A Novel Methodology for Hybrid Fire Testing

Ana Sauca[1]*, Thomas Gernay[2], Fabienne Robert[3], Nicola Tondini[4], Jean-Marc Franssen[5]

[1,2,5] *University of Liege, Department ArGEnCo, Liege, Belgium*

[3] *CERIB, Fire Testing Center, Epernon, France*

[4] *University of Trento, Department of Civil, Environmental and Mechanical Engineering, Italy*

ABSTRACT

This paper describes a novel methodology for conducting stable hybrid fire testing (HTF). During hybrid fire testing, only a part of the structure is tested in a furnace while the reminded structure is calculated separately, here by means of a predetermined matrix. Equilibrium and compatibility at the interface between the tested "physical substructure" and the "numerical substructure" is maintained throughout the test using a dedicated algorithm. The procedures developed so far are sensitive to the stiffness ratio between the physical and the numerical substructure and therefore they can be applied only in some cases. In fire field, the stiffness of the heated physical substructure may change dramatically and the resulting change in stiffness ratio can lead to instability during the test. To overcome this drawback, a methodology independent of the stiffness ratio has been developed, inspired from the Finite Element Tearing and Interconnecting (FETI) method, which has been originally developed for substructuring in numerical analyses. The novel methodology has been successfully applied to a hybrid fire test in a purely numerical environment, i.e. the physical substructure was also modelled numerically. It is shown that stability does not depend on the stiffness ratio and that equilibrium and compatibility can be consistently maintained at the interface during the fire. Finally, the ongoing experimental program aimed at employing and experimentally validating this methodology is described.

Keywords: *Fire Testing, Hybrid Methodology, Physical substructure, Numerical Substructure*

1 INTRODUCTION

The behaviour of structures in fire can be observed in fire tests. Generally, the tests are performed on single elements, without considering the global behaviour of the structure. In the literature some tests performed on entire buildings are described, but the high cost makes the practice uncommon. For this reason, fire tests are usually carried out on single elements with free

[1] Ph.D. student, a.sauca@ulg.ac.be

[2] F.R.S.-FNRS Post-doctoral researcher, thomas.gernay@ulg.ac.be

[3] Head of fire section CERIB, f.robert@cerib.com

[4] Assistant Professor, nicola.tondini@unitn.it

[5] Full Professor, jm.franssen@ulg.ac.be

* Corresponding author

thermal expansion. An appealing alternative consists in testing the structural element of which the behaviour must be determined and at the same time to consider the interaction with the surrounding by using hybrid fire testing (HFT). Inspired from substructuring theory, hybrid testing methods have been widely explored in the seismic field [1]. The implementation of a method developed from the seismic field to the fire field remains a challenge and only a few hybrid fire tests have been performed [2]-[5]. HFT is based on the decomposition of the analysed structure into two parts: i) a physical substructure (PS) tested in a furnace, and ii) a numerical substructure (NS), modelled aside. The method then consists in ensuring equilibrium and compatibility between these two substructures over the duration of the test. At each time step, data (displacements or forces) are measured at the substructure interfaces. Due to the fire exposure of the PS, equilibrium and compatibility at the interface are not generally satisfied any more at the end of the time step. To restore the equilibrium and compatibility at the interface, new data are computed (forces or displacements) and are imposed to the substructures, based on the measured data from the previous time step.

Few hybrid fire tests can be found in the literature. The first reported hybrid fire test was performed by Korzen [2] in 1999, where a column specimen was experimentally tested 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. Another hybrid fire test has been performed by Robert [3]-[4]. In the latter, the PS consisted of a concrete slab whereas the NS was a surrounding one floor concrete building. Three DoFs were controlled, i.e. one axial DoF and two rotational DoFs. A force-controlled procedure was employed. The behaviour of the NS was modelled by a constant predetermined matrix, which had been calculated before the test. Finally, Mostafaei [5] presented the hybrid fire test of the first floor central column part of a 3D concrete frame. The column was tested in the furnace (PS) while the surrounding was numerically modelled in the non-linear finite element software SAFIR® [6]. Every time step, the interaction between the PS and NS was ensured manually by the user. In particular, the axial force in the column was controlled. Unlike the previous cases, a part of the NS was also exposed to fire.

