The 2018 Structures Congress (Structures18)
Songdo Convensia, Incheon, Korea, August 27 - 31, 2018

Development of an innovative industrial building seismic system having vierendeel-inserted truss roof

Seon-Hu Kim[1)], *Cheol-Ho Lee[2)], and Sang-Hee Ha[3)]

[1), 2)] *Department of Architecture and Architectural Engineering, Seoul National University, Seoul 08826, Korea*
[3)] *Posco Engineering & Construction, Incheon 22009, Korea*
[2)] *cehole e@snu.ac.kr*

ABSTRACT

In this study, an innovative industrial seismic building system is proposed by inserting vierendeel segment into the middle of long-span truss roof and its seismic behavior and design method are investigated. In contrast to conventional industrial truss buildings which were shown to undergo undesirable column-hinging yield mechanism, the system is proposed to develop the yield mechanism through the plastic hinging at ends of the vierendeel beams and the upper column bases. Cyclic testing of vierendeel segments made of low yield point steel was also conducted in order to provide experimental data necessary for developing a rational design procedure per the capacity design concept. The effects of gravity loading-induced axial forces on flexural plastic hinging at the ends of the vierendeel girders may be significant and should be further investigated.

1. INTRODUCTION

After the 2016 Gyeongju and the 2017 Pohang damaging earthquakes, serious concerns have been raised about the seismic safety of major industrial plant facilities in the south-eastern part of the Korean peninsula (for example, Lee 2017 and Lee et al. 2018). Unfortunately, most of existing long-span, steel-trussed industrial buildings do not belong to any of standard seismic load resisting systems; they are undefined in current building seismic provisions such as KBC 2016 (AIK 2016) and AISC 341-16 (AISC 2016). So they have been often designed with a seismic response modification factor (R) of 3, just satisfying the basic strength and stiffness requirements for non-seismic buildings. Surely this approach is neither rational nor economical. Their actual behavior under strong ground motion remains unknown.

[1)] Graduate student
[2)] Professor
[3)] Assistant manager

In this study, nonlinear seismic behavior of a prototype roof-truss industrial building taken from steel mill plant construction is first investigated through nonlinear static (pushover) analysis. An innovative and ductile seismic framing concept called "vierendeel-truss system" is then proposed to overcome the shortcomings of current practice. Cyclic testing of vierendeel segments made of LYP (low yield point) steel is also conducted in order to provide experimental data that is necessary for developing a rational design procedure per the capacity design concept. Finally, on-going research on the effects of gravity loading-induced axial forces on flexural plastic hinging at the ends of the vierendeel girders is briefly discussed. .

2. SEISMIC BEHAVIOR OF CONVENTIONAL INDUSTRIAL BUILDING

As mentioned before, seismic performance of existing roof-trussed industrial buildings has been rarely investigated. In this study, a prototype frame was chosen from typical roof-trussed steel mill buildings and analyzed by pushover analysis. Fig. 1 illustrates the prototype structure chosen. For longitudinal direction, designers can select several "standard" seismic load resisting systems such as moment resisting frames or braced frames. The problem occurs in the transverse direction that should be spanned by roof truss. From the prototype, a transverse unit bay was extracted and laterally loaded in order to understand its nonlinear behavior first.

