EFFECT OF INSULATION ON THE FIRE RESISTANCE OF WOOD-FRAMED FLOOR ASSEMBLY

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ABSTRACT: A computer model has been developed to investigate the effect of insulation on the fire resistance of wood-framed floor / ceiling assemblies. The floor / ceiling assemblies considered in this paper was assumed to be 2 x 10 wood joist (38 mm x 241 mm) lined by 15.9 mm (5/8 inch) or 12.7 mm (1/2 inch) thick Type X gypsum board as a ceiling membrane and 15.9 mm (5/8 inch) thick plywood (or OSB) as a sub-floor. The insulation pad was installed in the ceiling cavity to investigate the effect of insulation layer on the fire resistance of the floor / ceiling assembly. When the ceiling is exposed to fire, the model calculates the heat transfer through the assemblies and predicts the temperature rise in the ceiling, insulation layer, joists and sub-floor. Based on those temperature data, the model examines the mechanical performance of wood joists when insulation is installed in the floor / ceiling assemblies. The results are discussed with comparing to the results when no insulation in the assemblies.

KEYWORDS: Wood-framed floor assembly, Wood joist, Fire resistance, Computer model, Insulation,

1 INTRODUCTION

The computer models have been developed for investigating the fire resistance of wood framed wall assemblies [1-5] and floor / ceiling assemblies [6,7]. The paper presented at the previous WCTE conference in Miyazaki [7] described the model for the floor / ceiling assemblies with no insulation in the ceiling cavity. When the ceiling is exposed to fire, the heat is transmitted by conduction through the ceiling (gypsum board) and then transmitted to the sub-floor surface and joist surface by radiation and convection through ceiling cavity as shown in Figure 1.

On the other hand, when insulation pads are installed in the ceiling cavity (Figure 2), radiant heat transfer through the ceiling cavity is supposed to be blocked by the insulation layer. Therefore heat could be transmitted by conduction through the insulation layer. Due to the low thermal conductivity of insulation, heat might be accumulated at the interface between ceiling and insulation layer. As a result, the temperatures of the lower part of the assembly might increase much more than those temperatures in the non-insulated assemblies.

2 COMPUTER MODEL

2.1 HEAT TRANSFER EQUATIONS

Figure 1: Heat transmission through ceiling cavity by radiation when there is no insulation in the cavity

Figure 2: The radiant heat flow would be blocked by insulation layer when insulation is installed in the cavity

The computer model calculates the flow of heat in the assembly with insulation layer in the ceiling cavity and investigates the effect of insulation on the fire resistance of floor / ceiling assemblies.
The computer model is based on the two-dimensional heat conduction equations in the ceiling (gypsum board), insulation layer, wood joists and wood sub-floor.

\[
\text{Cp} \rho \left( \frac{\partial T}{\partial t} \right) = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) \tag{1}
\]

where \( C_p \) is a specific heat (J/kg*K), \( \rho \) 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 thermo-physical properties \( C_p, \rho \) and \( k \) are defined as functions of temperatures [5] shown in the previous paper [7].

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

\[
-k \left( \frac{\partial T}{\partial x} \right) = h(T_F - T_g) + \varepsilon_{eff} \sigma(T_F^4 - T_g^4) \tag{2}
\]

where \( T_g \) 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, \( \varepsilon \) is the Stephan-Boltzmann constant and \( \varepsilon_{eff} \) is the effective emissivity calculated from the emissivity of furnace gas and the emissivity of gypsum board surface [5].

The boundary condition at the sub-floor surface facing the ambient environment is,

\[
-k \left( \frac{\partial T}{\partial x} \right) = -h_a(T_a - T_{su}) - \varepsilon_{eff} \sigma(T_{su}^4 - T_a^4) \tag{3}
\]

where \( T_{su} \) is the surface temperature of the sub-floor facing the ambient environment, \( T_a \) is the ambient temperature and \( h_a \) is the convective heat transfer coefficient (W/m\(^2\)*K) between the sub-floor surface and the ambient environment.

