Scale Modeling of Compartment Fires for Structural Fire Testing

MING WANG*
Beijing Normal University, Beijing 100875, P.R. China

JONATHAN. PERRICONE
Schirmer Engineering Corporation, San Diego, CA 92128, USA

PETER C. CHANG AND JAMES G. QUINTIERE
University of Maryland, College Park, MD 20742, USA

ABSTRACT: Current design for fire protection subjects an individual structural element to a standard temperature profile that is meant to ensure the element's load-carrying capacity for a predetermined period of time during a fire. While this approach satisfies the structural component's fire resistance requirement, it does not provide an understanding of the behavior of the structure in a fire. To fully understand a structure's behavior in a fire, a full-scale fire experiment is necessary. Scaled experiments offer an economical alternative to full-scale fire experiments. This paper discusses a method for scaling a compartment fire by using the laws of similitude. The profiles of hot gas temperature versus time in such a reduced-scale compartment will be similar to those in a full-scale compartment, which is a necessary condition for conducting reduced-scale structural fire testing. Experimental verification at two different scales are performed to show the validity of the proposed approach. It has been shown that the method can be applied to simulate the fire loading on the structure of the World Trade Center tower on 11 September, 2001.

KEY WORDS: scaled fire testing, scale modeling, compartment fire, similitude, structural test.

INTRODUCTION

FULLY-DEVELOPED FIRES IN a building can be disastrous. The collapse of the World Trade Center towers 1, 2, and 7 shows that global instability and failure of a tall building can result from fire and gravity loads.

*Author to whom correspondence should be addressed. E-mail: wangming@ires.cn

1042-3915/08/03 0223–18 $10.00/0 DOI: 10.1177/1042391508093337

SAGE Publications, Los Angeles, London, New Delhi and Singapore

The investigation of the performance of the buildings at the World Trade Center site conducted by the Federal Emergency Management Agency [1] suggests that the behavior of a structural system under fire loading should be considered as an integral part of the structural design.

The ASTM E119 [2] standard fire test is usually used to evaluate the performance of a stand-alone structural element. The test results, usually in the form of a fire resistance rating, provide guidelines for fire-safe structural design. However, this standard fire test is not intended to predict the performance of a structural system in a real fire because the standard fire curves do not necessarily represent natural fires. Rather, the test provides information on the relative response among different structural insulation materials when subjected to a standard fire curve. While this approach is adequate for design purposes, it does not help in understanding the global behavior of the structure in a fire. Full scale or properly designed reduced scale fire experiments can provide such insight.

Full-scale testing of structures under fire loading is difficult to conduct as the structure under consideration may be too large to reproduce and the equipment to apply the necessary loads to a substructure assembly may not be practical. Therefore, either full-scale tests of individual structural elements or reduced scale experiments on the structure can be performed. A methodology for fire resistance testing of structural components at reduced scales has been presented by Issen [3] and O'Connor et al. [4]. Their half-scale model fire tests showed the potential of using a scaled model to predict displacements and failure behavior under fire loading. In their articles, they proposed a time scale proportional to the square of the linear length ($t \sim s^2$) using geometrically scaled specimens. Herein, '$\sim$' is used to show proportionality and the scaling relations of all other parameters are expressed as a power of linear length, s. The time scale Issen and O'Connor used is based on thermal diffusion, $s \sim \sqrt{(k/\rho c)\mathrm{d}t}$. The net incident heat flux is then scaled by $\dot{q}'' \sim k(\mathrm{d}T/\mathrm{d}x) \sim s^{-1}$, which can be implemented by adjusting the furnace temperature profile. Their development of scaling focused on concrete structures in which the temperature gradient is significant and must be accounted for in the scaling.

In this study, instead of using a furnace to generate the high-temperature environment, the focus is on scaled compartment fires, because this creates a more realistic fire effect on structures. Entire structural assemblies can thereby be tested rather than a single element. However, the time scale used by Issen and O'Connor is not suitable for a compartment fire test, where the heat flow is driven by gravity or buoyancy forces. Quintiere [5] showed that time should be scaled by $\sqrt{s}$ instead. Proper scaling also requires that the fuel and compartment wall material be adjusted to obtain a temperature profile similar to that in the prototype. It is implied in this article that scaled structures with similar temperature profiles and mechanical loading have a structural response similar to that in the prototype.

SCALE MODELING OF COMPARTMENT FIRES

Gross and Robertson [6] of the National Bureau of Standards were one of the first researchers to conduct experiments to scale wood crib fires in enclosures. Their attempt was based on matching the Froude number because they recognized that the fire plume flow was governed by the buoyancy force. In their experiment, the scaling rules applied in the design phase were basically geometric relationships, and the same compartment wall material was used for all scales. The results obtained from different scales did not compare well. A more thorough investigation of scaling of wood crib fires in enclosures was undertaken by Heskestad [7], in which some important effects were considered besides geometric scaling. The burning rate of wood crib fires was found to be related to the flow rate of air through the internal structure of wood cribs. As a result, a relationship was developed between the ratio of burning rate outside an enclosure to that inside an enclosure and a defined porosity factor, P, which was a function of the exposed surface area of the crib, the area of vertical shafts within the crib, stick spacing and stick cross section. This relationship provided fundamental knowledge to design wood cribs for compartment fires at different scales. Recognizing the importance of the heat loss through vents via radiation and heat loss through enclosure boundaries, Heskestad [7] suggested that rules for scaling the material properties and dimensions of the compartment walls can be derived from the governing equation for heat conduction in walls. A characteristic time defined as the fire duration was determined based on the burning rate. The validation of Heskestad's scaling laws was attempted by Croce [8].

