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The Role of Numerical Simulation in Fire Door Testing and Certification

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Abstract

Passive fire protection is indispensable when designing and constructing safer buildings, particularly in industrial and public facilities, where consequences of a fire can be catastrophic. Although their purpose is not to extinguishing a fire, passive fire protection aims to delay flame and smoke propagation, gaining valuable time to save lives and goods. Fire doors are amongst the most common protection devices, and they must undergo strict certification tests to ensure they meet fire resistant standards. Such tests are expensive and time consuming, often carried out at longer distances in specialized facilities. Computational tools could provide a cost effective alternative to direct the design towards a viable product. Thus, with the objective of assessing the effectiveness of computational tools in the certification processes, a numerical model of a single-leaf sandwich door was developed. The simulations were carried out in Ansys Mechanical, using a one-way coupling approach between transient thermal and transient structural analyses. A key aspect of the model is the temperature-dependent convective heat transfer coefficient on the unexposed face, which greatly influences the predicted temperature evolution. From the numerical results, one may infer the maximum temperature of the door, as well as its displacements at the upper and lower edges. Thus the numerical model highlights the potential of using this methodology by allowing not only the temperature evolution to be recorded throughout the test at specific positions of the assembly, according to the standards, but also the identification of potential gaps between the door and the frame, which is critical for fire and smoke containment. Future work includes conducting an experimental trial to validate the model and refine the heat transfer parameters for improved predictive accuracy.

Keywords: Digitalization, Industrial Processes, Fire-doors, FEM, Ansys Mechanical, Certification Process.

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1. Introduction

The continuous growth of the urban population and the increasing market for high-rise and multi-story buildings reveals the urgency in developing effective solutions for mitigating the consequences of fire occurrences. This necessity extends to industrial and public buildings where specialized fire doors are essential for compartmentation and safety. Fire safety is a cornerstone of building construction, being passive fire protection a crucial component. Passive fire protection does not have the purpose of extinguishing a fire, but to compartmentalize an area and delay the fire and smoke propagation to other areas within the building. For this, fire resistant doors, walls and floors are implemented [1].

Fire doors are technical components that ensure resistance to fire and smoke, being able to prevent its spread, allowing lives and property to be safeguarded in the event of a fire [2–4]. These can be made up of one or two sheets, the frame and the door hardware accessories (hinges, locks and handles).

Given their critical role, fire doors must undergo meticulous and mandatory certification tests to ensure they meet fire resistant standards [5]. However, due to the high

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cost and time associated with performing certification tests, numerical studies play a crucial role in supporting the preliminary evaluation and validation of new designs, directly impacting the reduction in the number of physical prototypes and tests.

A number of studies have utilized FEM to investigate the thermal and structural behaviour of fire doors. For instance, Hugi et al. [6] developed 2D and 3D models in order to investigate the performance of a frame subjected to the standard temperature-time curve and the equivalence of the insulation criterion, to reduce the number of tests for certification. Numerical and experimental results showed good agreement and revealed that an opening direction outwards from the furnace (unexposed hinges) was the most critical case, mainly due to radiative heat exchange. Bozzolo et al. [7] developed a coupled 3D model to investigate the behaviour of large-sized fire doors when exposed to a fire. Given the impossibility of conducting full-scale tests, the authors validated their numerical results using experimental data from reduced-scale prototypes to ensure that the numerical model complies with the requested certification requirements. The numerical results showed good agreement with those of the prototype, demonstrating the reliability of the approach. Tabaddor et al. [8] conducted a thermal and structural (stationary non-linear) analysis on a double-leaf fire door to assess its behaviour when exposed to fire. According to the results, the door deforms towards the furnace, with greater displacement near the center of the active leaf, while the maximum stress occurs at the top and bottom hinges. A slight discrepancy between the measured and simulated at the early stages of the testing in the temperatures on the unexposed face was attributed to the use of a constant air convection coefficient. Although initial discrepancies between the numerical and experimental results were observed, the numerical model showed good overall agreement with the experimental tests, reinforcing its potential as a complement to certification processes. More recently, Nurić et al. [9] developed a transient thermal model in order to assess fire doors resistance when exposed to fire, having concluded the effectiveness of the numerical model in predicting fire safety, utilizing constant heat transfer coefficients for the unexposed face of the door.

