# PARAMETRIC STUDY ON POST-EARTHQUAKE FIRE BEHAVIOR OF STEEL MOMENT RESISTING FRAMES

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**Abstract:** Performance-based design of structures against the fire and seismic-induced fire is an important area that requires more attention. While experimental study is one of the most reliable methods to capture behavior of steel structures under fire, performing real case scenarios in laboratories is not economical due to expensive facilities required to conduct such a test. Nonlinear Finite Element (FE) analysis can overcome the limitation of experimental investigation and can be used to study the effect of fire on different steel frame configurations. In this paper, numerical models in ABAQUS were developed and validated with the results of experimental tests. Uncoupled thermal mechanical analysis scheme has been adopted in this study which requires prior heat transfer analysis of the structural elements. Then, an extensive parametric study is carried out on verified analytical models to investigate the structural response of frames with different configurations and various earthquake scenarios. The parameters considered in this study are: different span ratios, different columns' sections, different material modeling concept, effects of end fixity, travelling fire scenarios with varying vertical spread times. A suit of five near field and five far field ground motion records have been considered in the non-linear time history analysis. Finally, the deformation history is analyzed to find correlation between the size and location of the fire. The obtained results are used to extract their statistical patterns and provide insights on these classes of problems.

**Keywords**: post-Earthquake fire, performance evaluation, fire resistance, Performance-based design, steel frame.

## 1   INTRODUCTION

Fire is one of the extreme loads that a steel structure may experience in its life-time. When a fire occurs, considerable thermally induced forces lead to significant reduction in stiffness and strength of steel structural members. Johann et al. (2006) provided a framework for Performance-based design of fire-safe structures. Mousavi et al. (2008) studied the post-earthquake fire (PEF) hazard from different aspects such as structural and non-structural design as well as regional conditions. Many experimental tests have been conducted to evaluate behavior of steel members under fire. Sinaie et al. (2013) conducted an experimental test to assess the effect of loading history on mechanical response of structures under fire following earthquake. It was observed that loading history has no effect on the elastic modulus. Song et al. (2015) carried out an experimental program to investigate effect of post-earthquake fire on the welded I-beam to tubular columns connections. They observed that the fire resistance rating is mainly influenced by higher damage level.

Jiang et al. (2017) conducted tests to study global behavior of planar steel frame. The novelty of their research was consideration of the cooling phase after heating. It was reported that more damage may occur due to failed heated column during cooling phase. A companion numerical research has been done by the authors (2017) and the results complied with the experimental tests. They studied effects of damping ratio and strain rate on the behavior of tested frame. It has been observed that damping ratios less than 10% has no remarkable effect on behavior of the frame in the case of fire. However, strain rate in the heated column has significant effect on the heated column while buckling.

Memari et al. (2014) have investigated performance of low-rise, mid-rise and high-rise steel frames with RBS connections in presence of post-earthquake fire. They expressed that fire decreased the Interstorey Drift Ratio (IDR) caused by earthquake. They also stated that the change in IDR is related to the location of PEF and the smallest ones would happen in the first floor and the floor immediately above the highest story exposed to fire. On the other hand, the most reduction in IDR occurred in all stories starting from the second storey above the highest story exposed to fire.

Behnam and Ronagh (2014) developed analytical models to study the effect of post-earthquake fire on steel frames designed for residential and school occupancy. First, they used SAP2000 to apply gravity and seismic push-over loads. Then, the damaged frames were imported in SAFIR environment to perform fire analyses (ISO fire and natural fire). It was reported that the damaged frames had lower fire resistance in comparison to the undamaged ones. Furthermore, in this case, ISO834 fire provided more conservative results than natural fire. However, results of natural fire are more realistic since many factors have been considered simultaneously.

Zhao and Shen (1999) investigated the behavior of unprotected 2D steel frames under natural fire. They conducted three tests under different load level. Following the experiments, Finite element model was developed in NASFAS to compare the results. It was observed that heating rate had influence on the fire resistance of structures. Besides, out-of-plane instability could be critical.

