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STRUCTURAL PERFORMANCE OF LIGHT-FRAME WOOD BUILDINGS SUBJECTED TO POST-EARTHQUAKE FIRE EXPOSURE

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ABSTRACT:

Timber structures are constructed widely in North America for different usage like residential, commercial and industrial. As wood is a combustible careful attention must be given to the fire safety design of these structures. In a strong earthquake a timber structure may suffer significant damages to the structural and fire protection systems. The Post Earthquake Fire (PEF), which may be caused many factors including gas line leakage and electrical short circuiting, will find a weaker structure whose fire resistance of the new structure may be greatly reduced. An analytical model is developed for determining the PEF fire resistance of stud walls considering the temperature dependent material properties and charring of wood elements. The model is validated with some available experimental studies and found to be quite accurate. It is found that the PEF resistance of a stud wall is reduced considerably even due to a moderate level of damage.

Introduction

Earthquakes have several other undesired aspects associated with them besides causing damages to buildings, such as, landslide, and fire (Scawthorn et al., 2005). While ground shaking is a major concern in the case of an earthquake, other associated events like subsequent fire, which is usually caused by factors like damaged gas lines and electrical short circuiting, can pose a major risk to urban facilities and built infrastructure. Post-Earthquake Fire (PEF) can grow and spread out of control, in one or more neighborhoods which is known as conflagration. Literature shows that PEF scenario has not been given enough attention in designing buildings in seismically sensitive regions (Mousavi et al. 2008). Wood structures are common in housing industry in North America, and fire safety is a concern in these structures because of the combustible nature of wood (Yassin et al. 2008). A well designed wood frame structures usually has adequate fire-resistance, such that in case of a fire, the structure will resist it for a period of time before it fail and burn totally. This period, called fire resistance rating (FRR) of a building, is important for safe evacuation of occupants. Typical fire protection in wood framed structure is provided by gypsum boards which have a good resistant to fire. However, they are brittle and do not resist in-plane lateral load typically coming from an earthquake or wind. A structure subjected to an earthquake may suffer extensive damage and lateral deformation, and often assumed a new geometric configuration (Iqbal et al. 2008). A strong earthquake is usually followed by fire, in which case, a structure damaged due to the earthquake would not withstand a fire event for which it is originally designed. The new

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situation of the damaged structure after the quake should be taken into account while assessing the fire resistant of the post-earthquake structure. However, the current building codes ignore this aspect of fire safety design of structural systems and tend to uncorrelated both events when design a structure.

The goal of this article is to explore the post-earthquake fire performance of wood stud wall systems and highlight the behavior of these structures. Buckling of studs is a common failure mode of a wood stud wall under applied thermal load due to fire exposure to one side of the. The buckle occurs due to the gradual loss of material and strength in wood studs. An analytical model for stability analysis of wood frame walls has been proposed and tested to estimate the fire resistant of these systems. The results from the analytical model have been validated with the experimental data from fire tests conducted earlier at the National Research Council of Canada (NRC). The time dependent changes in strength, stiffness, sections and geometry due to earthquake and fire have been considered in the model in order to determine the time history of the response and collapse load.. The input temperature to the structure comes from a thermal analysis model named Fire Dynamic Simulator (FDS) developed by NIST (NIST,2008). A parametric study is conducted to identify the effect of post-earthquake damage to fire resistance of a wall system. A standard fire temperature time history such as CAN/ULCS101 fire curve has been used in the study.

Behavior of Wood Structure in Normal and Post-Earthquake Fires:

Previous fire events in Light wood frame buildings show that providing the structural members with adequate gypsum board coverings would prevent the spread of fire between compartments and keep on the load-bearing capacity for the duration of a severe fire (Buchanan 2001). However, at sustained elevated temperatures due to fire (e.g., 100^{o}C and beyond) gypsum board lining gets dehydrated and turns to gypsum powder in a process called ***calcinations***. At this stage the cavity gets directly exposed to extreme heat flux, and in that case, the cavity insulation plays an important role to contain the fire. In PEF scenario, gypsum boards could suffer cracks and damages due to an earthquake (Judd 2005), and as a result, the cavity will be exposed directly to elevated temperatures due to subsequent fire. As fire proceeds and temperature increases, the mechanical properties of construction materials change, and charring in wood sets in. Mechanical properties of wood such as the modulus of elasticity decreases and changes rapidly, while the thermal stresses in the end restrained stud increases due to the thermal expansion of wood. At a certain temperature, usually between 288° and 300° C, the charring in wood elements starts. The charring will deteriorate the cross sectional area and moment of inertia of studs and sheathing. A set of analytical expressions for the fire performance of glue-laminated beams and columns are provided in National Building Code of Canada (NBCC 2005), which imply a charring rate of 0.6 mm/min. Based on this rate of change in the cross sectional area, the centriod and moment of inertia of the stud-sheathing composite section, can be estimated at each time-step during the fire event. These parameters are then utilized in the computation of the buckling capacity of the wall assembly exposed to fire.

