Cyclic performance of flange-plate connection to box column with finger shaped plate

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1. Introduction

Built-up box columns are more efficient than wide flange columns in areas of high seismic risk because of two principal advantages; large bending and torsional stiffness and strength. The reliable approach to prevent the formation of plastic hinges near the face of I beam to the built-up box column connection is to strengthen the connection zone. This is due to the fact that the force transmitted by the beam flanges on the built-up box column is through the out of plane state; in which the force transfer mechanism in the system contains very low strength and stiffness. Among different methods of strengthening the connection zone [1,2], the indirect connections perform better than direct connections such as WUF-W connection [3] in which the beam section is directly connected to the column face when subjected to reversed cyclic loading. Since the separation between the beam section and the column in indirect connections reduces the stress demand on the CJP groove-welded joints, the indirect connections function as a structural fuse eliminates weld fractures at the joint [4–8]. The most popular approach of indirect connection for steel moment frames is the flange plate (FP) connection [9] that seems a less complicated and less costly design in comparison with the other different connections.

The design concept of FP connection is based on mitigating excessive force demand overload of beam flanges and local deformation in direct steel moment connections (in which beam connected to the column flange directly) by allowing the flange beam to yield freely; while the connection zone (the flange plates, panel zone and column flanges) remains elastic. In contrast to cover plate (CP) connection in which both cover plates and the beam flanges are welded to the column flange, in FP connection only the flange plates are welded to the column flange. Whereas in this study, the separation between the beam section and column face in the modified FP connection significantly reduces connection deformation constraints and eliminates any uncertainties such as brittle behavior which are intrinsic by the use of complete penetration groove weld in the connection to the box column.

The main point of using the FP connection is the length of the flange plates, which is generally chosen in such a way that it permits the placement of a sufficient length of the fillet weld in order to sustain at least the yield strength of the flange plates. The experimental study revealed that the flange plates cannot be made too long because of the buckling in compression before the beam develops its plastic moment capacity [3]. Moreover, using long flange plates increases the plastic rotation and plastic moments at the face of the column. This can result in a greater potential for fracture at the K-area region of the beam (Fig. 1), which was also proven by the experimental tests [10]. As shown in Fig. 1, plastic rotation in Specimen A with a longer flange plate is more than Specimen B. This increases the prospect of local buckling of the flange and web beam in the plastic hinge location that causes larger plastic strain and eventually it can result in greater potential of the fracture at
the K-area at the this location. To resolve this problem, the length of the top and the bottom plates was limited to one beam depth (d_b) since based on AISC requirements [11], the plastic hinge location in special moment frame (SMF) should be occurred in a distance of 1.0 d_b to 1.5 d_b away from the face of the column. As illustrated in Fig. 2, in this new connection configuration, the top flange plate has a finger shape, and it is welded to the beam flange by transverse along with longitudinal fillet welds. Moreover, in order to provide the required strength for the welds in the bottom flange plate, longitudinal fillet welds were used along with slot welds to share loads. The strength of all individual welds may be mathematically combined, when all the welds are on a single common plane [12].

In this study, two full-scale modified FP connection specimens were tested to prequalify the modified connection. In order to estimate the appropriate geometry of the finger-shaped top flange plate, an analytical parametric study was employed, and the best ratio of the longitudinal fillet weld to the transverse fillet weld was proposed based on this analytical exploration.

2. Experimental program

In the flange plate connection to the built-up box column, by considering the load path of different components as shown in Fig. 3, it was revealed that the shear force was transferred through the top plate, bottom plate and the shear plates acting as three parallel shear spring due to the same vertical displacement. The shear force distributed among the three connection elements was based on their stiffness ratios as follows:

\[
\frac{V_{\text{topl}}}{V_h} = \frac{K_{\text{topl}}}{K_{\text{topl}} + K_{\text{sh,pl}} + K_{\text{bpl}}} = \frac{E \left( \frac{b_{\text{topl}} t_{\text{topl}}^3}{I_{\text{topl}}} \right)}{E \left( \frac{b_{\text{topl}} t_{\text{topl}}^3}{I_{\text{topl}}} + 2 \frac{d_{\text{sh,pl}} t_{\text{sh,pl}}}{3 b_{\text{sh,pl}}} + \frac{b_{\text{bpl}} t_{\text{bpl}}^3}{I_{\text{bpl}}} \right)}
\]