Thirteen experimental tests were performed by Ooyanagi et al. (1983) to analyze thermal stresses in the steel frames. Afterward, the theoretical values were compared with the test results and good agreement was observed. During tests, it was seen that presence of braces increases vulnerability of heated girder to fire. Furthermore, it was reported that fire may cause damage to nonheated area. It should be noted that in the temperature below 200C, as the decrease in elastic modulus is not noticeable, one can use superposition rule to consider fire condition.

Current design code is based on uniform fire which is not realistic specifically in large, open-plan compartments. To tackle the discrepancy between actual fire and the traditional method, Traveling Fire Methodology (TFM) is developed. In this method, two fire-induced thermal regions are defined: near-field and far-field. The nearfield is related to the burning region in which structural elements are exposed to flames. On the other hand, far-field is related to the area that is exposed to hot combustion gasses. One of the pioneer researches in TFM is done by Rein et al. (2006). They used computational fluid dynamic to figure out behavior of high-rise building exposed to uniform and Traveling fire. Rackauskaite et al. (2017) studied response of a 10-story building exposed to multiple-floor travelling fire. They used finite element software LS-DYNA to model horizontal and vertical travelling fire. It was reported that the number of floors exposed to fire and fire type are indicative in failure time and assuming simultaneous horizontal and vertical spreading fire would be the worst-case scenario.

Research has shown that while there have been many researches to study structural response to the fire, there are still many untouched aspects that are not studied and need further research. Since experiments on behavior of steel frames are expensive, finite element software is widely used as a main tool in performance based design. Comparison between experimental and analytical results could give inspirational idea to the researchers about the methods of material and details' modeling for further studies. In this paper, the five experimental tests done by Ooyangi et al. (1983) are modeled in ABAQUS and the analytical results are verified by the experimental values. Then, a parametric study developed to assess structural response from different aspects. Finally, the results are compared and a pattern has been founded.

## 2 BRIEF DESCRIPTIONS OF THE FRAME TESTED

Five three-story two-bay steel frames shown in Figure 1 (Ooyangi et al. 1983) are selected for the validation. The frames' elastic modulus, tensile strength and yield strength are $1.86 \times 10^6 \, kgf/cm^2$, $5.00 \times 10^3 \, kgf/cm^2$ and $4.01 \times 10^3 \, kgf/cm^2$, respectively. Column and beam sections were H-shaped and brace section was made of steel bar. The details are listed in Table 1. Electric heat panels were used to increase temperature through the target girders. The temperature curves are illustrated in Figure 2.
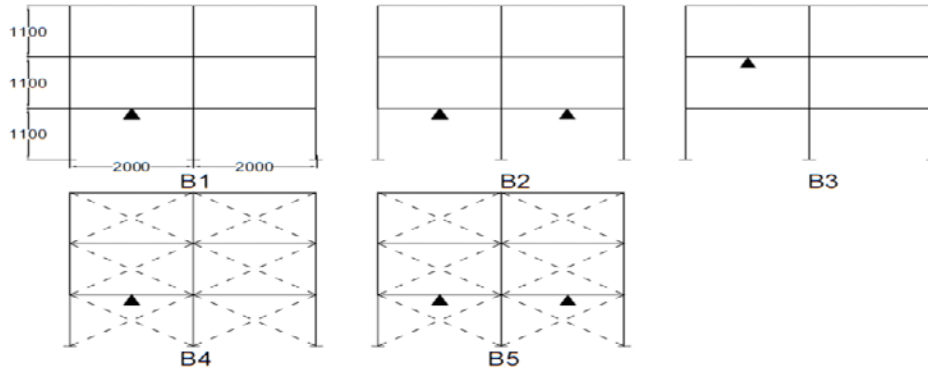


