Thermo-mechanical Analysis of Fire Doors Subjected to a Fire Endurance Test

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ABSTRACT: Fires doors are subjected to standard fire tests as a means of evaluating fire resistance. In this study, the thermal and mechanical response of steel double fire doors exposed to high temperatures was modeled using finite element software. The model included the necessary complexity of the product and test setup along with the temperature dependency of the constituent materials. For the thermal solution, a transient analysis was carried out while for the mechanical solution, it was found that a nonlinear steady state analysis was sufficient to capture the qualitative behavior of the fire doors seen during the test. The challenges of validating a numerical model with the limited data available from the standard fire test are described.

KEY WORDS: fire door, fire resistance, fire modeling, finite element, furnace test.

INTRODUCTION

IN THE DESIGN of buildings and structures against fire, the prevailing practice involves the selection of components such as doors, walls, and floors with individual fire resistance ratings based on standard fire tests [1]. In these tests, the component is placed within a specially constructed furnace, which delivers heat flux following a prescribed time-temperature curve [2]. The resistance rating stated in units of time provides a relative measure of the component's ability to support loads and limit heat transmission [3]. Many experimental and numerical investigations have been carried out studying various aspects of the standard fire resistance test.

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Thomson and Preston [4] examined the variations in heating rates of furnaces considering differences in furnace construction, fuel, and mode of operation. The variation seen in some of these parameters significantly affected the heating rate, which, in turn, impacted the assigned fire resistance time or rating. Sultan [5] compared the measured fire exposures of test specimens in a furnace controlled by two different measurement devices: shielded thermocouples and plate thermometers. He found that the discrepancy in fire exposure occurred in the initial stages of the testing (8 minutes) with specimens in a furnace controlled by the shielded thermocouples receiving much more heat flux in the initial fire exposure. Chow and Chan [6] reported results of a finite element (FE) thermal analysis of a fire resistance test. FE results were compared with data from test specimens constructed from different materials. They attributed the limited success of the analysis in matching experimental data to the 'phase transitions' occurring in the wood and concrete specimens. A great deal of work focusing on the fire resistance of various building components covering a range of materials through physical testing and numerical modeling has been conducted of which a few are cited here [7–9,10,11].

As building designers push the innovation boundaries, a more customized approach to ensuring fire safety in structures is being pursued. This approach is called performance-based fire safety engineering [12,13]. With this approach, the fire safety analysis and design are customized for a particular structure and its expected fire exposure scenarios. Some large-scale experiments, such as the Cardington building fire [14], and numerical studies on buildings and portion of buildings have been carried out [15–17] further to the knowledge on the response of structures to actual fires. However, full-scale experiments are very costly and time consuming and are likely to play a limited role in the progress of the performance-based approach. Instead, numerical modeling, such as FE-based programs, will very likely be extremely important tools in assessing the fire performance of a structure. Still, more work is necessary to validate models that can predict the complex behavior of a structure subjected to fire [18].

As many standard tests on fire resistance are being carried out regularly, these tests provide a worthwhile opportunity to lay the groundwork for validating numerical engineering programs and expanding the information gathered from these tests will create a strong foundation for the performance-based engineering approach to fire hazards [19]. In this study, results from a standard fire endurance test and from a numerical model are compared using the commercial FE code ANSYS v11.0 [20], applied to a pair of steel fire doors. The challenge of validating models with the typical setup for standard fire tests is described and recommendations for extracting more value from such tests are suggested. The ability to use numerical modeling programs to evaluate building component designs prior to, or in conjunction with, testing will at least streamline the costs and time associated with product development.

FIRE RESISTANCE OF FIRE DOORS

The presence of fire doors within a building is meant to resist the spread of fire from one part of a structure to another, with a secondary influence on the smoke and heat exposures to building occupants (Figure 1). As a means of evaluating such fire resistance, fire door assemblies are tested according to standards such as UL 10B [21]. For this standard test, there are two parts. The first part is referred to as the fire endurance test while the second part is called the hose stream test. This article focuses only on the performance of the fire door during the fire endurance portion of the test, which is described next. As part of the preparation for the test, the fire door along with

Figure 1. *Picture of typical double fire door showing hinges, lock, frame, and windows (not a test specimen) (The color version of this figure is available online).*

