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A study of research achievements and challenges on the application of HSS endplates in seismic resisting systems

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ABSTRACT

High strength steel is increasing in demand due to economic and mechanical benefits. A typical mechanical characteristic of HSS is that the ductility of the material decreases along with the increase in strength. This has been one of the main concerns of HSS in construction applications. The Y/T ratio and elongation requirement in Eurocode 3(1-8) and in NZS 3404 significantly constrains the application of HSS in seismic resisting systems, especially when dependable ductility from plastic action is required from the HSS component. Furthermore, the amount of strength loss resulted from high heat input during welding process is therefore a significant factor that may affect the performance of the connections. The implications of this are not straightforward to determine. This means that the mechanical performance of HSS beam-to-column connection has not been systematically studied, especially for bolted endplate connections which are widely used across New Zealand. In these connections, the HSS steel could be used to significantly reduce the thickness of the currently used thick endplates leading to appreciable reduction in weight and cost of these connections. To achieve that, it is necessary to study the impact of HSS on the structural behaviour of moment resisting endplate connections comprehensively and to determine what the performance limits are so that, ultimately, the limits in the standards can be relaxed. This paper discusses the current achievements and challenges of HSS connections in seismic resisting systems, and the key areas that need to be researched to better understand HSS connections behaviour under seismic loading.

1 INTRODUCTION

Structural steel is one of the most popular materials used in seismic resisting systems in New Zealand. Steel framing has over 50% market share of the national multilevel construction market and up to 80% in

Christchurch (Alistair Fussell, 2015).Bolted moment endplate connections are widely used in steel structures as a seismic resisting system for a number of reasons, such as simple fabrication, fast erection and eliminating problems associated with field welding. However, one of the concerns of this connection in multi-story design, according to industrial feedback, was that the continued growth in thickness of the endplate is likely to increase the complexity of the fabrication, especially in the welding process. NZS3404 (2007) requires an inspection after completing the welds where the plate thickness is over 50mm, indicating more attentions and challenges associated with thick endplates in connections.

Advanced modern smelting technology allows manufacturers to produce higher strength steel by precisely controlling the rolling and cooling process, which keeps the alloy and carbon content low, to improve mechanical properties such as ductility and weldability. This is known as High Strength Low Alloy steel (HSS). HSS is referred to the structural steel with a strength of often greater than 460Mpa (f_y >460mpa). A list of HSS definitions in different standards can be found in Fu et al. (2018) research. In moment endplate connections, HSS could potentially be used to significantly reduce the currently required thick endplates, leading to appreciable reduction in welding issues as well as weight and cost of these connections. However, due to differences in properties between mild steel (f_y<460Mpa) and HSS (f_y>460), a comprehensive research programme is needed to investigate the behaviour of the plate when the connection is subject to different types of loading. Moreover, the structural properties of the connection, such as moment resistance, rotational stiffness, and rotational capacity, require further studies to verify whether the HSS is appropriate to be used in moment endplate application.

A typical bolted moment endplate beam to column connection usually consists of a plate which is shop welded to the beam end and bolted to the column flange on site to form a moment resisting structural system. The connections can be classified into flush and extend endplate, with or without stiffeners. The most common types of flush and extended endplate configuration can be found in AISC Steel Design Guide Series 4 (Murray & Sumner, 2003). Research of endplate moment connections can be found as early as 1950 and the first application was around 1960's (Disque, 1962). The idea of endplate application came from split tee connection, where it produced a considerable conservative connection with a simple design method and the design procedure was likely to result in a thick plate with large bolt size at this stage (Murray & Sumner, 2003). Granstrom (1980), following Kato & McGuire (1973), and Nair et al. (1974), researched on the tee-hangers to propose a design method that led to a thinner plate and smaller bolts. However, this design did not take the prying action resulting from the thin plate deformation into considerations. The yield line theory was first used by Packer (1977) for endplate analysis. Kennedy et al. (1981) carried the tee-stub analysis and provided definition of "thick" and "thin" plate according to the yield line theory, and prying force associated with the three failure modes. Murray & Sumner (2003) confirmed that a proper design and detailed endplate connection was suitable for seismic resisting application through testing of a four-bolt extended, unstiffened mild steel endplate configuration.

