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REDUCED-ORDER THERMAL ANALYSIS OF FIRE EFFECTS ON COMPOSITE SLABS

Jian Jiang[1], Joseph A. Main[2], Jonathan Weigand[3], Fahim Sadek[4]

ABSTRACT

This paper describes a reduced-order modeling approach for thermal analyses of composite slabs with profiled decking. The reduced-order modeling approach consists of alternating strips of layered shell elements, representing the thick and thin portions of slab. Layered shell elements representing the thick portion of the slab adopt a linear reduction in the density of concrete within the rib to account for the tapered profile of the ribs. A “dummy material” with low specific heat and high through-thickness thermal conductivity is used to represent the voids between the ribs. The specific heat of concrete in the rib is also modified to indirectly consider the heat input through the web of the decking. The optimal ratio of modified to actual specific heat of concrete in the rib is determined, depending on the ratio of the height of the upper continuous portion to the height of the rib. The reduced-order modeling approach is validated against experimental results.

Keywords: thermal analysis; composite slab; reduced-order model; shell element; validation.

1 INTRODUCTION

Composite slabs consisting of concrete topping on profiled steel decking are widely used as floor systems in modern steel-framed buildings. Analyzing the response of composite slabs to fire-induced thermal loading requires both heat transfer analysis and structural analysis. Both thermal and structural analyses of composite slabs present their own unique challenges, and different types of models are typically used, which introduces an additional challenge of transferring analysis results between models with different element types and potentially different mesh resolutions. A key objective of this study is to develop a reduced-order modeling approach for thermal analysis that is also suitable for structural analysis. This would allow the same model to be used for both types of analysis, facilitating the analysis of structural response under various fire scenarios, with realistic thermal loading applied from computational simulations of fire dynamics.

Numerical analysis of heat transfer in composite slabs typically uses a high-fidelity finite element modeling approach, with solid elements for the concrete slab and shell elements for the steel decking [1-4]. This approach can realistically simulate the orthotropic behavior of composite slabs, but requires significant computing time. Thus, structural analysis of fire effects on composite slabs commonly uses grillage-type beam element models [5,6] or shell element formulations [7,8]. In considering the suitability of the reduced-order structural analysis approaches for heat transfer analysis, the grillage approach with beam elements [5,6] is unsuitable because of the inadequacy of

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the 1D elements to represent in-plane and through-thickness heat transfer in the slab. Modeling approaches that use a constant shell thickness [7,8] are unsuitable because they fail to capture the shielding effect of the ribs, which results in curved isotherms in the floor slab, significantly affecting both the structural response and the thermal insulation provided by the slab. Kwasniewski [9] and Main [10] proposed approaches in which alternating strips of layered shell elements were used to represent the thick and thin parts of a composite slab. This modeling approach has the potential to capture both in-plane and through-thickness heat transfer in composite slabs, including the shielding effect of the ribs, and this approach is pursued in this study.

This paper reports on a reduced-order modeling approach consisting of alternating strips of layered shell elements to represent the thick and thin portions of the composite slab. A “dummy material” with high through-thickness thermal conductivity and low specific heat is used to represent the voids between the ribs, and a linear reduction in the density of concrete in the ribs is used to represent the tapered profile of the ribs. Modifications in the specific heat of concrete in the rib are incorporated to indirectly account for heat input through the web of the decking, since thermal loading can only be directly applied to the upper and lower flanges of the decking in the reduced-order modeling approach. Comparisons with temperature histories from detailed finite-element models are used to determine the optimal modification of the specific heat as a function of the slab dimensions. Finally, the reduced-order modeling approach is validated through comparisons with experimental measurements.

2 DEVELOPMENT OF REDUCED-ORDER MODELING APPROACH

The proposed reduced-order modeling approach uses a layered composite shell formulation, in which a distinct structural material, thermal material, and thickness are specified for each layer (*PART_COMPOSITE in LS-DYNA [11]). This allows individual layers to be specified for the steel decking and the reinforcement, with multiple layers representing concrete through the thickness of the slab. The proposed approach uses alternating strips of shell elements to represent the thick and thin portions of composite slabs, with the width of the thick and thin portions each being spanned by a single shell element. For the simple half-slab configuration shown in *Fig. 1*, only two shell elements were needed, i.e., Shell A for the thick portion of the slab and Shell B for the thin portion as shown in the figure. A thick thermal shell formulation is used, which allows for both in-plane and through-thickness heat conduction, with thermal gradients through the thickness of each layer.