Although simulation techniques have become increasingly relevant as complementary tools to improve design and reduce the number of costly tests, experimental investigations remain fundamental to understand the behaviour of fire doors during standard tests. For instance, Capote et al. [10] conducted an experimental assessment of the physical phenomena occurring during standard fire tests on fire doors, highlighting key thermal behaviours and failure mechanisms. Similarly, other works, such as those focusing on the fire resistance of wooden fire doors [11], have provided valuable insights into how these systems respond under real testing conditions.

Therefore, this work aims to explore the feasibility of using numerical simulations as a supplementary method to the certification tests for fire doors. To this end, this study uses Ansys Mechanical, where a thermal-structural model is developed to predict and quantify its performance when exposed to fire, which will incorporate a convection coefficient varying over time on the unexposed face to predict and quantify the fire door's performance under fire exposure. This refined approach to the convective boundary condition is proposed to improve the accuracy of predicting the unexposed surface temperature, which is more effective than models relying on constant coefficients, such as [6], [8] and [9].

2. Fire door: Typologies and Materials

Fire doors can be classified by their operational mode, as well as by their constituent materials.

Regarding the operational mode of fire doors, they are commonly found in various types: hinged and swing doors, accordion doors, rolling doors, horizontal or vertical sliding doors, and tilting doors [12,13].

In relation to the materials that make up the door, these can be metallic, made of wood or wood derivatives, glazed, or wood-clad with a mineral core (door leaves clad in wood, containing a mineral material inside) [13,14]. Given their function as a protective barrier against fire, the materials applied inside the doors must have insulating characteristics. For this reason, particle agglomerates, mineral wool (such as rock wool or glass wool), and fibres (glass fibre or ceramic fibre) are used.

Furthermore, the materials typically used for the frame are steel, solid wood, MDF (Medium-Density Fibreboard) and aluminium [15]. Materials with insulating and fire-resistant properties can also be inserted inside the frame, such as glass wool [16].

Therefore, due to differences in materials and geometric characteristics, fire doors have a fire resistance ranging from 15 to 240 minutes.

3. Testing and Certification

Fire doors can only be used in residential buildings and high-demand locations (such as hospitals, healthcare facilities, and schools) after obtaining the necessary certification. Thus, they must be subjected to rigorous testing that ensures they fully comply with their function.

To this end, the certification process for any fire door consists of two phases:

- Testing Phase – A fire resistance test is conducted, following standards EN 1363-1 (Fire resistance tests - Part 1: General requirements) [17] and EN 1634-1 (Fire resistance and smoke control tests for doors, closing systems, windows and hardware – Part 1: Fire resistance tests for doors, closing systems and windows) [18].
- Classification Phase – A classification is assigned according to standard EN 13501-2 (Fire classification of construction products and building elements - Part 2: Classification using data from fire resistance tests, excluding ventilation services) [19].

Regarding the fire resistance test, a full scale fire door is placed inside a furnace (Figure 1) designed to use liquid or gaseous fuels. Here, the frame is screwed to the supporting structure, with the gaps between the frame and the support sealed with polyurethane foam. As for the door leaf, it is installed after the frame is fixed and is placed in the test rig with the opening direction facing either the outside of the furnace (hinges not exposed to fire) or the inside of the furnace (hinges exposed to fire). For this reason, two doors are necessary for the test, though only one is needed when just one face of the door is to be tested. Finally, hardware is installed to most accurately reflect the door's real-world working conditions. The door gaps must also be representative of those used in practice, with the test gaps falling between the average and maximum possible values for the door in question.