In previous hybrid fire tests [3]-[5], data (displacements or forces) are measured from the PS and sent to the NS at every time step Δt. The reactions (forces or displacements) of the NS at the interface are then calculated considering only the characteristics of the NS (i.e. disregarding the characteristics of the PS). This calculation can be done using a numerical model or a predetermined matrix for the NS. Then, the reactions are sent back to the PS and applied at the interface to restore equilibrium and compatibility. There may be an additional delay of time Δt_P requested for the calculation of the NS reactions and for the application of the reactions to the PS. When reaction forces or displacements are sent back to the PS, the procedure is either called force control procedure (FCP) or displacement control procedure (DCP), respectively. In this paper, this method will be referred to as “first generation method”; it is discussed further in the next section.

2 STABILITY IN FIRST GENERATION METHOD

In the case of the first generation method, when updating the interface forces or displacements, only the characteristics of the NS are considered, disregarding the characteristics of the PS. As already specified, the force control procedure (FCP) or displacement control procedure (DCP) can be used when performing HFT. The FCP entails to measure the displacements of the PS and to control forces at the interface of the PS. Here below, a step-by-step description of the first generation method using the FCP is presented.

a. The analysis of the entire system is performed in order to determine the interface forces and displacements before the fire.

b. The PS is placed in the furnace (in a real HFT) and loaded with the exterior loads and interface forces, while the NS is modeled aside. The NS can be modelled via numerical software as presented in [5] or by using a predetermined matrix as was the case in [3]-[4].
c. Heating of the PS starts. In force control procedure, the PS is free to expand, and the displacements are measured.
d. The measured displacements are imposed on the NS. This generates reaction forces.
e. The new reaction forces are imposed on the PS (time is needed to compute the reactions of the NS and to adjust the forces in the jacks).
f. The new imposed forces on the PS induce new displacements. Meanwhile, heating of the PS has continued and also induces variation in displacements, so equilibrium and compatibility are not satisfied.
g. Steps *d* to *f* are repeated during the hybrid fire test, in order to maintain equilibrium and compatibility at the interface.

The DCP follows the same steps as the FCP, but instead of measuring the interface displacements on the PS and computing the reaction forces of the NS, the reaction forces of the PS will be measured and the displacements of the NS will be calculated and therefore imposed on the PS.

The FCP 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 Fig. 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, and the NS of length L_N, whereas they are characterized by the same elastic modulus and area of the cross-section. Thus, 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.

PS (K_P, L_P, α) NS (K_N, L_N)

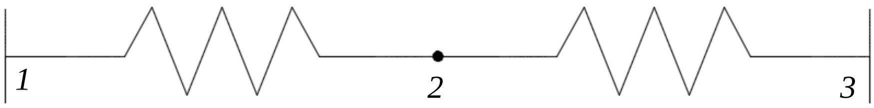


Figure 1 - Linear elastic system.

For every step *a-g*, the measured data from the PS and the calculated reaction of the NS can be expressed analytically for the elastic system presented in Figure 1.

The ratio between the NS's stiffness and PS's stiffness $R = \frac{K_N}{K_P}$ will be referred in this paper as stiffness ratio.

Equation (1) expresses the measured displacement u_P of the PS for the time t_n. The reaction force F_N, resulting from the NS's calculations, can be expressed using the Eq. (2).

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

$$F_N(t_n) = K_N \, \alpha \, L_P \sum_{i=0}^{n-1} \left[\left(-R\right)^i \; T\left(t_{n-i}\right) \right] \tag{2}$$

In the case of DCP, the measured reaction force F_P of the PS, for the time t_n is expressed by Eq. (3), whereas the calculated displacement u_N of the NS is expressed by Eq. (4).

$$F_P(t_n) = -K_P\,\alpha\,L_P \sum_{i=0}^{n-1}\left[\left(-\frac{1}{R}\right)^i T(t_{n-i})\right] \tag{3}$$

$$u_N(t_n) = \frac{1}{R}\alpha L_P \sum_{i=0}^{n-1}\left[\left(-\frac{1}{R}\right)^i T(t_{n-i})\right] \tag{4}$$

The measured and the calculated data during the HFT for the time t_n, depend on the substructure's characteristics such as the stiffness of the PS and NS (K_P, K_N), the length of the substructures (L_P and L_N), the thermal coefficient of the material α, the temperature in the heated substructure T, and the stiffness ratio R. The stiffness ratio between the substructures dictates the stability of the method. Indeed, 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.