Croce and Xin [9] studied a method for scaling wood cribs and compartment enclosures and their experimental results demonstrated similarity of enclosure fires at different scales. However, their experimental results exhibited a large scatter in fire temperature, especially at low ventilation conditions. The current study aims to develop a practical method to conduct reduced-scale compartment fires so as to obtain fires at different scales with similar temperature versus time profiles. This similarity is critically important for scaled structural fire testing. Since structural fires often occur inside residential or commercial buildings, an approach is developed using enclosures with small vents or under conditions of low ventilation. A time scale is selected to ensure that the temperature versus time relationship is similar at different scales. For a comprehensive review of fire scaling, see Quintiere [5]. This paper describes the experiments conducted to model wood crib burning in compartments at different scales based on the scaling theory of compartment fires proposed by Quintiere [5] which is also the basis of the fire scaling adopted here. It should be noted that the time scaling in reference [5] is derived by analyzing a fluid element of the fire-induced flow that is driven by buoyancy resulting from the change in density of heated gas in an enclosure. This time scale, which is effective in modeling smoke/gas flows, is different from that used by Croce and Xin [9], where time is scaled so that the burning time of the fuel array is directly related to the thickness of wood crib sticks.

The model depicted in Figure 1 shows the fire phenomenon in a compartment. The model displays the fire burning in the compartment with a room vent. The hot gas temperature in the compartment is dependent on the difference between the heat generation rate from the fire, $\dot{Q}$, and the heat loss rate through the compartment boundaries, $\dot{q}$.

The total heat loss consists of the heat loss by conduction through compartment walls $\dot{q}_k$ and radiation $\dot{q}_\mathrm{r}$ through the vent. This relation is expressed in the energy conservation equation:

$$\rho_\infty c_p V \frac{\mathrm{d}T}{\mathrm{d}t} + \dot{m} c_p (T - T_\infty) \sim \dot{Q} - \dot{q} \tag{1}$$

In a natural convection condition where there is no forced flow, the hot gas flow is driven by the buoyancy which is induced by the change of hot gas density. Therefore, the burning time of the fuel needs to be scaled according to $t \sim s^{1/2}$ [5].

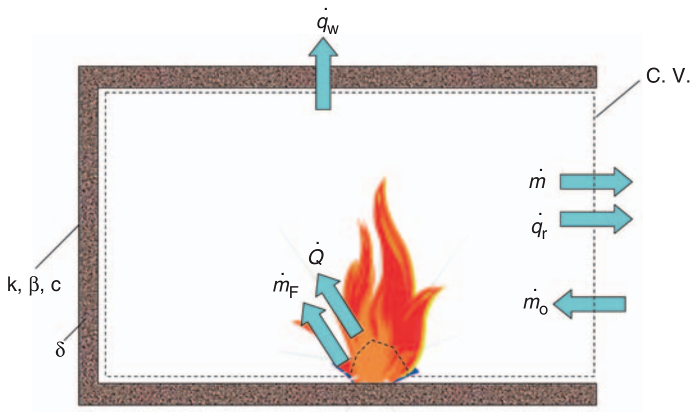


Figure 1. *Model of compartment fire phenomena. (The color version of this figure is available online.)*

Making Equation (1) dimensionless,

$$\rho_\infty c_p \hat{V} s^3 \frac{\mathrm{d}\hat{T}T_\infty}{\mathrm{d}\hat{t}\sqrt{s/g}} + \frac{\mathrm{d}\hat{\rho}\rho_\infty}{\mathrm{d}\hat{t}\sqrt{s/g}} c_p(\hat{T}T_\infty - T_\infty) \sim \dot{Q} - \dot{q} \tag{2}$$

where, $\hat{V} = V/s^3$ since the compartment dimension is geometrically scaled. Herein, '$\wedge$' denotes dimensionless parameters. Equation (2) can be written as:

$$\hat{V}\frac{\mathrm{d}\hat{T}}{\mathrm{d}\hat{t}} + \frac{\mathrm{d}\hat{\rho}}{\mathrm{d}\hat{t}}\hat{V}(\hat{T} - 1) \sim \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} s^{5/2}} - \frac{\dot{q}}{\rho_\infty c_p T_\infty \sqrt{g} s^{5/2}} \tag{3}$$

Thus, two dimensionless groups (Π terms) can be obtained:

$$\Pi_{\text{gen}} = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} s^{5/2}} \tag{4}$$

$$\Pi_{\text{los}} = \frac{\dot{q}}{\rho_\infty c_p T_\infty \sqrt{g} s^{5/2}} \tag{5}$$

Since the acceleration of gravity (g) cannot be changed, assume that $g \sim s^0$; i.e., gravitational acceleration for both prototype and scaled model are the same, the heat generation rate and heat loss rate are scaled according to

$$\dot{Q} \sim s^{5/2} \tag{6}$$

$$\dot{q} \sim s^{5/2} \tag{7}$$

The heat loss rate ($\dot{q}$) is determined by the boundary conditions of a compartment fire. The scaling relation of the heat loss rate in Equation (7) ($\dot{q} \sim s^{5/2}$) will be the basis for determining the design parameters of compartment boundaries. The heat loss through the compartment boundaries consists of the heat loss through ventilation openings by radiation, $\dot{q}_\mathrm{v}$, and heat loss through walls, $\dot{q}_\mathrm{w}$.

