Modern Strengthening Strategies for Steel Moment Resisting Frames: State – of – the – Art –Review

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Abstract

The Northridge (1994) and Kobe (1995) earthquakes caused widespread brittle fracture in the connections of steel moment-resisting frames. As a response to this unexpected damage, a variety of new designs have been proposed. Among many connections investigated recently, two categories of connections are mostly used to enhance ductility under severe earthquake loads. One of the two categories is the reinforced connections, in which the cover plate or haunch are used to strengthen the connections. The other category is the reduced beam section (RBS) connections. In present paper recent studies of strengthening strategies or reinforced connections are discussed. In this design philosophy, the portion of the beam adjacent to the column, where the maximum moment occurs during seismic loading, is strengthened. This will force the plastic hinge to form away from the joint. The strengthening may be done using: haunches cover plates, rib plates, side plates…etc.

Keywords: Strengthening schemes, reinforced connections, cover plates, rib plates, side plates, haunches

1. Introduction

After the incidences of Northridge (1994) and Kobe (1995) earthquakes, out breaking of brittle fracture of beam-to-column connections in a wide variety of welded steel moment resisting frames (SMRF's) challenged the previous thought about seismic behavior of special moment frames (SMF) and other types of SMRF's. Post-earthquake observations indicated that a wide spectrum of brittle connection damage was occurred, ranging from minor cracking to completely severed beams and columns (Miller 1998 and Nakashima 1998). Therefore, welded flange and bolted or welded web connection (the 'pre-Northridge' connection) became an unacceptable connection for use in areas of high seismicity, because it was observed that such connection cannot develop sufficient beam ductility in the beam, before fracture occurs at the joint. To access the unexpected damage considerable research has been carried out worldwide. Three general approaches were followed in improving connection detail:

A) Improving unreinforced connections /toughening schemes

B) Strengthening approach: strengthening connection by addition of cover plates, ribs or haunches. This paper focuses on state of art review for this approach

C) Weakening approach: locally weakening the beam away from the column face by reduced beam section (RBS) or slotted web

Strengthening approach for connections is used for new connections as well as for repair of the existing connections. In this design philosophy, the portion of the beam adjacent to the column, where the maximum moment occurs during seismic loading, is strengthened. This will force the plastic hinge to form away from the joint as well as will avoid fracture at the beam flange weld. The strengthening may be done using cover plates, rib plates, side plates, or haunches…etc. Numbers of analytical and experimental studies have been performed on reinforced connections. In an effort to gain an insight into the behavior of strengthening strategies, an attempt is made to study available literature.

1. Haunched Connections

Lee & Uang (1997), Uang & Bondad (1998) , Civjan & Engelhardt *et al.*(1999), Kent *et al.* (2000), Uang *et al.* (2000) and Chi *et al.* (2006) studied haunched connections (Figure1A) to investigate its effectiveness for repair schemes. It was observed that: a) An advantage of the haunch is that it provides a degree of redundancy to the connection; b) The presence of a welded haunch dramatically changes the beam shear force transfer mechanism. The majority of the beam shear is transferred to the column through the haunch flange rather than through either the beam web bolted connection or the beam flange groove welds. This strut action alters the moment distribution of the beam in the haunch region; c) The presence of a haunch forms a dual panel zone. It was found that the upper panel zone is subjected to a higher shear force and is more flexible than the lower panel zone; d) The presence of the composite slab appeared to help prevent fracture of the existing top flange weld in the haunch retrofit; e) The tests showed poor performance of the bottom flange dogbone retrofit scheme when compared with haunched connection. Further, the connections improved performance is proved by corresponding story drift ratio, improved plastic rotation capacity and hysteretic energy dissipation capacities of all repaired specimens.

Welding a triangular haunch beneath the beam was found to be very effective for repair, rehabilitation and new construction. But, the labor cost for fitting a triangular haunch connection is also expensive. In addition, the complete joint penetration groove weld at both ends of the haunch flange with an inclined angle requires a significant amount of overhead welding.

To minimize the construction cost, use of a straight haunch (Figure 1B) with one free end was proposed by Lee & Uang (2001) and Lee *et al.* (2003). The stress concentration at the haunch tip (Figure 1C) was observed. To lessen this stress concentration at the haunch tip, drilling a hole near the haunch tip was found effective in reducing the stress concentration, especially when it was combined with a sloped edge or a pair of stiffeners.

