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RESEARCH PAPER

Post-earthquake Fire Behavior of Steel Plate Shear Walls

Said Dusak*,1 and Vail Karakale*,2

[1]PhD in civil engineering, Governorship of Istanbul, Hırka-i Şerif Mah. Adnan Menderes Bulvarı No:64 Fatih/Istanbul-Turkey
[2]Professor PhD, Civil Engineering Department, Faculty of Engineering and Natural sciences ,Istanbul Medeniyet University, Unalan Mah, Unalan Sok, D100 Karayolu yanyol 34700, Uskudar /Istanbul, Turkey
*Corresponding author. Email: sdusak@gmail.com; Svail.karakale@medeniyet.edu.tr

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Abstract

Recently steel plate shear walls were used as a lateral load-resisting system in multi-story buildings due to their significant stiffness and post-buckling strength. Typical steel plate shear walls consist of a steel plate acting as the main shear-resisting element that is welded to the boundary columns and beams. These shear walls are preferred more and more every day because they are ductile, lightweight, and economical. On the other hand, it is important to examine the behavior of thin steel plate shear walls in the event of a fire that may occur after an earthquake due to natural gas leakage or electrical contact. In this paper, the change in stiffness and displacements of a steel plate shear wall due to fire-induced temperature is investigated using a single-story and single-bay steel plate shear wall ABAQUS model. Furthermore, effect of steel plate yield strength on the shear wall behavior was investigated. In the case of using higher yield strength steel, better behavior in stiffness and beam deflection, and a smaller value in out-of-plane displacement of the plate were obtained. As a result of the analytical study, the out-of-plane displacement in the infill plate increased with temperature. When the model was exposed to high heat for 35 minutes, it was observed that the permanent lateral stiffness was reduced by half. In 40 minutes, it lost almost all of its rigidity. When the steel grade was increased to S275, the loss of rigidity time was prolonged.

Keywords: Steel plate shear wall; fire; stiffness; earthquake

1. Introduction

Steel plate shear walls consist of thin steel plates infilled into steel frames. Tests and researches made in the last decades show that steel plate shear walls were able to carry lateral loads after crumpling and buckling of its thin plates, and this ductile behavior made them preferable to be used as a lateral load resistance system in buildings. The positive features in its ductility, energy absorbing feature, load carrying feature and rigidity are the superior aspects of this system. The first studies related to steel plate shear walls were made in Japan [9] in which the out-of-plane movement of the plates was prevented by using stiffeners. However, the idea of utilizing the post-buckling strength of thin steel plates was developed in Canada [14, 15]. Furthermore studies show that reinforced concrete frames [3] and perforated steel plates can be used to increase energy dissipation in the building [11]. In addition, some studies on the frame [4] and the steel plate with reinforced concrete or carbon fiber material [10] were made and positive results were shared. The design and construction conditions of steel plate shear walls are presented in detailed in Canadian [5] and American [1] specifications. As a result of the nonlinear dynamic analysis of a sample designed according to the Canadian regulation on the subject, it was found that the floor drift limit value was half, and the base shear force value was two times the recommended limit value [8]. Steel plate shear walls are preferred more recently due to their lightness, high level of energy absorption and contributing to the ductility of the steel frame. On the other hand, ensuring the fire safety of steel structures in possible fire situations that may arise after an earthquake is an important research topic. In the design of the structures, the fire-induced heat load should also be considered in the calculations. Thin steel plates may lose some of their bearing capacity as a result of repeated loading. It is important to examine the behavior of thin steel plate shear walls due to the decrease in the material properties strength due fire that may occur after an earthquake. Recent study in the literature, in which a composite plate shear wall was subjected to high thermal loading [12], it was reported that elevated temperatures result in the degradation of the mechanical properties of steel and concrete. Thus, it can cause local buckling of the steel plates or instability of the walls and lead to the collapse of the walls. In such cases, there is a decrease in the stiffness of the steel plate shear wall and an increase in the displacements. A series of nonlinear analyzes were performed [6] for a study in which the composite structure was exposed to realistic design fires. It has been reported that during the heating and cooling stages of the fire, the beams undergo large structural deformations and axial forces greater than their tensile capacities occur. In case of fire after an earthquake, the structure should be subjected to a multiple hazard loading scenario. A post-earthquake fire (PEF) case is one of the major multi-hazard events that has been the subject of little research in the literature, although it is a widespread occurrence. Current analysis methods and most design forms and regulations do not consider the relationship of the two risks together. Therefore, the design of structures based on existing standards ignores the potential risk. An additional method of analysis is required to investigate the behavior of structures that are likely to be exposed to sequential hazard situations. In a study [2] investigating this issue, a multiple hazard analysis was developed that considers a steel framed structure with a post-damage thermal analysis during and after an earthquake. In above mentioned study an analysis has been made to examine the nonlinear behavior of a steel structure in the event of a fire after an earthquake. There is a study [3] in which different steel plate shear walls, designed according to different material and combination properties, are subjected to cyclic lateral loading, gaining very good energy absorption capacity and recommended for use in seismic regions. However, it has been wondered how such a design will behave in a fire that will occur after an earthquake. In the light of the few studies in the literature on post-earthquake fire, the behavior of steel plate shear walls was studied. In this study, the change in stiffness and displacements of a steel plate shear wall due to post earthquake fire-induced temperature is investigated using a single-story and single-span steel plate wall ABAQUS model. Furthermore, effect of steel plate yield strength on the wall behavior was investigated.

