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Thermal Analysis of Fire Doors for Naval Applications

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Abstract

In this work the thermal response of fire doors for naval application is considered. In order to evaluate their behavior, fire doors are subjected to standard fire tests by means of a customized furnace, where the temperature rise follows a well-defined trend, according to the current regulations. A finite element model is developed with the aim of capturing the qualitative behavior of the fire door; results from non-linear transient and static analysis are then compared. To further validate its accuracy, the proposed model is compared with experimental measurements obtained during standard fire tests. Images from a thermographic camera and outputs from thermocouples confirm that the adopted methodology is adequate to properly describe the thermal behavior of the door.

Keywords

fire door; finite element modeling; fire test; fire resistance

Introduction

Fire doors are important elements in the fire safety design of buildings and ships in general. They are complex structures made of materials with different thermal and mechanical properties and designed to have complimentary performances in order to comply fire safety requirements. In the design of fire doors the dominant practice involves the selection of the doors with individual fire resistance ratings based on standard fire tests (Iwankiw, 2007). In these tests the door is placed within a specially constructed furnace, which provides a heat flux according to a prescribed time-temperature curve (IMO, 2012).

Many experimental and numerical investigations have been carried out studying various aspects of the standard fire resistance test. Thomson and Preston examined the variations in heating rates of furnaces considering different construction schemes, fuels and types of operation (Thomson and Preston, 1996). Also two fire tests were carried out with two almost identical butted steel frames with steel door leaves subjected to the standard fire (IMO, 2012).

Sultan compared the measurements on specimens undergoing fire test in a furnace performed with two different measurement devices: shielded thermocouples and plate thermometers (Sultan, 2006). Results of finite element (FE) thermal analysis of a fire resistance test were reported by Chow and Chan (1996). They made a comparison between finite elements results with data from test specimens constructed from different materials. Wang and Quintiere (2009) also investigated on compartment fire doors.

Hugi, Wakili and Wullschleger (2009) evaluated the thermal response of a steel door frame subjected to a fire test. Tabaddor and Gandhi and Jones (2009) studied the thermo-mechanical behavior of a fire door under endurance test. Some papers present the fire resistance of various building components covering a range of materials by means of physical testing and numerical modelling (Bisby and Kodur, 2004, Gardner, 2007 Kodur and Dwaikat, 2007, Franssen, Pineta, and Dotreppe, 2007).

As many standard tests on fire resistance are carried out regularly, it could be useful to develop a mathematical model which could give a realistic prevision of the physical behavior of the component (Beyler et al., 2007).

A realistic simulation of the heating process is needed during the design phase in order to reduce as much as possible the number of fire tests. Moreover, large size doors, for which an experimental trial is not feasible with standard equipment, must be tested only through computer aided simulations. The problem of defining a suitable mathematical model is then dealt with in this work. By a comparison with the experimental data, the accuracy of the model is evaluated.

Component Description and Fire Tests

Fire doors are one of the key elements in the fire safety design of buildings in general. They have to fulfill two functionalities at the same time: usability under normal conditions and safety and security in fire conditions. This leads to a complex structure made of different materials. Fig. 1 shows the standard fire door under investigation, whose structure is depicted in Fig. *2*: the outer part is constituted by steel sheets, while the inner portion is filled with an insulation material that acts as a thermal barrier to heat flux through the door.

Fig. 1: Example of fire door under investigation

Fires doors are subjected to a standard fire test in order to evaluate their fire resistance. The test needs to be performed by means of an appropriate furnace, in which the sample is heated from beneath, following a prescribed temperature–time relationship:

$$T_{\text{fi}} = 345\log\left(8t+1\right)+T_{\text{a}} \quad (1)$$

where T_{fi} and T_{a} are the fire and ambient temperatures, expressed in °C, and t is the fire exposure time, in minutes.

According to FTP code of the International Maritime Organization (IMO, 2012), the door should satisfy some requirements; the main relevant, with respect to this work are the following. The mean temperature on the unexposed surface should not exceed a defined value. Only small gaps between the door and the frame are tolerated, since no flame or smoke must pass through the door.