Buckling Failure Analysis:

A simplified model for calculating the critical load of the wall by modeling the whole assembly with pin-pin beam-column has been developed by Benichou and Morgan (2003). In that model they considered the degradation in the mechanical properties of wood due to elevated temperature. In addition to that they considered the eccentricity of the load on the stud due to the continuous weakening of members. However, that model was intended for stud walls without shear membrane. The load bearing wood stud walls are usually supported by shear panels. In North America Plywood and OSP boards are commonly used in such construction. The buckling analysis of the wood stud wall with shear membrane should consider the composite action between the sheathing and studs. In this paper, a simplified buckling model of stud walls including shear membrane exposed to fire has been proposed. The proposed model is based on the linear buckling model of stud-sheathing composite system developed by Kamiya (1987). The proposed model which is briefly described in this section accounts for time dependent material properties, and the effect of charring in wood. The thickness of the wood stud or the sheathing membrane can be written as a function of the charring rate as follow:

$$h_t = h_0 - C_R(t - t_C) \tag{1}$$

in which, h_t is the thickness of the element (stud or shear membrane) at any instance during the fire, h_0 is the initial thickness of the element, C_R is the charring rate, t is the time any instance during the fire, and t_C is the time at which charring starts. Here, t_C is determined from the heat transfer analysis of the wall section, considering the charring temperature to be between 280°C and 300°C. Charring is considered to happen through the thickness of the member, and the width of the member b is assumed to remain unchanged during the charring stage. The eccentricity between the centroid of the stud and point of application of the bearing load will increase because of the degradation in the cross section area as follow:

$$e_t = e_0 + C_R(t - t_C) \tag{2}$$

where e_0 is the initial eccentricity of the system. The critical buckling load is calculated at each instance during the fire history based on the composite interaction between the shear membrane and the studs. The effective width of the sheathing is assumed constant along the length and is the same as the effective width when the wall is bent by uniformly distributed loads. It is also assumed that the sheathing does not buckle and the stud and the sheathing do not separate. The material and geometric properties of the stud and the sheathing are assumed to remain constant along the length, and nails that fasten the sheathing to the studs have the same capacity and spacing. The load-slip relationship of the connections between the stud and the sheathing is considered to be reversible and is not hysteretic. These assumptions are valid for the normal static loading circumstances. However after the earthquake the wall could have deformed and assumed a new geometry. The damage due to seismic loads should be considered and degradation in the fasteners' stiffness must be accounted for. The slip of the nails inside the thickness of the plywood would reduce the wood shear wall capacity 5 to 22%, depending on the degree of slip (Fonseca 2004). To model the buckling behavior of sheathed walls linear and nonlinear analysis models were developed in Kamiya (1987) and Kamiya (1988), respectively. It was found that the nonlinear buckling model accounts for the effect of nail slip correctly, while the linear model produces acceptable results when the nail slip is small. The proposed model developed here is based on the linear analysis model (Kamiya, 1987) for its simplicity.

