Design considerations for fire resistance performance of lightweight-framed assemblies

Bénichou, N.; Sultan, M. A.

Publisher’s version / Version de l'éditeur:

CSCE 2003 Annual Conference [Proceedings], pp. 567-1 - 567-10, 2003-06-01

Design considerations for fire resistance of lightweight-framed assemblies

Bénichou, N.; Sultan, M.A.

NRCC-38776

A version of this document is published in / Une version de ce document se trouve dans:
CSCE 2003, Annual Conference, Moncton, N.B., June 4-7, 2003, pp. 567-1 – 567-10

Congrès annuel de la Société canadienne de génie civil

Annual Conference of the Canadian Society for Civil Engineering

Moncton, Nouveau-Brunswick, Canada
4-7 juin 2003 / *June 4-7, 2003*

DESIGN CONSIDERATIONS FOR FIRE RESISTANCE OF LIGHTWEIGHT-FRAMED ASSEMBLIES

N. Bénichou[A], M.A. Sultan[A]
A Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada

ABSTRACT: The effects of a number of design parameters have been investigated including the types of cavity insulation, resilient channels, gypsum board thickness, the number of gypsum board layers, stud arrangements, and type of framing. The results have shown that the main factors that affected the performance of stud wall assemblies were the type of insulation and the number of gypsum board layers. In addition, a description on how the information gathered from this study will be used to benefit practitioners, builders and regulators in choosing suitable assemblies for their designs is also presented.

1. INTRODUCTION

Lightweight-framed construction is widely used in up to four-storey residential buildings. This construction includes wall and floor assemblies, which are used as fire barriers in multi-family dwellings and are required to exhibit acceptable fire resistance prescribed in the National Building Code of Canada (NBC) [1]. The functions of the barriers are to contain the fire within the compartment of fire origin and to provide safety to the occupants and firefighters during evacuation and rescue operations. Aside from fire resistance, wall assemblies separating dwellings must also satisfy other requirements, including structural support and noise control between dwellings. Optimizing one factor may compromise others. In 1990, the Sound Transmission Class (STC) between dwellings was increased from STC 45 to STC 50 in the NBC. As well, construction materials have changed over the past decade. However, with these changes, are there any concerns on the fire resistance requirements of wall assemblies? To answer this question, the National Research Council of Canada (NRC), in collaboration with a number of partners, has carried out an extensive experimental program on lightweight-framed assemblies. The experimental tests included steel- and wood-stud walls where a number of parameters have been tested, including the types of insulation, resilient channels, gypsum board thickness, the number of gypsum board layers, stud arrangements and framing type. This paper provides an overview focussing on parameters that affected the fire resistance performance of wall assemblies. The paper will also describe how the information gathered from this experimental program will be used to generate: a) fire resistance ratings; b) key trends for design; and c) fire resistance models that could provide an alternative to testing of assemblies. In particular, a validated model for predicting the fire resistance of wood-stud walls is presented along with a parameteric study of the model.

2. EXPERIMENTAL PROGRAM

To determine the effects of various parameters on the fire resistance of wood- and steel-wall assemblies, a detailed experimental study was undertaken. The experimental program consisted of 14 full-scale fire tests (see Table 1). The systems tested were replicates of wall assemblies commonly used in North America and listed in the NBC [1]. Figure 1 shows a typical wood-stud wall.

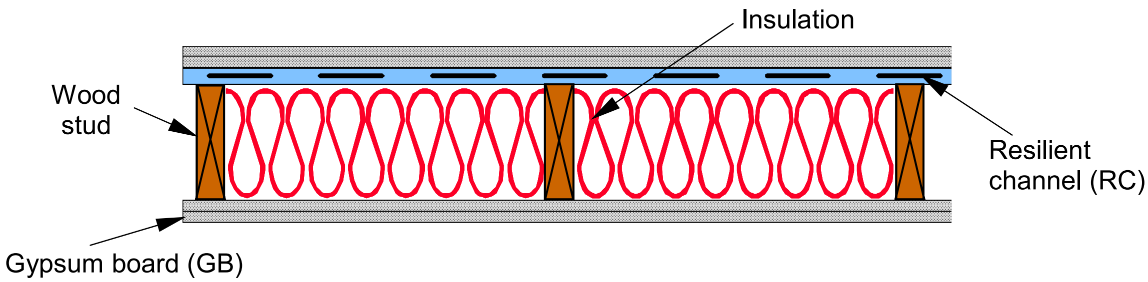


Figure 1. Typical wood-stud wall assembly.

