An Integrated Model to Predict Fire Resistance of Wood Floor Assemblies

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ABSTRACT: An integrated numerical model to predict the fire resistance of wood-framed floor assemblies has been developed. The assemblies considered in this article are floors constructed with nominal 2×8 ($38 \times 191\,mm^2$), 2×10 ($38 \times 241\,mm^2$) or 2×12 ($38 \times 292\,mm^2$) wood joists lined with Type X gypsum board (12.7 mm or 15.9 mm thickness) as a ceiling membrane with (or without) resilient channels and 15.9 mm thick plywood as a sub-floor. The model includes a heat transfer sub-model to calculate the flow of heat in the assembly and a structural sub-model to evaluate the mechanical performance of the assembly. The heat transfer sub-model employs two-dimensional heat conduction equations to predict the temperatures in the ceiling (gypsum board), wood joists and sub-floor of the assembly when the ceiling is exposed to fire. Using the temperature distribution in the joists predicted from the heat transfer equations, the structural sub-model analyzes the mechanical strength of the joists and calculates joist deflection in the assembly. Results from the numerical model are compared to results from full-scale tests. Reasonably good agreement is observed.

KEY WORDS: fire resistance, structural performance, floor assembly, heat transfer, structural model.

INTRODUCTION

A SERIES OF numerical models have been developed to predict the fire resistance of wood-framed wall assemblies and floor/ceiling assemblies. The models utilize two-dimensional heat-conduction equations and thermophysical property data to describe the heat transfer through the assemblies. The model for the wall assemblies has already been published [1–5]. The model discussed in this article is an integrated fire resistance model for wood-joist floor/ceiling assemblies when the ceiling is

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exposed to fire. The assemblies considered in this study are constructed with nominal 2×8 ($38 \times 191\,\mathrm{mm}^2$), 2×10 ($38 \times 241\,\mathrm{mm}^2$) or 2×12 ($38 \times 292\,\mathrm{mm}^2$) wood joists lined by Type X gypsum board (12.7 mm or 15.9 mm thickness) as a ceiling membrane with (or without) resilient channels, and 15.9 mm thick plywood as a sub-floor. The resilient channels are oriented perpendicular to the direction of the joists and usually placed between the ceiling and joists. If the ceiling cavity is not filled with insulation, radiant and convective heat transfer through the cavity is significant [6]. The model calculates the view factors for the radiant heat exchange between the ceiling surface, sub-floor surface and joist surface. In addition, the model considers opening of joints at the ceiling. Since the gypsum board shrinks and bends at high temperatures [1], the joints between two adjacent sheets of gypsum ceiling boards open and boards are apt to sag. Through the joint openings, hot fire gases come into the floor/ceiling cavity and heat the assemblies from the inside. The present model simulates this opening of joints at the ceiling of the assemblies and predicts the thermal and mechanical failure of the floor/ceiling assemblies with (or without) resilient channels.

HEAT TRANSFER MODEL

The heat transfer model employs two dimensional heat conduction equations to calculate the flow of heat in the ceiling, joists and sub-floor.

$$C_p \rho \left(\frac{\partial T}{\partial t} \right) = \frac{\partial}{\partial x} \left(\frac{k \partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{k \partial T}{\partial y} \right) \tag{1}$$

where C_p is specific heat (J/kg K), ρ is density (kg/m^3), and k is a thermal conductivity (W/m K), T is temperature (K), t is time (s), and x and y are space coordinates (m). The above thermophysical properties C_p, ρ, and k are defined as functions of temperatures [1–4].

The boundary condition at the surface of the gypsum ceiling board facing the fire is given by balancing heat conduction just inside the surface with the radiant and convective heat absorbed from the fire:

$$-k \left(\frac{\partial T}{\partial x} \right) = h(T_{\mathrm{F}} - T_{\mathrm{sf}}) + \varepsilon_{\mathrm{eff}} \sigma (T_{\mathrm{F}}^4 - T_{\mathrm{sf}}^{4)} \tag{2}$$

where T_{sf} is the surface temperature of the ceiling facing the furnace, T_{F} is the furnace temperature, h is the convective heat transfer coefficient (W/(m^2 K)) between the ceiling surface and the hot furnace gas, σ is the Stephan-Boltzmann constant, and $\varepsilon_{\mathrm{eff}}$ is the effective emissivity calculated from the emissivity of furnace gases and the emissivity of ceiling (gypsum board) surface [3].

The boundary condition at the sub-floor surface facing the ambient environment can be described as follows,

$$-k\left(\frac{\partial T}{\partial x}\right) = -h(T_a - T_{sa}) - \varepsilon_{eff}\sigma(T_a^4 - T_{sa}^4) \quad (3)$$

where T_{sa} is the surface temperature of the sub-floor facing the ambient environment and T_a is the ambient temperature.