$$\dot{q} = \dot{q}_\mathrm{v} + \dot{q}_\mathrm{w} \tag{8}$$

Heat Loss through Vent

Considering a control volume of the enclosure gas phase as shown in Figure 1, the heat loss through vent by radiation can be expressed as:

$$\dot{q}_\mathrm{v} = A_{\text{vent}}\sigma_\mathrm{g}\left[\varepsilon_\mathrm{g}\left(T^4 - T_\infty^4\right) + \left(1 - \varepsilon_\mathrm{g}\right)\left(T_\mathrm{w}^4 - T_\infty^4\right)\right] \tag{9}$$

where, A_{vent} is the area of the vent, ε_{g} is the gas emissivity, σ_g is the Stefan–Boltzmann constant, and T_{w} is the temperature of compartment walls. If the walls in the fire compartment are assumed to be blackbodies, the gas emissivity can be written as [5]:

$$\varepsilon_{\mathrm{g}} \sim 1 - e^{-\kappa s} \tag{10}$$

where, κ is the absorption coefficient of gas. Substituting Equation (10) into Equation (9),

$$\dot{q}_{\mathrm{v}} \sim A_{\mathrm{vent}}\left[\left(T^4 - T_{\infty}^4\right) + e^{-\kappa s}\left(T_{\mathrm{w}}^4 - T_{\infty}^4\right)\right] \tag{11}$$

If the heat loss rate through vent is scaled ($\dot{q}_{\mathrm{v}} \sim s^{5/2}$), both the area of vent and the absorption coefficient of gas should be scaled. However, the same fuel (wood cribs) will be used both in scaled models and the prototype, so maintaining $\dot{q}_{\mathrm{v}} \sim s^{5/2}$ exactly is often not practicable.

The compartment model considered in this study is an enclosure with a small vent. This is true for rooms in most buildings. The heat loss through the vent by radiation can be considered small compared to the heat loss through the compartment walls. Therefore, heat loss by radiation through the vent can be ignored. For a fire burning in an open space or in an enclosure with a large vent, this assumption is obviously not valid.

Heat Loss through Compartment Walls

The heat loss through compartment walls is shown in Figure 2. Heat is transferred to the exposed surface of walls via radiation and convection. The heat loss is then transferred through the walls and lost to the ambient environment.

$$\dot{q}_{\mathrm{w}} = \dot{q}_{\mathrm{w,k}} = \dot{q}_{\mathrm{w,r}} + \dot{q}_{\mathrm{w,c}} \tag{12}$$

$\dot{q}_{\mathrm{w,k}}$ is the heat loss rate through walls by conduction. $\dot{q}_{\mathrm{w,r}}$ and $\dot{q}_{\mathrm{w,c}}$ are the heat loss rate to walls by radiation and convection, respectively.

The total heat loss through compartment boundaries is the summation of the heat loss through vent and the heat loss through walls. As stated previously, the heat loss through vent is considered to be small comparing to the heat loss through walls for a compartment with a small vent. So the scaling rules can be obtained:

$$\dot{q} \approx \dot{q}_{\mathrm{w}} = \dot{q}_{\mathrm{w,k}} = \dot{q}_{\mathrm{w,r}} + \dot{q}_{\mathrm{w,c}} \Rightarrow \dot{q}_{\mathrm{w}} \sim \dot{q}_{\mathrm{w,k}} \sim (\dot{q}_{\mathrm{w,r}} + \dot{q}_{\mathrm{w,c}}) \sim s^{5/2} \tag{13}$$

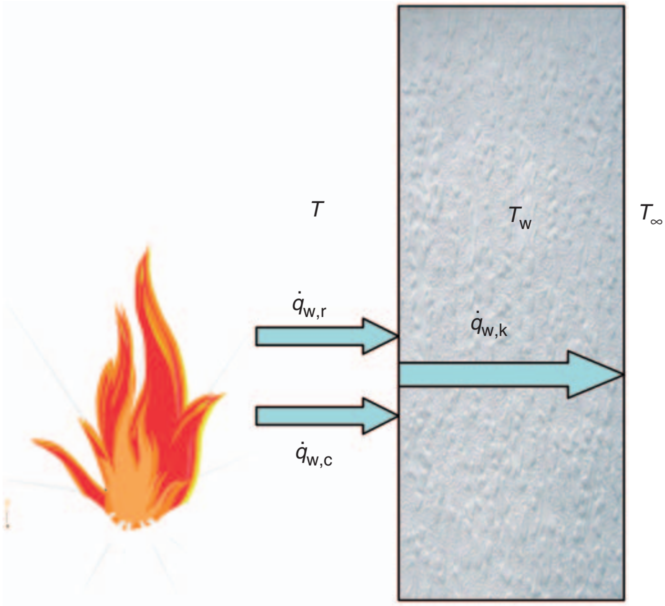


Figure 2. Heat loss through compartment walls. (The color version of this figure is available online.)

