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INCREASING ROTATIONAL CAPACITY OF GUSSET PLATES THROUGH HEAT TREATMENT

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Abstract: Gusset plates play an important role in the performance of braced frames in earthquakes. They typically are designed to bend as the brace buckles without fracture or causing damage to the beam or column. This has been achieved by other researchers by proposing various geometries for gusset plates with linear or elliptical fold lines. In this paper, a new approach is proposed in which, starting with a structural high strength steel, the desired yield path of the gusset plate is created through heat treating to locally weaken the steel and, at the same time, make it more ductile. Through this method, the gusset plate is forced to yield and deform over the predetermined path. The objective of the research is to develop a connection in which the failure mechanism is tightly controlled, eliminating unexpected damage mechanisms and aiming for more economical designs. First, small steel samples were heat treated using different time-temperature profiles to determine the potential strength reduction. Based on the initial results, localized heat treatment was performed on coupon test samples, and tensile tests were used to quantify the change in material properties. Using these properties, finite element analysis of the gusset plate-brace connection is performed to investigate the behavior of the proposed gusset plates. Various gusset plate geometries and yield paths are subjected to a series of loading. The analysis results including the predicted failure mechanisms are presented and used to make recommendations for the heat treated gusset plate design.

***Keywords**: Gusset plate, Braced frames, Heat treatment, Material behavior, Yield path, High strength steel*

1 INTRODUCTION

Extensive damage to steel frame connections during the 1994 Northridge earthquake initiated comprehensive research into seismic performance of connection details (Kunnath et al. 2000). After the Northridge earthquake, there was an increase in the use of special concentrically braced frames (SCBFs). Providing strength and lateral stiffness, SCBFs are considered an economical system to control drifts (Hsiao et al. 2013, Arzeytoon et al. 2015), which has made them a commonly used lateral load resisting system. In small, frequent service-level seismic events, these systems remain nearly elastic. However, in large infrequent earthquakes, these systems dissipate energy through axial tensile yielding and buckling deformation of the braces.

To allow this behavior, the gusset plates must undergo large inelastic rotations with simultaneous tensile and compressive loading (Zhang et al. 2011). This is most often achieved through designing the gusset plate with a 2tp free width between the restrained gusset line and the brace end, with the tp being the gusset plate thickness (Figure 1a). This ensures the free out-of-plane rotation of the gusset plate during brace buckling and prevents damage accumulation in the connection (Astaneh-Asl et al. 1984, 1985, Martinez 2008). This linear clearance works well; however, it leads to thicker, larger plates, which has negative effects on the inelastic deformation capacity. A more recent approach outlines the desired yielding sequence of the brace and connection components to eliminate unwanted failure modes thereby maximizing the ductility of the structure while minimizing any premature damage. In this alternative, an 8tp elliptical clearance is suggested (Figure 1b) (Yoo et al. 2008a, Lehman et al. 2008), which results in smaller and more compact gusset plates while reducing local yielding in the adjacent columns and beams (Yoo et al. 2008b).

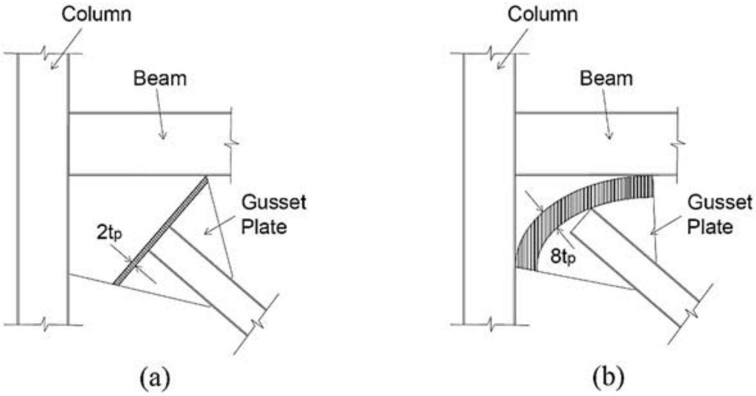


Figure 1. Corner gusset plate connections: (a) Linear clearance (b) Elliptical clearance.