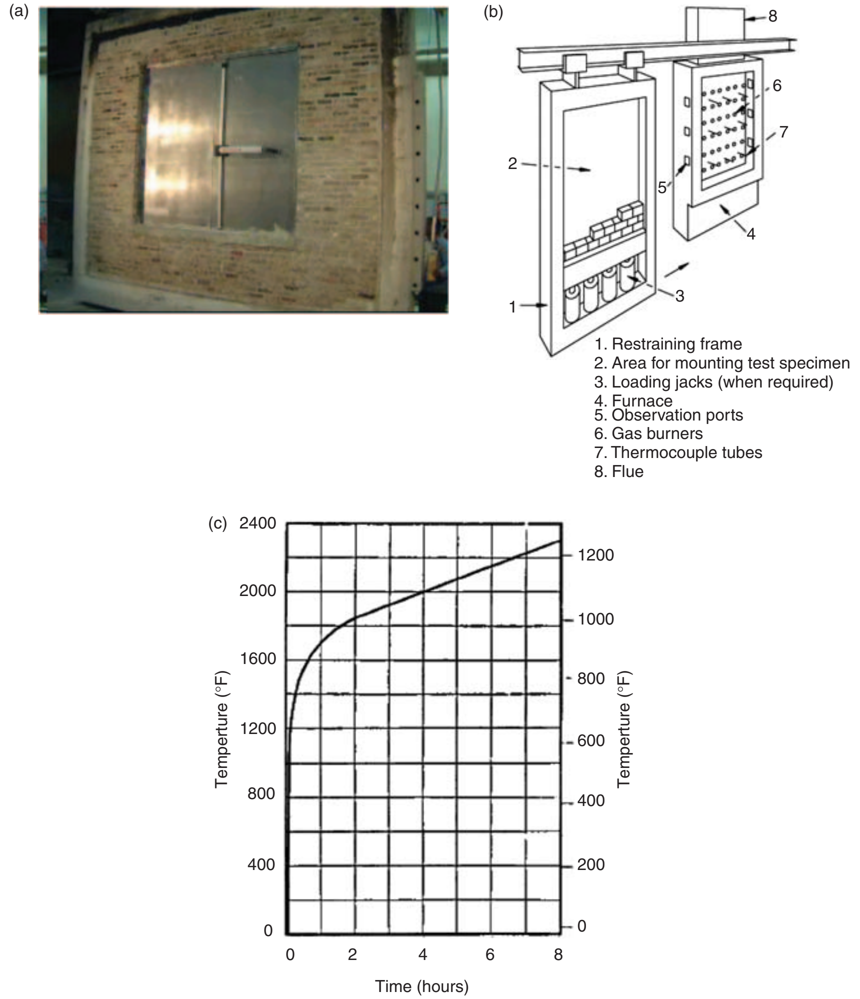

Figure 2. *(a) Picture of a fire door in restraining frame (not a test specimen); (b) Schematic of test and furnace setup; (c) Time-temperature curve from UL 10B standard (The color version of this figure is available online).*

supporting structure such as frame and walls are constructed according to specified instructions (Figure 2(a)). The door is part of a restraining frame (Figure 2(b)) that fits onto the furnace. With the assembly in place, the fire doors are subjected to a heat flux from gas burners (Figure 2(b)) based on a standard time-temperature curve shown in Figure 2(c). Some tests include a pressurized furnace to capture additional forces generated during a fire.

Further details on the test method are available in the [21]. The swinging fire door pair and frame assembly in this study were tested at the UL fire testing facilities in Northbrook, IL USA.

The conditions of acceptance for the UL 10B standard cover the movement of the door and flaming on the unexposed side. The steel fire door pair in this investigation was previously tested for 3 hours; however, it only achieved a 1 hour rating. The main reason for the fire doors not receiving a longer time rating was that the separation at the meeting edge of the doors had exceeded the conditions of compliance beyond 1 hour as stated in the standard. However, the frame retained its structural integrity throughout the 3 hours of the fire endurance test. During this test, thermocouple measurements on the unexposed side of the fire doors, simple manual deflection measurements at selected locations and visual observations were gathered, which will be compared with the predictions of the numerical model.

FINITE ELEMENT MODEL

To build a FE model of a fire door assembly, it is prudent to assess the necessary 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.

Fire doors generally consist of steel faces, steel stiffeners, and filler insulation material. The fire door in this study is a double door. The door without a lock handle is called the inactive leaf. It includes latching bolts that can lock the door into the frame at the top and bottom. During the test, the inactive leaf was latched to the frame. The other door with the lock handle is called the active leaf. The active leaf included the door lock, which was a latch bolt that engaged into the inactive leaf. The inner edges of the two doors facing each other are known as the meeting edge. The gap at the meeting edge was monitored during the test. In addition, fire resistance tests require inclusion of the frame and hinges that connect fire doors to the frame for an assessment of the fire performance of the entire fire door assembly. Some fire doors have windows and glazing. The fire door in this test did not include windows.

For this specific door design, observations, and measurements from the fire test were available and noted that the frame remained securely fastened to the wall. Therefore, the first assumption in building the model was to assume that the walls and frame were structurally rigid. This assumption very quickly narrowed the model to the fire doors only.

