Numerical methodology for thermal-mechanical analysis of fire doors

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1 Summary

The certification process of a fire door implies that the structure is subjected to a standard fire test, to evaluate its resistance to thermal load. In particular, the door must fulfil specific requirements, such as, that the gaps among the door labyrinths and frame are able to stop flame propagation and that the mean and maximum temperature on the unexposed surface does not exceed defined values.
The present paper describes the numerical methodology used to assess the fire performance of large fire doors (single-leaf and double-leaf sliding doors) commonly used for civil/industrial applications, having length and height of the order of 15-25m and 7-8m respectively. These fire doors cannot be tested at laboratory scale, due to their size, and the only way to verify their structural integrity when subjected to fire is via numerical simulations. The developed methodology aims at verifying thermo-structural response of fire doors when subjected to fire conditions for 60/90/120 minutes, starting from results of laboratories tests on specimen fire doors. The aforementioned methodology, based on the use of the Finite Element Method (FEM), foresees, first, the implementation of a coupled thermal-structural analysis on the 3D FE model of the specimen fire door, to predict the evolution of the distribution of temperature and deformations, to be validated with the values obtained from a set of instruments during the experimental tests. Then, the second step is the thermal-structural analysis on the FE model of the full scale fire door using the same materials and simulations' parameters used for the specimen fire door's model.
The experience carried out for different configurations of door for various applications confirms the procedure is valid and reliable.

Key words: Fire resistance; fire modelling; finite element; furnace test.

2 Acknowledgments

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3 Introduction

Fire doors are used as passive fire protection systems. In order to fulfil and guarantee that functionality is not compromised, they are subjected to certification processes. In general, the certification process of a fire door implies that the structure is subjected to a standard fire endurance test, to evaluate its resistance to thermal load. In particular, the door must fulfil specific requirements according to the standard used as reference (e.g. gaps among the door labyrinths and frame, mean and maximum temperature on door unexposed surfaces), so that to be able to stop flame propagation and maintain acceptable temperatures on the unexposed surface. In the standard test, the fire doors are subjected to a heat flux from gas burners based on a standard time-temperature curve [1].
During a standard fire-endurance test, data such as thermocouple measurements on the unexposed side of the door, deflection measurements at selected locations and visual observations are gathered [2].

4 Objectives

The present study describes the numerical methodology used to assess the fire performance of large fire doors (single-leaf and double-leaf sliding doors) commonly used for civil/industrial applications, having respectively length and height of 15-25m and 7-8m respectively. These fire doors cannot be tested at laboratory scale, due to their large sizes, and the only way to verify their structural integrity,

when subjected to fire, is via numerical simulations, using as reference results of standards laboratories tests on specimen fire doors.
The developed numerical methodology aims at verifying thermo-structural response of fire doors when subjected to fire conditions for 60/90/120 minutes, starting from results of laboratories tests on specimen fire doors. The aforementioned methodology, based on the use of the Finite Element Method (FEM), foresees, first, the implementation of a coupled thermal-structural analysis on the FE model of the specimen fire door, to predict the evolution of the distribution of temperature and deformations, to be validated with the values obtained from a set of thermocouples during the experimental tests. Then, the second step is the thermal-structural analysis on the FE model of the full scale fire door using the same materials and simulations' parameters used for the specimen fire door's model.

5 Methodological approach

The numerical analyses were performed using the LS-DYNA software. The implicit solver was used for performing the numerical calculations.
The thermal and mechanical analyses were coupled in the same computational run, thus allowing considerable savings in modeling and computing time. The temperature distribution in the structure was obtained by a transient thermal analysis and used to generate the thermal loads in the mechanical analysis [3].

The methodology adopted for performing the thermo-structural analysis of the enlarged fire doors is articulated in three steps as follows:

- Standard fire test performed on the "*specimen barrier*" (see Figure 1), to obtain reference experimental temperatures and displacements;

Fig.1: Standard fire test for one specimen barrier including a pass door – Exposed side (left side) and unexposed side (right side) after fire resistance test

- Finite Element (FE) analysis, able to accurately replicate the experimental test on the specimen barrier, by setting up the FE material model parameters. The following Figure shows, as example, a FE model of a specimen barrier (sliding door), having a wall opening dimension of 2600 x 2800 mm; as shown in the picture, the FE model includes a pass door;

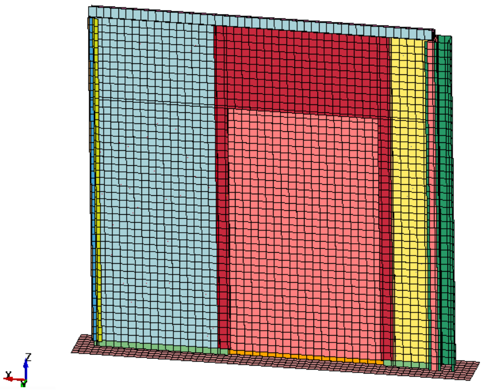

Fig.2: Example of Finite Element model of a specimen barrier having an opening wall dimension of 2600 x 2800 mm