If there is no insulation in the ceiling cavity, heat is transmitted from the ceiling to the sub-floor and to the joists by convection and radiation [6]. Thereby the boundary condition at the surface of the ceiling board facing cavity can be written as,

$$-k\left(\frac{\partial T}{\partial x}\right) = h(T_{cf} - T_c) + F_{12}\sigma(T_{cf}^4 - T_{cs}^4) + F_{13}\sigma(T_{cf}^4 - T_{cw}^4) \quad (4)$$

where F_{12} and F_{13} are the view factors for the radiant heat transfer through the cavity. T_{cf} is the surface temperature of the ceiling on the cavity side, T_{cs} is the surface temperature of the sub-floor on the cavity side, and T_c is the cavity gas temperature.

Figure 1 shows a schematic diagram of the view factors F_{12} and F_{13}. These view factors F_{12} and F_{13} are functions of joist size (height and width) and joist spacing, and also a function of the location Y_L as shown in Figure 1.

The boundary condition at the surface of the sub-floor facing the floor cavity can also be described as follows,

$$-k\left(\frac{\partial T}{\partial x}\right) = h(T_c - T_{cs}) + F_{21}\sigma(T_{cf}^4 - T_{cs}^4) + F_{23}\sigma(T_{cw}^4 - T_{cs}^4) \quad (5)$$

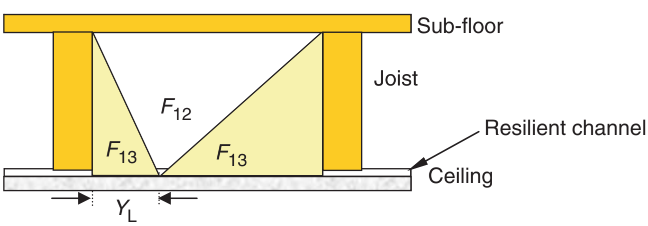


Figure 1. *Schematic diagram of the view factors F_{12} and F_{13} in the ceiling cavity. (The color version of this figure is available online.)*

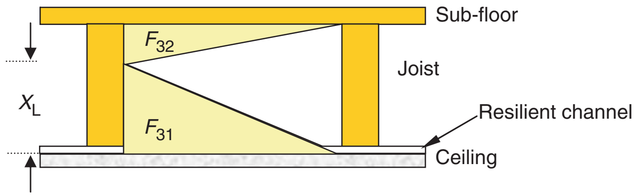


Figure 2. *Schematic diagram of the view factors F_{31} and F_{32} in the ceiling cavity. (The color version of this figure is available online.)*

The boundary condition at the surface of the joist facing the floor cavity can be described as,

$$-k\left(\frac{\partial T}{\partial y}\right) = h(T_c - T_{cw}) + F_{31}\sigma(T_{cf}^4 - T_{cw}^4) + F_{32}\sigma(T_{cs}^4 - T_{cw}^4) \qquad (6)$$

where T_{cw} is the joist surface temperature and F_{31} and F_{32} are the view factors shown in Figure 2.

At the interface between the joists and sub-floor, the following continuity equation is assumed as the boundary condition,

$$-k\left(\frac{\partial T}{\partial x}\right)_{joist} = -k\left(\frac{\partial T}{\partial x}\right)_{floor} \qquad (7)$$

Initial condition (at $t = 0$) can be described by using initial temperature in the assembly, T_a,

$$T = T_a \text{ at any } x \text{ and } y \qquad (8)$$

$$T_F = T_a \qquad (9)$$

The heat transfer coefficient, h (W/(m^{2}K)), is defined as a function of temperature [7] in this study.

Resilient Channels

Resilient channels, in general, are used for the improvement of acoustic performance of the floor/ceiling assemblies. National Research Council of Canada conducted numbers of full-scale tests to examine the fire resistance of the floor/ceiling assemblies with (or without) resilient channels [8]. The resilient channels are oriented perpendicular to the direction of the joists and usually placed between the ceiling and joists as shown in Figure 3. Therefore, a small air gap exists between the bottom surface of joist and

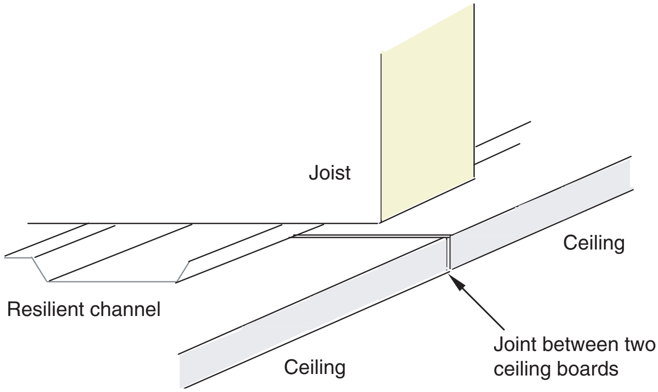


Figure 3. *Resilient channel in the floor/ceiling assembly. (The color version of this figure is available online.)*

ceiling surface, thereby, heat would be transmitted by radiation and convection from the ceiling surface to the bottom surface of the joists. The boundary condition at the bottom surface of the joist could be written as Equation (10).

$$-k\left(\frac{\partial T}{\partial x}\right) = h(T_{\rm c} - T_{\rm cw}) + \sigma(T_{\rm cf}^4 - T_{\rm cw}^4) \qquad (10)$$

Resilient channels, thermally, would be expected to work as a kind of cooling fin for the ceiling. If resilient channels are installed with 400 mm (16 in.) spacing, 17% more heat would be removed from the ceiling surface.

