PREDICTING THE BEHAVIOR OF STEEL FIRE DOORS SUBJECTED TO FIRE ENDURANCE TEST

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Abstract

The ability to predict the thermal and structural performances of steel fire doors subjected to fire tests described in safety standards via the finite element method is investigated. These doors must withstand high temperatures without deforming in a manner where gaps might appear allowing flames and smoke to pass through. There are 2 key challenges for modelling: first, deciding how much complexity to include since the tests involve high temperatures and possibly times lasting hours, and second, obtaining the needed material properties over the temperature range seen during the tests. In this investigation, we focus on, one aspect of complexity, the importance in capturing the thermal contact between steel parts within the fire door to improve the predictability of the finite element model.

Keywords: Fire Doors, Fire, Structures, Finite Element Analysis, Thermal Contact

INTRODUCTION

Knowledge about the fire resistance of structural components can be derived through physical or virtual testing. Physical testing is expensive due to the destructive nature of the tests. Also physical testing can be limiting due to instrumentation constraints. On the other hand, virtual testing or computer modelling, techniques such finite element analysis (FEA), provide a very data rich output but require tremendous input information such as material properties, loadings, boundary conditions and other details that an experimenter typically need not know in order to conduct experiments.

One method for evaluating the fire resistance of building components, such as fire doors, follows test methods described by fire safety standards (Iwankiw, 2000). Though there have been many numerical and experimental investigations studying various aspects of the standard fire resistance, in this study, we focus on predicting the performance of steel double fire doors subjected to the standard fire test such as described by UL 10 (UL 10 B, 1997). The FEA technique is employed building on previous modelling of steel fire doors (Tabaddor et al., 2009).

1 FIRE RESISTANCE TESTING

The presence of fire doors within a building is meant to prevent the spread of fire with a secondary influence on the smoke and heat exposures to building occupants. As a means of evaluating fire resistance, fire door assemblies are tested according to standards such as the UL standard for fire safety, UL 10B, ‘Fire Tests of Door Assemblies’ (UL 10B, 1997).

This paper only focuses 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 this test, the fire door along with supporting structure such as frame and walls are constructed according to specified instructions. The door is part of a restraining frame (Fig. 1) that fits onto the furnace subassembly. With the assembly in place, the fire doors are subjected to a heat flux from gas burners which generate temperatures according to a standard time-temperature curve shown in Fig. 2 (ASTM, 2007). Some tests include a pressurized furnace to capture additional forces generated during a fire. The conditions of acceptance for the UL 10B standard cover the movement of the door and flaming on the unexposed side.

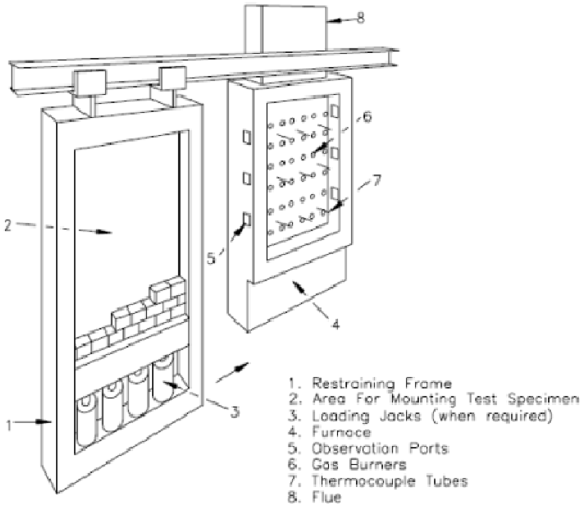

Fig. 1 Schematic of Setup

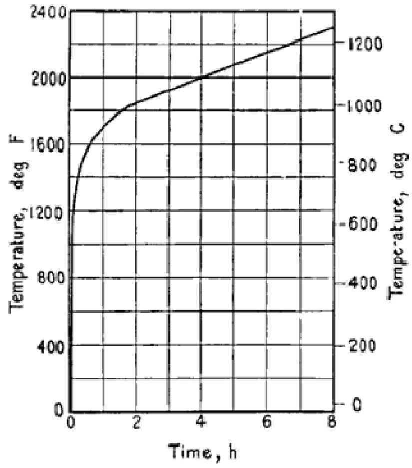

Fig.2 Standard time-temperature curve

2 FINITE ELEMENT MODEL

To build a finite element (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 was a double door. The door without a lock handle is called the inactive leaf. It included 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. The general assumptions guiding the model building process were as follows:

(i) The wall and frame holding the fire door are rigid during the entirety of the test.
(ii) The thermal insulation does not provide any structural strength to the fire door.
(iii) The coupling between thermal and structural response is one-way, that is, the structural response has negligible effect on the thermal response.

The software of choice was ANSYS (ANSYS, 2011). For the FE mesh, shell elements were chosen for both the thermal and structural analyses (except for the insulation materials). These 2-D 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 (Bathe, 1995). Some idea of the level of detail in the model can be seen in Fig. 3 and Fig. 4. Thermal and mechanical properties over the temperature range of test were found from several public resources (Milke, 2002; NIST, 2005) and can be found in (Tabaddor et al., 2009).

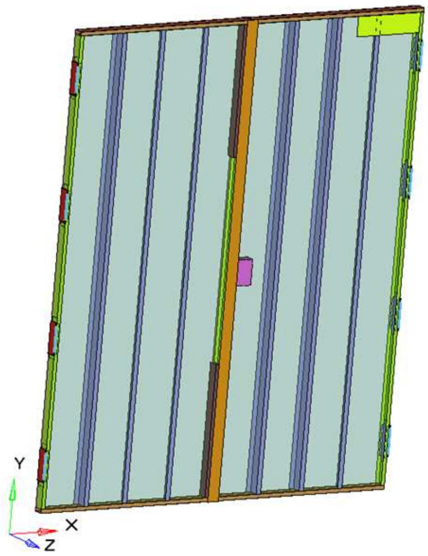

Fig. 3 Solid model of double steel fire door

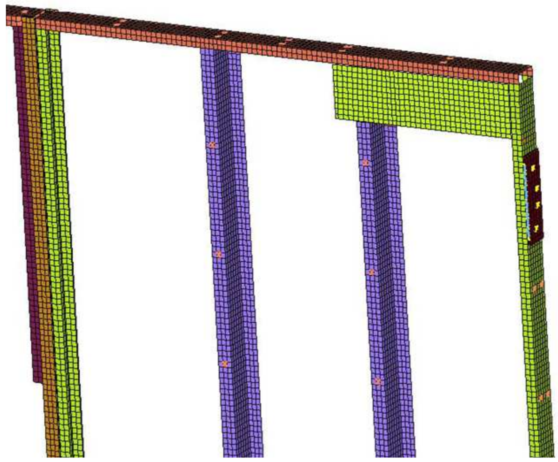

Fig. 4 Detail of connection in FE model

3 THERMAL CONTACT

For the transient thermal analysis, it was found that detail of the thermal contact between mating parts was very critical. For example, the steel stiffener is mechanically joined to the steel panel via welds. Clearly the welds will be a critical transfer path. However, depending upon tolerances and deformations, the actual thermal contact region is likely larger and changing. In the fire door, the metal portion on the face exposed to the furnace will be heated via radiation and convection. Heat then flows through the internals mostly through conduction ignoring air gaps between parts and within the insulation. However, due to the differences in thermal conductivities, the steel parts are the most thermally conductive paths and so mating between steel parts can affect the thermal results and subsequent structural predictions. So in this investigation, we developed several different thermal contact configurations.