Figure 1. Interior of a furnace for certification purposes [20].

After this, the sample is subjected to the standard fire curve given by Equation 1, as per standard EN 13501-2.

$$T = 345 \times \log_{10}(8t + 1) + T_{amb} \qquad (1)$$

Here T is the temperature, t the time and T_{amb} is the ambient temperature.

Once the test is completed, the door is evaluated for certification based on its integrity against flames and hot gases (Class E) and its thermal insulation (Class I). The integrity against flames and hot gases refers to the time (in min.) during which the sample maintains its function, with no penetration of flames or hot gases on the unexposed face. On the other hand, the fire resistance regarding thermal insulation corresponds to the time (in min.) during which the sample maintains its separating function without high temperatures being reached on the unexposed face. To meet this criterion, the average temperature increase on the unexposed face cannot exceed 140 ˚C, and the temperature at any single point must be limited to a maximum increase of 180 ˚C. The thermal insulation Class I can be further qualified with suffixes I_1 and I_2, which require specific testing procedures. Although the temperature increase limits remain the same, for class I_1 the temperature must be measured at least 25 mm from the visible leaf edge, and at least 100 mm for class I_2 (Figure 2). It is important to note that, for the frame, its temperature is limited to 180 ˚C and 360 ˚C for the I_1 and I_2 classifications, respectively (Figure 2).

The failure of any integrity criterion also implies the failure of thermal insulation.

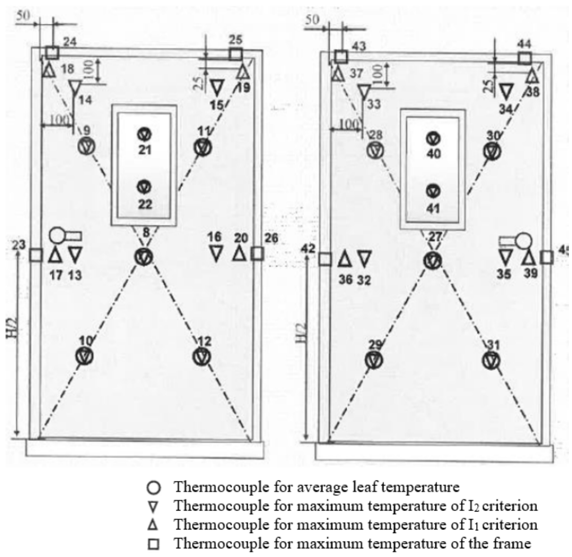


Figure 2. Layout of thermocouples on the unexposed surface for fire door testing [21].

Therefore, the classifications for Classes E and I for fire doors include the time during which the performance requirements are met, corresponding to the class immediately below the time obtained in the test. It is also worth noting that the combined EI rating is the most stringent and generally required classification for fire-rated doors, as it ensures both the containment of fire and the limitation of heat transfer.

Thus, Table 1 lists the possible classifications for fire-resistant doors and closing elements for classes E and EI.

Table 1. Fire-resistant doors and closing elements classifications, in compliance with EN 13501-2 and EN 1634-1 Standards [18,19].