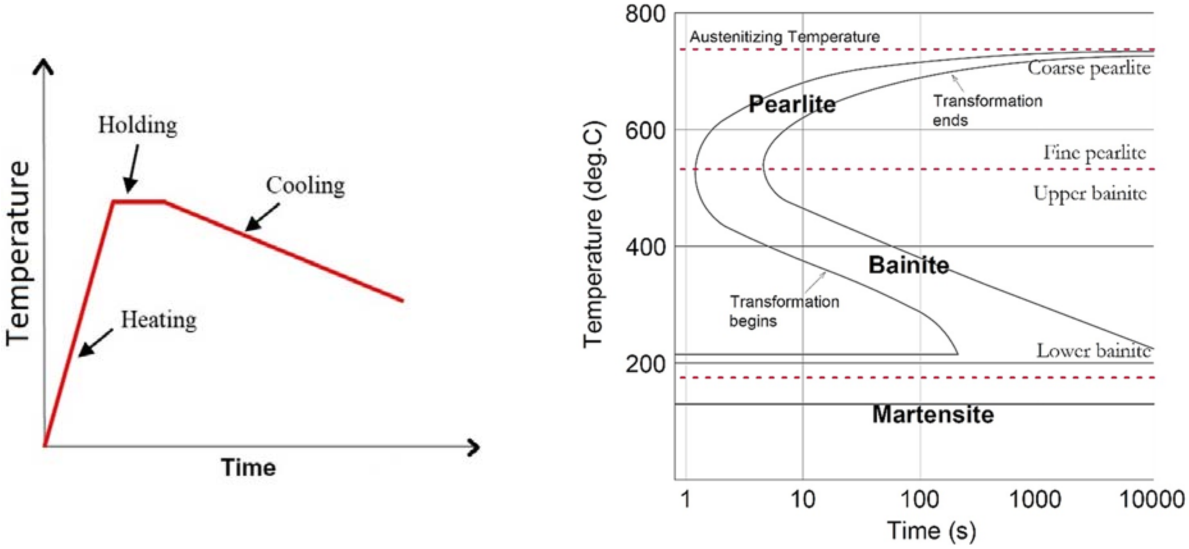
While both connection detailing methods have their benefits, both have been shown to result in damage surrounding the gusset plate: in the adjacent beam and column for the linear 2tp design [10], and in the gusset-to-frame connection weld for the 8tp elliptical design (Lehman et al. 2008, Roeder et al. 2011). Here, we propose a new method to achieve a more reliable yielding path through a heat softened zone. In this method, a pre-determined yield zone is created through reducing the local yield strength through heat treatment. The yielding path can be determined precisely, and the seismic performance of the gusset plate and connection in general is enhanced.

Heat treatment is not a new technology; however, it is a novel method in structural engineering, especially for seismic design. Morrison et al. Morrison et al. (2015) used heat treatment to reduce the strength and increase the ductility of A992 steel to develop a “heated beam section” (HBS) for moment frames. Similar to reduced beam sections, the beam flanges slightly away from the column face are weakened. For this study, the heat treatment was done using electric surface heating pads. Yu et al. (2015) investigated HBS with Q345B steel (Chinese code) for concrete filled rectangular tube connections to address problems with stress concentrations in the beam flanges due to column welding. Morrison et al. (2016) also used the HBS concept to address ductility deficiencies in welded unreinforced flange-bolted web (WUF-B) connection. The modified connection showed a shifting of yielding and buckling away from the critical zone of the connection. Yu et al. (2017) used heat treatment to weaken portions of steel plate shear walls. While steel coupons were heated and tested, the heat treatment for the shear wall was done through finite element simulation. They found that stripped strength-reduction zones could improve plasticity distribution and minimize boundary zone stress concentrations without significant loss of the strength and lateral stiffness.

2 HEAT TREATMENT PRINCIPLES AND MATERIAL TEST

2.1 Steel microstructures and phase transformation

Steel microstructures determine the mechanical properties of the steel material, including both strength and ductility (Babu 2006). These microstructures can be transformed through a heating and cooling processes, the most important parameter of which is the cooling rate (Figure 2). As shown in Figure 2b, from the austenitizing temperature, quick quenching results in creation of martensite, the hardest and most brittle microstructure, while a controlled slow cooling leads to a coarser and larger grain structure, resulting in pearlite which is softer and more ductile. Therefore, a sufficiently slow cooling rate is desirable to lower the steel strength while maintaining or increasing the ductility.