These doors are basically steel sheets and steel stiffeners (Figure 3). The stiffeners were connected to the front and back panels of the doors through

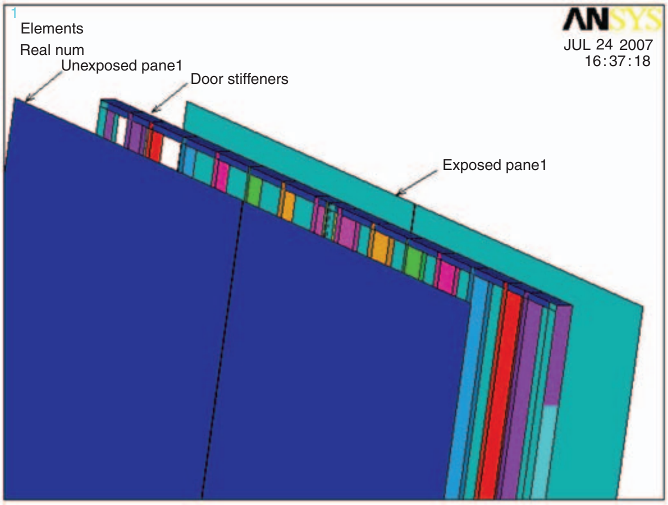

Figure 3. *Exploded view of FE model of fire doors (The color version of this figure is available online).*

spot welds. Another simplification was the modeling of the spot weld as rigid. In the model, at the location of each spot weld, a coincident node between the door panel and stiffener coupled the deformations for the structural analysis and allowed for perfect thermal contact in the thermal analysis. The upper and lower steel panels for each leaf were attached rigidly along the interface with the front and back panels of each leaf through spot welds (Figure 3). The additional hardware such as the hinges and lock were not modeled in full detail. For instance, for the hinges the bolts attaching the hinges to the doors and the frame were assumed to be rigid with only the rotations normally allowed by the hinges being modeled. The lock was modeled with a single block with a hole and a latch bolt. Finally, inside each door, a filler insulation material resides that acts as a thermal barrier to heat flux through the doors.

For the FE mesh, shell elements were chosen for both the thermal and structural analyses. These 2D elements are more computationally efficient than 3D elements and are applicable in cases, where the thickness of a component is much smaller than its other dimensions [22]. In ANSYS, for the thermal analysis SHELL57 elements were applied, while for the structural analysis SHELL181 elements were chosen. The door panels, stiffeners, and edge channels were all meshed using these shell elements, which have 4 nodes per element [20]. The latch bolts at the top and bottom of the inactive door were modeled with LINK33 elements for thermal

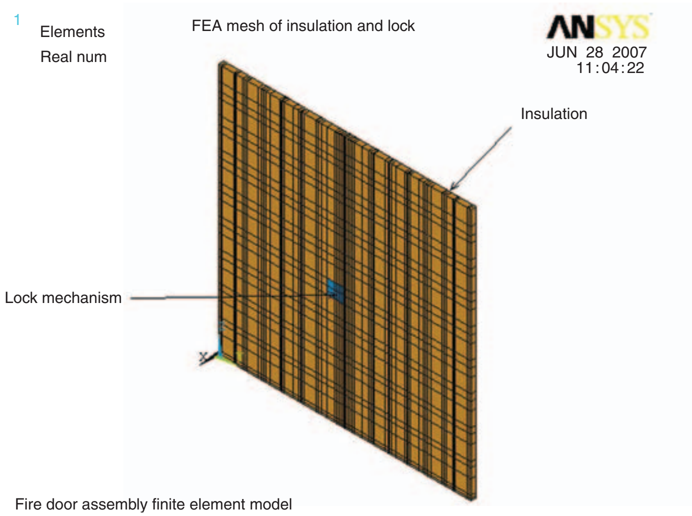

Figure 4. *Structural FE model showing lock and insulation (The color version of this figure is available online).*

analysis and BEAM4 elements for structural analysis (Figure 4). These elements have 2 nodes per element. For the insulation and lock mechanism, SOLID70 elements were chosen for the thermal analysis and SOLID45 elements for the structural analysis. Both elements contain 8 nodes. Except for the coincident nodes between the stiffeners and the door panels, no contact elements were included in this analysis.

For the thermal model, the panels facing the furnace were covered with SURF152 elements to include the radiation from the furnace.

MATERIAL PROPERTIES

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. Quite often manufacturers do not have such data and will not financially support the acquisition of such data. Therefore, it is very important to find suitable surrogate data that can capture these temperature dependencies.

For this fire door, the main material comprising the door panels and stiffeners was cold rolled steel. Compared to other materials comprising structural components and members, material property data for steel is readily available. For instance, the thermal properties for ASTM A36 steel were selected as it matched the steel used in the door with the following correlation showing the temperature dependency [23]:

$$k = -0.022T + 48\ \mathrm{W/(m\,K)}$$
$$c = 0.51T + 420\ \mathrm{J/(kg\,K)}$$
$$\rho = 7830\ \mathrm{kg/m^3}$$

where T is the temperature (°C), k is thermal conductivity and c is the specific heat. Another thermal parameter that was necessary for the analysis was the emissivity. Emissivity depends upon materials and their surface properties. Without any detailed information on the surface properties of the doors, the emissivity for steel was set to 1.0. The density for steel was assumed constant.