- Coupled thermal-structural analysis on the enlarged fire door (wall opening dimension of 15000 x 8000 mm, carried out by using the previously calibrated model;

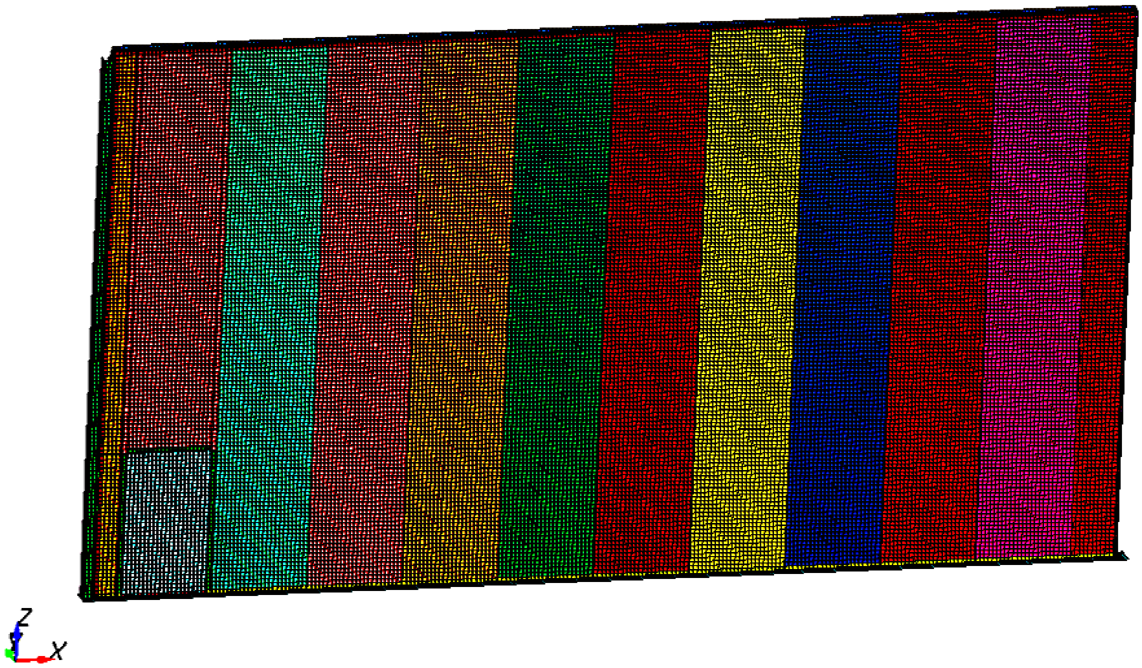

Fig.3: Example of Finite Element model of an enlarged fire door (wall opening dimension: 15000 x 8000 mm)

- Results analysis: the calculated displacements and temperatures distribution on the FE enlarged fire door model are analysed, to evaluate its structural integrity; more in detail, it must be verified that the gaps among the door labyrinths and frame are able to stop flame propagation and that the mean and maximum temperature on the unexposed surface does not exceed defined values.

6 Finite Element (FE) Model

The aforementioned methodology was adopted for the analysis of different sliding fire doors, commonly used for civil/industrial applications. The differences of the analysed fire doors were in terms of:

- Fire doors configuration: single-leaf or double-leaf sliding fire doors including/not including a pass door;
- Fire doors dimension: wall opening: 15-25m x 7.5-8m (length x height) and 80mm -100mm (thickness).

The geometrical features used for generating the 3D CAD models of the different fire doors were extracted from the available technical drawings of the specimen barriers, provided by MEVERIN [5].

The main features that characterize the analyzed fire doors are:

- Single/double leaves composed by modules of variable dimensions, made of steel (outer faces) and mineral wool (inner insulation layer);
- Labyrinths structures made of two parts: sliding part tack welded to the back side of doors' leaf (along the top and the sliding edge) and stationary part (not part of the door but included in the support structure);
- Lock handles;
- Roller devices fitting into the rail track along the top of each door leaf;
- Roller devices at the bottom of each doors' leaf;
- Moreover, for some of the analyzed fire doors, a pass door composed by a single modulus (steel faces and mineral wool) was included, together with its connections to the main fire door (i.e. hinges and lock handle).