Since the length of the flange plates considered as the beam depth (d_h), the thickness to length ratios of the flange plates are less than 0.1. According to the following equation, the shear force in flange plates can be neglected and the total force is to be carried out by the shear plates.

\[
L_{\text{topl}} = L_{\text{bpl}} = d_h
\]

\[
\frac{\tau_{\text{topl}}}{d_h} \frac{f_{\text{topl}}}{t_{\text{topl}}} \frac{1}{10} \frac{f_{\text{topl}}^2}{L t_{\text{topl}}} \frac{f_{\text{bpl}}^2}{L_{\text{bpl}}} \equiv 0.0
\]

\[
\frac{V_{\text{topl}}}{V_h} \frac{V_{\text{bpl}}}{V_h} \approx 0.0 \rightarrow V_{\text{sh,pl}} \frac{V_{\text{bpl}}}{V_h} = 1 - \frac{V_{\text{topl}} + V_{\text{bpl}}}{V_h} \approx 1.0 \rightarrow V_{\text{sh,pl}} = V_h
\]

Therefore, it can be concluded that the flange plates can be designed as an axial load element; while the shear plates carry the total shear force. In this study the flexural contribution of the shear plates was not considered and it was assumed that the plastic bending moment was divided between a tension and compression forces in the flange plates.

Given that the beam bending moment mobilizes the axial force in the flange plates, the design procedure can be divided into four parts: 1) calculating the connection design forces, 2) designing the connection in terms of the connection geometry, 3) detailing the top and bottom flange plates and their corresponding welds, and 4) sizing the connection panel zone and continuity plates. The plastic bending moment and the corresponding shear force developed in the beam section are:

\[
M_{\text{pl}} = C_{\mu} A_{\text{pl}} F_y
\]
Fig. 2. a) Plastic hinge location in SMF and b) geometrical specification of flange plates and shear plate.
Two criteria should be considered in design of the FP connection with the suggested modified configuration. First, as explained above, to locate the plastic hinge at the appropriate location according to AISC requirements, the length of the flange plates should be limited to one beam depth. Second, the length of the flange plates shall be determined based on the capacity of the fillet welds such that the yield forces could be developed in the flange plates. Third, in order to improve the welding performance as an additional criterion the width of the top flange plate should be slightly less than the width of the beam flange while the width of the bottom flange plate should be slightly more than the width of the beam flange (Fig. 2).

The experimental study revealed that the flange plates cannot be made too long because of the buckling in compression before the beam develops its plastic moment capacity [3]. Thus to minimize the length of the top flange plate and to provide more weld lines, the top flange plate is cut like a finger shape which provides more transverse as well as longitudinal fillet weld lines. In designing of the fillet welds, it was considered to deploy the maximum capacity of fillet weld strength along with $L_1$ by limiting the plate length to $d_b$ and the rest of the required strength of welding provided by fillet welds along with $L_2$ and $W$. The ratio of the strength of the longitudinal fillet welds to the total weld strength ($R_{11}/R_n$) with respect to $L_1$ (longitudinal fillet weld) and the ratio of $L_1$ to $L_2$ was illustrated in Fig. 4 to determine how much capacity will be contributed by the longitudinal fillet weld ($L_1$). Since the difference between the deformation capacities of the longitudinal and transverse fillet welds prevents the welding line from achieving their full strength simultaneously, AISC [12] permits combining these two patterns as the following:

$$R_n = \text{Max} \left\{ \frac{R_{11}}{0.85R_1 + 1.5R_t} \right\}$$

(9)

In designing of the bottom flange plate, it is required that the fillet weld terminate not less than the size of the weld from the edge because of carrying the weld out the full length of the joint increases the possibility of undercut and other weld quality problems [12]. Thus to limit the length of the bottom plate to one depth of the beam, the longitudinal fillet welds must be used with slot welding (Fig. 2).

A summary of the design steps of the test specimens is given in Table 1; and Fig. 5 illustrates the specifications and dimensions of the test specimens. To fabricate the experimental specimens, due to the difficulty of CJP welding of the continuity plates to the column, three sides of the continuity plates were welded by fillet welds and the welding of remaining side was made by CJP groove welds. In the process of groove welding of the top plate to the box column, the backing bar was attached to the plate by fillet weld and left in place after groove welding. As depicted in Fig. 5, the electrode E7018 (high toughness weld metal which has a minimum specified Charpy V-Notch toughness of 27 J at $-298 \, \text{C}$) was used for complete joint penetration (CJP) groove...
welding of the flange plates to the box column along with fillet welds and slot welds for joining the flange plates to the beam flanges. Moreover, for the protected zone (the portion of the beam between the face of the column and one beam depth, d, beyond the tip of the flange plates) additional reinforcing fillet welds was required.