The mechanical properties of steel and their dependency on temperature were found from the following correlations [24]:

$$\alpha = (0.004T + 12) \times 10^{-6}\ \text{coefficient of thermal expansion (m/(m K))}$$

where T is the temperature (°C). For the elastic modulus [24], we have the following polynomial equation

$$E(T) = e_0 + e_1 T + e_2 T^2 + e_3 T^3$$

where
$e_0 = 206.0$ GPa
$e_1 = -0.04326$ GPa/°C
$e_2 = -3.502 \times 10^{-5}$ GPa/(°C)^2
$e_3 = -6.592 \times 10^{-8}$ GPa/(°C)^3

and T is the temperature (°C). For the dimensionless Poisson's ratio [24] the following polynomial equation was found

$$\nu(T) = n_0 + n_1 T + n_2 T^2 + n_3 T^3 + n_4 T^4$$

where
$n_0 = 0.28737362$
$n_1 = 2.5302417 \times 10^{-5}$ (°C)$^{-1}$
$n_2 = 2.6333384 \times 10^{-8}$ (°C)$^{-2}$
$n_3 = -9.9419588 \times 10^{-11}$ (°C)$^{-3}$
$n_4 = 1.2617779 \times 10^{-13}$ (°C)$^{-4}$
where T is the temperature (°C).

The filler insulation material in the fire doors consisted of ceramic fibers. The manufacturer of the materials provided the material properties listed in Table 1.

One can see that the stiffness of the filler material is much less than the steel and so its contribution to the structural response will be negligible.

Finally, for the lock mechanism, the properties of Brass listed in Table 2 are used.

Table 1. Material properties of filler insulation as a function of temperature.

Temperature (°C)	
	Elastic modulus (GPa)
0.0–1100.0	1.E−06
	Density (Kg/m^3)
0.0–1100.0	128.00
	Conductivity (W/(m K))
20.000	0.22000E−01
400.00	0.90000E−01
800.00	0.16000
1000.0	0.20000
	Specific heat (J/(Kg K))
0.0–1100.0	0.11280E−02
	Poission's ratio (Dimensionless)
0.0–1100.0	0.10000E−01
	Coefficient of thermal expansion (m/(m K))
0.0–1100.0	0.10000E−06

Table 2. Properties of brass as a function of temperature [25].

Temperature (°C)	
	Elastic modulus (GPa)
0.0–1100.0	117
	Density (Kg/m^3)
0.0–1100.00	8800.0
	Conductivity (W/(m K))
0.0–1100.0	189.00
	Specific heat (J/(Kg K))
0.0–1100.0	376.90
	Poission's ratio (Dimensionless)
0.0–1100.00	0.30000
	Coefficient of thermal expansion (m/(m K))
0.0–1100.00	0.10200E−04

THERMAL AND STRUCTURAL FE ANALYSIS

In the real fire doors, the structural and thermal responses are coupled. However, even here, some decisions can be made, which will allow for simplifications in the computational effort. For coupled analyses, there are two options: one-way coupling and full coupling. In one-way coupling, the thermal response affects the structural response but not vice versa. In other words, as the door heats up, it deforms and bends. However, the bending and deforming of the doors does not change the temperatures within the doors. The temperature of the doors can only change by changing the heat source in the model, which follows the time-temperature curve described in the standard. This one-way coupling allows the solution of the thermal analysis to be completed first without consideration of the structural response. The structural analysis can be solved after reviewing and validating the thermal results [26].

In a fully coupled analysis, the bending and deformations of the door could possibly affect the thermal response. As such, a fully coupled analysis would require the solution of a thermal analysis and a structural analysis at each time step. The computational effort of the fully coupled analysis is significantly more.

As it was not expected that the deformations would significantly affect the temperatures within the fire doors, the one-way coupling approach was selected

Transient Thermal Analysis

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 necessary. 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.

In this model, the entire exposed side of the fire doors was assumed to receive uniform radiation heat flux with a view factor set to 1.0. The rate of heat radiation was simply calculated based on the time-temperature curve from Figure 1. In addition to radiation heat transfer, convection heat transfer was modeled on the exposed side of the door using the properties for air. The ambient temperature was set to follow the standard time-temperature curve while the natural convection film coefficient [27] was set to $5.7\,\mathrm{W/(m^2\,K)}$.

For unexposed side of the fire doors, only convection heat transfer was modeled using properties of air. The natural convection film coefficient