Consider the heat loss by conduction:

$$\dot{q}_{\mathrm{w,\,k}} \sim \frac{k_{\mathrm{w}}}{\delta_{\mathrm{T}}} A_{\mathrm{sf}}(T_{\mathrm{w}} - T_{\infty}) \tag{14}$$

where, k_{w} is the thermal conductivity of walls, A_{sf} is the surface area exposed to fire. The term, δ_{T}, is the thermal thickness. If the compartment wall behaves as thermally thin, then $\delta_{\mathrm{T}} = \delta_{\mathrm{w}}$ can be used, where, δ_{w} is the thickness of the compartment walls. If the wall behaves as thermally thick, δ_{T} can be written as in [5]:

$$\delta_{\mathrm{T}} \sim \left[\left(\frac{k_{\mathrm{w}}}{\rho_{\mathrm{w}} c_{\mathrm{w}}}\right) t\right]^{1/2} \tag{15}$$

Substituting Equation (15) into Equation (14), and using the scaling rules in Equation (13),

$$\dot{q}_{\mathrm{w,\,k}} \sim \frac{k_{\mathrm{w}}}{[(k_{\mathrm{w}}/\rho_{\mathrm{w}} c_{\mathrm{w}})t]^{1/2}} A_{\mathrm{sf}}(T_{\mathrm{w}} - T_{\infty}) \sim (k_{\mathrm{w}} \rho_{\mathrm{w}} c_{\mathrm{w}})^{1/2} s^{7/4} \sim s^{5/2} \tag{16}$$

As the compartment is geometrically scaled, $A_{sf} \sim s^2$, and time is scaled according to $t \sim s^{1/2}$. Preserving the effect of conduction results in the compartment boundaries scaling of

$$k_w \rho_w c_w \sim s^{3/2} \quad (17)$$

Equations (14) and (15) can also be substituted into Equation (5) to obtain a dimensionless group (Π term):

$$\Pi_{w,k} = \frac{(k_w \rho_w c_w)^{1/2} s^2 T_\infty}{\rho_\infty c_p T_\infty \sqrt{g} s^{5/2}} \sim \frac{\text{conduction}}{\text{enthalpy flow}} \quad (18)$$

Next, consider the heat loss by convection:

$$\dot{q}_{w,c} \sim h_c A_{sf} (T - T_w), \quad (19)$$

where, h_c is the heat convection coefficient. Preserving $\dot{q}_{w,c} \sim s^{5/2}$ in (19) requires that h_c be scaled according to

$$h_c \sim s^{1/2} \quad (20)$$

Similarly, a dimensionless group can also obtained by substituting Equation (19) into Equation (5):

$$\Pi_{w,c} = \frac{h_c s^2 T_\infty}{\rho_\infty c_p T_\infty \sqrt{g} s^{5/2}} \sim \frac{\text{convection}}{\text{enthalpy flow}} \quad (21)$$

The heat loss rate by radiation can be written as

$$\dot{q}_{w,c} \sim A_{sf} \sigma_g \varepsilon_g \left(T^4 - T_w^4\right) \quad (22)$$

Substituting Equation (22) into Equation (5),

$$\Pi_{w,r} = \frac{s^2 \sigma_g \varepsilon_g T_\infty^4}{\rho_\infty c_p T_\infty \sqrt{g} s^{5/2}} \sim \frac{\text{radiation}}{\text{enthalpy flow}} \quad (23)$$

Hence, preserving $\Pi_{w,r}$ requires that

$$\varepsilon_g \sim s^{1/2}, \quad \text{or} \quad T_\infty \sim s^{1/6} \quad (24)$$

The dimensionless groups for wall thickness can be written as

$$\Pi_{\mathrm{w},\delta} = \frac{\delta_w}{[(k_\mathrm{w}/\rho_\mathrm{w}c_\mathrm{w})s^{1/2}]^{1/2}} \sim \frac{\text{wall thickness}}{\text{thermal thickness}} \tag{25}$$

The four dimensionless groups, $\Pi_{\mathrm{w,k}}$, $\Pi_{\mathrm{w,c}}$, $\Pi_{\mathrm{w,r}}$, and $\Pi_{\mathrm{w},\delta}$, needed to determine proper scaling of the compartment boundary are summarized in Table 1.

Complete scaling requires preserving all four dimensionless groups in Table 1. Preservation of conduction may be achieved by changing the wall material. Preservation of convection requires a change in heat convection coefficient. Practically, this requires a material that may be difficult to find. Radiation scaling requires either a change of gas emissivity or a change of ambient temperature. For a 118-scale compartment with an ambient temperature of the prototype of, $T_\infty = 25°\mathrm{C}$, the ambient temperature of the 1/8-scale model needs to be changed to $(1/8)^{1/6}(273+25)\,\mathrm{K} = 211\ \mathrm{K} = -62°\mathrm{C}$. This is very difficult to obtain in typical lab environment. Changing gas emissivity is possible by using different fuels in scaled models. For convenience, wood cribs are used in both prototype and scaled compartment fires. Hence, convection scaling is difficult to achieve practically. Similarly, changing gas flow to match convection effects is difficult to achieve practically.

In scaling the compartment boundaries, the heat loss through the compartment walls can be assumed to be significantly greater than the heat loss through the vent. This assumption is appropriate because the compartment model considered is an enclosure with a small vent, such as a typical window in a room. If the vent is relatively large, this assumption is no longer proper, and the heat loss through vent must be taken into account.

Table 1. Dimensionless groups and scaling rules for compartment boundaries.