Classification	Duration (in min.)							
E	15	30	45	60	90	120	180	240

EI	15	20	30	45	60	90	120	180	240

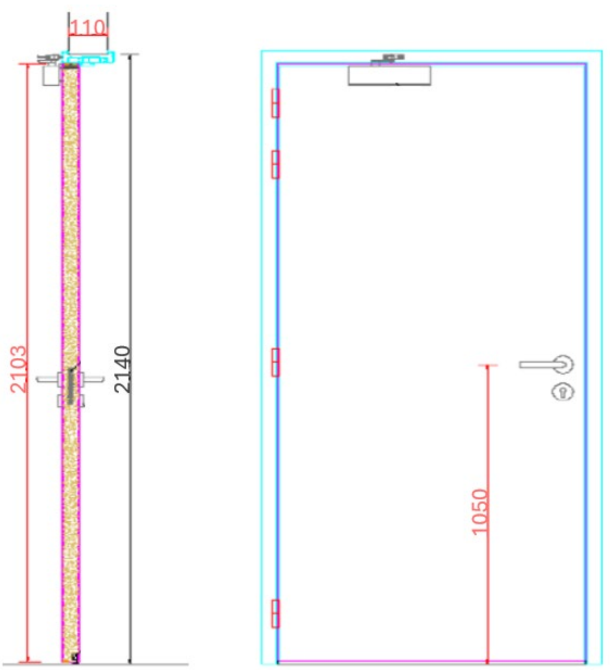
4. Numerical Model

4.1. Door-Frame Configuration

The door considered in this study is a single-leaf sandwich door characterized by a rectangular geometry, with overall dimensions of 1000 by 2103 mm and thickness of 60 mm. It is composed of phenolic panels and Halspan for the core. The door also has handles, hinges, key entry, door closer and door seal and intumescent strips.

Regarding the frame, it is made of solid Meranti wood up to the wall, however, it incorporates an internal cavity filled with fiberglass positioned adjacent to the central area of the door.

Figure 3 shows the door-frame assembly under analysis.



a) b)

Figure 3. Door under analysis: a) cross-section view; b) front view: door (in dark blue) and frame (in light blue).

4.2. Initial and Boundary Conditions

In order to capture the thermal behavior of the door-frame system, the numerical model involved transient thermal and transient structural simulations.

Regarding the transient thermal analysis, an initial temperature of 22 °C was defined for all the components of the model.

For the face exposed to the fire, the normalized Temperature-Time curve represented by Equation 1 is defined. On the unexposed face, a convective heat transfer coefficient (h) varying over time is applied, according to the graphic shown in Figure 4.

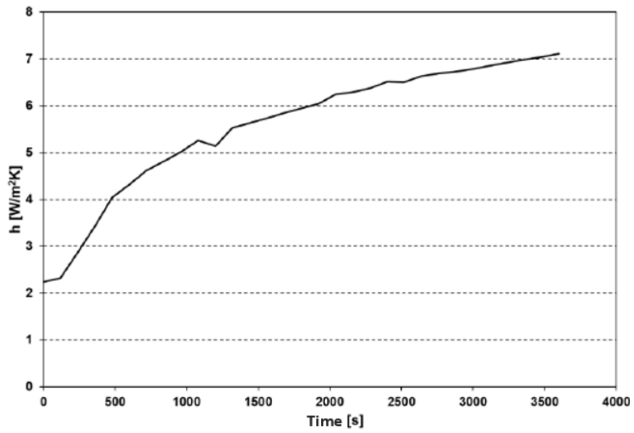


Figure 4. Convective heat transfer coefficient varying over time.

Although there is no contact between the door and the frame due to existing gaps, for thermal purposes, a frictionless contact condition was applied with a conductance of 10 W/(m².K). Additionally, a pure penalty formulation was considered due to the possible interpenetration of the elements.

As far as the transient structural analysis is concerned, the initial condition of 22 °C was maintained.

Fixations and displacement constraints were defined accordingly. Thus, a Fixed Support was applied on the interior part of the frame that fits into the wall, aiming to simulate the embedding of the frame into the wall. Regarding the hardware (hinges and lock), a null displacement was applied on all the faces of these elements in the x, y and z directions, as these components are fixed to the door and frame and serve to join them, thus restricting their deformation. On the other hand, on the lower face of the door (face usually near the threshold), a null dis-placement was applied only on the z-axis, because this face of the door can-not deform inward towards the threshold. It should be added that the contact between the door and the frame was not considered in this analysis, since neither are in direct contact.

4.3. Mesh Discretization

The mesh used in both thermal and structural analyses was kept consistent to ensure compatibility between the results, with 21154 elements. Slight variations in mesh density occur depending on the geometry details.