The tests were conducted on exterior type specimens which consisted of one beam attached to a column as illustrated in Fig. 6. Specimens were subjected to the loading sequence proposed by the AISC seismic provisions for testing of beam-to-column moment connections [11]. Beam, column, the continuity plate and the shear plate were all ST37 steel (similar to A36 steel). Standard coupons were cut from the plates for each test specimen (FP1 and FP2) separately [13].

3. Experimental results
3.1. Global response

The experimental force versus story drift hysteresis diagrams (Fig. 7) indicate that the FP connection with the suggested modified configuration fulfills the AISC seismic provision requirements given for the special moment frames [11,14]. It should be noted that the strength degradation of the specimens was caused by the beam local and global buckling during the reversed cyclic loading and no fracture was observed in the plate at the end of the test.

3.2. Plastic hinge evaluation

Observation of whitewash flaking and the beam deformation (Fig. 8) revealed that yielding was typically concentrated in the region near the tip of the flange and the bottom flange plates. It can therefore be concluded that limiting the length of the flange plates to db eliminated any uncertainties in the k-area of the beam at the plastic hinge location and led to a ductile behavior during the reversed cyclic loading. Furthermore, using high toughness electrodes and re-welding the protected zone with reinforcing fillet welds played a very important role in the connection’s ductile performance.

The normalized measured axial strains at a distance from the column face along the centerline of the beam flange in the top and bottom flange plates were lower than the yield strain even at the 4% total story drift (Fig. 9); furthermore, the distribution of axial strain along the width of the top flange plates revealed that the maximum strain in the plates was lower than the yield strain. In the bottom flange plates, however, the stress concentration was more severe at the edges than stress concentration at the center of the plates, and the normalized strain was found to be between 1 and 3 at the plate edges. Since the thickness of the bottom plate was smaller than the top plate thickness, stress distribution through the thickness can result in the higher strain at the edges of the plate. The strain in the flange plates decreased at the larger drift angles because the beam flange local buckling along with the web local buckling led to a loss of strength and stiffness in the beam which eventually lowered the force and displacement demand on the flange plates.

4. Parametric study
4.1. Finite element model

The main objective of this analytical study was oriented toward the finger-shaped type of the top flange plate geometry. In order to study the effects of the fillet weld lines ratio, Lw/W, (Fig. 10) on the seismic
performance of the FP connection, two specimens with three different top flange plate geometries were used. In each category the weld lines \((L_z \text{ and } W)\) were determined in order to transfer the demand force from the beam to the top plate. For instance, the difference between SP1-TP1 specimen and SP1-TP2 specimen was only in the ratio of \(L_z/W\), whereas \(L_z/W\) in SP1-TP1 was 1.0 while this ratio increased to 1.8 in SP1-TP2. The geometrical properties of the analytical specimens (specimen SP1 and SP2) for the beam, column, top and bottom flange plate are presented in Table 2, which were used herein for the purpose of sensitivity study on the top flange plate. Moreover, as the groove welding process of the top plate to the column face is one of the main difficulties of using FP connections especially in thick plates, thus, in the next part of the parametric study, the top plate thickness \((t_{PL})\) was used as an independent parameter. In order to investigate the effects of top flange plate thickness in different connection geometries on the nonlinear behavior of the connection, the thickness varied in increments of 10% of the plate thickness.

The ABAQUS computer program [15] with 20 node quadratic brick elements (C3D20R), plasticity and large deformation capabilities was used in order to analyze the finite element models. The welded plates and the connection area were modeled with a finer mesh in order to get more accurate results. The plasticity model was based on the von Mises yield criterion; whereas in cyclic analyses, it was based on the kinematic hardening rule and a bilinear stress–strain relationship for all components. The fundamental assumptions made to idealize the mechanical properties of ST37 (A36) were as follows: Young’s modulus
Fig. 6. Test set up and instrumentation layout.

Fig. 7. Beam tip load versus the total story drifts and the normalized moment at the column face versus total inelastic rotation.
relationship was assumed and the mechanical behavior is depicted in Fig. 11.