2. Welded Cover/Flange Plates and Bolted Flange Plates Connections

Recently Kim *et al.* (2002), Maranian *et al.* (2003) conducted study of two types of plate-reinforced connections (Figure 2A, B) cover-plate (CP) and flange-plate (FP) connections. For the CP connection, the cover plates and the beam flanges were complete joint penetration (CJP) welded to the column flange, whereas only the flange plates were welded to the column flange in the FP connection (plate sides to beam flanges are welded with fillet weld). Parameters like, reinforcing plate geometry, plate-to-flange fillet weld geometry, lateral-torsional buckling, and loading history were observed. They found it was inappropriate to draw broad conclusions regarding the optimal type of reinforcement plate based on limited analytical data. However, the FP connection appeared marginally superior to the CP connection. The rectangular plate was found superior to the trapezoidal plate for two reasons. First, the use of a rectangular plate provided a greater length for the placement of the longitudinal and transverse fillet welds than a trapezoidal plate of the same length, which led to a reduction in the size of the fillet weld. Three-sided fillet welds should be used regardless of the adopted plate shape. Second, the quality of the weld metal at the junction of the longitudinal and transverse fillet welds found to be better for the rectangular plate shape because these welds were separated by the thickness of the flange and runoff tabs could be used to provide high-quality weld metal at the end of each weld.

Engelhardt & Sabol (1998) suggested that: 1. Cover plated connections can provide highly ductile response and significantly better performance than the previous 'pre-Northridge' connection. 2. Connecions showed excellent inelastic deformation capacity, developing large levels of plastic rotation capacity under cyclic loading. 3. Compared to a number of other reinforcement options, cover plated connections appear to be less costly. 4. Higher toughness weld metal should be used for connection purpose. 5. The data suggested that the performance of cover plated connections may worsen when the cover plates become very long. 6. Similarly, very thick plates may cause problems. The large groove weld needed for the combined thickness of thick cover plate and flange results in very high shrinkage and restraint.

Schneider *et al.* (2002), Maranian *et al.* (2003) observed that, bolted flange plates connection (Figure 2C) appears to engage several mechanisms of inelastic behaviour, including panel zone deformations, bolt-slip, inelastic flange plate deformations, and girder hinging beyond the flange plate connection.

3. Side Plate (Proprietary) Connection

Houghton (1997) showed that due use of side plate connection (Figure 3), physical separation between the face of the column flange and the end of the beam eliminates peaked tri-axial stress concentrations. Physical separation is achieved by means of parallel full-depth side plates that eliminate reliance on through-thickness properties and act as discrete continuity elements to sandwich and connect the beam and the column. The increased stiffness of the side plates inherently stiffens the global frame structure and eliminates reliance on panel zone deformation by providing three panel zones (i.e., the two side plates plus the column's own web). Top and bottom beam flange cover plates are used, when dimensionally necessary, to bridge the difference between the flange widths of the beam and the column. This connection system uses all fillet-welded fabrication.

4. Bolted Bracket (Proprietary) Connection

The connection consists of cast-high strength steel brackets (Figure 4) that are fastened to the flanges of a beam and then bolted to column. Beam shear and flexural stresses are transferred to the column through a pair of heavy bolted brackets, located at the top and bottom beam flanges. The brackets can be either fillet welded or bolted to the beam

Test results by Kasai *et al.* (1998), Adan (2008) showed that, all connections exceeded the qualifying AISC (American Institute of Steel Construction) interstory drift angle without significant strength degradation. Based on the tests, the research concluded that the bolted bracket was capable of restoring a damaged moment connection to a rigid and ductile state. The stiffness of the tested subassemblies was essentially the same as that calculated for a theoretically welded connection. The haunch brackets directed yielding and inelastic beam deformation away from the column face and outside the connected region.

5. Rib Plate Connection

Among the various strengthening schemes use of vertical rib plates (Figure 5A, 5B) to improve the seismic performance of steel moment connections is common. These ribs generally have the form of a tapered triangular plate. The ribs welded to the top and bottom beam flanges at the column face are used to reduce the stresses at the beam flange groove weld and to move the critical section away from the column face.