Although the standard fire resistance test is a convenient way for quality control and grading the relative fire performance of different types of structural members, it could be not sufficient to completely understand the realistic structural behavior in fire. In Purkiss (2007) the drawbacks of the standard fire resistance test method are pointed out. The main concerns the fact that the standard fire exposure is only one of various types of realistic fire conditions. The thermal action from the conventional fire can be considered representative or over-designed compared to the natural fire in many situations. Some conditions, however, lead to more severe thermal actions compared to conventional fire. Some works in literature, such as (Harmathy, 1981), attempt to correlate real-world fires with standard fire tests, while in (Joyeux, 2002) an experimental investigation of fire doors during a natural fire is performed.

Another limitation is related to furnace dimensions: as test furnaces are restricted in size, it is generally impossible to test large elements of construction and thus only representative specimens are considered.

A well calibrated predictive model can be useful to overcome some of these drawbacks: if the model response under a simulated standard fire fits well with experimental measurements, different loading conditions, such as longer or real fire exposure, can be simulated. Furthermore, the behavior of doors with different sizes can be obtained (in general it is difficult to apply scaling to fire test results due to the nonlinear behavior of materials) by reducing the number of tests needed.

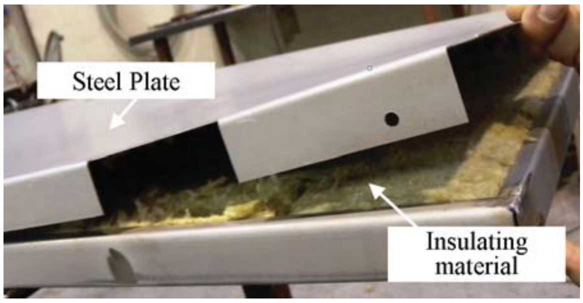

Fig. 2: Close view of door's structure

Numerical model

This work focuses on the thermal response of a fire door subjected to the standard fire test. From a thermal point of view, the leaf can be considered as separated from the frame. Thus, heat flowing through the hinges can be neglected in preliminary calculations. In order to assess a reliable numerical strategy, only the leaf was firstly modeled. The characteristics of this component (shown in Figure 1) are: 2m high, 1m wide and 60 cm thick. A mathematical model is developed by means of the Finite Element method. As shown in Fig. 3, symmetry is considered. The insulating material is modeled with solid elements, whereas two different strategies were adopted for the steel plates; i.e. solid or shell elements. The close view of Fig. 3 shows the differences of these models. It has to be noted that shell elements are depicted for seek of clarity with a fictitious thickness.

Table 1: Conductivity values for insulating material

Temperature (°C)	Conductivity (W/mK)
10	0.035
100	0.043
300	0.073

The thermal properties of materials needed for the numerical analysis (thermal conductivity, density and specific heat capacity) are obtained from (Eurocode 3) for steel, assuming a constant density of 7800 kg/m^3.

The filler insulation in the fire door consists of rock-wool as the main material. The manufacturer of the materials provides the material properties listed in Table 1, that were integrated with values available in (Hugi et. al. 2009) for higher temperatures.

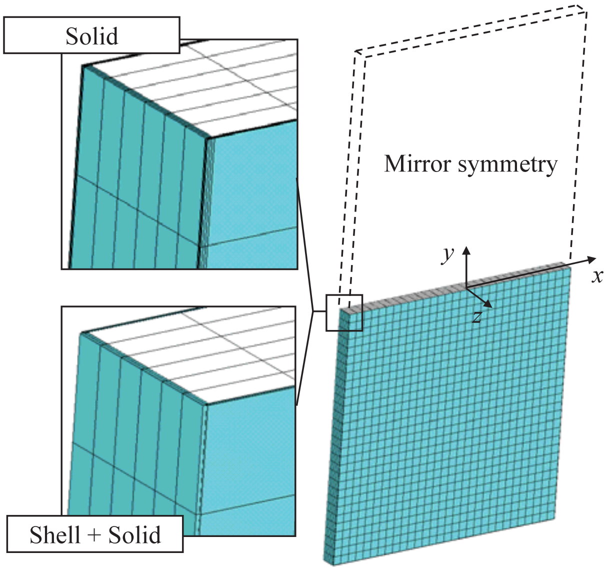

Fig. 3: Finite element model of the door

The thermal analysis is performed taking into account radiative and convective heat exchange on the exposed side of the door, while only convection is considered on the unexposed side. The natural convection film coefficient was set to 10 W/(m^{2}K), while the environmental temperature was set to 20 °C, according to standards provided in (Eurocode 3).