However, the effect of nail slip has been approximately accounted for by decreasing the initial composite stiffness based on the magnitude of an earthquake and expected degree of damage, and the temperature dependent material and section properties are used based on the temperature time history due to fire. With the proposed model the buckling capacity of the sheathed wall can be calculated at each time step according to the temperature time history. Figure 1 shows the interaction in sheathing-stud composite behavior. The elastic buckling load of stud-sheathing composite section (Figure 1) as proposed by Kamiya (1987) is given by,

$$P_{cr} = -\frac{\beta D\pi^4 + L^2(CD + z^2)}{\beta L^2\pi^2 + CL^4} \tag{3}$$

where, $\beta = S_p/K$ is a factor related to the composite section stiffness, in which S_p is the spacing between the fasteners, and K is the stiffness of those fasteners; L is the height of the wall, D is the flexural rigidity as calculated from Equation 4, C is defined following Equation 5, and z is given by Equation 6.

$$D = E_s I_s + E_p I_p \tag{4}$$

$$C = 1/E_s A_s + 1/E_p A_p \tag{5}$$

$$z = h_s/2 + h_p/2 \tag{6}$$

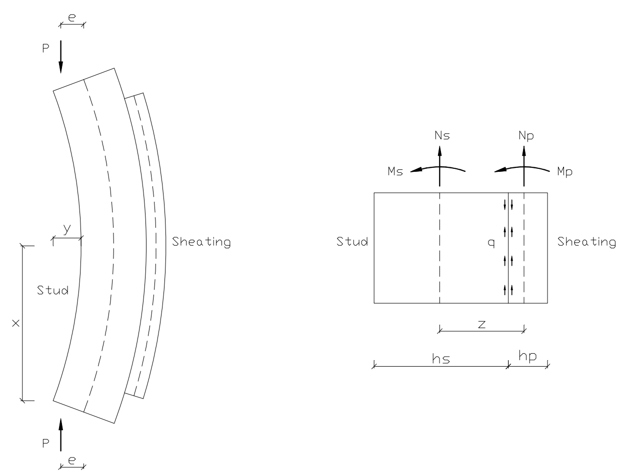

Figure 1: The sheathing to framing buckling model.

In the above equations, E_s ,E_p are the modulii of elasticity of stud and plywood board respectively; I_s, I_p are the moments of inertia; A_s, A_p are cross-sectional areas; and h_s, h_p are the depths of the stud and the sheathing, respectively. During the analysis of the stud wall, the critical load with normal fire and PEF can be calculated and compared with the applied one. Modulus of elasticity of wood is expressed as a function of temperature as follows:

$$E_i = E_0 * 106 * [1 - (0.4 * (T - 20)/(T_c - 20))] \tag{7}$$

where, E_i is the modulus of elasticity of wood at instant *t,* E_0 is the modulus of elasticity of wood at normal ambient temperature, T is the temperature at t, and T_c is the charring temperature.

PEF Modeling Issues:

For fire performance analysis, fire assumed to happen at the center of a room space and temperature is assumed uniform inside the compartment and monotonically increasing in accordance with the time–temperature curve suggested by the standard CAN/ULC-S101-M89 (CSA, 1989) which is similar to ASTM E119 as shown in Figure 3. It is apparent that one of the main problems with fires following an earthquake is the damage to passive and/or active fire protection systems. Conservatively speaking, we will consider a fire-protected structure before the earthquake and a completely fire un-protected one after a strong earthquake. On the other hand, it could be assumed that the fire protection systems are in-place and partially effective after the earthquake (Della Corte at el. 2003).