2. ABAQUS Finite Element Model

To investigate the post-earthquake fire effects on a steel plate shear wall a simple one bay one story finite element model was established using ABAQUS software [7]. The model is shown in Figure 1. The span was 3.53 m, and the column height is 3 m. HEB 240 profile was used for the beam and HEB 280 profile was used for the columns. The infill plate steel thickness was 0.1 mm. To examine the effect of the infill plates of the steel plate shear wall, frame sections were selected so that no yielding occurs in the frame members before the steel plates reach the yield value. The infill plate is welded on all sides to the steel frame. This type connection is defined as a fixed connection to the model. Beam-to-column connections of the frame are also welded connections and represent rigid connections. Hinge supports were used to connect the columns to the foundation as shown in Figure 2. In the finite element model, the S4RT shell element is used to define both the frame elements and the thin and thick plates. S4RT is a 4-node thermally coupled doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains. Mesh size is 5 cm in all elements model as shown in Figure 3.

Temperature has a degrading effect on the characteristic mechanical properties of steel. High temperature decreases the yield strength and modulus of elasticity. Thus, the temperature causes a decrease in the overall strength of the system. If temperature loading continues to be applied, it will lead to a constant load resistance over time so that as a result, sustainability is severely reduced. For this reason to investigate the effect of steel grade on the fire performance a higher steel grade were used in the second model (Table 1).

