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MODELING AND BEHAVIOR OF RIVETED STIFFENED SEAT ANGLE CONNECTIONS

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ABSTRACT

Riveted stiffened seat angle connections have been used in the beam-to-column joints of many old steel buildings. Generally, moment resistance of these connections, categorized as flexible, is ignored for design purposes, and therefore conservatively left un-quantified. A concern exists as to the adequacy of the lateral-load resistance and performance of existing steel frames built with these connections, particularly when subjected to earthquake excitations which can cause these connections to undergo severe inelastic excursions. This study involves experimental and analytical studies on the behavior as well as ultimate capacity of two different configurations of riveted stiffened seat angle connections. Large inelastic hysteretic curves as well as actual moment resistance of theses connections were experimentally obtained. Possible failure mechanisms were identified and physical model of the connection components were established. The moment capacities according to the developed model as well as those obtained from the experiments are presented. It is concluded that riveted stiffened seat angle connections can actually develop considerable amount of moment capacity and ductility which need not be ignored in the structural resistance evaluation of their frames subjected to lateral loads. The analytical results, using the models developed in this study, agree well with the experimental measurements.

KEYWORDS

Riveted connections; hysteretic curves; cyclic testing; seismic retrofit, selective welding, failure mechanism, top angles, stiffener angles, seated connections.

INTRODUCTION

Riveted stiffened seat angle connections, commonly used as rigid connections in old steel frames, have been categorized as flexible connections by practicing engineers for many decades now. Although such connections, are no longer desirable in today's moment resisting steel frame connections in seismic regions, there exists many old buildings originally built using this type of connections, and whose seismic survival is essential. Engineers, when required to assess the seismic resistance of such buildings would typically ignore the lateral resistance of frames having this type of connection, which translates into a greater perception of seismic vulnerability, and could eventually lead to the demolition or the need to perform major seismic retrofit for many steel buildings.

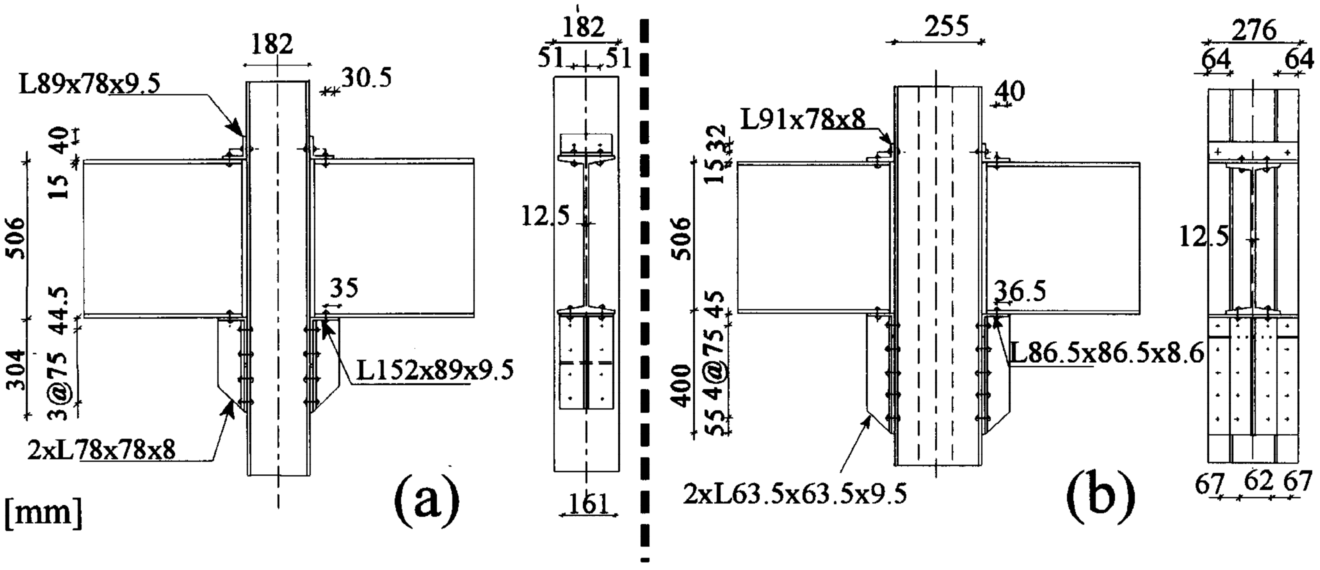

Fig. 1. Detail of riveted stiffened seat angle connections:
(a) Single Column detail; (b) Built-up column detail

This paper first reviews the full scale testing of existing riveted stiffened seat angle connections obtained from an existing building to establish the potential resistance of these connections. Then, analytical models of the observed behavior and ultimate moment resistance are proposed along with a newly developed physical model to predict the moment capacity of riveted stiffened seat angle connection to built-up column sections.

