Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1779

PERFORMANCE OF STEEL MOMENT RESISTING FRAME BUILDINGS SUBJECTED TO POST-EARTHQUAKE FIRE EXPOSURE

M. H. Yassin[1], A. Bagchi[2], and V. K. R. Kodur[3]

ABSTRACT:

Post-Earthquake Fire (PEF) is an important factor causing damage to buildings in case of a strong earthquake. Many structures in North America are steel framed structures which are vulnerable to fire exposure. In a post-earthquake scenario, the structure and its fire protection systems may be considerably damaged and therefore its resistance to subsequent fire is reduced. The current study presents and analysis of PEF vulnerability and performance of steel-frame building frames. An analytical study of simple unprotected steel frame structures under the effects of PEF has been presented. The study reveals that the PEF performance of steel frames is strongly related to the residual lateral deformation caused by the seismic ground motion. Extensive studies in this direction are useful in understanding PEF effects on structures based on which appropriate design guidelines can be developed.

Introduction

Fire following an earthquakes cause devastating damage to urban facilities, which may be sometimes larger than the damage caused by the earthquake itself. Modern structures are adequately designed to have sufficient seismic resistant, and fire safety assuming that these events are to occur separately. However, these two events, i.e. fire and earthquake, are strongly correlated and most earthquakes are followed by fires because of many factors such as the damages gas lines or electrical short-circuiting caused by seismic vibration. After an earthquake the structure and its fire protection system may sustain some damage and hence fire resistance of the whole system will be significantly impaired. Such conditions may seriously threaten the stability and integrity of the structure and as a result the life safety of the occupants and rescue workers. Thus, it is necessary to consider such scenarios in the design of a building constructed in an area of moderate and high seismicity, especially for the post disaster facilities, such as, hospital and fire station. Steel structures are particularly vulnerable to fire hazard. The mechanical strength of steel reduces drastically at high temperature. In a post-earthquake scenario, the building frame and its fire protection system may be significantly damaged and consequently resistance to subsequent fire is reduced.

The financial and human losses because of the fires following an earthquake are sometimes much bigger than that caused by the earthquake itself (Mousavi et al. 2008). Buildings are

[1] Graduate Research Assistant, Department of Building, Civil and Env Eng., Concordia University, Canada
[2] Associate Professor, Department of Building, Civil and Env Eng., Concordia University, Canada
[3] Professor, Department of Building and Civil Engineering, Michigan State University, USA.

usually designed to sustain gravity and lateral loads (seismic or wind events). Fire safety issues are generally dealt with separately to ensure adequate fire resistance of a structure under normal or accidental fire events. Codes and regulations do not usually consider the effect of fire subsequent to an earthquake. Very limited number of studies on the building performance under the combination of both of these events has been reported. Past experience shows that post-earthquake fire plays an important role is safety and emergency event management. The integrity of structures under such events is extremely important. History shows that the lack of adequate attention to PEF in both individual building design and urban design can result in a catastrophe. Past records show that PEF in Japan and America have been a major factor for post-earthquake damage in the twentieth century (Mousavi et al. 2008). Therefore, besides satisfying the structural design requirements for normal loads such as dead, and live loads including the seismic forces and normal fire hazards, buildings should also be designed to withstand the PEF events for certain minimum duration of time, which is critical for the safe evacuation of the buildings. An analytical study of two-dimensional steel frames under the effects of seismic lateral loads and subsequent fire has been presented. The buildings considered in the study are single-story and two-story high, and have simple configuration.

Materials used for structural component and their mechanical behavior under fire and the intensity of external forces are important factors affecting fire performance of building. Under high temperature the loss of strength and stiffness is considered to be the major weakness of steel structures exposed to fire. Steel under fire looses its strength and stiffness faster than concrete. So the steel structures are always provided with some fire protection. These fire-proofing materials are also susceptible to damage (such as peeling off from steel surface) even during non earthquake fire events. The possibility of such damage become much higher in the event of earthquake due to vibration and hence might be a governing factor on the fire performance of structural system. More attention should be given to the selection of appropriate fire-proofing materials for the use in earthquake regions. Another issue is the assessment of the structure state after an earthquake, which represents the initial condition for the subsequent fire action. Della Corte et al (2003) assumed a simplified schematization of seismic damage, where they considered the first of the following two forms of damage: (i) geometric damage, which is the change of initial structure geometry owing to the residual deformation produced by plastic excursions during the earthquake; and (ii) mechanical damage, which is the degradation of mechanical properties of those structural components engaged in the plastic range of deformation during the earthquake. The work presented here obviates some of the assumptions made in Della Corte et al (2003) by subjecting the structure to lateral loads followed by a fire in the same simulation session so that the residual displacements and stresses are properly represented in the fire induced stress analysis.

