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Stability in Hybrid Fire Testing

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ABSTRACT

Hybrid testing is an appealing technique to observe the behavior of an element in an experimental test while taking into account the interaction with the rest of the structure which is modelled numerically. Being widely used in the seismic field, this technique has been recently proposed in the fire field. The purpose of this paper is to demonstrate that the loading control process may be unstable during the hybrid testing when using the methodology applied in former tests presented in the literature. The stability in the latter method depends on the stiffness ratio between the two substructures. For the purpose of discussion, a one degree-of-freedom elastic system is studied. To overcome the stability issues, a new method is presented, independent on the stiffness ratio. Finally, the hybrid testing of a 2D beam being part of a moment resisting frame is analyzed in a virtual environment (both parts being modeled numerically) using the "first generation method" and the new proposed method.

INTRODUCTION

Fire tests are required to observe the behavior of structures exposed to fire. Generally, the tests are performed on single elements, without considering the interaction with the rest of the structure. Entire buildings can also be tested but this approach is very expensive and therefore uncommon.

Using hybrid fire testing (HFT), it is possible to test only selected elements while taking into account the effects of the surrounding structure at the interface.

The methodology is based on substructuring method and it has been widely explored in the seismic field [1]. In fire field, a few hybrid tests have been performed [2]-[5] but the implementation of a method developed from seismic field to the fire field remains a challenge with many aspects to be solved. The principle of HFT is to divide the analyzed structure in two parts, a physical substructure PS (tested in a furnace) and a numerical substructure NS (modelled aside), and to ensure equilibrium and compatibility between these two substructures during the test.

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At frequent intervals (time step Δt), the displacements or the forces at the interface are measured from the PS and this information is sent to the NS. The reactions (forces or displacements) of the NS at the interface are calculated and then sent back to the PS. There may be an additional delay of time Δt_P requested for the calculation of the NS reaction and for application of the reaction to the PS. The procedure is either called force control procedure FCP or displacement control procedure DCP, when reaction forces or displacements are sent back to the PS.

Korzen [2] presents the hybrid test method applied to a column specimen as part of a simulated building environment. The mode of action between both parts is exemplified on a one degree-of-freedom (DoF) basis, i.e. the axial column force is measured and adjusted continuously to the model force, which is represented through a – not necessarily constant – stiffness, in displacement control.

Robert [3]-[4] presents a hybrid fire test where the PS is a slab, with 3 DoF controlled at the interface i.e. one axial and two rotational. The behavior of the NS is modelled through an elastic predetermined matrix defined before the test.

Mostafaei [5] presents the results of a hybrid test performed on a concrete column (one axial DoF at the interface) extracted from a 3D concrete frame. Unlike the previous cases, the NS is modelled in SAFIR® [6] and a part of the NS is also exposed to fire. The interaction between the PS and NS during the hybrid fire test is done manually by the user.

The methodology presented in previous hybrid fire tests [3]-[5] will be referred in this paper as "first generation method" and is discussed here below.

FIRST GENERATION METHOD FOR HFT

In the case of the first generation method, when updating the interface forces and displacements, only the characteristics of the NS are considered, disregarding the effect of the PS.

The method has been modelled analytically for a simple linear system with a single DoF located at the interface, which is the axial displacement at node 2 (see Figure 1). The temperature in the PS increases with time which induces thermal expansion but, for the sake of simplicity, the stiffness of the PS remains constant. The stiffness of the NS also remains constant during the entire duration of the test. The system is composed of two bars, the PS of length L_P, respectively the NS of length L_N. The heated PS is defined by the axial stiffness K_P and thermal coefficient of the material α whereas the cold NS is characterized by the axial stiffness K_N. In HFT the structure is decomposed and the PS is placed in a furnace, while the NS is modelled via numerical software or characterized by a predetermined matrix.

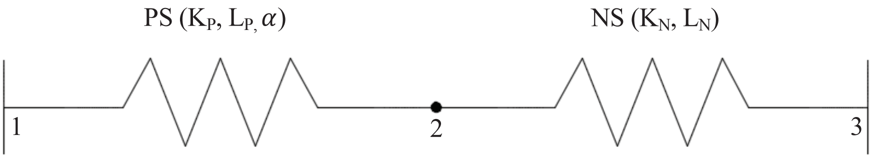


Figure 1. Linear elastic system.