Figure 1: Types of frame and the position of electric heat panel for each test

Table 1: Details of member section

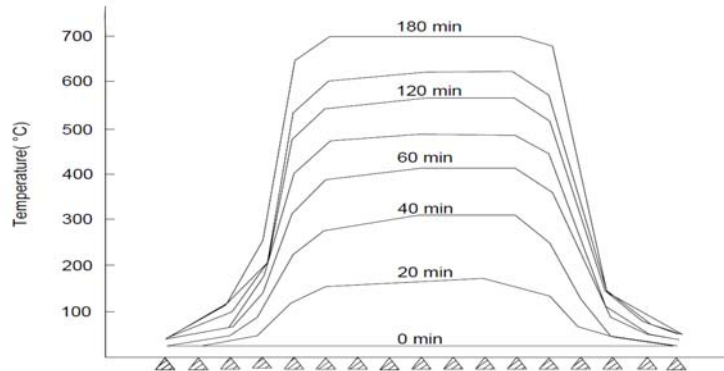| Frame | Column | Beam | Brace |
|-------|--------|------|-------|
| B1 | 150 X150X7X10 | 200X100X5.5X8 | - |
| B2 | 150 X150X7X10 | 200X100X5.5X8 | - |
| B3 | 150 X150X7X10 | 200X100X5.5X8 | - |
| B4 | 150 X150X7X10 | 200X100X5.5X8 | $\varphi 13$ |
| B5 | 150 X150X7X10 | 200X100X5.5X8 | $\varphi 13$ |



Figure2: Temperature distribution along the beam.

## 3 NUMERICAL MODEL AND ANALYSIS RESULTS COMPARED WITH TEST DATA.

Numerical models are developed in ABAQUS and they have the same geometry as the selected test specimens. To model the frames, beam element B21 is selected and bases of the columns are rigidly connected to the ground. For the material, a bilinear elastic perfectly plastic curve is adopted. The temperature curve is assigned at the static step. To obtain accurate results, mesh size is chosen adequately small. Figure 3 compares the lateral displacements obtained from analysis with test results for frame B1.
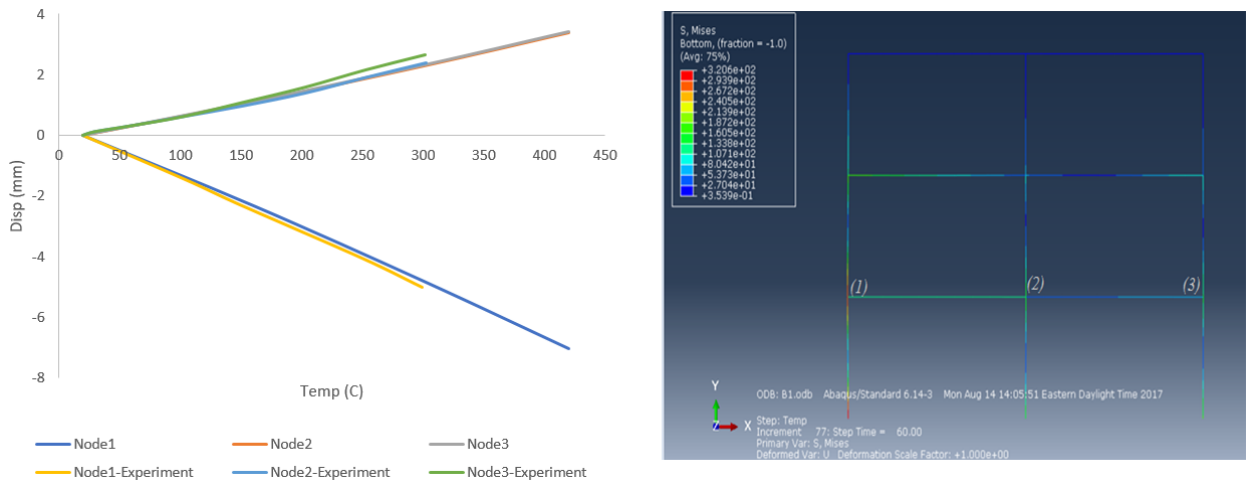
Figure 3: Fire behavior of steel frame/Lateral Displacement (Frame B1)