Structural fire safety design

Structural members are normally designed to satisfy the requirements of serviceability and safety limit states for various environmental conditions. Fire represents one of the most severe undesired conditions and hence the provision of appropriate fire safety measures for structural members is a major safety requirement in building design.

The basis for this requirement can be attributed to the fact that, when other measures for containing the fire fail, structural integrity is the last line of defense. In General, structural members or systems are designed for required fire resistance rating (FRR) which is defined as the duration in which a structural member or system exhibits resistance with respect to structural integrity, stability and heat transmission. FRR depends on a number of factors including the features of building, and the occupancy type. The intention is to provide occupants with adequate time to evacuate the building, fire fighters to put out the fire, and to avoid any possible progressive collapse. Typical FRR requirements for specific building members are provided in the building codes (e.g. IBC 2006; NBCC 2005). However, much of this criterion is developed for fire exposure under normal conditions (i.e. without earthquake). These guidelines may not be fully applicable in the case of post-earthquake fire events since the structure under fire exposure may experience significant lateral loads from an earthquake prior to the fire. The performance-based design paradigm requires that the effect of earthquakes on the level of fire resistance of a building structure be determined even if no subsequent fire develops (Della Corte et al. 2003). In that case, the post-earthquake retrofit schemes for fire proofing systems can be evaluated. Therefore, fire safety codes need to differentiate between structures in seismic areas from the other, and require a more stringent FRR for them.

Major factors in post-earthquake fires

It is also essential to know the behavior of structural and non-structural components of a building under the interactive combination of seismic loads and subsequent fire. Improper reliance on the codes' allowance for reduction in passive fire protection systems may increase the inadequacy of overall fire protection systems in the event of severe earthquakes. Post-earthquake fire may be viewed as a course of events consisting of the followings (Scawthorn et al. 2005): (1) seismic event causes damage in structural and non-structural components and might result in falling down of items such as candles or overturning of cooking stoves; (2) ignition may be caused by breakage of utility lines such as gas line, or electrical short-circuiting; (3) discovering the existence of a fire may be difficult because of panic following an earthquake; (4) reporting a fire to the fire department is the next important step; (5) response of the fire department may be impeded by damage to the station itself or the transportation and communication networks; (6) failure of water distribution systems due to earthquake affects the fire-fighting effort; and (7) if the fire control measures fail, the fire could end up in a conflagration and fire spread, which will stop only when all the fuel is burnt up.

Strategies for mitigation of post-earthquake fire hazard

Mitigation measures for post-earthquake fire can be achieved at the following two levels: (a) regional or area level, and (b) individual building level. At the area level, an approach based on Geographical Information System (GIS) can be effective in the analysis process (Chen *et al.* 2004, Zhao *et al.*, 2006). This will provide sufficient information on geographical distribution of human injuries and ignited fires, locations of the emergency services such as fire station and hospitals, damage intensity of the facilities and transportation system and the localized damage area due to earthquake and subsequent fire. This information is important for prioritizing and optimizing the emergency services, and making necessary provisions for building redundancy. On the other hand, at the individual building level four fundamental types of analyses are to be incorporated into the performance-based design approach. These steps are as follows (Chen et al. 2004): (i) analysis of the hazard that provides input data like duration of earthquake and its intensity, fire load and resulting compartment temperatures; (ii) analyses of the structural and non structural components based on the prior estimation of hazards that include structural demand parameters like drift and acceleration experienced by the building, peak structural temperatures and deflections; (iii) damage analysis of the buildings including condition evaluation and required modifications; and (iv) loss analysis consisting of casualties, injuries, direct and indirect financial losses. At the individual building level, mitigation strategies for the post-earthquake fire hazard involve a number of aspects such as, analysis of the hazard, scale of damage and consequent losses, the characteristics of the materials used in the construction, and the type of fire protection systems employed.

