ASSESSMENT OF POST-EARTHQUAKE FIRE PERFORMANCE OF STEEL-FRAME BUILDINGS

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ABSTRACT :

Post-Earthquake Fire (PEF) is an important factor causing damage to buildings and life-line structures. While PEF events are not uncommon, current design codes do not consider it explicitly in the structural design. It is important to note that when all efforts to contain the fire fail, the structure provides the last line of defense. Therefore, in a multi hazard scenario such as PEF, the individual and the probable combination of events must be considered in the context of performance-based design. This paper presents a review of PEF hazard and performance of steel-frame building structures under PEF conditions. Unprotected steel is 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. An analytical study of two-dimensional steel frames under the effects of seismic lateral loads and subsequent fire has been presented. The study reveals that the PEF performance of steel frames is affected by the lateral deformation caused by the seismic ground motion.

KEYWORDS:

post-earthquake fire, multi hazard events, performance-based design, structural strengthening, simulation.

1. INTRODUCTION

Earthquakes cause devastating damage in the urban facilities, and in many cases earthquake events are followed by fire which may cause more damage than the earthquake itself. Modern buildings are designed to have adequate resistance against an expected level earthquake, and sufficient fire safety, considering these events to occur separately. However, fire following an earthquake event is not uncommon. After an earthquake the structure may sustain a considerable damage and the fire resistance of the system will be significantly impaired. In this case, the fire performance of the structure will be significantly reduced, and such condition may pose a serious threat to structural integrity detrimental to 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 a seismic zone, especially for the post disaster facilities. 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 that follow an earthquake are sometimes much bigger than that caused by the earthquake itself (Mousavi et al. 2008). Buildings are usually designed to sustain considerable amount of resistance to 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. The 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). The 1994 Northridge earthquake caused relatively minor damage due to PEF events mainly because of a lower level of damage to the water distribution system and quick response of the fire department (Todd et al, 1994). The 1995 Kobe earthquake resulted in huge damage due to both ground shaking and PEF events (EQE 1995).

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 be designed to withstand the PEF events for certain minimum duration of time, which is critical for the safe evacuation of the buildings. This paper presents the state-of-the-art review on PEF hazard and the performance of steel-frame building structures under PEF conditions. 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 behaviour under fire and the intensity of external forces are the factors important factors affecting fire performance of building. Under high temperature the loss of strength and stiffness is considered as major weakness of steel structure exposed to fire. Steel under fire looses its strength and stiffness faster than concrete. So the steel structures are always used provided with some 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 the earthquake, which represents the initial condition for the subsequent fire action. It is very difficult to obtain sufficiently detailed information about the earthquake-induced structural damage, because of large uncertainties and the randomness of both structural properties and earthquake ground motions. To overcome these difficulties Della Corte et al (2003) assumed a simplified schematization of seismic damage, which is convenient to be used for parametric analysis. Accordingly, they considered the first of the following two forms of damage:

1) Geometric damage, which is the change of initial structure geometry owing to the residual deformation produced by plastic excursions during the earthquake.
2) 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 of Della Corte et al (2003) by subjecting the structure to lateral loads followed by a fire in same simulation session so that the residual displacements and stresses are represented in the fire induced stress analysis.

2. 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 defence. In General, structural members or systems are designed for required *fire resistance rating* which is defined as the duration in which a structural member or system exhibits resistance with respect to structural integrity, stability and heat transmission. Fire resistance rating 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 fire resistance rating 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. Earthquake-induced damage to the structure makes it more vulnerable to subsequent fire as both active and passive fire proofing systems may have been damaged and the residual lateral drift in the building frames produces additional stresses from gravity loads due to the P-Δ effect. This might lead to lower fire resistance of the structural system. 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 fire resistance rating for them.

3. MAJOR FACTORS IN POST-EARTHQUAKE FIRES

Mitigation of post-earthquake fire hazard will not be meaningful if the causes are not well understood. 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. In addition, proper attention should be given to the interaction of the causes and a building's status as the change in either of them influences the magnitude and intensity of the other. 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. However, in the performance-based design process, post-earthquake fire should be suitably dealt with by considering it as a design scenario, which is particularly important in the regions where significant earthquakes can take place. Post-earthquake fire may also be viewed as a course of events consisting of the followings (Scawthorn *et al.* 2005): (1) ground shaking due to an earthquake may result in 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 can take place in a variety of ways including breakage of utility lines such as gas line, electrical wiring shortcut, or leakage of highly combustible materials such as petroleum or alcohol-based substances; (3) finding out 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 if the fire is not self-extinguished and/or put out by occupants; (5) response of the fire department is crucial in the event of a post-earthquake fire scenario, and damage to the station itself or the transportation and communication networks will affect such response time; (6) failure of water distribution systems due to earthquake affects the fire-fighting effort; and (7) if the fire control measures taken by the emergency crews are not successful, the fire could end up in a conflagration and fire spread, which will stop only when all the fuel is burnt up.

