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Improvement of Fire Door Design Using Experimental and Numerical Modeling Investigations

Abstract

Fire doors should withstand high temperatures without significant deformation. In this paper, novel internal stiffeners configurations are introduced and tested in pair swinging-type fire door. From the fire side, the door was cooled using pressurized water at 4 bar while on the other side, 8 thermocouples were arrayed to measure the temperature variation in different positions. A fire door with double S internal stiffeners of a height 2.2 m was tested experimentally and a numerical model was created using ANSYS 19 to simulate the cooling and the deformation process. The simulation model showed a very close agreement with the experimental results with an error margin not exceeding 0.65%. Afterwards, six models were created to simulate fire doors performances with internal configurations of double S, double C, and hat Omega for two different doors heights of 2.2 and 3 meters. The results obtained from the numerical simulation showed that, for the 2.2 m height door, the maximum deformations were 7.2, 5.43, and 5.02 cm for double S, double C, and hat omega stiffeners, respectively. The 3 m door showed maximum deformations of 6.57, 4.26, and 2.11cm for double S, double C, and hat omega stiffeners, respectively. Results indicated that hat omega stiffeners can reduce the deformation by two thirds compared with the double S configuration which is the commercial configuration for now.

Keywords: Fire doors design, Fire resistance, Finite element modeling, Standard furnace test, Thermal performance, Fire test.

1. Introduction

The fire doors are used generally to obstruct the fire propagation, so that it represents the main element for safety [1,2], as the fire doors prevent the spread of direct flames and also prevent the leakage and spread of fumes and suffocating gases to reach the people in the building. The fire doors are designed to achieve certain thermal and structural requirements. The deflections associated with thermal stresses strongly affect the safety considerations of the door. Pressurised water jets are the most common mechanism for fire extinguishing processes. During the fire extinguishing process, due to the non-uniformity of temperature distribution and applied water jet pressure, the door edges tend to bend away causing gaps between doors' sheets. These gaps leads to flame and smoke propagation from a side to another. The problem with smoke propagation is not only a problem because its toxicity but also because it decrease the ability to extinguish the fire. For that stated reasons, the performance improvement of the fire door during the fire disaster became a strong point of research that being studied recently by researchers. Many researchers studied the influence of gaps on the leakage behaviour of fire doors. Other researchers studied the design improvement of the fire door for achieving a better deformation resistance.

Gaps between the fire door, walls and floor cannot be eliminated. Larger gaps can dramatically affect the pressure and temperature distributions that controls the smoke propagation. Several researchers have studied the leakage from fire door in different ways. Cooper et al. [3] numerically and experimentally studied the leakage from fire door. They reported that there were inaccuracy problems when following the ISO test standards for testing fire doors and they introduced a new testing criteria that overcome the ISO problems. Worth mentioning, they studied the testing criteria for fire doors but not the design.

Cheung et al. [4] studied numerically the effect of door gaps on the smoke propagation without studying thermal stresses and deflection during fire test. Their results showed that gaps allow smoke to escape as well as allowing fresh air into the room on fire which can increase the risk in that room. They concluded from the studies that the safe criterion for the gap that ensures blocking the spread of smoke is 3 mm.

Several researchers studied the behaviour of the fire door frame during the fire extinguishing process. Wakili et al. [5] investigated numerically and experimentally the temperature distribution in a steel frame of a fire door. The study has been performed on a steel door leaf subjected to fire. Then they designed a model which simulated the test. They used this model to study the effect of boundary conditions and insulation material on the temperature growths. The study focused only on the factors affected the insulation of the frame without scrutiny of the entire door structure.

Hugi et al. [6] developed a computational simulation model to analyse the behaviour of the fire door frame. They concluded that optimising the frame geometry as well as the filling insulation are promising parameters to study.

Other team of researchers focused on the fire door thermal behaviour. Tabaddor et al. [7] have introduced a finite element modeling for the swinging type steel fire door subjected to fire test using ANSYS 11. They used transient solution for thermal analysis and steady state solution for mechanical modeling. They concluded that FE model was able to predict the thermal and structural responses if a proper validation scheme is used.

Chen et al. [8] have investigated numerically the structural behavior of fire door of an elevator during high temperature conditions. They conducted the FE modeling with ANSYS software. They studied the effect of the geometric parameter and material with time during fire. They concluded that the dimensions of the door should be as small as possible to enhance fire resistance time. Also, the door materials should have a low thermal expansion coefficient in order to reduce deformation in high temperature situations.

In a recent work, Kyaw et al. [9] have introduced a finite element study for the marine fire door subjected to fire test. The model didn't have enough refinement as mentioned by authors also they recommended considering more properly derived convective and radiation coefficients in the simulations. Zhang et al. [10] have introduced the design criterion of fire door and they have established a numerical simulation for performance of the door using FEM. The results show that with the existence of thermal load the large fire door's structure can withstand a maximum fire resistance time of 3 hours. The maximum temperature of unexposed surface is within 130 °C depending on the thermal resistance of the door.

Bozzolo et al. [11] have introduced a numerical study using FEM for large fire doors performance including; single and double door leafs subjected to fire. They discussed the thermal and structural response of the doors. They confirmed the ability of FE models to capture the key thermal and structure responses. The following are the most recent researches that considered experimental studies for the fire door behavior.

Joyeux et al. [12] have described the altered behaviours of fire doors during standard and natural fire tests. They have performed natural fire test to investigate the fire door behaviour. They have considered wooden and steel doors affected by severe fires which involving reduction of fire resistance. They concluded that the ISO-fire tests might not be always representatives of the behaviour of door and in order to make a reliable fire safety engineering analysis, the behaviour of fire resistance element in fire situation should be deeply studied which is the core of the present study.

Capote et al. [13] have also studied experimentally different phenomena of the fire door during test in a furnace. They investigated the thermal behaviour of doors. They stated that there is an increase in heat transfer coefficient due to separation between the component material of the door during furnace test which allows appearing of convection current between that layers. Also, the they found that the resulting opening in the door affected directly the temperatures of the unexposed side of the door.

Boscariol et al. [2] have introduced an experimental test of single leaf fire door for naval application. They developed a FE model to simulate the experimental case. They used the experimental results to validate the FE model. They concluded that the numerical model can predict the behavior of the door during heating with good accuracy. Both frame and door behaves as plates bent under a thermal load. They considered two leafs configuration which allowed a gap formation and thus flame propagation. The increased thermal insulation thickness may lead to increase the relative gap between the door leafs.

Izydorczyk et al. [14] have discussed the resistance of fire doors and compared between the temperature rise of unexposed surfaces of fire doors with different surface material including; timber, aluminum and steel. From the discussed results, change in the fire door's structure or the method of mounting significantly affect the fire resistance characteristics. In addition, the trusted way to evaluate the actual fire resistance is to conduct an adequate test.

Moro et al. [15] studied experimentally and numerically introduced a novel simulation for a new design of single leaf fire door. They improved the mechanical response of the door by changing the order of the constitutive elements such as structural plates and insulating material. The maximum displacement was reduced to the third that of the conventional configuration. They did not focus on the real-world installation of the internal door structure or the stiffeners configurations. The maximum temperature during the heating process was limited by 950 C.

McDermott et al. [16] have examined the occupant behaviour in relation to self-closing fire doors. They studied the fire door application in domestic buildings application and studied the door behaviour during fire extinguishing. They come to conclusion that the effective strategies of fire safety needs to consider both behavioural and environmental effects concurrently. Hopkin et al. [17] have introduced a literature that shows the importance of closing doors habits on fire spread and life losses.

The aim of the present work is to design an internal door stiffener that is able to withstand a high temperature without significant deformation. The work includes an experimental fire test and finite element analysis for a swinging type fire door. The fire test according to standard fire test ANSI/UL 10 C – Positive Pressure of Fire Tests of Door Assemblies was performed twice, one both the conventional door and the modified design. The conventional fire door with double S stiffeners internal design and 2.2 door height was experimentally tested. A numerical study was performed using ANSYS 19 to predict the maximum deflection using different stiffeners cross sections. The simulated stiffeners configurations were double S, double C and hat omega stiffeners. They were numerically tested against different door heights of 2.2 m and 3 m in order to relate the door height with the maximum deflection. On the other hand, the finite element model (FEM) was validated with fire test of actual fire door. The most promising design corresponding to minimum deflection was used for manufacturing. The second fire test was done according to FEM result of minimum deflection using standard fire test ANSI/UL 10C – Positive Pressure of Fire Tests of Door Assemblies.

2. Experimental Procedure

The purpose of the experimental work is to investigate the internal configuration of fire doors under standard endurance and hose stream test. The accepted design must fulfil with product certification requirement which states that the maximum deflection should not to exceed the one and half of the door thickness.