It can be seen that the FE analysis results agrees very well with the test results. Figure 4 compares the axial loads of the first-floor beams. N1 is the beam exposed to Electrical heat panel and N2 is referred to the adjacent beam.
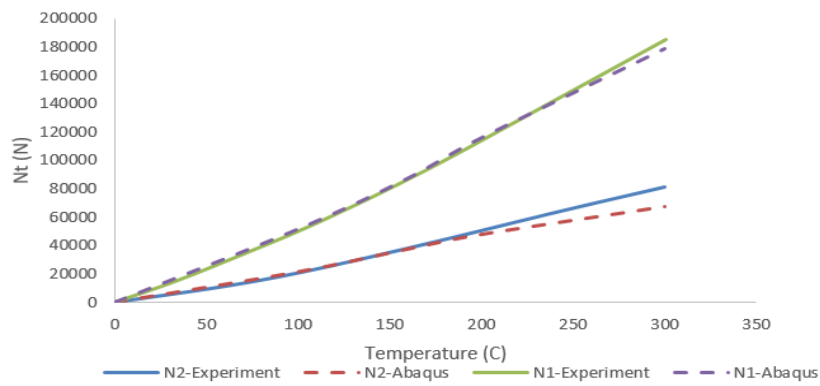


Figure 4: Fire behavior of steel frame/Axial Loads (Frame B1)

To compare the effect of braces, frames B4 and B5 were tested. Figures 5 and 6 are compared the stresses of heated girders.
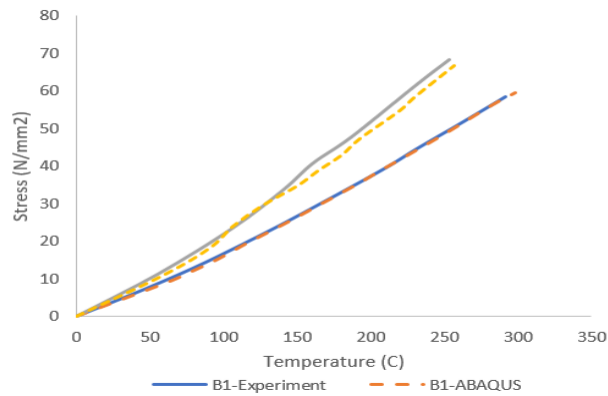


Figure.5: Fire behavior of steel frame with/without brace (B1-B4)
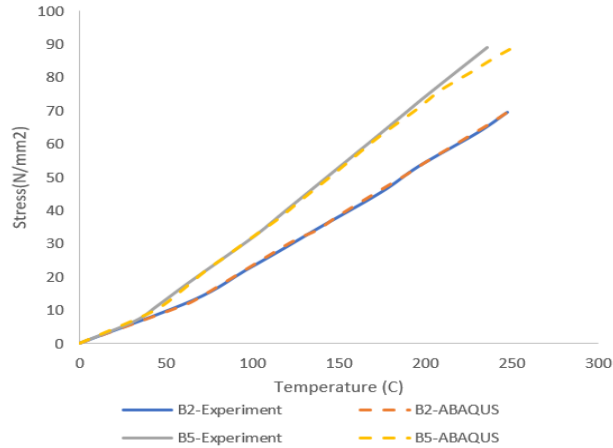
Figure 6: Fire behavior of steel frame with/without brace (B2-B5)

It can be seen that 2D nonlinear finite element models are in good agreement with experiments.

## 4  Parametric study on behavior of frames exposed to fire and post-earthquake fire.

The validated models are used for the comprehensive parametric study to elaborate on behavior of damaged and undamaged frames exposed to fire.

To study behavior of frame exposed to fire, sequentially coupled thermal analysis procedure is used. To model heat transfer due to convection and radiation, the emissivity, coefficient of convection and Stephan Boltzmann constant are considered 0.5, 25 W/m$^2$K and $5.67 \times 10^{-8} \, W/m^2K^4$ respectively for Standard fire. The temperature dependent strength and stiffness degradation as well as thermal expansion are chosen based on Eurocode 3. The temperature of beam and columns cross section captured from heat transfer analysis is used for static analysis step of frame exposed to fire and post-earthquake fire. In case of post-earthquake fire, earthquake load is applied in dynamic-Implicit step.

### 4.1  Effect of ULC fire

To simulate fire event in analytical models, different time-temperature curves such as ISO 834, ASTM E-119, Euro Code parametric fire and ULC standard fire are employed. In this research, ULC standard fire is selected to simulate fire in the frames.