If there are no resilient channels in the assembly, the joists are in direct contact with the ceiling. The boundary condition in this case would be,

$$-k\left(\frac{\partial T}{\partial x}\right)_{\rm joist} = -k\left(\frac{\partial T}{\partial x}\right)_{\rm ceiling} \qquad (11)$$

THERMAL PROPERTIES OF SOLID COMPONENTS

Thermal conductivity of gypsum board [9] and wood [10] is defined as a function of temperature as shown in Figure 4. For comparison, the figure also shows different data for wood (dashed line), which yields a higher conductivity than data from Janssens [10] in the high temperature region (>600°C). The present model basically employs the test data provided by Janssens [10].

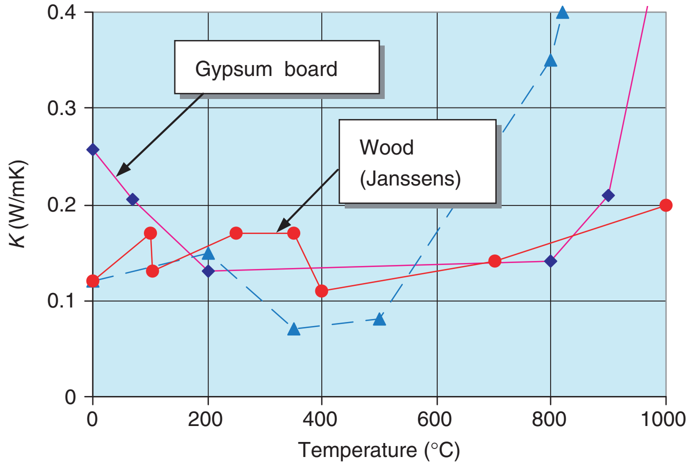


Figure 4. *Thermal conductivity of gypsum board [9] and wood from Janssens [10] (dashed line is data for wood thermal conductivity from Konig [19]). (The color version of this figure is available online.)*

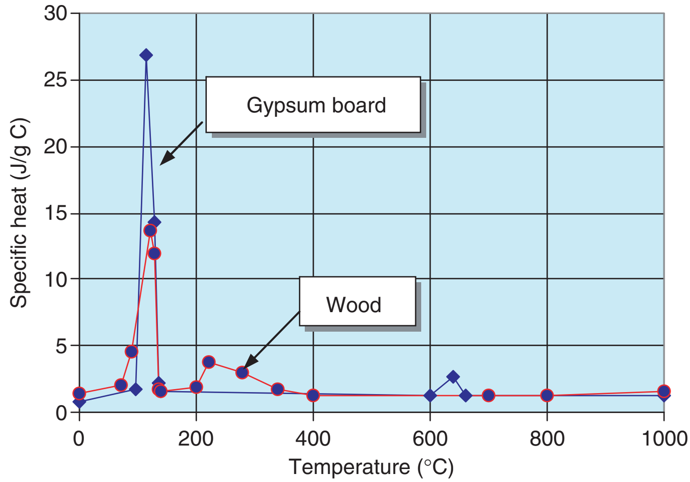


Figure 5. *Specific heat of gypsum board [9] and wood [10] as a function of temperature. (The color version of this figure is available online.)*

Figure 5 shows the specific heat of gypsum board [9] and wood [10] as a function of temperature.

Figure 6 shows the mass loss of wood and gypsum board as a function of temperature. According to this figure, wood loses 60% of its weight by 400°C and 70% by 600°C. Wood would be expected to release combustible

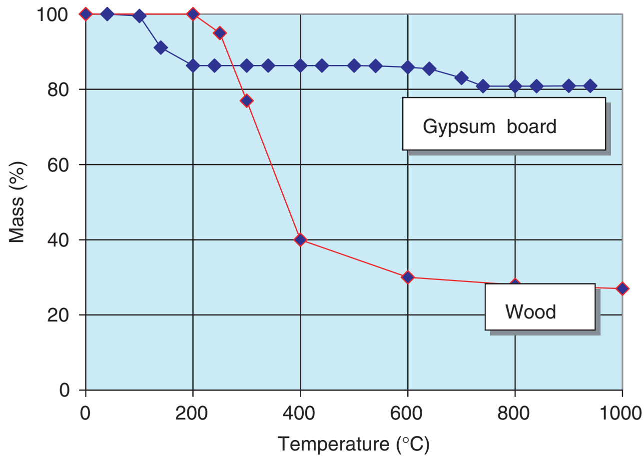


Figure 6. *Mass loss curves of wood and gypsum board as a function of temperature. (The color version of this figure is available online.)*

gases while the mass is decreasing. If those combustible gases burn, either within the ceiling cavity or outside the assemblies, approximately 13 kW/m^2 (average) of heat will be released [11].