REVIEW

Only a few tests of riveted semi-rigid connections were found in the existing literature. Early investigations of these riveted connections to determine their rigidity started with a series of monotonic tests conducted by Moore and Wilson (1917) and later by Rathbun (1935), and Young and Jackson (1934). In that latter case, reversed loading was applied, to a limited level, on typical wind resisting connections to assess their rigidity when subjected to wind loads. Behavior and modelling of angles in semi-rigid connections was first studied by Lewitt et al. (1966). A recent study by Roeder et al. (1994) reported the result of investigations on the inelastic cyclic behavior of some selected types of bolted and riveted connections built using new materials to simulate old ones. Some findings of this recent study regarding hysteretic behavior agree with those of Sarraf and Bruneau (1996). However, the specimens studied by Sarraf and Bruneau, extracted from an old building, were significantly different from those of Roeder et al. Moreover, Sarraf and Bruneau quantified and explained the role of stiffener angles in the behavior of connection as well as their contribution to the moment resistance.

EXPERIMENTAL PROCEDURE

A limited number of specimens were obtained from the Daly Building (constructed in 1910 on the corner of Rideau and Sussex streets in downtown Ottawa and demolished in 1992), providing a unique opportunity for the experimental part of this investigation. Two specimens, in good condition, not rusted, and of slightly different joint configurations were obtained. Their details are shown in Fig. 1. To improve the hysteretic behavior of riveted stiffened seat angle connections, the connections used for the built-up shape column joints were retrofitted according to selective welding approach as proposed by Sarraf and Bruneau (1994).

Tension test on steel coupons, in accordance with ASTM E8, indicated that the specimens are of a mild steel, with average yield point, F_y, of 225 MPa, and average tensile strength, F_u, of 400 MPa. Also, the tension test of typical rivet used in these connections gave yield and tensile strengths of 258 MPa

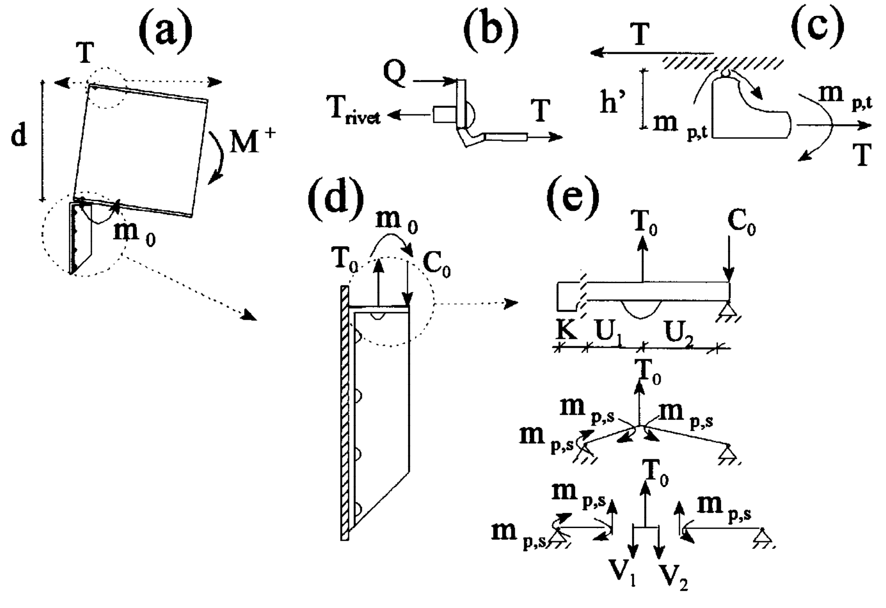

Fig. 2. Plastic failure mechanism and partial free-body diagram of:
(a) Full connection under positive moment; (b) Top angle connection;
(c) Top angle Fillet; (d) Seat connection and (e) seat angle leg.