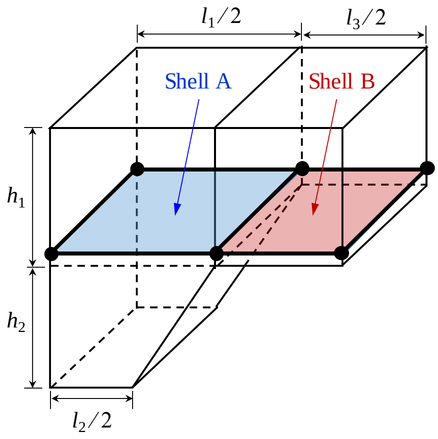

Fig. 1. Schematic of the reduced-order model of composite slabs with dimensions described in the text

Fig. 2 illustrates the layers used to represent the thick part of the slab (shell A) and the thin part of the slab (shell B) in the composite shell formulation. Based on mesh sensitivity analyses reported by Jiang et al. [12], it was found that sufficient accuracy could be achieved by using four layers in the composite shell representing the upper portion of the concrete slab and using an additional four layers to represent the concrete in the rib (see *Fig. 2*). An additional layer in shells A and B was used to represent the lower and upper flange of the steel decking, respectively. *Fig. 2* illustrates the following two aspects of the reduced-order modeling approach: (1) reduction of the concrete density in the ribs to represent the tapered profile. The reduced concrete density for the *i*th layer of the rib, ρ_i, is calculated based on the ratio of the average rib width for that layer, w_i, to the total width at the top of the rib, l_1, as $\rho_i = \rho_0 \times (w_i / l_1)$, where ρ_0 is the concrete density; (2) use of a "dummy material" to represent the voids between the ribs. This is done to allow shell A and shell B to have the same thickness, which is required for proper modeling of in-plane heat conduction between corresponding layers of adjoining shell elements. Radiation and convection boundary conditions are applied at the fictitious lower surface of shell B. A high through-thickness thermal conductivity for the dummy material, along with low specific heat (values of 100 W/(m·K) and 1 J/(kg·K), respectively, were used in this study), ensure an essentially equivalent temperature at the top of the dummy material, thus providing appropriate thermal boundary conditions for the upper flange of the steel decking.

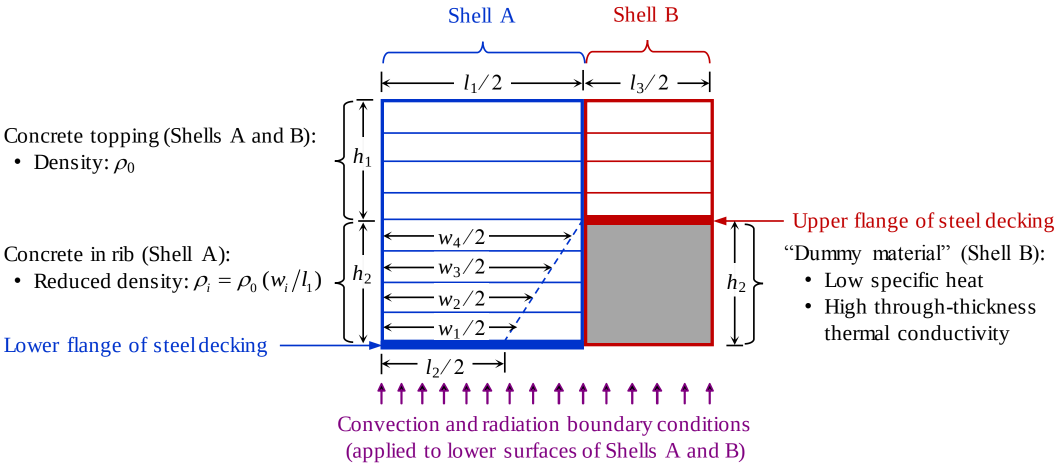

Fig. 2. Layered-shell representation of thick and thin portions of composite slab.