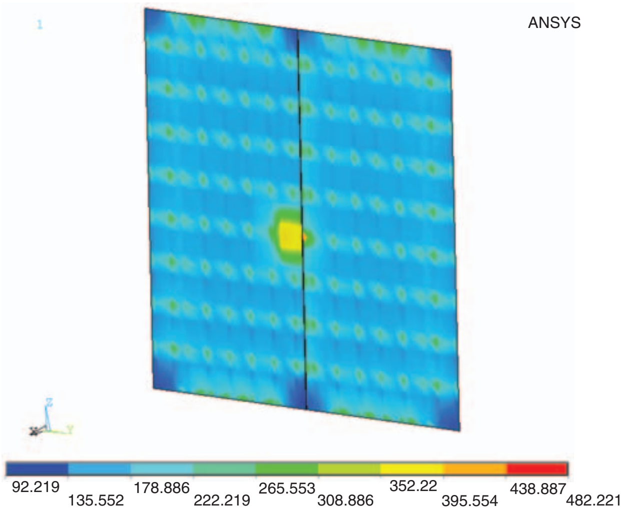

Figure 5. *Temperature (°C) contours at 15 minutes on unexposed side of fire doors (right door is inactive) (The color version of this figure is available online).*

was set to 5.7 W/(m^2 K), while the ambient temperature was set to 20°C. As the bulk of the heat transfer was expected to occur through the thickness of the fire door, another simplifying assumption was that the frame and supporting structure could be represented by adiabatic boundary conditions.

Figure 5 shows the temperature contours on the unexposed side of the fire doors at 15 minutes. The hot spot is at the lock, which is a solid brass piece. Some other hot spots are seen peppered throughout the door panels. These are indicators of the locations of the spot welds. The spots welds allow more readily for heat transfer through the stiffeners from the exposed side panel to the unexposed side panel. Observe that no deformations exist in this model as it only calculates the heat flux and temperature distribution.

Figure 6 shows the temperature contours at 15 minutes for the exposed panels of the fire doors. The lock shows the lowest temperature as it quickly dissipates heat into the ambient. However, heat builds up along vertical outlines of the stiffeners as time passes.

Next, results for 60 minutes are presented in Figures 7 and 8. For the unexposed side the lock remains the hot spot, but temperatures begin to rise near the panel edges on all sides. For the exposed side the door temperature tends towards uniformity. However, it is the temperature gradient especially from the exposed to unexposed side that governs the deflections that is seen in the fire doors.

As seen in Figures 5–8, numerical models provide detailed data on the response of the structure for review. However, in standard fire tests,

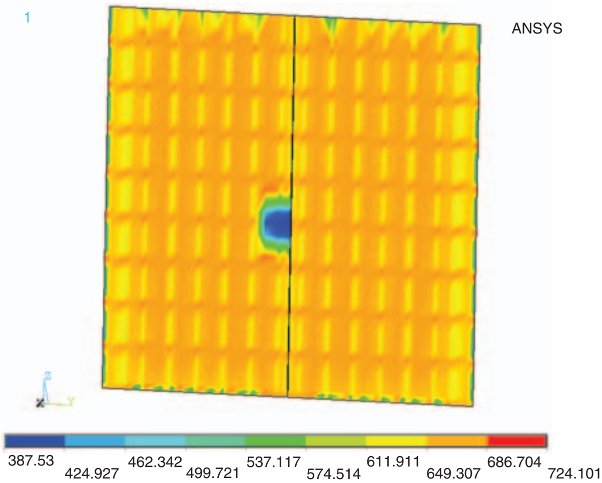

__Figure 6.__ Temperature (°C) contours at 15 minutes on exposed side of fire doors (The color version of this figure is available online).

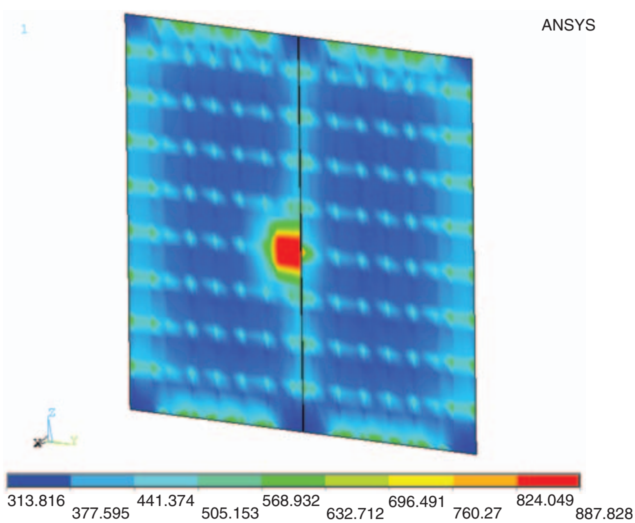

__Figure 7.__ Temperature (°C) contours at 60 minutes on unexposed side of fire doors (The color version of this figure is available online).

typically only a few points are measured and if temperatures are very high, then these measurements can become challenging. To check the temperatures of the model against available test data, only the averaged temperature of six points [21] on the unexposed side of the fire doors (Figure 9)