483 MPa, respectively. This indicates that the rivets present in the acquired specimens are comparable to ASTM A502 grade 1 rivets.

Test Observations and Hysteretic Response of Existing Connections

The evolution of this hysteretic behavior is explained in details elsewhere (Sarraf and Bruneau 1994). The M-θ hysteretic curves of the tested connections were found to be highly pinched. According to the experimental observations, slippage at rivet holes, rocking of top angles and lack of integrity of stiffened seat connection caused such behavior. Significant yielding of the connections subjected to positive moment was observed at $M^+ = 55$ kN.m Tensile yielding of the rivets connecting the vertical leg of the top angles was detected by special custom-made clip-gages at $M^+ = 65$ kN·m. Similarly, tensile yielding of the first row of rivets under the seat angles was detected when $M^- = -95$ kN·m. The connection failure occurred due to shear failure of a rivet in the seat angle when maximum negative moment (M^-_{max}) reached -139 kN.m.

PHYSICAL MODELS - EXISTING CONNECTIONS

Two different models have been developed and will be explained in the following sections, as significant dissimilarity in connection behavior under positive and negative moments exists.

Positive Moment Capacity

The proposed physical model is shown in Fig. 2. This model assumes a rigid body rotation of the beam about a point located at the tip of the stiffened seat angle. In this model both the top angle and seat angle resistance mechanism contribute to the connection's total moment resistance, *M*, the former having a dominant effect under positive flexure. As the edge of a rivet head is very close to (or overlaps) the toe of the fillet in the vertical leg (as is the case here) only one plastic hinge can develop in the vertical leg and the second plastic hinge required to form a plastic mechanism develops at the toe of the fillet of the horizontal leg of the angle (Fig. 2b). To obtain the contribution of the top angle connection to moment resistance, the total resisting shear, *T*, needed to develop the plastic hinge mechanism of the top angle shown in Fig. 2c is given by:

$$T = \frac{2\, m_{p,t}}{h'} = \frac{2\left(\frac{L t^2}{4} F_y\right)}{h'} = \frac{L t^2 F_y}{2 h'} \qquad \textbf{(1)}$$

where $m_{p,t}$ is the plastic moment capacity of leg of the top angle, h' is the vertical distance between the plastic hinges in the top angle (edge of rivets head to mid-thickness of horizontal leg), and L and t are respectively the length and thickness of this angle. Also, the seat angle moment resistance, m_0, expressed as a function of tensile force, T_0 (as shown in Fig. 2d), is:

$$m_0 = T_0 \cdot U_1 \qquad \mathit{when,} \qquad T_0 = Min\,(V_1 + V_2\,,\; n A_b\, F_{y,r}) \qquad \textbf{(2)}$$

where A_b is the rivet section area, $F_{y,r}$ is the rivet yield stress, n number of rivets. V_1 and V_2 are: $2\, m_{p,s}/U_1$ and $m_{p,s}/U_2$ respectively, in which $m_{p,s}$ is the plastic moment of the seat angle, U_1 and U_2 are the distances shown in Fig. 2e.

Finally, the total positive moment resistance, which includes the contribution from both the top and seat angle can be determined from the following equation.

$$M^+ = T \cdot d + m_{p,t} + m_0 \qquad \textbf{(3)}$$

in which d is the depth of the beam, and all other parameters have been already defined. Numerically, for the connection specimen tested, L = 161 mm, t = 9.5 mm, F_y = 225 MPa, d = 0.507 m, h' = 17.37 mm, U_1 = 31.8 mm, U_2 = 35 mm, A_b = 334.2 mm^2, $F_{y,r}$= 258 MPa and a maximum positive moment resistance, M^+ of 51 kN·m is obtained. This compares well with the value of 55 kN.m observed experimentally by a change in slope of the M-θ curve. It is noteworthy that the contribution of the terms $m_{p,t}$ and m_0 in Eq.3 are rather small compared to the term $T \cdot d$.

Negative Moment Capacity

Some preliminary analyses were conducted to understand the extent of contribution to the resistance and role of each component of the seat connection in the global failure mechanism. Results of such analyses showed that the maximum moment in this equivalent beam occurs at the level of the second row of rivets, and that the two rivets in the first row under the seat angle are likely to reached their tensile yield capacity under the magnitude of ultimate loading expected in this case. This led to development of the plastic failure mechanism model of the stiffener angles shown in Fig. 3 which involves formation of plastic hinge in the stiffener angles and tensile yielding of the two first rivets. This model was also verified by experimental observations.

