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An Investigation into the Impact of Fire on Lateral Stability and Strength of Thin Steel Plate Shear Walls

G. Pachideh[1], M. Gholhaki[1*], Y. Noori[2]

[1]Department of Civil Engineering, Semnan University, Semnan, Iran.
[2]Department of Civil Engineering, Ferdowsi University, Mashhad, Iran.

ABSTRACT: The SPSWs has been enthusiastically applied in some of the tall buildings across the world as a novel lateral load-bearing system and due to their proper stiffness, strength, ductility, and energy absorption, as well as remarkable reduction in buildings', weigh compared to the concrete cases, they are deemed as an efficient alternative for the traditional load-resisting systems. Fire-related hazards and their impacts on the structural systems have been of major concern for practitioners, which is of utmost significance for special structures and tall buildings. Accordingly, in the case of thin steel plate shear walls, fire is most likely to leave detrimental effects on the lateral stability and strength of them due to their small values of thickness. To better understand the behavior of such systems in the event of a fire, this paper aims to investigate the impact of heat caused by a fire on the stability, elastic stiffness and yield strength of a 3-storey frame equipped with SPSW system. Based on the results derived by connected stress-heat analyses, thickening the wall results in a substantial reduction in the column's deformations. Moreover, an increase in thickness and yield strength of the steel plate plays an effective role in less reduction in yield strength and elastic stiffness of the system after fire events although, while the plate thickness is kept constant, the system's elastic stiffness does not vary as the yield strength raises. In addition, simple relations were achieved to estimate the post-fire elastic stiffness and yield strength of the SPSW system.

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1- Introduction

In 2012, Ruirui et al. [1] conducted a progressive collapse analysis on steel buildings subjected to fire loads. Based on their results, it can be inferred that in the case of unbraced frames with lower loading ratio and greater beam's cross-sectional area, higher failure temperature is required during which total collapse takes place. However, local damage in the elements more easily occurs when loading ratio raises and the beam's cross-section becomes smaller. It is of note that the application of the bracing system can remarkably prevent the occurrence of progressive collapse mechanisms in the structure. Larger lateral stiffness of the frame can cause smaller vertical deflections in the failed column in the re-stable condition. However, it was found that the temperature in which total collapse occurs does not depend on the lateral stiffness.

In June of 2016, experimental investigations of the performance of a six-storey, cold-formed steel (CFS) framed building were conducted on the Large High-Performance Outdoor Shake Table (LHPOST) at the University of California, San Diego (UCSD). The building's lateral load resistance system consisted of cold-formed steel framing members sheathed by panels of sheet steel adhered to gypsum board. These and other light-weight construction material lateral load resisting systems are widely used in seismic regions in the western United States, where they offer significant advantages in construction costs and speed. For information about the design and construction of these wall systems for seismic applications, interested readers are referred to the National Earthquake Hazards Reduction Program (NEHRP) document Seismic Design of Cold-Formed Steel Lateral Load-Resisting Systems - A Guide for Practicing Engineers [2]. The aim was to study the earthquake performance of this construction method for midrise structures (five to ten stories), as well as the earthquake-damaged building's response to fire. After the fire tests, additional earthquake shaking was conducted to study the response of the fire-damaged building to earthquake aftershocks. The aftershock test results were intended to help inform decisions about first responder access to a building in the case of fire following earthquake, as well as repair versus replace assessments. Details about the six-storey building tests are provided in [3].

In 2016, Matthew et al. [4] carried out investigations on the behavior of steel plate shear walls under interactive actions of seismic and fire loads. In doing so, several tests were conducted on 6 2.7×3.7 m shear wall specimens surrounded by cold-formed framing in a way that steel plates sheathed one side of the wall and, on the other side, was covered by gypsum panels. The results indicate the fire can vary the failure mode

*Corresponding author's email: : mgholhaki@semnan.ac.ir

Table 1. Mechanical Properties of Experimental Model's Components

Members	Yield Strength (N/mm²)	Ultimate Strength (N/mm²)
Plate	180	300
Space Beams	310	446
Column and Top Beam	366	550

of the wall such that local buckling in the steel plate turns into global buckling and its lateral load-resisting capacity is reduced by 35%. Based on the viewpoint of residual lateral-load resisting capacity under multi-hazard events, it could be predictable to observe this behavior.