4. STRATEGIES FOR MITIGATION OF POST-EQRTHQUAKE 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, each of which are discussed bellow.

4.1. Mitigation at the area 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. There are several factors that need adequate attention and enhancement for PEF mitigation in the regional level. Some of which are as follows (Chung *et al.* 1995): (a) post-earthquake fire ignitions due to short circuit; (b) fire ignition due to the breakage of gas distribution system; (c) supplementary mechanism such as, automatic shutoff valves, extra gas valves on the supply network, and relevant measures to stop and control gas distribution systems; (d) fire spread between buildings; (e) special attention given to the areas where a large likelihood exists for post-earthquake fires; (f) disruption of the water distribution network; (g) enhancing the water-based fire protection systems; and (h) life-line systems design for earthquake and subsequent fire. From the report on the 1994 Northridge Earthquake (Todd *et al.*, 1994), it can be observed that the post-earthquake fire damage during the earthquake was relatively lower perhaps because of the presence of some of the above-mentioned measures such as, auto shut-off valve in the gas lines in the San Fernando valley.

4.2. Mitigation at the individual building level

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):

(1) Analysis of the hazard that provides input data like duration of earthquake and its intensity, fire load and resulting compartment temperatures;
(2) 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;
(3) Damage analysis of the buildings including condition evaluation and required modifications; and
(4) 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.

5. 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 proposed by Mousavi et al. (2008) is shown in Figure 1, which is briefly described here.

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 single degree of freedom system. 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, in the building frames. This deformation in the damaged structure causes additional stresses in the frame due to the moment 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 or through actual calculations based on ventilation, fuel load and surface lining characteristics. Figure 2 shows the typical standard and real fire exposure curves that can be used for performance-based fire safety design. 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.