Joint Opening

Test specimens used in the full-scale tests [8] are 4.8 m long and 3.9 m wide. The ceiling is exposed to heat in a propane fired horizontal furnace, in accordance with the ASTM E-119 or CAN/ULC-S191-M89 standard. Video cameras have been mounted at observation ports along each side of the furnaces to provide a visual record of the fire-exposed faces of assemblies during tests.

Visual observations from the full-scale fire endurance tests demonstrated that gypsum filler-compound used to cover fasteners and joints, loosens and begins to fall from the ceiling in 5 minutes after exposure to the fire, and after 15 minutes almost all filler compound fell from the ceiling [12]. The temperature of the gypsum ceiling board at this time was around 100°C, and no deformation of the board was observed. When the temperature of the gypsum ceiling board reached around 300°C, a small gap was observed halfway between two sets of nails. Once the joints open, the gypsum ceiling board was seriously heated by convection. Therefore the temperature of the board rapidly increases and the ceiling tends to separate from the assemblies. Figure 7 shows the temperature/time curves at key locations in the floor/ceiling assembly obtained from the full-scale fire test [6].

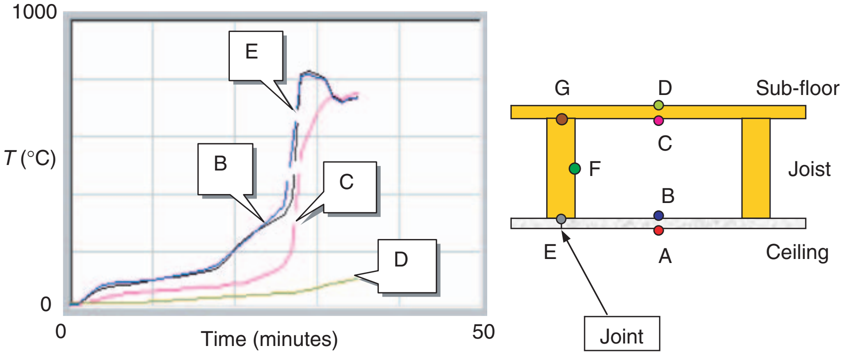


Figure 7. *Temperature/time curves at key locations in the assembly from the results of the full-scale tests. Thermocouple locations are indicated in the right figure. (The color version of this figure is available online.)*

The test was conducted in National Research Council of Canada, using 2×10 wood joists floor assembly which was lined by 12.7 mm thick gypsum board as a ceiling membrane and 15.9 mm plywood as a sub-floor. There was no insulation and no resilient channels in the assembly. A rapid increase in temperature was observed at around 27 minutes. This might indicate the joint between two sheets of ceiling board open and board are apt to separate. This rapid increase of temperature, however, might not be only due to the opening of joints but also due to the wood combustion in the assembly. Since the limited oxygen concentration in the assembly, smouldering combustion might be expected in the ceiling cavity.

Wood Combustion

Figure 8 shows the DSC test data of wood by Markova [13]. From this result, the model assumed that when the temperature at the surface of wood joist (and sub-floor) reaches 220°C, wood begins to decompose and release combustible gases in the floor cavity. The combustible gases from wood would react with oxygen and release heat in the cavity.

HEAT TRANSFER MODEL PREDICTION

Equations (1)–(11) were solved using the finite difference method. The space element along x and y were defined to be $\Delta x = 0.0015875$ m and $\Delta y = 0.003175$ m in gypsum board and sub-floor, and the space element in the joist was defined to be $\Delta x = 0.003175$ m and $\Delta y = 0.003175$ m. The time increment was defined to be 1 second. A graphical display from the computer program used to implement this solution is shown in the Appendix.

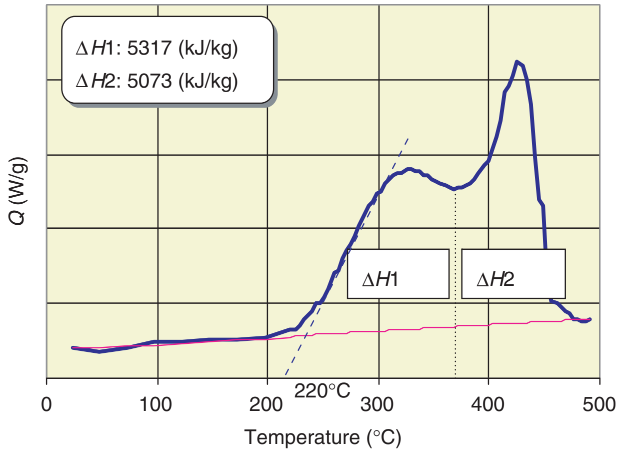


Figure 8. *Wood combustion data by DSC (Differential Scanning Calorimeter) by Markova [13]. (The color version of this figure is available online.)*