(a) (b)

Figure 2. (a) Annealing heat treatment parameters. (b) An example of time-temperature-transformation of a typical carbon steel.

2.2 Heat treatment on steel samples

First small samples 10x10x6 mm of common types of steel plates and sections used in construction, including normal steel A992 and A572 and high strength steel A514, were tested to identify appropriate heating and cooling protocols. An initial estimate of the austenitizing temperature was made based on the chemical composition (Rudnev et al. 2003) using

[1] $Ac_1 = 723 - 10.7Mn - 16.9Ni + 29.1Si + 16.9Cr + 290As + 6.38W = 727°C$

[2] $Ac_3 = 910 - 203\sqrt{C} - 15.2Ni + 44.7Si + 104V + 31.5Mo + 13.1W = 856°C$

Based on the austenitizing temperature, a heating temperature of 900°C was used to guarantee austenite formation. All the samples were held in the target temperature for 10 minutes, and were cooled with different rates to 500°C, after which they were air cooled. The different heat treatments used are shown in Table 1. The Vickers microhardness test was then performed to compare the effects of the different heat treatments. Note that the tensile strength values, compared in Figure 3, were estimated from the microhardness tests.

Table 1. Heat treatment scenarios

Heat treatment case	Cooling rate (Degrees Celsius per minute)
Non-heat-treated	Without heat treatment
Air cooled	Cooled in the room temperature
C10	10
C5	5
C2	2
C1	1

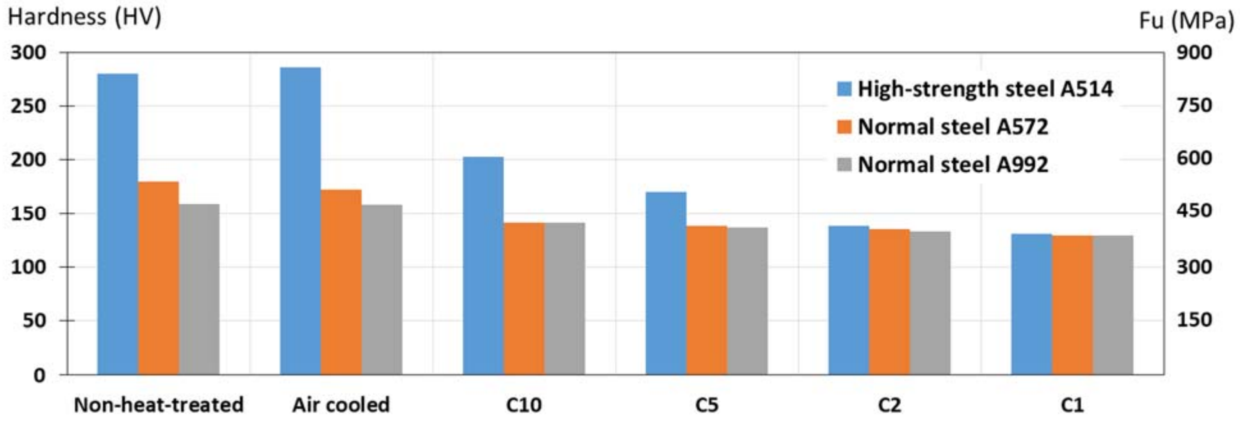
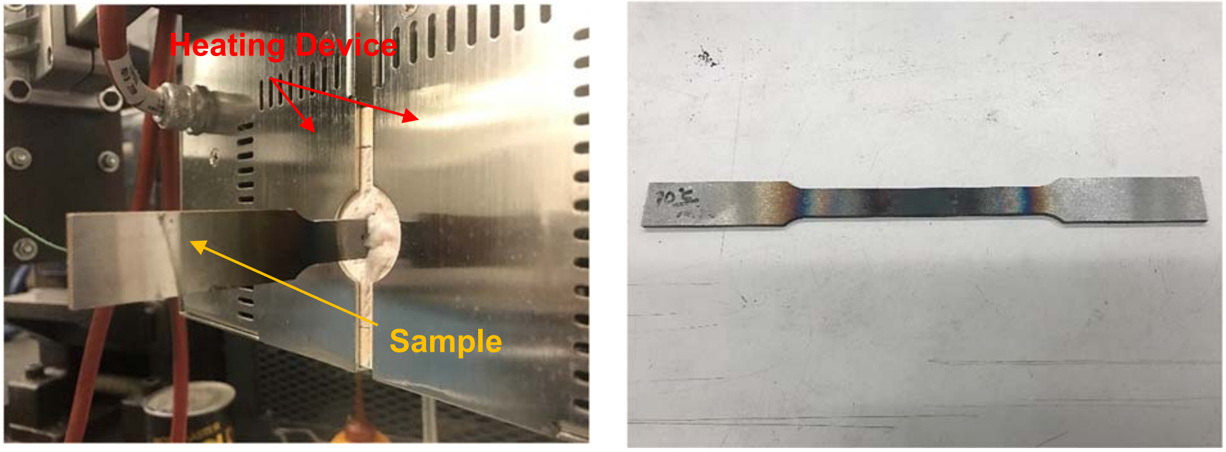


