FIRE PERFORMANCES OF A MARINE BULKHEAD: NUMERICAL EVALUATION OF THERMOMECHANICAL BEHAVIOR

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Abstract. The fire performances of marine products are assessed with large scale fire resistance tests following dedicated Standards. However, regarding the conditions of such normative tests, orientation studies for research and development purposes are limited. The aim of the present study is now to develop a numerical model to investigate others configurations. Using the fire performance results of a given bulkhead achieved by fire resistance tests, extrapolation of thicknesses, material properties, joint configuration, etc. can be numerically assessed and used to validate or orientate the final configuration to be tested.

1 INTRODUCTION

The fire performances of marine products are assessed with large scale fire resistance tests following dedicated Standards [1]. Considering marine bulkheads, fire resistance furnaces are used. The performed tests allow the measurements of temperature criteria on the unexposed side of bulkhead, and the evaluation of the panel deflection. However, regarding the conditions of such normative tests, orientation studies for research and development purposes are limited using the results of such a test.

The aim of the present study is now to develop and validate a numerical model in order to study several configurations of the tested product. Using the fire performance results of a given bulkhead achieved by fire resistance tests, extrapolation of thicknesses, material properties, joint configuration, etc. are assessed numerically and used to validate or orientate the final configuration to be tested.

In a previous project, the numerical model of a virtual fire resistance furnace designed with the CFD code FDS [3] has been validated for partition walls [4] and wooden doors [15]. A fairly good agreement was found for each quantity to validate the hypothesis of the developed numerical model [5]. In the same manner, the virtual facility is adapted for marine application. The predicted thermal loads are applied as boundary conditions on the exposed side of a marine bulkhead modelled with the FEM code SAFIR [6]. The considered bulkhead is constituted 4 panels made with 2 steel sheets and an inner layer of mineral wool, with a total thickness of 25 mm, and joint with continuous steel plates. The thermal properties of each constitutive material have been implemented.

The numerical results achieved for the thermomechanical behaviour of the marine bulkhead are compared with experimental ones. The global agreement allows further extensions studies of the product (dimensions, materials, design...). The developed numerical tool is then validated for such application and a strong coupling between FEM and CFD codes will be addressed.

3 DESCRIPTION OF THE STUDIED MARINE PRODUCT

In this study, the marine product considered is a bulkhead provided by the manufacturer MAPAC Panel [7].

The fire performances of this bulkhead were evaluated during the test named 14V025 [8] following the Standards [1] requirements. A second fire resistance test named 14V030 [9] was ordered by the manufacturer as an orientation test for research improvements.

3.1 Description of the specimen

The bulkhead is realized by 4 panels “25T ECO” type. The individual panel dimensions are 600 x 2472 x 25 mm (width x height x thickness). Each panel is made out by a layer of mineral wool with density of 168 kg/m^3 and a 23.6 mm thickness, inserted and glued between two steel sheets with a 6/10 mm thickness on the unexposed side and a 45/100 mm on the exposed side. On the edges, each steel sheet realized a 8.5 mm folding.