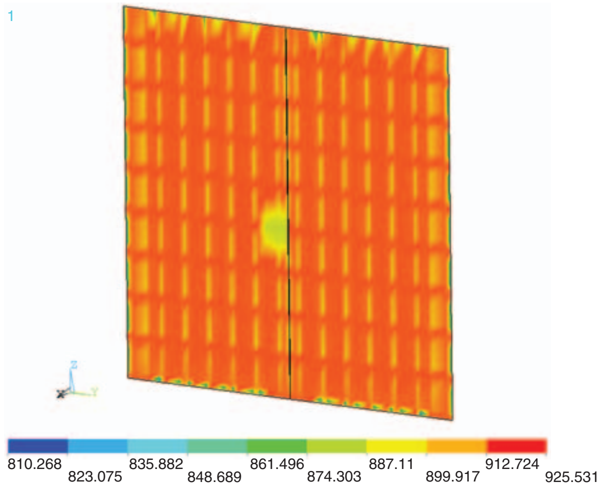

Figure 8. *Temperature (°C) contours at 60 minutes on exposed side of fire doors (The color version of this figure is available online).*

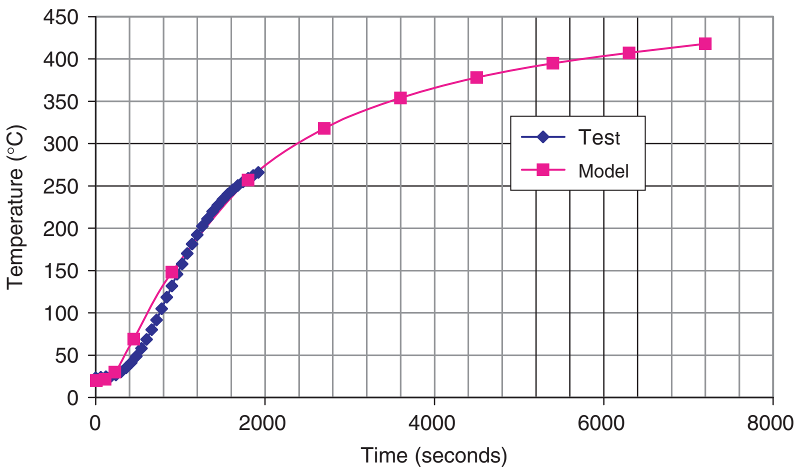

Figure 9. *Average temperature of select points on the unexposed side of the fire doors (The color version of this figure is available online).*

could be selected. The selected points matched closely with the thermocouple locations from the test as prescribed by the standard. A slight discrepancy is seen in the early part of the curve, which is likely due to the choice of a constant value for the air convection film coefficient. Measurements were taken from these thermocouples for only the first

Figure 10. *Photographs of the fire doors during the fire endurance test after 1 hour (The color version of this figure is available online).*

30 minutes of the test, as the standard only prescribed the recording of temperature data for this time period. Clearly, in hindsight, acquisition of thermocouple data during the entirety of the test would have given an opportunity for more thorough evaluation of the thermal response from the model. In the early stages of heating of the fire doors, convection heat transfer dominates. As the temperature increases, the dominance of radiation heat transfer grows to the fourth power of the temperature.

Finally, Figure 10 shows some of the trends observed in the numerical results of the unexposed side such as the heating of the edges and the heat transfer through spot-welds and the lock as noted by the darkened areas. The test specimen also displays darkened vertical lines, which suggest that the stiffener contact with the fire door panels is not only at the spot welds. If, in the review of structural response from the model, the comparison with test data is found to be inadequate, then addition of contact between the stiffeners and the door panels may be necessary.

Nonlinear Structural Analysis

Now with the thermal analysis complete, the structural analysis can follow two routes. The most accurate but more time-consuming and difficult choice is to run a nonlinear transient structural analysis. The second choice would be to run a steady state nonlinear structural analysis at select temperatures. In this study the second option has been chosen, as the first option might require a much finer mesh and longer numerical analysis run times. A best practice is to build up gradually the necessary complexity that will adequately capture the key behaviors of the fire doors observed during the test. Of course, simplicity that does not properly model the physics is never correct. For instance, if the key constituent materials for the fire door were visco-elastic, where the deformation histories are very important, then a transient analysis would be essential.

For the structural model, there were locking pins for the inactive door. The friction between the locking pins and the frame was neglected. The locking pins could move vertically, but were otherwise constrained. Similarly the friction between the latch bolt and the inactive leaf was neglected. The latch bolt for the lock was allowed to move laterally. The stiffeners were attached to the front and back panels through the individual spot-welds. Hinges were not modeled in detail except to allow for the proper rotation. The only loads that were applied to the structural model were derived from the thermal results and gravity. Though not addressed here, the transfer of thermal data to the structural model in cases where a single software package is used is very streamlined [26].

The structural analysis included geometric nonlinearity to allow for large deflections. The addition of this type of nonlinearity was a consequence of an initially linear analysis, not presented here, which failed to predict the deformation trends of the test.

For this study, we present a subset of the results of the structural model choosing to discuss only the results for 15 and 60 minutes. Figure 11 is a contour plot of the normal displacements of the fire doors at 15 minutes. The entire door is deformed towards the furnace with most of the motion occurring near the middle of the doors. The active door shows more deformation than the inactive door due to the bolts. In the test bowing began within a few minutes from the start of the test. Figure 12 shows a picture of the fire door assembly taken during the test. The bowing of the doors towards the fire is clearly seen. Furthermore, the active door shows larger bowing than the inactive door. The analysis appears to qualitatively match the observations of the test.