4.2. Finite element result

To ensure the accuracy of the numerical models utilized in this study, a comparison of the experimental and analytical results for the two tested specimens (specimens FP1 and FP2) was performed. Fig. 12 shows that the analytical results are in a very good agreement with the experimental measurements. In addition, a maximum plastic equivalent strain (PEEQ) and von Mises stress at the end of loading (6% story drift) were revealed that the plastic hinge was occurred in the beam flanges precisely after the nose of the flange plates as expected (Fig. 12). Based on the work of Hancock and Mackenzie [17] distribution in the groove weld, joining the top flange plate to the column flange, at 1%, 4% and 6% story drift (Fig. 13), implied that the capacity of the modified configuration of the top flange plate as a reliable fuse can be effectively mobilized to avoid any brittle fracture in the welded connection at the face of the built-up box column.

The effect of the longitudinal fillet welds with respect to transverse fillet welds \( (L_2/W) \) on the local response of the connection was also investigated. The normalized longitudinal strain along the width of the top flange plate at the face of the column and along the width of the plate at the end of the curve portion of the top plate at 1%, 4% and 6% story drift is presented in Fig. 14. Moreover, the PEEQ distribution of the top plate is illustrated in Fig. 15. Studying the behavior of the modeled connections showed that by increasing the \( L_2/W \), the longitudinal strain on the width of the top flange plate at the face of the column remained near the yield strain whether the normalized strain along the width of the plate at the end of the curve portion of the plate increased significantly due to the stress concentration phenomenon. This can cause fracturing the weld if the fracture toughness of the weld metal is not sufficient. The stress concentration was more obvious when the \( L_2/W \) ratio was more than 4.0. Therefore, in order to get the best performance of the top flange plate with a finger shape, it is suggested that the ratio of the longitudinal fillet welds to the transverse fillet welds should be set as follows:

\[
L_2/W < 4
\]  

Moreover, in order to prevent the use of an excessively heavy reinforcement which may be detrimental to the connection, the local response of analytical specimens was investigated through the different top plate thicknesses with increment of 0.1 t_{fl.} As illustrated in Fig. 16, the normalized strain pattern along the width of the top plate at the face of the column revealed that the width of the top plate adjacent to the face of the column remained elastic at 0.9 t_{fl} thickness without any strength degradation. Full width yielding of the top plate width occurred in different \( L_2/W \) ratios when thickness was reduced to 0.8 t_{fl}. That demonstrates a contradiction to the philosophy of maintaining the plates of the FP connection in an elastic state in order to cause the plastic hinge to be formed in the beam. Similar behavior was observed at the end of the curve portion of the top plate (Fig. 17) due to the stress concentration in the region. As stated before, it is possible for a weld to fracture if the fracture toughness of the weld metal is low, especially when the thickness of the top plate is decreased to 0.8 t_{fl}. This difference was more distinct when \( L_2/W > 4 \).

The Rupture Index, as a parameter to evaluate the ductile fracture of the top plate, as indicated in Tables 3 and 4, depicted that the \( L_2/W \) ratio strongly influenced the top plate performance when its thickness was decreased. For instance, when the top plate thickness of SP1 with \( L_2/W = 1 \) decreased from 0.9 t_{fl} to 0.7 t_{fl}, the RI increased from 4 to 6.7; in SP2 with \( L_2/W = 7 \), the RI increased from 40.1 to 146.1. This was accompanied by an increase in the PEEQ Index from 0.25 to 0.47 (a 88% increase) in SP1 with \( L_2/W = 1 \), while in SP2 with \( L_2/W = 7 \),
the PEEQ Index increased from 3.34 to 7.42 (a 122% increase). Additionally, the comparison of the ratio of yielding area to total area of the top plate at 6% story drift, in different configurations, implied that allowable thickness reduction of the top plate without any strength degradation was significant with the $L_2/W$ ratio. The findings are summarized as follows:

\[ L_2/W < 2 \rightarrow \text{Allowable thickness} = 0.8t_{\text{tpl}} \] 
\[ 2 \leq L_2/W \leq 4 \rightarrow \text{Allowable thickness} = 0.9t_{\text{tpl}} \] 
\[ 4 < L_2/W \rightarrow \text{Allowable thickness} = 1.0t_{\text{tpl}} \] 

In order to investigate the efficiency of the top plate with different geometries, in transferring the flexural demand at the plastic hinge to the column face, the parameter $\Psi$ indicating plastic moment transition rate from the beam flange to the top plate is suggested as follows:

\[ \Psi = \frac{M_{\text{pe}}}{M_{\text{pl-H}}} \] 
\[ M_{\text{pl-H}} = \frac{L_0 - L_2}{L_0 - L_{\text{tpl}}} M_{\text{pe}} \]