Figure 5 shows the mesh density of the door-frame assembly.

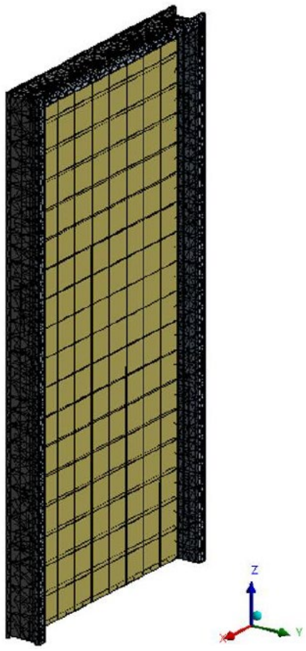


Figure 5. Mesh applied to the door and frame.

4.4. Simulation Parameters

With respect to the simulation parameters, the Analysis Settings are common to both simulations, with 30 steps of 120 s each defined, resulting in a total simulation time of 3600 s. As for the time step of 120 s, this value was chosen to allow the implementation of the convective heat transfer coefficient without compromising the results or the simulation time. Additionally, Auto Time Stepping was disabled, and 10 sub-steps were defined given the fact that this number showed the best balance between result accuracy and simulation time.

These simulations were coupled using a one-way coupling approach, in which thermal results were transferred to the structural model. Regarding the import of these thermal results into structural analysis, this was done through the Imported Body Temperature, for which the Thermal Solution must be linked to the Structural Setup. It should be noted that it is necessary to select all the bodies of the geometry.

5. Results and Discussion

The results shown in Figure 6 illustrate relevant contributions of the numerical model. As expected, the temperatures recorded in the case of the exposed hinges are higher than those of the unexposed hinges to fire, with the latter recording a temperature of 292 ºC after 3600 s (end of the test). Furthermore, a noticeable oscillation in the curve is evident in the initial phase of the test - a rise, followed by a decrease in temperature, and then a new increase - something that is not seen in the furnace heating curve, which is a continuously rising curve without oscillations over time. This oscillation may be related to the fact that, although the simulation does not account for phenomena such as turbulence inside the furnace, the convection heat transfer coefficient was calculated from real tests where these actual phenomena do exist. Thus, these phenomena may be indirectly influencing the numerical results through the convection heat transfer coefficient.

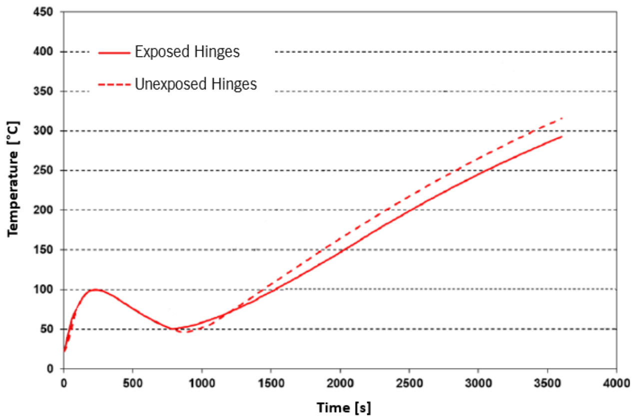


Figure 6. Door's temperature over time for exposed and unexposed hinges (solid line and dashed line, respectively).

In addition, the numerical model allows for the analysis of the temporal evolution of the displacement of the upper and lower corners of the door, shown in Figures 7 and 8, respectively. The results show that, in the case of unexposed hinges, the upper and lower corners undergo a displacement of 93 and 55 mm, respectively, at the end of the test. Although the results do not refer to the gap between the door and the frame, which will determine whether or not flames and gases pass through to the opposite side of the door, these values can be obtained using this model, once again highlighting its potential.