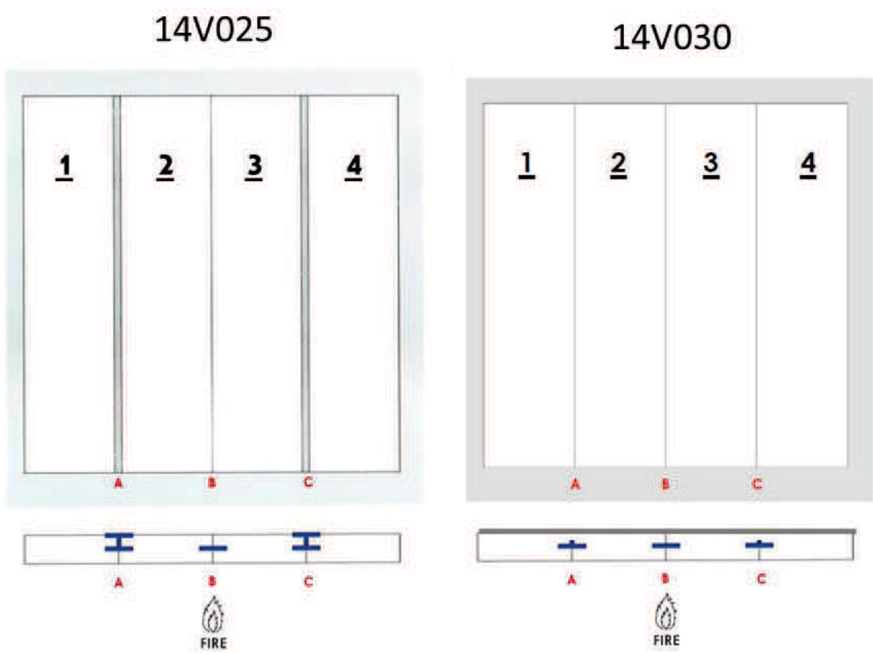

Figure 1: Fire test of a marine bulkhead – classification test 14V025 [8] and orientation test 14V030 [9]

For the test 14V025 [8], the junctions between panels are realized with a continuous steel plate with a 20/10 mm thickness folded in “H” shape with overall dimensions of 34 x 15 mm and inserted into a groove created into the edges of the panels. A gap of 2 mm exists between the panels on the unexposed side.

Concerning the orientation test 14V030 [9], the "H" studs have been replaced flat steel sheets. The central junction between the panels is realized by a continuous steel plate with a 20/10 mm thickness and a 50 mm length inserted into a groove created into the edges of the panels. Laterally, the panels are equipped with a closing steel profile with a 10/10 mm thickness and folded in “U” shape with a section of 25 x 26 x 25 mm. The bulkhead is tested with fire opposite to the vertical “H” profile during test 14V025 as indicated in the **Figure 1**.

3.2 Description of the frame

The bulkhead is blocked inside a concrete frame aperture by means of 8 steel angles (4 on each face) with a 20/10 mm thickness and folded in "L" shape with a section of 50 x 50 mm and 150 mm high fixed to the concrete by dowels after interposition of mineral wool between the closing profiles and the concrete frame. On the upper and lower parts, the panels are fixed together by means of a steel profile folded in "U" shape with 10/10 mm thickness. The supporting frame has dimensions of 2440 x 2500 x 200 mm (width x height x thickness).

2 EVALUATION OF THE FIRE PERFORMANCES OF A MARINE BULKHEAD

This section is dedicated to the implementation of a fire resistance test for marine bulkhead. The fire resistance furnace and the dedicated instrumentation are described.

2.1 Fire resistance furnace

The fire performances of marine products such as bulkhead are assessed with large scale tests performed in fire resistance furnaces with different designs by accredited laboratories and following dedicated Standards [1].

These tests must comply with requirements of European Standard EN 1363-1 [2], which impose conventional values of relative static pressures and temperatures at 100 mm from the exposed side of the tested elements. Two constrains must be achieved simultaneously:

- The static overpressure must be maintained to 20 Pa at the top of the vertical tested element, like bulkhead;
- The thermal program inside the furnace is defined by a time dependant logarithmic curve ranging from 20°C at the start of the test to approximately 1050 °C after 2 hours of test (see equation (1), with T in °C and t in minutes).

$$T = 345 \log_{10}(8t + 1)+20 \tag{1}$$

In the furnace, the instrumentation consists in six plate thermometers placed at 100 mm of the exposed side of the tested specimen to control the thermal elevation indicated in **Figure 2**. These plate thermometers are constituted by an Inconel steel sheet insulated on its backside by a refractory board. An Inconel thermocouple is welded on the Inconel steel sheet. The pressure inside the furnace is controlled continuously using a probe located at the head of the vertical tested specimen. During the test, the temperature in the laboratory is also recorded.