Assessment of post-earthquake fire performance of structures

Evaluation of the post-earthquake fire performance of a structural system is a key to the performance-based design. There is a need for developing a systematic approach to such evaluation. A scheme for the evaluation of PEF performance of structural systems for buildings has been proposed by Mousavi et al. (2008). Prior to the occurrence of an earthquake a building frame is primarily subjected to gravity loads, P due to dead and live loads. To evaluate the seismic damage in the structure, first the seismic hazard level is determined from the seismic hazard spectrum for the given site, followed by the selection of appropriate ground motion records and structural analysis. The seismic hazard spectrum or the response spectrum of expected seismic motions is expressed as the variation of the spectral acceleration, S_a, with the fundamental period, T_0 of a structure. On the other hand, the time histories of ground acceleration, a, are expressed as functions of time, t. The seismic excitation induces lateral vibration of the building and inflicts damage and permanent lateral deformation, Δ. This deformation in the damaged structure causes additional stresses in the frame due to the secondary moments caused by P-Δ effect. Structural members and joints are also weakened by the cyclic inelastic deformation causing stiffness and strength degradation. In addition, the fire proofing systems are also damaged. Once the earthquake induced damage in the structure is determined, the damaged structure is subjected to a post-earthquake fire scenario, which involves fire hazard analysis to determine the time history of fire growth and spread, and stress and collapse analysis of the structure. The design fire scenarios for any given situation should be established either through the use of parametric fires (time-temperature curves) as specified in the codes and standards (e.g., CAN/CSA ULC S101-M89) or through actual calculations based on ventilation, fuel load and surface lining characteristics. Alternatively, the fire exposure curve can be developed through simulation based on different possible load combinations including expected earthquake ground motions. Incorporation of appropriate monitoring systems in buildings and other fire-sensitive structures can provide the response history records for regular fire and post-earthquake fire events.

Behavior of steel structures under fire

Loss of strength and stiffness due to high temperature are known to be steel structure's paramount weaknesses (Wastney 2002). For this reason, it is common to protect structural steel from high temperature, and/or minimize the use of unprotected structural steel. Moreover, it is a common a practice in design of structures exposed to high temperature not to account for the effect of other members while designing an individual component. However, actual fire events and tests show that where unprotected steel structural components are part of a frame they demonstrate a greater magnitude of resistance to high temperature than that evaluated from single element tests (Gillie et al., 2002). The changes in steel properties have been considered in numerical models developed here using SAFIR (Franssen et al, 2000) and ANSYS. Figure 1 shows the changes in the modules of elasticity of steel in high temperatures. The reduction factor in modulus of elasticity of steel is shown in Figure 2.