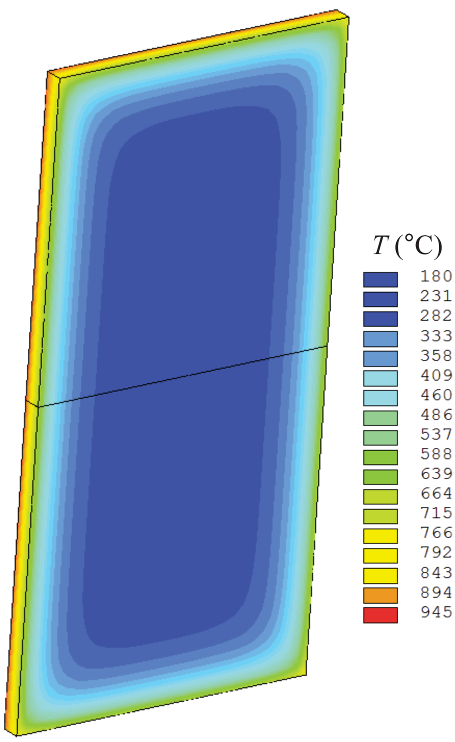

Fig. 4: Numerical temperature distribution on the unexposed side of the door.

The theoretical temperature law of the furnace given by Equation (1) is considered performing a transient analysis, which implies an extra node representative of the hot ambient inside the furnace. Values of convective and radiative coefficients are imposed according to (Eurocode 3, Tabaddor et. al. 2009). This strategy thus considers the exposed surface as uniformly loaded by the heat coming from the furnace air.

The implemented analysis is therefore a non-linear transient one, and the resulting temperature distribution on the door is depicted in Fig. 4.

Preliminary numerical tests performed with shell or brick elements shows almost negligible differences, thus the two approaches seems equivalent, if the number of degrees of freedom of the models are comparable. Fig. 5 shows the temperature distribution in the middle region of the unexposed side, along a path in the transverse direction from the left edge to the right one. Differences between the two models can be considered negligible.

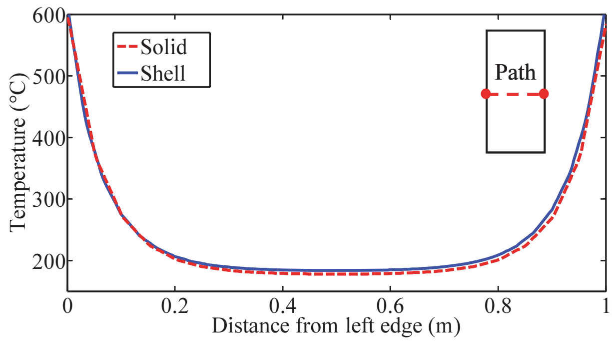

Fig. 5: Temperature trend in the middle region of the unexposed side obtained with solid and shell model.

It is possible to notice that, as depicted in Fig. 6 , the temperature on the hot side reaches the simulated furnace temperature after only few minutes from the beginning of the heating process (time scale is limited to 10 minutes for the sake of clarity) and the final temperatures after 60 minutes are practically coincident. Since the slope of these curves, after the initial time interval, is not extremely high, a steady-state thermal analysis can be performed with a tolerable accuracy on the results.

