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
Outline of the Presentation

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Introduction

How a structure behaves when exposed to fire?

**Individual testing**
- Individual structural elements
- Unreal boundary conditions

**Full scale testing**
- Real boundary conditions
- Expensive approach

*(TFRI, 2007)*

*(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

(PS) (Cardington test) (NS) (TFRI, 2007)
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

![Graph showing mid-span displacement over time for two configurations.](image)
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)
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

Physical Substructure (PS)

Transfer System

Data-acquisition System

HFT method and Numerical Substructure (NS)
Control Process

Physical Substructure (PS)

Transfer System

Data-acquisition System

HFT method and Numerical Substructure (NS)
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

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Seismic field</th>
<th>Fire field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of tests</td>
<td>Slow tests possible</td>
<td>Real time needed*</td>
</tr>
<tr>
<td>Solved equation</td>
<td>Dynamic equation needed</td>
<td>Static equations possible</td>
</tr>
<tr>
<td>Size of the PS</td>
<td>Small scale possible</td>
<td>Real scale needed*</td>
</tr>
<tr>
<td>Transfer system and data-acquisition system</td>
<td>Ambient temperature</td>
<td>Elevated temperatures</td>
</tr>
</tbody>
</table>

* Except for specific elements
State of the Art in the Fire Field

Korzen (1999)
- 1 DoF
- NS \rightarrow \text{constant stiffness}

Robert (2008)
- 3 DoFs
- NS \rightarrow \text{constant stiffness}

Mostafaei (2013)
- 1 DoF
- NS \rightarrow \text{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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Conclusions and future work
First Generation Method (FGM)

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

$R: \text{the stiffness ratio}$

$R = \frac{K_N}{K_P}$

Complete structure

Physical Substructure

Numerical Substructure
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

<table>
<thead>
<tr>
<th>Test</th>
<th>Method</th>
<th>R</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Korzen</td>
<td>FCP</td>
<td>R&lt;1</td>
<td>✓</td>
</tr>
<tr>
<td>Mostafaei</td>
<td>FCP</td>
<td>R&lt;1</td>
<td>✓</td>
</tr>
<tr>
<td>Robert</td>
<td>FCP</td>
<td>0.167 (R&lt;1)</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.756 (R&lt;1)</td>
<td>✓</td>
</tr>
</tbody>
</table>

• 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

Complete structure

\[ K_P, L_P, \alpha \quad K_N, L_N \]

Physical Substructure

Numerical Substructure

1. Read \( F_P(t_n) \) and \( F_N(t_n) \)

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

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)

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

\textit{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 $t_n + \Delta t_P$

\[
\Delta F(t_n + \Delta t_P) = F_P(t_n + \Delta t_P) + F_N(t_n + \Delta t_P)
\]

\[
= -K_P \cdot \alpha \cdot L_P \cdot \left( T(t_n + \Delta t_P) - \frac{K_N + K_P}{K_N + K_P^*} \cdot T(t_n) \right)
\]

\[
\Delta F(t_n + \Delta t_P) \cong 0
\]

**Observations:**

\[
\Delta t_P \cong 0
\]

\[
K_P^* \cong K_P
\]
C) Reproduction of the Exact Solution (DCP)

Exact solution

\[ u(t_n) = \frac{E_P \cdot A_P}{K_N + K_P} \cdot \alpha \cdot T(t_n) \]

HFT solution

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

Equal because

\[ E_P A_P = K_P L_P \]
New Method

Inspired from FETI

Unconditionally stable on $R$

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

The exact solution is reproduced
(for proper values of $\Delta t_P$ and $K_P^*$)
Ambient temperature analysis of the complete structure

\[ F_{20}, u_{20} \]

Load the PS and NS

Equilibrium at ambient temperature restored

Start the fire

Initialization

\[ u_0 = u_{20} \]
\[ n = 0 \]
\[ t_0 = 0 \]

New Method

Increment the time step

\[ n = n + 1 \]
\[ t_n = t_{n-1} + \Delta t \]

Read the restoring force vector of the PS

\[ F_{P,n} \]

Calculate the force vector of the NS

\[ F_{N,n} \]

Calculate the increment of displacement

\[ \Delta u_n = -(K_N + K_P^*)^{-1} \cdot (F_{P,n} + F_{N,n}) \]

Calculate and impose the new displacement

\[ u_n = u_{n-1} + \Delta u_n \]

Failure of the PS is reached?