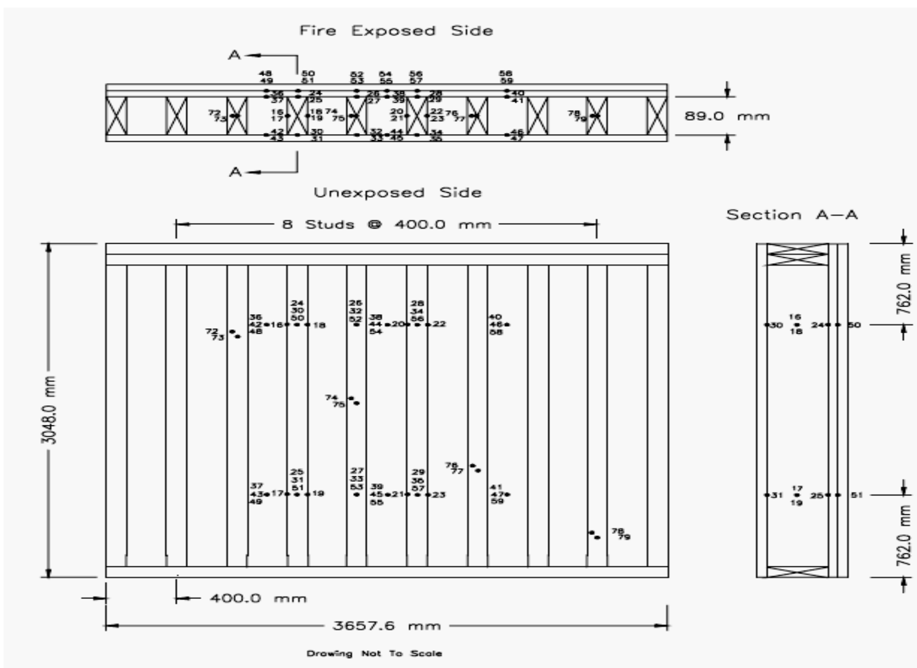

Figure 2: Wood stud assembly F-19, NRC fire test (Kodur and Sultan, 1996)

The analysis process consists of the following two basic steps: (1) heat transfer to determine the temperature distribution across the cross section corresponding to the time history of fire temperature; and (2) time history analysis of the structural response to the mechanical loads, and temperature distribution and time history obtained in Step 1. The first step is implemented in this study by using a fire dynamic simulator FDS (NIST, 2008) followed by the structural stability analysis using the proposed numerical model.

Description of Test Assemblies:

The full-scale assembly wall unit studied here was constructed in accordance with CAN/CSAA82.31-M91 (CSA, 1991) and has been assembled and tested in the NRC fire testing facilities by Kodur et al. (1996). Details on the assemblies for the test #F-19 from Kodur at el.

(1996) are shown in Figures 2 and 7. Type X gypsum board (Westroc "Fireboard" C/Type X) of thickness 12.7 mm, conforming to the requirements of CAN/CSA-A82.27-M91 (CSA, 1991) was used. The thickness of this Type X gypsum board was 12.7 mm. The framing Materials comprises wood studs of nominal size 2x4's (SPF No. 2, S-Dry, 38 mm thick by 89 mm deep) conforming to CSA 0141-1970 (CSA, 1970); and shear wall panels (Plywood) of thickness 12.5 mm. Glass Fiber insulation with a mass per unit area of 1.08 kg/m^2 was used.

Analysis stages and results:

Step 1: Thermal Analysis

Heat transfer analysis using FDS simulator: the FDS runs 1D heat transfer analysis to determine the thermal gradient through the wall. In other words, in FDS the heat transfers assumed to happen through the thickness of the wall layers not in the plane of the wall. The temperature of the exposed surface of gypsum board during the fire is presented in Figure 4. The lab measurements of this layer are not available from NRC test due to limitations in instrumentations. During the NRC fire test no thermocouples on the exposed surface have been installed, practically they would melt in the early stage of the experiment when they are exposed directly to the fire. Figures 5 and 6 present the change in temperatures inside each layer through the wall with comparison to the experimental values from NRC test for the same layer. The results from the heat transfer analysis shows reasonable matching with the experimental data as can be seen through previous figures.