For the $\Psi$ parameter in the connection, it is normally desirable to have the value of one. According to the experimental results obtained for the FP connection, the location of the plastic hinge occurred after the top plate length, so the $\Psi$ parameter was expected to reach 1.0. Tables 5 and 6 illustrate that, for the top plate of 0.9 $t_{\text{tpl}}$ thickness and with a $L_2/W$ ratio of less than 2.0, the parameter $\Psi$ remained near 1.0, which therefore implies that the plastic hinge formed in the beam flange after the end of the top plate as expected in the FP connection.

With all the parameters considered in the above example, the thickness of the top plate can be reduced to 0.9 $t_{\text{tpl}}$ without any design assumptions being violated. This reduction of the top plate assists in improving groove welding and reduces the potential of brittle fracture.

5. Conclusions

With plastic hinge forming in the beam at the tip of the flange plate, the length of the flange plates substantially increases the bending moment at the face of the column. Hence, in order to limit the length of the flange plates as well as to permit placement of a sufficient length of the fillet weld to develop at least the yield strength of the plate, the flange plate connection with modified configuration was proposed. To address the above issue, this study investigates the cyclic performance of the FP connections with modified configuration to

![Fig. 9. Axial strain along the length and the width of the top and bottom plates for a) FP1 and b) FP2 specimens at different story drifts.](image-url)
the built-up box column through the experimental as well as the analytical approaches.

In the new configuration, the length of the flange plates was restricted to the beam depth \(d_b\) in order to impose the plastic hinge at the distance of \(d_b\) to 1.5 \(d_b\) from the face of the column according to the AISC seismic provision requirements for a special moment frame. For this purpose, the top flange plate was fabricated in a finger slot shape; and welded to the top beam flange via the transverse as well as longitudinal fillet weld. The bottom flange plate was fabricated as a rectangular shape and slot welding was applied in addition to the longitudinal fillet welds in order to provide adequate strength for the welds. Based on this research study, key conclusions can be drawn; as follows:

1. Because of the low strength and stiffness of the shear plates compared to the connecting flange plates, shear forces are mainly transferred through the flange plates to the built-up box column. However, von Mises yielding criterion indicated that the flange plates could be designed as an axial load only element.

![Fig. 10. a) 3D finite element model of the modified FP connection. b) Top plate specifications in analytical models.](image-url)

### Table 2
Geometric specifications of the analytical specimens for parametric study on the modified FP connection (unit: mm).

<table>
<thead>
<tr>
<th>Analytical specimen</th>
<th>Beam No.</th>
<th>(d_c)</th>
<th>(t_c)</th>
<th>(t_{pl})</th>
<th>(f_{pl}) / (f_y)</th>
<th>(\sum M_{pl} / \sum M_{pb})</th>
<th>Top Pl. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1</td>
<td>PG1</td>
<td>330</td>
<td>20</td>
<td>37</td>
<td>0.5</td>
<td>1.13</td>
<td>TP1, TP2, TP3</td>
</tr>
<tr>
<td>SP2</td>
<td>PG2</td>
<td>460</td>
<td>25</td>
<td>43</td>
<td>0.5</td>
<td>1.08</td>
<td>TP4, TP5, TP6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam section property</th>
<th>Bottom Pl. specification</th>
<th>Shear Pl. specification</th>
<th>Top Pl. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG No.</td>
<td>(b_1)</td>
<td>(b_2)</td>
<td>(l_{pl})</td>
</tr>
<tr>
<td>PG1</td>
<td>380</td>
<td>250</td>
<td>15</td>
</tr>
<tr>
<td>PG2</td>
<td>540</td>
<td>300</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Top pl. No.</th>
<th>(b_1)</th>
<th>(b_2)</th>
<th>(L_{pl})</th>
<th>(l_{pl})</th>
<th>(L_1)</th>
<th>(L_2)</th>
<th>(W)</th>
<th>(R)</th>
<th>(L/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP1</td>
<td>270</td>
<td>200</td>
<td>380</td>
<td>30</td>
<td>270</td>
<td>70</td>
<td>70</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>TP2</td>
<td>270</td>
<td>200</td>
<td>380</td>
<td>30</td>
<td>270</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>1.8</td>
</tr>
<tr>
<td>TP3</td>
<td>270</td>
<td>200</td>
<td>380</td>
<td>30</td>
<td>270</td>
<td>90</td>
<td>50</td>
<td>50</td>
<td>3.7</td>
</tr>
<tr>
<td>TP4</td>
<td>370</td>
<td>270</td>
<td>540</td>
<td>40</td>
<td>410</td>
<td>210</td>
<td>100</td>
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</tr>
<tr>
<td>TP5</td>
<td>370</td>
<td>270</td>
<td>540</td>
<td>40</td>
<td>410</td>
<td>250</td>
<td>60</td>
<td>75</td>
<td>4.2</td>
</tr>
<tr>
<td>TP6</td>
<td>370</td>
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<td>540</td>
<td>40</td>
<td>410</td>
<td>270</td>
<td>40</td>
<td>95</td>
<td>6.8</td>
</tr>
</tbody>
</table>
2. Experimental specimens made of proposed flange plate connections with built-up box column subjected to cyclic loading met the criteria of being prequalified connection for the special moment frame. None of the experimental specimens failed in a brittle manner, and the strength of each specimen degraded slowly toward the end of the test loading cycles due to the local buckling of the beam web and beam flanges.