Dimensionless groups	Scaling rules	Adjustment
$\Pi_{\mathrm{w,k}} = \frac{(k_\mathrm{w}\rho_\mathrm{w}c_\mathrm{w})^{1/2}s^2T_\infty}{\rho_\infty c_p T_\infty \sqrt{g}s^{5/2}} \sim \frac{\text{conduction}}{\text{enthalpy flow}}$	$k_\mathrm{w}\rho_\mathrm{w}c_\mathrm{w} \sim s^{3/2}$	Change wall material
$\Pi_{\mathrm{w,c}} = \frac{h_\mathrm{c}s^2T_\infty}{\rho_\infty c_p T_\infty \sqrt{g}s^{5/2}} \sim \frac{\text{convection}}{\text{enthalpy flow}}$	$h_\mathrm{c} \sim s^{1/2}$	Change gas flow
$\Pi_{\mathrm{w,r}} = \frac{s^2\sigma_\mathrm{g}\varepsilon_\mathrm{g}T_\infty^4}{\rho_\infty c_p T_\infty \sqrt{g}s^{5/2}} \sim \frac{\text{radiation}}{\text{enthalpy flow}}$	$\varepsilon_\mathrm{g} \sim s^{1/2}$ or $T_\infty \sim s^{1/6}$	Change fuel or ambient temperature
$\Pi_{\mathrm{w},\delta} = \frac{\delta_\mathrm{w}}{[(k_\mathrm{w}/\rho_\mathrm{w}c_\mathrm{w})s^{1/2}]^{1/2}} \sim \frac{\text{wall thickness}}{\text{thermal thickness}}$	$\delta_\mathrm{w} \sim \left(\frac{k_\mathrm{w}}{\rho_\mathrm{w}c_\mathrm{w}}\right)^{1/2} s^{1/4}$	Adjust thickness

Table 2. Scaling rules for wood cribs design.

Design parameters	Scaling rules
Thickness of wood sticks, b_w	$b_w \sim s^{1/3}$
Spacing between wood sticks, s_w	$s_w \sim s^{1/3}$
Length of wood sticks, L_w	$L_w \sim s^{7/6}$
Number of layers, N_w	$N_w \sim s^{1/3}$
Number of wood sticks per layer, n_w	$n_w \sim s^{5/6}$

It is hypothesized that it is sufficient to scale the effects of conduction and wall thickness for a typical compartment having a small vent.

The scaling rule for heat generation rate in Equation (6) is used as the basis of the design of fuel array (wood cribs). In this paper, the derivation of scaling rules for wood cribs is similar to Croce and Xin's method. A detailed description can be found in reference [10]. The only difference is that the time scale is first fixed. The burning time of wood cribs should follow $t \sim s^{1/2}$. Scaling rules for the design of wood cribs are summarized in Table 2.

EXPERIMENTAL VERIFICATION

Two different types of fire scenarios are used to verify the partial scaling strategy.

A 'small fire' is defined as a fire with 15 minutes burning time, and a 'large fire' is defined as a fire with 60 minutes burning time. The burning time is defined as the duration between the start of the fire to the time at which flame is no longer visible. The prototype represents a room with a $3.7\,\text{m} \times 3.7\,\text{m}$ floor and a 2.44 m height (inside dimensions). The wall material of the prototype is assumed to be Type C Gypsum wallboard [11] having a density of $678\,\text{kg/m}^3$. The thickness of the compartment walls in the prototype is 15.9 mm. The vent width of the prototype is 0.5 m, and the height of the vent is 2.44 m.

Experiments at two scales (1/4 and 1/8) are designed. The purpose of these two reduced-scale experiments is to show the similarity of compartment fires at two different scales can be achieved by using the theory of scaling presented in this article. The wood cribs used for the two fire scenarios are designed using the scaling rules [10] found in Table 2.

White oak with density of $720\,\text{kg/m}^3$ is used due to its high density and availability. The wood cribs designed for the prototype and the wood cribs used in the two scaled fires are shown in Table 3. The prototype design is chosen in order to achieve 15 minutes burning duration for a small fire scenario and 60 minutes duration for a large fire scenario (Figure 3).

Table 3. Design parameters of cribs.

Scale	N_w	n_w	b_w (mm)	L_w (mm)	P_{or}
	Small fire scenario				
1	8	28	19.1	1257	0.70
1/4	5	9	12.0	250	0.68
1/8	4	5	9.5	111	0.71
	Large fire scenario				
1	8	28	44.5	2335	0.73
1/4	5	9	28.0	463	0.68
1/8	4	5	22.2	206	0.72

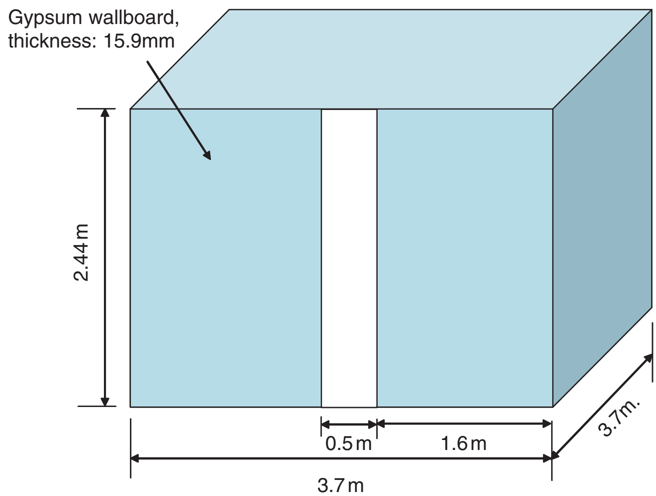
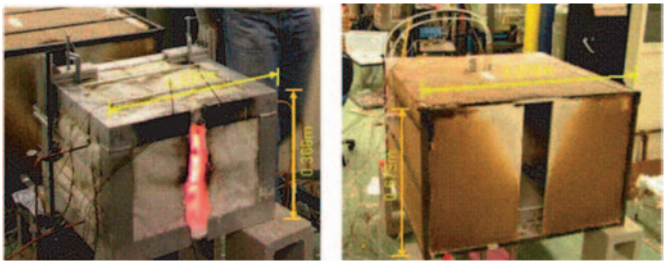