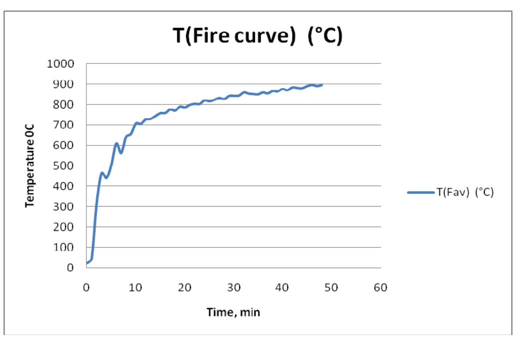

Figure 3: CAN/ULCS101 fire curve

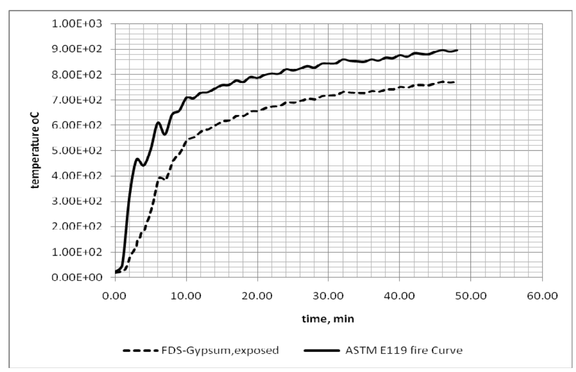

Figure 4: Temperature on the gypsum board

Illustration of the temperature inside the plywood layer from FDS model and NRC test is shown in Figure 5. The analytical model shows very good matching with the experimental one. NRC reported the temperature inside this layer by placing a thermocouple inside the plywood board during the fire test. A similar approach has been considered during building the analytical model by placing a device point inside this layer. A device in FDS model refers to a mathematical integration point in the finite difference model. The value captured by the analytical device could by any output result from the analysis such as temperature, pressure or heat flux. In Figure 6 the analytical temperature result of the wood stud is presented with the experimental one as well. A similarity in the results can be observed in the diagram; however the imperfection in matching between the results is due to a trivial difference between the analytical and experimental models. In the real model the thermocouple is placed on the surface between the stud and the insulation layer because it is not possible to place it inside the stud. The technical difficulty in the analytical model does not exist; a thermocouple device could be placed anywhere in the wood layer and thus a more representative results for the element temperature can be achieved.

Step 2: Structural Stability Analysis for normal Fire exposure

In this stage a fire resistance analysis is performed for normal fire exposure using the proposed analytical model. The critical buckling load of the wall unit degrades with time during fire until it drops to the level of the applied load at which point the unit is deemed to have failed. The duration between the start of the fire event and the buckling failure of the wall unit represents the FRR of the wall. The existent of the gypsum board has been considered here as a protective element and the wall temperature obtained from step 1 has been used to calculate the overall properties and loads. Figure 8 shows the reduction in buckling capacity of the F-19 unit with time. It should be noted that when the stud ends are retrained against axial movement, internal compressive stress will develop in the stud-sheathing composite due to temperature rise. In that case, the resulting compressive force in the system will not remain constant at the level of the applied load as shown in Figure 8. The resulting compressive force will in fact, go up as temperature increases, and meet the critical buckling curve earlier as indicated by Point A' in Figure 8 than the failure point A corresponding to the unrestrained case. The present numerical model shows similar results to the NRC fire tests which reported a failure in the wall F-19 between 43 and 48 minutes. In Figure 7-10, Part I of the curves represents the degradation in the capacity before the charring starts, and Part II represents the reduction in capacity because of the mass loss in the section beside the continuous degradation in the elements' mechanical properties. It can be noted that Part I lasts for about 0 to 20 minutes, and Part II lasts for about 20 to 43 minutes for the F-19 unit.

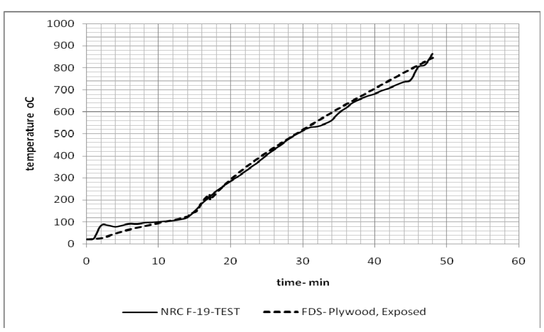

Figure 5: Temperature history results in the plywood layer

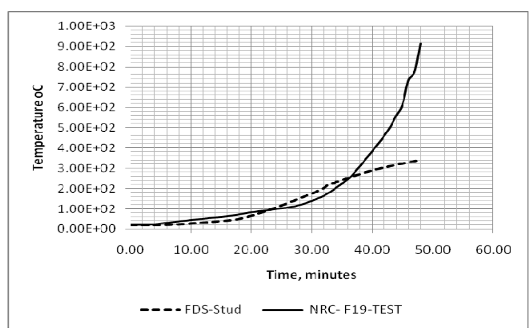

Figure 6: Temperature history results in the stud

Step 3: Structural Stability Analysis for PEF events

In this stage a fire resistance analysis due to PEF is performed using the same model used in Step 2 and by modeling the damage due to earthquake using the following assumptions:

a) The permanent lateral deflection in the wall is between 1.3% and 5% (Judd 2005), and in some cases 15% Dinehart et al. (1983).

b) The reduction in the fasteners stiffness and modulus of elasticity of wood and sheathing after the earthquake is between 30% and 50% (Judd 2005) and Dinehart et al. (1983)
c) The axial component is approximately equal to the vertical load since the lateral deflection is relatively small and the drift angle is very small.
d) The gypsum board damaged due to ground shaking and thus it is assumed to have lost the capacity to protect the structure from the fire. The thermals analysis is then calculated without considering the gypsum board.