The full-scale wall tests were carried out by exposing one side of the assemblies to heat in a propane-fired vertical furnace, in accordance with the CAN/ULC-S101-M89 standard [2]. The furnace can accommodate wall assemblies that are approximately 3.0 m high by 3.6 m wide. Nine shielded thermocouples were used to control the furnace temperature. Other thermocouples were also used for measuring temperatures at a number of locations throughout an assembly. Wall assemblies were tested either loaded or unloaded. For load-bearing walls, the furnace had a loading device at the top of the wall to simulate vertical structural loads. Loads on walls were calculated in accordance with CAN/ULC-S101-M89 standard [2]. The applied loading on the wall assemblies is given in Table 1. In addition, the deflection at the unexposed surface was measured at nine different locations. All measurements were recorded at 1-min intervals. Complete details on the experimental program are given in other references [3, 4, 5]. The failure criteria were determined in accordance with the CAN/ULC-S101-M89 standard [2], i.e., thermal, integrity or structural failure.

3. DESIGN PARAMETER INVESTIGATED

3.1 Effect of Insulation Use and Type

Tests 1 to 4 represented the effect of the use and type of insulation in (1 & 2) non-load-bearing steel-stud assemblies. The wall with glass fibre provided the same fire resistance (FR) as the assembly without any insulation (65 min). The assembly with rock fibre provided an increase of 54% in FR (100 min) while the assembly with cellulose (wet sprayed on the exposed gypsum board (GB) surface in the cavity between studs) showed a decrease of 4% in FR (62 min) compared to a non-insulated wall. The rock fibre remains in place and protects the stud and the GB on the unexposed side when the GB on the exposed side falls off. On the other hand, when the GB on the exposed side falls off, the cellulose fibre falls off and glass fibre melts allowing the GB on the unexposed side and the studs to be exposed to heat, resulting in earlier failure. These results indicate that an assembly with rock fibre insulation provide higher fire resistance than an assembly with either glass or cellulose fibre or with non-insulation in the wall cavity. Kodur et al. [5] conducted a similar study but with load bearing steel-stud walls. Their results indicate that uninsulated wall assemblies provide a higher fire resistance than those assemblies with insulation and presented their reasons for this reduction in fire resistance (FR) as follows: a) the insulation keeps the gypsum board facing the fire hotter, causing it to crack and fail more quickly than in the case with an empty cavity. Once it has failed, the insulation and studs are exposed to the furnace heat; and b) the insulation allows the heat to build up and become trapped in the cavity, thus hastening the structural failure of the studs. In addition, the use of rock fibre provides a higher fire resistance compared to glass fibre insulation, but a lower fire resistance compared to cellulose insulation.

Results from fire resistance tests 5 to 8 were used to determine the effect of insulation type on (1 & 2) load-bearing wood-stud assemblies. The fire resistance is 51 min for an assembly with glass fibre (5) and 52 min with rock fibre (6). The results show that in these assemblies, the insulation type did not affect the fire resistance, as the unprotected GB vertical joints on the fire-exposed side are the dominant factor in the FR, given that these are loaded assemblies and the stud edges were being attacked with the heat after failure of the GB. When resilient channels (RCs) are on the unexposed side, the fire resistance is 58 min for assembly with rock fibre (7) and 56 min with cellulose fibre (8), and therefore also has litttle or no effect in this case (failure of the fire-exposed side GB is the dominant factor).

Table 1. Wall assembly parameters and fire resistance test results [3, 4, 5].

Test No.	Stud			Shear Panel	Gypsum Board			Insulation Type	Resilient Channels	Load (kN)	Failure Time (min)	Failure Mode
	Type	Spacing (mm)	Rows		Type	Thickness (mm)	Exp./Unexp.					
1	Steel	400	Single	No	X	12.7	1 & 2	No	No	No	65	Thermal
2	Steel	400	Single	No	X	12.7	1 & 2	Glass	No	No	65	Thermal
3	Steel	400	Single	No	X	12.7	1 & 2	Rock	No	No	100	Thermal
4	Steel	400	Single	No	X	12.7	1 & 2	CFI[5]	No	No	62	Thermal
5	Wood	400	Single	No	X	12.7	1 & 2	Glass	Yes[1]	68	51	Structural
6	Wood	400	Single	No	X	12.7	1 & 2	Rock	Yes[1]	68	52	Structural
7	Wood	400	Single	No	X	12.7	1 & 2	Rock	Yes[2]	68	58	Structural
8	Wood	400	Single	No	X	12.7	1 & 2	CFI[6]	Yes[2]	68	56	Structural
9	Steel	400	Single	No	X	12.7	1 & 2	Rock[3]	No	No	60	Thermal
10	Wood	400	Single	No	X	15.9	1 & 2	Glass	Yes[1]	67	52	Structural
11	Wood	400	Single	No	X	12.7	2 & 2	Glass	Yes[1]	68	79	Structural
12	Wood	400	Double[4]	No	X	12.7	1 & 2	Glass	No	143	51	Structural
13	Steel	400	Single	No	Reg.	12.7	2 & 2	No	No	No	63	Thermal
14	Wood	400	Single	No	Reg.	12.7	2 & 2	No	No	No	65	Thermal