Despite having expressed the stability condition clearly as a function of the stiffness ratio R, it is important to note that it is still not easy to choose the type of procedure to be used during a HFT in order to avoid instability. The fire exposed substructure is affected by a degradation of stiffness with time. The procedure chosen as appropriate before the test might become inappropriate during the test with the change of the stiffness ratio. In addition, 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.

In the previous test performed by Robert and Mostafaei, the FCP has been used and no instability occurred. Note that the stiffness ratio for all three DoFs, in the case of Robert's HFT, was always smaller than one during the test. The stiffness ratio was also smaller than one in the hybrid test performed by Mostafaei. In the situation when the PS is a column, and only the axial DoF is controlled during the HFT, the axial stiffness of the column is generally much higher than the axial stiffness of the NS, so the FCP was a good choice.

There are other sources of instability during the HFT e.g. the equipment accuracy, noise effect [7] which will not be treated in this paper. The above discussion addresses the instability induced by using an inappropriate method. Further analyses and discussions on the instability of the first generation method can be found in [8].

3 A NOVEL METHOD TO PERFORM HFT

This section presents a novel method that is unconditionally stable, independently of the stiffness ratio between the substructures. The method has been inspired from the finite element tearing and interconnecting method (FETI) [9], and it controls the displacements during the HFT, based on the out of balance forces between the substructures.

A step by step description of the method is given here below.

a. The interface forces and displacements are determined before the start of the test by performing the analysis of the entire structure.

b. The PS is placed in the furnace and loaded with the exterior loads and interface displacements, while the NS is modeled aside. If numerical software is used to model the NS, the exterior forces and the interface displacements calculated at step *a* are applied. If a predetermined matrix is used to represent the behavior of the NS, this is the tangent matrix corresponding to the loaded structure before the fire.

c. Heating of the PS starts. The interface displacements of the PS are blocked for the duration of a time step (displacement control procedure) and the reaction forces are measured.

d. Meanwhile, the corresponding displacements are blocked at the interface of the NS and the reaction forces of the NS are computed. If the NS is heated, the reaction forces will be different compared with the one from the previous time step. If the NS is kept cold, then the reaction forces are the same as the one from the previous time step.

e. The measured reaction forces of the PS are compared with the computed reaction forces of the NS. Generally the equilibrium is not ensured due to the fire effect.

f. To restore the equilibrium, a correction of displacement vector $d\mathbf{u}$ will be calculated and applied at the interface. The calculation is based on the measured reaction forces of the PS and NS (the vector of out of balance forces $d\mathbf{F}$). In this calculation of the displacements correction, the stiffness of both the PS and the NS are accounted for, according to Eq. (5). This is the main difference with the first generation method (in which only the stiffness of the NS was considered) and the most important contribution that allows ensuring stability of the method.

$$d\mathbf{u}\left(t_n\right) = (\mathbf{K}_N + \mathbf{K}_P)^{-1}\, d\mathbf{F}\left(t_n\right) \tag{5}$$

g. The new calculated displacements are imposed on the PS and NS. There is some time needed to compute the reaction of the NS and to adjust the new displacements in the jacks.

h. The new imposed displacements will generate new reaction forces in the PS and NS. So the steps *e-g* are repeated until the end of the fire test.

As can be seen in Eq. (5), the stiffness of the PS is used for the correction of displacements. As this stiffness is generally unknown during the HFT, several iterations would normally be needed at each time step to converge to the correct solution. In a fire test, the evolution of temperature in the PS cannot be put to a hold during the period requested to perform the iterations at every time step. During the time needed to perform the calculation in the computer and for the testing equipment to apply the corrections of displacements, the temperatures are still increasing, which modifies the stiffness of the PS, the restraint forces, etc. Hence, the convergence process tends to achieve an equilibrium that is constantly changing. As a result, it is not relevant to distinguish between iterations and time steps. Instead, the test can be performed by applying continuously Eq. (5), with a cycling frequency that is as high as possible, which requires computing techniques and testing equipment that has a short response time (hence the advantage of representing the NS by a predetermined matrix). Note that the compatibility is continuously respected, as the same displacements are imposed on the PS and NS at the interface. The purpose of the methodology is thus to constantly adapt these displacements to satisfy equilibrium between the substructures throughout the entire test duration.