Figure 3. *Geometry of the prototype compartment. (The color version of this figure is available online.)*

Since thermal properties of wall materials are usually temperature dependent, it is difficult to find a material whose thermal properties can match the scaling rules for every temperature point. A single material, therefore, cannot accurately represent the wall material throughout the experiment. The strategy in this study is to pick the expected mean temperature of compartment walls which can be predicted by using CIB data [12]. For the compartment fires considered in this study, the mean temperature of walls is in the range of 400–600°C. Thus, the wall materials for scaled models can be determined for this specific temperature range. The chosen material will be reasonably representative of the prototype throughout the entire experiment.



1/8-scale 1/4-scale

Figure 4. *1/8-scale and 1/4-scale compartments. (The color version of this figure is available online.)*

Saffil LD mat [13] was used as the wall material to build the 1/8-scale compartment and Kaowool 3000 [14] for the 1/4-scale compartment. The density of Saffil LD mat is 208 kg/m^3, and the density of Kaowool 3000 is 40 kg/m^3. Their specific heat values are similar to that of Type C gypsum board (1.0 J/kg K) used in the prototype. The parameters, $\Pi_{w,k}$ and $\Pi_{w,\delta}$, are approximately satisfied at the two different scales with the use of Saffil LD and Kaowool 3000. The thickness of the compartment wall of the 1/4 scale model is 34 mm, and the thickness of the compartment wall of the 1/8 scale model is 13 mm.

Compartment fires at two model scales are conducted. For each scaled compartment, two different wood crib designs, one to represent a small fire and the other to represent a large fire, are used to represent a building fire of 15-and 60 minutes duration, respectively. For the design of scaled compartments, the inside space dimension is geometrically scaled. Figure 4 shows the compartments used to conduct the experiments.

For each compartment-fire test, the wood mass loss rate is measured by a load cell. Hot gas temperature in the enclosure and temperature at different elevations are measured by type K thermocouples and heat flux on the compartment walls is measured by using heat flux sensors. Figure 5 is a schematic drawing of the typical experimental measurement set-up.

RESULTS OF SCALED COMPARTMENTAL FIRES

Figure 6 shows the burning of two scaled fires. The burning time of wood cribs should be scaled according to $t \sim s^{1/2}$. The temperature in the compartment should be independent of scales, $T \sim s^0$. These two relations are fundamental scaling relations for the scaled fire experiments. Figure 7 shows the location of the hot gas temperature measurement points. The thermocouples are located insides the compartment 25 mm from the surface of the compartment wall. The five thermocouples are equally spaced.

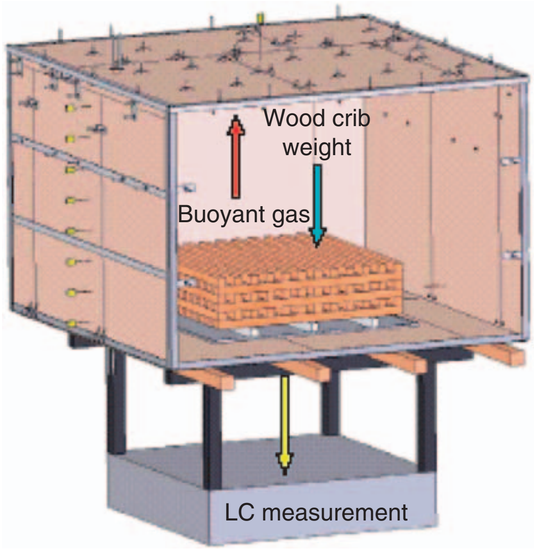


Figure 5. *Measurement set-up (front walls not shown). (The color version of this figure is available online.)*

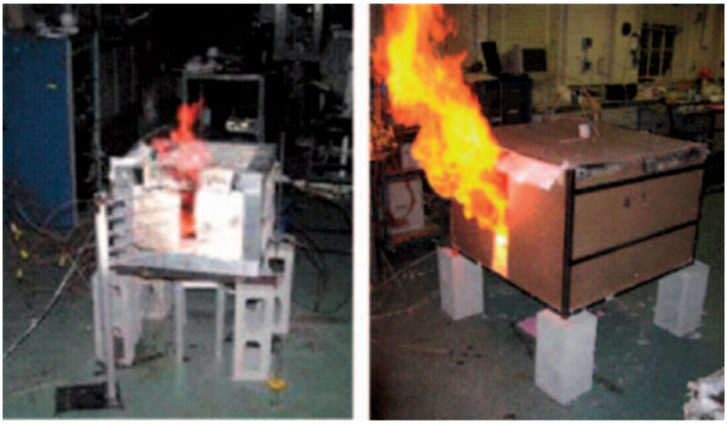


Figure 6. *Scaled compartment fires. (The color version of this figure is available online.)*

Figures 8 and 9 show the hot gas temperature profiles for the small fires and large fires, respectively. The figure plots are in prototype time scale ($t_p = t_m/s^{1/2}$). The results show the similarity of the compartment fires at two different scales. The maximum fire temperature and the time–temperature curves compare well at different scales. However, there is a

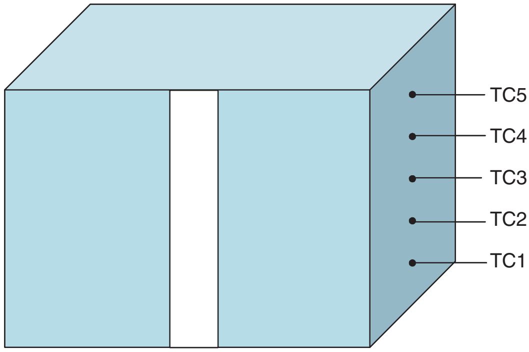


Figure 7. Location of five typical hot gas temperature measurement points. (The color version of this figure is available online.)