Figure 3. Microhardness test results for heat-treated steel materials

For the high-strength A514 steel, the heat treatment cooling at 10 ºC/min reduced the tensile strength by 24%. This strength reduction was 48% for the same steel by a cooling rate of 2 ºC/min. However, there was no significant further reduction with 1 º/min. The A572 had a tensile strength reduction of 22% with a cooling rate of 10 ºC/min. However, there was no substantial reduction for slower cooling for this material. A992 showed the least strength reduction among all the steel materials. Its tensile strength was reduced by 11% and 18% when cooling at 10 ºC/min and 1 ºC/min, respectively. Larger strength reductions can be achieved for the higher strength steel (A514) because its initial microstructure is bainite which is then transformed to pearlite, whereas is the lower strength steels (A992) begin at this softer microstructure. The strength of all the steels converged when the slowest cooling rate was used. This indicates that the microstructures of all the steel materials have transformed into pearlite when cooling is conducted sufficiently slowly.

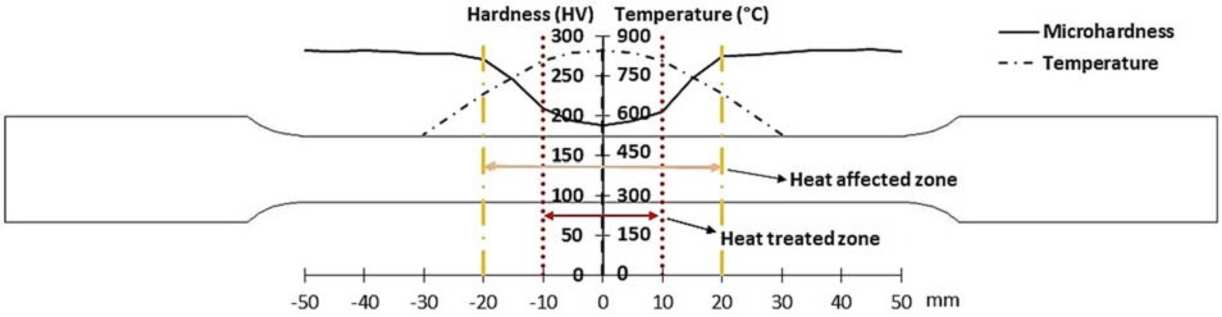
Larger coupon samples (Figure 4) were then used to investigate the strength-weakening effect of local heat treatment. Tensile test samples of high strength steel A514 with cross-sections of 20 mm by 8 mm were cut and heat treated locally. The heat treatment was done by heating the middle 20mm of a sample for 10 minutes followed by cooling rates at 10 ºC/min and 2 º/min. The temperature profiles after 10 minutes of heating and before cooling were measured across the length of the coupon. The Vickers microhardness test was then done along the specimen. Figure 5 shows the heat treated samples with hardness test results and temperature profiles.