For the first thermal contact configuration, we assumed only thermal contact via spot welds. Clearly this will lead to the least heat flow through the interior of the door to the unexposed side. The next thermal contact configuration relies upon thermal links placed between all metal surfaces that are expected to be in contact. With the inclusion of thermal links, now an additional variable, the thermal resistance of the thermal link is a required input. As a starting point, we selected the thermal conductivity of air which is 2.0 W/(m K). In this case, now more heat will flow through the stiffeners. Fig. 5 provides some detail on the various thermal contact configurations.

4 THERMAL RESULTS

Fig. 6 show a snapshot of the temperature contours at 15 minutes for both the unexposed and exposed surfaces of the fire door assembly for the metal-to-metal thermal contact configuration of only welds. For the unexposed side, hot spots include the lock and the edges of the door. As mentioned previously, the lack of welds on the unexposed side reduces the thermal paths through the stiffeners to the panel. For the exposed surface, cool spots include the lock and edges. Temperatures on the exposed surface reach as high as 800°C. On the unexposed side, the model predicts that most of the panel surface is below 130°C. The same general patterns holds as the door heats up further.

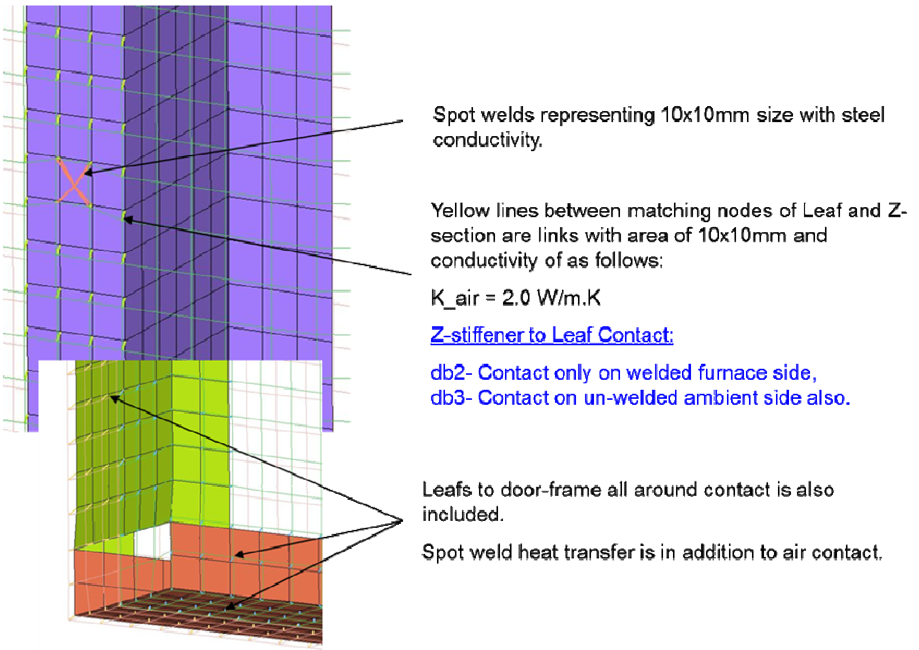

Fig. 5 Description of different thermal contact configurations

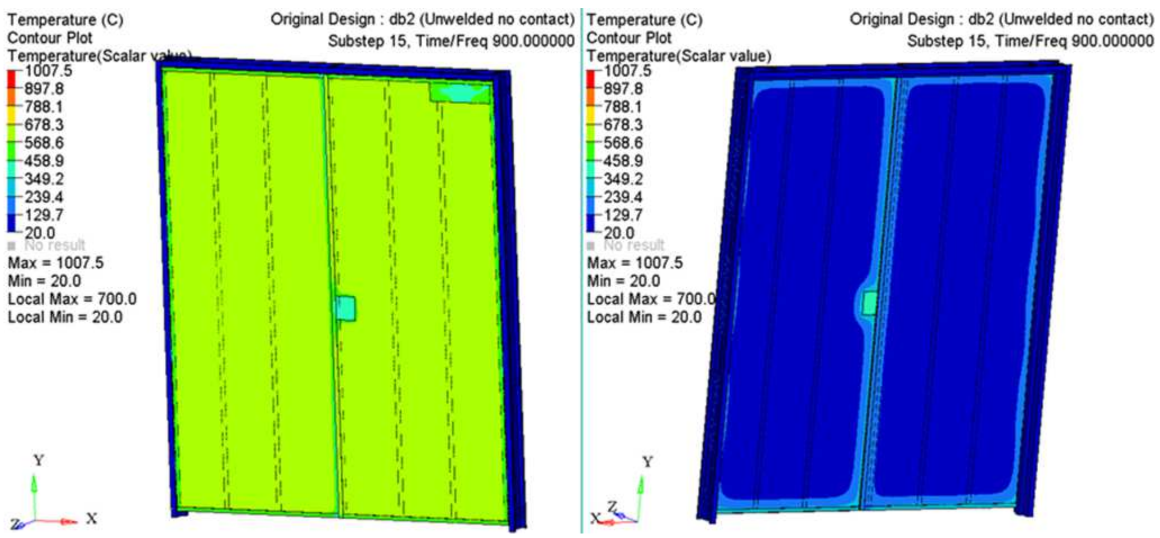

Fig. 6 Temperature contours on exposed (left) and unexposed (right) surfaces at 15 minutes with only thermal contact through the welds

Fig. 7 shows the temperature at 3 different points along one of the unexposed panels, similar to measurements taken during the test. The plot shows that the temperatures on the unexposed side are considerably lower than the temperatures measured during the test. Clearly, this model with no metal-to-metal thermal contact between stiffener and unexposed panel under-predicts temperatures. Despite the presence of welds on only one side of the stiffeners, it is expected that there is more metal-to-metal contact.