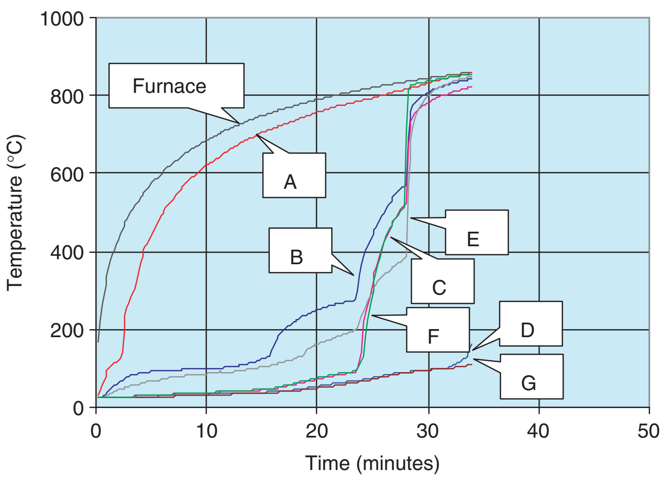


Figure 9. *Temperature/time curves predicted from the computer model. (The color version of this figure is available online.)*

Figure 9 shows the results predicted from the model, describing the temperature-time curves at key locations in the floor assembly (the locations A to G are indicated in Figure 7). The assembly was assumed to be 2 × 10 (38 × 241 mm^2) wood joists lined by 12.7 mm (1/2 in.) thick type X gypsum board as a ceiling membrane and 15.9 mm (5/8 in.) thick plywood as a sub-floor. There were no resilient channels.

The rapid increase of temperature appeared at 27 minutes at location B, C, E, and F. Compared to the results from the full-scale test (Figure 7), reasonably good agreement was observed. The surface temperature of wood joist (location F) is almost the same as the surface temperature of sub-floor (location C). The computer model predicted the following additional information,

- Joints between two sheets of gypsum ceiling board opened at 24 minutes (23 minutes 40 seconds)
- Char was observed on the surface of joist at 24 minutes (24 minutes 19 seconds)
- Thermal failure occurred at 34 minutes

The thermal failure is defined as the time when the temperature at location D has risen by 140°C above the ambient temperature. If the different data for thermal conductivity of wood shown in Figure 4 by dashed line is used, the model predicted that the thermal failure would occur at 34 minutes (34 minutes 20 seconds), which is almost the same as the results shown above (34 minutes). This is because the temperatures in the wood joist would be mostly under 600°C before thermal failure occurs.

Figure 10 shows the model prediction when resilient channels were installed in the assembly. Compared to Figure 9, the results look similar to each other; however, the figures show the resilient channels would somewhat

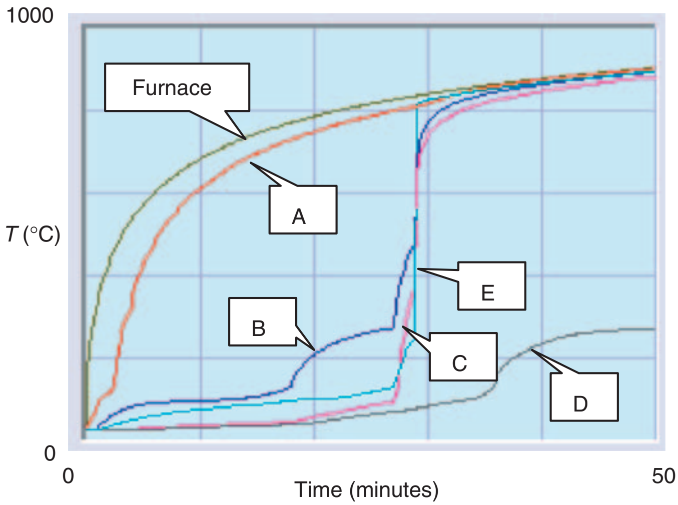


Figure 10. *Temperature/time curves predicted from the computer model when resilient channels were installed in the assembly. (The color version of this figure is available online.)*

improve the fire resistance of the floor/ceiling assemblies. The time to thermal failure was predicted to be 36 minutes when resilient channels were installed, which is better than the results when there are no resilient channels in the assembly (34 minutes). Also, the time to joint opening was predicted to be 27 minutes when the resilient channels were installed, which is better than the results when no resilient channels are in the assembly (24 minutes).

MECHAICAL PROPERTIES OF WOOD

As shown in Figure 6, wood loses its mass at high temperatures. Wood is expected to lose its strength at the same time.

Figure 11 shows the yield stress of wood as a function of temperature. Benichou [14] assumed the linear relation for the yield stresses for compression and tension. Kacikova measured the strength of wood with various temperatures [15].

Modulus of elasticity also decreases with temperature (Figure 12). Frangi and Fontana [16] discussed the test data of modulus of elasticity measured by Glos and Henrici [17] and Konig and Walleij [18]. The test data by Kachikova [15] is comparatively higher than those data. Benichou [14] assumed in his article the linear relationship between modulus of elasticity and temperature, which is also higher than those results by Glos and Henrici [17] and Konig and Welleij [18].