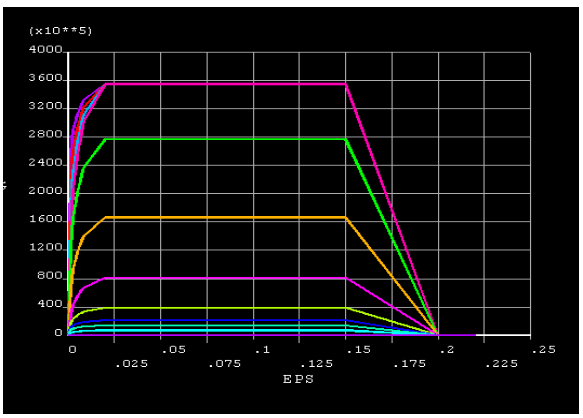


Figure 1: Stress strain relationship for steel

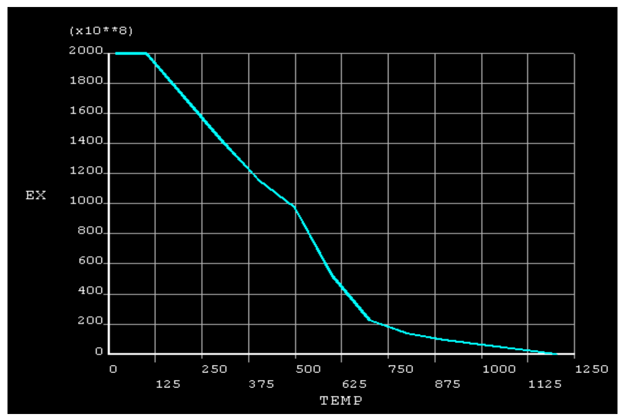


Figure 2: Reduction factor for steel modulus of elasticity due to high temperatures

PEF Case Studies and Preliminary Results

In a preliminary study, one and two story one bay moment resisting steel building frames have been considered here. Temperature dependent material properties for steel have been used. Two types of structural models have been considered, one with fixed support condition, and the other with hinged support condition. Vertical load on the beams is assumed to be 24 kN/m. Lateral loads or seismic ground accelerations are applied to cause lateral drift before fire load is applied. For the fire load standard fire curve (CSA, 1989) is considered. For the fire load three sides of section are considered exposed to fire. The time history of temperature distribution across the cross section has been obtained using SAFIR, a specialized finite element software for fire-structure analysis (Franssen et al. 2000), and sample snapshots of the results are shown in Figures 5 and 5. Three cases have been considered.

In the first case, a one-story one-bay moment-resistant steel frame has been modeled in ANSYS. Canadian steel section W920x446 is used for column. The beam moment of inertia is considered five times that of the column section. The damage induced by El Centro earthquake is obtained as a resultant of the nonlinear dynamic analysis performed by using ANSYS. The heat transfer analysis is performed on the elements sections in 2D by using SAFIR. ANSYS is also used to perform the thermal stress analysis in the frame. The limited capability in performing nonlinear dynamic analysis in SAFIR makes it necessary to divide the analysis procedure steps between SAFIR and ANSYS. PEF analysis results are presented through Figures 5 to10. The comparison between the lateral or vertical displacement in the frame nodes in normal and post-earthquake fire as presented in Figures 8 and 9, respectively, shows a shift in the deflection occurrence; which indicates an earlier failure in the structure in the case of PEF. The shift in the time duration between the two curves is about 4 minutes for the applied magnitude. It can be noted from this analysis that the PEF analysis should be performed by combining between different types of simulators. The analysis could be simplified by dividing the whole procedure into sup steps which can be performed separately and in sequence.

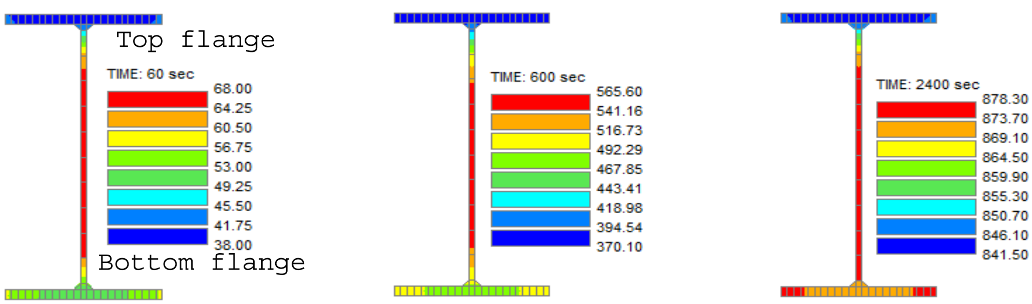


Figure 3: Snapshot of temperature distribution at different times in Section W360X51