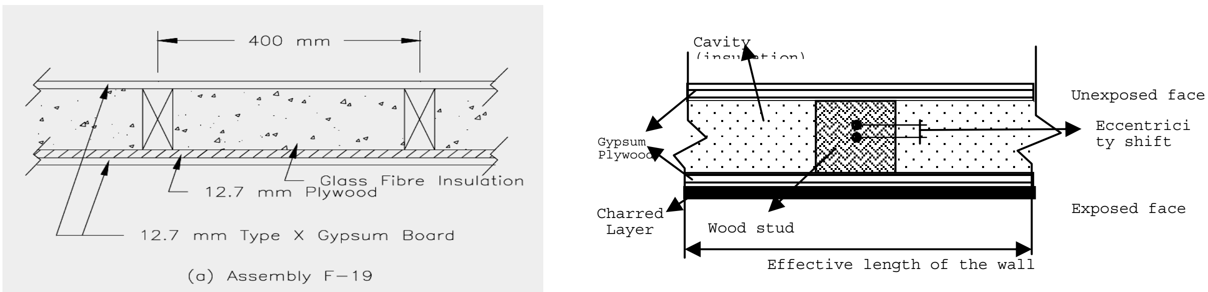

Figure 7: The effective length of the wood stud wall with charred layer

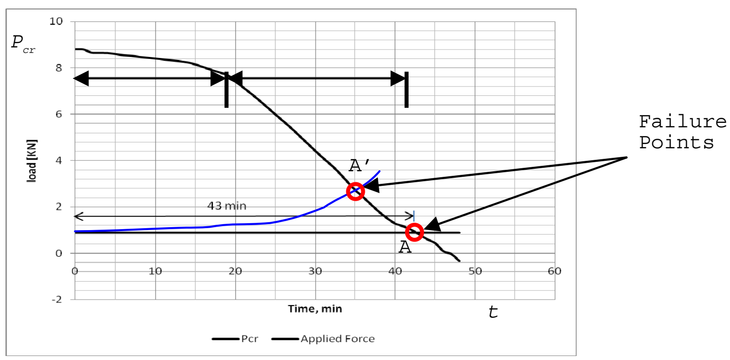

Figure 8: F-19 Buckling capacity degradation with time during fire

After and earthquake a stud wall may suffer a permanent lateral drift as presented in Figure 9. The wall at this stage has different geometric configuration from that before the earthquake. Damage in the wall is presented by the permanent lateral deflection and the reduction in the stiffness and mechanical properties of members reduce the overall capacity of the structure.
In the present study a percentage reduction in the stiffness of nails K and mechanical properties of wood E_s and plywood E_p are assumed based on the expected level of earthquake to calculate the buckling capacity of the wall during the fire. For example, a 30% earthquake damage ratio would reduce the fire resistant capacity of the F-19 wall to from 43 minutes to 28 minutes as presented in Figures 10 and 11. The curve shows a continuous degradation in the capacity until it drops to the applied load line. As the gypsum board is damaged due seismic vibration, wood elements may be exposed to direct fire sooner than in normal fire situation, and consequently, charring starts in the first 10 or 15 minutes of fire instead of 20 to 25 minutes as in normal fire.

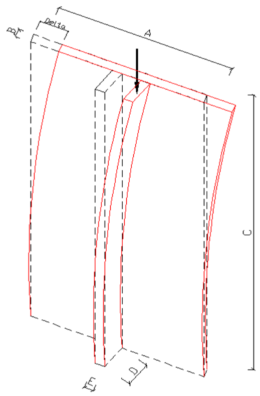

Figure 9: lateral deflection in the wall strip due to earthquake load.