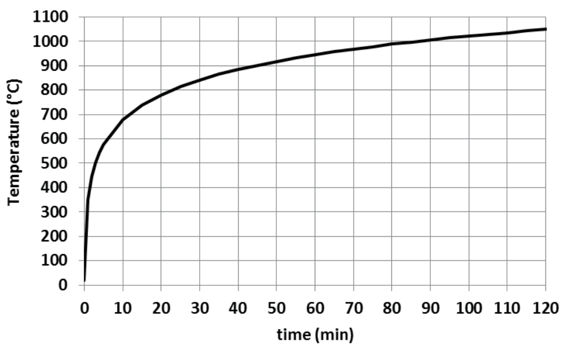

Figure 2: Fire resistance test of a marine bulkhead – thermal elevation in the furnace [2]

2.2 Fire performances of a marine bulkhead

The tested bulkhead is installed as the closure wall of the large industrial fire resistance furnace and a specific instrumentation is implemented on its unexposed side as indicated on the **Figure 3**. The instrumentation consists in thermocouples placed on the unexposed side of the specimen, at intersection and quarters of the diagonal of the panel, and at 15 mm of the junction of the panels. The bulkhead deflection is measured by potentiometric sensors.

The temperature criteria on the unexposed side of bulkhead allow the evaluation of the fire performances of the specimen. They are based on a maximal temperature rise of 225°C and/or an average temperature rise of 140°C on the unexposed side of bulkhead.

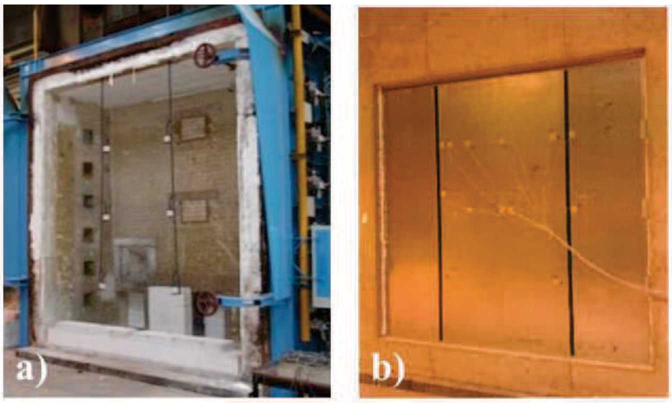

Figure 3: Fire resistance test of a marine bulkhead – a) Fire resistance furnace b) Instrumentation of the unexposed side of the bulkhead installed on the furnace [8]

3.3 Description of the instrumentation

For each test, the instrumentation consists in thermocouples placed on the unexposed side of the specimen, at intersection and quarters of the diagonal of the panel, and at 15 mm of the junction of the panels. The bulkhead deflection is measured by potentiometric sensors. Furthermore, during the orientation test 14V030 [9], additional displacement and temperature sensors have been added, particularly in the thickness of the bulkhead. The instrumentation location for each test is indicated in **Figure 4**.

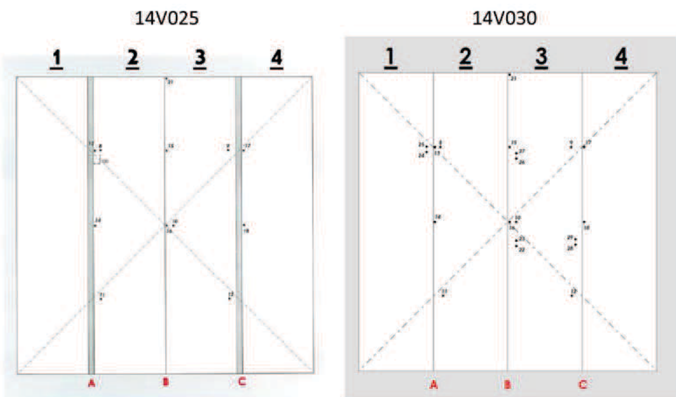

Figure 4: Instrumentation location for tests 14V025 [8] and 14V030 [9]

4 NUMERICAL EVALUATION OF THE FIRE PERFORMANCES OF THE MARINE BULKHEAD

Regarding the conditions of the normative fire resistance tests, orientation studies for research and development purposes are limited. In order to study several extrapolations of a primary tested specimen, Efectis is leading a R&D project called VIRGILE which consists in a virtual test furnace simulator.