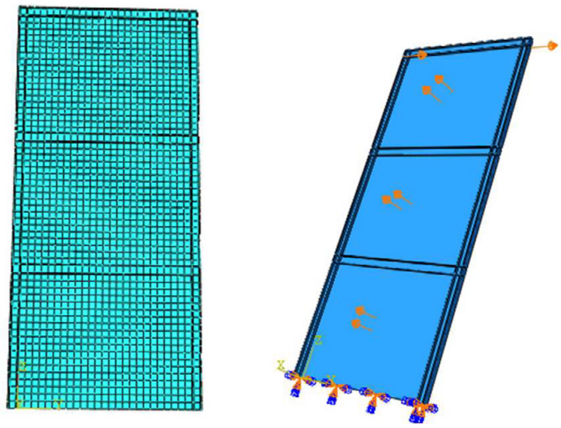
Thereby, concerning the recently conducted studies on the impact of fire loads on steel structures, especially steel plate shear walls, it can be said that very few studies have been performed in this respect to date. Consequently, this paper aims to study the behavior of steel plate shear walls subjected to fire and measure their vulnerability. Not surprisingly, in case of exposure to fire or thermal gradient rising the steel's temperature, might degrade the shear wall's strength meaning that in case the wall has been already subjected to fire loads and left unchanged or unrepaired, it is less likely to exhibit a proper performance under lateral induced loads such as earthquake. In this respect, it is of utmost significance to get insight over the interactive impact of fire and seismic loads on steel plate shear walls. Hence, the novelty of this study is attributed to exploration of a correlation between thermal gradient and amount of reduction in lateral strength or stiffness of thin walls with different thickness values (0.5, 2 and 4 mm) and yield strengths (180 and 240 MPa) which has been analyzed utilizing first-order mathematical relations.

2- Methodology

With respect to the impact of fire loads on the behavior of load-resisting systems, it is attempted to study the effect of fire on the stability and performance of thin steel plate shear walls. In this respect, a steel plate shear wall placed in a 3-story frame with rigid beam-column connections has been modeled using FEM-based software to analyze the fire effects on the wall thoroughly. To validate the modeling procedure conducted by ABAQUS Software [5], the experimental model studied by [6] was adopted whose materials' mechanical properties are presented in Table 1.

Due to the occurrence of multiple buckling and entrance of the plate into the post-buckling zone, computer analyses on the thin steel plate shear walls are accompanied with numerous challenges, and analysis of the large displacements can considerably affect the results.

Numerical convergence is barely achieved in the case of thin plates due to multiple buckling in various zones, as mentioned earlier. Thus, it is required to consider small mesh sizes for the plat. Accordingly, after conducting a sensitivity analysis, a mesh size of 50 mm was employed to perform the analyses. On the other hand, the Shell S4R element was applied for the modeling process owing to a wide range of stress variations.



(a) FEM Mesh (b) Loading Process

Fig. 1. Meshing and Loading Procedure

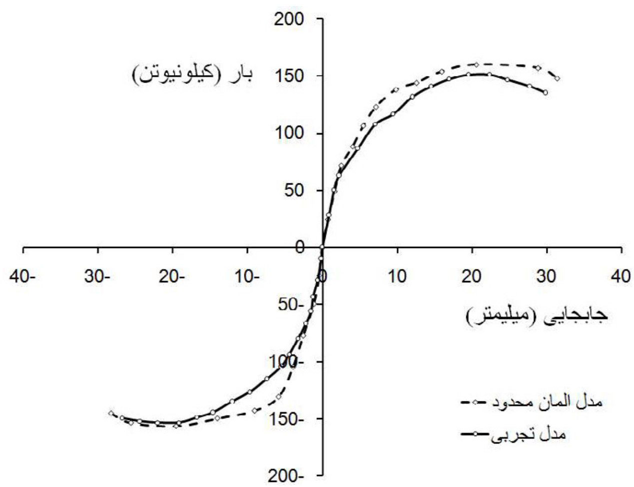


Fig. 2. Comparison between Numerical and Experimental Results

Moreover, both types of nonlinearity, including material and geometric nonlinearities, were taken into account during the analyses. For the sake of simplicity, the bilinear plasticity model with kinematic hardening and Von-Misses yield criterion were utilized. Besides, the slope of the hardened part of the stress-strain curve was taken as 5% of the elastic area.