NO

YES

End of the test
Numerical Example 1 DoF Linear System

Stiffness ratio $R = 1.33$

Stiffness ratio $R = 0.75$
Outline of the Presentation

Introduction

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**Numerical analysis of the case study**

Experimental studies

Conclusions and future work
Description of the Case Study

Configuration of the PS

\[ \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix} \]

\( K_N \) defined by the elastic predetermined matrix
Predetermined Matrix vs. Initial Tangent Stiffness Matrix

Predetermined matrix of the NS

- Computed in SAFIR, tangent to the loaded stage

\[ K_N = 10^6 \begin{bmatrix} 11 & -12 & 8 \\ -12 & 65 & -9 \\ 8 & -9 & 64 \end{bmatrix} \]

Stiffness Matrix of the PS

- Computed in SAFIR, tangent to the loaded stage

\[ K_P^* = 10^6 \begin{bmatrix} 479 & 0 & 0 \\ 0 & 26 & 13 \\ 0 & 13 & 26 \end{bmatrix} \]
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 $\Delta t$ and $K_P^*$
Virtual HFT of the New Method (DCP)

**Procedure:** Displacement control

**NS:** constant predetermined matrix defined before the HFT

**Parametric study:** $\Delta t$ and $K_P^*$

<table>
<thead>
<tr>
<th>Case</th>
<th>Time step</th>
<th>The PS's stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>$\Delta t = 1\ s$</td>
<td>$K_P^* = 1.50K_{P0n}$</td>
</tr>
<tr>
<td>Case 2</td>
<td>$\Delta t = 10\ s$</td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td>$\Delta t = 30\ s$</td>
<td></td>
</tr>
<tr>
<td>Case 4</td>
<td>$\Delta t = 60\ s$</td>
<td></td>
</tr>
<tr>
<td>Case 5</td>
<td>$\Delta t = 5\ min$</td>
<td></td>
</tr>
<tr>
<td>Case 6</td>
<td>$\Delta t = 10\ min$</td>
<td></td>
</tr>
<tr>
<td>Case 7</td>
<td>$\Delta t = 1\ s$</td>
<td>$K_P^* = 5K_{P0n}$</td>
</tr>
<tr>
<td>Case 8</td>
<td>$\Delta t = 1\ s$</td>
<td>$K_P^* = 10K_{P0n}$</td>
</tr>
<tr>
<td>Case 9</td>
<td>$\Delta t = 1\ s$</td>
<td>$K_P^* = 50K_{P0n}$</td>
</tr>
<tr>
<td>Case 10</td>
<td>$\Delta t = 1\ s$</td>
<td>$K_P^* = 0.50K_{P0n}$</td>
</tr>
</tbody>
</table>
Virtual HFT of the New Method (DCP)

Case 1 ($\Delta t = 1 \text{ s}; K_p^* = 1.50 K_p$)

**Axial DoF**

**Left rotational DoF**

**Right rotational DoF**
Virtual HFT of the New Method (DCP)

Case with elastic NS

Axial DoF

Left rotational DoF

Right rotational DoF

Graphs showing the relationship between time (min) and various forces and rotations (mm, kN, mrad) for different cases: Correct, NS, and PS.
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 $\Delta t$ needed
- Too Small $\Delta t$ might induce incremental displacements smaller than the resolution of the transducers

Increase of $K_P^*$ influences negatively the equilibrium and compatibility
Decrease of $K_P^*$ induces instability
Constant $K_N$ 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:**

\[
R = 0.20 \text{ (horizontal displacement)} \quad \rightarrow \text{ FCP}
\]

\[
R = 2.53 \text{ (rotation left)} \quad \rightarrow \text{ DCP}
\]

\[
R = 2.48 \text{ (rotation right)} \quad \rightarrow \text{ DCP}
\]
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**Experimental studies**

Conclusions and future work
Tests

Tests performed in CERIB

- **Test 1** (standard test)
Tests performed in CERIB

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

- PS CERIB
- DAS CERIB
- External company
- Transfer System CERIB
- NS and HFT method ULg

Control system
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

Transfer System

PS

Control System

Data-acquisition system

NS and HFT method
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

Too flexible!

Sensor

Measurement point
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

PS

Data-acquisition system

Control system

Transfer System

NS and HFT method

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Equilibrium at Ambient Temperature

Measured versus computed values

Axial DoF

Left rotational DoF

Right rotational DoF
Equilibrium at Ambient Temperature

Displacements

**Computed**   **Measured**

$u^c_0 \rightarrow u^m_0$

$u^c_i \rightarrow u^m_j$

Correct  NS  PS

H (kN)

Time (min)

0  60  120  180  240

0  -50  -100  -150  -200

-250  -300  -200  -150

-100  -50  0

0  60  120  180  240

0  -50  -100  -150  -200

-250  -300  -200  -150

-100  -50  0

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) $\rightarrow$ OK

Stage 2 $\rightarrow$ 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
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Control Process

PS

Data-acquisition system

Transfer System

NS and HFT method
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

PS

Data-acquisition system

Control system

Transfer System

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

THANK YOU!