The first generation method using the force control procedure is applied step by step:

a. First, the analysis of the entire system is performed in order to determine the forces and the displacements at the interface between the PS and NS before the fire starts.

b. The PS is placed in the furnace (in a real HFT) and loaded with the exterior loads and interface conditions, while the NS is modeled aside. Herein the exterior loads, the interface forces and displacements are equal to zero.

Note:

$u_x(t_n)$ is the interface displacement of substructure x (P for the PS and N for NS) at time t_n (i.e. displacement of node 2).

$F_x(t_n)$ is the interface force of substructure x (P for the PS and N for NS) at time t_n.

$T(t_n)$ is the temperature of the PS at time t_n.

n is number of the reading.

c. Heating of the PS starts. In force control procedure, the PS is free to expand, and the displacement is measured. In this example, it yields to the value expressed by Eq. (1).

$$u_P(t_1) = \alpha L_P \, T(t_1) \tag{1}$$

d. The measured displacement (1) is imposed on the NS. This generates a reaction force that is computed using Eq. (2).

$$F_N(t_1) = K_N \, \alpha \, L_P T(t_1) \tag{2}$$

e. The new reaction force is imposed on the PS (Eq. (3)). A time delay Δt_P is used to capture the time needed to compute the reaction of the NS and to adjust the force in the jacks, as for a real HFT.

$$F_P(t_1 + \Delta t_P) = -K_N \, \alpha \, L_P T(t_1) \tag{3}$$

f. The new force induces a new displacement of the PS. Meanwhile, heating of the PS has continued and also induces variation in displacement. The updated displacement of the PS at the interface $u_P(t_2)$ is measured (given here by Eq. (4)) and imposed on the NS. This generates a new reaction force $F_N(t_2)$ given by Eq. (5).

$$u_P(t_2) = \alpha L_P \, T(t_2) + \frac{F_P(t_1)}{K_P(t_2)} = \alpha L_P \left(T(t_2) - \frac{K_N}{K_P} T(t_1) \right) \tag{4}$$

$$F_N(t_2) = K_N \, \alpha L_P \left(T(t_2) - \frac{K_N}{K_P} T(t_1) \right) \tag{5}$$

Steps *e* and *f* are repeated in order to maintain equilibrium and compatibility at the interface. For future discussion, the ratio between the stiffness of the NS and PS will be referred in this paper as stiffness ratio $R = \frac{K_N}{K_P}$.

Expanding Eq. (4) and (5), for n time steps, the displacement can be expressed by Eq. (6), while the reaction force generated by the NS, by Eq. (7).

$$u_P(t_n) = \alpha L_P \sum_{i=0}^{n-1} \left[(-R)^i \ T(t_{n-i}) \right] \tag{6}$$

$$F_N(t_n) = K_N \ \alpha \ L_P \sum_{i=0}^{n-1} \left[(-R)^i \ T(t_{n-i}) \right] \tag{7}$$

The same developments can be made for the displacement control procedure. In this case, the measured reaction force can be determined using Eq.(8), while the displacements can be calculated using Eq. (9).

$$F_P(t_n) = -K_P \ \alpha \ L_P \sum_{i=0}^{n-1} \left[\left(-\frac{1}{R} \right)^i \ T(t_{n-i}) \right] \tag{8}$$

$$u_N(t_n) = \frac{1}{R} \alpha L_P \sum_{i=0}^{n-1} \left[\left(-\frac{1}{R} \right)^i \ T(t_{n-i}) \right] \tag{9}$$

From the Eq. (6)-(9) it is clear that the results during the HFT, using the first generation method, are influenced by the stiffness ratio R.

In order to avoid instability, the value of the parenthesis which involves the stiffness ratio should be smaller than 1, i.e. $R < 1$, for the force control procedure and $\frac{1}{R} < 1$ or $R > 1$ for displacement control procedure. If not, the value tends toward infinity when the number of iteration i increases, irrespectively of the size of the time steps, and the process becomes unstable.

CONDITIONS FOR STABILITY IN FIRST GENERATION METHOD

It has been shown that the first generation method is sensitive to the stiffness ratio between the substructures. When the NS is more flexible than the PS, i.e. $R < 1$, then the force control procedure FCP is stable, but the displacement control procedure DCP is not. In the case of $R > 1$, the DCP is stable, whereas the FCP is not.