4 CASE STUDY

4.1 Description. General information

The novel methodology will be implemented and verified on two full scale fire tests in the Prométhée furnace, CERIB, France. The analysed structure is a moment resisting concrete frame as presented in Figure 2. The frame is composed of four spans of 5.60 m with a main floor and the three upper floors, every floor being 3.00 m high. Based on the HFT principle, the structure is divided into a PS and NS. In this case, the PS is the last floor, second span beam. Only the PS is considered as heated, while the NS properties are kept constant during the hybrid test.

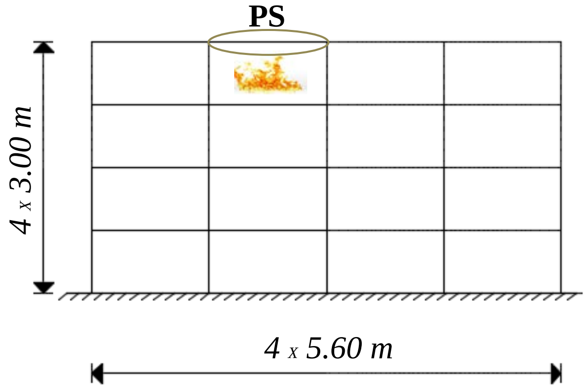


Figure 2 – Moment resisting concrete frame.

Figure 3 presents the configuration of the PS. A concrete beam of 0.25 m x 0.40 m x 8.00 m, will be tested in three different tests. The beam will be exposed to fire only between the supports (5.60 m), while the two cantilever parts of the beam are used to generate the support bending moment. The horizontal jacks H_1 is used to apply the horizontal displacement u to the specimen. The vertical jacks P_1 and P_2 are used to apply the rotations θ_1 and θ_2. The jacks P are used to apply the constant loads.

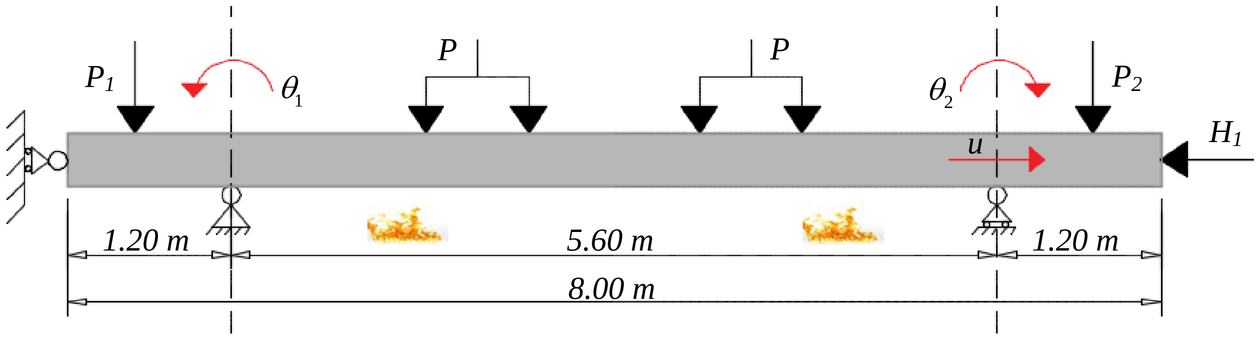


Figure 3 – The configuration of the physical specimen PS.

Table 1 presents a summary of the jacks and controlled DoF during the different tests. As can be seen in Figure 3, the beam is simply supported. From the total number of 6 DoF at the interface, only 3 DoF will be controlled during the hybrid test. The condensation of the DoF will be taken into account in the predetermined matrix.

Table 1: Description of the jacks and controlled DoFs

Jacks	Controlled DoFs	TEST 1	TEST 2	TEST 3
H_1	u	*Inactive*	*Active (variable)*	*Active (variable)*
P_1	θ_1	*Active (constant)*	*Active (variable)*	*Active (variable)*
P_2	θ_2	*Active (constant)*	*Active (variable)*	*Active (variable)*

The first test, Test 1, is a non hybrid test (traditional test), where the effect of the surrounding is assumed constant during the test (constant negative moments applied at the supports and no axial restraint). Only the jacks P_1, P_2, and P are active, applying constant forces during the test, due to the fact that no evolution of interaction with the NS is considered during the test. The horizontal jack H_1 is inactive (see Table 1) meaning that no axial restraint is assumed during the test.