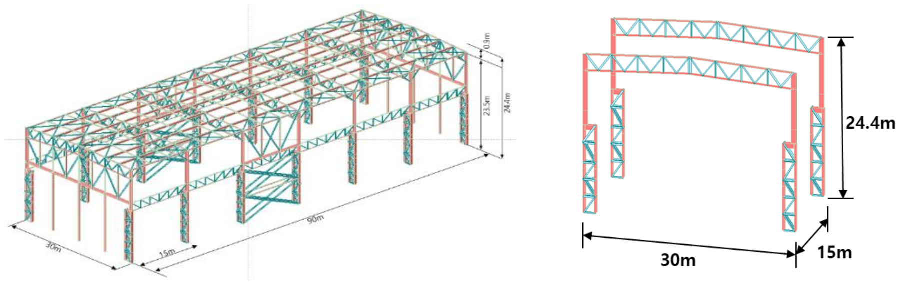


Fig. 1 Prototype of existing industrial building and its unit frame

In Fig. 1, typical structural elements of an industrial building can be seen. The main elements include the first-story (crane-supporting) column, the stepped upper column, and the roof truss (with a 1/10 slope in this particular case). The crane column is the first-story column which supports the crane and generally has a deep and heavy section to ensure strength and stability under the large axial force transferred from the crane. The upper column transfers the loads from the roof to the crane column and is often stepped because it is subjected to light loading. So preventing the crane column from severe seismic damage should be among the significant considerations in seismic design.

For pushover analysis, a commercial software ABAQUS (Simulia 2014) is used. Before applying static lateral load, the structure is first loaded by gravity loading including self-weight, imposed dead and live loads on roof, and crane loads as well. Under the presence of gravity loading, the lateral seismic loads with the first mode shape profile are applied with a lateral load ratio of 1:1.5 for the crane and roof level, respectively. Four-node shell elements (S4R in ABAQUS) are adopted. Following current design practice, the columns and the truss chords are modeled with the SM490 steel grade while the SS400 grade is used for the truss web elements. Nominal yield strengths of SM490 and SS400 are 315 MPa and 235 MPa, respectively. The original lattice crane columns are lumped into a single H section column with equivalent elastic stiffness and strength for analytical convenience.

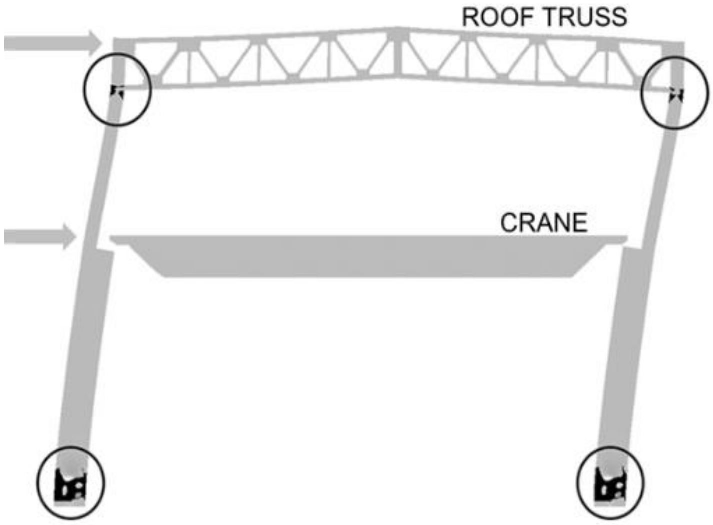


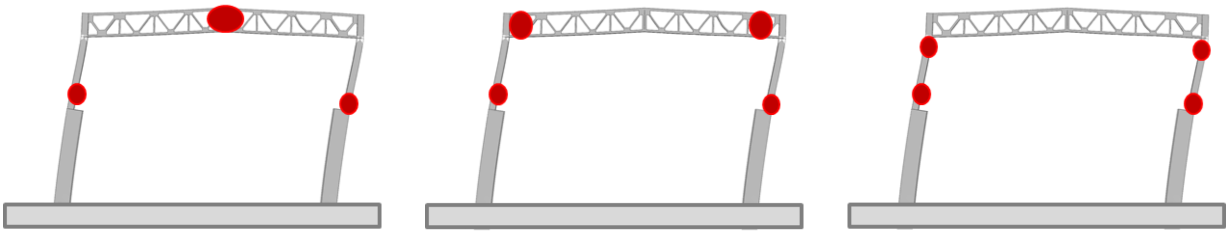
Fig. 2 Yield mechanism from pushover analysis of the prototype
(black region shows yielding)