Choosing the right procedure between force control and displacement control is not easy. One of the reasons is that the stiffness of the PS is constantly changing during the HFT. The procedure chosen as appropriate before the test might become inappropriate during the test with the change of the stiffness ratio.

In addition to that, the number of controlled DoFs at the interface can be higher than one. The stiffness ratio of some DoFs may require one procedure, while others would require the other procedure, which makes the method difficult to be applied.
This demonstrates the need of a method that is independent on the stiffness ratio to ensure stability during the whole HFT.

An example of a situation when the FCP is applicable is when the PS consists of a column with the axial DoF to be controlled. A compressed column will generally be stiffer than the surrounding, even when its modulus is reducing due to the fire exposure. This explains why, in the HFT performed by Mostafaei no instability occurred, because the FCP was the good choice. In the case of HFT performed by Robert, the stiffness ratio was always smaller than one during the test, for all the DoFs, which explains why no instability occurred either.

A NEW METHOD TO PERFORM HFT

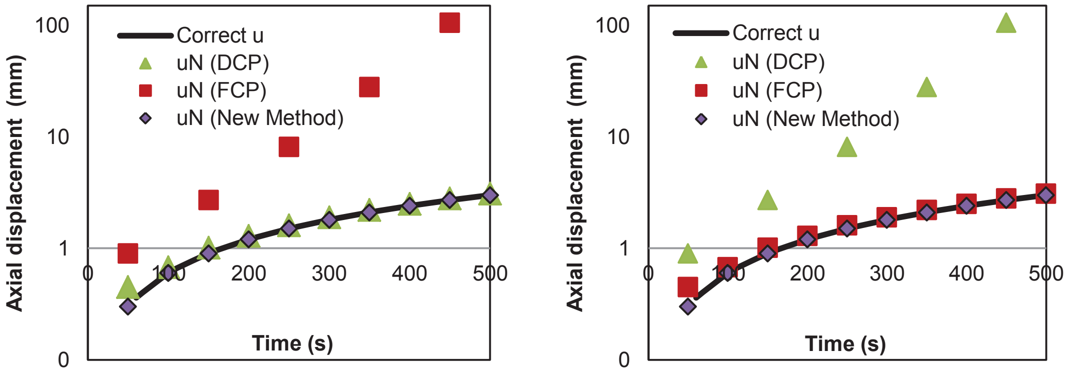
This section presents a novel method that is unconditionally stable, independently of the stiffness ratio value. The method has been inspired from the finite element tearing and interconnecting method (FETI) [7], and it controls the displacements during the HFT, based on the out of balance forces between the substructures.

During one step, displacements are blocked in the substructures. The variation of temperatures in the heated PS modifies the reaction forces at the interface, due to the thermal expansion and PS's stiffness variation. The reaction forces are measured in the PS and they are not in equilibrium with those that existed at the NS interface at the beginning of the step. The correction of the displacements du is calculated from the out of equilibrium forces dF, based on the stiffness of the PS and NS, as is presented in Eq.(10) .

$$du(t_n) = (K_N + K_P)^{-1}\, dF(t_n) \tag{10}$$

Because the real stiffness value of the PS is unknown, only an estimate of it is used in this equation, for example the value calculated at room temperature. Nevertheless, convergence can be obtained in a Newton-Raphson iteration scheme approach even if the matrix is not exactly equal to the tangent matrix.

In fact, it has been shown by hybrid fire tests performed numerically that it not necessary to apply Eq. (10) iteratively to ensure equilibrium at every time step. During the time that is needed to perform the calculation in the computer and for the testing equipment to apply the corrections of displacements, the temperatures are still increasing and the convergence process is running after an equilibrium that is constantly running away. It is thus not necessary to distinguish between iterations and time steps. The test is performed by applying continuously Eq. (10), with a cycling frequency that is as high as possible, which requires testing equipment that has a short response time. Note that the compatibility is continuously respected, as the same displacements are imposed on the PS and NS at the interface.



a) Stiffness ratio $R = 2$

b) Stiffness ratio $R = 0.5$

Figure 2. Instability in HFT depending on the stiffness ratio (logarithmic scale).

The results obtained numerically for the system of Figure 1 are used to illustrate this statement. The temperature evolution in the PS is taken as $0.5t_n$.