Figure 13 shows the lateral displacement of the fire doors at 15 minutes. For this specific fire door design, the testing achieved a 1 hour rating for fire resistance though the test was run for 3 hours. The movement and separation of the doors created a through opening along the meeting edges of the doors that was not in accordance beyond 1 hour and was the cause for noncompliance. For this reason, the lateral displacements were examined in this analysis. At 15 minutes, the relative displacement of the fire doors at the meeting edge was not uniform or equal. In the test, not until over 30 minutes

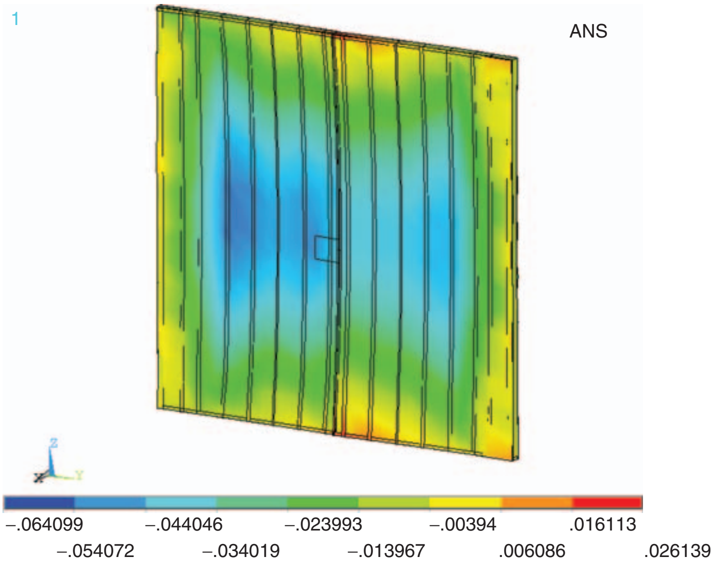

Figure 11. *Normal (x-direction) displacements (m) of fire door at 15 minutes (The color version of this figure is available online).*

Figure 12. *Photograph of fire door assembly during the test after 1 hour (The color version of this figure is available online).*

was a gap of the meeting edge noticed. This gap only measured 6.4 mm, while the model shows a gap of ~5 mm.

Figure 14 shows the normal displacements of the fire doors at 60 minutes. The normal deflections of the doors are now greater with the increase

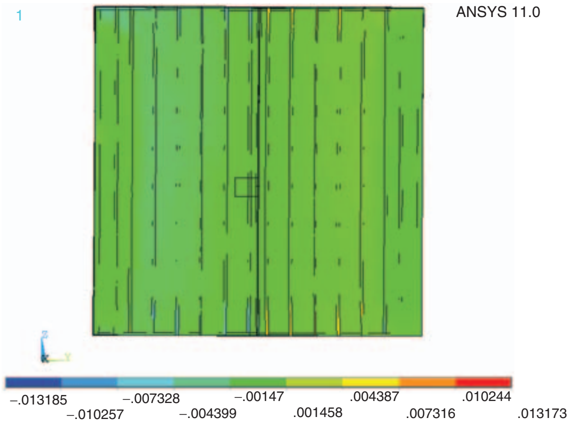

Figure 13. *Lateral (y-direction) displacements (m) of the fire doors at 15 minutes (The color version of this figure is available online).*

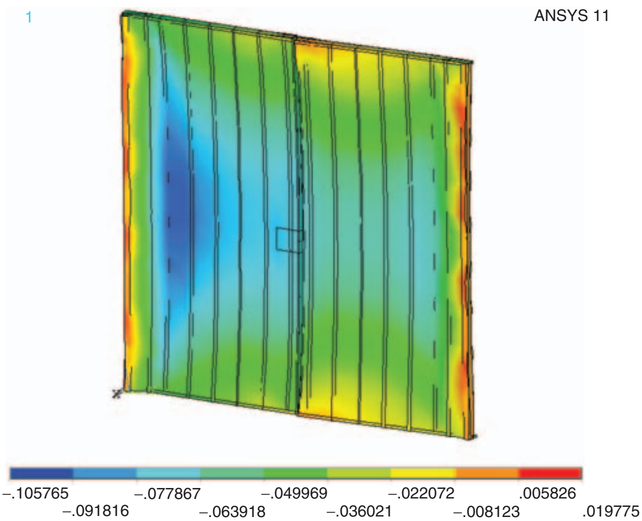

Figure 14. *Normal (x-direction) displacements (m) of the fire door at 60 minutes (The color version of this figure is available online).*

in temperature. The active door continues to display larger motions relative to the inactive door especially near the hinged edge. In the test the doors continued to bow while the furnace was operating. In the test, the bow of the fire doors was also noted visually to increase with time.