Fig. 2 shows the yield mechanism of the prototype. The structure can resist the base shear close to its self-weight (95% of self-weight). However, it exhibits ~~an~~ undesirable yield mechanism with the plastic hinges formed at the top and bottom of the columns. This shear building-like failure mode is especially dangerous for the crane supporting columns. High gravity loading from the crane (the utilization ratio only under gravity loading is often said to be over 0.70) induces high axial loading into the crane column bases such that stable column hinging is improbable because of fatal P-Delta effect.
From the analysis, it is anticipated that conventional heavy-duty crane buildings may remain elastic under moderate-to-low earthquakes due to their high system overstrength. However, in the case of extreme events which drive them into inelastic range, the crane column hinging with greatly reduced ductility can cause fatal damage to the whole structure. This should be avoided for an improved system.

3. VIERENDEEL-TRUSS SEISMIC SYSTEM PROPOSED

In conventional truss-roof industrial buildings mentioned above, no ductile seismic behavior has been explicitly considered in their design process, and brittle behavior with column-hinging mechanism is anticipated. Thus, the main strategy in developing a seismically improved system should include changing the yield mechanism by providing a clear demarcation between yielding elements and elements remaining in the elastic range.

Alternatives for relocating plastic hinging are illustrated in Fig. 3. In all three alternatives, in order to protect the crane columns with high axial force, the hinges at the column base are shifted up to the bottom region of the upper columns. Protection of the crane column is also important in seismic performance point of view, as serviceability of such building is directly governed by normal crane operation. The first two alternatives place the energy dissipating elements at the centre or the ends of the roof truss. The last alternative with the upper column hinges appears not desirable as the first two with hinges at the truss. However, it may be a still possible solution since the axial force level is generally very low in the upper column. In this study, the first alternative is investigated.



(a) alternative 1 (b) alternative 2 (c) alternative 3

Fig. 3 Alternatives for yield mechanism

Fig. 4 shows the proposed vierendeel-truss system in which vierendeel panel is inserted into the middle of the roof truss. The frame should be designed such that the plastic hinges are formed at the ends of two vierendeel beams of I-shaped section and at the upper column bases. The vierendeel beams, which behave as energy dissipating elements, are analogous to the long link in the eccentrically braced frame (EBF), as they yield in flexure at their ends. For effective realization of the desired yield mechanism, lower-strength seismic steel should be used for energy-dissipating vierendeel beams while higher-strength steels should be used for the rest of the structure, or for the non-dissipative elastic elements. For the ease of field work, extended end plate bolted moment connection can be employed to connect vierendeel beams to outside truss members. The vierendeel-truss system proposed in this study is similar in concept to the special truss moment frame (STMF) in the US practice (AISC 2016). The section configuration, member requirements, and design equations seem somewhat unique in the current STMF design. The proposed system uses different member configuration and connecting schemes to provide more simpler construction and design procedure per the capacity design concept as will be discussed below.

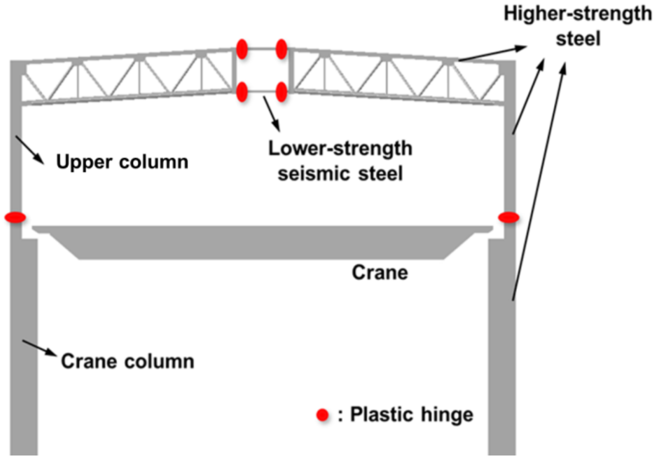


Fig. 4 Key concepts for vierendeel-truss system proposed

A three-step design procedure is proposed to achieve the intended behavior of the vierendeel-truss system in the below. The first step is to simply conduct conventional strength and stiffness (LRFD) design according to the load combinations specified in the applicable building code (for example, KBC 2016). When seismic loading is involved in the load combination, with the guaranteed ductile behavior, take the seismic response modification factor (R) as high as 6 or 7 for preliminary design purposes; the appropriateness of assumed R value would be checked in the final performance check stage.