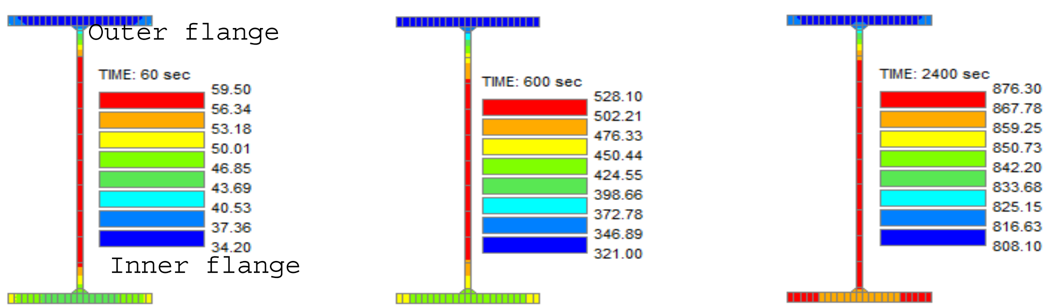


Figure 4: Snapshot of temperature distribution at different times in Section W460X74

The results presented in Figures 6-10 are for the frame with fixed support and with vertical loads combined with lateral load followed by fire. For the hinged support condition, the results are similar except the zero moment at the support and slightly higher displacements at the top. The analyses are performed for different magnitudes of the ground motions.