A number of researchers had provided sufficient data showing that HSS has different mechanical properties other than mild steel (Ban et al., 2011) (Beg & Hladnik, 1996) (McDermott, 1969) (Rasmussen & Hancock, 1992) (Shi et al., 2019) (Ban et al., 2017 Figures 1&2), including high yield to tensile (Y/T) ratio indicating low ductility of the material. The decrease in elongation capacity along with the increase in strength also place limitations on HSS used in component where inelastic demand is expected. However, Ban & Shi (2017) pointed out that the strain to failure for HSS could be very close to 20%, which suggested that steel with high strength and ductility could be possibly produced. Given the differences on the mechanical properties, it is necessary to investigate the actual behaviour of the HSS component under different loading conditions to ensure the adequate performance.

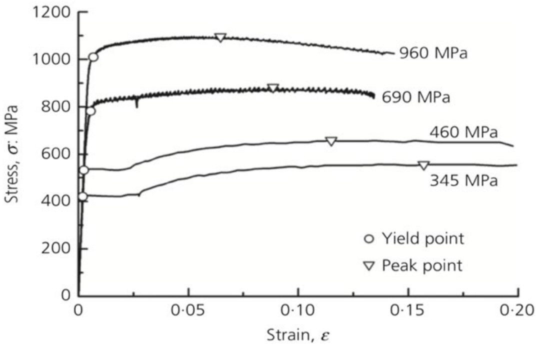

Figure 1: Stress-Strain Curves comparison for various steel grades ***(Ban et al., 2017)***

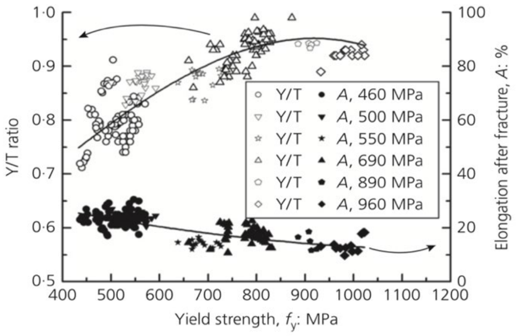

Figure 2: Summary of tension coupon test results of HSS ***(Ban et al., 2017)***

2 RESEARCH ON HSS MOMENT ENDPLATE CONNECTION

For decades, HSS has not been so popular in construction as researchers believe that the Young's modulus would be almost the same as that of mild steel. Steel structures are likely governed by serviceability limited state which is determinate by the stiffness rather than yield capacity of material. Moreover, design standards, such as Eurocode 3 (2005) restricts the use of steel graded above S460. A committee within CEN/TC250/SC3 added a supplementary provision Part 1-12 (Collin, 2005), which provided additional rules to allow the use of steel graded up to S700, however, such additional rules are mainly based on the development of mild steel, thus it may not truly represent the actual behaviour of the HSS component. AISC-LRFD (1999) also applied mild steel design principles to HSS to introduce this new steel family in the LRFD. In a steel moment resisting system, for the reason that the connections are usually the main source of deformation, although some plastic hinges may be developed in the beam through reduced section (Murray & Sumner, 2003). This further emphasizes the importance of deformation capacity of HSS components being used in a connection.

To study the behaviour of an endplate connection, it is widely accepted to simplify the connection as a T-Stub model, use the yield line theory to calculate the flange bending capacity and to predict the failure mode of the connection (Hyland & Clifton, 2008). According to the yield line theory, there are three possible failure modes namely 4 plastic hinges in T-Stub (mode 1); 2 plastic hinges in T-Stub (mode 2); and no plastic hinge or bolt only modes (mode 3); as shown in figure 3. Coelho & Bijlaard (2007) experimentally tested 7 specimens of S690 steel bolted endplate connections to investigate the initial stiffness and the moment resisting capacity. A positive relationship was found between the thickness of the plate and the test variables. That is, the initial stiffness and moment resisting capacity grew along with the increase in thickness of the plate. Moreover, a minimum of 30 mrad plastic rotation could be developed when the connection was governed by mode 1 failure.