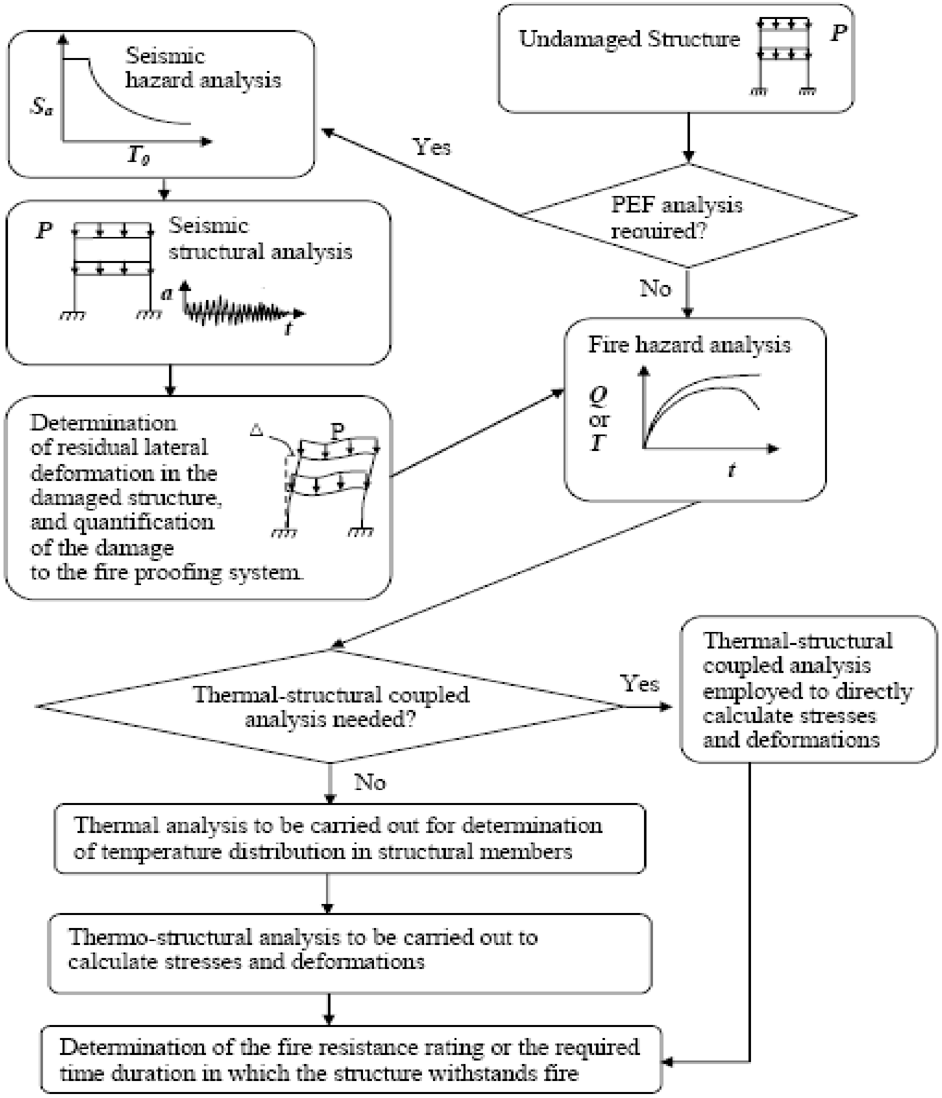


Figure 1 – Steps involved in the PEF performance evaluation of building frames

6. BEHAVIOUR 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) which is clear from the stress-strain and strength-temperature relationships for ASTM A36 steel shown in Figure 3. 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.

Tests have shown that high tensile forces are generated in steel beams throughout heating and cooling periods. Moreover, beam connections can undergo significant axial tensile forces while cooling (Harmathy 1978). This may result in failure of beam connection. Two-dimensional structural/thermal analysis of composite section of unprotected steel beams and RC slabs that span between fire-protected steel columns show that the tensile axial forces in the frames to be larger when no composite action is present. The maximum compressive forces in solid connections are found to be bigger but the maximum induced tensile force is independent of connection type. Investigations also showed that stronger columns provoke greater tensile forces in the cooling period, while beams behave very similar to single span beams with pin connections. In addition, the axial forces in the steel and composite beams are found to be strongly dependent on the maximum temperature of the steel during fire and mostly independent of the fire duration. Structural integrity can be greatly enhanced due to composite action between the steel frame and concrete deck (Gillie et al. 2002).

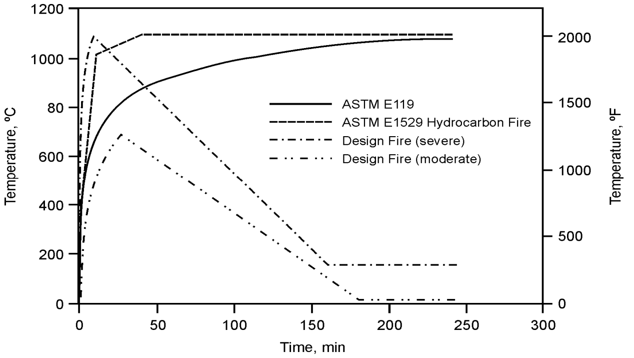


Figure 2 – Typical Fire Exposure Scenarios for Performance-Based Design

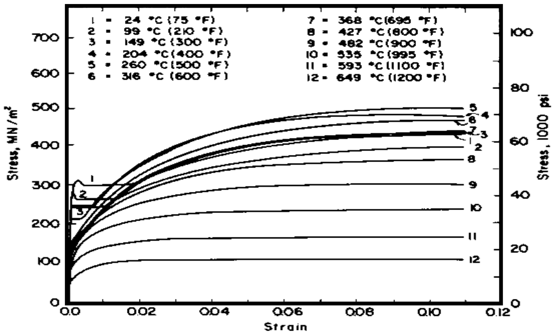


Figure 3 – Temperature dependent stress-strain curves for ASTM A36 steel (Harmathy 1978)

7. PEF CASE STUDIES AND PRELIMINERY RESULTS

In a preliminary study, a one story and two storey one bay moment resisting steel building frames have been considered here. Temperature dependent material properties for steel have been used. Canadian steel section W460X74 is used for column, and W360X51 steel section is used for beam. Two types of structural models have been considered, one with fixed support condition, and the other with hinged support condition. Vertical load on the beam is assumed to be 24 kN/m acting on the beams. Static loads are applied to cause lateral drift before foire load is applied. For the fire load standard fire curve similar to ASTM E119 fire curve as shown in Figure 2 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 some of the snapshots are shown in Figures 4 and 5. The structure is analyzed using SAFIR for the vertical load and lateral load followed by fire.