To find the total failure load using this plastic mechanism, the contribution to shear resistance from the stiffener, *F*, is first determined by static equilibrium to be:

$$F = \frac{m_{p,st} + 2\, A_b\, F_{y,r} \cdot l_2}{l_1 + l_2} \qquad \textbf{(4)}$$

where $m_{p,st}$ is the plastic moment of the stiffener angles, l_1 and l_2 are geometric dimensions shown in Fig. 3 , $F_{y,r}$ is the yield stress of the rivet steel, and A_b is the section area of one rivet. The distance, l_1 must be measured from the centerline of the first row of rivets to the end of the stiffener immediately underneath the seat. An additional force, *V*, needed to develop the plastic hinge mechanism in the seat

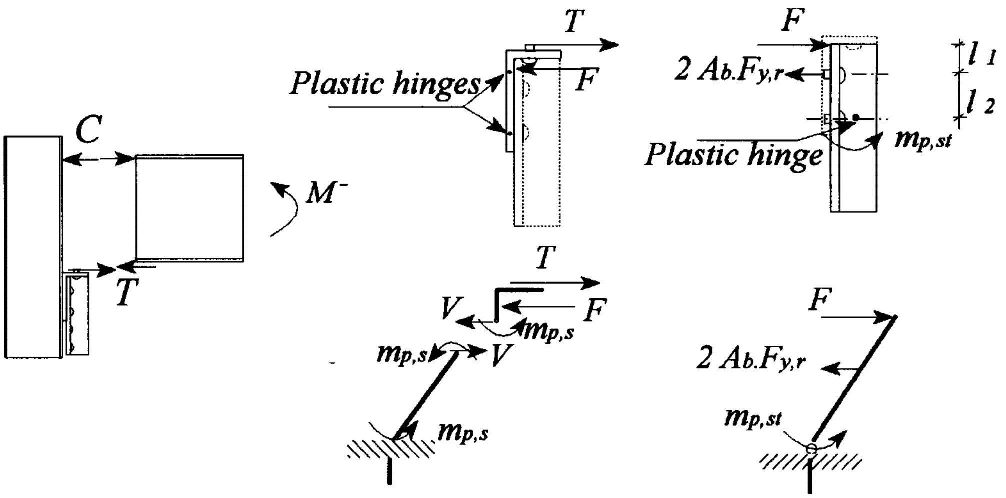

Fig. 3. Ultimate limit state model for prediction of negative moment capacity

angle, also contributes to the total resistance and can be simply determined by:

$$V = \frac{2\,m_{p,s}}{l_2} \tag{5}$$

where $m_{p,s}$ is the plastic moment capacity of the seat angle and l_2 is defined in Fig. 3. Using the depth of the beam, d, as a lever arm, the resulting total negative moment resistance is:

$$M^- = (F+V)\cdot d = \left(\frac{m_{p,st} + 2A_b\,F_{y,r}\cdot l_2}{l_1 + l_2} + \frac{2m_{p,s}}{l_2} \right)\cdot d \tag{6}$$

For the tested existing connections, l_1 = 35.5 mm, l_2 = 75 mm, d = 0.507; $2\,A_b \times F_{y,r}$ = 172 kN·m, and, $m_{p,st}$ = 0.607 kN·m, which give a maximum negative moment resistance, M^-, of 109.7 kN·m. This compares well with the approximate value of 100 kN.m observed experimentally.

TEST OBSERVATIONS OF RETROFITTED CONNECTIONS

The onset of yielding of the connection subjected to the positive moment was observed at M= 43 kN·m and negative yielding rotation occurred at flexural moment of -70.8 kN·m. When moment reached 60.5 kN·m, fairly large deformations of the angle legs were observed near the heads of the high strength bolts and adjacent to the fillet of the top angles as a sign of development of a plastic hinge mechanism. By the time moment reached -116 kN·m formation of a plastic hinge mechanism in the stiffener angles, in addition to their limited local buckling, occurred near the level of the second row of the rivets under the seats; the onset of this yielding occurred at about -110 kN·m, detected by strain gages located on the legs of the stiffener angles at the level of the second row of rivets. The connection experienced maximum positive moment of 74 kN·m and maximum negative moment, M^-_{max}, of -136 kN.m. The experiment ended after 10 cycles when the applied moments caused relatively large inelastic deformations in the seat angles as well as formation of plastic hinges and buckling of the stiffener angles.