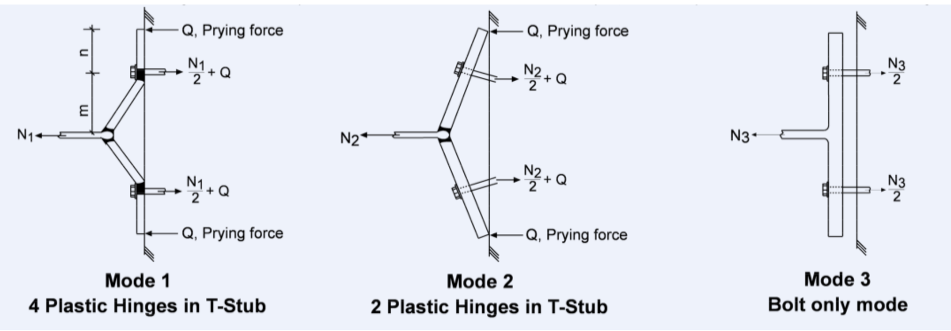

Figure 3: T-Stub Modes of Failure (Hyland et al, 2008)

Sun et al. (2014) conducted a similar experiment and found that when applying Eurocode 3 1-8 (EN, 2005) mild steel formula to HSS endplate, a reasonable accuracy could be obtained in terms of bearing capacity, but would overestimate the initial stiffness which depends heavily on the thickness of the plate, rather than other factors such as thickness of the column flange. Girão et al. (2004) pointed out that HSS T-Stub yield at higher resistance with a lower deformation capacity. Use of stiffener improved the loading resistance significantly at the expense of deformation capacity. Može et al.(2007) investigated whether local ductility of high strength steel bolted connections can assure enough ductility to transfer loads between bolts. Experiments undertaken on 26 specimens of grade S690 steel connections with three to four bolts positioned in the direction of where loadings were performed, showed that even the position of the bolts was unfavourable, the HSS plate assured sufficient local ductility to redistribute the loads between the bolts, thus reduced the chance of bolt failure under ultimate loading conditions. Može & Beg (2010) also conducted 38 tension splices tests in double shear to investigate the bearing resistance, and found that large plastic deformation could be achieved in all specimens. Furthermore, a modified bearing resistance formula to control the type of failure was proposed.

Coelho & Bijlaard (2010) further investigated the strength and ductility of members and joints made of S460, S690 and S960 to validate the current Eurocode 3 specifications for mild steel, and deformation analysis of high strength steel endplate connection. The test suggested that the EN 1993-1-8 gave accurate design resistance for mild and HSS T-Stub, but the stiffness of the connection was overestimated for HSS. The rotational capacity for HSS plate achieved 30 mrad (and above), which satisfied high deformation demand and the formula from Eurocode 3 could be conservative for some specimens. Furthermore, given the deformation of these endplates was higher than a thicker mild steel endplate, investigations into accurate ductility and deformation requirements for designers to utilize the strength of the material were necessary. Coelho & Bijilaard (2007) also pointed out that the initial stiffness and moment resistance of the connection increased along with the thickness of the endplate, while rotation capacity would decrease. This might cause other components, such as bolts, to fail before the plate. Therefore, 12.9 grade bolts might need to be avoided to use as they have less ductility compared with lower grade bolts.

During a seismic event, top and bottom flanges of the beam were subject to tension and compression over time as the structure moved from side to side. The endplate therefore, would be under cyclic loading requiring high ductility to avoid fracture failure, and this could become a concern of using HSS components. Shi et al. (2013) investigated the behaviour of high strength steel Q460C base metal and welded connection subject to repeated cyclic patterns under large inelastic strains. The experiments showed the cyclic loops and strain amplitudes significantly affected the HSS ductility, and the fracture occurred in advance due to accumulated damage. The hardening phenomenon was observed in the weld which had worsened poor ductility capacity.