2.1. Fire door design:

The fire door has thickness of 45 mm and has two separated leaves each of 1.10 m fixed width. All metal sheets are made from plain steel (St-37) of 1.5 mm sheet thickness. The sheets are attached together with lock-seam edge construction. The door's leaf construction contained three main vertical stiffeners and four C shaped channel are attached by spot welding to the sheets along the leaf circumferential edges. The main stiffeners cross sections are the focus of the study. Three different stiffeners shapes of double S, double C and hat omega are taken for design improvement. The insulation firmly packed to fill all voids inside the door. Thickness of insulation is cut flush to top of stiffener height. The insulations used is

Rockwool. The door leaves are fixed to an external steel frame through three or four hinges according to door height Figure 1. The maximum acceptance limit of deflection is 1.5 the door thickness according to the ANSI/UL 10C standard fire test.

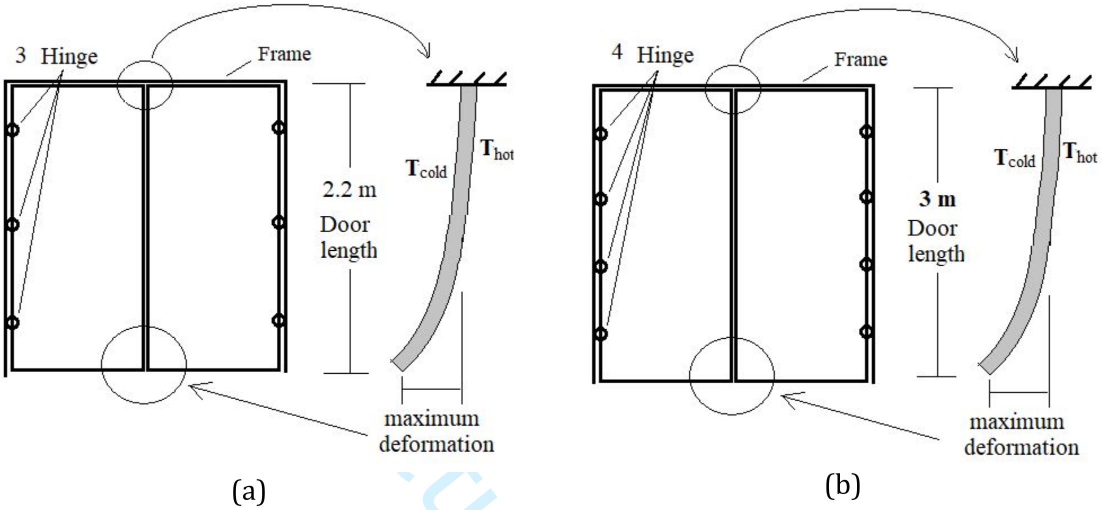


Figure 1 schematic drawing fire door deflection (a) 2.2 m three hinges door length (b) 3 m four hinges door length

2.2. Fire test:

The fire door is tested experimentally by heating in a special electric furnace which simulated the true fire accident. Where one side of the door is directly exposed to the generated heat by the furnace. The furnace provides a maximum temperature equals 1000 °C. Based on the engineering study and test results for certification, the pair swinging-type fire door assembly was found to be suitable for use in 1-1/2 hour fire endurance. Then, the door was subjected to hose stream test. The study included two fire tests for fire door with different stiffeners shapes. The test included subjected of pressurized water stream of 4 bars until the exposed surface temperature reached the ambient temperature.

Regarding the standard time-temperature relationship of the furnace, the European codes were used, which include safety factors allow design values to be obtained from characteristic values. Figure 2 shows the vertical fire resistance test furnace.

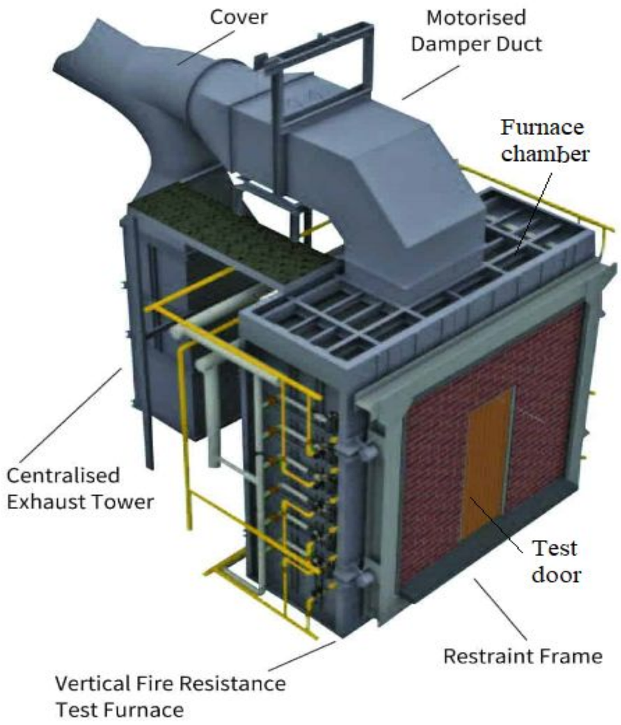


Figure 2 Vertical fire resistance test furnace, [18]

During the test for 1-1/2 hour fire endurance one side of the door heated according to the standard time-temperature relationship mentioned in Eurocode 3 [19] as,

$$T_{fire} = 345 \log_{10} (8\,t + 1) + T_{\infty} \qquad (1)$$

Where:

- T_{fire}, and T_{∞} are the fire and environment temperatures, expressed in C, respectively.
- t is the fire time, in minutes.

The measured mean furnace temperature curve compared to the standard temperature curve was obtained by Eqn. 1 is presented in figure 3.

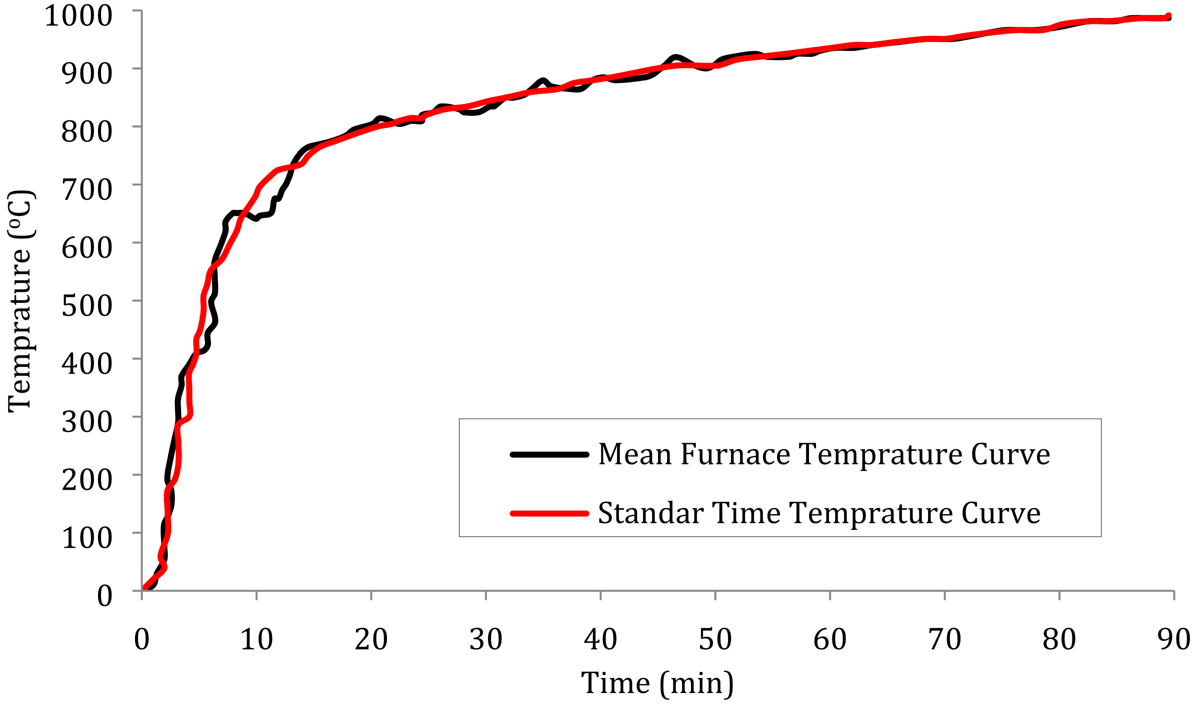
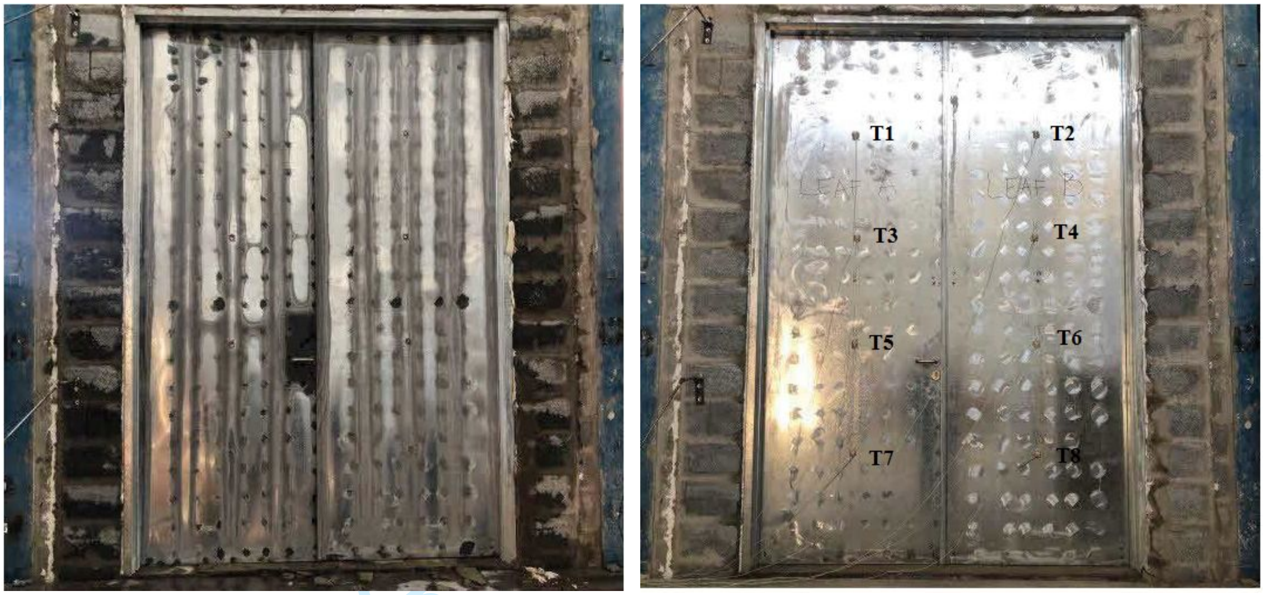