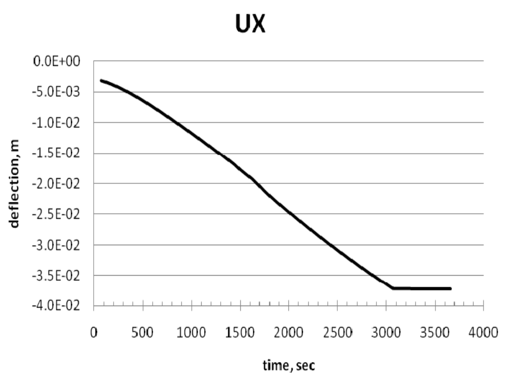


Figure 5: Horizontal deflection at the mid-span node in case of normal fire

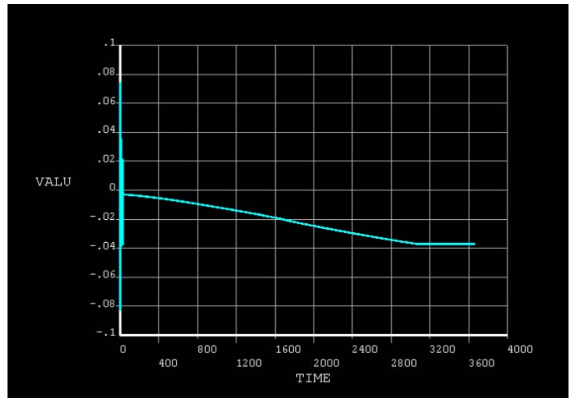


Figure 6: Horizontal deflection in the beam in case of PEE

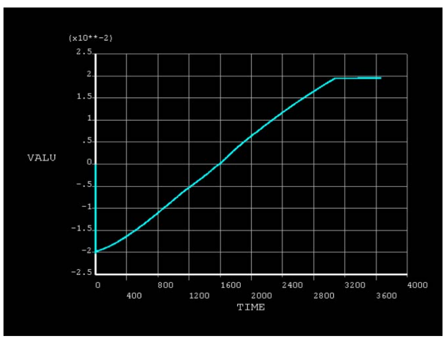


Figure 7: vertical deflection at the mid-span node in case of PEF

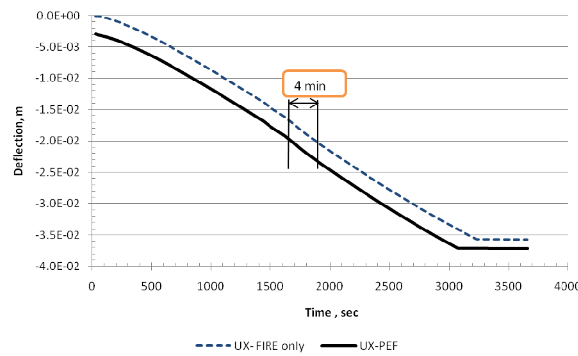


Figure 0: Horizontal deflection in case of normal and PE fire

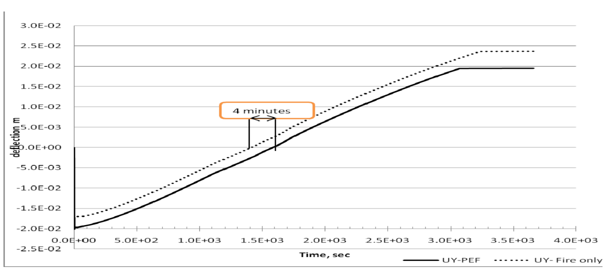


Figure 9: Vertical deflection in case of normal and PE fire

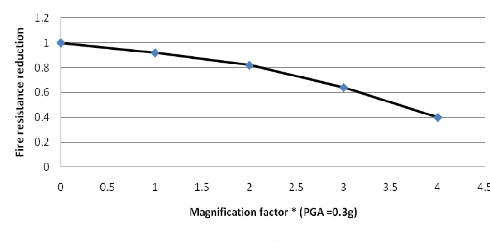
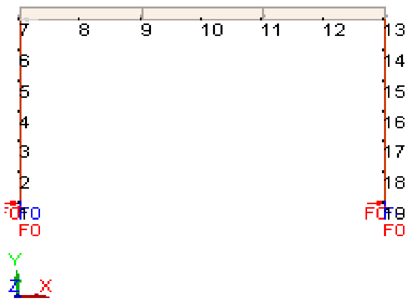
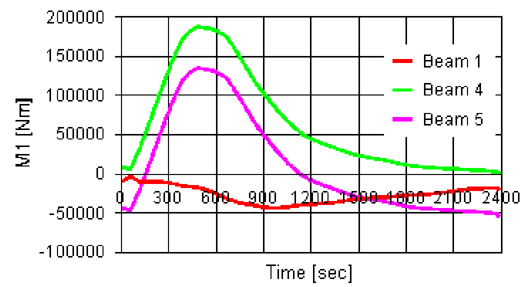


Figure 10: The correlation between the acceleration magnitude and the fire resistance

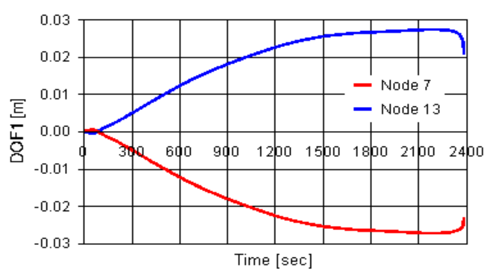
In the other two cases, Canadian steel section W460X74 is used for column, and W360X51 steel section is used for beam. SAFIR has been used for both thermal and thermo-structural analyses. In the second case, a single story frame has been analyzed for lateral loads followed by fire, and the sample results have been shown in Figure 11. The lateral load is varied and fire resistance and maximum fire induced deformation have been determined at ach level. In the third case, a two story frame is considered, and the sample results for the fixed support conditions are shown in Figure 12. The displacement shape indicates that due to the influence of lateral loads, the fire induced failure is asymmetric. In the absence of lateral deformation, the deformation pattern is symmetric until the fire induced deformation becomes excessive. In that case, the frame undergoes sway as observed in Fig. 12(c). In the single story frame sway does not occur as the frame is much stiffer and the fire induced deformation is much higher compared to the deformation due to gravity and lateral loads. Figure 12(h) shows the variation of normalized fire resistance (tf/tf0) with lateral story drift, where tf is the time of failure of the frame under fire with lateral deformation, and tf0 is that for no lateral drift.



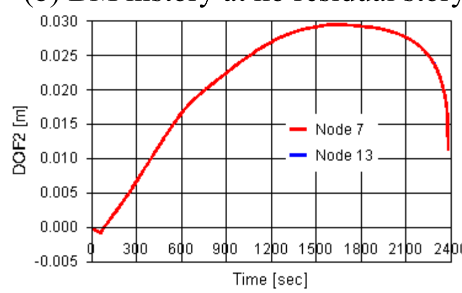
(a) Geometry of the single story frame



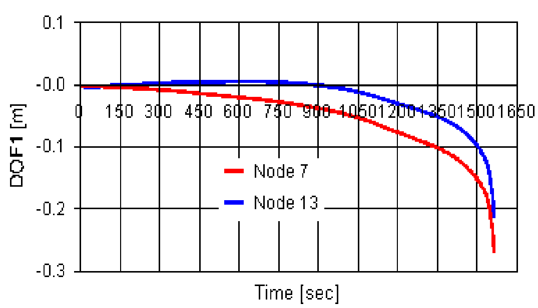
(b) BM history at no residual story drift