The evolution of displacements at the interface is presented for different stiffness ratios in Figure 2. The reference solution (correct u) is the one obtained when the entire system is analyzed, without subdivision. For a stiffness ratio $R > 1$, Figure 2 a) shows that the solution diverges from the reference solution when the force control procedure (FCP) is used, while convergence is obtained with displacement control procedure (DCP). Figure 2 b) shows the evolution of displacements for the case of a stiffness ratio $R < 1$, and it can be observed that in this situation the DCP diverges from the correct solution whereas the FCP is stable. In contrast, the new method is stable, independently on the stiffness ratio, as can be seen in Figure 2.

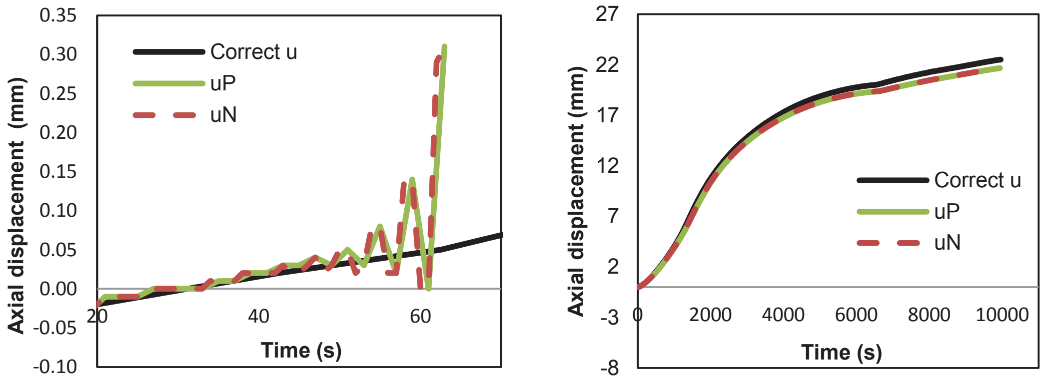
The logarithmic scale is chosen to represent the evolution of displacements in time to be able to plot the divergent solutions, which quickly reach large values. To be noted that in the case of instability, positive and negative values alternate. The negative values cannot be represented in the logarithmic scale, but nevertheless the instability is obvious when looking at the positive values.

Compatibility and equilibrium at the interface are ensured in the case of the new method, as well as in the case of the first generation method provided the correct stiffness ratio is used.

The above discussion addresses the instability induced by using an inappropriate method. The study of other sources of instabilities [8], such as the resolution of actuators and transducers, or effect of the noise, will not be addressed in this paper.

REAL HYBRID FIRE TEST

The new methodology will be implemented and verified on three full scale fire tests in the laboratory of CERIB in France. A concrete beam of 0.25 m x 0.40 m x 5.60 m, which is part of a moment resisting concrete frame, will be tested, where three DOF's, i.e. the axial displacement and the supports rotation will be controlled during the test. Only two of the three tests will be hybrid fire tests. In the hybrid tests, the behavior of the NS will be pre-calculated, using a predefined matrix defined in the software which controls the furnace [9].



a) The first generation method (FCP)

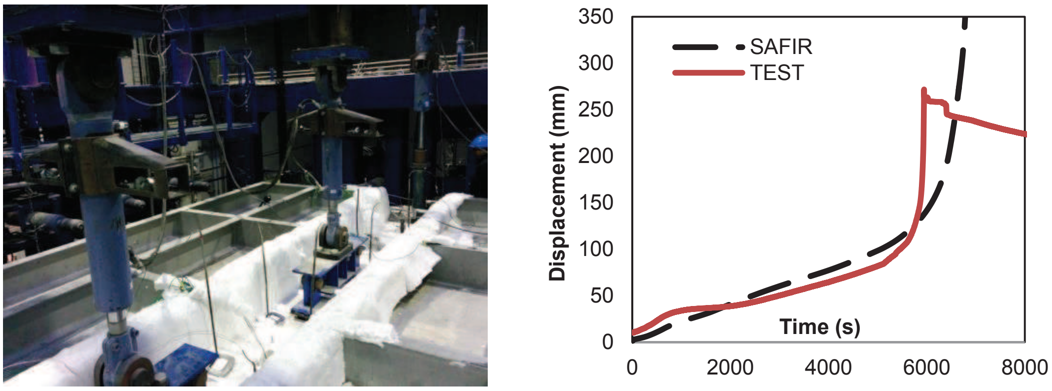
b) The new method

Figure 3. Virtual HFT of a concrete beam part of a frame.