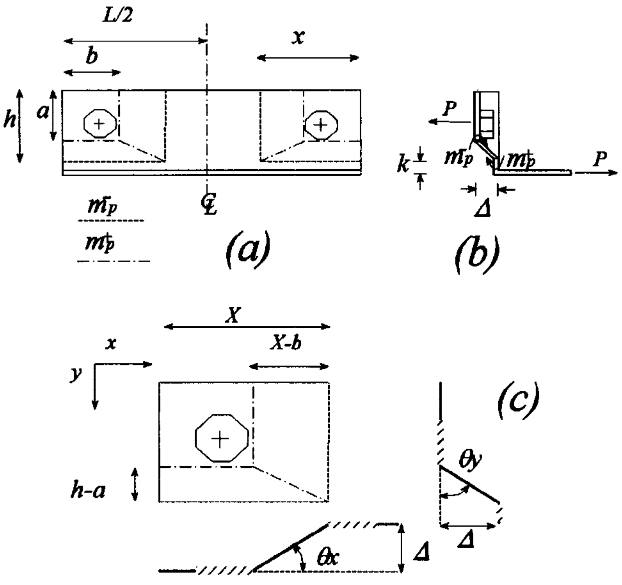

Fig. 4. Plastic yield mechanism of the top angle, (a) Proposed yield line pattern, (b) Virtual displacement and external load P, (c) Definition for angles of rotations, θ_x, and θ_y.

PHYSICAL MODELS - RETROFITTED CONNECTIONS

Plastic Mechanism of Wide Top Angle - Positive Moment Capacity

Kishi and Chen's (1990) assumption that the plastic hinge mechanism of the top angle consists of two straight lines across its vertical leg is not applicable and unconservative in this case. An improved yield-line pattern in the top angle is proposed, and illustrated in Fig. 4. It is consistent with, and a simplification of experimental observations. The definition of some geometric parameters are shown in Fig. 4a. To find the maximum load, *P,* that can be applied to the top angle, a virtual displacement, *Δ,* is assumed as shown in Fig. 4b. Using the principal of virtual work, the upper bound theorem of plastic theory (Horne and Morris 1981), and the yield lines defined in Fig. 4c, the load *P* becomes:

$$P = t^2 . F_y \left(\frac{h}{(x-b)} + \frac{x}{(h-a)} \right) \tag{7}$$

Where *h,* is the height of the angle leg less the size of the angle fillet, *a* and *b*, are the size of the assumed rigid rectangle, *t* is the thickness of the angle leg and F_y is the yield stress of the steel, and *x* is the length of the affected region. The unknown, *x*, which will give the minimum plastic yield capacity, can be obtained by minimizing Eq. 7 with respect to *x*. Doing so gives:

$$x = b + \sqrt{h^2 + h \cdot a} \quad when \quad x \le L/2 \tag{8}$$

where *L* is the length of the angle. The capacity of the top angle based on the above model can then be used to predict the positive moment capacity of the connection.

Combining the above result with the analytical method presented earlier, the positive moment capacity, M^+, For the tested connection which was retrofitted by selective welding, $d = 0.506$ m, $L = 276$ mm, $h = 59$ mm, $a = 45$ mm, $b = 58$ mm, $t = 8$ mm, $F_y = 225$ MPa, which gives $P = 118$ kN. The positive moment yield capacity is simply obtained by multiplying this load, *P*, by the depth of the beam, *d,* such that $M^+ = P \cdot d = 60.2$ kN·m (v.s 60.5 kN.m, obtained experimentally)