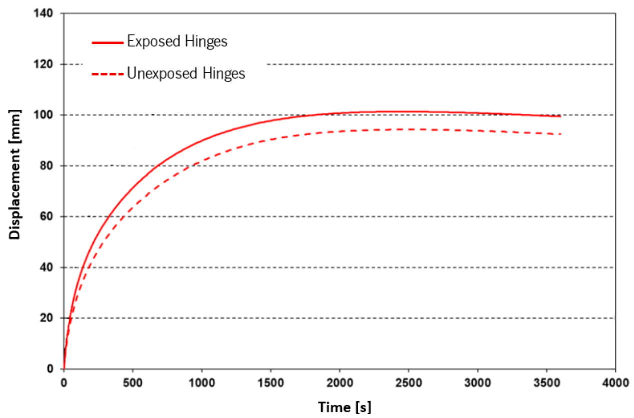


Figure 7. Upper corner displacement over time for exposed and unexposed hinges (solid line and dashed line, respectively).

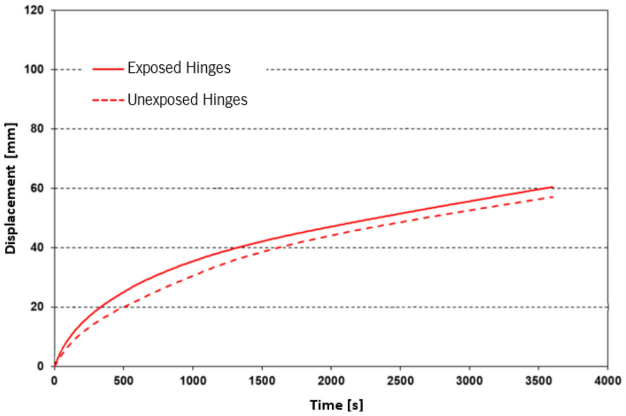


Figure 8. Lower corner displacement over time for exposed and unexposed hinges (solid line and dashed line, respectively).

That said, the numerical model developed allows the characterization of the temporal evolution not only of the temperatures of the door, but also of the displacements undergone throughout the test. This dual analysis capability can assist in identifying the most critical element of the assembly. Furthermore, although this study only extracted the maximum temperatures of the door and the displacements of the upper and lower corners, the results clearly demonstrate the potential of this methodology to numerically reproduce the temperature record at specific points on the door, as required by the standards, as well as to monitor the gap between the frame and door.

6. Conclusions

With the aim of exploring the full potential of numerical simulations as an aid in fire door certification processes, a numerical model was developed. This model proved capable of predicting the thermal behaviour of the door when subjected to a 3600 s fire exposure test, taking into account standards EN 1363-1 and EN 1634-1.

A pivotal contribution of this work is the incorporation of a time-dependent convective heat transfer coefficient on the unexposed face, a feature that distinguishes this methodology compared to those typically adopted in fire doors FEM analyses. Although in the case studied the temporal evolution of the maximum temperatures of the door, together with the displacement history of the upper and lower corners was analysed, the results demonstrate the potential of applying this methodology. By allowing the temperature evolution, as well as the deformation to be recorded throughout the test at specific positions of the assembly, it is possible to determine the temperatures at the locations corresponding to those of the thermocouples during a certification test and the gap between the door and the frame. However, it is worth noting the influence of the convective coefficient in the temperature evolution, as its indirect incorporation of real furnace phenomena may explain the oscillations observed in the numerical temperature curves, despite the absence of these effects in the model itself.

Therefore, although no direct numerical verification of the possible certification level of the fire door under study was carried out, the model developed demonstrated its ability to extract the values necessary for this purpose. It is important to note that, despite this possibility, numerical simulations cannot be seen as a substitute for actual certification tests, but rather as complementary tools that promote greater time and cost efficiency.

In the future, obtaining comprehensive experimental data – temperatures at the thermocouples positions and displacement measurements – will be necessary to validate the numerical model results and determine its accuracy. Furthermore, a sensitivity analysis will be performed to assess the model's robustness against variations in key inputs, thereby strengthening the claim of its practical implementation and overall reliability.

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