2.1 Welding of HSS

The strength of HSS is obtained by introducing microstructures, which can break down under elevated temperatures, inside the material. The amount of strength loss resulted from high heat input during welding process is a significant factor that may affect the performance of the connection in terms of stiffness, ductility, and deformability. After the welding process, Heat Affected Zone (HAZ) is formed in the area near a weld toe and such effect should be considered for design purposes. Sun et. al. (2018) investigated the effect of HAZ and combined axial and shear loads on the connection behaviour of HSS T-Stub. Shielded Metal Arc Welding (SMAW) was employed for fabrication of Q690 components, and all specimens were designed to fail on complete flange yielding. The main finding was that the collapse behaviour took places where cracks occurring in the HAZ area near the weld toe. Value of the first yield resistance from the experiment suggested that the Eurocode 3 formula cannot directly be applied to HSS T-Stub. Coelho & Silva (2004) reported that in HSS T-Stub connections, increase of weld throat thickness improved stiffness and load resistance capacity at the expense of reducing the deformation capacity. Sun et al. (2019) studied the hysteretic behaviours of HSS endplate under cyclic loading and pointed out that there was a cracking problem in the HZA, and an obvious decrease in moment capacity was observed until the crack was developed largely.

Kuhlmann et al (2008) investigated the strength and ductility of welded high strength steel connections through experimental and numerical analysis. They've been investigating cruciform joints with different base metal combinations of mild and high strength steel, ranging from S355 to S690, with different filler metals. The nominal yield strength of the filler metals either equal to the nominal yield strength of the base metal with lower or higher strength, resulting in different mismatch conditions. The result showed a tendency with the growth in strength of the filler metal and the load bearing capacity increased almost independently of the base metal used. The experiment results also pointed out that the increase in strength was closely related to a loss in ductility as seen from the load-displacement curve. Gunther et al (2012) studied the strength ductility and safety against brittle fracture of S460 and S690 HSS welded connections, and gave suggestions for design process and applications based on testing and numerical models. Ahola & Barsoum (2019) investigated the fatigue strength capacity of load-carrying fillet weld on S960 HSS plate subjected to out-of-plane bending, and pointed out that the strength of the weld was closely related to the thickness of the weld throat as well as the level of weld penetration. Furthermore, they suggested that the thickness of the throat should be measured in a different way according to the directions of the load.

Zhang et al. (2016) investigated the influence of welding on two different types of high strength steel, namely Reheat, Quenched and Tempered (RQT) steel in grade S690, and thermos-mechanically controlled processed (TMCP) steel in grade S385. The RQT-S690 specimen had a yield strength of 745MPa and elongation of 15.5%, while the TMCP-S385 was 443MPa and 37.8% respectively. Test results showed that the welding could cause significant deterioration in both strength and ductility of RQT-S690, while the strength of TMCP-S385 increased slightly at the expense of reduced ductility. Different levels of hardness were observed in the HAZ between RQT and TCMP specimens. This could be a causation of the strength deterioration. The tensile performance of the welded T-Stub joint was also evaluated. It showed that the load carrying capacity of RQT-690 were below the upper bound, and the TMCP achieved a much higher strength when comparing to the value obtained from Eurocode 3 formula. The test also suggested the welding heat input could significantly affect the plastic hinges at the weld toe, thus the behaviour of the joint.

2.2 Bolts performance

Ling et al. (2018) experimentally tested 12 HSS Q 690 welded T-Stub with various bolt diameters, strength grades, levels of bolt pretension, and flange sizes to investigate the mechanical properties of the connection. Load bearing capacity and initial axial stiffness was obtained and compared to Eurocode 3 formula. Results showed Eurocode 3 overestimated the initial stiffness of the HSS connection. The proportion of bolt elongation, and the joint deformation decreased with an increase in bolt diameter, bolt edge, and the bolt distance from the web. A numerical model was developed demonstrating the initial stiffness of the connection would rise linearly with an increase of bolt pretension. However, weak influence on the initial stiffness after a certain level of bolt pretension was found. Further experiments by Ling (2019) showed Q690 achieved about 24-66% higher in design resistance, about 1-23% higher in ultimate bearing capacity when comparing to Q345. However, the ductility index, which is the ratio between the total deformation to the elastic limit deformation at maximum load, for Q690 was only about 0.12-0.5 times larger comparing to Q345 joint.