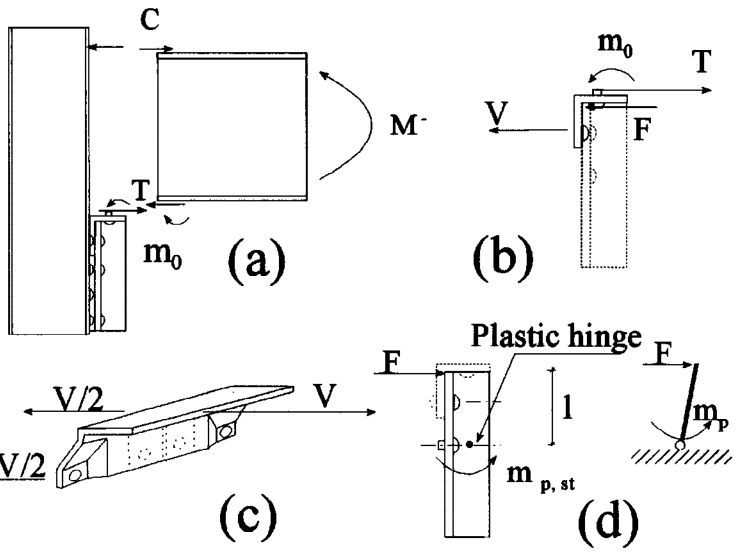

Fig. 5. Analytical model of the beam end under ultimate negative moment, (a) Free-body diagram of the beam end under ultimate negative moment; (b) Free-body diagram of seat angle assembly, (c) seat angle plastic mechanism, (d) Free-body diagram of stiffener angles assembly

Plastic Mechanism of Connection - Negative Moment Capacity

The proposed model for the connection, when used with built-up sections, under ultimate negative moment is illustrated in Fig. 5a. The total resisting shear, *T*, is again equal to the sum of two forces, *F* and *V* shown in Fig. 5b, which are respectively the contribution of stiffener angles and seat angle to the connection's capacity.

The seat angle plastic mechanism is shown in Fig. 5c, and its plastic capacity, *V*, can be obviously evaluated using Eq. 7 above, i.e.

$$V = t^2 . F_y \left(\frac{h}{(x-b)} + \frac{x}{(h-a)} \right) \leq \sum_{i=1}^{n} T_{yi} = 2 A_b F_{y,r} \quad (n=2 \ here) \tag{9}$$

where T_{yi} is the axial yield strength of rivet *I*, A_b is the section area of each rivet joining the seat angle to column flange, and $F_{y,r}$ is the rivet yield stress. Contrary to the physical model described earlier, there is no contribution here from the tensile resistance of the first row rivets which join the stiffener angles to the seat angles. This is because these rivets are not connected to the column flanges in this case and only move as a subassembly of the seat angle and stiffener angle; they never undergo tension. However, those first row rivets which connect the seat angle to the column flange do experience tension, but only limit the maximum load, *V*, as per Eq. 9.

The stiffener angle's contribution to resistance, as illustrated in Fig. 5d , is given by the horizontal force needed to develop a plastic moment in the stiffener angles at the level of the second row of rivets.

Therefore, this resisting force, F, can be expressed as:

$$F = \frac{m_{p,st}}{l} \tag{10}$$

where $m_{p,st}$ is the plastic moment of the pair of stiffener angles, and l is the distance measured from the tip of the stiffener angles to the level of the second row of the rivets in the stiffeners as shown in Fig. 5d. From the free body diagram of Fig. 15a, the total ultimate moment resistance of the connection can be expressed as:

$$M = T \cdot d + m_0 \approx T \cdot d = (F + V)\, d \tag{11}$$

where d is the beam depth and m_0 is the moment required to satisfy moment equilibrium. As m_0 cannot exceed the plastic moment capacity of the seat angle leg, $m_{p,s}$, It can be conservatively taken as $m_{p,s}$. In most practical cases, the value of $m_{p,s}$ is small compared to the term $T \cdot d$, therefore it can even be ignored.

Numerically, for the retrofitted connections using selective welding, h = 67.5 mm, a = 56 mm, b = 55.8 mm, L = 276 mm, A_b = 334.2 mm^2, $F_{y,r}$ = 258 MPa, l = 114 mm, F_y = 225 MPa, and d = 0.506 m results a negative moment capacity, M^-, of 115 kN.m (v.s -110 kN.m from the experiment).

CONCLUSION

Although riveted stiffened seat angle connections have not been designed to resist moments, they can develop a considerable moment capacity and exhibit a relatively ductile hysteretic behavior which could be beneficially considered when evaluating frames built of these connections and subjected to earthquakes. The proposed physical modes for ultimate behavior of the riveted stiffened seat angle connections, detailed for single as well as built-up columns, can be reliably used to predict plastic moment capacity. Results from analytical procedures and formulas developed here have shown to be in very good correlation with experimental values.

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