In this section, the virtual fire resistance test simulator is used to evaluate the fire behavior of the marine bulkhead described in paragraph 3. The numerical method implemented is discussed and validated based on the experimental results acquired during tests 14V025 and 14V030.

4.1 Virtual fire resistance facility

Lot of experimental works has been led on the measurement methods [10][11][12], but, few studies have been presented concerning the simulation of furnaces used for fire resistance tests [13][14].

The VIRGILE project is dedicated to the development of a numerical model for a virtual fire resistance furnace designed by the way of a modified version of the CFD code FDS.5 [3].

Among the different fire resistance facilities simulated in the frame of this project, the modelled so-called V furnace was based on one vertical furnace of Efectis France laboratory. The dimensions of the main chamber of this furnace are 3.1 x 1.5 x 3.6 m (width x length x height). A mesh size of 10 cm^3 was employed. A total of 45344 cells are needed to model the furnace, the chimney and the burners. The model of the considered geometry and internal dimensions of the furnace are plotted in **Figure 5**.

The thermal and physical properties of the furnace constituent materials are taken into account because the heat transfer in the solid walls is computed with FDS 5.

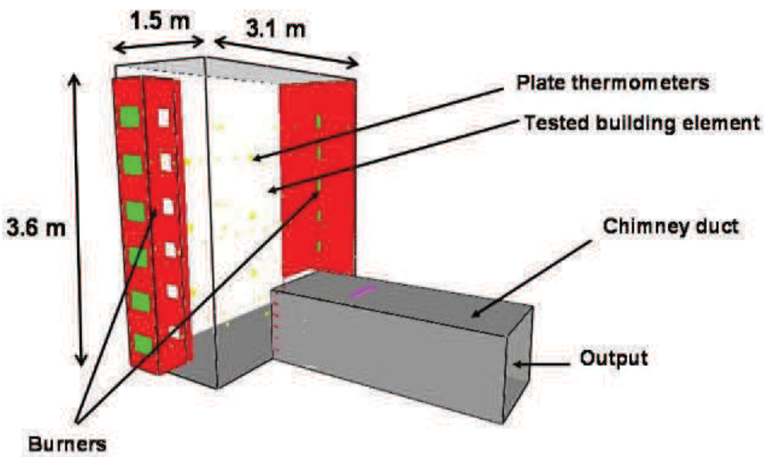

Figure 5: Outline of the virtual V furnace structure

The chimney flue communicates with the furnace through a rectangular opening on the rear wall of the furnace. At the other end of the pipe, there is the aspiration area, transcribing the effects of the chimney. An opening on the surface of the duct, 1 m behind the flue, is introduced to set a reference pressure in the computational domain.

The facility is fitted with 12 burners, fed with natural gas. The burner model involves an external combustion cavity. Thus, 12 openings of 0.2 x 0.2 m are installed on lateral sides of the furnace. Air and gas are injected into the external cavities of the furnace, so that the air/methane combustion mixture takes place in these cavities and not in the furnace one. Only the hot smoke from burning is injected into the furnace in the form of jets, as observed on furnaces of Efectis laboratory.

To achieve the thermal program requirements, the adopted approach is based on an iterative method for correcting the outflow of the chimney to regulate the pressure, and the percentage of the burner's air valve opening to regulate the temperature at each time increment. The CFD code FDS has been modified to introduce an automatic control of the 12 gas burners and another one for the output flow imposed at the chimney exit. The control model was done by considering 3 groups (stages) of 4 burners (two on each side of the furnace). Each floor was considered independent at the air supply and gas (**Figure 6**).

The control of the air/gas mixing and the hot gases exhaust permits to comply simultaneously with both general conditions imposed by EN 1363-1. The integrated error between the imposed program and the thermal gas temperatures recorded by the Plate Thermometers located 100 mm from the closure wall of the furnace is estimated during the calculation.

