method

- Analyze the case when the NS is represented using a nonlinear predetermined matrix or nonlinear finite element software
- Update the stiffness of the PS when possible
- Study the propagation of errors in a general context
- Dynamic approach close to failure might be needed
- Definition of a theoretical framework for selecting the time step, the stiffness of PS and the resolution of the data acquisition system
- Validate the concepts experimentally

Liege University– Faculty of Applied Sciences
Department ArGEnCo
Structural Engineering Sector

Development and implementation of a methodology for hybrid fire testing applied to concrete structures with elastic boundary conditions

THANK YOU!