[1] On exposed side
[2] On unexposed side
[3] Loose fit (548 mm)
[4] Staggered (single plate)
[5] Cellulose wet sprayed
[6] Cellulose dry blown
Exp. = Number of GB layers on exposed side
Unexp. = Number of GB layers on unexposed side
Reg. = Regular GB

3.2 Effect of Insulation Width

Results from fire resistance tests 3 and 9 can be used to determine the effect of insulation width in non-load-bearing steel-stud assemblies. The fire resistance is 60 min for an assembly with loose-fit rock fibre (9) and 100 min for an assembly with tight-fit rock fibre (3). The results show that it is important to have the insulation installed tightly between studs since a loose fit produces gaps between stud faces and the insulation leading to an earlier failure of the assembly. When rock fibre insulation was installed tightly in non-load-bearing assemblies, it provided a 60% better fire resistance than when it was loose.

3.3 Effect of Resilient Channels Use and Location

Tests 6 and 7 were conducted to investigate the effect of the resilient channels' location on the fire resistance of load-bearing wood-stud walls. The fire resistance is 52 min for an assembly with the resilient channel on the exposed side (6) and 58 min for an assembly with the resilient channel on the unexposed side (7). The results show that the location of resilient channels plays a role in FR as the assembly with RC on the double layer side provides an increase in FR of 11%. The difference in fire resistance is caused by the presence of an unprotected vertical GB joint on the fire-exposed side in the assembly when RCs are installed. With direct application to the studs, joints in the GB can be aligned with the studs.

3.4 Effect of Gypsum Board Thickness

Tests 5 and 10 were conducted to investigate the effect of GB thickness on the fire resistance of (1 & 2) load-bearing wood-stud walls. The failure of the wall assembly with 12.7-mm GB (5) occurred at 51 min while in the assembly with 15.9-mm GB (10), the failure occurred at 52 min. The results show that in (1 & 2) wall assemblies with RC installed on the fire exposed side, increasing the thickness of the gypsum board layer does not improve the FR when resilient channels are present on the single-layer side. However, the fact that the fire-resistance did not improve with the increased thickness was mainly due to the ignition of the wood studs, caused by the penetration of the hot gases through the unprotected vertical gypsum board butt joints. The gap between the studs and the gypsum board, created by the presence of the RCs, acted as a passageway through which the flames and hot gases spread freely after entering the cavity.

3.5 Effect of Number of Gypsum Board Layers

Tests 5 and 11 were conducted to investigate the effect of the number of GB layers in load-bearing wood-stud assemblies. The failure of a wall assembly with one layer of GB (5) occurred at 51 min, while in an assembly with two layers of GB (11), the failure occurred at 79 min. The results show that the installation of a second layer of GB on the fire-exposed side (with staggered joints) increases the FR by 55% compared to an assembly with one layer of GB on the exposed side. Having a backing to the fire-exposed GB layer adds significantly to the fire resistance, as it reduces the penetration of hot gases.

3.6 Effect of Stud Arrangement

Tests 5 and 12 were conducted to investigate the effect of the stud arrangements in (1 & 2) load-bearing wood-stud assemblies. For both single row wall assembly (5) and double-row staggered (single plate) assembly (12), the failure occurred at 51 min. The double-row staggered assembly does not have an RC, which may lower the FR. The results suggest that the wood-stud arrangements in these assemblies do not benefit the FR for wall assemblies, although they may be beneficial for sound attenuation.