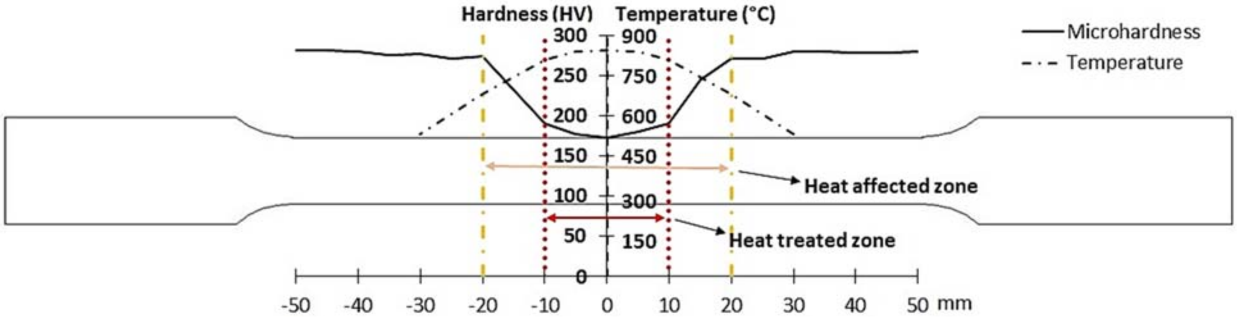
(a)

(b)

Figure 4. (a) Heat treatment setup (b) Locally heat-treated tensile sample



(a)



(b)

Figure 5. Microhardness and temperature profiles for tensile samples heat treated with: (a) cooling rate of 10°C/min (b) cooling rate of 2°C/min

The average heating temperature in the middle was 830°C, which is sufficient for austenite transformation. However, in both cases, the temperature profile is not uniform across the 20mm heat-treated region. At 20mm away from the center, the temperature dropped to 680°C, which is less than the austenitizing temperature. Therefore, after this point, there was no change in hardness due to heat treatment. Thus, the total width of the heat-affected zone (HAZ) was roughly twice the heat-treated zone (HTZ). The average reduction in microhardness with 2°C/min cooling rate is 37% in the center, while it is 32% with 10°C/min cooling rate. While these are similar reductions, the tests do show a correlation between the strength reduction and cooling rate so that a proper cooling rate can be selected to lead to the needed strength reduction amount.

Tensile tests were conducted for the heat-treated samples and one untreated sample; the results of which are shown in Table 2. The tensile strength from the tensile tests closely match the estimates from the microhardness test. The ductility increased substantially for the heat treated coupons.

Table 2. Tensile test results of steel A514

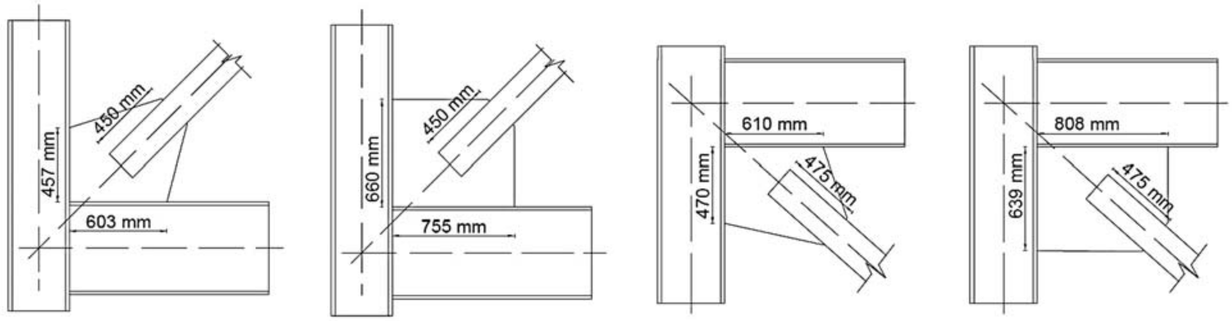
Material	Fy (MPa)	Fu (MPa)	εu (%)
Non-heat-treated	810	853	11
Heat-treated with a cooling rate of 10°C/min	380	579	18
Heat-treated with a cooling rate of 2°C/min	365	530	21

3 FINITE ELEMENT MODELLING

Nonlinear inelastic finite element models of heat-treated and non-heat-treated gusset plates were created and analyzed using ABAQUS. Tapered and rectangular shapes were both used (Figure 6). The balanced design procedure introduced by Roeder et al. (2011) was used for design. An elliptical clearance of 8tp was considered for all plates. High-strength steel A514 with yield and tensile strength of 810 and 845 MPa, respectively, was used for the gusset plates. Because of the high strength, the size and thickness of the gusset plates are reduced compared if normal strength steel was used. The reduced thickness has an added benefit of improved inelastic behavior, as thick and stiff gusset plates can show poor inelastic behavior (Lehman et al. 2008, Roeder et al. 2010).