Next, the capacity design concept is implemented to induce the intended yield mechanism. The local and lateral stability requirements for ductility should follow the provisions for special moment frames in KBC 2016 or AISC 341-16 Seismic Provisions (for example, Section 0714 in KBC 2016). Fig. 5 illustrates the key aspects of the capacity design procedure proposed. Probable shear forces and bending moments at the vierendeel hinges, together with gravity design loads, should be applied to a half structure. The shears and bending moments at the vierendeel ends should be calculated based on the expected material strength and cyclic strain-hardening experimentally found (see Section 4 below). Under this maximum snapshot loading condition, except for the upper column base, all the other parts are checked for whether they remain elastic. If some parts yield, the sections should be resized until when the yielding is eliminated. In Fig. 5, design strength between the upper column and the crane-supporting column was differently assigned in order to induce the upper column hinging earlier.

The last step includes performing pushover analysis of the designed structure in order to find the performance point corresponding to design seismic hazard. Since higher mode effect is expected slight in this type of frame, either the capacity spectrum method (CSM) or the displacement coefficient method (DCM) may provide satisfactory results. The detailed information like nonlinear hinge modelling and acceptance criteria may be referred to the standard documents such as ASCE 41-17 (ASCE 2017).

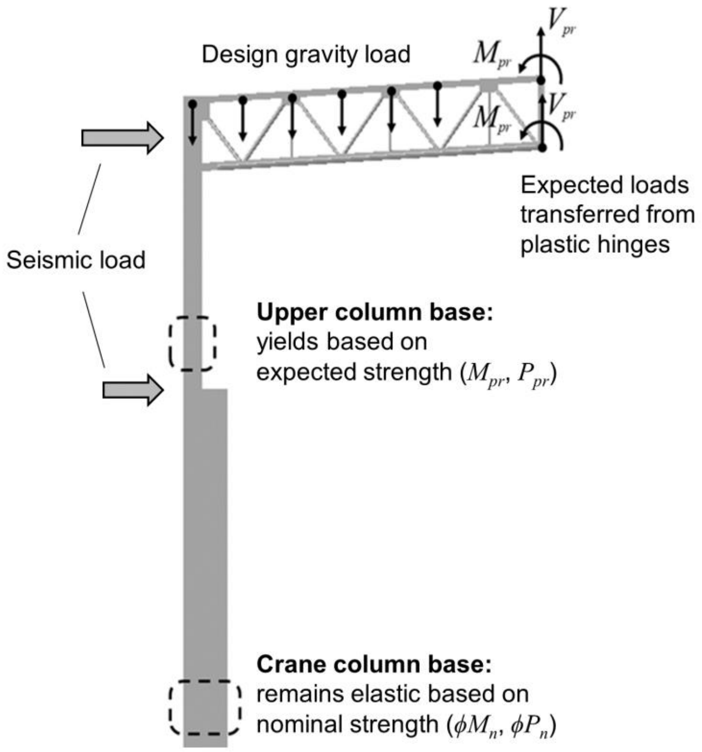


Fig. 5 Capacity design procedure illustrated

Fig. 6 shows the yield mechanism realized as intended in the proposed vierendeel-truss system.