3.7 Effect of Stud Type

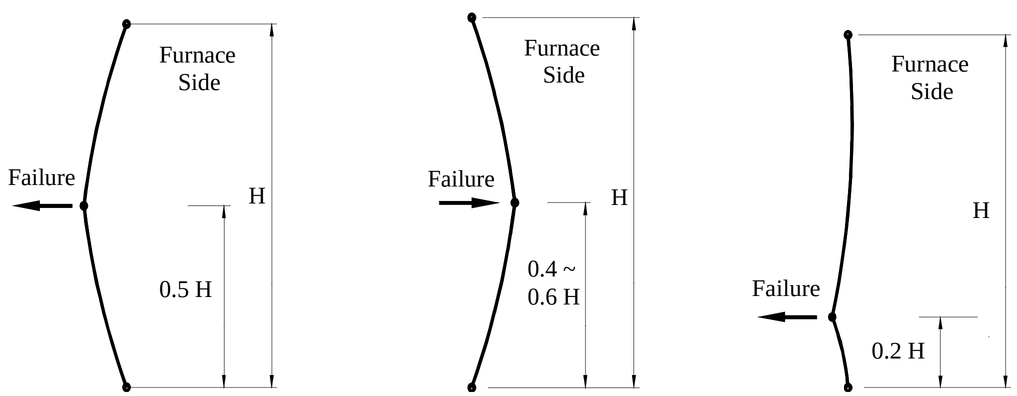
Results from fire resistance tests 13 and 14 can be used to assess the effect of stud type in (2 & 2) non-load-bearing stud assemblies. The failure in steel-stud wall (13) occurred at 63 min while in the wood-stud wall (14), it occurred at 65 min. The type of stud used in non-load-bearing walls is insignificant for assemblies with two layers of gypsum board on each side.

4. HOW CAN WE USE THIS INFORMATION?

The information obtained from this experimental program can be used in 3 ways: a) development of listing tables for codes; b) key trends for design; and c) development and validation of fire resistance models. In the first way, fire design of wall assemblies is usually carried out by reference to standard fire test results. Test results were used to produce generic fire resistance rating listings for codes. Appendix A of the NBC [1] shows examples of generic listings, but the user can choose from any other acceptable source. For the key trends, below is a summary of what has been observed:

- Fire resistance increases considerably with an increase in the number of GB layers on each side.
- With RCs beneath the single GB layer, increasing the GB layer thickness does not improve the FR.
- The use of RCs reduces the FR of stud walls, especially when fixed to a single gypsum board layer. To minimize this fire resistance reduction, RCs should be installed under the double GB layer.
- For (1 & 2) non-load-bearing steel-stud walls, installing rock fibre contributes significantly to the FR. To maximize the FR benefits of rock fibre, it is important to install the batts tightly between the studs.
- For load-bearing (1 & 2) wood-stud walls, cavity insulation type has no significant effect on fire resistance.
- The type of stud used in non-load-bearing walls has no significant effect on the fire resistance.

Another way of using the information is in the development of models, which would lower the testing costs and overcome the geometry and loading limitations. The models would also help in designing an experimental program, improve products manufacturing, and facilitate performance-based design. To develop fire resistance models for wall assemblies that replicate test results, the fire resistance behaviour from the experimental program must be carefully observed. During the tests, the behaviour of wood- and steel-stud wall assemblies was observed and Figure 2 shows representations of the failure modes of wall assemblies. Insulated and non-insulated wood-stud walls bow away from the furnace; bowing in non-insulated steel walls remains towards the furnace for the duration of the exposure; and bowing in insulated steel walls is towards the furnace, but the final failure is away from the furnace. From the observed behaviours, NRC, in collaboration with the steel and wood industries, has developed a number of models to predict the fire resistance of wood and steel-stud wall assemblies. A wood-stud wall model is presented below.



a) wood-stud walls b) non-insulated steel-stud walls c) insulated steel-stud walls

Figure 2. Schematic representations of failure modes for wood- and steel-stud walls.