The next two tests, Test 2 and Test 3, are hybrid tests. In this case only the jacks P will be applying a constant load during the test. However, the jacks P_1 and P_2 (generating the support bending moment) and H_1 (controlling the axial DoF) will apply varying forces, depending on the characteristics of the NS and PS. In the hybrid tests, the behaviour of the NS will be pre-calculated, using a predefined matrix defined in the software which controls the furnace [10].

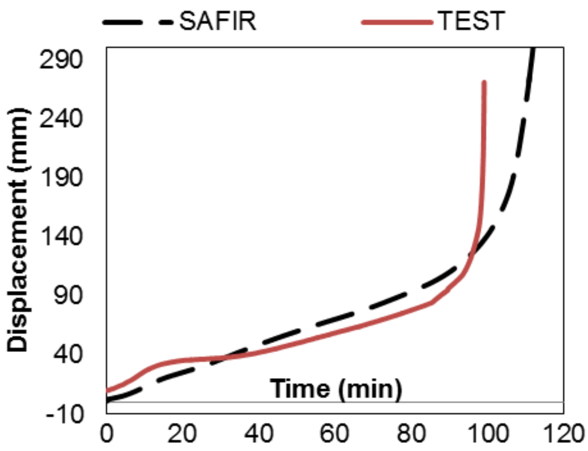
The first generation method would require using a force control procedure to control the axial DoF and a displacement control procedure to control the rotational DoFs. This illustrates the impracticability of the latter when several DoFs need to be controlled. Yet, the novel method presented in this paper can be applied and is stable as will be shown hereafter.

4.2 Test 1 (non hybrid test)

The first test (non hybrid) has been conducted on January 19, 2016, and the effect of the surrounding was constant during the test. 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. It also ensures that the behaviour of the PS can be modelled reasonably correctly with SAFIR®.

a) The setup of the beam outside the furnace

b) The setup of the beam inside the furnace



c) The evolution of mid-span displacement

Figure 4 - Non hybrid fire Test 1 performed on a concrete beam.

Figure 4 a) and b) present the setup of the test outside and inside the furnace. Fig. 4 c) shows the evolution of the measured and calculated mid-span displacement. As can be seen, the test showed a good agreement with the numerical analysis performed with SAFIR®.

Spalling was observed close to the end of the test, which was not modelled in the numerical analysis. Therefore the failure time of the test was earlier than predicted in SAFIR®.

4.3 Test 2 (hybrid test)

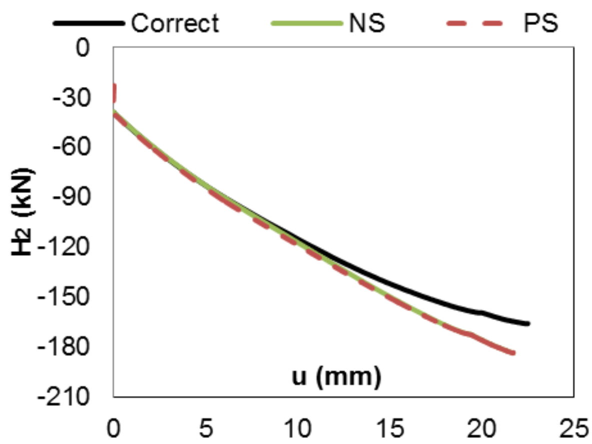
In anticipation of the hybrid test, Test 2, a numerical simulation has been done considering the novel method but modelling here the PS with SAFIR® whereas the behaviour of the NS is pre-calculated and kept constant (virtual HFT). The fire exposure of the PS leads to a reduction of the PS's stiffness during the test, value which cannot be measured in practice. So a constant value of the PS's stiffness was used in the calculations (namely the elastic tangent stiffness).

For compatibility and equilibrium between substructures, the time step should be as small as possible, depending on the time calculation of the new solution and on the facility of the furnace.