Insulation layer in the ceiling cavity are assumed to be 89 mm (3.5 inch) thick in this study.

Where \( T_g \) is the temperature at the surface of the ceiling facing the insulation layer and \( T_{su} \) is the temperature at the surface of the insulation facing the ceiling.

The boundary condition at the surface of insulation facing the ceiling can be similarly described as follows,

\[
-k \left( \frac{\partial T}{\partial x} \right) = -h(T_{ig} - T_b) \cdot \sigma(T_{ig}^4 - T_b^4) \tag{5}
\]

The boundary condition at the other side of insulation facing the ceiling cavity can be described as,

\[
-k \left( \frac{\partial T}{\partial x} \right) = h(T_{ic} - T_c) + F_{12} \sigma(T_{ic}^4 - T_c^4) + F_{13} \sigma(T_{ic}^4 - T_{wm}^4) \tag{6}
\]

Where \( T_{ic} \) is the surface temperature of the insulation layer facing the ceiling cavity, \( T_{ic} \) is the temperature at the surface of the floor facing the ceiling cavity and \( T_c \) is cavity gas temperature. \( F_{12} \) and \( F_{13} \) are the view factors for the radiant heat transfer [7].

At the interface between gypsum board and joists, and joists and sub-floor, the following continuity equations are assumed as the boundary conditions,

\[
-k \left( \frac{\partial T}{\partial x} \right)_{\text{gypsum}} = -k \left( \frac{\partial T}{\partial x} \right)_{\text{joist}} \tag{7}
\]

\[
-k \left( \frac{\partial T}{\partial x} \right)_{\text{joist}} = -k \left( \frac{\partial T}{\partial x} \right)_{\text{floor}} \tag{8}
\]

The heat transfer equations are solved using finite difference method in this study. The size of the calculation element in the ceiling and sub-floor is assumed to be 1.5875 mm (1/16 inch) x 3.175 mm (1/8 inch) and 3.175 mm (1/8 inch) x 3.175 mm (1/8 inch) in joists and in the insulation layer. Implicit method is employed along X direction. The time increment is assumed to be 1 sec for the calculation in gypsum board, ceiling and wood joist, and 0.02 sec for the calculation in insulation layer.

### 2.2 Calculation Procedure in Insulation Layer

Since the density of insulation is around 15 kg/m\(^3\), which is quite low comparing to gypsum board (660 kg/m\(^3\)) and wood (425 kg/m\(^3\)), special consideration would be needed for the calculation of heat transfer through insulation layer.

Finite difference implicit method, therefore, is applied in this study for the calculation of heat transfer for x-direction and explicit method for y-direction. Thereby, each term of Equation (1) can be described as follows,

\[
\text{Cp} \rho \left( \frac{\partial T}{\partial t} \right) \rightarrow \text{Cp}_i(i, j, k) \rho_i(i, j, k) \tag{9}
\]

\[
(T_i(i, j, k + 1) - T_i(i, j, k))/\Delta t
\]
Where

\[ \frac{\partial}{\partial x}\left( k \frac{\partial T}{\partial x}\right) \rightarrow K_i(i, j, k)(T(i-1, j, k + 1) - T(i, j, k) + T(i+1, j, k + 1))/\Delta x^2 \]

(10)

\[ \frac{\partial}{\partial y}\left( k \frac{\partial T}{\partial y}\right) \rightarrow K_j(i, j, k)(T(i, j-1, k) - T(i, j, k) + T(i, j+1, k))/\Delta y^2 \]

(11)

Therefore the basic equation (1) was written as follows,

\[ A(i, j)T(i-1, j, k + 1) - 2B(i, j)T(i, j, k + 1) + C(i, j)T(i+1, j, k + 1) = D(i, j) \]

(12)

Where,

\[ A(i, j) = \frac{K_i(i, j, k)}{C_p(i, j, k) \rho(i, j, k) \Delta x^2} \Delta t \]