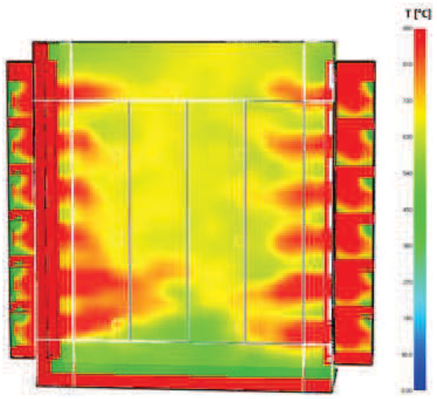

Figure 6: CFD simulation of the fire resistance V furnace

The Plate Thermometer model corresponds to that described in detail in the report [11] and used for the virtual V furnace. They are composed of an Inconel stainless steel sheet of thickness of 0.7 mm, and an inorganic insulating refractory plate of thickness of 10 mm. These two plates are nested and form a square of 10 cm length, as shown in **Figure 7**. The alloy part of each plate thermometer is oriented to the furnace side. This design makes plate thermometers quite sensitive to the radiative heat flux coming from flames of burners and lining of furnaces.

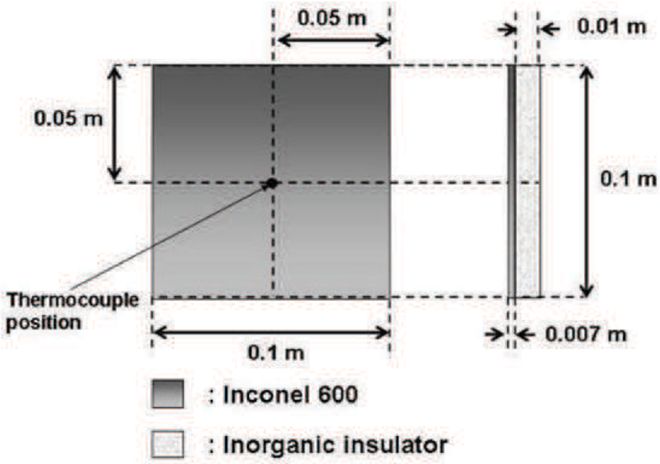

Figure 7: Outlines of the plate thermometer structure

To create a realistic simulator, it has been necessary to model the furnace behavior and its interaction with the tested element by the way of a coupling between this furnace simulator and the element modelled with a FEM code.

In a previous study, a strong coupling between FDS and the FEM code CASTEM [16] has been implemented. An interface has been created between this code and the modified version of FDS 5 to ensure the thermal coupling between the virtual furnace and the element. Thermal constrains delivered by FDS 5 are refreshed regularly on the exposed element surface. These thermal constrains are constituted by a radiative flux coming from the furnace lining, a convective flux due to the hot gases on the vicinity of the element and a radiative flux emitted by the exposed side of the tested element (see **Figure 8**). Thanks to these constrains the temperatures of the exposed side of the tested element are determined and they constitute the new boundary conditions for the calculation of the thermo-dynamic equilibrium of the furnace inner volume for the next time increment step. This integrated tool has been validated for partition walls [4] and then to study the fire behavior of wooden doors [15]. A fairly good agreement was found for each quantity to validate the hypothesis of the developed numerical model [5].

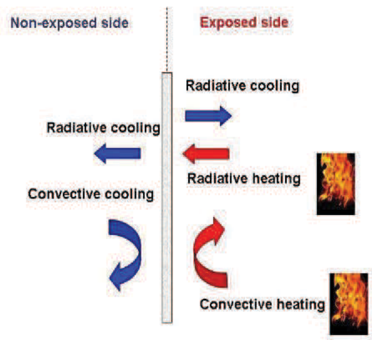

Figure 8: Heat flux at the exposed and unexposed sides of the tested element

4.2 Virtual fire resistance test for marine bulkhead

In the same manner, the virtual facility is now adapted for marine application. In this study, a weak coupling between CFD and FEM codes is performed. The thermal loads predicted by the virtual fire resistance furnace modeled with the CFD code FDS are applied as boundary conditions on the exposed side of the marine bulkhead described in paragraph 3 and modelled with the FEM code SAFIR [6]. The thermal properties of each constitutive material have been implemented in the CFD and FEM codes. First, the thermal behaviour of the bulkhead is investigated. The reference tests are reproduced using the V furnace simulator as shown on **Figure 9**. The correct regulation of the furnace in terms of temperature and pressure control according to the test standard EN 1363-1 is verified (**Figure 10**).