It is worthwhile that in the FEM Software if the initial unevenness in the centroid of the plates is not considered, the plate will not buckle under in-plane loads and as a result, stiffness and yield strength of the wall will be overestimated. Consequently, after conducting the sensitivity analysis about the initial distortion, lastly, 3 mm distortion was applied to the center of plates.

Finite element mesh, as well as the loading process of steel plate shear wall in ABAQUS Software, are shown in Fig. 1.

To calibrate the numerical model, the nonlinear static analysis was performed by applying incremental displacement to the 3rd story's beam. A comparison between the curve derived by FEM and experimental analyses are demonstrated in Fig. 2.

Table 2. Equations for Yield Strength at different Temperatures

	F_y = 180 MPa	F_y = 240 MPa
t= 0.5 mm	P_T = -210T + 155000	P_T = -235T + 18000
t= 2 mm	P_T = -900T + 530000	P_T = -210T + 670000
t= 4 mm	P_T = -1150T + 860000	P_T = -1250T + 96000

Table 3. Equations for Elastic Stiffness (KN/mm) at different Temperatures (^{0}C)

	t=0.5 mm	t = 2 mm	t = 4 mm
F_y=180 , 240 MPa	K = -75T + 57500	K = -190T + 150000	K = -270T + 220000

3. Results and Discussion

In order to evaluate the post-fire lateral stiffness and strength of the steel plate shear wall, the connected stress-heat analysis was carried out.

In this analysis, the wall is first under gravity loads subjected to various temperatures caused by fire and at the end of each thermal load, a lateral load is applied at the level of 3rd story to measure the strength. This means that yield strength and elastic stiffness can be computed after each fire-induced damage level.

To study the impact of plate thickness and yield strength, different values have been considered for them. Accordingly, thickness values of 0.7, 2 and 4 mm together with yield strengths of 180 and 240 MPa have been chosen for the modeling process and yield strength of the system was calculated under different temperatures. As the temperature rises and propagates in the structural members, each member encounters a reduction in its strength and as a result, the total lateral strength of the system is degraded.

Subsequently, increase in plate thickness and yield strength, enhanced the lateral capacity of the system in a way that for the plates with thickness of 4, 2 and 0.7 mm, raise in yield strength from 180 to 240 MPa, led to an increase respectively equal to 24, 46 and 36%. In temperatures ranging from 200 to 3000c, the value of sudden loss in yield strength is considerable which is attributed to heat distribution in all elements. For instance, in the plate with the yield strength of 240 MPa and thickness of 0.7, 2 and 4 mm, the value of loss within a 1000c thermal interval is equal to 30, 23 and 32%, respectively. Equations related to each one of the regressed lines for determination of yield strength (Py) in each model are given in Table 2.

Moreover, equations concerning the elastic stiffness (k) of the steel plate shear wall are presented in Table 3 for different values of plate thickness.

4. Conclusions

To analyze the stability and determine the elastic stiffness as well as the yield strength of thin steel plate shear walls, a numerical study using connected stress-heat analysis and relations proposed by credible references, Was conducted in two cases of fire with gravity loads and fire acting interactively with lateral loads. The most notable results are as follows:

With respect to direct connection of plate to the perimeter beams and columns, rising the temperature has considerably affected the deformations induced in beam and column and on the contrary to the typical systems in which a gap as an expansion joint between beam and column is recommended, this system is incapable of placing the gap and by means of providing a proper thermal coating on the members, particularly plates and columns, detrimental effects of heat on stability as well as stiffness and strength degradation should be lessened and hindered, subsequently.

Post-fire Elastic stiffness and reduced yield strength of the structures equipped with steel plate shear walls can be evaluated using simplified relations.

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