(13)

\[ B(i, j) = -\frac{2K_j(i, j, k)}{C_p(i, j, k) \rho(i, j, k) \Delta y^2} \Delta t - 1 \]

(14)

\[ C(i, j) = \frac{K_i(i, j, k)}{C_p(i, j, k) \rho(i, j, k) \Delta x^2} \Delta t \]

(15)

\[ D(i, j) = -Ti(i, j, k) - K_j(i, j, k) \]

\[ \frac{T(i+1, j, k) - 2T(i, j, k) + T(i-1, j, k)}{C_p(i, j, k) \rho(i, j, k) \Delta y^2} \Delta t \]

(16)

Where \( \Delta x = 3.175 \) mm (1/8 inch), \( \Delta y = 3.175 \) mm (1/8 inch) and \( \Delta x = 0.02 \) sec.

The matrix that should be solved in this study is as follows,

\[
\begin{bmatrix}
B_{i1} & C_{i1} & 0 & 0 & 0 & D_{i1} \\
A_{i1} & B_{i1} & C_{i1} & 0 & 0 & T_{i1} \\
0 & A_{i1} & B_{i1} & C_{i1} & 0 & T_{i1} \\
- & - & - & - & - & - \\
0 & 0 & 0 & A_{i1} & B_{i1} & C_{i1} & T_{i1} \\
0 & 0 & 0 & 0 & A_{i1} & B_{i1} & D_{i1}
\end{bmatrix}
\]

(17)

\[ A_{i1} \] can be obtained by the following equation, Equation (18) and the equation from the boundary condition, Equation (5), which is converted to Equation (19) in finite difference form.

\[ A_i(i, j)T_i(0, j, k + 1) - 2B_i(i, j)T_i(1, j, k + 1) + C_i(i, j)T_i(2, j, k + 1) = D_i(1, j) \]

(18)

\[ -K_i(i, j, k)T(2, j, k + 1) - T(0, j, k + 1) = \frac{2\Delta x}{h(T(1, j, k + 1) - T_c) - \sigma(T(1, j, k + 1)^4 - T_c(n, j, k + 1)^4)} \]

(19)

Also \( C_{i1} \) can be similarly obtained from the boundary condition, Equation (6) and also Equation (12).

2.3 THERMAL CONDUCTIVITY OF INSULATION

Before discussing about the effect of insulation on the fire resistance of wood floor assemblies, important thermal properties of insulation should be described comparing to the properties of wood and gypsum board. Heat transfer through the insulation can be considered to be a combination of gas-phase conduction, solid-phase conduction and radiation [8]. By a practical determination of the three modes of heat transfer, an effective thermal conductivity coefficient, as functions of temperature and density, could be derived. The following equations describe the effective thermal conductivity for glass-fibre insulation:

\[ k_{glass} = a + bT^{1.5} + cT^{3.0} \]

(20)

\[ a = a_1 + a_2 \rho + a_3 \]

(21)

\[ b = b_1 + b_2 \rho + b_3 \]

(22)

\[ c = c_1 + c_2 \rho + c_3 \]

(23)

where \( T \) is temperature (ºC) and \( \rho \) is the density of glass-fibre insulation. The coefficient ‘a’ corresponds to conductive heat transfer, ‘c’ corresponds to radiant heat transfer and ‘b’ to the interaction between conduction and radiation. Coefficients \( a_1, a_2, a_3 \), are constants and defined as follows

\[ a_1 = 1.492E-02 \quad b_1 = 2.777E-07 \quad c_1 = 3.557E-10 \]

\[ a_2 = 3.274E-05 \quad b_2 = 6.090E-10 \quad c_2 = 7.804E-13 \]

\[ a_3 = 1.202E-01 \quad b_3 = 2.235E-06 \quad c_3 = 2.864E-09 \]

On the other hand, the thermal conductivity of rock-fibre insulation is almost independent of density and defined as a function only of temperature.

\[ k_{rock} = a + bT^{1.5} + cT^{3.0} \]

(24)

\[ a = 0.035 \]

\[ b = 1.709E-05 \]

\[ c = 6.394E-11 \]

Figure 3 shows the thermal conductivity of glass-fibre insulation when the density is 15.0 kg/m³ and rock-fibre insulation when density = 40 kg/m³, comparing to the
thermal conductivities of wood and gypsum board. The thermal conductivity of glass-fibre insulation is relatively low at the lower temperature region ($T_i < 500^\circ$C).