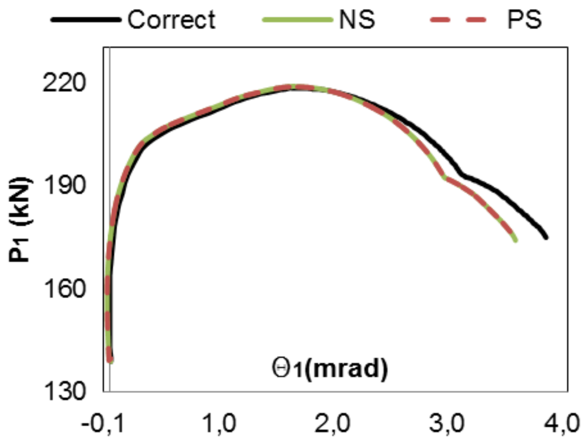
Figure 5 presents the displacements-reaction forces dependency for the controlled DoFs for the case study presented in section 4.1.. Fig. 5 a) shows the evolution of the reaction force induced in the jack H_1 depending on the imposed horizontal displacement u. Fig. 5 b) presents the interaction between the hinged support rotation θ_1 and the reaction force in the jack P_1. The interaction between the rolling support rotation θ_2 and the reaction force in the jack P_2 is illustrated in Fig. 5 c).

For every DoF (every figure), three curves are plotted. The "correct" solution is representing the displacement-force evolution at the interface when the analysis of the entire structure is done, thus making no use of substructuring. The "PS" representation shows the interaction between the interface displacement and interface reaction force registered from the PS. The calculated values (displacement-reaction force) from the NS are plotted as "NS".

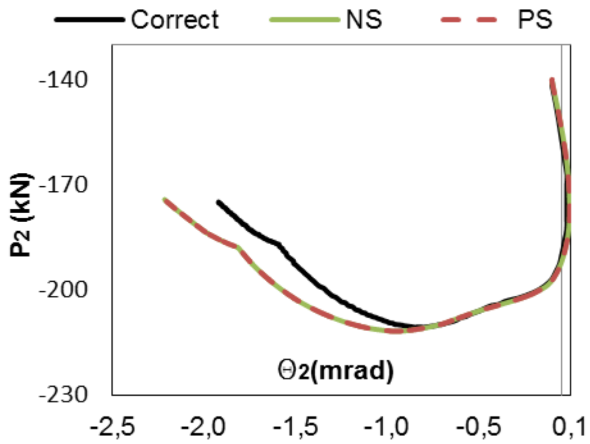
The principle of HFT is to reproduce the global behaviour of a structure, by respecting the equilibrium and compatibility at the interface. Note that using the novel method presented in this paper, the compatibility is always respected. If the equilibrium is ensured, then the curve "PS" should match the curve "NS". The global behaviour of the structure is reproduced in HFT if the curves "PS" and "NS" (when they match each other) match the "correct" solution.



a)H_1-u dependency



b) P_1*-* θ_1 *dependency*



c) P_2*-* θ_2 *dependency*

Figure 5 – Virtual HFT for the case study

In the example presented in Figure 5, the curves “PS” and “NS” are matching for every DoF (equilibrium satisfied). The time step chosen here was one second but in a real HFT performed in Prométhée, (i.e. with predetermined matrix and a very fast hydraulic system) a smaller time step is expected to be obtained.

The behaviour of the NS is characterized in this example by a constant matrix (an elastic behaviour). As a consequence of this simplification, the curves “PS” and “NS” slightly diverge from the “correct” curve for the largest displacements when nonlinearities appear in the NS.

In the virtual HFT, the concrete class of the beams was C25/30, while for the columns C30/37.

4.4 Test 3 (hybrid test)

The difference between the Test 2 and Test 3 is how the predetermined matrix will be defined. In the case of Test 2, the values of the predetermined matrix will be constant. During the Test 3, the predetermined matrix may vary depending on the interface displacements (in order to consider the nonlinear behaviour of the NS).

5 CONCLUSION

This paper has highlighted the inherent instability of first generation methods for Hybrid Fire Testing that depends on the stiffness ratio. A novel method has been presented to perform stable HFT independently on the characteristics of the substructures. The difference compared with the first generation method is that in the calculation process the stiffness of the PS and NS are used, whereas previously only the stiffness of the NS was considered.

Full scale HFTs are being prepared on a concrete beam that is part of a moment resisting frame. Prior to the HFT, a traditional test (non hybrid) has been performed, showing good results with the numerical analysis. The Test 2 (hybrid) has been simulated in a virtual environment, i.e. with the PS modelled as substructure in SAFIR®, while the NS was described by a predetermined matrix. The results show that the new method succeeds in being stable. Compatibility is automatically ensured throughout the test as the same displacements are applied on the substructures. Results also show that using a time step of the order of one second equilibrium is maintained for every DoF. For performing the HFT, a time step shorter than one second will be used.

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