Fig. 8 shows the temperature at 3 different points on the unexposed panel similar to measurements taken during the test. As expected, the temperatures on the unexposed panel are much closer to the test temperatures as compared to the previous thermal model which only assumed thermal contact through welds. Clearly, metal-to-metal contact is present and may be changing as the door deforms. This effect is especially more difficult to capture in the absence of welds that would help maintain contact between the stiffener and door panels.

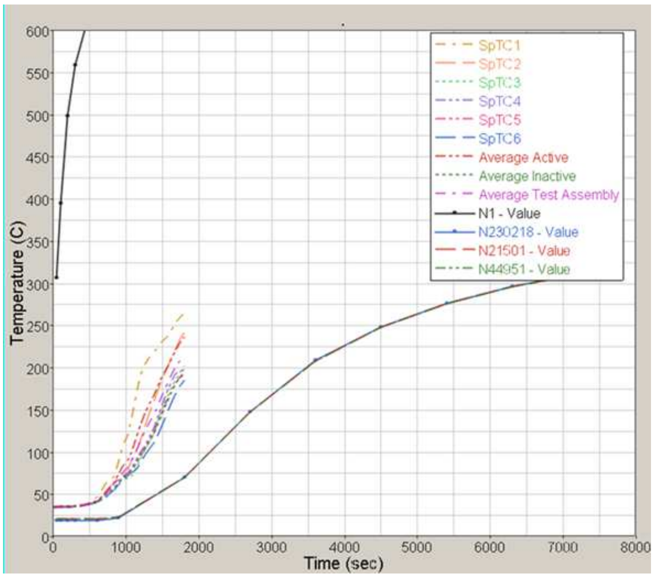

Fig. 7 Temperature over time from unexposed surface with weld only thermal contact

5 STRUCTURAL RESULTS

For the structural analysis, it was not necessary to run a transient analysis. Instead, the thermal results at different particular points in time where fed into the structural model to establish heat loads and material properties. This approach is computationally more efficient so that if it shows promise in predicting the structural deflections, a great advantage is gained. However, as noted in the thermal FE results section, the temperature predictions from the original door design show sensitivity to how the thermal contact between metal parts. Therefore the structural analysis results for the original fire door design will show the effect of varying thermal contact conditions. Of course, with this level of uncertainty in the details of the fire door construction, the structural results may not provide accurate quantitative deflection predictions. In addition, the structural analysis was linear not accounting for geometric or material nonlinearities or contact nonlinearity. A nonlinear analysis requires more model building and computational effort and was outside of the scope of the project. Nevertheless, there is value in running a structural analysis for this original door design and comparing the results with the concept fire door design. It is expected that if significant differences exist that they will reflect the proper trends in fire performance simply due to design changes.