![Figure 4: Thermal conductivity $k$ of glass-fibre insulation and rock-fibre insulation, comparing to the thermal conductivities of wood and gypsum board](image)

### 2.4 EFFECT OF INSULATION

In order to investigate the effect of insulation, the above equations were solved numerically for the floor ceiling assembly and compared to the results from the non-insulated assembly. The floor / ceiling assembly considered in this calculation was assumed to be 2 x 10 wood joist (38 mm x 241 mm) lined by 15.9 mm (5/8 inch) type X gypsum board as a ceiling membrane and 15.9 mm (5/8 inch) OSB as a sub-floor. 89 mm (3.5 inch) thick glass-fibre insulation (density: $\rho_i = 15$ kg/m$^3$) was installed in the ceiling cavity.

![Figure 5: Time / temperature curves at the locations of B and E, comparing to those at B' and E'](image)

Figure 5 shows the calculated results for the temperatures at the surface of the ceiling on the cavity side (B) and the interface between the ceiling and wood joist (E) for the insulated assembly and the temperatures at B’ and E’ for non-insulated assembly, when the ceiling was exposed to ASTM E-119 standard fire curve [10]. The locations B and E (and also B’ and E’) are shown in Figures 1 and 2.

The figure clearly shows the temperature at location B which is the interface between ceiling and insulation layer is much higher than that at the location B’ which is the same location when there is no insulation in the ceiling cavity.

Also the temperature at location E is higher than that at location E’. Those results demonstrate that the insulation layer blocks the flow of heat at the interface between the ceiling and insulation layer, as a result, the heat tends to accumulate the lower part of the assembly, when insulation layer is in the ceiling cavity.

### 3 RESULTS AND DISCUSSION

#### 3.1 MODEL VALIDATION

The computer model can be validated when comparing to the test data. National Research Council of Canada conducted small-scale tests for the floor / ceiling assemblies [9]. The test specimen for the floor / ceiling assembly was made of 2 x 10 wood joists (38 mm x 241 mm) lined by 15.9 mm (5/8 inch) type X gypsum board as a ceiling membrane and 15.9 mm (5/8 inch) thick plywood as a sub-floor [9].

![Figure 6: Test specimen for floor / ceiling assembly](image)

89 mm (3.5 inch) thick glass-fibre insulation pad was installed in the ceiling cavity as shown in Figure 6. The size of the specimen was 914mm long and 914mm wide [9].

The tests were carried out using ASTM E119 standard curve [10] as a furnace temperature. Figure 7 shows the time / temperature curves at locations B, C and D obtained from the tests. The temperature at location B rapidly increases at around 20 min. This might be due to the heat accumulation at the interface between ceiling and insulation.

On the other hand Figure 8 shows the test results when no insulation in the ceiling cavity. The temperature at location B is much lower than that at the same location B in Figure 7. This might be due to the heat accumulation at the interface between ceiling and insulation.

On the other hand Figure 8 shows the test results when no insulation in the ceiling cavity. The temperature at location B is much lower than that at the same location B in Figure 7. The effect of insulation on the temperatures at locations B and C is clearly observed when comparing those two figures.

Figures 9 and 10 show the model predictions. Figure 9 is the results when there is insulation in the ceiling cavity which corresponds to the test results in Figure 7, and...
Figure 10 is the results when no insulation which corresponds to Figure 8. When comparing those two figures, Figures 7 and 9, and also Figures 8 and 10, it can be observed that the computer model well simulated test data.