Table 1: *Steel Properties.*

	1. Model	2. Model
Yield strength (Mpa)	235	275
Ultimate strength (Mpa)	370	440
Elastic modulus (Mpa)	210,000	230,000

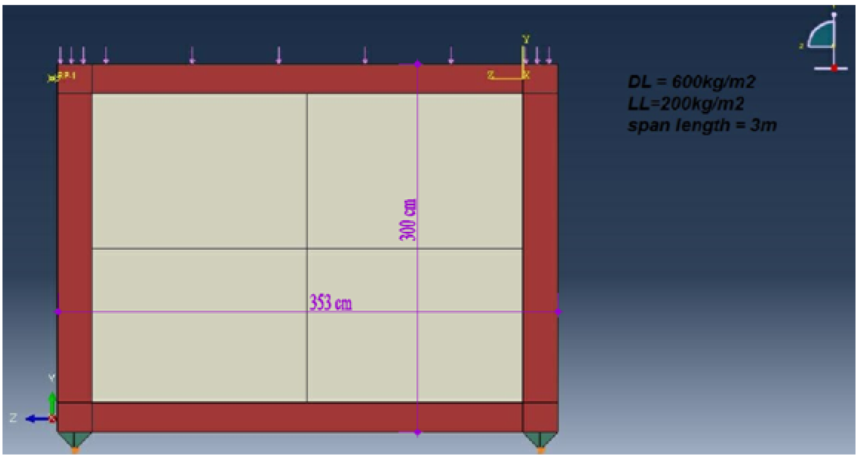

Figure 1: *ABAQUS finite element model, dimensions and loads.*

3. Analysis and Results

The fire hazard after the earthquake should be considered together with the earthquake. After the gravitational loading to the structure is assigned, lateral loading is defined to assign earthquake loads. For the fire situation following the end of the earthquake, the lateral load is deactivated. Temperature loading was done only under gravitational loads. The displacements and stiffness were determined depending on the time. Similarly, the same analysis was repeated for the steel grade with a higher yield strength of 275 Mpa and the results were compared.

This analysis was carried out in two steps, in the first step the loads were applied to the shear wall so that the panel was stressed due to lateral and gravitational loads (static analysis). Then in the second stage, lateral load deactivated and, the only gravitationally loaded structure was exposed to fire (Couple Stress-Temperature Analysis). Dead and Live loads were applied to the beam 600kg/m^2 and 200kg/m^2 respectively for 3.0 m span. The stress-strain relations of steel in high temperatures are considered based on Eurocode3 equations as shown in Figure 4. Thermal properties of the steel such as specific heat, heat transfer coefficient for thermal analysis are adopted from Eurocode3. Fire loads was applied according to the fire curve of ASTM-E119 [13] which shown in Figure 5 . The history