3. Experimental results revealed that the flange plate region of the connection adjacent to the column slightly yielded or did not yield at all as primarily intended in design. In both tested specimens because of the decrease in the plastic rotation demand, the local beam flange buckling did not cause a gradual tearing of the fillet welds. In conclusion, limiting the flange plate length, using high toughness weld metal and re-welding the protected zone with a reinforcing fillet welds played a very important role in ductility of the connection.

4. Studying the maximum Rupture Index in the groove weld joining the top flange plate to the column flange at the end of the test loading cycles indicated that the capacity of a finger-shaped top flange plate could be effectively mobilized while avoiding any brittle fracture in the welded connection at the face of the built-up box column.

5. In order to investigate the performance of the top flange plate with different geometries and the use of the combination of the transverse fillet welds (W) along with the longitudinal fillet welds (L2), the local and global response of the flange plate connection was studied through a parametric analytical study with different L2/W ratios. It was suggested that, to obtain the best performance of the flange plate connection and to prevent the connection from a potential brittle fracture, the L2/W ratio in the top flange plate should be kept less than 4.

6. Since the large groove weld needed for the thick plates may cause high shrinkage and restraint problems, nonlinear finite element analyses were conducted for further investigation on the various aspects of the reduction of top plate thickness. Theoretical results revealed that, for optimizing purposes, top plate thickness can be reduced by 10%.

Nomenclature

- A
  - \( A_g \): gross area of column
  - \( A_{pl} \): plate area
- b
  - \( b_1 \): width of the top plate at the face of the column
  - \( b_2 \): width of the top plate at the end of the top plate
  - \( b_{bp} \): bottom plate width
  - \( b_{cl} \): column flange width
  - \( b_f \): beam flange width
  - \( b_{pl} \): flange plate width
  - \( b_{sh.pl} \): shear plate width
  - \( b_{tpl} \): top plate width
- \( b_w \): horizontal length of fillet weld at shear plate
- C
  - \( C_p \): compressive force
  - \( C_{pl.H} \): factor to account for peak connection strength
  - \( C_{pl.R} \): plastic moment transition rate
- \( D \): size of the fillet weld
- \( \Delta_{pl} \): Plastic displacement of the tip of the beam
  - \( d_b \): beam depth
  - \( d_c \): column depth
  - \( d_{sh.pl} \): shear plate depth
  - \( d_w \): vertical length of fillet weld at shear plate
- \( d_{zl} \): panel zone depth between continuity plates
- E
  - \( E_{pl} \): modulus of elasticity
  - \( f_a \): axial stress
  - \( f_c \): shear stress
  - \( f_{ec} \): shear capacity in panel zone
  - \( f_p \): yield strength of the member
  - \( f_{pl} \): specified minimum yield stress of column
  - \( f_{pl.c} \): polar moment of inertia of fillet welds at shear plate
  - \( K_{bpl} \): shear stiffness of the bottom plate
  - \( K_{sh.pl} \): shear stiffness of the shear plate
  - \( K_{tpl} \): shear stiffness of the top plate
- \( L_{1 \& 2} \): length of the fillet weld
  - \( L_{1pl} \): theoretical distance between plastic hinge location and column face
  - \( L_{2pl} \): bottom plate width
  - \( L_{3pl} \): distance between plastic hinge locations in the beam
  - \( L_{4pl} \): length of the slot weld
  - \( L_{5pl} \): top plate length
  - \( L_{6pl} \): fillet weld length
  - \( M_{av} \): additional moment due to shear amplification from the plastic hinge location to the column centerline
  - \( M_{CS} \): maximum moment at the face of the column
  - \( M_{gravity} \): beam moment resulting from gravity loads
  - \( M_{pl} \): plastic moment of the beam
  - \( M_{pl.H} \): plastic moment in plate
  - \( M_{pl.R} \): moment at plastic hinge location
  - \( P_{e} \): force at the tip of the beam
  - \( P_{e.r} \): required compressive strength using ASD load combinations
  - \( P_{eq} \): plastic equivalent strain
  - \( R \): radius of the top plate as a finger-shaped
  - \( \chi_{pl} \): plastic moment transition rate