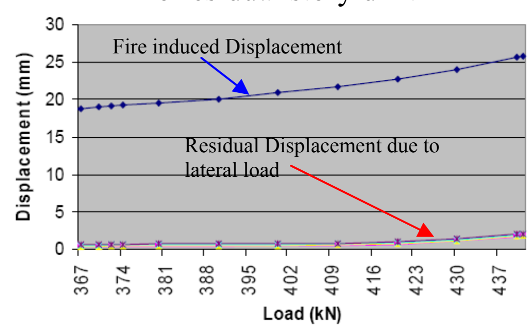
(c) Horizontal displacement at BM history at no residual story drift



(d) Vertical displacement at BM history at no residual story drift



(e) Horiz disp at story drift of 0.43%

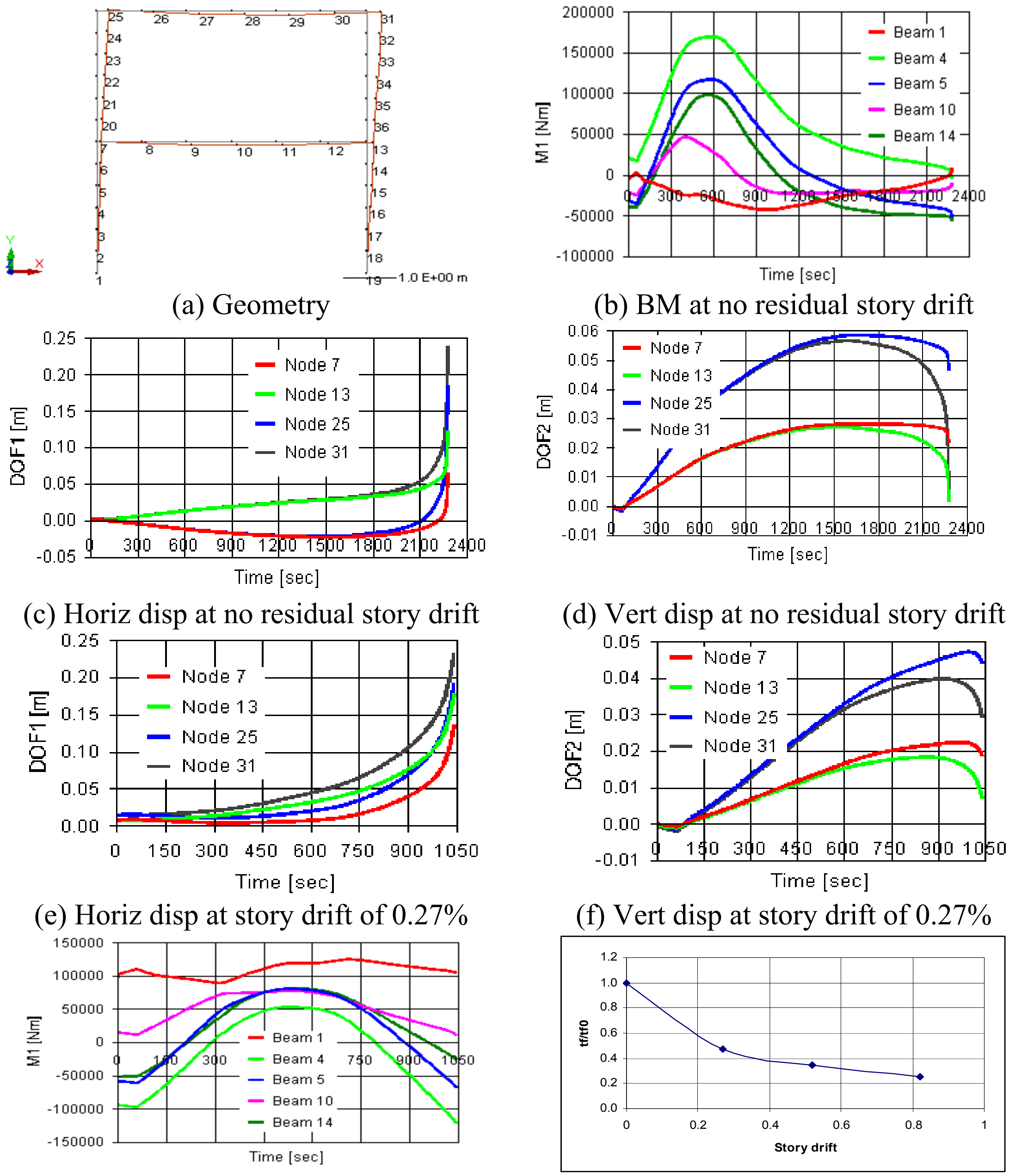


(f)

Figure 11: Structural model and summary of results for the single story frame

Discussion and Conclusions

Although major earthquakes are followed by subsequent fires, the current design codes do not explicitly consider it as a design scenario. However, in a performance-based design pattern, such scenario should also be considered in order afford a desired level of performance, particularly of the important structures and post-disaster facilities (e.g., hospital, fire-station). Steel structures are vulnerable to fire in normal conditions. For that reason, they are usually fire-proofed. Earthquake may cause damage to the fire protection system as well as the structure itself. Fire followed by such events finds steel structures particularly vulnerable. The paper presents a preliminary study of a limited set of steel frames for buildings have been presented, which shows that prior deformation/damage due to events such as earthquakes are likely to reduce the fire performance of such building frames.



(a) Geometry

(b) BM at no residual story drift

(c) Horiz disp at no residual story drift

(d) Vert disp at no residual story drift

(e) Horiz disp at story drift of 0.27%

(f) Vert disp at story drift of 0.27%

(g) BM at no residual story drift of 0.27%

(h)

Figure 12: Structural model and summary of results for the two story frame

Acknowledgement

Financial support of the Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged.

References