The temperatures captured from heat transfer of beam, column and brace cross section are shown in Figure.7.
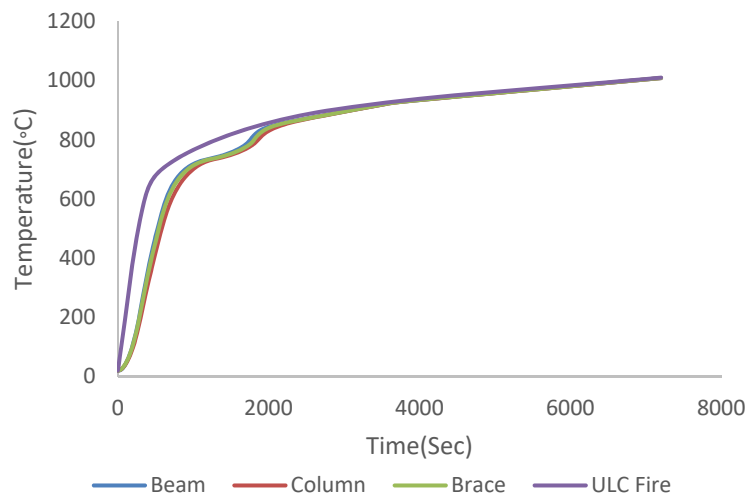
Figure7: Temperature of beam, column and brace exposed to ULC fire

The lateral displacement of the respective floor exposed to fire has shown in Figure 8.
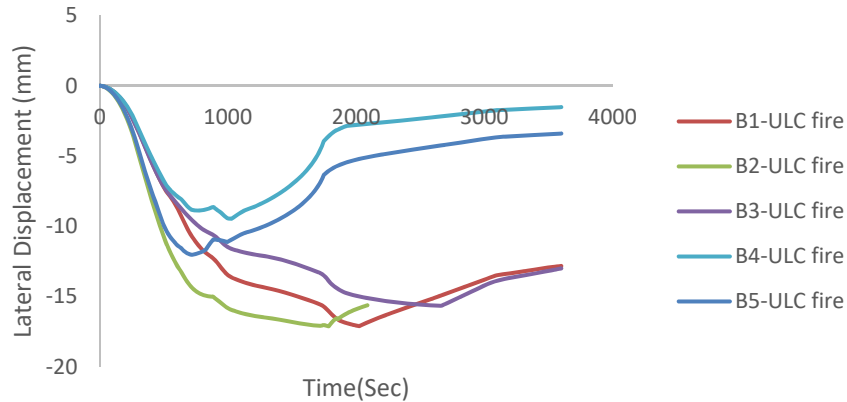


Figure 8: Lateral displacement of frames exposed to fire

## 4.2 Material Modeling

One of concerns in numerical analysis is material modeling to get reliable results. Elastic perfectly plastic and Elastic plastic with strain-hardening are two approaches to model stress-strain relationship for steel in finite element software. The elastic perfectly-plastic model is simple however in high-nonlinearity it has issue of convergence. To study the difference between these two approaches in fire scenarios, the strain-hardening material model is defined based on Fujita and Kuki (2016). Then, the frames exposed to the ULC fire with afore-mentioned materials and the results are depicted in Figure 9.
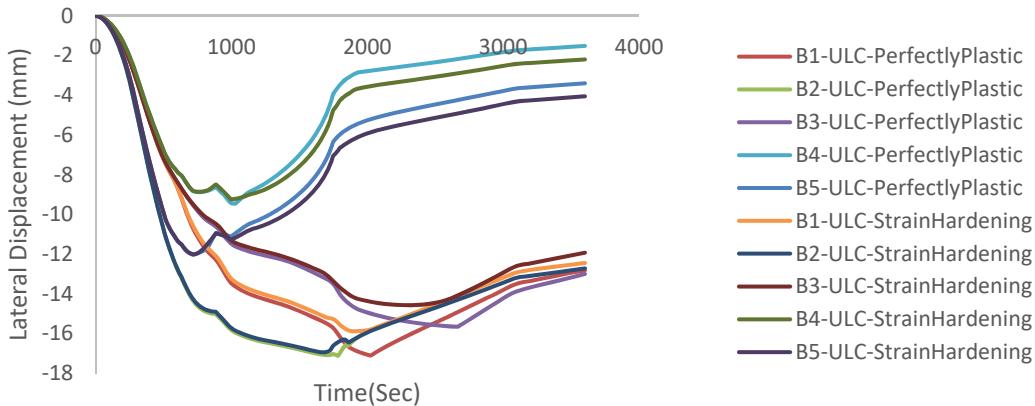