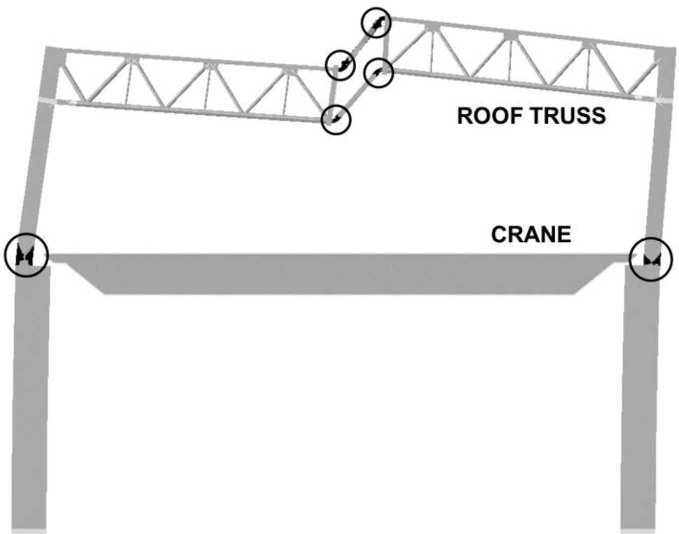


Fig. 6 Yield mechanism of proposed vierendeel-truss system
(black region shows yielding)

4. CYCLIC TESTING OF VIERENDEEL SPECIAL SEGMENT

Pilot tests were conducted in order to investigate the hysteretic behavior of energy-dissipating vierendeel segments made of low yield point (LYP) steel. In specimen design, the vierendeel beams were regarded as EBF long links. Long links, where bending moment governs the plastic behavior, have the shear span (length) ratio exceeding 2.6, according to the AISC Seismic Provisions (AISC 2016). The length ratio (e) is defined as Eq. (1):

$$e = \frac{LV_p}{M_p}, \tag{1}$$

where L, V_p, and M_p stand for link length, plastic shear strength, and plastic moment capacity, respectively. Table 1 shows the geometries and the length ratios of the test specimens. All three specimens were designed as long links with the length ratio of 2.92, 4.37, and 5.95.

Table 1 Geometries and length ratios of test specimens

Specimen	Beam section	Beam length (L, mm)	M_p (kN-m)	V_p (kN)	length ratio $e = LV_p / M_p$
D200-W150-L1500	H200×150×15×15	1500	89.18	260.1	4.37
D200-W100-L1500	H200×100×15×15	1500	65.60	260.1	5.95
D200-W150-L1000	H200×150×15×15	1000	89.18	260.1	2.92

LYP steel with a nominal yield strength of 160 MPa was used for energy dissipating vierendeel segments. The stress-strain relationships from the coupon tests are illustrated in Fig. 7. LYP steel has an excellent property for both ductile behavior and economic capacity design; it has low yield strength, narrow range of actual yield strength, low yield ratio, and large toughness.

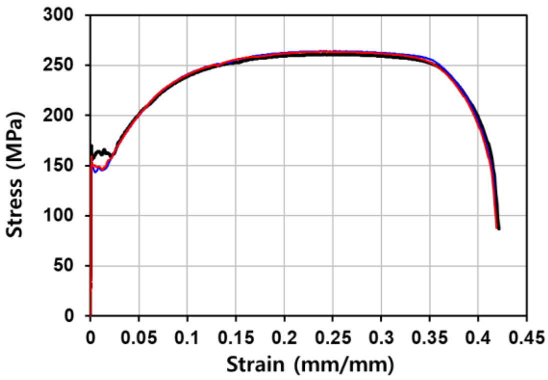
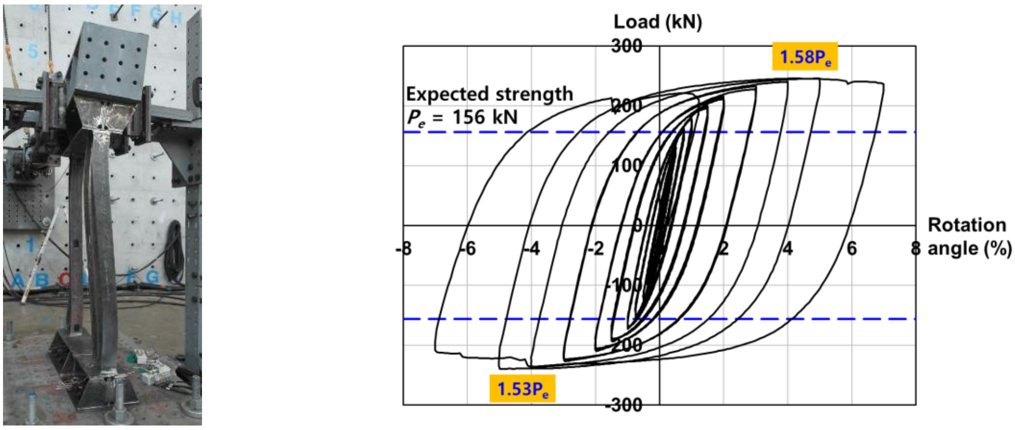