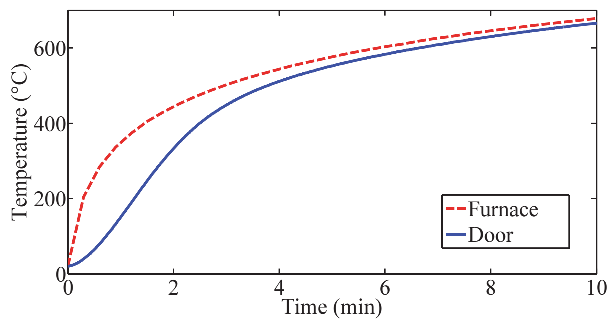

Fig. 6: Temperature trends on the hot side

The transient analysis in which radiative and convective heat exchange are considered for the exposed side, can then be replaced in a satisfactory way by a steady-state analysis in which a fixed temperature (equal to the temperature after 60 minutes of the heating curve) is directly imposed on the hot side of the leaf. Fig. 7 schematically represents the two implemented strategies.

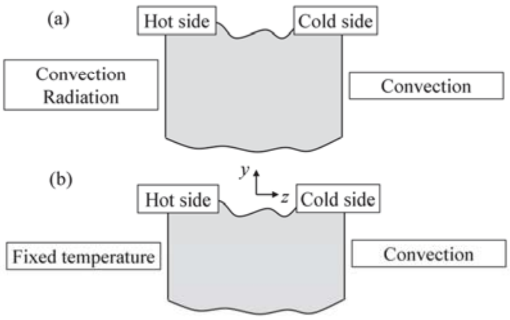

Fig. 7: Strategies of implemented thermal analysis: (a) transient, (b) steady state.

The results obtained adopting the technique with fixed temperatures are very similar to that shown in Fig. 4. The only difference is due to the fact that absolute values are somewhat higher, suggesting that the transient state is not completely concluded. This is clearly pointed out in Fig. 8, where the temperature trend for the same path of Fig. 5 is plotted for both the performed analysis. Nevertheless, this drawback is largely compensated by considering the drastic reduction in computational time required to perform the steady-state thermal analysis compared to the transient one, despite the slight error introduced.

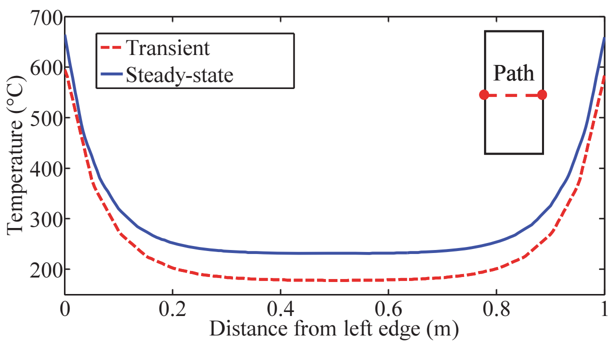

Fig. 8: Temperature trend in the middle region of the unexposed side obtained with transient and steady-state analysis.

Experimental measurements

In order to gain insights into the thermal behavior of the component, the temperature distribution on both exposed and unexposed side of fire door were monitored during a standard fire test. The adopted furnace is a vertical one (4 m horizontally and 3 m vertically) with four burners (two per side) that guarantee a quite uniform temperature during the heating phase. The experimental set-up includes:

- A set of 12 magnetic *TC Direct* thermocouples, type *K*[1], to monitor the temperature variation on different point of the unexposed side assembly.
- 4 rigid thermocouples *TC Direct* with mineral insulation[2], located inside the furnace.
- A 16-Channel isothermal thermocouple input module *NI* 9214[3], embedded in a real-time controller *NI cRIO*-9014[4], used to log all the output signals from the thermocouples.
- An infrared camera *Optris PI* 400[5], adopted to gain insights into the heat transfer mechanisms on the unexposed side.

Fig. 9 includes some details of the adopted experimental apparatus, while in Fig. 10 the average temperature variation inside the furnace is plotted against the theoretical distribution of Equation (1), showing a good calibration of the burners.

A sample of images recorded from thermographic camera is shown in Fig. 12, while measurements from thermocouples on the unexposed side are plotted in Fig. 11.