Figure 3 Mean furnace temperature curve and standard –time temperature curve

Figure 4 shows the pre-test exposed and unexposed surfaces of the fire door standing in the furnace test frame. Figure 4 (b) shows also the eight thermo couple (K-type) distribution. Whereas the exposed surface of the fire door, post-fire and pre-hose stream test is presented fig. 5(a). while the exposed surface, post-fire and post -hose stream test are presented in fig. 5 (b). The hose stream jet used in cooling is presented in fig. 6.



(a) (b)

Figure 4 Fire door before fire (a) exposed surface (b) unexposed surface

(a) (b)

Figure 5 Fire door after fire (a) pre-hose stream test (b) post -hose stream test

Figure 6 hose stream random jet cooling for the exposed surface under 4 bar water pressure

3. Mathematical modeling

This section shows the heat transfer equations, structural analysis and welding calculations.

3.1 Heat transfer equations

In order to deep insights into the thermal and mechanical behavior of the fire door, a simplified model is developed. The model considered the steady-state heat transfer at high temperature. The conventional fire door can be considered as an arrangement of layers attached one by one to each other. And each layer is represented by a thermal resistance. Neglecting heat dissipation through the edges, each leaf can be described by two external steel layers and an internal layer made of insulating material. Figure 7 shows the heat transfer modes for the heat transfer rate across the door to the surrounding. The exposed door's surface temperature equals the furnace maximum temperature of 1000 °C.

The main governing equations for the steady one-dimension heat transfer are presented.

$$\therefore Q = \frac{\text{temperature difference}}{\text{total thermal resistance}} = \frac{\Delta T}{\sum R_{th}}$$

Conduction is expressed by Fourier's law of conduction as,

$$Q_{cond} = -kA\frac{dT}{dx}$$

Convection is expressed by Newton's law of cooling as,

$$Q_{conv} = hA_s(T_S - T_\infty),$$

Radiation is expressed by Stefan-Boltzman law as,

$$Q_{rad} = \varepsilon A_s \sigma\left(T_S^4 - T_{sky}^4\right)$$

$$T_{sky} = 0.0552\ T_\infty^{1.5}$$

The thermal resistance for the different heat transfer modes of conduction , convection and radiation can be expressed by

$$R_{th,cond} = \frac{L1}{k1A} + \frac{L2}{k2A} + \frac{L3}{k3A}$$

$$R_{th,conv} = \frac{1}{h}$$

$$R_{th,rad} = \frac{(T_S + T_{sky})(T_S^2 + T_{sky}^2)}{h_{rad}A_s}$$

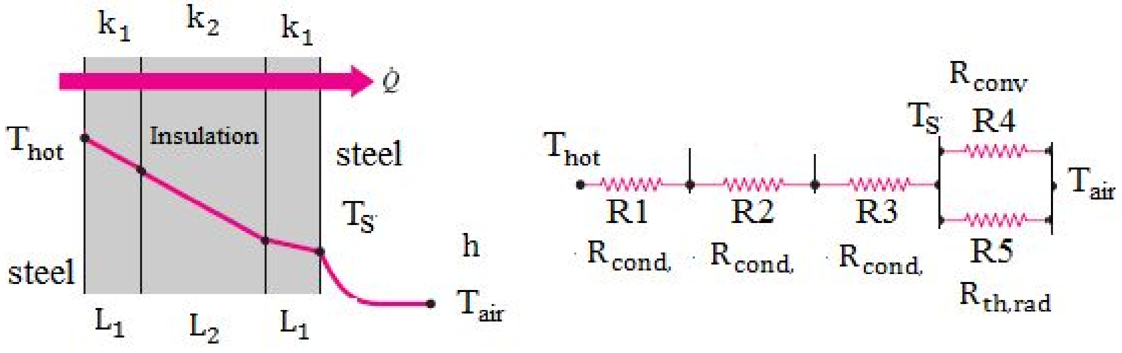


Figure 7 Thermal resistance representation to the heat transfer through the door

In order to represent the mechanical behavior of the door, the door is treated as a cantilever beam fixed at the top with the outside frame and free at the bottom as shown earlier in figure 1. The maximum displacement takes place at the free end due to thermal and hydraulic loads. The maximum displacement can be computed as:

$$d_{max} = \frac{L^2}{2}\frac{\alpha(T_{hot} - T_S)}{(L_1 + L_2 + L_3)}$$

Where

d_{max} is the maximum deflection, (m)

L is the door length, (m)

α is the thermal expansion, (1/°C)

T_1 , T_2 are the unexposed and exposed surfaces temperature respectively, (^{o}C)

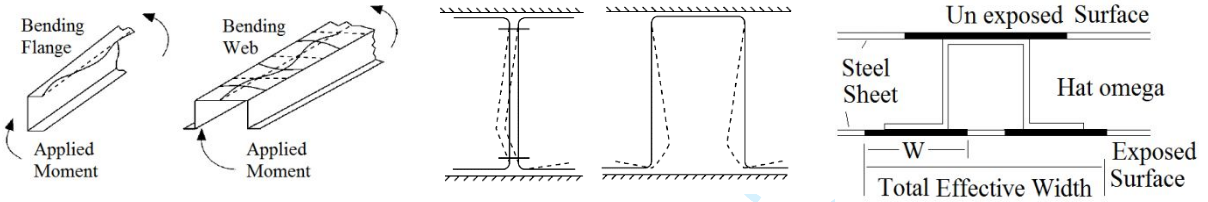
L_1, L_2 and L_3 are the inner steel sheet, insulation and outer steel sheet thicknesses respectively, (m)

3.2 Structural analysis

Fire door internal stiffeners cross section shape selection depending on:

1. Facility of manufacturing, fabrication and erection.
2. Resistance of thermal stresses of heating and sudden cooling.
3. Mechanical force of pressurized water jet stream.

For thin walled element, the width-to-thickness ratios of individual elements are usually large. As a result, these thin elements buckle locally at a stress level lower than the yield point of steel where they are subject to compression in flexural bending fig. 8. Therefore, for the selection of such thin-walled sections, local buckling and post buckling strength of thin elements have often been the major selection considerations. In addition, shear buckling, and web crippling should also be considered in the selection cross section.