Coelho & Silva (2004) pointed out that if the failure mode of the connection was governed by bolt fracture, the overall deformation capacity could increase with a long-threaded bolt compared to an equivalent short-threaded bolt. A close relationship between the bolt size and the joint performance was observed, suggesting larger bolt enhanced the strength, stiffness, and ductility of the connection. Wang et al. (2018) experimentally studied two-bolt connection perpendicular to loading direction made of Q550D and Q690D to investigate the effect of end distance on failure mechanism. Two failure modes namely tear out and splitting failures were observed. The main finding was that the bearing resistance reduction factor in Eurocode 3 was unnecessary since the designed resistance was already conservative.

2.3 Fire

Given the arrangement of microstructure inside the HSS is not stable under elevated temperatures, there might be a permanent strength decrease, hence a need to investigate its performance under severe fire. Qing et al (2015) presented a full scaled post-fire experiment on 7 endplate connections made from HSS and mild steel cooling down from 550°C, to compare with their performance at an ambient temperature without the fire exposure. The main findings were: 1) The post-fire bearing and rotation capacity was dependent on the strength and thickness of the endplate; 2) Both thicker HSS (Q690) and mild steel (S235) achieved a higher bearing capacity after elevated temperatures, but the post-fire rotation capacity significantly reduced after cooling down from fire; 3) HSS endplate could reach sufficient ductility after cooling down from 550°C ; 4) Thinner HSS endplate achieved the same failure mode as mild steel plate, and even a higher rotation capacity could be observed; 5) The post-fire plastic flexural capacity prediction from Eurocode 3 is acceptable for HSS endplate connection.

3 DISCUSSION OF THE CURRENT KNOWLEDGE GAP

Eurocode 3 requires that, for mild steel, the specified yield strength, ultimate tensile strength, elongation at failure and minimum Charpy V-notch energy value of the filler metal, should be equivalent to, or better than that specified for the parent material (EN, 2005). It is generally safe to use electrodes that are overmatched with regard to the steel grade being used. By satisfying this requirement, the weld section is assumed to be at least equal or stronger than the plate theoretically. This requirement allows the calculation of design resistance of the endplate to be based upon the steel grade of the connection components, i.e. the strength of the plate. However, this may not be the case for high strength steel, where Eurocode 3-1-12 stated that for steel with a grade greater than S460 and up to S700, the filler metal may have a lower strength than the base material to increase the ductility of the welded connection. If the connection is welded using under matched electrodes, the material strength to be used in the design should be based on the strength of the filler metal (ČSN, 2008). While following those rules for HSS, the strength of the material may not be fully utilized, thus reducing the benefit of using HSS components. For this reason, a study of the welding performance is necessary to verify whether a matched electrodes welding can provide sufficient ductility to prevent welding failure in an endplate application.

It can be assumed that mild steel (S235, S275 and S355) can regain about 90 percent of its mechanical properties after cooling from 600°C (Outinen & Mäkeläinen, 2004). There is a large amount of research on post-fire performance of steel-concrete composite structures (Pucinotti et l., 2011), concrete filled steel tubular column (Yang et al., 2008) and mild steel frames (Della et al., 2003) (C. Clifton, 1996). However, limited suggestions or assumptions about the percentage of strength regained for HSS may be found from current design standards around the world. Thus, the ability of strength regain for HSS should be systematically studied, especially for different types of HSS, i.e. Q&T and TMCP, to establish a solid foundation to advance the application of HSS in construction industry. HSS endplate connections are likely contains different grades od steel, i.e. HSS plate with mild steel beam and column, hence different levels of strength regain after a fire may lead to a failure of strong connection - weak beam design philosophy (Murray & Sumner, 2003).

3.1 Mechanical properties of the HSS

There are limited database to determine the basic mechanical properties of HSS around the world, and the partial factor of the material have not been comprehensively studied and analysed so far (Fu et al., 2018). Main mechanical properties such as stress-strain relationship, modulus of strain hardening, ultimate strain and ductility, hysteretic behaviour under seismic loading should be experimentally studied. The ductility and deformation capacity of welding under stress and the pattern of stress distribution in the bolts resulting from plate deformation is of importance, hence further studies are needed to evaluate the strength of the material (Fu et al., 2018).