The results demonstrate that the insulation blocks the flow of heat in the floor / ceiling assembly, and therefore, the heat tends to accumulate at the interface between the ceiling and insulation layer. Thus, the temperatures at B and E are much higher than those at the same locations in Figure 10. The temperature at location D is slightly lower when there is insulation in the cavity (Figure 10) comparing to the temperature at the same location when there is no insulation (Figure 9). The model predicted the thermal failure would occur at 68min 49sec when there is insulation and 62min 9 sec when no insulation.

3.2 EFFECT OF INSULATION ON WOOD JOIST CHARRING

The computer model predicted the time to charring of wood joists. The time to charring was 29min 10sec when insulation is installed in the ceiling cavity and 37min 0sec when no insulation. Char formation in wood joists are also predicted by the computer model. Figure 11 shows the char formation at 35, 40, 45, 50 and 55 min when insulation was installed in the ceiling cavity, and Figure 12 the char formation when there is no insulation in the ceiling cavity. Comparing those two figures, the effect of insulation in the cavity is obvious, such that, heat is accumulated at the bottom part of the assembly when insulation is installed in the cavity, while the upper part of wood joist is protected by the insulation.
3.3 MECHANICAL STRENGTH OF WOOD JOISTS

As the char layer develops in the joist, joist loses its mass and gradually loses its strength. The structural model in this study, using the temperature distribution data predicted from the heat transfer model, 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,

\[ M = \frac{wLz}{2} - \frac{wz^2}{2} \]  

(25)

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,

\[ M_{\text{max}} = \frac{wL^2}{8} \]  

(26)

The strength of wood and the modulus of elasticity of wood decrease with temperature as shown in Figure 13 [7].

\[ E I_j = \sum_{j=1}^{n} E_j b_j h_j^3 \]  

(27)

Where \( b_j \) is the element width, \( h_j \) is the element depth in wood joist, \( d_j \) is the distance from the element centroid to the neutral axis, and \( E_j \) is the modulus of elasticity. \( b_j \) and \( h_j \) were assumed to be 3.175mm (1/8 inch) in this study. If the maximum deflection of joist occurs at the midpoint, \( L/2 \), the maximum deflection can be described as,

\[ D_{\text{max}} = \frac{5wL^4}{384\sum_{j=1}^{n} E I_j} \]  

(28)

If the floor assembly is constructed with 2 x 10 wood joist (38mm x 240mm x 3874mm length) lined by 15.8mm Type X gypsum board as a ceiling membrane and 15.8mm plywood as a sub-floor loaded by 3938N/m, the resistive moment of joist can be predicted as shown in Figures 14 and 15. Where the modulus of elasticity at room temperature was assumed to be 7000Mpa, and tensile and compressive strength at room temperature was assumed to be 25Mpa.
The results predicted that the mechanical failure would occur at 55 min 9 sec when insulation is installed in the ceiling cavity and 50 min 39 sec when no insulation in the ceiling cavity. This suggests that the insulation in the cavity would improve the fire resistance of the floor/ceiling assemblies. Also the results show that the mechanical failure always occurs earlier than the thermal failure occurs.

If rock-fibre insulation is installed in the ceiling cavity instead of glass-fibre insulation, the results are slightly different, because the density of rock-fibre insulation is higher than that of glass-fibre insulation and also thermal conductivity of rock-fibre insulation is higher than that of glass-fibre insulation. The time to charring in wood joists was predicted to be 29 min 30 sec. On the other hand, when glass-fibre insulation is installed, it was predicted to be 29 min 10 sec. The time of mechanical failure was predicted to be 60 min 30 sec when rock-fibre insulation is installed and 55 min 9 sec when glass-fibre insulation is installed. Rock-fibre insulation, therefore, would be somewhat better than glass-fibre insulation.

3.4 EFFECT OF JOINT OPENING

The computer model was validated by comparing to the small-scale test in sub-chapter 3.1. Since the small scale tests employed small piece of gypsum board as a ceiling membrane and there was no joints in the ceiling. But the full-scale assemblies have joints between two sheets of gypsum ceiling board. As already mentioned in the previous WCTE conference [7], gypsum board shrinks at high temperatures so that the joints between two adjacent sheets of gypsum ceiling board would open. If joints open, hot fire gases may come into the assemblies. Insulation layer would be expected to protect the assemblies against the hot fire gases coming. But this depends on the condition of installation of insulation pads. If there is a gap between wood studs and insulation pads, hot gases come into the assembly through the gap and goes up to the upper part of the assembly.