Fig. 8 shows the deflection plot for the different cases. The key pattern repeats at all other times, where the basic global feature is bowing of the door towards the furnace. Recall that once the thermal contact condition is set, it does not change. The plot in Fig. 8 compares the deflections at the same point for the original fire door design and the concept fire door design. The first thermal contact configuration (labeled db2) results in higher deflections than the weld/thermal link contact configuration (labeled db3). This suggests that a higher temperature gradient through the thickness of the door will lead to higher deflections from greater bowing of the doors. This effect is documented in the published literature.

Examining the results over time show that deflections increase rapidly during the early part of the test and then exhibit a gradually rising form. Though the deflection values are plotted up to 1 hour, the relative movement of stiffeners and panels for this first-level of modeling is not expected to be applicable beyond 30 minutes. Furthermore, the actual values are not reliable without full model validation. However, the qualitative features of the results for the first 30 minutes are expected to be insightful for design decisions.

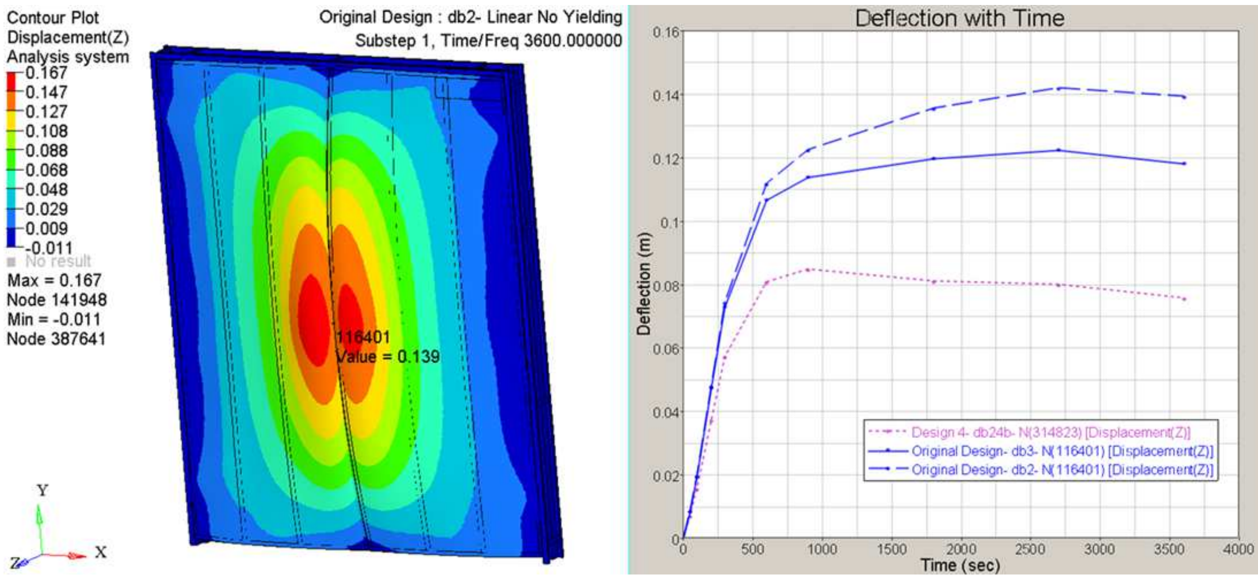

Fig. 8 Normal deflection contours (left) and deflection time plot (right) for 2 different thermal contact configurations and a baseline design

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