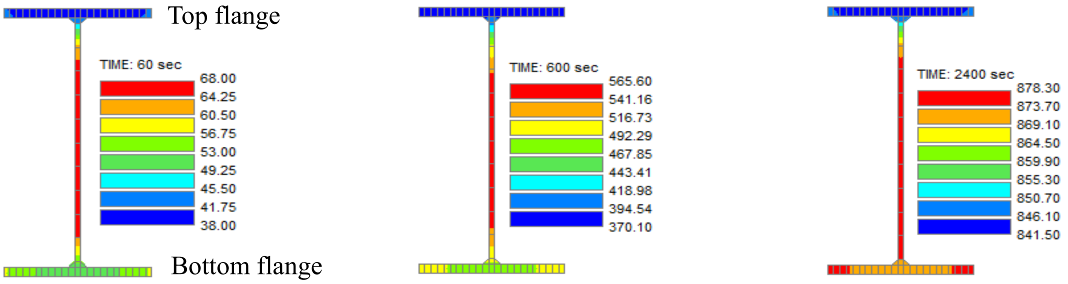


Figure 4: Snapshot of temperature distribution at different times in Section W360X51

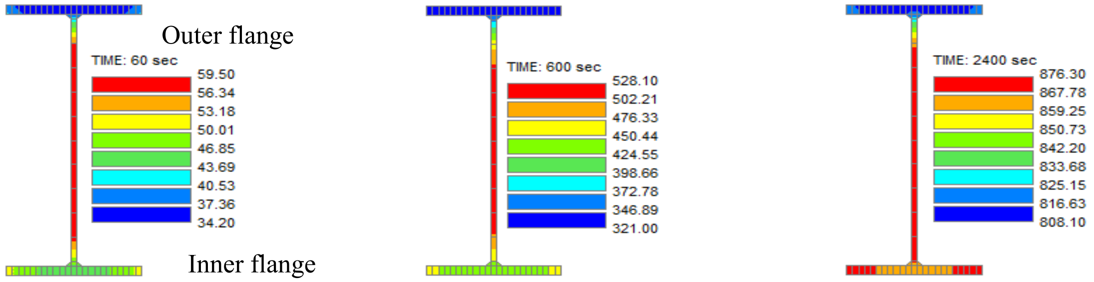
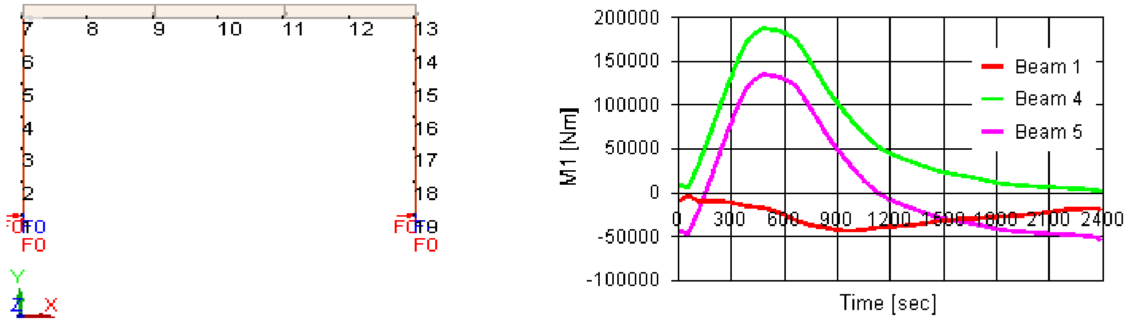
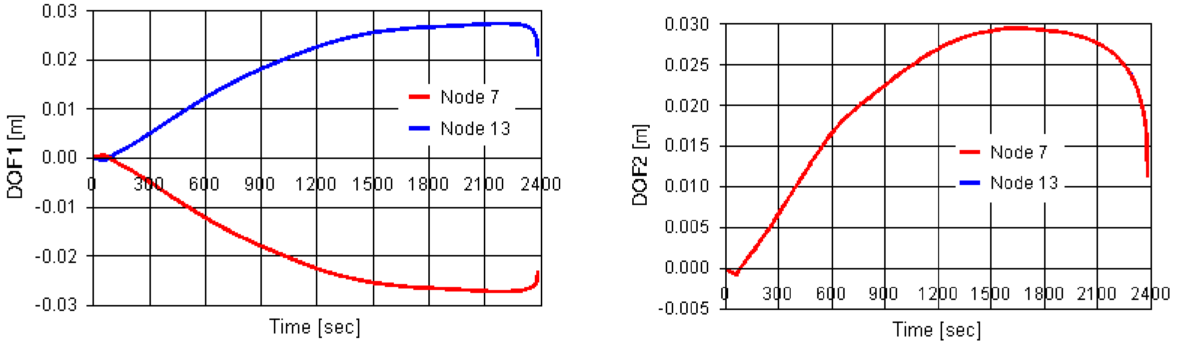