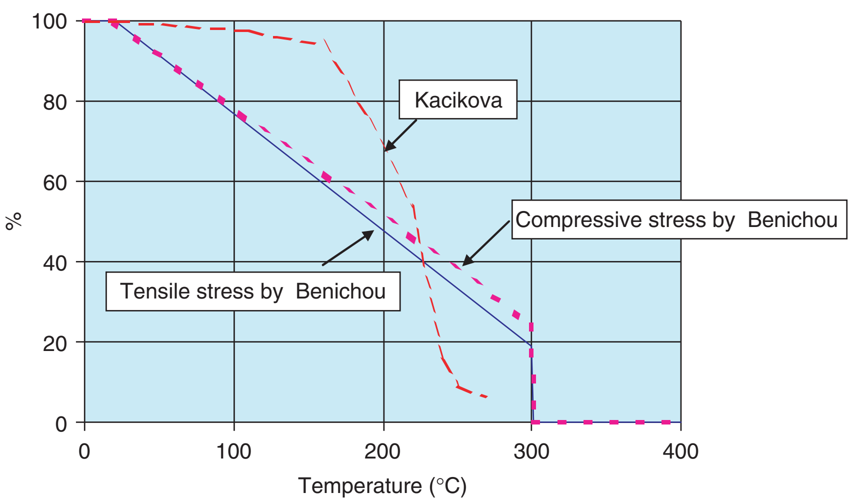


Figure 11. Yield stress of wood as a function of temperature. (The color version of this figure is available online.)

STRUCTURAL MODEL

The heat transfer model provides the temperature distribution in the wood joist. The structural model in this study, using those temperature distribution data, calculates the resistive moment of wood joist and deflection of joist. If the joist is a simply supported member with a uniform distributed load, the moment applied to the joist can be described,

$$M = \frac{wLz}{2} - \frac{wz^2}{2} \tag{12}$$

where M is the applied moment, w is the uniformed distributed load, L is the length of the joist, and z is the space coordinate along the joist length. The maximum moment can be described by $z = L/2$, because the midpoint is the weakest location in the joist, such that,

$$M_{\max} = \frac{wL^2}{8} \tag{13}$$

As each element, i, of wood joist decreases its strength, the neutral axis of joist moves, affecting the value of the moment of inertia I_i.

$$I_i = \frac{b_i h_i^3}{12} + b_i h_i d_i^2 \tag{14}$$

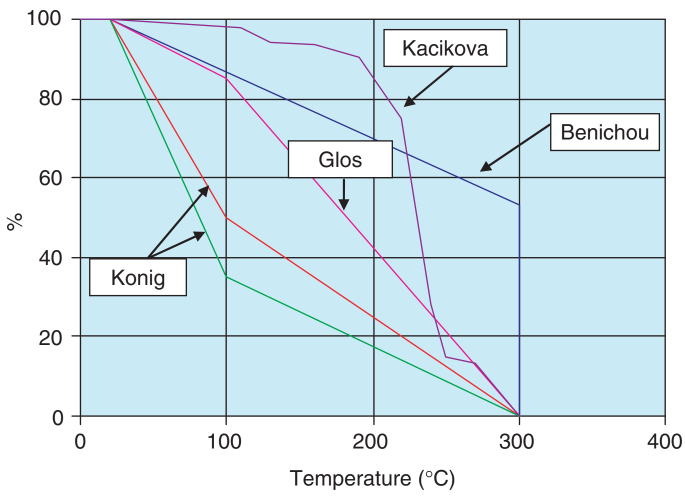


Figure 12. *Modulus of elasticity of wood as a function of temperature. (The color version of this figure is available online.)*

where b_j is the width of an element, h_j is the depth of element and d_j is the distance from the center of the element to the neutral axis. The width and depth, b_j and h_j, are defined as follows:

$$b_j = \Delta y \ (= 0.003175\,\mathrm{m}) \tag{15}$$

$$h_j = \Delta x \ (= 0.003175\,\mathrm{m}) \tag{16}$$

If the maximum deflection of a joist occurs at the midpoint, $L/2$, the maximum deflection can be described as follows:

$$D_{\max} = \frac{5wL^4}{384EI} \tag{17}$$

where EI is calculated from $\sum E_j I_j$ (from $j = 1$ to $j = 6$). E_j is the modulus of elasticity.

Calculations are conducted for the floor/ceiling assembly built with 2 × 10 wood joists (38 × 240 × 3900 mm^3 length) lined by 12.7 mm (1/2 in.) thick Type X gypsum board as a ceiling membrane and 15.9 mm (5/8 in.) thick plywood as a sub-floor loaded at 3.8 $\mathrm{kN/m}^2$. There is no insulation in the ceiling cavity and no resilient channels. The calculated results for joist deflection are shown in Figure 13 with different elasticity data provided by Kacikova, Benichou, Glos, and Konig in Figure 12. The modulus of elasticity at ambient temperature was assumed to be 7000 MPa