Fig. 11. Assumed bilinear stress–strain relationship for a welding material in finite element models.
Fig. 12. Verification of the experimental tests and the contour of the PEEQ and von Mises stress for FP1 and FP2 specimens.

$R_l$, strength of the longitudinally loaded fillet welds in the top plate
$R_{lw}$, strength of the longitudinally loaded fillet welds in the bottom plate
$R_n$, strength of the combination of longitudinally and transversely loaded fillet welds
$R_s$, radius of slot weld
$R_{sw}$, total strength of the slot welding
$R_t$, strength of the transversely loaded fillet welds in the top plate
$S_t$, distance between two slot welds
$T$, tensile force
$f_{bpl}$, bottom plate thickness
$f_c$, column flange thickness
$f_{cpl}$, continuity plate thickness
$f_f$, beam flange thickness
$f_{fpl}$, flange plate thickness
$f_{pzt}$, panel zone thickness
$f_{sh.pl}$, thickness of shear plate
$t_{sh.pl}$, torsion result in shear force at shear plate
$f_{tpl}$, top plate thickness
$f_w$, web beam thickness
$\tau_{pz}$, shear stress of the panel zone
$\theta_p$, plastic rotation of the beam
shear force at the plastic hinge location
beam shear force resulting from gravity loads
shear force of the panel zone
shear capacity of shear plate
length of the transverse fillet weld
width of the slot weld
width of panel zone between column flange
central point of fillet weld at shear plate
beam plastic modulus
column plastic modulus

References


Fig. 13. Rupture index along the top plate width for FP1 and FP2 specimens at different story drifts.

Fig. 14. Normalized strain along the top plate width at the face of the column and at the end of the curve for SP1 and SP2.
Fig. 15. PEEQ distribution in top plates at 0.06 total story drift.
Fig. 16. Normalized strain along the top plate width at the face of the column for different top plate thicknesses.
Fig. 17. Normalized strain along the top plate width at the end of the curve portion for different top plate thicknesses.
Table 3
Effect of different top plate thicknesses on RI and yielding ratio in SP1 specimens (unit: MPa).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Geometry</th>
<th>PEEQ</th>
<th>Mises stress</th>
<th>Hydrostatic stress</th>
<th>RI</th>
<th>$A_{pfr}/A_{ppl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp1 (1.0 t_{pl})</td>
<td>L_2/W = 1.0</td>
<td>0.19</td>
<td>271.9</td>
<td>107.7</td>
<td>3.0</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>L_2/W = 1.8</td>
<td>0.25</td>
<td>276.5</td>
<td>133.7</td>
<td>4.7</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>L_2/W = 3.7</td>
<td>0.59</td>
<td>278.1</td>
<td>192.3</td>
<td>14.5</td>
<td>0.09</td>
</tr>
<tr>
<td>Sp1 (0.9 t_{pl})</td>
<td>L_2/W = 1.0</td>
<td>0.25</td>
<td>274.1</td>
<td>108.3</td>
<td>4.0</td>
<td>0.05</td>
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<tr>
<td></td>
<td>L_2/W = 1.8</td>
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<td>132.1</td>
<td>6.5</td>
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<td>L_2/W = 3.7</td>
<td>0.94</td>
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<td>198.2</td>
<td>23.7</td>
<td>0.11</td>
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<tr>
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<td>L_2/W = 1.0</td>
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<td>276.0</td>
<td>106.2</td>
<td>5.4</td>
<td>0.13</td>
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<td>L_2/W = 1.8</td>
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<td>132.6</td>
<td>9.9</td>
<td>0.15</td>
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<td>L_2/W = 3.7</td>
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<td>293.4</td>
<td>142.7</td>
<td>27.7</td>
<td>0.53</td>
</tr>
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<td>Sp1 (0.7 t_{pl})</td>
<td>L_2/W = 1.0</td>
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<td>303.1</td>
<td>99.2</td>
<td>6.7</td>
<td>0.28</td>
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<tr>
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<td>L_2/W = 1.8</td>
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<td>319.7</td>
<td>147.0</td>
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Table 4
Effect of different top plate thicknesses on RI and yielding ratio in SP2 specimens (unit: MPa).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Geometry</th>
<th>PEEQ</th>
<th>Mises stress</th>
<th>Hydrostatic stress</th>
<th>RI</th>
<th>$A_{pfr}/A_{ppl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp2 (1.0 t_{pl})</td>
<td>L_2/W = 2.1</td>
<td>0.29</td>
<td>276.9</td>
<td>117.6</td>
<td>4.8</td>
<td>0.09</td>
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<tr>
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<td>L_2/W = 4.2</td>
<td>1.10</td>
<td>165.1</td>
<td>65.1</td>
<td>17.4</td>
<td>0.11</td>
</tr>
<tr>
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<td>L_2/W = 6.8</td>
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<td>293.2</td>
<td>73.1</td>
<td>35.3</td>
<td>0.45</td>
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<td>L_2/W = 2.1</td>
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<td>129.5</td>
<td>5.4</td>
<td>0.09</td>
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<td>L_2/W = 4.2</td>
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<td>132.5</td>
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<td>231.3</td>
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Table 5
Effect of different top plate thicknesses on parameter $\Psi$ in SP1 specimens (unit: mm).