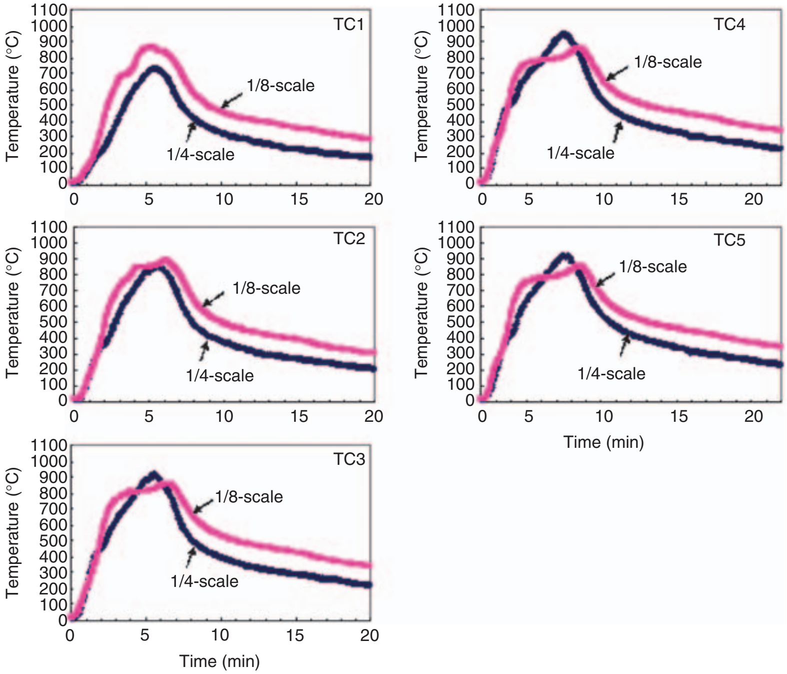


Figure 8. Hot gas temperature profiles of small fires. (The color version of this figure is available online.)

shift in the temperature profiles in the large fires as shown in Figure 9. The hot gas temperature in the 1/4-scale model reaches a relatively stable high temperature (800–900°C) in the early burning stage (4–20 minutes, full-scale time); however, in the same time range, the hot gas temperature in the

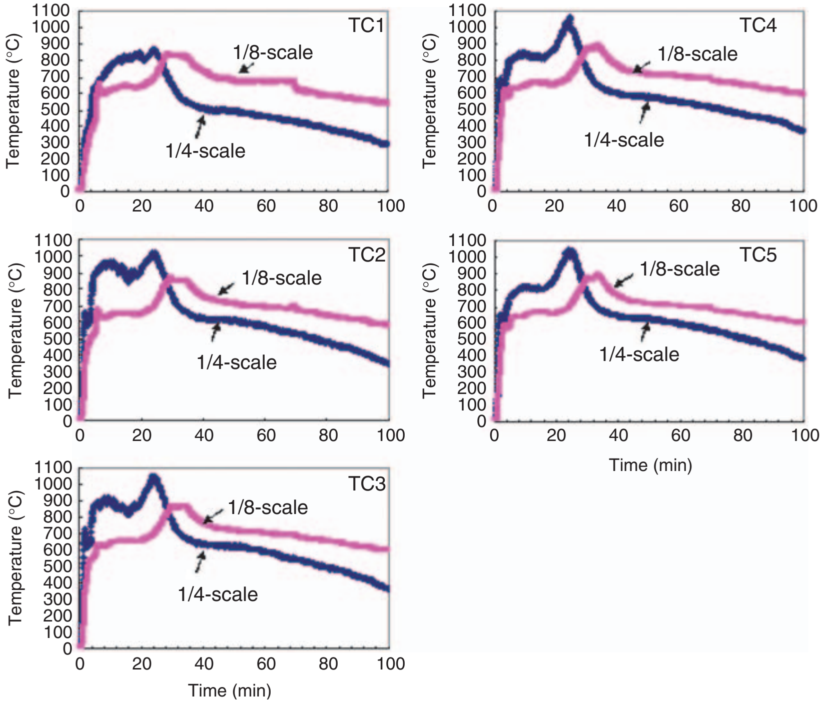


Figure 9. *Hot gas temperature profiles of large fires. (The color version of this figure is available online.)*

1/8-scale model is approximately 20% lower. This inaccuracy may be due to the assumption that the heat loss through the vent by radiation is neglected. Figure 6 shows that a significant amount of flame is observed to have spread out of the vent in the large fires. In this case, the effect of the heat loss through the vent may be significant. Therefore, neglecting the heat loss through the vent may have generated errors.

In this study, the validity of the proposed scaling method was examined by the experiments at two scales: 1/4 and 1/8, while the test of the prototype was not available due to the lack of resources. This scaling method has been implemented by simulating the interaction of fire with structures on the 96th floor of the World Trade Center tower 1 by conducting a 1/20-scale experiment [15]. The fire temperature profiles at different locations on the floor and the corresponding structure temperature profiles from the scaled test were found to be consistent with visual evidence and analytical results. These experimental results showed that small-scale tests can replicate a prototype fire in a satisfactory manner if the proposed scaling method is used.