The heat treatment path is shown in Figure 7. This heat treatment oriented yield path is aimed to shift the yielding and damages away from the gusset-to-frame connection areas. Based on the tensile samples heat treatment results, the width of the HAZ was taken half of the width of HTZ. Widths of 3tp and 4tp were considered for the HTZ, making a total of 6tp and 8tp for the HTZ and HAZ together, respectively. The yield and tensile stress values for the analysis were selected for the HTZ and HAZ based on the values of the case with the cooling rate of 2°C/min presented in Figure 5 and Table 2.

Eight-node brick elements with reduced integration (C3D8R) were used in the modeling. A mesh size equal to half of the gusset plate thickness was used for meshing the elements. To simulate the effect of brace buckling on the gusset plate, the brace end was modeled and out-of-plane rotation was imposed. Studies have shown that brace fracture and failure happens before a story drifts equal to 3% (Roeder et al. 2011, Chen et al. 2017). To model the rotational demands in the gusset plate under severe brace buckling, the out-of-plane rotation of the brace end was increased up to 14 degrees measured from the working point; this is proportional to a drift of 3% (Figure 8).



(a) (b) (c) (d)

Figure 6. Gusset plate designs with thickness of (a) t=12mm (b) t=12mm (c) t=10mm (d) t=10mm

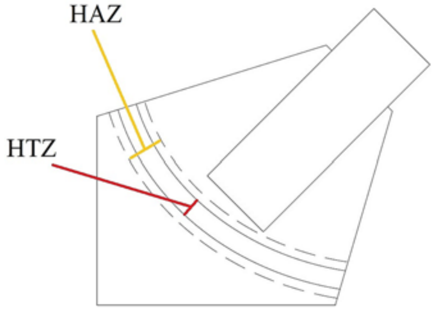


Figure 7. Heat treatment path on the gusset plate

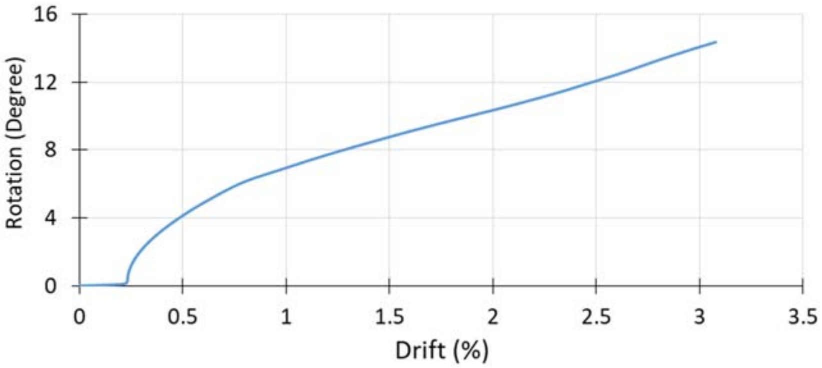
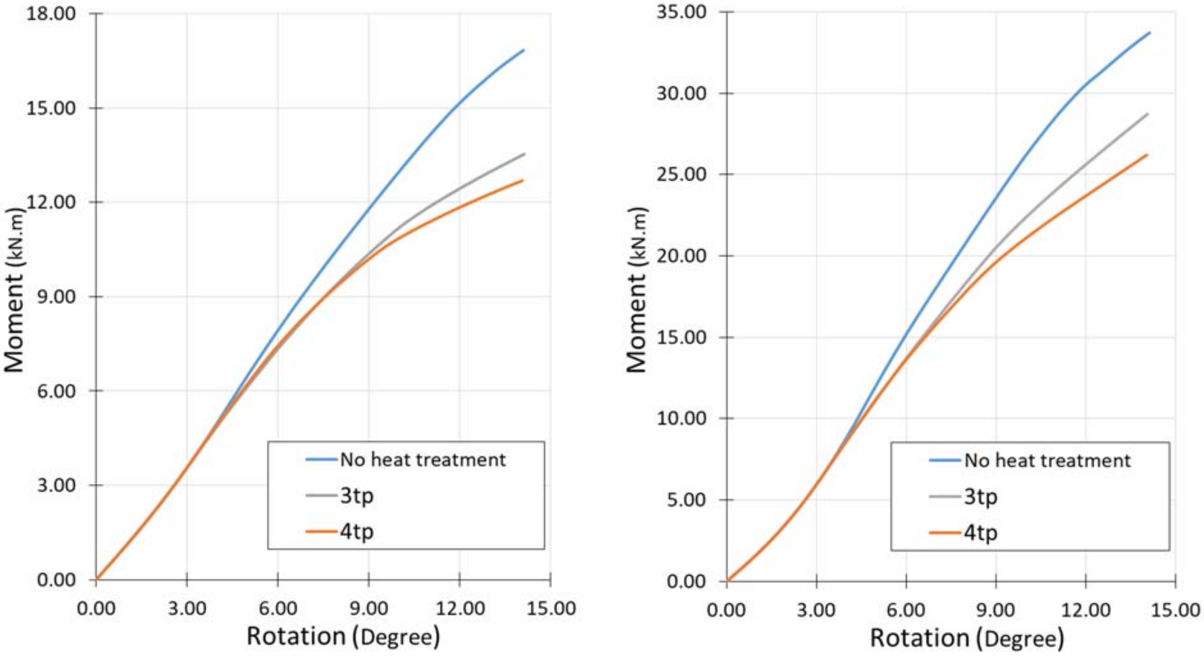