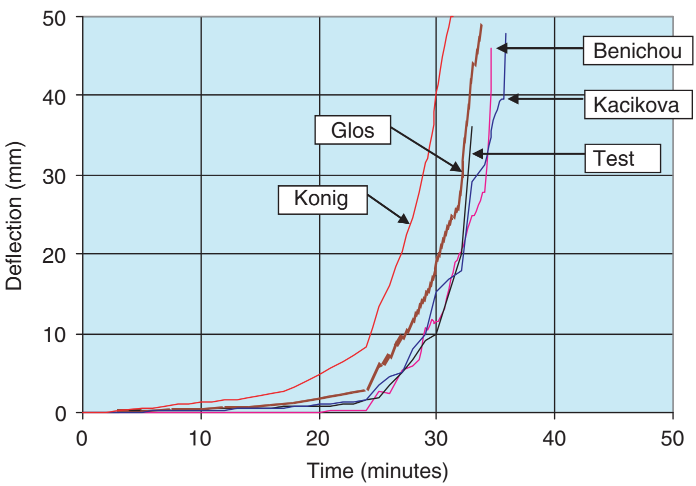


Figure 13. *Deflection of joist (model prediction and test data). (The color version of this figure is available online.)*

(7000 N/mm^2) for a 2×10 wood joist from the study by Benichou [14]. The figure shows that the results calculated from the data provided by Kacikova, Benichou, and Glos are close to each other and also close to the full-scale test data.

Figure 14 shows the calculated results for the resistive moment of wood joist with different strength data provided by Kacikova [15] and Benichou [14] shown in Figure 11. The strength of 2×10 wood joist at ambient temperature was assumed to be 25 MPa from the study by Benichou [14]. The results show that mechanical failure would occur at 29 minutes (28 minutes 49 seconds) when the test data from Kacikova [15] were used, and 28 minutes (27 minutes 40 seconds) when the data from Benichou were used [14]. The actual test was terminated at 30 minutes because the flame penetrated through the sub-floor [6]. The results predicted by using the data from Benichou are more conservative, while the results predicted by using data from Kacikova are closer to the test results.

When resilient channels (RC) were installed between the gypsum board and joists, the time to mechanical failure was predicted to be 31 minutes, when the data by Kacikova were used. Thus, RC would improve fire resistance. Those results are reasonably consistent with the results of the tests conducted at National Research Council of Canada [8].

Table 1 shows the summary of the model prediction for the thermal and mechanical failure of the wood floor assemblies with or without RC.

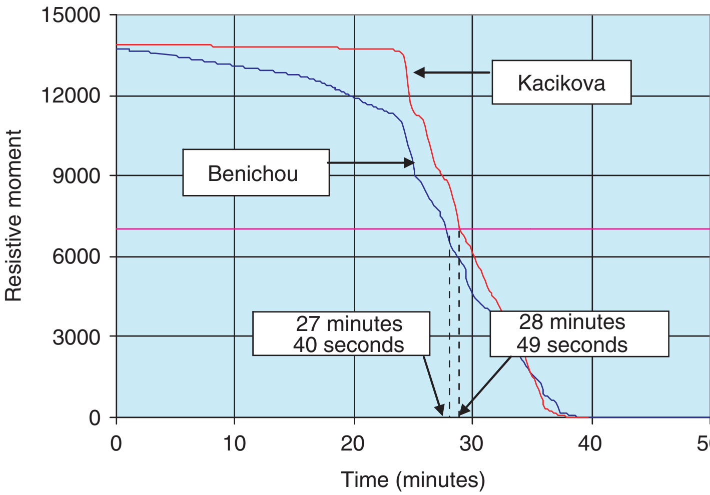


Figure 14. *Resistive moment of joist predicted by the model. (The color version of this figure is available online.)*

The results demonstrated that mechanical failure always occurs earlier than thermal failure. This means mechanical failure would be the crucial factor rather for floor/ceiling assemblies. The results also show that increasing the thickness of ceiling board would greatly improve the fire resistance of the assemblies and RC would also contribute some improvement.

CHAR FORMATION IN WOOD JOIST

Figure 15 shows the char development in joists predicted by the model. It was observed that the char spread along the joist surface at the beginning and develop toward the joist centre. Those results are consistent with the photographs of char formation in wood joists taken by Richardson [12].

Figure 16 shows the detailed char formation at the time when the mechanical failure would occur (left), at the time when the test was terminated (=30 minutes) and at the time when the thermal failure would occur (right).

Since a finite difference element in the calculation was defined as $0.003175 \times 0.003175\,m^2$, char depth was predicted by using this size, as shown in Table 2.

Table 1. Thermal and mechanical failure of floor/ceiling assemblies (model prediction).