<table>
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<th>Specimen</th>
<th>Geometry</th>
<th>$l_b$</th>
<th>$l_{pfr}$</th>
<th>$l_{ppl}$</th>
<th>$\Psi$</th>
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</thead>
<tbody>
<tr>
<td>Sp1 (1.0 t_{pl})</td>
<td>L_2/W = 1.0</td>
<td>2500</td>
<td>380</td>
<td>370</td>
<td>1.00</td>
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<tr>
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<td>L_2/W = 1.8</td>
<td>2500</td>
<td>380</td>
<td>321</td>
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<tr>
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<td>L_2/W = 3.7</td>
<td>2500</td>
<td>380</td>
<td>263</td>
<td>0.95</td>
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<tr>
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<td>2500</td>
<td>380</td>
<td>355</td>
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</tr>
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<td>380</td>
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<td>2500</td>
<td>380</td>
<td>355</td>
<td>0.99</td>
</tr>
<tr>
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<td>L_2/W = 1.8</td>
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<td>380</td>
<td>295</td>
<td>0.96</td>
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<td>2500</td>
<td>380</td>
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<td>L_2/W = 1.0</td>
<td>2500</td>
<td>380</td>
<td>355</td>
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<td>2500</td>
<td>380</td>
<td>241</td>
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Table 6
Effect of different top plate thicknesses on parameter $\Psi$ in SP2 specimens (unit: mm).

<table>
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<th>Specimen</th>
<th>Geometry</th>
<th>$l_b$</th>
<th>$l_{pfr}$</th>
<th>$l_{ppl}$</th>
<th>$\Psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp2 (1.0 t_{pl})</td>
<td>L_2/W = 2.1</td>
<td>2500</td>
<td>540</td>
<td>488</td>
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<tr>
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<td>2500</td>
<td>540</td>
<td>401</td>
<td>0.93</td>
</tr>
<tr>
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<td>L_2/W = 6.8</td>
<td>2500</td>
<td>540</td>
<td>127</td>
<td>0.83</td>
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<tr>
<td>Sp2 (0.9 t_{pl})</td>
<td>L_2/W = 2.1</td>
<td>2500</td>
<td>540</td>
<td>488</td>
<td>0.97</td>
</tr>
<tr>
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<td>L_2/W = 4.2</td>
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<td>540</td>
<td>401</td>
<td>0.93</td>
</tr>
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<td>L_2/W = 2.1</td>
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<td>476</td>
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<td>540</td>
<td>107</td>
<td>0.82</td>
</tr>
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<td>2500</td>
<td>540</td>
<td>463</td>
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<tr>
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<tr>
<td></td>
<td>L_2/W = 6.8</td>
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<td>540</td>
<td>107</td>
<td>0.82</td>
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</table>