Figure 8. The gusset plate rotation under increasing story drift

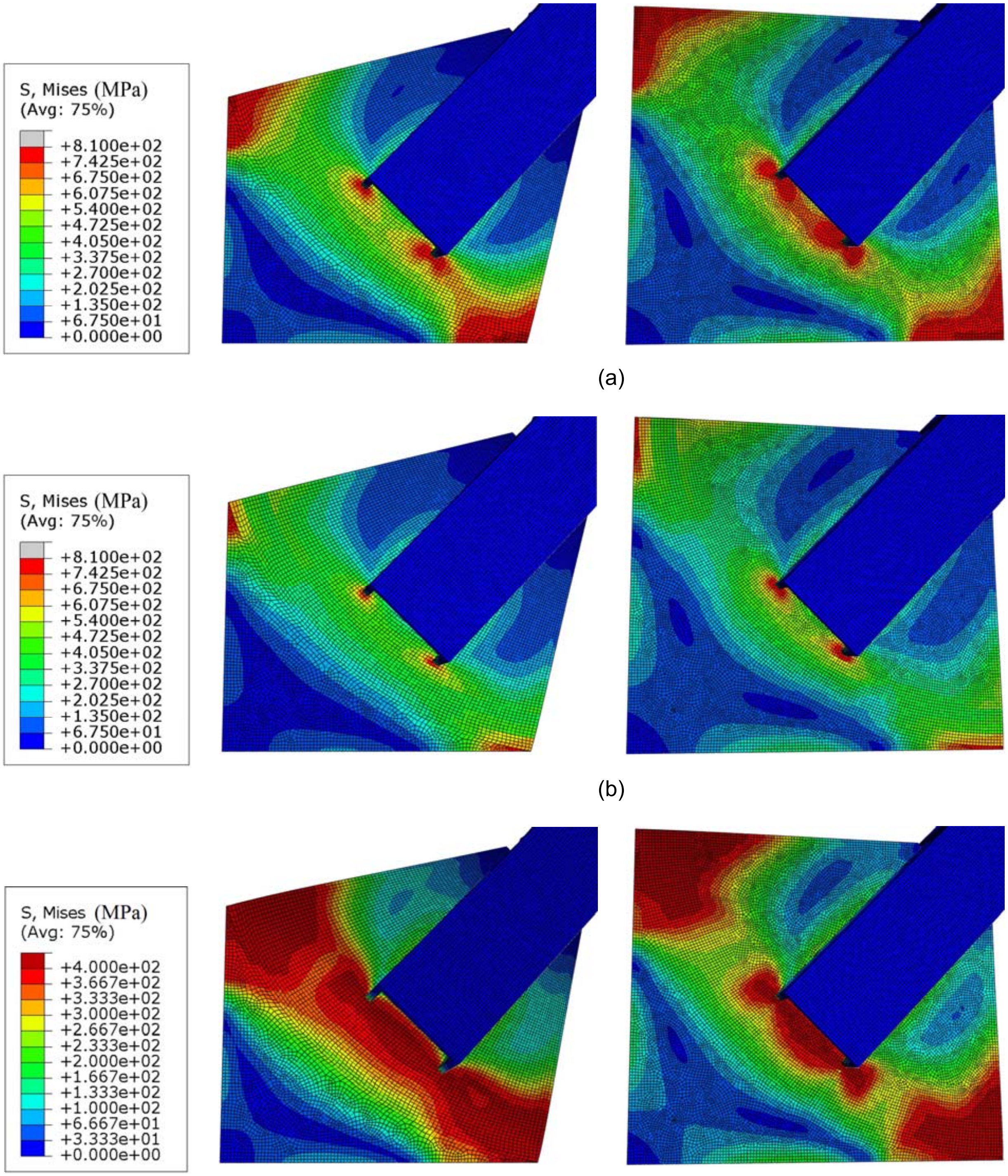
The moment-rotation diagrams of the gusset-brace connections for the models with 10mm thickness with different heat treatment width are shown in Figure 9. The heat-treated connections developed lower moment for the same rotational demands, facilitating brace buckling, which is beneficial for capacity design. With 3tp heat treatment, the moment demand reduced by 20% in the tapered gusset plate at a rotation of 14 degrees. This amount was 15% for the rectangular plate. With 4tp, this value was 25% and 19% for tapered and rectangular gusset plates, respectively. It should be noted that up to a bending of 5 degrees, there is no substantial difference since the gusset plate remains mainly in its elastic zone.