Figure 5: Snapshot of temperature distribution at different times in Section W460X74



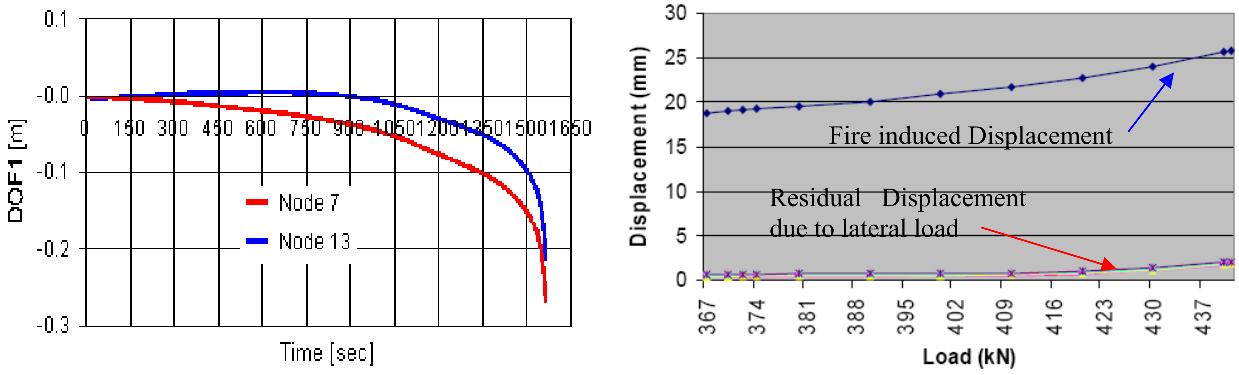
(a) Geometry of the single story frame

(b) BM history at no residual story drift



(c) Horiz disp at BM history at no residual story drift

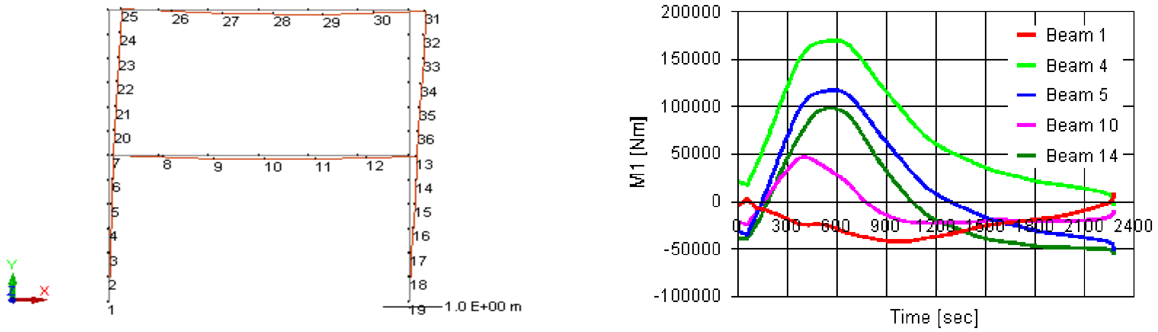
(d) Vert disp at BM history at no residual story drift