To build a Finite Element (FE) model of a fire door assembly, it is important to assess the needed amount of detail that should be captured. As the full complexity of the fire door assembly is transferred into the FE model, both the model building task and the time to solve the analysis increase substantially [2]. Both solid and shell elements were used for implementing the different FE models. The solid elements were used to represent the mineral wool and the brass roller devices, whereas the other fire door components (steel sheets) were represented by shell elements. Shell elements are more computationally efficient than solid elements and are applicable in cases where the thickness of a component is much smaller than its other dimensions. The door panels and edge channels were all meshed using these shell elements, which have 4 nodes per element. Numerical analyses were performed on single-leaf sliding door, symmetric and asymmetric double-leaf sliding fire door, all including pass door. The FE model of enlarged doors are composed by approximately 214,000 elements: 108,000 are shell elements, 106,000 are solid elements.

6.1 Materials

The analyzed fire doors are built of composite modules of variable thickness (in the order of 80mm - 100mm) in steel and mineral wool. One of the greatest challenges in modeling structures in fire is the availability of accurate material property data over the wide temperature ranges typically seen during such fire tests [2]. The calibration of the temperature dependent physical material characteristics was obtained via the time simulation of the heat transmission within the structural assembly of the door, taking into account also the heat transmission through insulating material [2].
According to the Eurocode [4], the thermal properties of the carbon steel (thermal conductivity, specific heat) were considered dependent on the temperature. The thermal material card used in LS-DYNA to implement these properties was *MAT_THERMAL_ISOTROPIC_TD: the card allows temperature dependent isotropic properties to be defined. The temperature dependency is defined by specifying a minimum of two and a maximum of eight data points

Similarly, also the mechanical properties (Young's modulus and thermal elongation) were imposed variable with the temperature. Moreover, in order to implement a correct model of the material, an elastic-plastic behavior of steel was included by means of temperature dependent stress-strain curves. The yield strength of the steel was imposed equal to $f_{y,0}$ = 240 MPa at ambient temperature. The numerical model takes into account the reduction factor for the stress-strain relationship of steel at elevated temperatures. The mechanical material card used in LS-DYNA to implement these properties was *MAT_ELASTIC_PLASTIC_THERMAL: Temperature dependent material coefficients can be defined. A maximum of eight temperatures with the corresponding data can be defined. A minimum of two points is needed. When this material type is used, it is necessary to define nodal temperatures by activating a coupled analysis

The time dependent thermal properties of the insulating mineral wool (120 kg/m^3) where extracted from ref. [5]: the thermal conductivity k [W/(m K)] and the specific heat c [J/kg K] were considered as a function of the temperature [℃].

From the experimental test report (ref. [4]), it was noticed that inside the mineral wool insulation, the effect of latent heat due to the phase change effect on the temperature field is significant: the small conductivity and the highly non-linear insulation properties, e.g. due to moisture evaporation, pore pressure build-up etc, lead to steep temperature gradients with the activation phase and slight temperature differences in correspondence of the phase change: in order to simplify the numerical calculation, the phase change effect was not considered in the numerical analysis and the FE models were calibrated by modifying the thermal conductivity curve k=k(T) of the mineral wool, in order to obtain the temperature history closer to the experimental data coming from the fire resistance test

The contribution of the insulation material to the mechanical strength of the structural assembly is negligible, even if the mechanical behavior of the insulation material was considered.

6.2 Boundary conditions and loads

For the thermal analysis, the heat source was simply heat flux from the furnace burners. As the temperature of the heat source was varying with time, a transient thermal analysis was considered. The thermal analysis accounted for conduction through the fire doors, convection, and radiation heat transfers on the exposed side of the fire doors, and convection heat transfer on the unexposed side of the fire doors [7].

Gravity was applied to the FE model. Several mechanical constraints were applied to the fire door models:

- The nodes in correspondence of the roller devices that are placed on the door's top edge have null displacements out of plane and along the height of the door. Displacements in the sliding direction were permitted;
- The nodes in correspondence of the bottom were considered as in contact with the lateral roller device;
- The node in correspondence of sliding door handle lock was properly constrained;
- The interaction of the door/frame that is created following its expansion was modeled by means of appropriate non-deformable contact surfaces having initial distance equal to the design nominal distance;
- The interaction between the joined steel modules was simulated using the contact surfaces;
- The modules were connected with the top and bottom of the fire door using contact elements;
- Part of the nodes of the fixed labyrinths had null displacements in all directions;
- The interaction between the pass door and the sliding door leaf was been represented by means of appropriate non-deformable contact surfaces having initial distance equal to the design nominal distance;
- The nodes in correspondence of the pass door handle lock and hinges were properly constrained to the correspondent nodes on the sliding door leaf.

7 Comparison between experimental and numerical results

A fully implicit coupled thermal-structural analysis was performed to evaluate the stress-train distribution of the fire door. The structural analysis calculates, at each load step, the displacements of the nodal points in the structure following the expansion of the material due to the distribution of the temperature inside the structure. This computation is a mechanical analysis, which solves the stress-strain problems induced by the change in the thermal field.
Based on the results temperature from the thermal analysis and on information on temperature dependent material properties, the thermal stresses and deformations on the geometry were simultaneously evaluated.