NRC, in collaboration with Forintek Canada Corp. (FCC), has developed an analytical model for predicting the fire resistance of wood-stud wall assemblies. The model couples a thermal response sub-model and a structural response sub-model. The thermal response sub-model, called WALL2D [6], predicts the temperature profile inside the wood-stud wall and the time to insulation failure using the finite difference method. The sub-model takes into account the heat absorbed in the dehydration of gypsum and wood, and in the pyrolysis of wood, without considering mass transfer. The heat transfer, through gypsum boards and wood studs, is described using an enthalpy formulation, which is governed by the following partial differential equation:

$$[1] \qquad \rho\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)$$

where ρ is the density in kg/m^3, H is the enthalpy in J/kg, t is the time in s, k is the thermal conductivity in W/m°C, T is the temperature in °C, and x and y are spatial co-ordinates in m. The structural fire performance of wood-frame assemblies is affected by the rate of charring, degradation of the mechanical properties of the wood at elevated temperatures and the load sustained by the assemblies. To determine the structural response, a buckling load sub-model is implemented with WALL2D. The sub-model uses the temperature distribution predicted by WALL2D as an input, then calculates the deflection and the critical elastic buckling load for a wood-stud wall. The buckling of the wood studs is restricted to the strong axis because of the lateral support by the gypsum board, with the critical elastic buckling-load, given as:

$$[2] \qquad P_{cr}=\frac{\pi^2 EI}{(KL)^2}$$

where P_{cr} is the elastic buckling-load (N), E is the modulus of elasticity of the resisting member (MPa), I is the moment of inertia (mm^4), and KL is the effective stud length (mm), with K = 1 in this case. The values of the moment of inertia and modulus of elasticity change with time and are based on the temperature profile in the stud cross section. The change, with temperature, of the modulus of elasticity is obtained from the literature [7]. Structural failure is assumed to occur when the load applied on the wall exceeds the buckling load. The stud's out-of-plane deflection can be calculated by considering the stud as a beam-column structure. The out-of-plane deflection, y, at any height x on the stud at any time, is:

$$[3] \qquad y(x)=\frac{M_0L^2}{8EI}\left[\frac{2\cos\left(\Psi-\frac{2\Psi}{L}x\right)-\cos(\Psi)}{\Psi^2\cos(\Psi)}\right] \text{ with } \Psi=\frac{\pi}{2}\sqrt{\frac{P}{P_{cr}}} \text{ and } M_0=P(e_c-e_p)$$

where L is the length of the stud (mm), P is the applied load (N), e_c is the eccentricity of the centroid of the resisting member (mm), and e_p is the applied load eccentricity (mm). The maximum deformation occurs at mid-height.

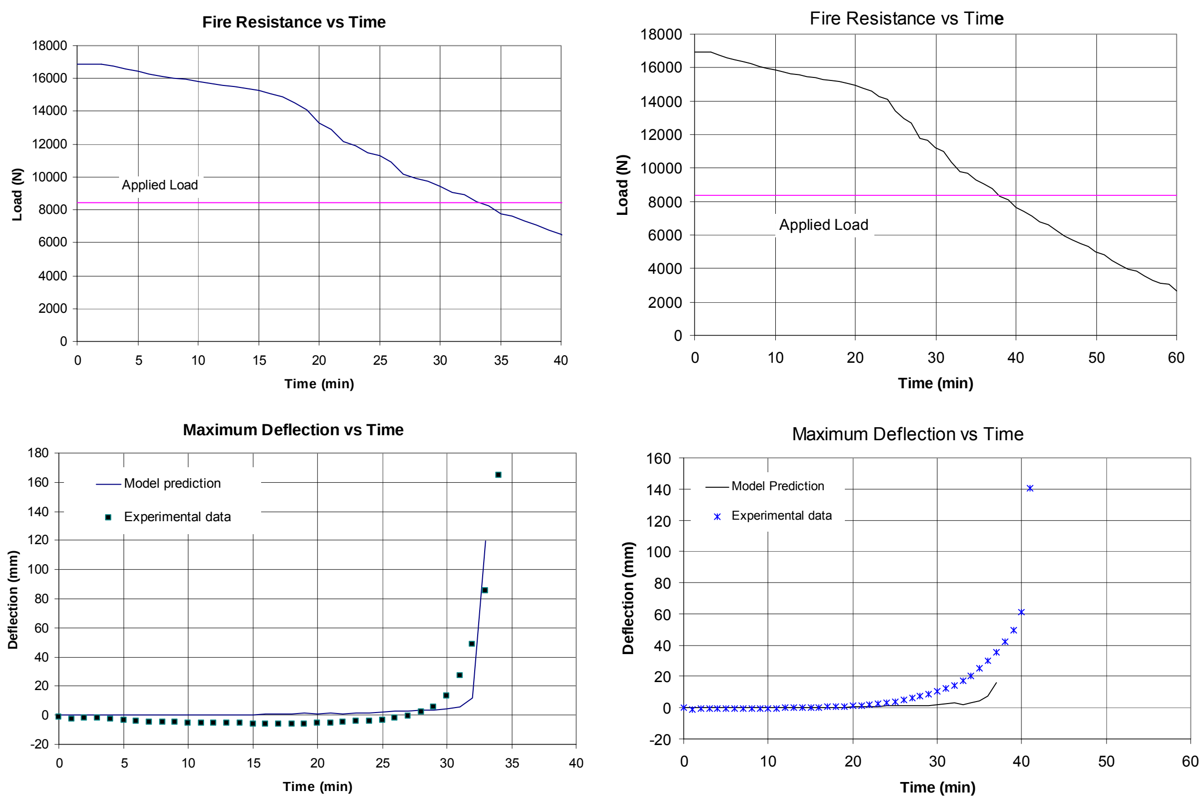
Two tests were used to evaluate the predictions by the fire resistance model. Details of the assembly are shown in Table 2. The predictions of time-temperature curves generated by the heat transfer have been used to calculate the reduction in load-carrying capacity of the studs and the degradation in the modulus of elasticity, which was assumed to be equal to 7000 MPa at ambient temperature. Temperatures on the unexposed sides did not reach the insulation failure criterion, as the assemblies failed by structural instability at 36 and 41 min for tests a and b, respectively. Table 2 summarizes the model predictions and experimental results. The model predicts conservatively the onset of charring.