Fig. 3 shows a comparison of temperature histories computed using the reduced-order modeling approach with corresponding temperature histories computed using a validated, detailed modeling approach described by Jiang et al. [12], in which the concrete slab was modeled using solid elements and the steel decking was modeled using shell elements. The comparison corresponds to a commonly used composite slab with a Vulcraft 3VLI decking. The temperature histories presented in *Fig. 3* correspond to layer-averaged temperatures. Shell-element temperatures at the lower, middle, and upper surfaces were presented from the reduced-order model, and layer-averaged temperatures from the detailed model were calculated at consistent elevations. The high through-thickness thermal conductivity of the dummy material ensured that the temperature at the fictitious lower surface of shell B was virtually equivalent to the temperature in the upper flange of the steel decking. For this reason, the upper flange of the steel decking is labeled as the lower surface in *Fig. 3b*. The temperature differences between the reduced-order and detailed models in *Fig. 3* resulted from approximations inherent in the layered composite shell formulation, which underestimated the heat input through the web of the decking. This resulted in delayed heating just above the rib (middle surface in *Fig. 3a*), where the reduced-order model underestimated the temperature by about 16 % at the end of the analysis. To reduce this error, it is necessary to more accurately capture the heat input through the web of the decking. This can be achieved by modifying the specific heat for concrete in the ribs, as presented in the next section.

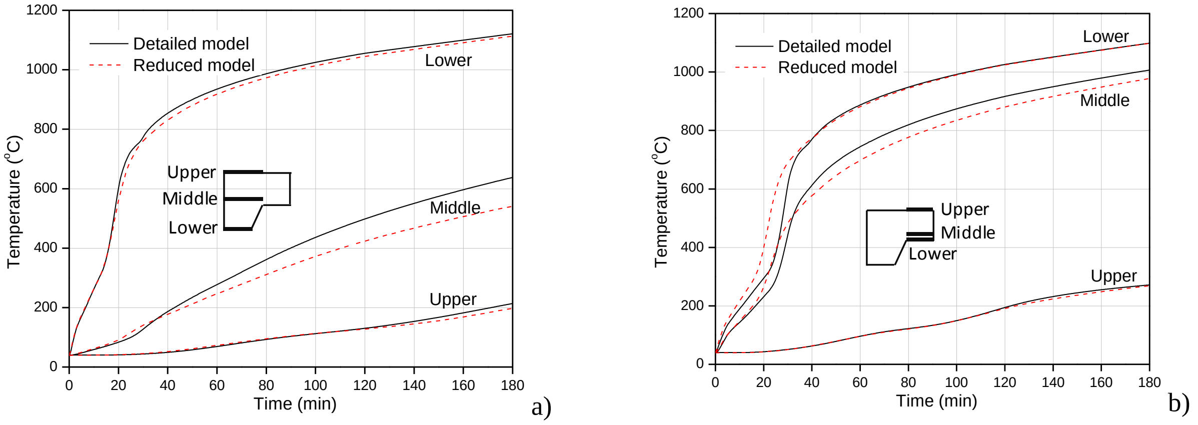

Fig. 3. Comparison of layer-averaged temperature histories from detailed model and reduced-order model: a) thick portion of slab; b) thin portion of slab

3 MODIFICATION OF SPECIFIC HEAT FOR CONCRETE IN THE RIBS

The most effective approach to account for the influence of heat input through the web of the decking was found to be through modification of the specific heat of the concrete in the rib. In this approach, an artificial specific heat, c'_p, was used for the concrete in the rib, while the actual specific heat, c_p, was used for the rest of the concrete in the slab. A reduction in the specific heat indirectly accounts for additional heat input through the web, since the reduced specific heat increases the thermal diffusivity, thus increasing the rate of heat flow through the rib. This approach allowed for improved accuracy in the temperature above the rib, with minimal effect on the temperatures at other locations in the slab.

The optimal value of $c'_\mathrm{p} \,/\, c_\mathrm{p}$ was determined by minimizing the root-mean-square (RMS) difference between the temperature histories from the reduced-order and detailed models, defined as follows:

$$T_{\mathrm{RMSD}} = \sqrt{\frac{\sum_{i=1}^{n}\left(T_\mathrm{R}(t_i) - T_\mathrm{D}(t_i)\right)^2}{n}} \tag{1}$$

where T_D and T_R are the temperatures obtained from the detailed and reduced-order models, respectively, t_i is the ith time sample, and n is the total number of time samples over the heating period. The RMS temperature deviation was evaluated for temperature histories from the middle surface of the thick part of the slab, where the largest discrepancy was observed in *Fig. 3*.