(a) (b) (c)

Figure 8 Local buckling of compression in flexural bending for beam element (a) stiffeners alone (b) stiffeners assembled with door sheet behaviors (c) door sheet total effective width

The selected sections from shapes of cold-formed (thin walled sections) steel structural members of fire door internal stiffeners are:

1. Double S (not included in library for thin walled element)
2. Double C
3. Hat omega stiffeners

However the double S steel is not a standard recognized as a cold formed steel structure member in real life, it was selected referring to its ease of assembly with the door sheet faces. The double C was selected for its superiority on the I, H, C channel and double Z sections. The hat omega cross section, after assembly with door sheets, is treated as a box cross section. Also, it provides a total effective width larger than that of other shapes. This leads to high resistivity to all forces, buckling and torsion compared with other sections due to its enhancement in the total effective width.

The cross sections are subjected to different types of stresses, the elastic local buckling stress, $\sigma_{cr},$ and stress for yield moment M_n, which computed as follows,

$$\sigma_{cr} = \frac{k_C \pi^2 E}{12\left(1 - \upsilon_e^2\right)} (t/w)^2$$

$$w = 2.52 t \sqrt{E/F_y}$$

$$M_n = S_e F_y, \; S_e = I_x / y_{c.g}$$

Where

k_C=local buckling coefficient,

E= modulus of elasticity of steel, (N/m^2)

t =web thickness, (m)

w= sheet effective width, (m)

υ_e= Poisson's ratio

S_e = elastic section modulus, (m^3)

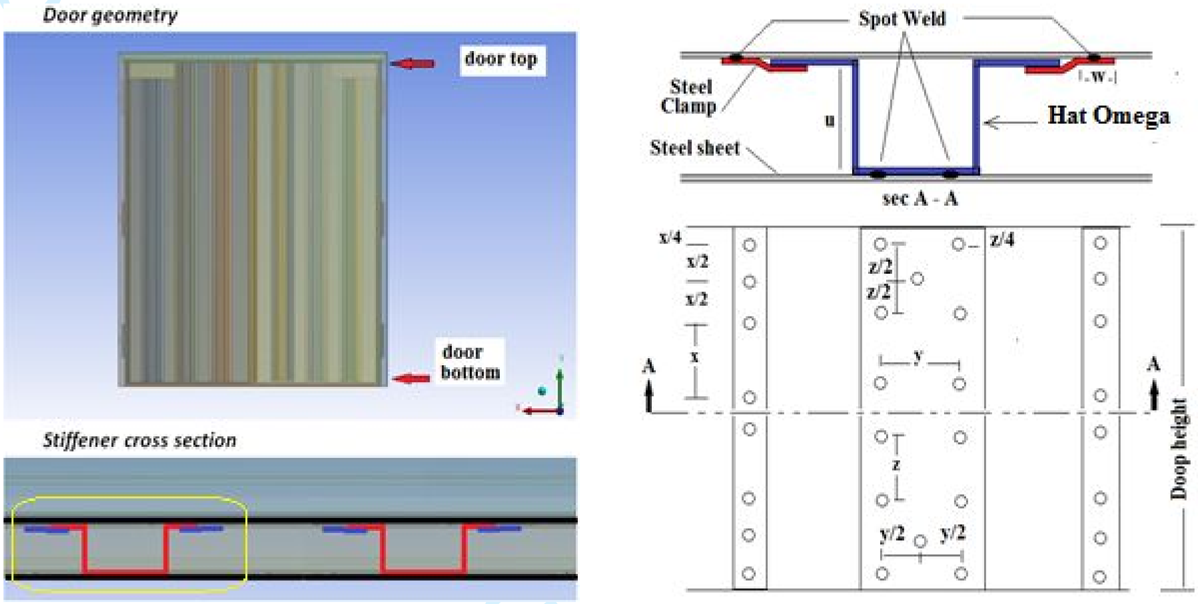
F_y = design yeild stress, (N/m^2)

I_x = second moment of eniritia of the full section about its own centroidal axis parallel to the ellement to be stiffined (door sheet), (m^4)

$y_{c.g}$ = section center of gravity, (m)

3.3 welding calculations

In the real life of fabrication of steel structure and especially for thin walled elements, the welding method of low heat input is preferred to avoid the residual stresses and thermal deformation after welding. So, the Resistance Spot Welding (RSW) is used in assembly of the door sheets with the internal stiffeners. Firstly, the hat omega web was welded with the unexposed steel sheet surface. Secondly, a two small z section steel clamps were welded using (RSW) with the exposed steel sheet. Finally, after filling gaps between stiffeners with insulation rips, the hat omega's flanges were planned to slide inside the steel clamps to build the complete door leaf product as shown in figure 9.



(a) (b)

Figure 9 overview internal door structure (a) welding map for the hat omega cross section assembly with the door sheets (b)

The American institute of steel construction AISC is representing a standard code in steel structure design and welding factor of safety calculation. Because it simplify, as much as possible, expressions for experts use of safety coefficients to ensure reasonable margins of safety, it has been used in the design of RSW. The design of RSW depended on the direct shear or tear stress. Design stress is the maximum value of τ /η or σ_t /η, Where η is the coefficient of the spot weld joint are due to shear failure, η=0.65 and due to tearing failure, η=0.5.

$$\tau = \frac{4F}{n\pi d^2} \quad , \quad \sigma_t = \frac{F}{n\pi dt}$$

Where,

τ is the allowable shear stress, (N/m^2)

σ_t is the allowable tearing stress, (N/m^2)

d is the spot weld diameter, (m)

n is the number of spot weld

t is the thickness of the plate to be spot welded, (m)

The current design was based on direct shear stress. The welding process is an important factor in the test setup to avoid the mislead in thermal behavior while treating the door leaf as one unit. The welding procedure specifications (WPS) are described in table 1.

Table 1 WPS for the fire door assembly

Test number: one / two Welding Process: RSW	Joint Type : fillet (overlap) Filler metals : None
Material Spec. : DIN 17100 Type or Grade : St. 37-3N Thickness : 1.5 mm	Current : AC Transfer Mode: short- circuiting Welding Position : 1G
Postweld heat treatment : None	Preheat : None
Shielding : None	Interpass temperature : None

4. Numerical Modeling and Simulations

4.1 Problem Statement and assumption

The door is constructed form layers of metal sheets associated with upper, sides and intermediate supports and filling insulator. The swinging type fire door is constructed from active leaf and inactive leaf. The current study covered the 3D fire door geometric model and its simulations for heating due to fire and cooling with water jet stream. The simulations were performed with ANSYS 19. The numerical modelling of the prescribed fire test involves both thermal and mechanical analysis. Consequently, the thermal and mechanical analyses are considered as uncoupled. So the resulted temperature field from the thermal analysis is considered as input for the structure analysis.

Indeed, the current study used an experimental data provided by the manufacturing company RTIC (Radwan for Trading & Industry Company). The experimental results included the temperature field and deflections of the door which were used to validate the simulating software setup. The setup included the boundary, initial conditions, number of cells and number of nodes. Then after validation for the computational model, it was able to predict the deflection in variety of different internal stiffeners designs available for other door heights. Subsequently, the computational model was used to simulate other prescribed cases. The results for different cases were then compared to achieve the specified safety behaviour of the door according to ANSI/UL 10C standards. The most promising design was then selected which have minimum deflection and maximum strength to withstand against the heating and sudden cooling with the applied water jet pressure.

4.2 Model geometry construction

The outer door edges were fixed to the frame at the sides with hinges. The gap between the door leafs at the meeting edge was monitored during the simulations to predict the maximum deflection. Regarding the FEM simulation, we are used European codes, which include safety factors allow design values to be obtained from characteristic values. On the other hand, the American approach does not clearly highlight the transition between characteristic and design values. The holding frame was considered rigid frame during the simulations according to Eurocode 1 [20]. According to National Fire Protection Association (NFBA 80) standards, the pair swinging-type fire door with 2.2 m length should have 3 hinges. The filling insulator has not provided any strength to the door from structure point of view. The three geometric models were constructed for the door with various longitudinal stiffener. The stiffeners have three different cross sections, double S, double C back to back and hat omega. The stiffener cross sections considered in the geometric models are presented in fig. 10.