The analyses were performed modeling fire conditions with variable duration (60/90/120 minutes) on the basis of the resistance class to achieve.
The first step was to compare the displacements calculated on the FE models of the specimen barriers with the experimental data extracted from the report in which fire resistance tests carried out in the dedicated laboratories are described. The comparison resulted in the calibration of the FE models material properties in order to achieve a good matching between numerical and experimental results (i.e. temperatures and deformations).
As example, we discuss here the results achieved on the single-leaf sliding door. Similar results were calculated considering symmetric and asymmetric double-leaf doors.

In the following figures, the temperature distribution of the specimen door at the end of the fire-endurance test (6600s) is shown. As a FE model simplification, windows and glazing were not considered.

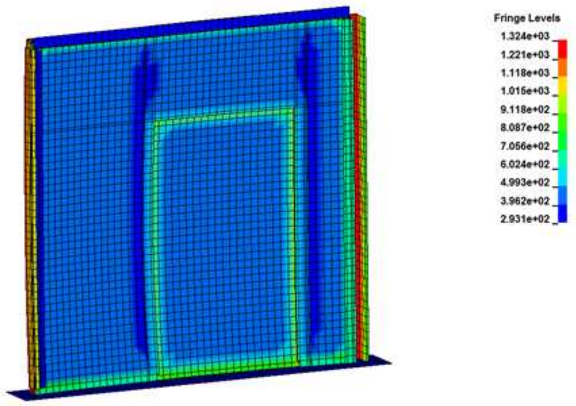

Fig.4: FE specimen barrier model - Temperature distribution [K]- Unexposed side @90minutes

Fig.5: Specimen barrier - Unexposed side @90minutes

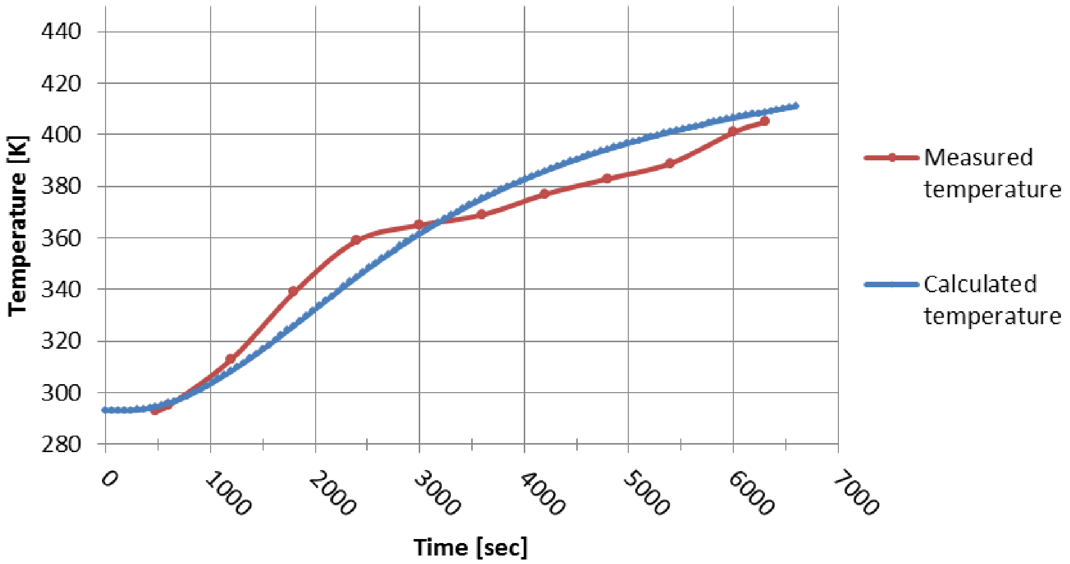

Fig.6: Specimen Fire Door: calculated vs. measured temperature [K] - Unexposed side @90minutes

Figure 7 shows the calculated out-of-plane distribution of the specimen fire door (unexposed side, @ 6600s); Figure 8 compares the numerical and experimental out-of-plane displacements of a node (F) placed in the center of the pass door (unexposed side) versus time [s].