Parametric studies were conducted to evaluate the optimal value based on a set of slab geometries [12], as shown in *Fig. 4*. The recommended optimal specific heat ratio $c'_\mathrm{p} \,/\, c_\mathrm{p}$ was expressed as a function of $h_1 \,/\, h_2$, where h_1 is the thickness of the continuous upper portion of the slab and h_2 is the thickness of the rib. The ratio $c'_\mathrm{p} \,/\, c_\mathrm{p}$ was reduced linearly from a value of 1.0 for $h_1 \,/\, h_2 = 1$ to a value of 0.5 for $h_1 \,/\, h_2 = 1.2$. An upper limit of $c'_\mathrm{p} \,/\, c_\mathrm{p} = 1.0$ is recommended for $h_1 \,/\, h_2 < 1$, because values of $c'_\mathrm{p} \,/\, c_\mathrm{p}$ exceeding 1.0 can result in underestimation of temperatures in the later stages of heating, which is not conservative. Similarly, a lower limit of $c'_\mathrm{p} \,/\, c_\mathrm{p} = 0.5$ is recommended for $h_1 \,/\, h_2 > 1.2$, because reducing $c'_\mathrm{p} \,/\, c_\mathrm{p}$ below 0.5 produced only marginal reductions in the RMS temperature deviation.

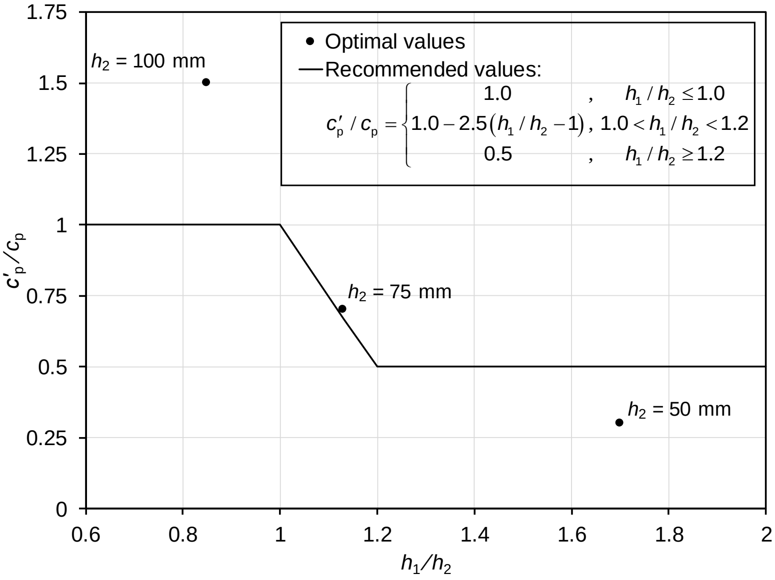

Fig. 4. Recommended specific heat of concrete in the rib as a function of $h_1 \,/\, h_2$

4 VALIDATION OF REDUCED-ORDER MODELING APPROACH

A standard fire test per ISO 834 [13] on a simply supported one-way concrete slab (Test 2 from Hamerlinck et al. [1]) was selected to validate the proposed reduced-order modeling approach. *Fig. 5* shows the configuration of the tested slab. The slab had six ribs and used Prins PSV73 steel decking and normal-weight concrete with a measured moisture content of 3.4 %. Heat transfer parameters reported by Hamerlinck et al. [1] were used in the modeling, as summarized in the following. The convective heat transfer coefficient for the lower flange of the steel decking was taken as 25 W/(m^2·K), and a lower value of 15 W/(m^2·K) was used for the web and upper flange of the decking to account for the shielding effect of the ribs. A convective heat transfer coefficient of 8 W/(m^2·K) and an emissivity of 0.78 were used for the unexposed top surface of the concrete. View factors for the upper flange and the web of the steel decking were 0.3 and 0.6, respectively, and a view factor of 1.0 was used for the lower flange of the steel decking and the unexposed top concrete surface.