Figure 9: effect of material modeling in frames exposed to ULC fire

It is observed that there is slight difference between lateral displacements of frames with different material models. It should be noted that the frame B2 with elastic perfectly-plastic couldn't converge and the analysis stopped at -15.6 mm lateral displacement. Hence, the elastic perfectly plastic materials could be a good approximation provided convergence is obtained during analysis.

## 4.3 Effect of column shape

Section factor ($^{A_m}/_V$), which is defined by Eurocode is one of the selected criteria to study performance of structures exposed to fire. To investigate this parameter, a box-section with the same lateral stiffness has been selected. The section factor for the box shape is 0.125 and for the H-shape section factor is 0.226. Figure 10 illustrated lateral displacement of frames with H-section and box-section columns. It can be seen that the Box-section with same lateral stiffness has better performance in case of fire.
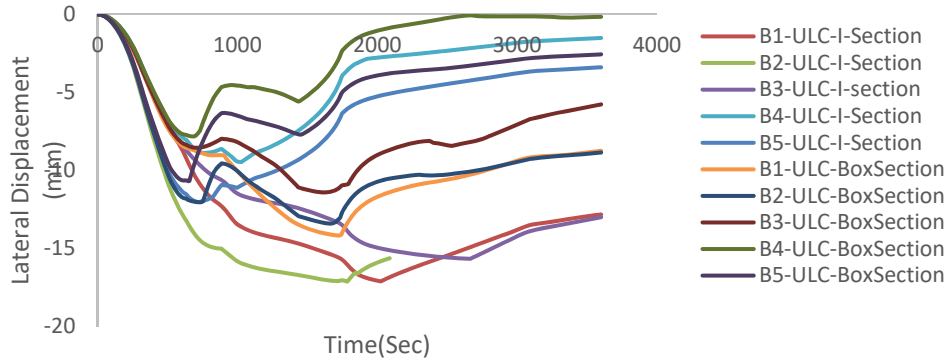
Figure 10: Effect of column sections with same lateral stiffness

## 4.4 Effect of end-fixity

Fixed-end frames have lower lateral displacements in comparison to the frames with hinge-end. However, adding fixity to the structures exposed to fire results in developing more axial loads. To investigate the effect of end-fixity in presence of fire, a simulation carried out with two groups of frames with hinge-end and fixed-end columns and figure 11 illustrates that lateral displacement is decreased when the columns are hinge-ended.
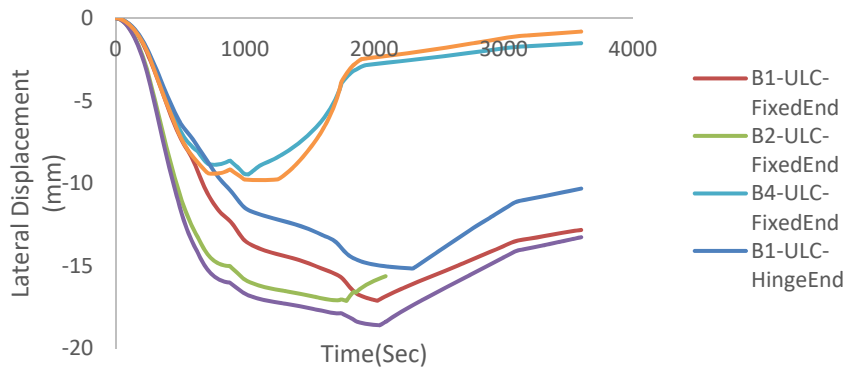