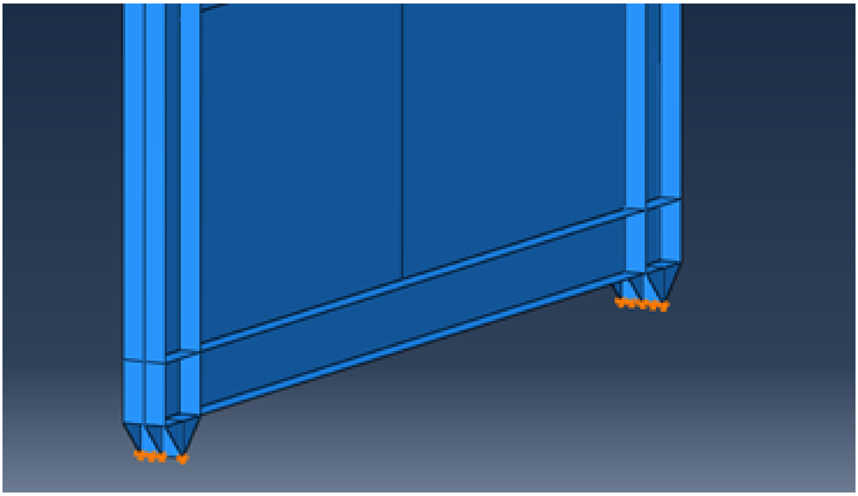

Figure 2: *Boundary conditions: In both columns, the hinge connection used.*

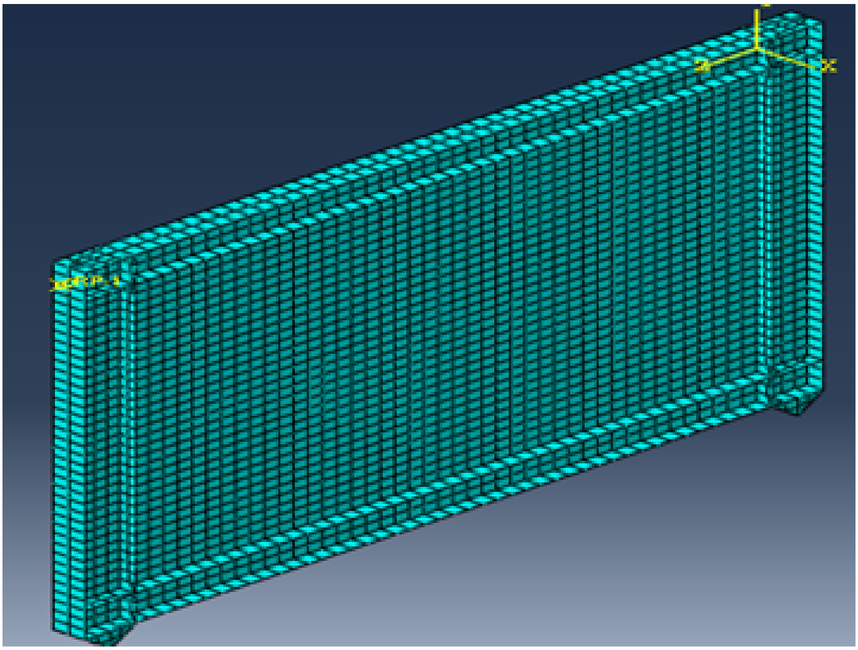

Figure 3: *Finite element model mesh size.*

of temperature - time for each element was considered separately in the couple temperature-stress analysis. On this basis, the rate of increasing temperature in each element determines the rate of degradation in mechanical properties of steel over time.

To evaluate the elastic strength and elastic stiffness of the steel plate shear wall after fire, the shear wall was analyzed under lateral and gravitational loads. The model was loaded at the second stage lateral load was deactivated and the gravitational load was kept constant during heating the steel plate shear wall. The gravitational loading is shown in Figure 1.

Analysis results are shown in Figures 6, 7, 8, and 9. The out-of-plane displacement of the infill