3.2 Seismic performance

So far limited HSS structural systems have experienced a severe earthquake strong enough to push the structural elements into plastic/nonlinear states (Fu et al., 2018). Experiments to investigate the potential seismic performance of the HSS connections is highly recommended to fill in this knowledge gap.

3.3 Residual stress in the HSS member

Welding process changes the residual stress in the HAZ regardless the steel grade. According to current perspectives, the difference of residual stress in HSS between the weld zone and the base material is smaller than that of in mild steel. The real residual stress distribution of different types of HSS with different welding techniques has not been fully understood yet, thus it requires further studies to lay a solid foundation for analysing and determining the behaviour of the connection accurately (Fu et al., 2018).

3.4 Yield line theory

Given the effect of a potential weaker weld and the strength reduction at the HAZ, the accuracy of applying the current yield line pattern, developed from mild steel, onto HSS endplate deformation is questionable (Dessouki et al, 2013). Given a thinner HSS plate is more flexible, a multiple row extended endplate configuration, where the failure is governed by endplate capacity, could potentially develop a different yield line pattern due to the increase in the number of fixation points, which would lead to formation of more plastic hinges and larger yielding capacity. Thus, verifying the accuracy of the current effective length of the yield line pattern is required in order to calculate more realistic bending capacity of the plate in multiple bolt row configurations.

4 CONCLUSION AND FUTURE RESEARCH AREA

This paper reviews the current research and achievements of the application of HSS in moment endplate connections, followed by a discussion on the knowledge gap and research that needs to be further undertaken to understand the seismic behaviour of such connections comprehensively. The potential research areas are identified as follows:

- The HAZ in Q&T and TCMP HSS exhibits different mechanical properties which may significantly affect the behaviour of the connection thus it requires further investigations through T-Stub joint to verify its performance.
- The welding design standards NZS1554 provides guidelines for welding Q&T HSS. However, it does not provide any information on the strength reduction and the change of ductility in the HAZ. A model is needed to predict the strength and ductility of the weld zone in order to evaluate the capacity of the connection. The application of NZS 1554 on TCMP HSS should also be investigated. The actual residual stress distribution in various types of HSS with different welding technique should also be covered.
- The welding performance could depend on a number of factors, such as thickness of the plate, the filler material, type of welding process, amount of heat input, and the grade/type of HSS. A comprehensive study is in needed to verify whether a particular combination is favourable for moment endplate application.
- Reviewing the accuracy of effective length of the yield line pattern when the failure mode is gravened by plate fracture, particularly for thinner plate with multiple bolt row.
- Investigating the ability of stress redistribution on the bolt, and the amount of the prying force resulting from the plate deformation, thus evaluating the performance and the fracture mechanisms of the bolts.
- Developing a model to accurately predict the bearing capacity, rotational stiffness, and the deformation capacity of the connection.
- Experimentally investigating the failure and energy dissipation mechanisms and the hysteretic characteristics of the connections under seismic loading to develop reliable predictive equations for ductility and load carrying capacity.
- Investigating the post-fire structural performance of the connection after cooling down from an elevated temperature.

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REFERENCE

Ahola, A., Björk, T., & Barsoum, Z. (2019). Fatigue strength capacity of load-carrying fillet welds on ultra-high-strength steel plates subjected to out-of-plane bending. *Engineering Structures, 196* 10.1016/j.engstruct.2019.109282

AISC-LRFD, R. F. D. S. (1999). for Structural Steel Buildings, American Institute of Steel Construction. *Inc., Chicago, Illinois*

Alistair Fussell. (2015, August/September). Steel construction booms. *Build, 149,* p54-55.

Ban, H., & Shi, G. (2017). A review of research on high-strength steel structures. *Proceedings of the Institution of Civil Engineers-Structures and Buildings, 171*(8), 625-641.