(a) (b)

Figure 9. Moment-rotation curves for the model with thickness of 10 mm: (a) Tapered (b) Rectangular.

Figure 10 shows the stress distribution in the gusset plates at a rotation of 10 degrees. For a better comparison, the results of the fully-heat-treated gusset plates have also been shown. The maximum stress value has been normalized to the gusset plate yield stress. The stress concentrations near the gusset-to-beam and gusset-to-column connections for the heat treated plate is reduced compared to the non-heat-treated plate and fully-heat-treated one. This reduces the stresses in the welds, and in the beam and the column near the connection. The result of the heat treatment is a strength-weakened path which protects the gusset-to-frame connection. This modification is seen in both tapered and rectangular gusset plates.



(a)

(b)

(c)

Figure 10. Stress distribution in gusset plates with thickness of 12 mm for (a) non-heat-treated, (b) 4tp heat-treated, (c) fully-heat-treated connections

4 CONCLUSIONS

A novel technique was proposed to enhance the seismic behavior of gusset plate connections. In this approach, heat treatment was used to create a strength-weakened zone in the out-of-plane bending clearance. Different heat treatment processes were used for the steel materials commonly used in construction. The Vickers microhardness test and tensile tests were used to quantify the effects of the heat treatment scenarios on the steel materials. Heat treatment can reduce the strength of the high strength steel A514 by 52%, whereas this strength reduction was 28% for normal steel A572, and 18% for the normal steel A992. The ultimate strain of the A514 was almost doubled using a slow cooling rate.

The experimental results were used to create finite element models of heat treated gusset plates with elliptical clearances. The results showed that the heat treatment reduced the moment developed in the gusset plates, creating more pin-like behavior to encourage buckling, and reduced the stress concentrations at the brace-to-frame and gusset-to-brace connections, protecting the welds. These benefits can increase the bending capacity of the gusset plate and by extension, the overall seismic performance of the concentrically braced frame. Further analytical modeling and experimental tests are needed to consider cracking and low-cycle fatigue in the heat treated and untreated regions, as well as any changes to energy dissipation. Experimental verification is also necessary.

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