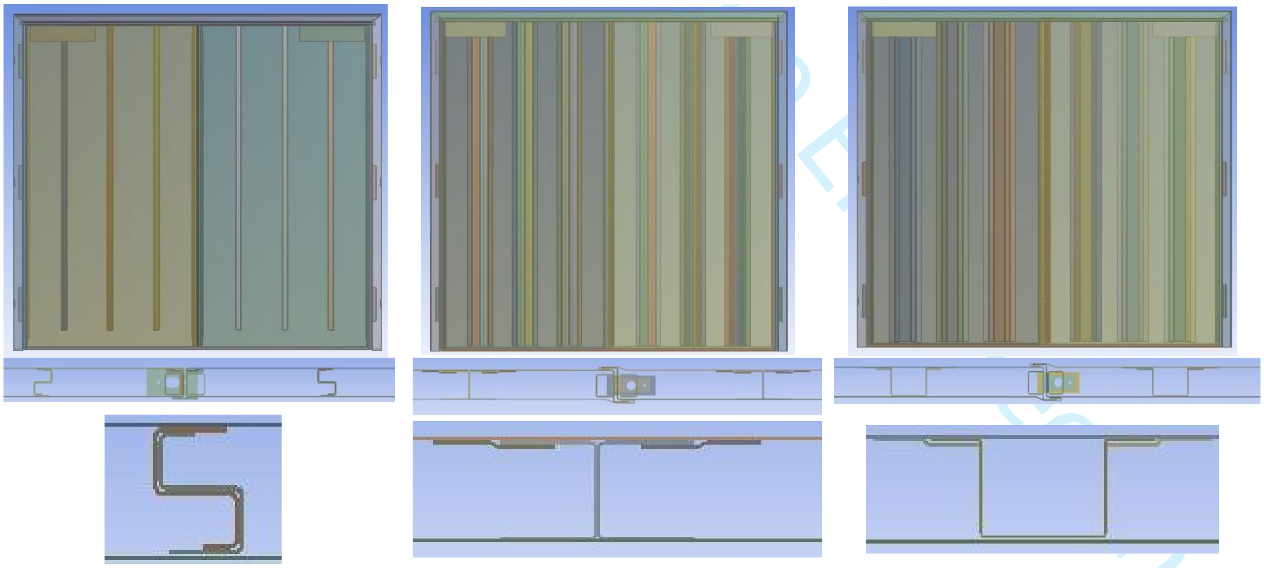

(a) (b) (c)

Figure 10 Door layout with longitudinal stiffener; (a) double S, (b) double CC back to back and (c) hat omega Ω cross sections

4.3 Boundary Conditions, Grid and computational domain

A numerical modeling of the whole geometry was developed through the FEM. The surfaces shell were modeled as steel plates while the insulation is modeled as solid elements. The filler insulation inside the door is mineral wool. The material properties, initial and boundary conditions were settled to compute the deformation under high temperature. Figure 11 presents the 3D geometric model. The heating specifications and boundary conditions have simulated the experimental case. The face subjected to heat form the furnace has initial temperature of 25 ^{o}C and heated up to 1000 ^{o}C. The convection heat transfer coefficient equal 25 W/m^{2}.C was considered for the exposed side and 10 W/m^{2}. C was considered for the unexposed side. The insulation and frame thermal properties are listed in table 2. The frame thermo-mechanical properties are obtained from [21], considering the temperature dependence for the Young's modulus and the yield stress, while the insulation properties are obtained from [22]. Subsequently the simulation was conducted to the cooling process using water jet stream with 4 bars pressurized water subjected to the exposed surface until cool down.

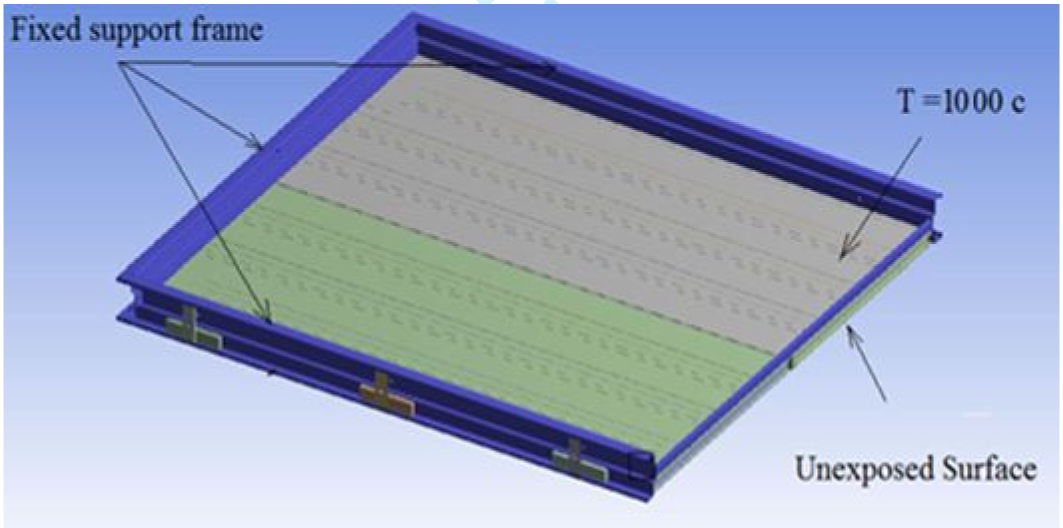


Figure 11 Door layout with applied boundary conditions

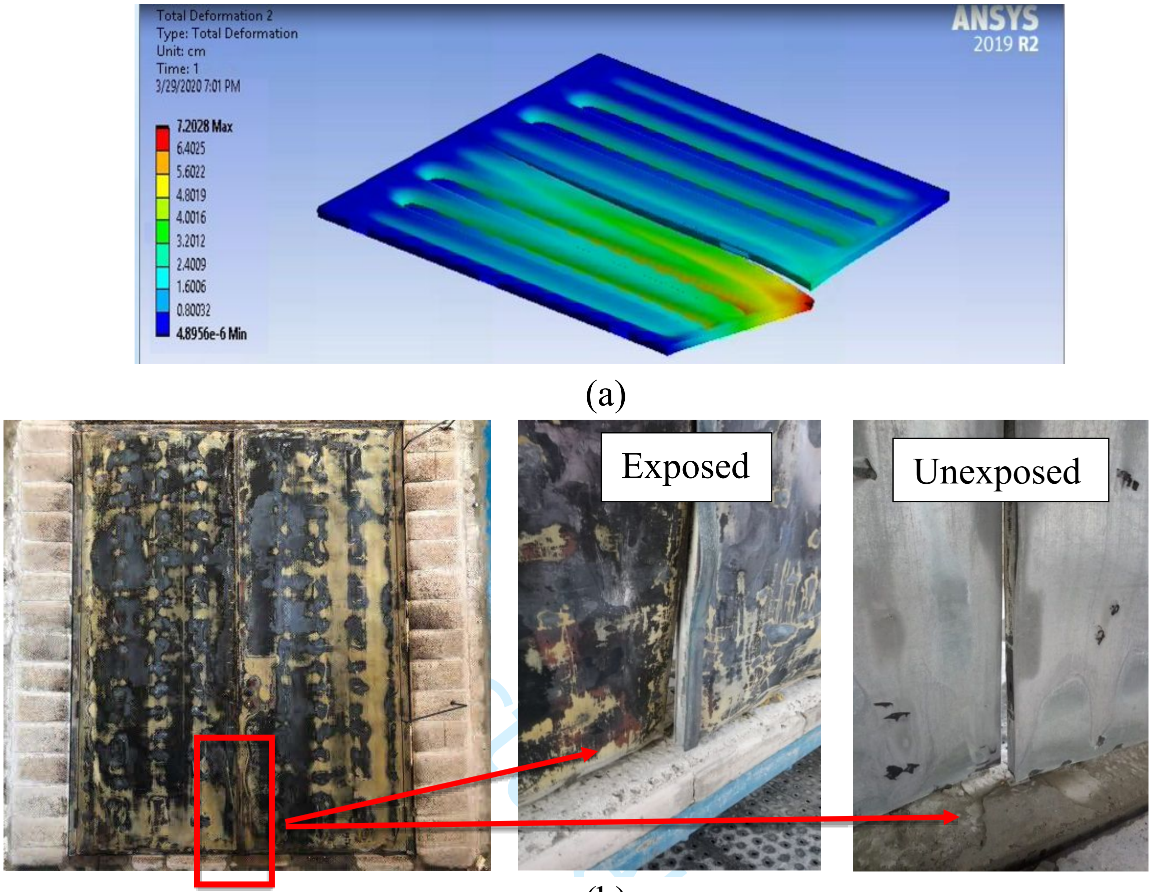
Finite element analysis was conducted using suitable computational grid. The grid and computational domain used in the simulations consists of number of nodes of 260E3 to 335E3 for the 2.2 m and 3m door lengths respectively. The number of elements within the computational domain varied from 87 E 3 to 142 E 3 elements for the 2.2 m and 3m door lengths respectively. The skewness and orthology was kept in order of 0.73 and 0.27 respectively. The element quality within the grid was in order of 0.3. The input for the FE model was the temperature field distribution resulted from the heating process. The final temperature obtained from the heating simulation showed good agreement with the measured values.