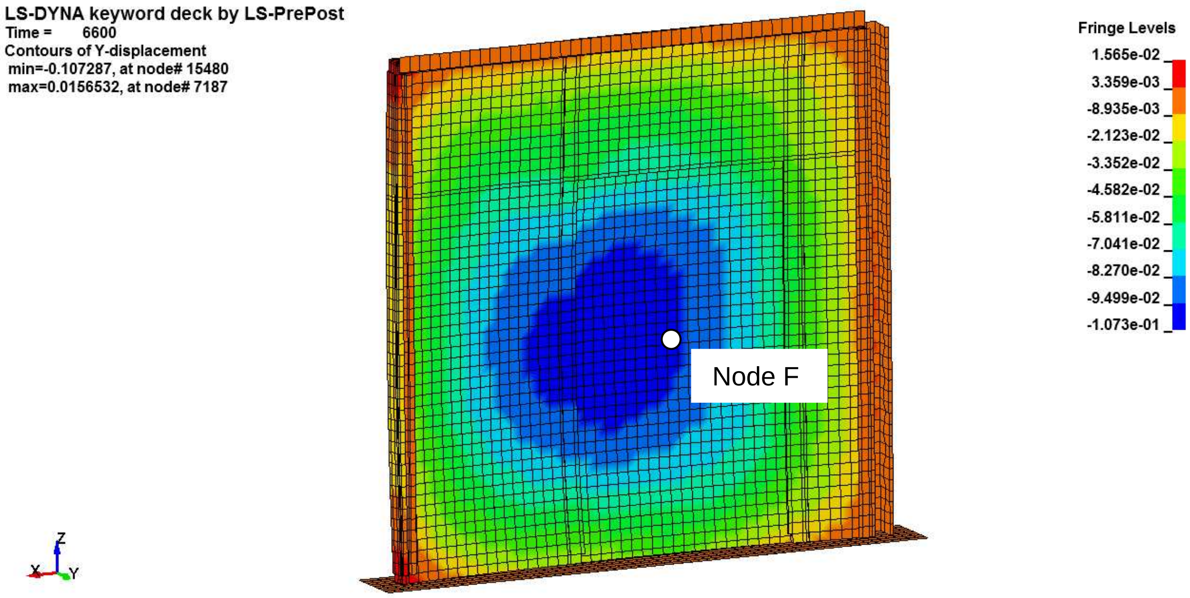

Fig.7: Specimen Fire Door: Calculated out-of-plane displacement [m] - Unexposed side @6600 s

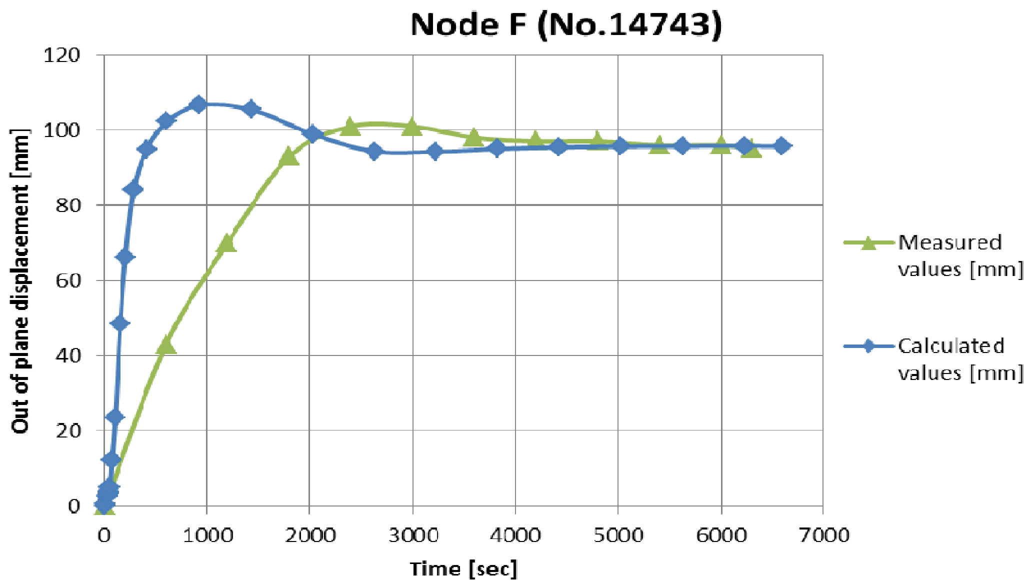

Fig.8: Specimen Fire Door: Out-of-plane displacement distribution [mm] vs. Time [s] of node F (unexposed side)

Details of deformations of the bottom part of the fire door and vertical labyrinths are shown in the Pictures below. The results at the end of the fire test highlight the interaction of the door edges with the external frames, as consequences of the high thermal elongation of the steel. It can be seen that the labyrinths to prevent the flame passage are maintained (Figure 9-10). Figure 10 shows details of the deformation of the bottom part of the door at the end of the test.