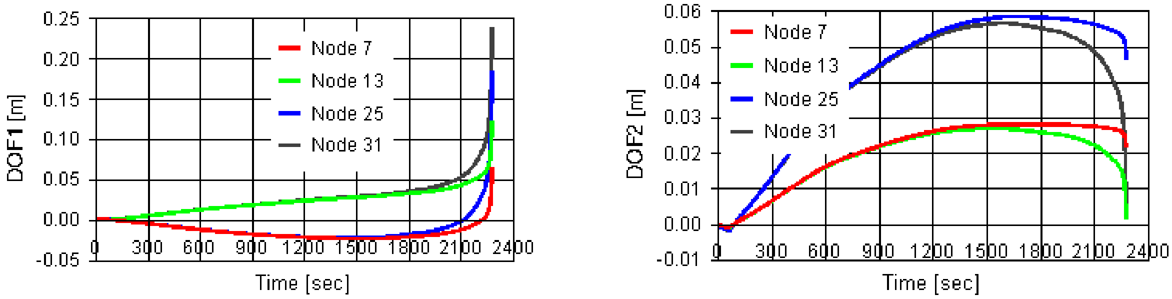
(e) Horiz disp at story drift of 0.43%

(f)

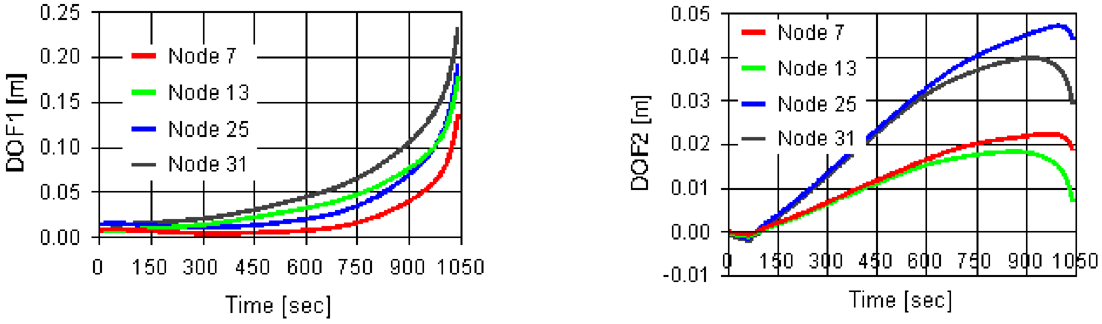
Figure 6 – Structural model and summary of results for the single storey frame



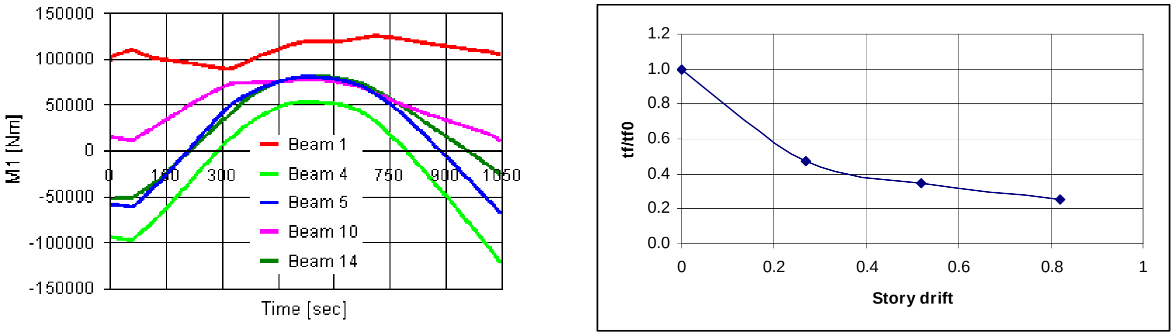
(a) Geometry (b) BM at no residual story drift



(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 4 – Structural model and summary of results for the two storey frame

The results presented in these graphs 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 lateral loads. The sample results of the single storey frame have been shown in Figure 6. The lateral load is varied and fire resistance and maximum fire induced deformation have been determined at ach level.

Figure 7 shows the model of a two storey frame along with sample results for the fixed support conditions. The displacement shape indicates that due to the influence of the lateral load, 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. 7(c). In the single storey 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 7(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.

From the above analysis it can be concluded that performance evaluation of building under fire or under earthquake separately is not sufficient. Building should be evaluated under the combined effect of fire following earthquake. The level of seismic performance of the structure should be correlated with the fire performance of the structure.

7. 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 paradigm, such scenario should also be considered in order afford a desired level of performance, particularly of the important structures. Steel structures are vulnerable to fire in normal conditions. For that reason, they are usually fire-proofed. Earthquake structure 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 review of literature on post-earthquake fire and a methodology for evaluation of structures under such events. A preliminary study of a limited set of steel frames for buildings have been presented, which shows that lateral load induced deformation can reduce the fire performance of such building frames.

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