Ban, H. Y., Shi, G., Shi, Y. J., & Wang, Y. Q. (2011). *Research progress on the mechanical property of high strength structural steels.* Paper presented at the Advanced Materials Research.

Beg, D., & Hladnik, L. (1996). Slenderness limit of class 3 I cross-sections made of high strength steel. *Journal of Constructional Steel Research, 38*(3), 201-217.

C. Clifton. (1996). *Fire Models For Large Firecells* (R4-83). HERA Steel Design &Construction Bulletin: HERA.

Coelho, A. M. G., & Bijlaard, F. (2010). High strength steel in buildings and civil engineering structures: Design of connections. *Advances in Structural Engineering, 13*(3), 413-429.

Coelho, A. M. G., & Bijlaard, F. S. (2007). Experimental behaviour of high strength steel end-plate connections. *Journal of Constructional Steel Research, 63*(9), 1228-1240.

Collin, P., & Johansson, B. (2005). Eurocode for high strength steel and applications in construction.

ČSN, E. (2008). 1-12: Eurocode 3: Design of steel structures–Part 1-12: Additional rules for the extension of EN 1993 up to steel grades S700: Praha: ČNI.

Della Corte, G., Landolfo, R., & Mazzolani, F. (2003). Post-earthquake fire resistance of moment resisting steel frames. *Fire Safety Journal, 38*(7), 593-612.

Dessouki, A. K., Youssef, A. H., & Ibrahim, M. M. (2013). Behavior of I-beam bolted extended end-plate moment connections. *Ain Shams Engineering Journal, 4*(4), 685-699. 10.1016/j.asej.2013.03.004

Disque, R. O. (1962). End-Plate Connections. *National Engineering Conference Proceedings, AISC*, P30-37.

EN, B. (2005). 1-8: 2005. Eurocode 3: design of steel structures–Part 1–8: design of joints. *British Standards Institution, United Kingdom*

Fu, L., Xu, G., Yan, Y., Yang, J., & Xie, J. (2018). *The Application and Research Progress of High Strength and High Performance Steel in Building Structure.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

Girão Coelho, A. M., & Bijlaard, F. S. K. (2007). Experimental behaviour of high strength steel end-plate connections. *Journal of Constructional Steel Research, 63*(9), 1228-1240. 10.1016/j.jcsr.2006.11.010

Girão Coelho, A. M., Bijlaard, F. S. K., Gresnigt, N., & Simões da Silva, L. (2004). Experimental assessment of the behaviour of bolted T-stub connections made up of welded plates. *Journal of Constructional Steel Research, 60*(2), 269-311. 10.1016/j.jcsr.2003.08.008

Granstrom, A. (1980). Bolted End-Plate Connections. *Stalbyggnads Institute SBI Report, 86*, 5-12.

GÜnther, H.-P., Hildebrand, J., Rasche, C., Christian, V., Wudtke, I., Kuhlmann, U., . . . Werner, F. (2012). Welded connections of high-strength steels for the building industry. *Welding in the World, 56*(5-6), 86-106.

Hyland, C., Cowie, K., & Clifton, C. (2008). *Structural steelwork connections guide*: Steel Construction New Zealand.

Kato, B., & McGuire, W. (1973). Analysis of T-stub flange-to-column connections. *Journal of the Structural Division, 99*(5), 865-888.

Kennedy, N., Vinnakota, S., & Sherbourne, A. (1981). The split-tee analogy in bolted splices and beam-column connections. *Joints in structural steelwork, 2*(2.157)

Kuhlmann, U., Günther, H.-P., & Rasche, C. (2008). High-strength steel fillet welded connections. *Steel Construction: Design & Research, 1*(1), 77.

Liang, G., Guo, H., Liu, Y., & Li, Y. (2018). Q690 high strength steel T-stub tensile behavior: Experimental and numerical analysis. *Thin-Walled Structures, 122*, 554-571. 10.1016/j.tws.2017.10.042

Liang, G., Guo, H., Liu, Y., Yang, D., & Li, S. (2019). A comparative study on tensile behavior of welded T-stub joints using Q345 normal steel and Q690 high strength steel under bolt preloading cases. *Thin-Walled Structures, 137*, 271-283. 10.1016/j.tws.2019.01.023

Lyu, Y., Wang, Y., & Li, G. (2018). *Experimental investigation of two-bolt connections for high strength steel members.* Paper presented at the 12th International Conference on Advances in Steel-Concrete Composite Structures (ASCCS 2018). Proceedings.