Table 2 Density and thermal conductivity versus temperature

Temperature (°C)	Density (kg/m^3)		Conductivity (J/m/°C/s)	
	steel	Rockwool	Steel	Rockwool
0	7900	100	45.9	0.035
100	7880	100	44.8	0.046
300	7790	100	41.4	0.075
600	7660	100	33.6	0.16
800	7560	100	28.7	0.26
1000	7370	100	28.6	0.44

4.4 Validation of numerical model

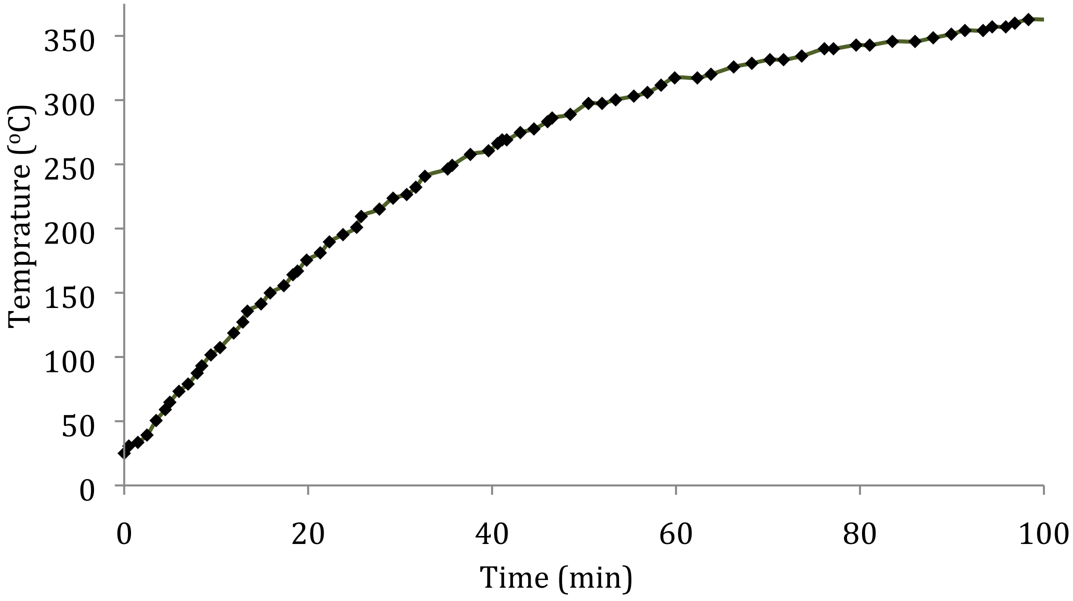
Obviously, in order to validate the numerical model, the numerical simulations were conducted for a swinging-type fire door has 2.2 m length and 2.2 m width. Where the internal construction of the hollow-metal steel door contained three longitudinal double S stiffeners per each leaf as shown in fig. 10 (a). The numerical results indicated a maximum deflection due to thermal stresses and suddenly cooling with the 4 bar water jet stream equals 7.2028 cm which is with excellent agreement with experimental value equals 7.25 with error 0.65%. Figure 12 provides the overall view for both computational FEM model and actual experimental measuring test for both exposed and unexposed door surfaces. On the other hand, fig. 13 shows the temperature trend for unexposed surface from zero time to 90 min obtained from FEM simulations and measured using 8 individual thermocouple temperature. The surface average value obtained by FEM is 365.55 ^{o}C after 90 minutes from heat starting which closely agreed with the average measured value obtained from the 8 thermocouple after the same time period.



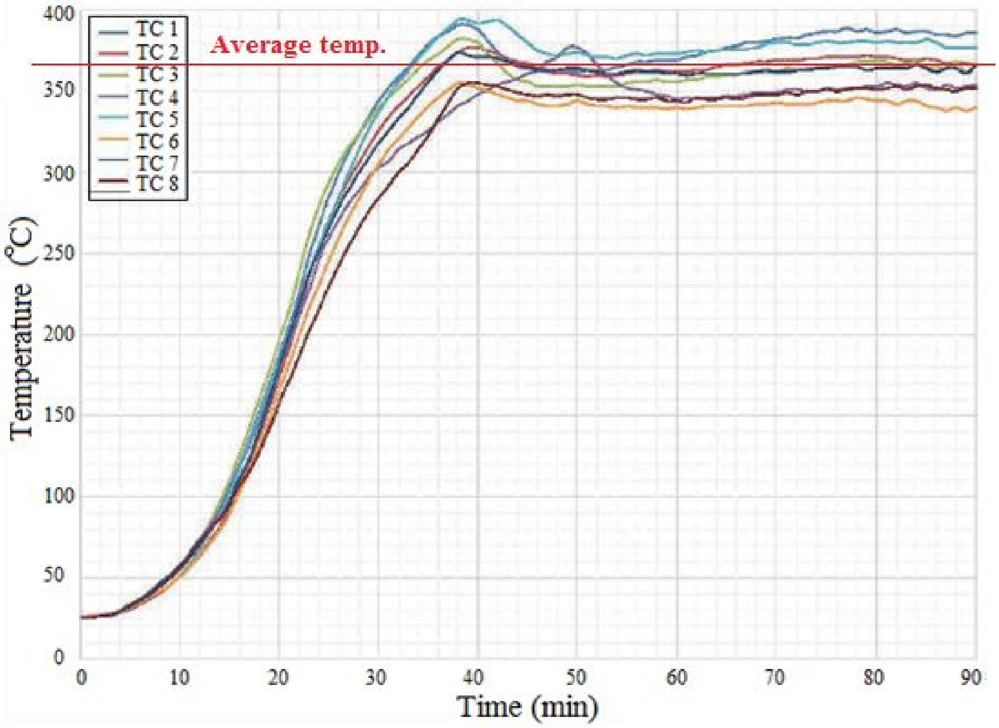
(a)

(b)

Figure 12 3D door deflection using (a) FEM (b) experimental



(a)



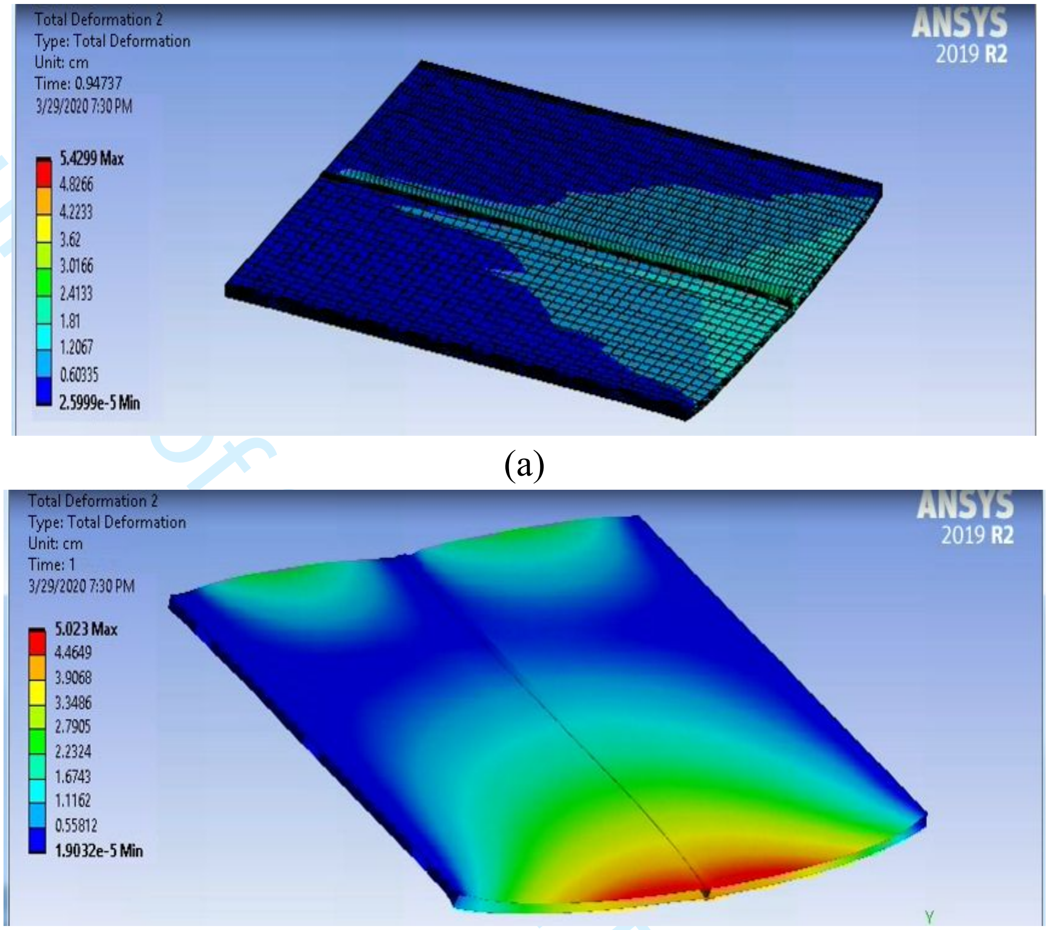
(b)