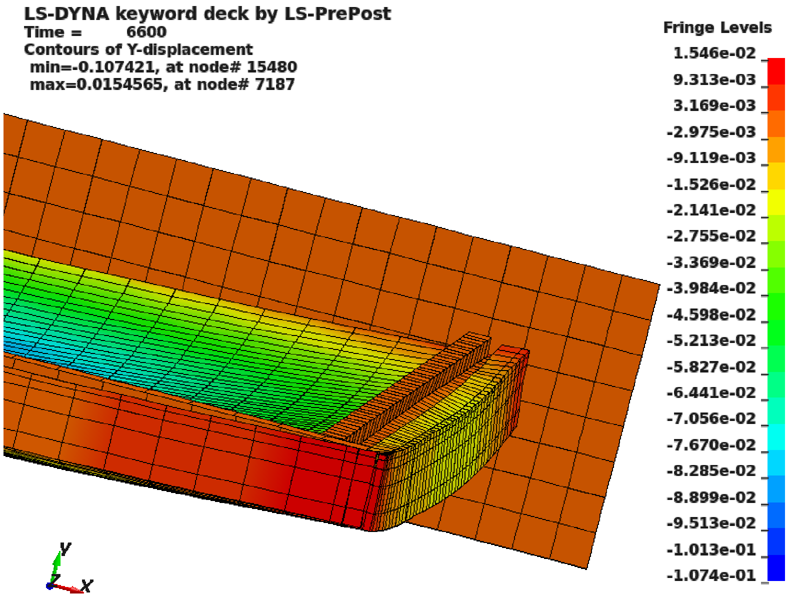

Fig.9: Specimen Fire Door: integrity of the vertical labyrinth at the end of the test

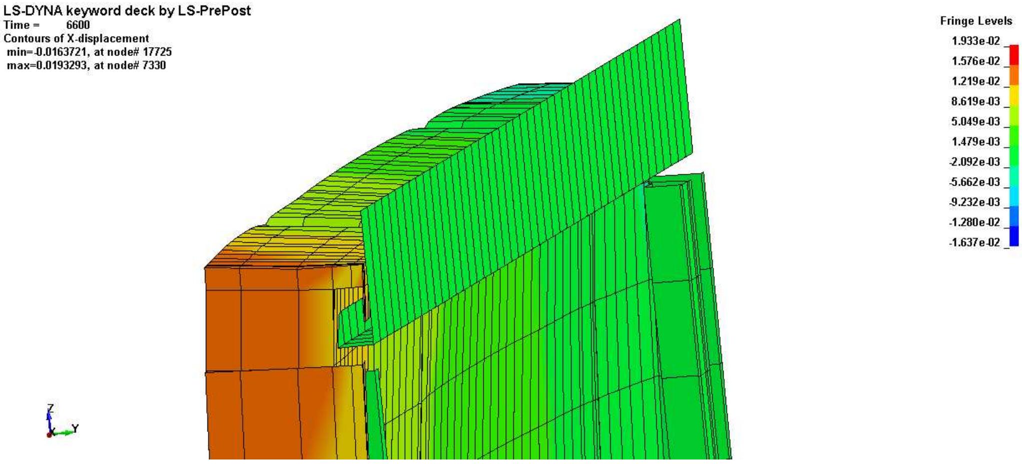

Fig.10: Specimen Fire Door: integrity of the horizontal labyrinth at the end of the test

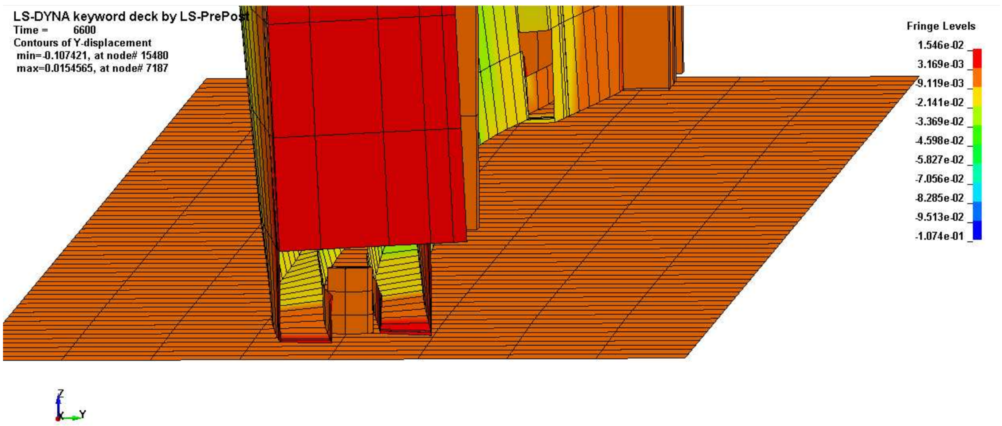

Fig.11: Specimen Fire Door: out –of-plane displacements of the bottom part @ 6600 s

After having calibrated the FE model of the specimen barrier, the enlarged fire door model (wall opening: 15000 x 8000 mm) were developed, applying the same loads, boundaries conditions, materials properties of the specimen barriers model. The simulation performed on the enlarged fire

door correctly converged over all duration of the fire-endurance test (60/90/120 minutes). The results of the thermal analysis were similar to the specimen door.
Figure 12 shows the out-of-plane displacement [m] of the enlarged fire door @ 5400s; Figure 13 shows the deformation of the horizontal labyrinth, able to prevent the flame passage.