Lee (2002) described seismic design procedure for rib-reinforced steel moment connections based on an equivalent strut model. Plastic hinging of the beam is often assumed to occur at the rib tip. It had been found difficult to justify this assumption due to the light reinforcement nature of the rib. The beam span with the radius-cut RBS (reduced beam section) was introduced to both confine the plastic hinging of the beam effectively outside the rib region and to push the occurrence of local buckling away from the rib tip. The diagonal strip in the rib acted as a strut, and strut action tends to produce reverse shear in the beam web. It was observed that the load transfer by one rib in the single rib configuration was about two times that by one rib in the dual rib configuration. Idealizing the rib as a strut, an equivalent strut model that was used to determine the interaction forces at the interface between the beam and rib and step vise design model was proposed. In the finite-element model, a circular hole was included near the rib tip to reduce stress concentration.

Lee *et al.* (2005) performed an experimental program to verify seismic design procedure for rib-reinforced steel moment connections based on an equivalent strut model. It showed that a combined strategy of rib reinforcement plus slight beam flange trimming in the form of the radius cut was found very effective in reducing the cracking propensity at the rib tip by pushing both the plastic hinging and local bucking (especially flange local buckling) away from the rib tip.

Chen *et al.* (2005) observed that the rib-reinforced connection can reduce the stress concentration in the access hole region as well as the stress demand in the beam CJP groove weld. Furthermore, a single rib was found more effective than double spaced ribs for reducing the localized stress concentration near the weld access hole.

Chen *et al.* (2003) proposed another rib type shown in Figure 6, 7. A single lengthened rib was welded to the centerline of the top and bottom beam flanges to increase the rib effect. As revealed from the numerical and experimental studies, a single rib was more effective than double spaced ribs for reducing the localized stress concentration near the weld access hole, and decreasing the potential for fracture. The lengthened portion of the rib was an intentional design feature that prevents beam flange fracture at the rib tip. The lengthened rib-reinforced connections sustained during application of cyclic lateral force and provided sufficient ductility during the large deformation. Chen *et al.* (2005) further, mentioned that a single lengthened rib can be used to reduce the stress concentration and plastic strain demand in the beam flange groove weld and the weld access hole region, and diminished the fracture potential of the beam flange at the beam-to-column interface. The numerical results for the rib-reinforced connection revealed that extensive yielding occurs in the beam away from the column face, and the plastic hinge reliably forms in the beam. Moreover, the rib extension had effectively eliminated the localized high stress that occurs in the beam flange at the rib ip.

In the recent study Arlekar & Murthy (2004) presented the results of nonlinear finite element analyses of strong-axis exterior steel beam-to-column subassemblies with connection reinforcement (Figure 8). In the connection considered: 1. Beam flanges were butt welded to the column flange. 2. The cover plates were fillet welded to the beam flange and butt welded to the column. 3. The vertical rib plates were fillet welded to the cover plates and butt welded to the column. Cover plates were designed for pure axial forces, and the vertical rib plates were designed for combined axial and shear forces. The welds between the various connection components are designed for actual combined axial and shear stresses. This is verified by nonlinear finite element analyses and is in contrast with the location of the truss assumed in the truss analogy model to start at the face of the column. The improved truss model presented in this paper gave realistic design forces for the connection elements.

6. Side Plate Connection (other types)

Chou *et al*. (2010) used full depth side plates (Figure 9) between the column (box) and beam flange inner side to rehabilitate 3 connections in 34 storeys building in Kashiung, Taiwan. Further, it was stated that scheme differs from the proprietary connection which completely eliminates the reliance on the existing beam flange groove welded joints at the column face for transferring beam moment.

Chou & Jao (2008) suggested the scheme which was different than using full-depth side plates (Figure 10) for rehabilitation because only a small part of side plates near the beam flanges remained. The study presented experimentally and analytically the cyclic behavior of the proposed moment connections, and provided recommendations for seismic design of such connections to built-up box columns. However, three rehabilitated moment connections failed as the un-rehabilitated moment connection due to insufficient stiffener stiffness and strength.

7. Connections with Internal Stiffeners

Deylami & Yakhchalian (2008) showed that due to the provided internal stiffener as shown in Figure 11: a) common moment connection was partially restrained and using a vertical stiffener plate inside the column , b) reduced the column cover plate deformations. It has a considerable effect on improving connection strength, stiffness and compels inelastic deformations in beams.