Figure 11: Effect of end fixity on performance of frames

## 4.5 Effect of span ratio

To study the effect of span to column ratio (L/H) of steel structures, frames B1 and B2 are compered to the similar frames with double span. It is observed that the deflection of frames with longer span is greater in up to 500 ∘C however, the trend changes abruptly and the deflection decreased.
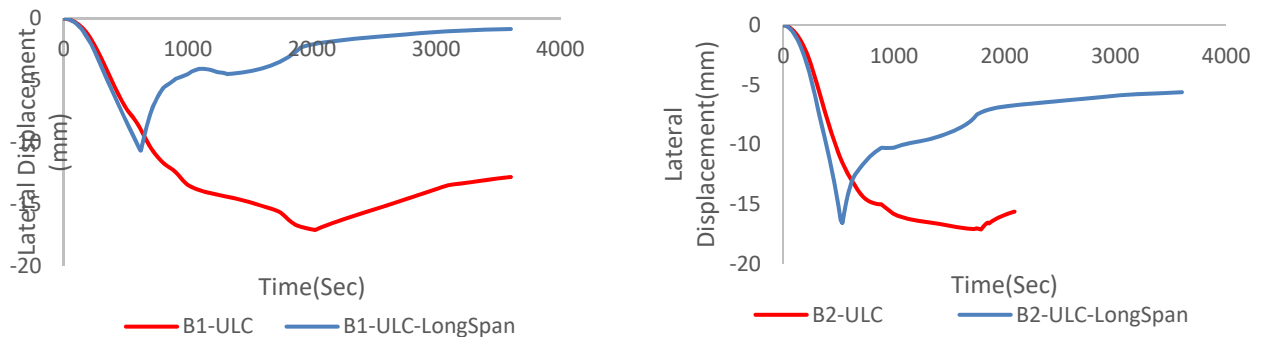


Figure 12: Effect of span ratio on lateral displacement of frames B1 and B2

## 4.6  Vertically travelling fire

Estimating spread rate of upward fire is complicated and it depends on the various factors. However, based on the study of Fletcher et al. (2006), the rate is about 10 to 30 minutes. In order to obtain better insight about structural response in case of vertical fire, the frame B2 exposed to fire with 10 min and 25 min delays. As seen in figure 13, the lateral roof displacements of frame exposed to fire without delay, with 10-minute delay and with 25-minute delay are shown. It is concluded that the rate of spreading fire considerably changes the fire resistance.
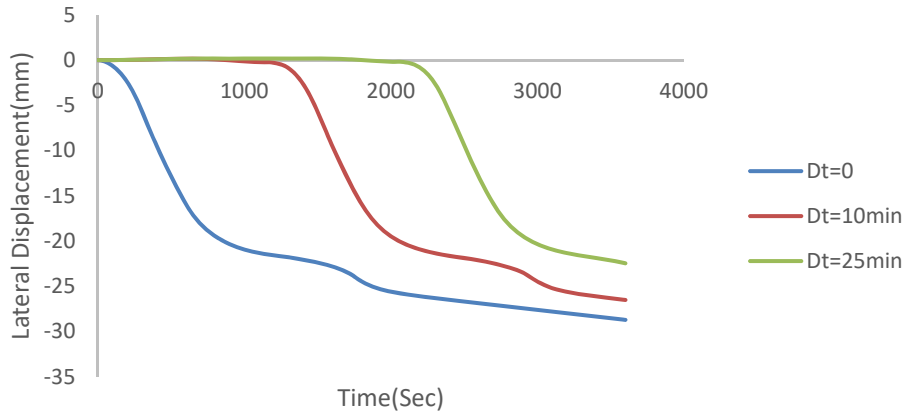


Figure 13: Roof lateral displacement based on deferent rate of fire spreading

## 4.7  Earthquake simulation and results

Strong earthquakes can result in severe damage in structural and non-structural members of buildings and consequently may cause fire. Hence, one of the worst scenarios in designing safe buildings in the areas with high seismicity is post-earthquake fire (PEF). To study PEF behavior of steel structures, ten suits of ground motions (5 near-field and 5 far-field records), as shown in table 2, are selected to perform nonlinear time-history analysis. The seismic records are scaled based on Vancouver spectrum. Results of nonlinear seismic analyses are shown in Figure 14. In Figure 14, Interstory Drift Ratio (IDR) indicates global stability of frames under earthquake.