Ceiling thickness	Resilient channels	Thermal failure	Mechanical failure
12.7mm (1/2 in.)	Without RC	34 minutes	28 minutes 49 seconds
12.7mm (1/2 in.)	With RC	36 minutes 20 seconds	31 minutes 3 seconds
15.9mm (5/8 in.)	Without RC	43 minutes 9 seconds	38 minutes
15.9mm (5/8 in.)	With RC	45 minutes 25 seconds	39 minutes 8 seconds

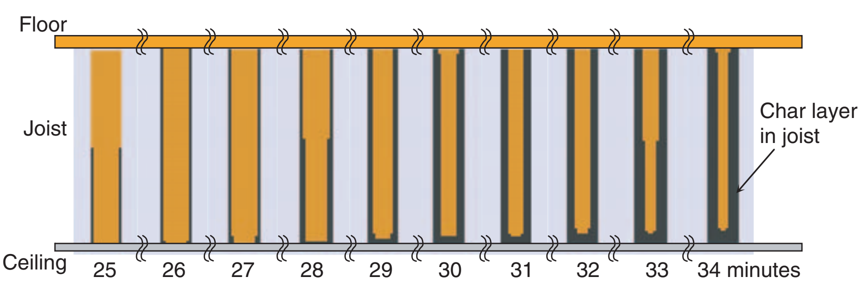


Figure 15. *Char formation in wood joists from 25 to 34 minutes, where the black part is the char layer. (The color version of this figure is available online.)*

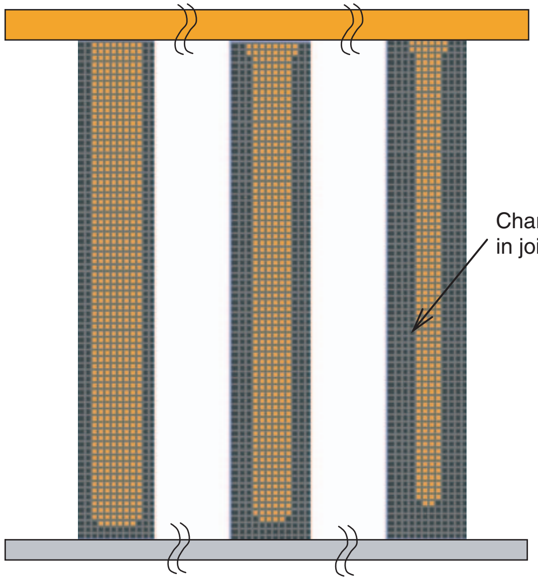


Figure 16. Detailed char formation in wood joists at the time when mechanical failure would occur (left), at the time when the test was terminated (center), and at the time when thermal failure would occur (right). (The color version of this figure is available online.)

Table 2. Char depth in wood joists (model prediction).

Time	Char depth, side (mm)	Char depth, bottom (mm)
At the time when mechanical failure would occur	6.35	6.35
At the time when the test was terminated	9.53	9.53
At the time when thermal failure would occur	12.7	15.88

CONCLUSIONS

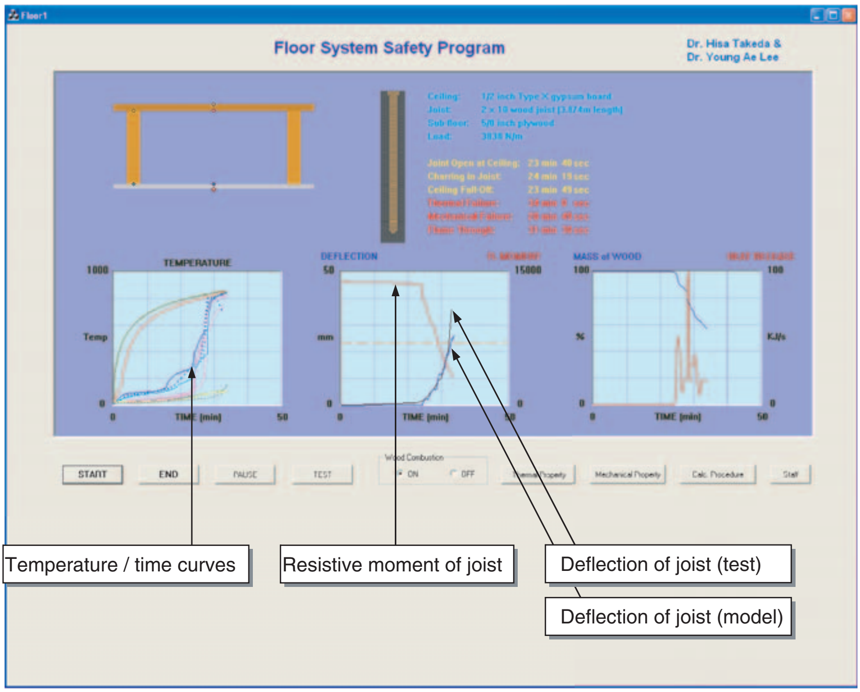
An integrated model has been developed for the prediction of fire resistance of wood-framed floor/ceiling assemblies. The model calculates the flow of heat in the assemblies and predicts mechanical failure of the assemblies.

Results show that mechanical failure rather than thermal failure is a crucial factor for the floor/ceiling assemblies.

The thickness of the gypsum ceiling board is the primary factor for the improvement of the fire resistance of the assemblies. RC also contribute some fire resistance improvement.

APPENDIX: COMPUTER PROGRAM OUTPUT

The computer program for implementing the model discussed in this article is available from the author. A typical graphic output with calculated and test results is shown below.



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