8. Conclusion

A summary of recent strengthening strategies is discussed in the present paper. A straight and triangular haunch are effective in moving the plastic hinge location of the beam away from the haunch tip and develops satisfactory levels of connection ductility without fracture. Study also observed that welded cover plated flange connection is the least costly reinforced connection. Side Plate (Proprietary) connection improves ductility of an entire connection and used effectively where upper slab is present and story height constraints occurs. Bolted Brackets (proprietary) are readily available in various sizes and shapes reduces amount of workmanship required on the site. Current study on upstanding ribs has shown that, combined strategy of rib reinforcement plus slight beam flange trimming in the form of the radius cut is very effective in reducing the cracking possibility at rib tip by pushing plastic hinge location away from rib tip. Recent study with full depth side plates between beam flanges was found more effective than side plates with limited height.

Varieties of strengthening options are available as discussed in sections 2 to 7. As per the requirement connection may be reinforced by any one suitable strategy. It is observed that to learn more aspects like a) application of strengthening strategies to weak axis connections, b) study of combination of above mentioned reinforced connections, c) application of reinforcing techniques to connections with deep slender section members, d) study of strategies for different loading protocols, e) Mostly specimens were studied with respect to US (United States) section profiles, study for section profiles of other countries may be considered.

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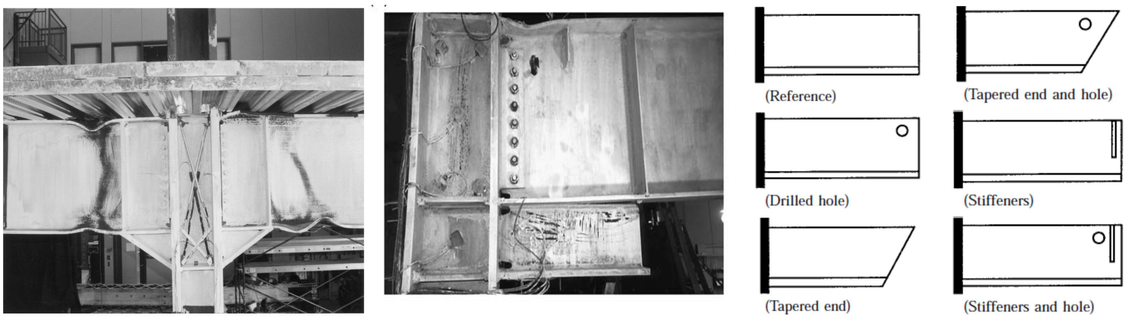

Figure 1. A) Haunched connection, Civjan S A and Engelhardt M D et al. (1999), B) Straight haunch, Lee C H and Uang C M (2001), C) Various straight haunch models suggested, Lee C H et al. (2001)

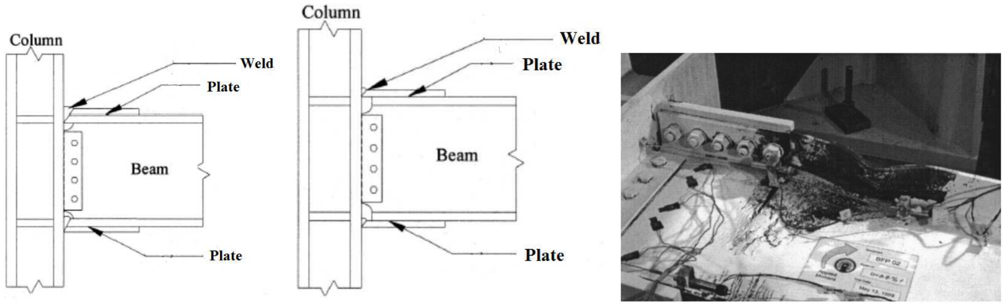

Figure 2. A) Cover plates connection, Kim T et al. (2002) B) Flange plates connection Kim T et al. (2002) C) Bolted flange plates connection, Schneider S P et al (2002),