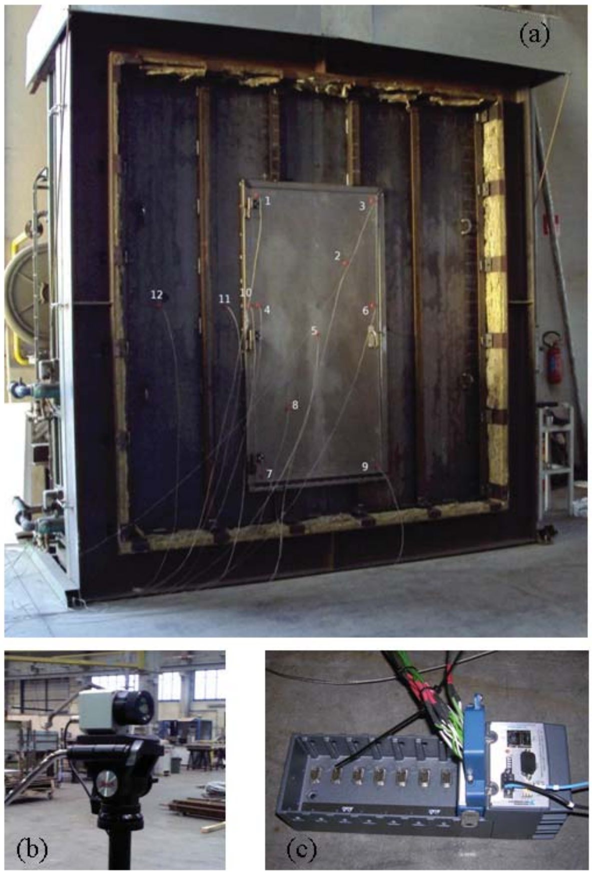

Fig. 9: Experimental apparatus: (a) thermocouples on the unexposed side, (b) infrared camera and (c) data acquisition system

Different fire doors were tested, and some basic features

[1] http://www.tcdirect.it/deptprod.asp?deptid=180/42
[2] http://www.tcdirect.it/deptprod.asp?deptid=190/1
[3] http://sine.ni.com/nips/cds/view/p/lang/it/nid/209412
[4] http://sine.ni.com/nips/cds/view/p/lang/it/nid/203500
[5] http://www.optris.com/thermal-imager-pi400

were recurrent in every test. In particular, the temperature of the central portion of the door starts increasing only after 20 minutes from the beginning of the test, probably due to the non-linear conductivity of the insulation material.

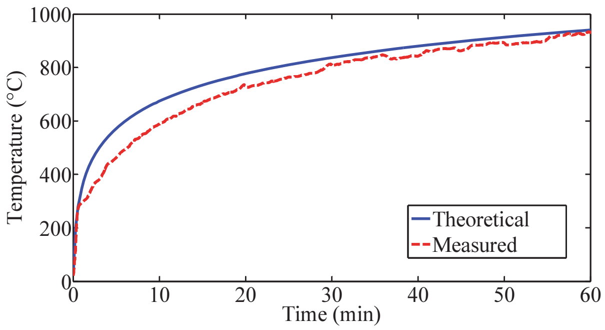

Fig. 10: Average temperature inside the furnace

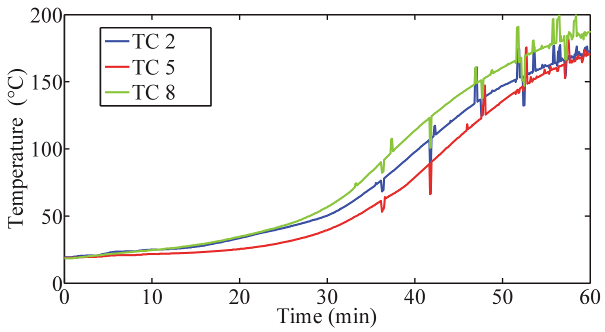

Fig. 11: Temperature measured on the unexposed face of the door by different thermocouples

Furthermore, on the unexposed side, the higher temperatures were measured near the edges of the door, while the central area results better insulated. This suggests the presence of a thermal bridge; indeed, the door edges are made of steel with higher thermal conductivity with respect to the insulation material.