In addition, insulation itself shrinks and/or melts at high temperatures.

Figure 16 shows the shrinkage behaviour of glass-fibre insulation and rock-fibre insulation. The figure shows a linear dimension (%) of the insulation as a function of temperature. Glass-fibre insulation begins to shrink at about 420°C and its linear dimension quickly decreases with temperature. On the other hand, rock-fibre insulation has much more thermal resistance. Rock-fibre insulation does not shrink nor melt at the temperature less than 620°C.

Therefore, glass-fibre insulation, even if it is perfectly installed in the ceiling cavity, that is, if there is no gap between the insulation pad and wood joists, still there is a possibility of some space appearing between insulation layer and joists when the temperature of insulation exceeds 420°C.

Figure 17 shows an example of theoretical prediction, when insulation pads are not perfectly installed, that is, there is a gap between insulation layer and wood joists. The figure shows the time / temperature curves when joints at the ceiling membrane open. The temperature at location B rapidly increases at around 20 min, because of
the opening of joints. Hot fire gases quickly come into
the assembly and goes up to the upper part of the
assembly through the gap between the insulation layer
and wood joist.

Figure 17: Time / temperature curves at the locations of
A, B, C, D and E if joints open (The locations are shown
in Figure 2)

Figure 18 shows how the strength of wood joist reduces
with time.

Figure 18: Resistive moment of wood joist if joints open

The resistive moment begins to reduce at around 20 min
and goes down almost linearly. Mechanical failure was
predicted to occur at 40 min. This result suggests that
the condition of installation of insulation is crucial, when
the joints open.

3.5 FULL-SCALE TESTS

National Research Council of Canada conducted full-
scale tests for the floor / ceiling assemblies. The test
assemblies were 2 x 10 wood joists (38mm x 240mm x
3874mm length) lined by 12.7 mm (1/2 inch) thick
gypsum board as a ceiling membrane and 15.9 mm (5/8
inch) thick plywood as a sub-floor. 89 mm thick glass-
fibre insulation was installed in the ceiling cavity. The
size of the full-scale test assembly was 4.8 m long and
3.9 m wide. The tests were conducted by heating the
ceiling with ASTM E-119 standard curve. Test results
showed that the assembly failure occurred at 36 min.
In order to simulate this full-scale test, the computer
model calculated the temperatures in the assembly and
resistive moment of wood joist using the input data for
12.7 mm thick gypsum board as a ceiling membrane.
Figure 19 shows the model prediction for the
temperatures at the locations, A, B, C, D and E, and
Figure 20 shows the mechanical strength of wood joist
as a function of time. The model predicted that the
mechanical failure would occur at 36 min, shown in
Figure 20. Good agreement was observed between the
model prediction and the full-scale test results.

Figure 19: Time / temperature curves at the locations of
A, B, C, D and E for the assembly with 12.7 mm thick
ceiling (The locations are shown in Figure 2)

Figure 20: Resistive moment of wood joist for the
assembly with 12.7 mm thick ceiling

4 CONCLUSIONS

A computer model has been developed for investigating
the effect of insulation on the fire resistance of floor /
ceiling assembly. The model was validated by
comparing to the small-scale test data.
The results show that the insulation in the ceiling cavity
would somewhat improve the fire resistance of the
wood-framed floor / ceiling assemblies. However, if
insulation is imperfectly installed, that is, if there is a gap
between insulation and wood joists, insulation might not improve the fire resistance of the floor / ceiling assemblies. The key point is the perfect installation of insulation. There should be no gap, no hole, no defect in the insulation in the assembly. Otherwise insulation in the ceiling cavity might not protect the assemblies against fire.

REFERENCES