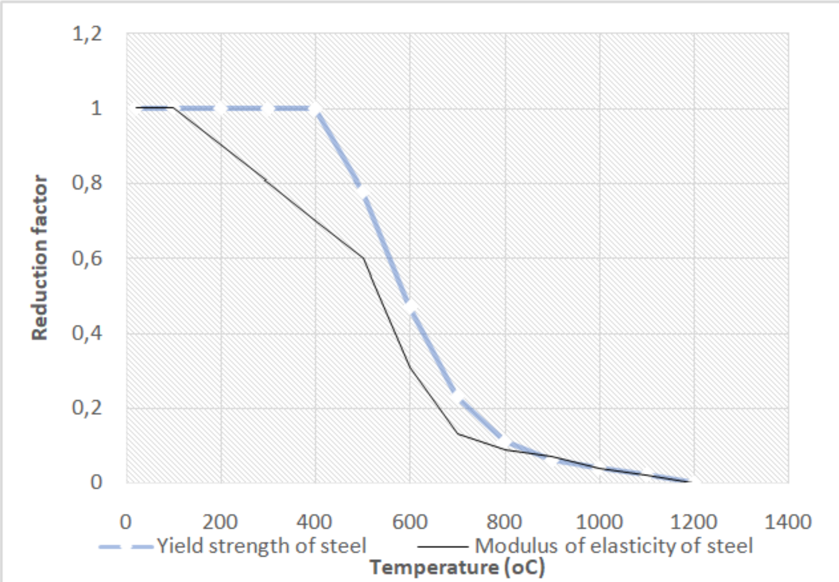

Figure 4: *Eurocode equations.*

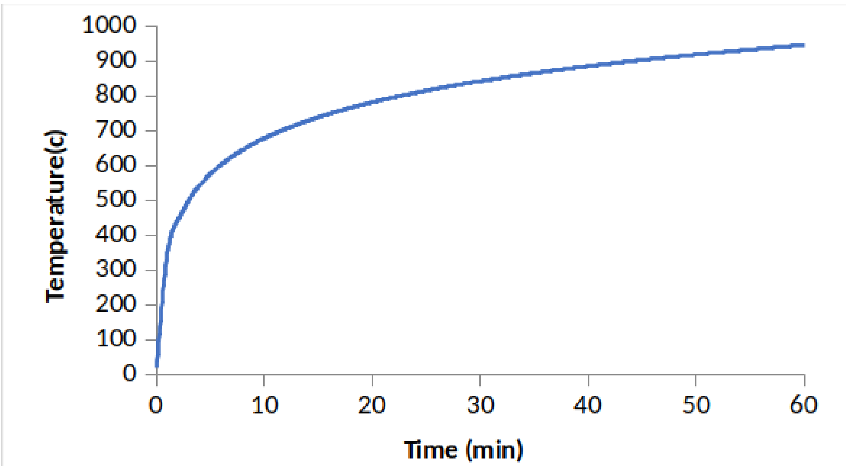

Figure 5: *Temperature-Time relation of steel according to ASTM E119.*

plate, which is the most important part of the steel plate shear wall, reached 0.12 mm in the first 5 minutes, then decreased to 0.02 mm at the end of 45 minutes (Figure 6). At the end of 20 minutes of the temperature increase, the stiffness started to decrease suddenly, it lost half of its stiffness in 35 minutes, and at the end of 40 minutes it lost almost all of the stiffness (Figure 7). The upper beam displacement of the steel plate shear wall changed by 0.30 mm in the negative direction in the first 2 minutes and returned to the same point at the end of 45 minutes (Figure 8). The deformation change resulting from the time dependent temperature loading of the steel plate shear wall model is given in Figure 9. On the other hand, when the steel grade used was increased to yield strength of 275 Mpa, the system lost its rigidity completely in 60 minutes instead of 20 minutes (Figure 9). In the model using high yield strength steel grade, better results were obtained in terms of rigidity. The results shows that the stiffness of the steel plate shear wall will reduce according to the fire duration. In studies conducted in the literature, it is stated that similar thermal loading causes a decrease in stiffness depending on time.

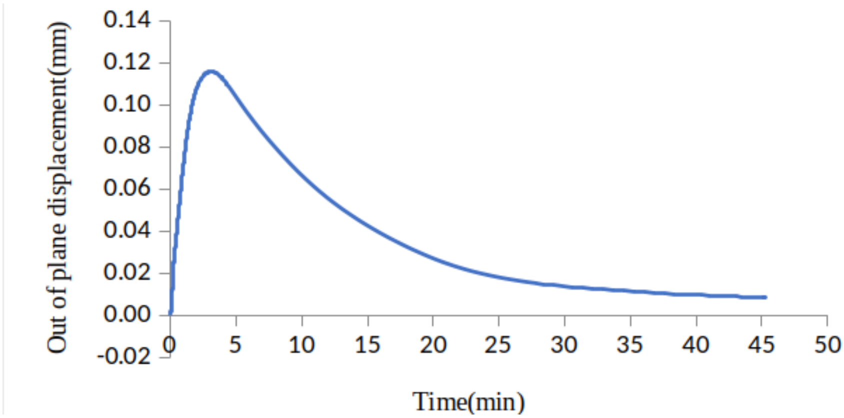

Figure 6: *Change of out of plane displacement with time.*

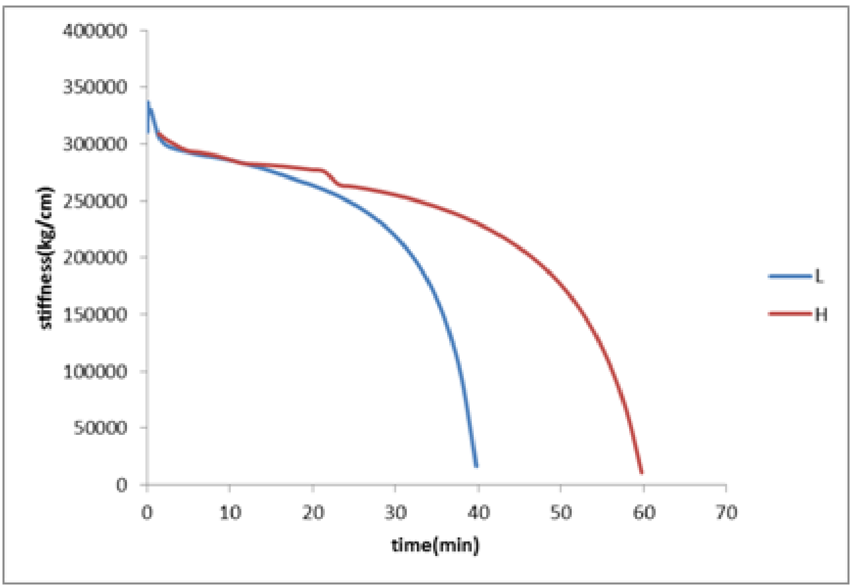

Figure 7: *Change of stiffness with time.*

4. Conclusions

Analysis results indicate that at fire duration of about 35 minutes the lateral stiffness of the steel plate shear wall will reduce in half. Furthermore, the high strength steel shows better performance than low strength steel. In the future it is better to conduct experimental research work to get better understanding of the shear wall behavior post-earthquake fires. Furthermore coating by special fire resistant paintings the steel plate shear wall elements, may reduce the time of failure of the steel panel and this could postpone the shear wall failure and the reduction of the stiffness can be reduced.