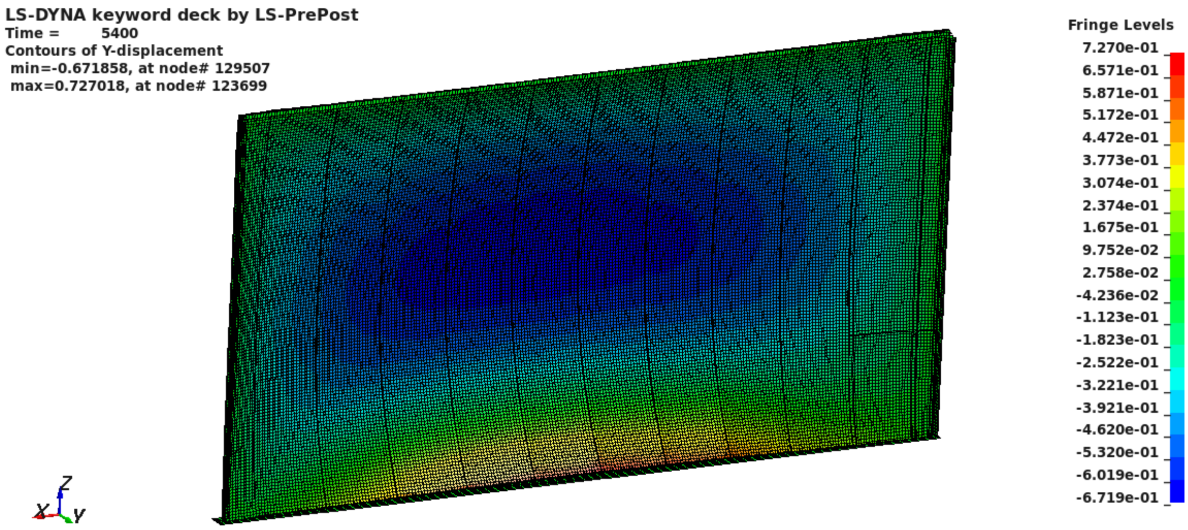

Fig.12: Enlarged Single-Leaf Sliding Fire Door: out –of-plane displacements @ 5400 s

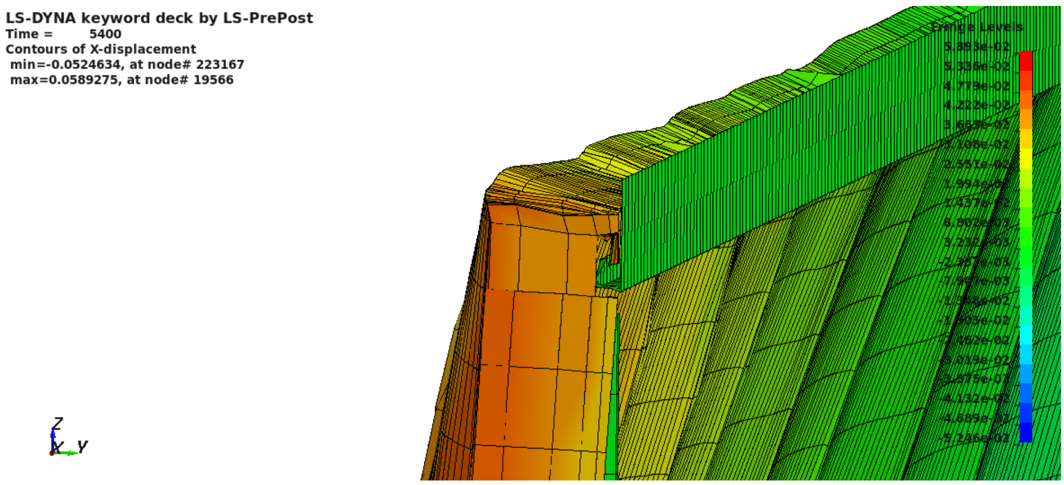

Fig.13: Enlarged Single-Leaf Sliding Fire Door: integrity of the horizontal labyrinth at the end of the test (5400 s)

The Von Mises stress [Pa] distribution on the unexposed side is shown in Figure 14.