Figure 13 temperature trend for unexposed surface (a) obtained from FEM simulations (b) Measured individual 8 thermocouples temperature

5. Results and Discussion

5.1 Deflection of fire door with 2.2 m length

A pair swinging-type fire door assembly of longitudinal hollow-metal steel with double c back to back and hat omega cross sections are shown in fig. 10 (b) and fig. 10 (c) respectively. The numerical simulations were performed at applied door's surface pressure of 4 bar and with temperature 1000 ^{o}C subjected to sudden cooling. The maximum door deflection under thermal stress and sudden cooling has reached 5.4299 cm and 5.0230 cm for the double C back to back and hat omega stiffener cross sections. Figures 14 (a) and (b) show the total deformation contour for the 2.2 m door length with different stiffened cross section. As inferred from the figures the maximum deflection occurs at the lower portion of the door leaf.



(a)

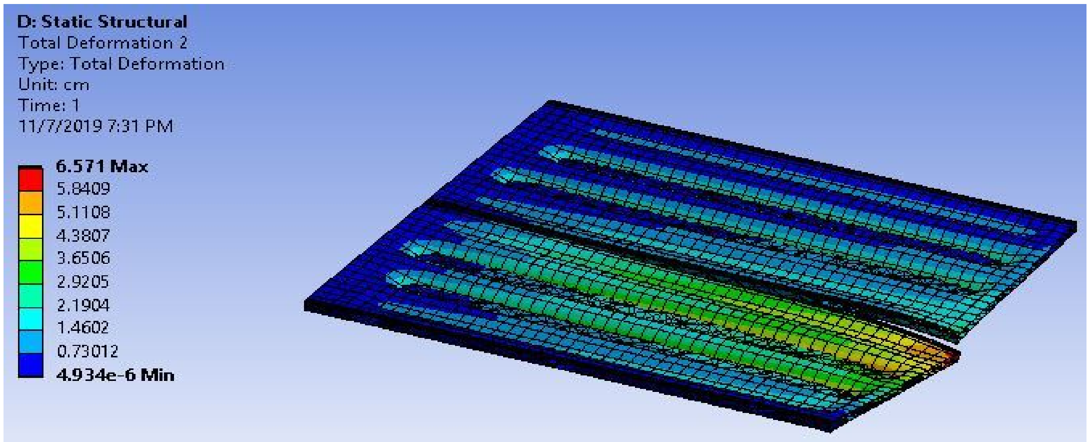
(b)

Figure 14 total deformation contours for the 2.2 m door length with double c back to back (a) and omega (b) stiffened cross sections.

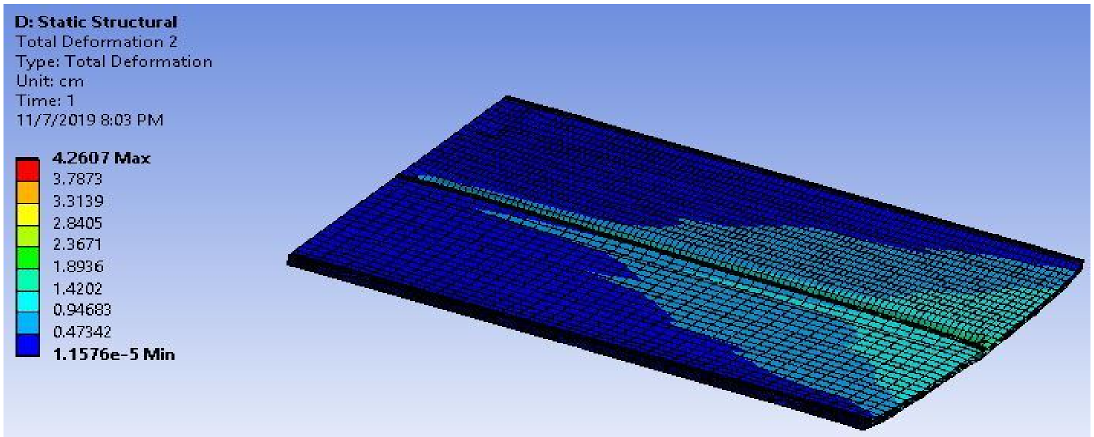
5.2 Door length of 3 m different stiffened cross section

For the purpose of design improvement the simulation was performed for a 3m door length. The extent in door length has accompanying with increase in hinge number according to National Fire Protection Association (NFBA 80) standards. This worked on reducing the deformation at the most affected zone. A pair swinging-type fire door assembly of longitudinal hollow-metal steel with double S, double C back to back and hat omega cross sections are shown in fig. 10. The numerical simulations were performed with the same conditions applied for the door with length 2.2 m. The maximum door deflection under thermal stress and sudden coolant has reached 6.57 cm for the double S stiffener cross section while the maximum door deflection has reached 4.26 cm for the double C back to back stiffener cross section. The lowest deflection was achieved for the hat omega stiffener cross section which equal to 2.1

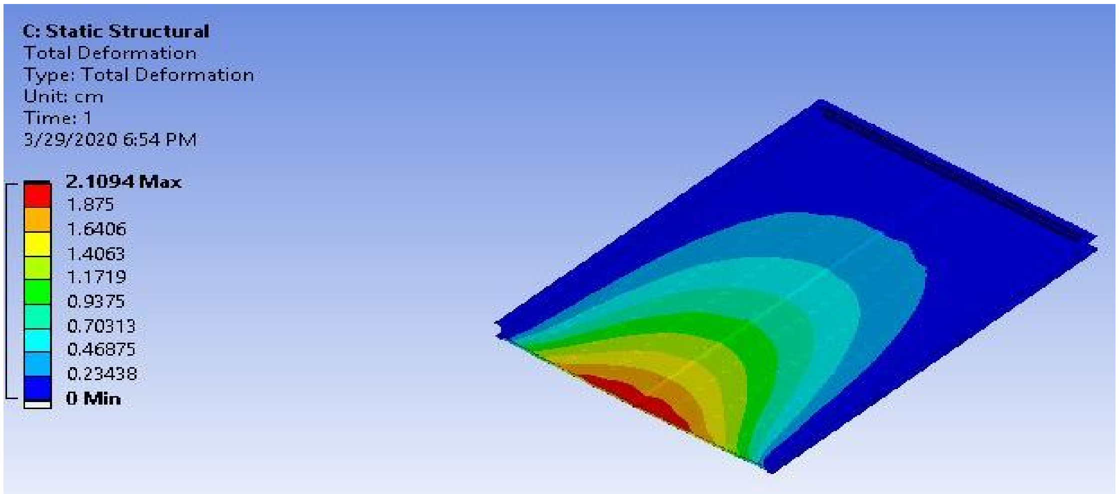
cm. Figures 15 (a), (b) and (c) show the total deformation contour for the 3 m door length with different stiffener cross sections.



(a)



(b)

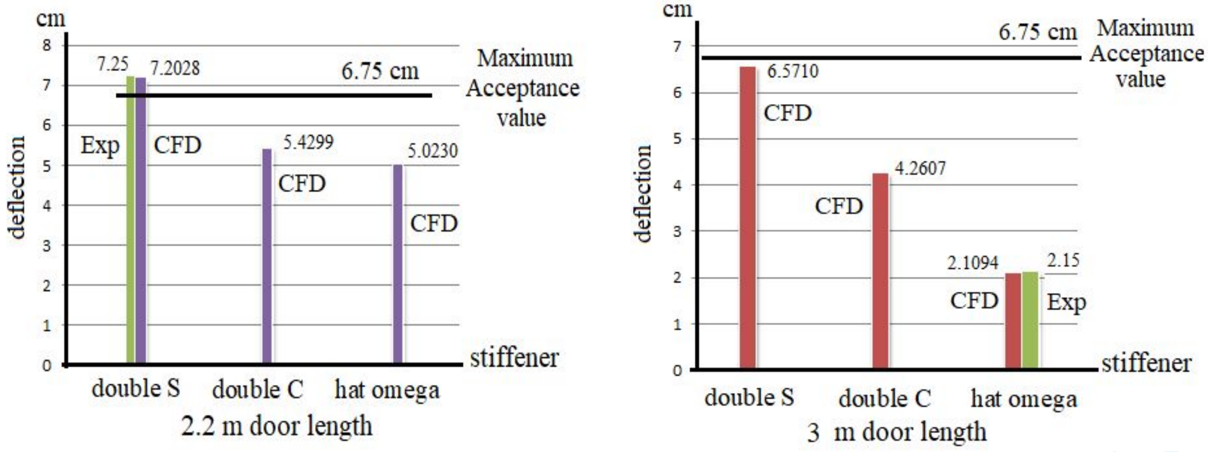


(c)

Figure 15 total deformation contours for the 3 m door length with double S (a), double c back to back (b) and hat omega (c) stiffened cross sections.