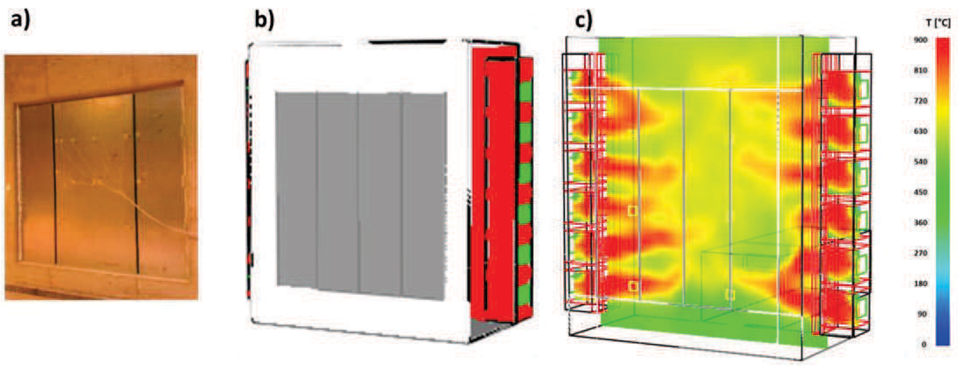

Figure 9: CFD simulation of the fire resistance test for the marine bulkhead – a) real test b) virtual test c) temperature field in the burner's axis

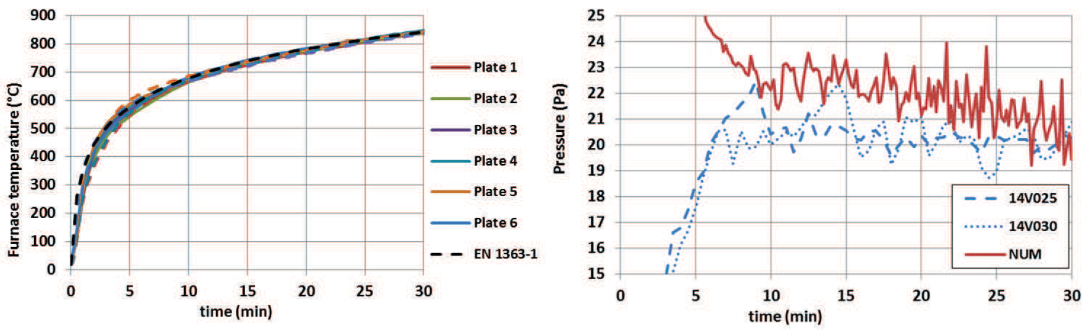

Figure 10: Furnace regulation for temperature and pressure – experimental values (dotted lines) and numerical results (straight lines)

Then, detailed FEM models of the panels are built to reproduce the material layers as well as the junction elements used in tests 14V025 and 14V030. These models and the corresponding boundary conditions are indicated on **Figure 11** in a transverse view of the panels.

The boundary conditions consist in heat fluxes and convective transfer coefficients H evaluated with the virtual fire resistance furnace. These quantities take into account the interaction between the facility and the tested element by the way of the burner regulation. So, even if the thermal solicitation follows the test standard requirements, the heat fluxes imparted to the tested element depend on its thermal properties. In a same manner, the convective transfer coefficient H will be adjusted depending on environment conditions in the furnace.