For these hybrid tests, the stiffness ratio of the axial DOF would require a force control procedure, whereas the rotational DOF's would require a displacement control procedure if the first generation method was used. In anticipation of the test, a numerical simulation has been done considering the first generation method (using FCP with $\Delta t = 1$ s and $\Delta t_P = 1$ s), with SAFIR® modelling the PS whereas the stiffness of the NS is pre-calculated and kept constant. Instability occurred right at the beginning of the analysis as can be seen in Figure 3 a). However, by applying the new method the analysis was stable and showing good results (see Figure 3 b)).

The first test (non-hybrid) has been conducted on January 19, 2016, and the effect of the surrounding was constant during the test (constant negative moments applied at the supports and no axial restraint). The purpose of this test is, first, to compare the results with the one of the two following hybrid tests, and to prepare and check the instrumentation (the transducers and the jacks) for the HFT.

Figure **4**Figure 4 a) presents the setup of the traditional test and Figure 4 b) the evolution of the measured and calculated mid-span displacement. Note that failure occurs earlier when the effect of the remainder structure is constant. As can be seen, the test showed a good agreement with the numerical analysis performed with SAFIR®.



a) The setup of the beam b) The evolution of mid-span displacement

Figure 4. Fire test (non hybrid) performed on a concrete beam.

CONCLUSION

The objective of the paper was to show that the first generation HFT method used in the literature, where the correction of the interface forces/displacements depends only on the characteristics of the NS, is not always stable. It has been shown, using an elastic system as illustrative example, that the stiffness ratio between the NS and PS will dictate the stability of this method. Yet, the stiffness ratio is not easily predictable before a fire test, because the stiffness of the exposed substructures is reduced during the test. Moreover the need of controlling multiple DoFs makes the method impossible to be applied, when different types of procedure should be used for different DoFs.

A new method has been proposed in this paper, unconditionally stable no matter the stiffness ratio, and assumes controlling the displacement during the HFT.

Full scale HFTs are planned on a concrete beam that is part of a moment resisting frame. These tests have been simulated in a virtual environment, i.e. with the PS modeled as substructure in SAFIR®, while the NS was described by the predetermined matrix. The results show that the first generation method cannot be applied due to the fact that the axial DOF requests a force control procedure, while the rotational DOFs request a displacement control procedure. However, the new method succeeds in being stable, ensuring compatibility and equilibrium at the interface.

Prior the HFT a traditional test has been performed, showing good results with the numerical analysis.

REFERENCES

1. Saouma, V.E., and M.V. Sivaselvan. 2008. "*Hybrid simulation: Theory, implementation and application*," Taylor and Francis, London, UK.
2. Korzen, M., G. Magonette, and Ph. Buchet. 1999. "*Mechanical Loading of Ccolumns in Fire Tests by Means of the Substructuring Method*," Zeitschrift für Angewandte Mathematik und Mechanik, Vol. 79, pp. S617-S618.
3. Robert, F. 2008. "*Comportement des bétons sous haute température et en cas d'incendie: caractérisation multi-échelle*,"(Unpublished doctoral thesis). L'Ecole Normale Supérieure de Cachan, Cachan, France.
4. Robert, F., S. Rimlinger, C. Collignon. 2010. "*Structure fire resistance: a joint approach between modelling and full scale testing (substructuring system)*", 3rd fib International Congress
5. Mostafaei, H. 2013. "*Hybrid fire testing for assessing performance of structures in fire – Application*," Fire Safety Journal, 56, 30-38.
6. Franssen J.-M., "*SAFIR, A Thermal/Structural Program Modelling Structures under Fire,*" A.I.S.C. Engineering Journal 42 (3) 143-158.
7. Farhat, C., and F.-X. Roux. 1991. "*A method of finite element tearing and interconnecting and its parallel solution algorithm*," International Journal for Numerical Methods in Engineering, 32:1205-1227.
8. Tondini, N., G. Abbiati, L. Possidente, B. Stojadinovic. 2016. "*A Static Partitioned Solver for Hybrid Fire Testing*", 9th International Conference on Structures in Fire, June 8-10, 2016
9. Sauca, A., T. Gernay, F. Robert, J.M. Franssen. 2015. "*Characteristics and implementation of Hybrid Fire Testing (HFT),*" presented at the Engineering Mechanics Institute Conference, June 16-19, 2015.