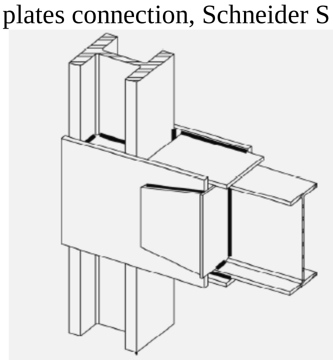

Figure 3. Proprietary side plate connection, Houghton D L (1997)

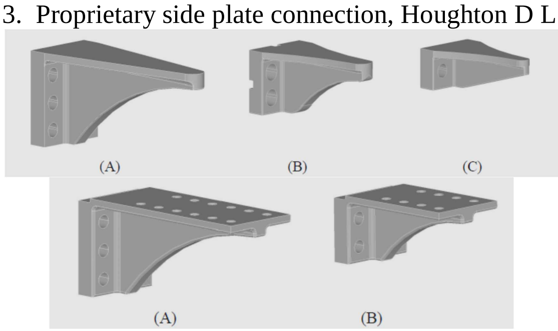

Figure 4. Various available configurations of Kaiser bolted bracket, Adan S M (2008)

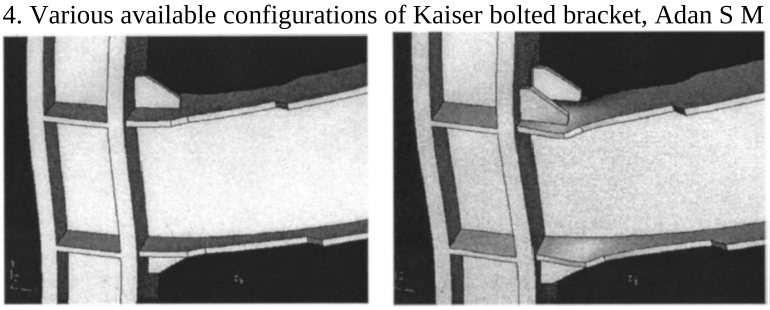

Figure 5. Flange rib strengthened connection, Lee C H et al (2002), A) Single, B) Double

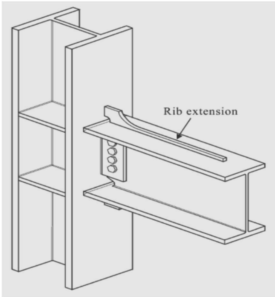

Figure 6. Lengthened flange rib strengthened connection, Chen C C et al. (2003)

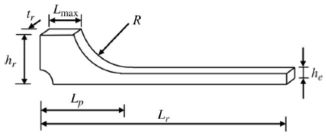

Figure 7. Geometry of lengthened flange rib, Chen C C et al. (2003)

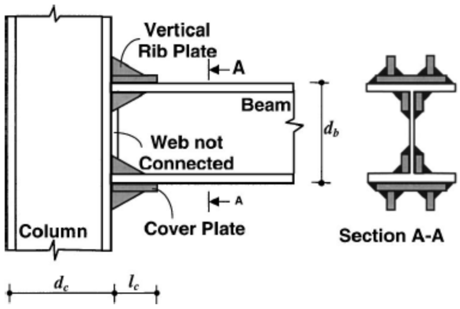

Figure 8. Beam–column subassemblage configuration, Arlekar J N and Murthy C V R (2004)

Figure 9. Full depth side plates, Chou C C et al. (2010)

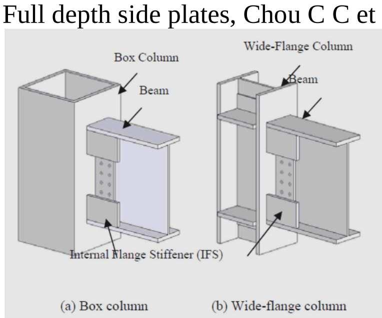

Figure10. Rehabilitated moment connection with internal stiffeners, Chou C C & Jao C K (2008)

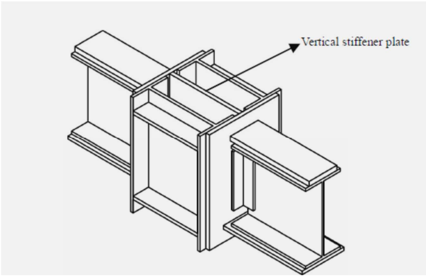

Figure 11. Vertical stiffener with double-I built-up column, Deylami A & Yakhchalian M (2008)