To measure the performance of the structural response model, the theoretical predictions of the structural fire resistance and deflection at mid-height are evaluated. Figure 3 (a and b) illustrates the critical elastic buckling load versus time as predicted by the structural response sub-model. The fire resistance decreases with increasing time because the value of the modulus of elasticity decreases with time and the cross-section of the studs reduces after charring. The intersection of the horizontal line, at the level of the applied load, with the elastic buckling-curve, represents the theoretical time to structural failure of the wall. The time is 33 and 38 min for Tests a and b, respectively, while the time to structural failure measured experimentally is 36 and 41 min for Tests a and b, respectively. Therefore, the model predictions are very close to the test results, with the analytical time to structural failure underestimated by a maximum of 8%. Table 2 also shows a summary of the model predictions and experimental results for the test.

Table 2. Details of assemblies and comparison between tests results and model predictions.

Test No.	GB Type X	Insulation Type	Load (kN)	Onset of Char (min)			Insulation Failure (min)		Structural Failure (min)		
				Test	Model	Diff.	Test	Model	Test	Model	Diff.
a	12.7	Glass	76	19.0	17.0	10%	N/A	48.0	36.0	33.0	8%
b	15.9	Glass	76	22.0	21.1	4%	N/A	59.0	41.0	38.0	7%

The maximum mid-height deflections are also plotted versus time for both the analytical predictions and the test results, see Figure 3 (a and b). As shown in this figure, the deflection is very small in the first 30 to 35 min. After this, the model predictions and the test measurements start increasing at a faster rate. The rate of increase in the model predictions is similar to that of the test results. The rate in the model, however, starts a few minutes later. The model underestimates the deflection close to failure. The difference in the predictions may be due to the nominal value of the modulus of elasticity which could be different than the actul value of the studs tested.



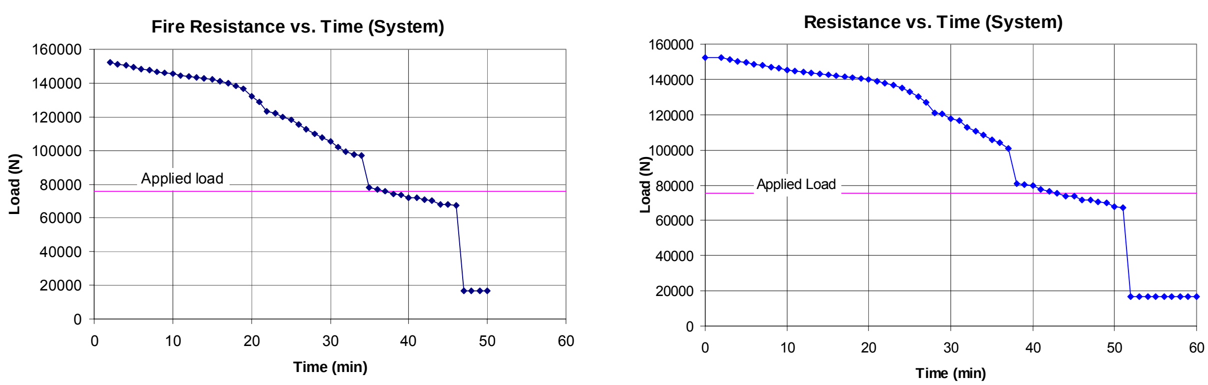
(a) Test a (b) Test b

Figure 3. Fire resistance determination and deflection comparisons.