McDermott, J. F. (1969). Plastic bending of A514 steel beams. *Journal of the Structural Division, 95*(9), 1851-1871.

Može, P., & Beg, D. (2010). High strength steel tension splices with one or two bolts. *Journal of Constructional Steel Research, 66*(8-9), 1000-1010.

Može, P., Beg, D., & Lopatič, J. (2007). Net cross-section design resistance and local ductility of elements made of high strength steel. *Journal of Constructional Steel Research, 63*(11), 1431-1441.

Murray, T., & Sumner, E. (2003). Steel design guide 4 extended end plate moment connections seismic and wind applications. *Chicago: AISC*

Nair, R. S., Birkomoe, P., & Munse, W. H. (1974). High strength bolts subject to tension and prying. *Journal of the Structural Division, 100*(st2)

NZS3404. (1997/2001/2007). *Steel structures standard, incorporating Amendments 1 and 2*, Wellington [N.Z.]: Standards New Zealand.

Outinen, J., & Mäkeläinen, P. (2004). Mechanical properties of structural steel at elevated temperatures and after cooling down. *Fire and materials, 28*(2-4), 237-251.

Packer, J. (1977). A limit state design method for the tension region of bolted beam-column connections. *The Structural Engineer, 55*, 446-458.

Pucinotti, R., Bursi, O., & Demonceau, J.-F. (2011). Post-earthquake fire and seismic performance of welded steel–concrete composite beam-to-column joints. *Journal of Constructional Steel Research, 67*(9), 1358-1375.

Qiang, X., Jiang, X., Bijlaard, F. S. K., Kolstein, H., & Luo, Y. (2015). Post-fire behaviour of high strength steel endplate connections — Part 1: Experimental study. *Journal of Constructional Steel Research, 108*, 82-93. 10.1016/j.jcsr.2014.10.028

Rasmussen, K. J., & Hancock, G. J. (1992). Plate slenderness limits for high strength steel sections. *Journal of Constructional Steel Research, 23*(1-3), 73-96.

Shi, G., Gao, Y., & Wang, X. (2019). Material properties and partial factors for resistance of low yield point steels in China. *Construction and Building Materials, 209*, 295-305.

Shi, G., Wang, M., Wang, Y., & Wang, F. (2013). Cyclic Behavior of 460 MPa High Strength Structural Steel and Welded Connection under Earthquake Loading (Vol. 16, pp. 451-466).

Sun, F., Sun, M., Li, G., Xiao, Y., Wei, M., & Liu, L. (2014). Experimental study on seismic behavior of high-strength steel beam-to-column end-plate connections. *Journal of Building Structures, 35*(4), 116-124.

Sun, F. F., Xue, X. Y., Jin, H. J., Sun, M., Tang, Z. M., Xiao, Y., & Li, G. Q. (2019). Hysteretic behavior and simplified simulation method of high-strength steel end-plate connections under cyclic loading. *Journal of Constructional Steel Research, 158*, 429-442. 10.1016/j.jcsr.2019.03.014

Sun, F. F., Xue, X. Y., Xiao, Y., Le, Y. M., & Li, G. Q. (2018). Effect of welding and complex loads on the high-strength steel T-stub connection. *Journal of Constructional Steel Research, 150*, 76-86. 10.1016/j.jcsr.2018.08.002

Yang, H., Han, L.-H., & Wang, Y.-C. (2008). Effects of heating and loading histories on post-fire cooling behaviour of concrete-filled steel tubular columns. *Journal of Constructional Steel Research, 64*(5), 556-570.

Zhang, X.-Z., Zhao, M.-S., Chiew, S.-P., Lee, C.-K., & Fung, T.-C. (2016, 2016). *Influence of welding on the strength of high performance steels*, Barton, ACT.