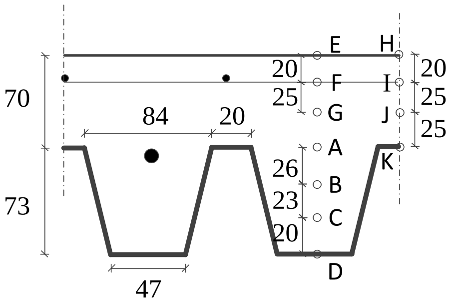

Fig. 5. Geometry of TNO tested slab (Hamerlinck et al. 1990) (dimensions in mm)

Fig. 6 presents a comparison of the measured temperature histories from the slab test with the computed temperatures from the detailed and reduced-order models. For consistency with the experimental measurements, point temperatures rather than layer-averaged temperatures are presented from the numerical models (i.e., nodal temperatures, rather than element temperatures, are presented from the reduced-order model). The tested slab had a height ratio of $h_1 \,/\, h_2 = 0.96$, for which *Fig. 4* recommends a specific heat ratio of $c'_p \,/\, c_p = 1.0$, and therefore, no modification of the specific heat of concrete in the rib was used. For comparison with the computed results, the measured temperature at point M (mid-height of the thick portion of the slab) was obtained by interpolation of measured temperatures at adjacent points (points A and G in *Fig. 5*). The largest discrepancies were at point K, where the RMS temperature differences were 42 °C and 73 °C for the detailed and reduced-order models, respectively. At all other locations, the RMS temperature differences were less than 30 °C. The largest percent differences at the end of the test were +14 % and +17 % for the detailed and reduced-order models, at points H and E, respectively.

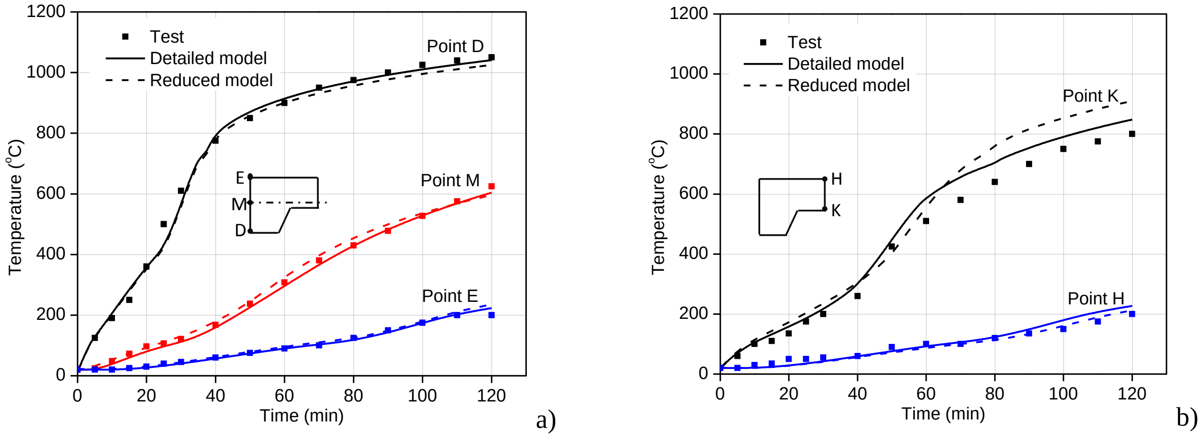

Fig. 6. Comparison of measured temperatures from TNO test [1] with computed temperatures from detailed and reduced-order models: a) thick portion of slab; b) thin portion of slab

5 CONCLUSIONS

This paper presented a reduced-order modeling approach that used a layered composite shell formulation for heat transfer analysis of composite slabs. This modeling approach can be readily extended to structural analysis, allowing thermal and structural analysis to be performed using the same model. The geometry of composite slabs was captured by using alternating strips of shell elements to represent the thick and thin portions of the slab. The density of concrete was reduced linearly with depth in the rib to account for the tapered profile of the ribs. Shell elements representing the thin portions of the slab incorporated a "dummy material" with low specific heat and high through-thickness thermal conductivity to represent the voids between the ribs. This approach allows the thick and thin portions of the slab to be modeled using shell elements with the same thickness. Adequately accounting for heat input through the web of the decking was the greatest challenge in the reduced-order modeling approach, and modifying the specific heat of concrete in the rib was found to be an effective method to achieve this. The modification factor for the specific heat in the rib, c'_p / c_p, was recommended as 0.5 for slabs with $h_1 / h_2 > 1.2$ and as 1.0 for slabs with $h_1 / h_2 < 1.0$, with a linear interpolation between these values for h_1/h_2 between 1.0 and 1.2. The reduced-order modeling approach was calibrated against detailed models of composite slabs and validated against experimental results.

DISCLAIMER

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