The fire resistance model described above is based on the elastic buckling theory of a single stud. However, in a wall assembly, failure of one stud may not mean failure of the whole wall system. This is due to the possible redistribution of the load to the other studs, which did not fail, especially to those at the ends. It is sometimes suggested to cut the end studs so that they do not contribute to the load and a realistic comparison may be made with model predictions that are based on the load on a single stud. In the tests presented here, the end studs were not cut and consequently we need to find another alternative to treat the walls as assembly systems. To achieve this, the following method was used:

1. The wall assemblies tested contain 10 studs each and 2 vertical GB joints (for direct application): 2 studs where joints open, 6 studs where joints do not open and 2 end studs.
2. Run the fire resistance model with 3 cases: a) simulation with joint opening, b) simulation without joint opening, and c) simulation with conditions kept as ambient (for end studs).
3. Calculate the total assembly resistance by adding the resistance from all cases with the appropriate coefficients (stud number) at each time step as: 2 x case1 + 6 x case2 + 1 x case3.
4. Compare the total resistance to the total applied load at every time step.
5. Determine the fire resistance when the load becomes higher than the buckling resistance.

Figure 4 shows the buckling resistance of Tests a and b vs. time, calculated based on the method described above. As illustrated in the figure, when the first 2 studs fail (at 33 or 38 min for Tests a and b, respectively), the wall can still resist for 3 to 5 more minutes as the load is redistributed to other studs that have not reached failure. The method, however, assumes that the end studs remain at ambient temperatures, which may not be realistic. Based on this, it can be concluded that using a model based on a single stud, as opposed to a complete system, may provide reasonable and conservative predictions.



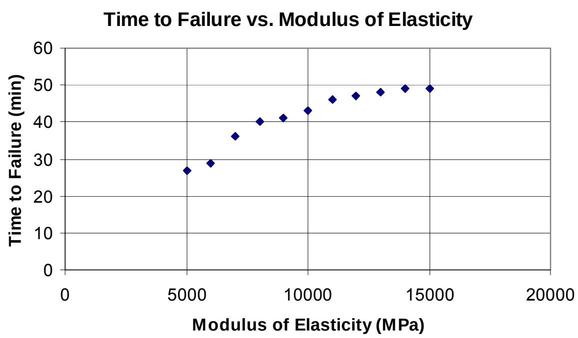
(a) Test a (b) Test b

Figure 4. Fire resistance determination based on load redistribution for a wall system.

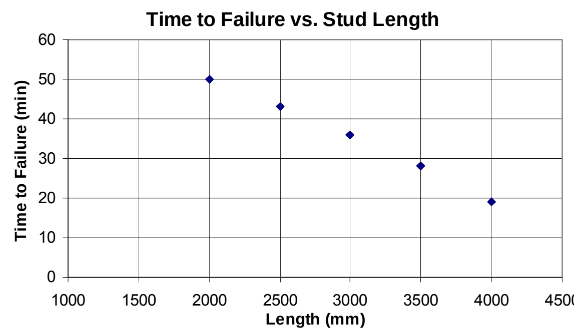
5. PARAMETRIC EFFECTS ON THE MODEL

In order to determine the critical factors affecting the fire resistance model, a parametric study has been carried out using the model. For the parametric study, all of the wall assemblies consisted of 10 studs with a cross-section of 89 mm by 38 mm wide, 400 mm apart, held in place by nails. The parameters considered included the modulus of elasticity, stud length and the applied load on the assembly.