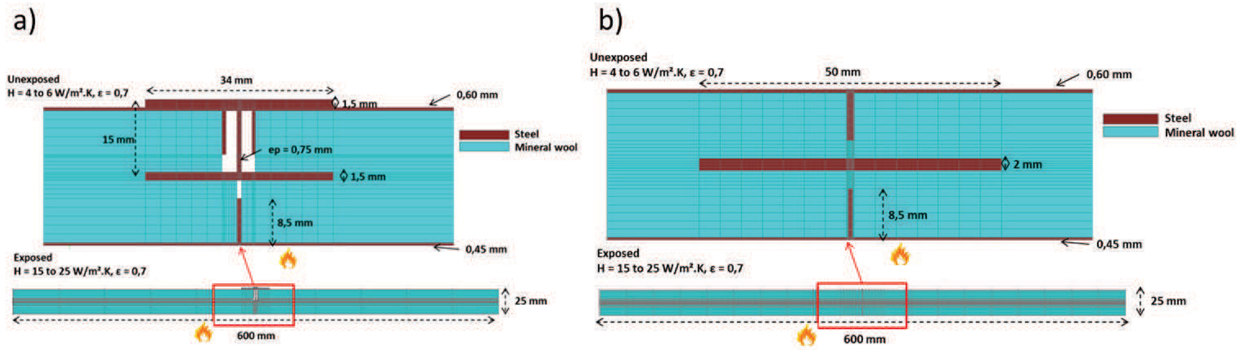

Figure 11: FEM model and boundary conditions for the tested bulkhead with a) "H" steel junction (test 14V025) b) plate steel junction (test 14V030)

To validate the thermal transfer analysis performed, the numerical results obtained in terms of temperature at the unexposed side of the bulkhead are compared with experimental ones for the two reference tests in **Figure 12** a). This temperature corresponds to the surface temperature measured in the center of panel 2, far from junctions and impact of hot smoke releases through openings (Thermocouples 19 and 20 in **Figure 4**). Then, the numerical results obtained in terms of average temperature at the unexposed side of the bulkhead are compared with experimental ones for the two reference tests in **Figure 12** b). This average temperature corresponds to the surface temperature of the panels measured at intersection and quarters of the diagonals of the bulkhead (Thermocouples 8 to 12 in **Figure 4**). Regarding the temperature criterion required, the fire performance of the bulkhead is lost numerically 10 seconds after the experimental time.

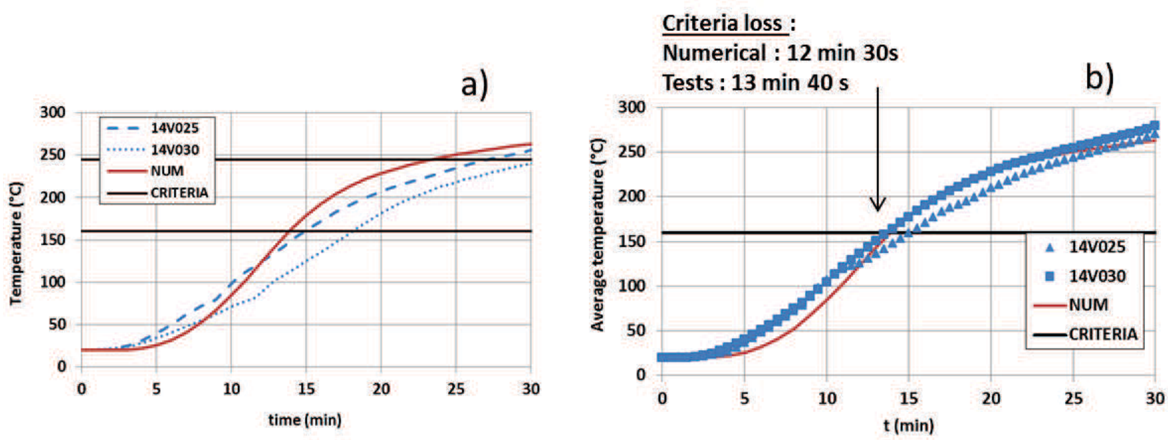

Figure 12: Numerical and experimental temperature at unexposed side of the bulkhead a) far from junctions (center of panels) b) at quarters and intersection of diagonals – fire performance loss criteria

A global agreement is observed and allows further thermomechanical analysis of the bulkhead. For the average temperature evaluated at quarters and intersection of diagonals, the main differences between experimental and numerical values are explained by the hot gas released through openings at junctions. In the numerical model, the junctions are heated faster than the core of the panel because of steel elements and gap between steel and wool layer.