Chen S., Lee G.C., and Shinozuka M., 2004. Hazard Mitigation for Earthquake and Subsequent fire. *ANCER Annual Meeting: Networking of Young Earthquake Engineering Researchers and Professionals*, July, Honolulu, Hawaii, U.S.A.

CSA, 1989, CAN/ULC-S101-M89, "Standard Methods of Fire Endurance Tests of Building Construction and Materials", Underwriters' Laboratories of Canada, Scarborough, Ontario.

Della Corte, G.; Landolfo, R.; Mazzolani, F. M.; (2003). Post-earthquake fire resistance of moment resisting steel frames. *Fire Safety Journal*, 38: 593–612

Franssen J. M., Kodur V. K.R., and Mason J. 2000. *User's Manual for SAFIR 2002* – A Computer Program for Analysis of Structures Submitted to Fire. Department Structures du Génie Civil, Service Ponts et Charpentes, Univ of Liège, Belgium.

Gillie, M., Usmani, A. and Rotter, M. 2002, "A structural analysis of the Cardington British Steel corner test", *J of Constructional Steel Research*, 58(4) p.427-442.

IBC, 2006. *International Building Code*. Int Code Committee, Wash, D.C., U.S.A.

Mousavi, S.; Bagchi, A.; Kodur, V.K.R.; (2008). Post-Earthquake Fire Hazard to building structures, Canadian Journal of Civil Engineering, 35: 689-698.

NBCC, 2005. National Building and Fire Code of Canada. *National Research Council*, Ottawa, Canada.

Scawthorn C., Eidinger J.M., and Schiff A.J., 2005. Fire following earthquake. *Technical Council on Lifeline Earthquake Engineering*, Monograph No. 26, American Society of Civil Engineers (ASCE), Reston, VA.

Wastney, C. 2002. "Performance of unprotected steel and composite steel frames exposed to fire", *res report*, Univ of Canterbury, Christchurch, New Zealand.

Zhao S.J., Xiong L.Y., and Ren A.Z., 2006. A Spatial-Temporal Stochastic Simulation of Fire Outbreaks Following Earthquakes based on GIS. *Journal of Fire Sciences*, 24: 313-339.