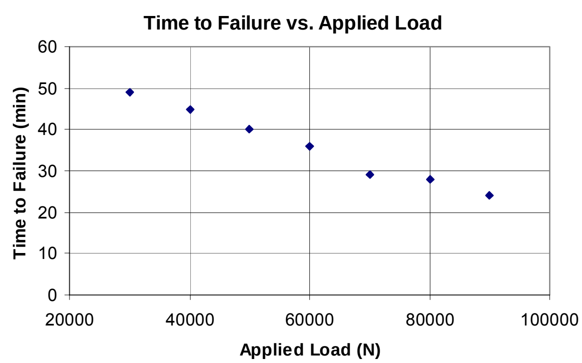
Because of space limitation, the figures below show the influence of the different parameters performed on one non-insulated assembly with 12.7-mm layer of gypsum board on each side. The modulus of elasticity, E, was increased from 5000 to 15000 MPa. This change had a significant effect on the fire resistance of this assembly, as is indicated in Figure 5a. At 5000 MPa, the assembly had a fire resistance of 27 min and at 15000 Mpa, it had a fire resistance of 49 min. The time to failure of this assembly due to the different moduli of elasticity follows an increasing exponential relationship. The length, L, was increased from 2000 to 4000 mm. This change had a significant effect on the fire resistance of this assembly, as indicated in Figure 5b. At L = 2000 mm, the assembly had a fire resistance of 50 min and at L = 4000 mm, it had a fire resistance of 19 min. The time to failure of this assembly due to the different lengths follows a decreasing linear relationship. The applied load was increased from 30000 N to 90000 N. This change had a significant effect on the fire resistance of this assembly, as indicated in Figure 5c. At 30000 N, the assembly had a fire resistance of 49 min and at 90000 N, it had a fire resistance of 24 min. The time to failure of this assembly due to the different applied loads follows a decreasing linear relationship. These effects and others can be used to come up with a simple correlation to calculate the time to structural failure that would be a function of the geometry of the assembly, the applied load, the modulus of elasticity without the need to run heat transfer analyses.



(a) Modulus of elasticity



(b) Stud length



(c) Applied load

Figure 5. Effect of different parameters.

6. SUMMARY, CONCLUSIONS AND FUTURE WORK

To evaluate the impact of changes in code requirements and building construction materials, an extensive experimental program has been undertaken to investigate the effects of a number of design parameters including the types of insulation, resilient channels, gypsum board thickness, the number of gypsum board layers, stud arrangements and type of framing on the fire performance of wall assemblies. The results have shown that the main factors that affected the performance of stud-wall assemblies are the type of insulation and the number of gypsum board layers. The data gathered from this study was used to produce key design trends, to propose generic ratings for possible incorporation in the appendices of the National Building Code of Canada, and to develop fire resistance models for wood- and steel-stud wall assemblies. This information is of great benefit to practitioners, builders and regulators in choosing suitable assemblies for their designs. In particular, a wood-stud wall fire resistance model, developed with the wood industry, was presented and validated against the results of two tests. A parametric study of the model was carried out and will help in the development of simple correlations. As a next step, the model will be further refined and validated against more experimental data that include exposure to both standard and non-standard fire.

ACKNOWLEDGEMENTS

This research was funded by NRC and industry partners that included the Canadian Wood Council, Canadian Home Builders Association, Canadian Sheet Steel Building Institute, Forintek Canada Corp., Owens-Corning Canada, Roxul Inc., Gypsum Manufacturers of Canada. The authors are grateful to J. Latour, P. Leroux, R. Monette and J. Henrie for constructing the assemblies and conducting the tests.

REFERENCES

[1] Canadian Commission on Building and Fire Codes (1995), National Building Code of Canada, IRC, NRC, Ottawa, Canada.

[2] CAN/ULC-S101-M89 (1989) Standard Methods of Fire Endurance Tests of Building Construction and Materials, Underwriters' Laboratories of Canada, Scarborough, Canada.

[3] M. A. Sultan and G. D. Lougheed, Results of Fire Resistance Tests on Full-Scale Gypsum Board Wall Assemblies, Internal Report (in press), IRC, NRC, Ottawa, Canada

[4] V.K.R. Kodur, M.A. Sultan and E.M.A. Denham, Temperature Measurements in Full-Scale Wood Stud Shear Walls, Internal Report No. 729, IRC, NRC, Ottawa, Canada, (1996).

[5] V. K. R. Kodur, M. A. Sultan, J.C. Latour, P. Leroux and R.C. Monette, Experimental Studies on the Fire Resistance of Load-Bearing Steel Stud Walls, Internal Report (in press), IRC, NRC, Ottawa, Canada.

[6] H.Takeda and J.R. Mehaffey, WALL2D: A Model for Predicting Heat Transfer through Wood-Stud Walls Exposed to Fire," Fire and Materials, 22: 133-140, 1998.

[7] E.L. Schaffer, Elevated Temperature Effect on the Longitudinal Mechanical Properties of Wood, Ph.D. Thesis, Department of Mechanical Eng., Univ. Wisconsin, Madison, USA, 1970.