CONLUSIONS

Techniques to scale compartment fires by using small-scale models are explored. Based on the time scaling, $t \sim s^{1/2}$, the proposed scaling rules for designing open-packed wood cribs and determining the composition and size of compartment boundaries are validated by tests of wood cribs burning in enclosures at two scales (1/8-scale and 1/4-scale). Results from the two scaled models compared well. While proper scaling is not always practical, the experiments conducted show that for realistic compartments with small vents, scaling for the effects of conduction results in a relatively accurate temperature profile in the scaled compartment if flame is contained within the compartment. The maximum temperatures at the two scales differ by <10% when the flame is contained within the compartment. When a significant amount of flame occurs outside of the compartment, the maximum temperature difference is still <20%. In both cases, the temperature profile and duration at the different scales are similar. These results suggest that the scaling rules can be used to simulate fire events at different scales.

NOMENCLATURE

b_w = Stick thickness
c_i = Specific heat of insulation
c_w = Specific heat of wall material
dT = Increment of temperature
g = Acceleration of gravity
h_c = Coefficient of heat convection
k = Thermal conductivity
k_w = Thermal conductivity of wall material
m = Mass
$\dot{m}$ = Mass flow rate, burning rate of fuel
p = Pressure
$\dot{q}$ = Heat loss rate
$\dot{q}''$ = Heat flux onto object
$\dot{q}_v$ = Heat loss rate through vent
$\dot{q}_w$ = Heat loss rate through walls
$\dot{q}_{w,c}$ = Heat loss rate to walls by convection
$\dot{q}_{w,k}$ = Heat loss rate through walls by conduction
$\dot{q}_{w,r}$ = Heat loss rate to walls by radiation
s = Linear length scale
s_w = Stick spacing

t = Time
t_m = Model time
t_p = Prototype time
t_r = Reference time (or cribs burning time)
u = Gas flow velocity
A = Area (or sectional area)
A_{sf} = Area of wall surface
A_{vent} = Area of vent
L_w = Length of stick
P = Porosity factor
$\dot{Q}$ = Heat generation rate
T = Temperature
T_∞ = Ambient temperature, room temperature
T_f = Hot gas temperature or fire temperature
T_w = Temperature of compartment walls
V = Volume
α_s = Absorption of surface
δ_T = Thermal thickness of walls
δ_w = Thickness of walls
ε_f = Emissivity of flame
ε_g = Gas emissivity
ρ = Density
ρ_w = Density of wall material
ρ_∞ = Density of air at ambient temperature
σ_g = Stefan-Boltzmann constant
$\Pi_{w,k}$, $\Pi_{w,c}$, $\Pi_{w,r}$, $\Pi_{w,\delta}$ = Dimensionless groups of wall conduction, convection, radiation, and wall thickness, respectively

ACKNOWLEDGMENTS

This work was funded by the US National Science Foundation under award No. 0301643. Special thanks are extended to Mr. Peter Veloo for providing help in the experimental work.

REFERENCES

1. FEMA, "World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations," In: McAllister, T. ed., FEMA 403, Federal Emergency Management Agency, Washington, D.C., 2002.

2. ASTM E 119, Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, USA, 2006.
3. Issen, L., "Scaled Models in Fire Research on Concrete Structures," Journal of the PCA Research and Development Laboratories, Vol. 8, No. 3, 1966, pp. 10–26.
4. O'Connor, D.J., Silcock, G.W.H. and Morris, B., "Furnace Heat Transfer Processes Applied to a Strategy for the Fire Testing of Reduced Scale Structural Models," Fire Safety Journal, Vol. 27, 1996, pp. 1–22.
5. Quintiere, J.G., Fundamentals of Fire Phenomena, John Wiley & Sons, Inc., 2006.
6. Gross, A.F. and Robertson, D., "Experimental Fires in Enclosures," In: 10th International Symposium on Combustion, The Combustion Institute, 1965, pp. 931–942.
7. Heskestad, G., "Modeling of Enclosure Fires," Journal of Fire and Flammability, Vol. 6, No. 3, 1975, pp. 253–273.
8. Croce, P.A., Modeling of Vented Enclosure Fire Part 1. Quasi-Steady Wood-Crib Source Fire, Technical Report, Norwood, MA, USA, Factory Mutual Research Corporation, 1978.
9. Croce, P.A. and Xin, Y., "Scale Modeling of Quasi-steady Wood Crib Fires in Enclosures," Fire Safety Journal, Vol. 40, 2005, pp. 245–266.
10. Perricone, J.A., Scale Modeling of the Transient Behavior of Wood Crib Fires in Enclosures, MS Thesis, 2005, University of Maryland.
11. Harmathy, T.Z., Properties of Building Materials at Elevated Temperatures, National Research Council of Canada, Division of Building Research, Ottawa, Canada, 1983.
12. Thomas, P.H. and Heselden, J.M., C.I.B. International Co-operative Programme on Fully-Developed Fires in Single Compartment: Comprehensive Analysis of Results.
13. Unifrax Corporation, http://www.unifrax.com
14. Thermal Ceramics, www.thermalceramics.com
15. Wang, M., Chang, P.C., Quintiere, J.G. and Marshall, A., "Scale modeling of the 96th Floor of World Trade Center Tower 1", ASCE Journal of Performance of Constructed Facilities, Vol. 21, No. 6, 2007.