Figure 15 shows a close-up of lateral displacements of the meeting edge above the lock at 60 minutes. Looking at the sign of the displacements,

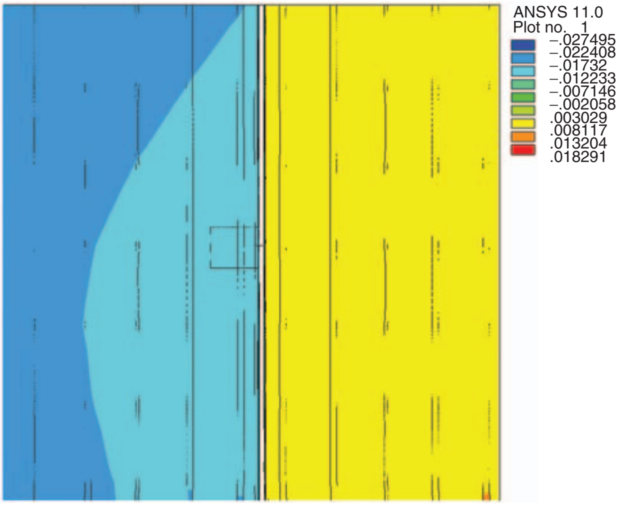

Figure 15. *Close up of meeting edge gap of the fire door at 60 minutes: legend indicates the value of lateral displacements (m) (The color version of this figure is available online).*

we see that the two doors move away from each other. As a result, a gap at the meeting edge of the doors near the lock mechanism is clearly visible. In the test, the meeting edge gap was measured to be ~16 mm at 58 minutes at a point almost midway between the lock and the top of the door. In comparison, choosing a point similarly located, the measured gap from the analysis is ~17 mm. In this case, it cannot be stated that the error of the model is only 6% as the validation process is very weak due to the extent and size of the test data [28]. Instead it is more prudent to state that the order of magnitude for the gap as predicted by the analysis matches well with that of the test. Also according to the analysis, though not shown here, the fire doors did not begin to develop a gap in the meeting edge until after 30 minutes, similar to what happened in the test. The comparisons so far with the available test data and the test photographs appear to corroborate the qualitative and, to a lesser extent, the quantitative predictions of the analysis.

The analysis did not converge for the 90 minutes or 120 minutes cases. For the 60 minutes case, as noted, there was a gap that develops along the meeting edge. Based on a review of the model response, the gap is believed to be a consequence of highly localized deformations of the active door near the hinged edge. Observations of the fire doors during testing indicate that localized buckling of the fire door was noticeable. At the longer times, and therefore higher temperatures, the buckling worsens and the FE mesh requires further refinement to improve the convergence at these longer times. So the fact that the model did not converge for the longer times may indirectly indicate that the performance of the door is possibly not satisfactory. In addition, for the 60 minutes analysis case, the stiffeners begin to penetrate the panels as the door bows, since in the model no contact elements were inserted between the stiffeners and panels as a first approximation.

Finally, the advantage of the model is not only the availability of detailed data such as deflections, which can only be measured at small number of discrete points during a test, but also data such as stress and strains can also be extracted that help to provide insights helpful to the redesign of the doors to improve fire resistance. For this door design, the maximum stresses occurred in the active door near the hinges at the top and bottom of the door. These stresses were above the yield strength of A36 steel of $2.48 \times 10^8\,\text{N/m}^2$, which suggests that there may be some plastic flow near the hinges. These stresses are highly localized at the hinge locations and a mesh sensitivity study would be necessary to check these values. However, the overall stress levels in the doors were below the yield point of the material.

CONCLUSIONS

This study illustrates the challenges of typical projects involved in modeling the response of structural components subjected to standard fire tests. In such projects, a small number of tests are carried out according to a particular standard, which may not require an instrumentation scheme that would provide adequate data for model validation. In addition, clients may not be willing to support a model validation project. However, even in such cases, modeling tools may be able to give valuable qualitative information for manufacturers of tested components in assessing fire performance, e.g., by cost effectively providing relative performance ranking of various designs. Furthermore, the experience gained through such modeling projects will increase the likelihood that future tests will include enhanced instrumentation [29]. In this article, a case study showing how these challenges were addressed is presented. The case study involved the thermal and structural FE analyses of a pair of steel fire doors using ANSYS software.

One serious challenge during this study was the gathering of accurate material properties and their temperature dependencies – over the wide temperature range – necessary for the structural and thermal analyses. Manufacturers of building components may not have such data and comprehensive material databases do not exist. In this study, published data were available.

An initial structural analysis excluding nonlinearity failed to predict the separation in the meeting edge recorded during the test. The nonlinearity in this analysis stemmed from large deformations. The nonlinear structural analysis was able to predict the increase in the gap of the meeting edges of the fire door pair at the specified time with values matching the order of magnitude of the test data. The model response also displayed global features seen during the test, such as thermal bowing.

The FE model was shown able to capture key thermal and structural responses, thereby giving confidence in its ability to assess the relative performance of incremental design changes. As in all such projects, a fire door of a dramatically different design, potential failure mode, or material composition would require a new validation scheme.

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