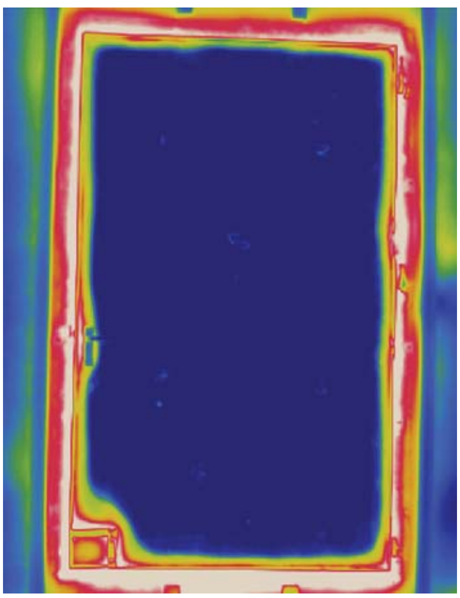

Fig. 12: Image from thermographic camera during a test.

Comparison between experimental and numerical results

As can be seen by comparing the experimental temperature distribution of Fig. 12 and the numerical contour map of Fig. 4, the model implemented can be considered adequate to accurately describe the thermal behavior of the leaf: the temperatures of lateral edges are higher than those in the central part for the presence of the thermal bridge, as experimentally observed. Furthermore, as shown in Fig. 13 the evolution of temperatures at different levels on the unexposed side (with the transient analysis) is very close to the measured trend.

A numerical model that correctly evaluates the temperature distribution of the door can be of practical use to achieve sensitivity analysis on geometrical parameters and to implement strategies for reducing the temperature levels on the unexposed side of the door.

Furthermore, the thermal analysis represents the foundation for a subsequent structural analysis, in which the temperature distribution can be used as input to numerically evaluate the deformed shape of the door.

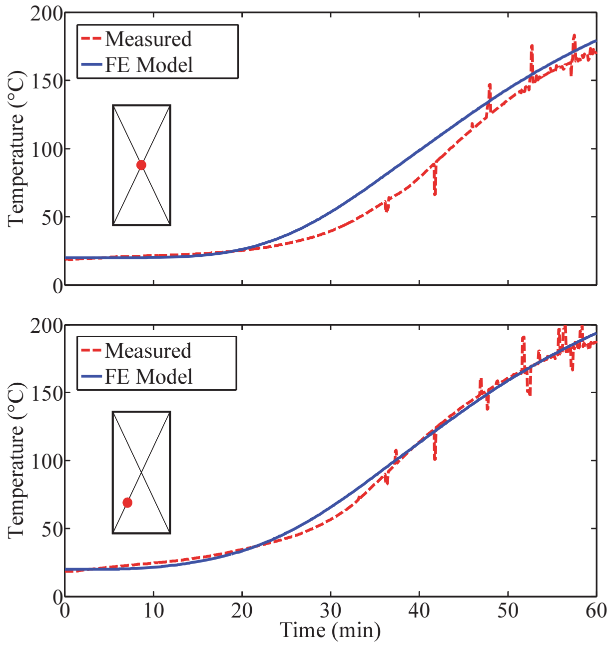

Fig. 13: Temperature trends on the unexposed side

Conclusions

In this work the numerical simulation with FEM of the thermal behavior of a fire door undergoing a fire test was performed. From the methodological point of view similar results could be achieved both adopting solid or shell element. A strong reduction in computational time can be obtained referring to a steady state analysis. In this case, the obtained temperatures distribution shows only slight discrepancies with respect to that resulting from a transient analysis.

A measuring system was set up, in order to verify the numerical simulation. It consists of a temperature controlled furnace, a set of thermocouples and an infrared thermo camera. The experimental apparatus enables one to perform a fire test according to the standard codified procedure.

The obtained results show that the numerical model can predict the thermal behavior of the door with good accuracy; in particular it was observed that the temperature in the unexposed door side shows a gradient from the frame edges to the door perimeter, due to the presence of reinforcing metal elements, which make thermal bridges. In the central part of the door lower temperatures were observed, with a reduced gradient. It is therefore possible to conclude that the proposed modeling approach could represent a useful tool to support the designer on the preliminary definition of the door construction detail and in particular to decrease the number of fire tests to be performed, thus strongly reducing the overall cost of the product.

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