Fig. 7 Stress-strain curves from 160MPa LYP steel

A typical test setup is shown in Fig. 8. Cyclic lateral load was applied at the top of the specimen. Fig. 9 shows the specimen D200-W100-L1500 after testing and its hysteresis curve. The hysteresis curve shows that vierendeel hinges fabricated from

LYP steel can exhibit excellent cyclic performance. The plastic rotation angle achieved is as high as 5.92%, and the maximum strength exceeds 1.5 times the expected strength calculated based on the measured yield strength. The cyclic strain-hardening factor for the capacity design using 160 MPa LYP steel should be as high as 1.50; but material overstrength factor needs not to be applied since the yield point of this material is guaranteed within just 20 MPa variation.
Note that the maximum design plastic rotation capacity for EBF long links is 2% (AISC 2016), and typical overstrength ratios in the EBF long link database range around 1.2 or 1.3 (Okazaki et al. 2005). Fig. 10 shows the cyclic test result of the STMF by Basha and Goel (1995). Comparing Figs. 9(b) and 10, the vierendeel-truss system performs excellent inelastic behavior compared to the STMF.

Fig. 8 A typical test setup



(a) Deformed shape at end of test (b) Hysteresis curve

Fig. 9 Test result of specimen D200-W100-L1500

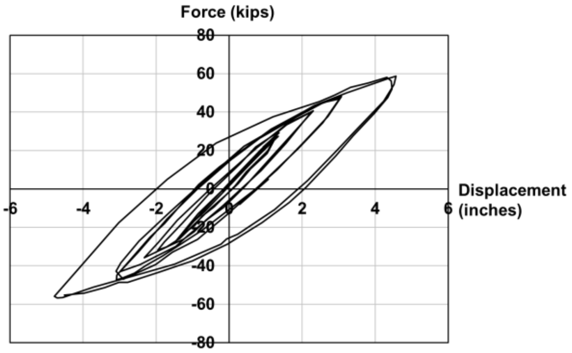


Fig. 10 Cyclic behavior of STMF (Basha and Goel 1995)

5. AXIAL FORCE EFFECT ON FLEXURAL HINGING

In this section, ongoing research efforts related to the vierendeel-truss system proposed is briefly discussed. For complete development of the system, robust details for the vierendeel beam to outside truss connections should be developed and appraised experimentally. Possible robust details for the beam ends include flare connection and reduced beam section (RBS). See Fig. 11. The vierendeel beams are recommended to be connected to truss part by using extended end plate moment connections for the ease of field work.