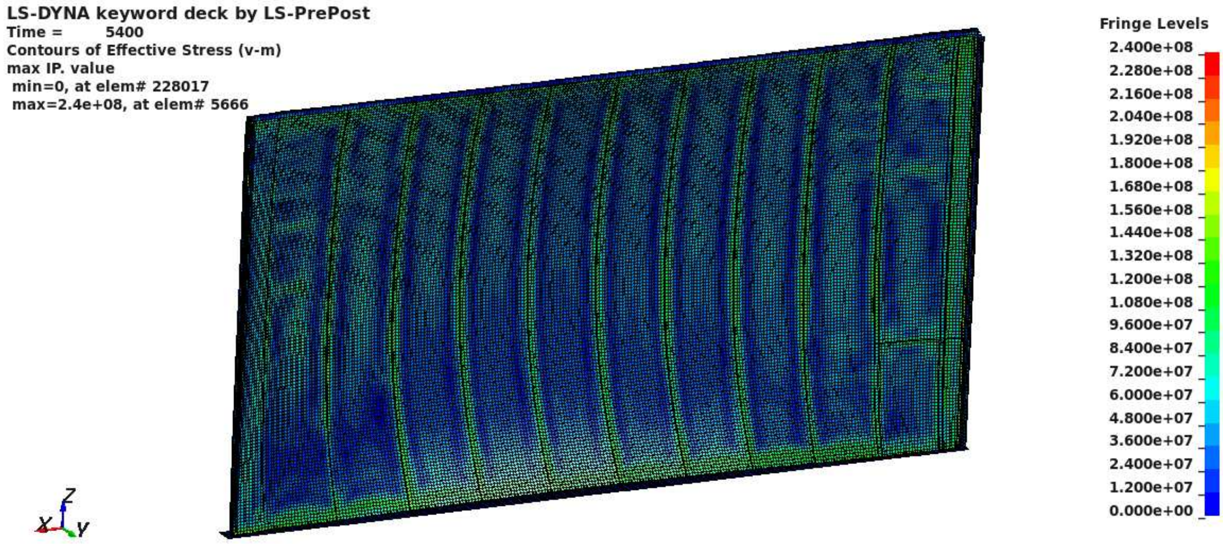

Fig.14: Enlarged Single-Leaf Sliding Fire Door: Von Mises [Pa] @ 5400 s

8 Conclusions

This work has described the numerical approach that has been developed by RINA Group to assess the fire performance of large fire doors (single-leaf and double-leaf sliding doors), commonly used for civil/industrial applications. These fire doors cannot be tested at laboratory scale, due to their large size (length and height of the order of 15-25m and 7-8m respectively), and the only way to verify their structural integrity when subjected to fire is via numerical simulations.
The methodology, starting from experimental standard fire tests carried out on specimen barrier of reduced sizes, is articulated in several steps: first, the generation of FE models for the 'specimen' fire doors, properly calibrated on the basis of the available experimental results; second, the development of enlarged FE models, where the same loads, boundaries conditions, materials properties of the specimen barrier are applied; third, the development of coupled thermal structural simulations of enlarged doors, reproducing the standard fire test of different time duration (60/90/120 minutes, on the basis of the resistance class to achieve), according to the standard UNI EN 1634-1 [1].
The FE models described in this paper included the necessary complexity of the fire doors and test setup along with the temperature dependency of the constituent materials. The challenges of validating FE numerical models with the data available from the standard fire test have been also described.
The FE models were shown able to capture key thermal and structural responses, thereby giving confidence in its ability to reproduce the real behavior of 'specimen' barriers and enlarged fire doors, when subjected to fire.

9 Literature

[1] EN 1634-1, Fire resistance and smoke control tests for doors and shutter assemblies, openable windows and elements of building hardware, 2014

[2] M. Tabaddor, P. D. Gandhi, G. Jones, 'Thermo-mechanical Analysis of Fire Doors Subjected to a Fire Endurance Test', Journal of Fire Protection Engineering 2009 19: 51, DOI: 10.1177/1042391508098899

[3] A. B. Shapiro, 'Heat transfer in LS-DYNA', Livermore Software Technology Corporation, 4th European LS-DYNA Users Conference – Implicit/New Development

[4] Eurocode 3 ‘Design of Steel Structures - Part 1-2: General Rules - Structural Fire Design’ European Prestandards ENV 1993-1-2

[5] MEVERIN, Engineering Fire Doors and Wall; web site: http://www.meverin.com

[6] S. Lundberg, ‘Material Aspect of Fire Design’, TALAT Lectures 2502, Date of Issue: 1994

[7] P. Boscariol, F. De Bona, A. Gasparetto, S. A. H. Kiaeian Moosavi, L. Moro, ‘Thermal Analysis of Fire Doors for Naval Applications”, Proceedings of the PRADS2013, pp. 451~456 20-25 October, 2013 CECO, Changwon City, Korea