Figure 16 shows a comparison between the numerical computed door maximum deflection at different door length of 2.2 m fig. 16 (a) and 3 m fig. 16 (b) for the all selected internal stiffeners. On the other hand, it shows also two experimental tests measurements for the 2.2 m door length with double S stiffener fig. 16 (a) and for the 3 m door length with hat omega stiffener fig. 16 (b). As inferred from the figure the numerical computations results agreed very closely to the experimental test measurements for both 2.2 m and 3 m door lengths with double S and hat omega stiffener cross section respectively. The acceptance values for the maximum deflection are 6.75 cm. The FEM succeeded to accurately predict the door deflections for all the door stiffener cross section type and this illustrated clearly in two validated cases with experimental tests. Finally, the hat omega was found to be the best internal stiffener can be used in manufacturing of fire door.

Table 3 summarizes the computed and measured maximum deflections at the same conditions. According to the allowable limits of acceptance, the door with stiffener double S and length of 2.2 m is failed in the computational and actual test. While the door with suggested hat omega and length 2.2 m and 3 m are computationally succeeded. The door of hat omega and 3 meter length is validated with an experimental test successfully giving the lowest deflection value and then confirmed to go on in the manufacturing production line.



(a) (b)

Figure 16 a comparison between the numerical computed door maximum deflection experimental and tests measurements

Table 3 Summary of experimental and numerical simulation including different stiffener shapes

Stiffener cross section	Door Size (width * length)	Finite element results Max. deflection at 4 bar & 1000 ºC (cm)	Experimental results max. deflection (cm) per max. accepted limit (cm)	Error % between the CFD and experimental
Double SS	2.2 * 2.2 m^2	7.2028	7.25/6.75	0.651 %
Double CC	2.2 * 2.2 m^2	5.4299	---	---
Omega Ω	2.2 * 2.2 m^2	5.0230	---	---
Double SS	2.2 * 3 m^2	6.5710	---	---
Double CC	2.2 * 3 m^2	4.2607	---	---
Omega Ω	2.2 * 3 m^2	2.1094	2.15/6.75	1.888 %

6. Conclusion

The aim of this work was to investigate and propose new internal configuration for fire doors. A test rig was developed to test fire door under a fixed internal temperature of 1000 C and trying to cool in using a water jet at 4 bars. A numerical model was created to simulate the cooling process and the associated deformation. The work included two experimental fire door tests according to standard fire test (ANSI/UL 10C – Positive Pressure of Fire Tests of Door Assemblies), for door 2.2 m height with double S stiffeners and 3 m height with hat omega stiffeners. It also includes six simulation models to investigate three internal configurations of double S, double C and hat omega for door heights of 2.2 and 3 m. The results can be summarised as follow:

1. The experimental fire door test measurements for the 2.2 m door height with double S internal stiffeners indicated a maximum deflection of 7.25 cm which exceeded the acceptance limit of 6.75 cm.
2. The FEM has the ability of predicting the thermal response of the fire door during heating for different cases when specifying the realistic boundary conditions.
3. The FEM validation with the first experimental test results assured the accurate model setup.
4. The FEM results indicated the maximum deflections for door height 2.2 m are 7.2028, 5.4299 and 5.0230 at stiffeners shapes of double S, double C and hat omega Ω respectively.

5. The maximum deflections for door height 3 m are 6.5710, 4.2607 and 2.1094 at stiffeners shapes of double S, double C and hat omega Ω respectively.
6. Comparing with the experimental test values, the error percentage in maximum deflection predicted with FEM in the first test was 0.65% for the door height 2.2 m with double S stiffeners.
7. The temperature trend for the unexposed surface which was obtained by FEM is very similar to the experimental value of 365 °C after 1.5 hours of test.
8. The FEM and experimental test results indicated that the door with double S stiffeners has a highest deflection value.
9. The FEM and experimental test results indicated that the door with hat omega stiffeners has a lowest deflection value.
10. According to minimum deflection and ease of assemble criteria, the hat omega stiffener with using steel clamps technique is the recommended by authors for fire door's manufacturer for any door size.

The practical significance of the present work is crucial in the fire safety measurements and needs to be taken in consideration in real life applications.

Acknowledgement

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Conflict of interest

The authors declare that they have no conflict of interest

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Author response to reviewer's comments

The authors would like to extend their sincere thanks and gratitude to the reviewers for the very valuable comments.

Reviewer: 1

Pg 1 - line 45/46: "so that it represents the main element for safety" mention the reference and explain further why do you think this is the main form of security.

"A reference was made that fire doors represent the first and main line of defense for the safety of people in public buildings [by adding 2 references and clarifying the importance of fire doors in buildings]"

Pg 2 - line 40-43: "Several researchers have studied the leakage from fire door in different manner Cooper et al. [1] have performed numerical and experimental studies considering the leakage from the fire door" - restructure this sentence.

"The senesce was restructured"

Pg 2 - line 46: Isnt it ISO and not IS0 (with a zero)?

"Corrected"

Pg 2 - Lines 53/54: "They demonstrated that 3 mm gap for obstructing smoke spread."
does this cause what? what was the demo? explain better.

"The purpose was to summarize the most important results of previous studies to find out the safe criterion for the gap, which ensures that the spread of smoke is obstructed. (The meaning has been changed with a clearer sentence)"

Pg 3/4/5 (and mainly Pg 4) with very big paragraphs, restructure. The agreement between the sentences is impaired in many points, reassess the writing

"Restructure for the very big paragraphs was conducted and reassessing the writing was conducted."

General Comments:

1) Evaluate the use of European standardization mixed with American standardization (why not use only one of them? Justify)

"The American institute of steel construction AISC is representing a standard code in steel structure design and welding factor of safety calculation. Because it simplify, as much as possible, expressions for experts use of safety coefficients to ensure reasonable margins of safety, it has been used in the design of RSW. The door is exposed to heat and thermal loads, so it was necessary to use an accurate code that includes safety factors that take into account the thermal loads that are difficult to calculate. Regarding the FEM simulation and the standard time-temperature relationship of the furnace, we are used European codes, which include safety factors allow design values to be obtained from characteristic values. On the other hand, the American approach does not clearly highlight the transition between characteristic and design values."

The aforementioned clarification has been added on pages 6, 13, 15, divided according to the application (with under line with red colored text)

2) Are the fire exposure temperatures of the doors measured on the doors or the it referes to ambient temperature? Justify and report implications.

"The fire exposure temperatures of the doors measured on the doors surface directly. It was necessary to measure the temperatures on the door surface which unexposed to the flame in order to know the temperature of the surface facing people (the exterior), which is important in:
1- Measuring the rate of heat transferred skip through the door towards the people.
2- Using it for the purposes of validation the code used in the FEM simulation"

3) The study is interesting and pertinent, but the writing form as a whole needs to be improved. Too many sentences are without proper unctuation, too many long paragraphs, a lot of information without a good link between them. Carefully analyze these writting points

"The writing format as a whole has been improved in many paragraphs. Long paragraphs were shortened and links were added between information and accurate analysis as well"

Reviewer: 2

Comments to the Author
This paper provides an experimental and numerical investigation of the fire door design. The authors discuss the influence of using three types of internal stiffeners (double S, double C and hat omega stiffeners) on the deformation of the fire door. The article contains a good topic.
However, a "Major modification" is recommended:
1. A revision of the abstract with a clear objective and outcome of the paper is recommended.
"The abstract has been thoroughly reviewed and clarifies the main objective and important findings"

2. The introduction should include updated references and related studies
"Despite the lack of references in this field of scientific research, a new reference (No. 1) has been added, with the renumbering again for all references."

3. The methodology section needs to be enhanced.
"Methodology was enhanced and rearranged for the governing equation section, structural analysis, and welding calculations"

4. Many statements need to be rephrased. The structure and clarity of English need improvement.
"Many statements was rephrased and the structure and clariy were improved_"

5. The conclusion section needs to be concentrated on the current study.
"The conclusion was revised to be concerned on the current study"