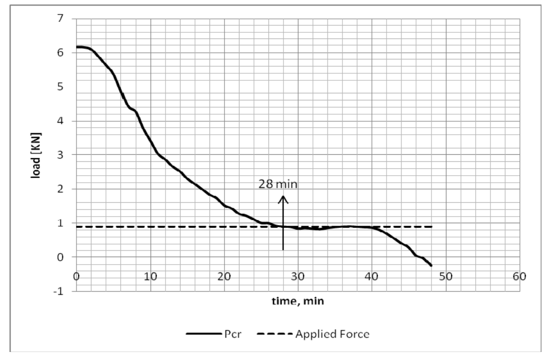

Figure 10: The wood stud wall buckling capacity during PEF and 30% earthquake damage ratio.

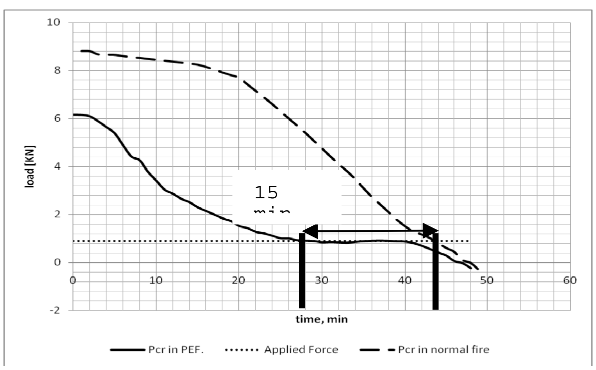

Figure 11: comparison between the wall buckling capacities in fire with and without earthquake (with 30% damage ratio)

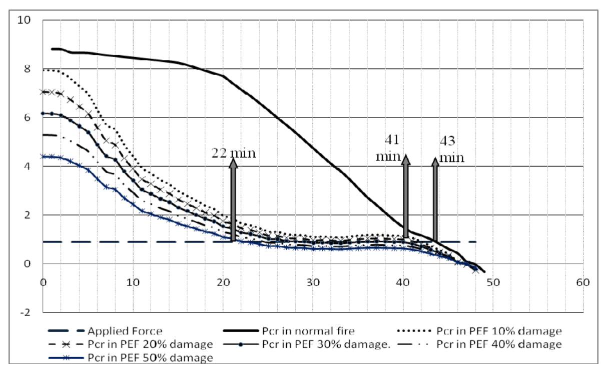

Figure 12: Reduction in the wall buckling capacity due to earthquake

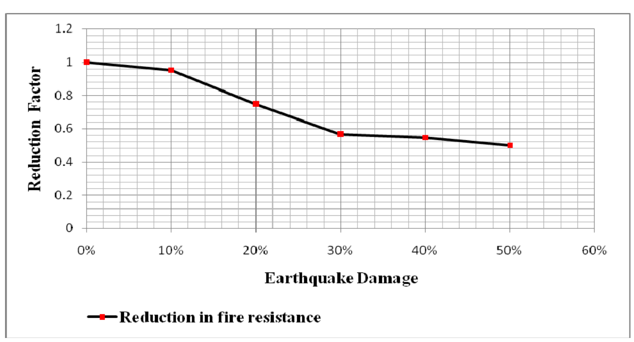

Figure 13: Reduction in fire resistance of the wood shear wall

A comparison between the FRR of wall F-19 before and after an earthquake is presented in Figure 12. The results show a reduction in the fire resistance of the wall to 28 minutes; which means that the wall has a fire resistance 33% less than its original estimate. Similarly, different earthquake damage ratios have been considered to calculate the reduction in the wall fire resistance rate. Figure 13 clearly shows that the FRR for the F-19 wall is inversely proportional to the percentage of damage because of earthquake. A correlation between the fire resistant and earthquake damage ratios is presented in Figure 13.

Conclusions:

It can be concluded here that there is a strong link between the FRR of the timber structure and the damage caused by earthquake. Wood stud walls in PEF are more vulnerable than in normal fire exposure. This is due to the earthquake-induced damage in the structural elements, gypsum boards and the loss of fire protection members. A numerical model has been developed for estimating the failure load and FRR of stud wall systems under normal fire and PEF events by considering the stud-sheathing composite actions, temperature dependent materials properties, charring in wood and damage due to lateral vibration. The model has been validated with an experimental study conducted earlier at NRC on stud walls under normal fire exposure. Using the validated model, the PEF performance of stud walls is estimated for various levels of seismic damage. The study indicates that even a small level of damage to the structural and non-structural elements (i.e. gypsum board) can reduce the fire resistance of a stud wall significantly.

Acknowledgement:

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