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Predicting the structural response of a compartment fire using full-field heat transfer measurements

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ABSTRACT

Inverse heat transfer analysis (IHT) was used to measure the full-field heat fluxes on a small scale (0.9 m×0.9 m×0.9 m) stainless steel SS304 compartment exposed to a 100 kW diffusion flame. The measured heat fluxes were then used in a thermo-mechanical finite element model in Abaqus to predict the response of an aluminum 6061-T6 compartment to the same exposure. Coupled measurements of deflection and temperature using Thermographic Digital Image Correlation (TDIC) were obtained of an aluminum compartment tested until collapse. Two convective heat transfer coefficients, h =35 W/m^2-K and h =10 W/m^2-K were examined for the thermal model using the experimentally measured heat fluxes. Predictions of the thermal and structural response of the same compartment were generated by coupling Fire Dynamics Simulator (FDS) and Abaqus using the two values for h, h =35 W/m^2-K and h from convection correlations. Predictions of deflection and temperature using heat fluxes from IHT and FDS with h=35 W/m^2-K agreed with experimental measurements along the back wall. The temperature predictions from the IHT-Abaqus model were independent of h, whereas the temperature predictions from the FDS-Abaqus model were dependent on h.

1. Introduction

Fires produce temporal and spatial varying exposures onto structures, which affects how the structure deforms and fails during a fire. Computational models are needed to quantify the temporal and spatial fire exposures for input into finite element models to accurately predict the thermal and structural response of the enclosure.

Previous studies that have measured the thermo-structural response have focused on measuring the heat transfer, temperature, and structural response at point locations. References [1–4] have used the temperature rise of steel plates with one insulated side to calculate the absorbed and cold surface heat flux based on one-dimensional inverse heat transfer analysis. Dillon [2] extended this concept to larger plates and used two-dimensional inverse heat transfer on the plates to develop heat flux maps for fires located in the corner of an ISO 9705 fire test room. More recently, a technique has been developed to predict the spatial and temporal variation to a two dimensional (2D) surface based on IR thermography on a metal plate [5]. The method can be used to determine the net heat flux or standard heat flux (defined as the heat flux to a surface at the standard temperature of 298 K).

Some efforts have been performed to predict the thermal and structural response of elements using Fire Dynamics Simulator (FDS) to predict the thermal exposure and finite element models to predict the temperature and structural response [6,7]. In these efforts, the adiabatic surface temperature was used to define the thermal boundary condition. The adiabatic surface temperature and the standard heat flux provide the same boundary condition information to the thermal model, just expressed differently [8]. In both cases, the heat transfer coefficient used in the FDS simulation must be used in the FE thermal model to ensure accurate results. Recently, thermography digital image correlation (TDIC) has been used to measure both the temperature and deflections in the same framework so that temperatures and deflections are tracked even in cases where excessive deflections occur [9].

The focus of this paper is to conduct an experiment that accurately measures the response of 3D collapse of a compartment containing a fire and predict the response of the compartment collapse. For this, methods were developed to spatially and temporally measure the heat transfer from the compartment fire to the boundaries. These results were input into a finite element model to predict the thermal and structural response. In addition, the fire dynamics were predicted using FDS and the predicted heat transfer were input into the finite element model to predict the thermal and structural response. The thermal and

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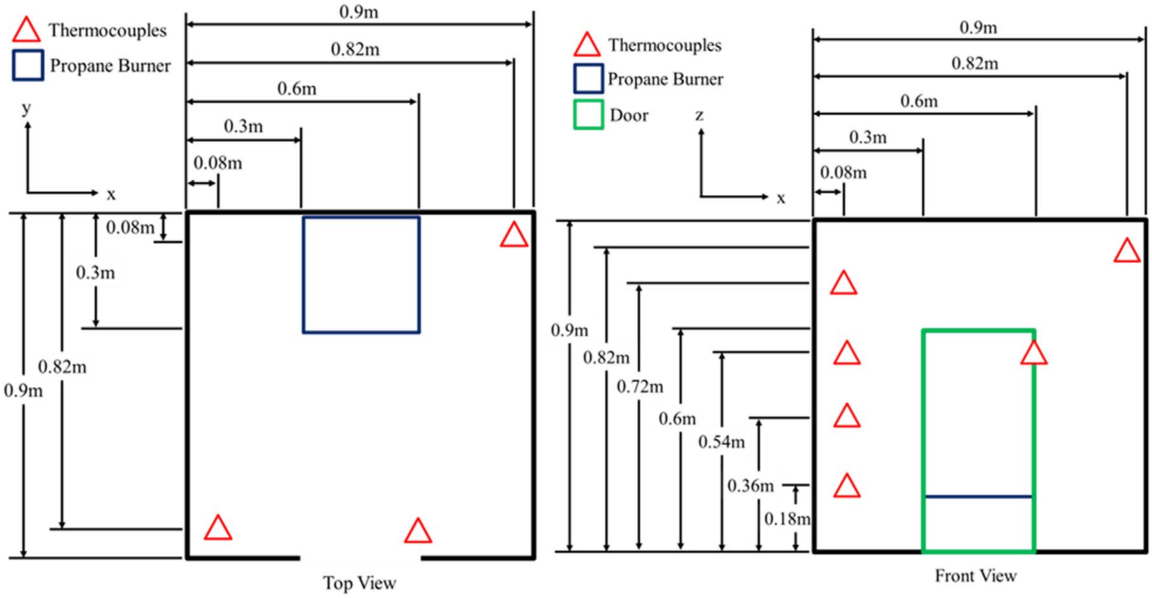

Fig. 1. Experimental setup for the heat flux mapping experiments.

structural responses from the two approaches were compared and the sensitivity of the thermal boundary condition details (primarily the heat transfer coefficient) were evaluated.