Then, the thermomechanical behaviour of the bulkhead is investigated. The steel profiles modelled are considered blocked in terms of movements in the 3 directions (UX, UY and UZ) at the top and at the bottom. The rotation along the central axis is also locked at both ends to avoid twisting. The mechanical loading applied corresponds to the weight of the profile as well as the section of the panel taken up by this profile, equivalent of a width of 600 mm of panel per profile.

The **Figure 13** provides a comparison between numerical deflections evaluated at the half-height displacements of the "H" studs and the steel plate with the experimental deflections measured at the center of the bulkhead during tests 14V025 and 14V030.

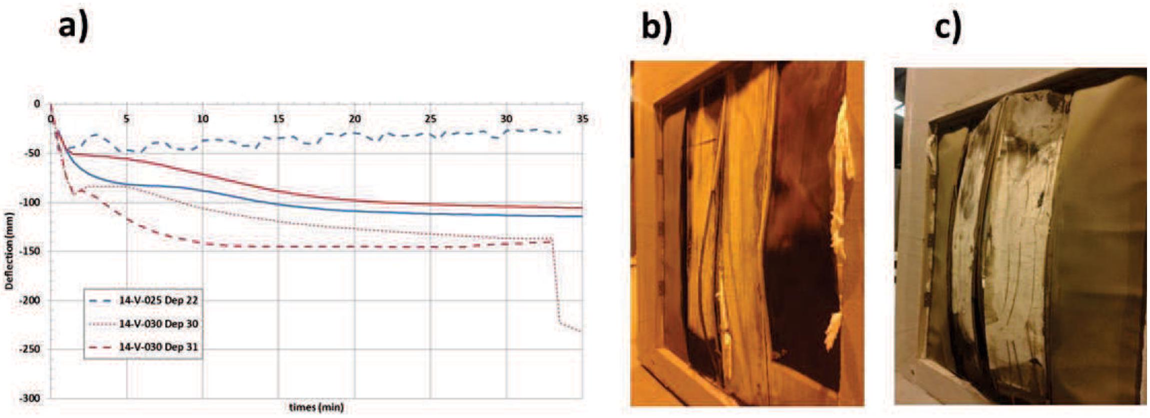

Figure 13: a) Numerical (straight lines) and experimental (dotted lines) deflections at the center of bulkhead for tests 14V025 (H stud) and 14V030 (flat steel profile) b) exposed side of the bulkhead after test 14V025 c) exposed side of the bulkhead after test 14V030

The experimental deflections correspond to those of the exposed and unexposed side measured at the center of the panel at half height of the stud. Although test 14V030 is slightly different from the 14V025 test, the order of magnitude for the displacements measured is quite close to the numerical ones. The values at the end of the simulation are respectively 115 mm and 107 mm for the "H" profile and the steel plate, against 139 mm for the experimental measurement at 33 min for the test 14V030 (before the final ruin of the bulkhead). Differences between numerical and experimental results can be explained by different reasons:

- The displacements of the reinforced concrete frame have an impact on the displacement of the central stud of the bulkhead. This impact has not been measured experimentally and is therefore not taken into account.

- During test 14V030 the head of the central steel stud dislodged from its support near the upper rail, allowing a greater displacement towards the fire (phenomenon hardly predicted numerically).

5 CONCLUSIONS

The present study was dedicated to the development of a numerical model to study a product configuration in order to propose further extensions. The numerical model of a virtual fire resistance furnace designed with the CFD code FDS has been validated for marine application. The predicted thermal loads were applied as boundary conditions on the exposed side of a marine bulkhead modelled with the FEM code SAFIR.

The numerical results achieved for the thermomechanical behaviour of the marine bulkhead are compared with experimental ones. The global agreement allows further configurations studies of the product (dimensions, materials, design...). Thus, using the fire performance results of a given bulkhead achieved by fire resistance tests, extensions of thicknesses, material properties, joint configuration, etc. are assessed numerically and used to orientate the final configuration to be tested.

The developed numerical tool is then validated for such application and a strong coupling between FEM and CFD codes will be addressed. By evaluating junction deflection, hot gas release through these openings will be taken into account.

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