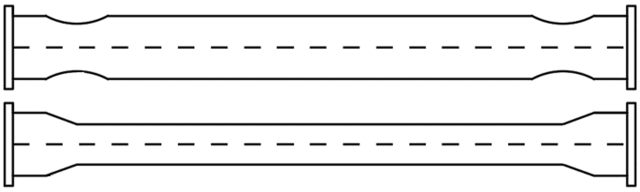


Fig. 11 Robust vierendeel beam end details: RBS (top) and flare connection (bottom)

Since the vierendeel beams are subjected to axial forces induced by roof gravity loads, the effect of these axial forces should be closely investigated. A recent study of Sim et al. (2017) revealed that not only compressive stress, but also tensile stress could affect the cyclic performance of moment hinges. From the preliminary analysis of the vierendeel-truss system (Fig. 6) the axial stress level induced by gravity loading was about 10%, compressive for the upper beam, and tensile for the lower beam. Compressive axial stress can accelerate local buckling of the flange, and tensile axial stress can cause premature fracture of the weld. To fully understand inelastic behavior of the vierendeel-truss system, the coupled response, as well as the individual responses, of the vierendeel beam pair under axial stresses should be thoroughly investigated.

5. CONCLUSIONS

In this study, an innovative seismic load resisting system for steel-trussed industrial buildings was proposed. In the proposed system, a vierendeel segment is inserted into the middle of the roof truss. Along with the system, a step-by-step design procedure was recommended as well. Main features and the design method of the proposed system are summarized below.

i) In contrast to conventional roof-trussed systems, which were shown to exhibit undesirable column-hinging yield mechanism, the proposed system develops a ductile yield mechanism with the plastic hinges at the ends of the vierendeel beams and the upper column bases.

ii) Especially inducing the column hinging into the upper column bases serves dual purposes; protection of the crane-supporting columns and avoidance of the column hinging at the location subjected to high axial force.

iii) The proposed design framework consists of three steps. The first step achieves the basic stiffness and strength requirements. In the second step, the capacity design is implemented to induce the proposed yield mechanism with ample ductility. Finally, pushover analysis is performed in order to find the performance point and check whether the seismic response is acceptable.

iv) Pilot cyclic testing of vierendeel segments made of 160 MPa LYP steel demonstrated excellent hysteretic behaviour with significant strain-hardening. The cyclic strain-hardening factor was observed to be as high as 1.50. The effects of gravity loading-induced axial forces on the inelastic behaviour of the vierendeel beams should be further investigated.

REFERENCES

AIK (Architectural Institute of Korea) (2016), "*Korean Building Code: Chapter 7 – Steel structures*".

AISC (American Institute of Steel Construction) (2016), "*ANSI/AISC 341-16: Seismic provisions for structural steel buildings*," Chicago, Illinois.

ASCE (American society of civil engineers) (2017), "*ASCE/SEI 41-17: Seismic evaluation and retrofit of existing buildings*," Reston, Virginia.

Basha, H.S. and Goel, S.C. (1995), "Special truss moment frames with Vierendeel middle panel," *Engineering structures*, **17**(5), 352-358.

Lee, C.H. (2017), "Analysis of damage potential of the 912 Gyeongju earthquake," *Proc. of the 19th Taiwan-Japan-Korea Joint Seminar on Earthquake Engineering for Building Structures* (*SEEBUS 2017*), 3-9, Seoul, Korea.

Lee, C.H., Kim, S.Y., Park, J.H., Kim, D.K., Kim, T.J., and Park, K.H. (2018), "Comparative analysis of structural damage potentials observed in the 9.12 Gyeongju and 11.15 Pohang earthquakes," *Journal of the Earthquake Engineering Society of Korea*, **22**(3), 175-184.

Okazaki, T., Arce, G., Ryu, H.C., and Engelhardt, M.D. (2005), "Experimental study of *Journal of Structural Engineering*, *ASEC*, **131**(10), 1526-1535.

Sim, H.B., Ballantyne, G., Chen, A., and Uang, C.M. (2017), "Effect of Beam Tension on Cyclic Performance of WUF-W Steel Moment Connection," *Journal of Structural Engineering*, *ASCE*, **143**(9), 04017102.

Simulia (2014). "*Abaqus 6.14: Abaqus/CAE user's guide*," Providence, RI.