Table 2: Near-field and far-field set of records used in this study

| $M_W$ | Year | Earthquake | Station | Distance (Km) |
|---|---|---|---|---|
| *Near-field records* | | | | |
| 6.95 | 1940 | Imperial Valley | Elcentro Array #9 | 6.09 |
| 6.5 | 1976 | Friuli | Tolmezzo | 14.97 |
| 6.61 | 1971 | Sanfernando | Pacoima Dam | 1.81 |
| 7.35 | 1978 | Tabas | Tabas | 2.05 |
| 7.35 | 1978 | Tabas | Dayhook | 13.94 |
| *Far-field records* | | | | |
| 6.5 | 1942 | Borrego | Elcentro Array #9 | 56.68 |
| 7.36 | 1952 | Kerncountry | Taft Linconschool | 38.89 |
| 6.61 | 1971 | Sanfernando | Puddingstone Dam | 52.64 |
| 6.61 | 1971 | Sanfernando | Wrightwood | 62.23 |
| 6.61 | 1971 | Sanfernando | Lake Hughes | 19.3 |
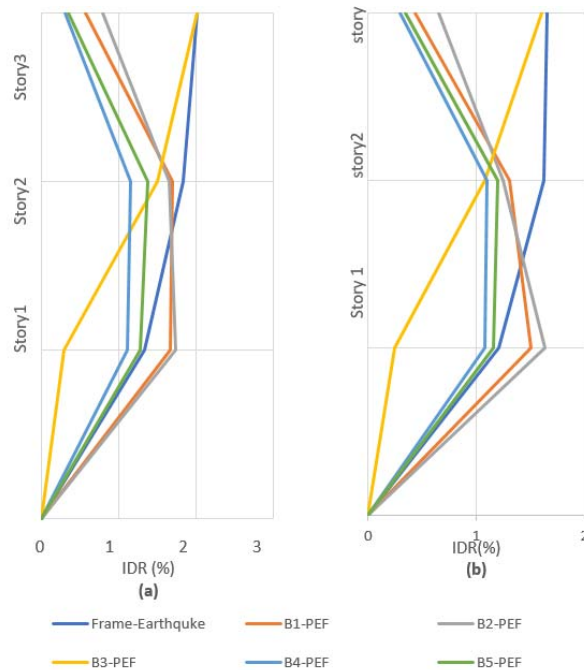
Figure 14: IDR of frames exposed to a) near-field earthquakes b) Far-field earthquakes

From the figure 14, it can be concluded that near field or far field earthquakes do not affect IDR significantly. It is also observed that in PEF scenarios IDR has decreased.

## 5  Summary and Conclusion:

A series of verification analysis are conducted to validate the FE model used in this study to investigate the performance of steel frame subjected to fire and post-earthquake fire. The evaluation of an experimental test provides a good opportunity to advance analytical modeling's knowledge about fire. The analysis includes nonlinear dynamic time-history analysis for earthquake part and sequentially uncoupled thermal-mechanical analysis for fire part. The material is assumed temperature-degradation material according to Eurocode. The ULC standard fire is applied to the beam and corresponding columns from all directions. The parameters considered in this study are: different span ratios, different columns' sections, different material modeling concept, effects of end fixity, different upward fire spreading rate. The conclusions can be summarized as below:

1- In presence of braces, thermal stresses increase dramatically.
2- The fire may affect non-heated structural member and damage them due to increase in thermal stress.
3- Considering strain hardening material doesn't change the results considerably. However, in complicated models, it helps to converge the solutions.
4- Section factor affects on the temperature of the cross-sections exposed to fire. In this study, response of frames with same lateral stiffness columns changed due to different section factors.
5- Lateral displacement of frames with longer span is greater in up to 500 C however, the trend changes abruptly and the deflection decreased.
6- Rate of spreading time changes fire resistance considerably and choosing the precise rate needs extensive investigations.
7- In this case, post-earthquake fire decreases the lateral displacement. And type of earthquake has negligible effect on the PEF behavior of frames.

## Acknowledgements

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