2. Experimental methods

Compartment fires tests were performed using 0.9 m×0.9 m×0.9 m compartments with a 0.3 m×0.6 m door on one side. A 0.3 m×0.3 m propane sand burner was placed at the center of the wall opposite the door. All testing was performed with a 100 kW fire. Each compartment was made from 3 separate pieces of metal which were attached with screws. Silicone sealant was used to make the compartment air tight at the bolt holes and each air gap. The compartments were placed on a slab of drywall and sealed along the bottom to remove air leaks. The first compartment was built from SS304 stainless steel (0.8 mm thickness) and was used to quantify the heat flux from the fire exposure. The second compartment was built from 6061-T6 aluminum (1.6 mm thickness) and was used for structural collapse testing. The details of each experiment and data analysis are described in the following sections. A schematic of the experimental setup for the heat flux mapping experiments is shown in Fig. 1.

2.1. Heat flux mapping experiments

Full-field temperature measurements were obtained on each of the exterior surfaces of the stainless steel compartment through infrared (IR) thermography. All interior and exterior surfaces were painted with Rust-Oleum® Specialty High Heat matte black paint which was previously shown to have an emissivity of 0.95 by [9]. The IR cameras used in this work were FLIR SC655 (640×480 pixels, up to 50 Hz, 16-bit, 7.5 – 14.0 μm). Two cameras were placed to provide an isometric view of the compartment, focusing on opposite corners of the top surface as shown in Fig. 2a-b. The last camera was placed orthogonal to the back wall where the sand burner was located, as shown in Fig. 2c. Each image in Fig. 2 has been scaled to the minimum and maximum temperatures measured by the camera within that frame. No mechanical load was applied to the compartment during the heat flux mapping experiments. Gas temperature was measured at the left corner of the compartment by the door at elevations of 0.18 m, 0.36 m, 0.54 m and 0.72 m using 24 gauge ceramic braid, bare bead Type K thermocouples.

The heat release rate of the fire was set to 20 kW for ten seconds and then increased to 100 kW for the remaining duration of the experiment until the surface temperatures reached steady-state (approximately 50 s additional heating, for a total exposure of 60 s). The fire was then turned off and the compartment was allowed to cool.

Spatial and temporal variation in the heat transfer to the boundaries of the compartment were determined using inverse heat transfer (IHT) analysis on the thermography images using the method described by Rippe et al. [5]. Previously this was applied to a single 2D surface. In this work, an isometric view of a 3D object was imaged using the IR cameras (Fig. 2). To determine the heat transfer to each surface, the 3D images were rectified to create 2D images of each surface with time. In the analysis, it was assumed that there was no conductive heat transfer along the edges between surfaces of the compartment; this assumption is reasonable due to the relatively small value of the plate thickness.

One unknown in the IHT method necessary to obtain the standard heat flux is the convective heat transfer coefficient, h. Prior published studies have presented temperature dependent relations for h for compartment fires. Correlations of h by Dembsey et al. [10], Veloo and Quintiere [11], and a modified version of the Emmons correlation presented in Sincaglia and Barnett [12] are provided in Fig. 3. Since the gas temperatures in the compartment fire tests ranged from 300 to 800 K, it was decided to complete two trials, one with the heat transfer coefficient on the interior and exterior was $h_{int} = h_{ext} = 10\ \mathrm{W/m^2\text{-}K}$ and one with $h_{ext} = 10\ \mathrm{W/m^2\text{-}K}$ and $h_{int} = 35\ \mathrm{W/m^2\text{-}K}$ where the subscripts correspond to the interior and exterior h, respectively.

The heat fluxes obtained from the experimental measurements using the stainless steel compartment were imported into Abaqus to predict the thermal and structural response of the aluminum compartment. Since the surfaces in each compartment were painted with the same emissivity paint, the heat fluxes obtained from the stainless steel compartment can be directly applied to the aluminum compartment. As discussed below, the spatial and temporal measured standard heat fluxes, q_O, (i.e., heat flux to a surface at the standard temperature of 298 K) were input into a thermal model to predict the temperature of the boundaries. Based on the formulation of the standard heat flux, it will be shown that the use of a different estimate of the heat transfer coefficient does not influence the predict boundary temperature as long as the same heat transfer coefficient is used in the thermal modeling. Note, that the IHT method measures the net heat flux from the fire into the surface and is independent of the heat transfer coefficient. The relationship between the net heat flux and the standard heat flux is given by