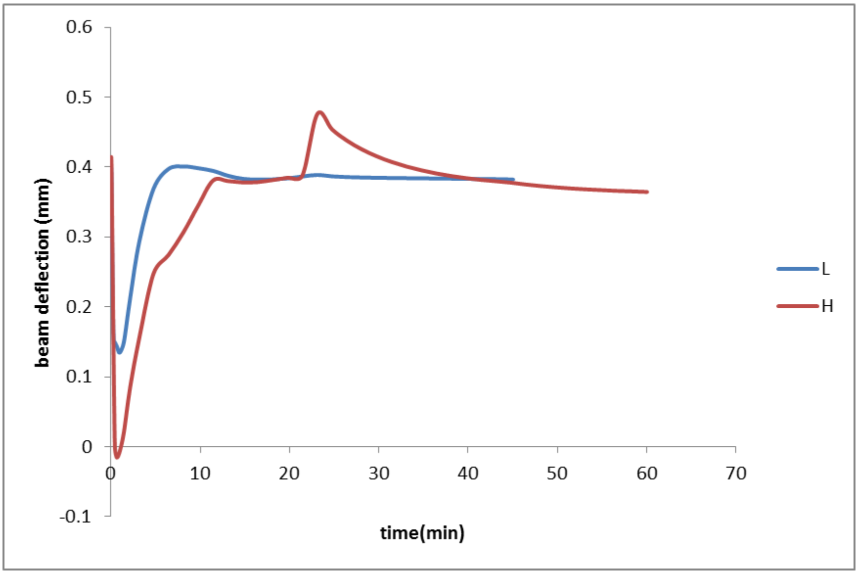

Figure 8: *Change of beam deflections with time.*

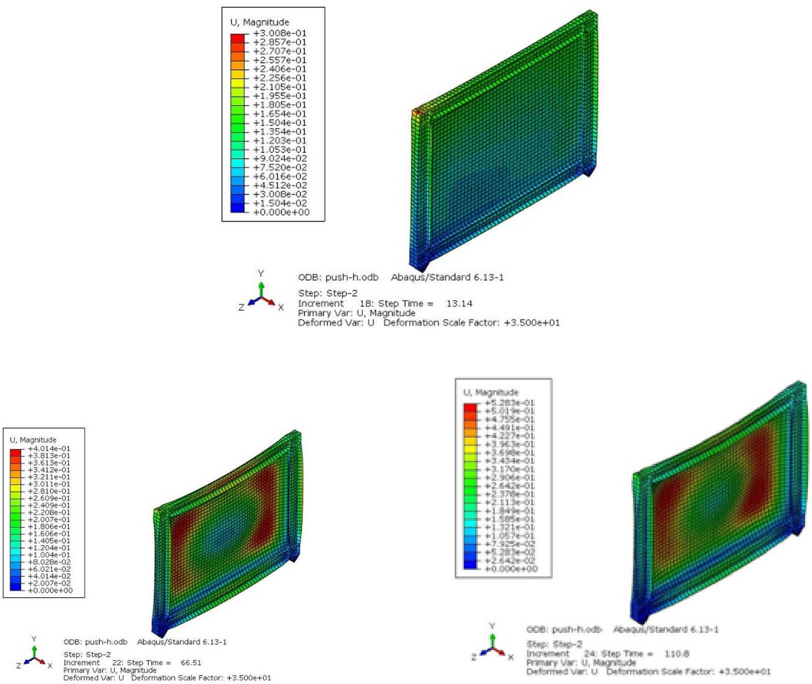

Figure 9: *Change of deformations with time.*

Conflicts of Interest: The authors have no conflict of interest to any part.

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