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INVESTIGATION OF REPLACEABLE SACRIFICIAL STEEL LINKS

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ABSTRACT

Eccentrically braced frames depend on the inelasticity of specially designed links to provide ductility and to dissipate energy during earthquakes. The links are typically formed from continuous wide flange beams. With increasing emphasis on performance based design, the link's replaceability becomes a desired quality. The feasibility of links utilizing end plate bolted connections were numerically investigated prior to experimental implementation using detailed non-linear analyses. An effective connection needed to be developed, one that would resist shear and moment at the ends of the link as well as accommodate inelastic deformations of the active section of the link. Innovative stiffening alternatives were investigated for shear dominated and flexure dominated links including the use of stiffeners parallel to the web, angled toward the web, and the use of partial hollow structural shapes. The advantage of these options was the containment of stiffeners within the depth of the beam. Preliminary results from large scale experiments are also presented. The details considered were found to shift the localized plastic strain demand away from the location of the flange-to-plate welds for both short and long links.

Introduction

The eccentrically braced frame (EBF) is a lateral load structural steel framing system utilizing diagonal bracing members that are offset at the beam intersections in order to create an eccentric link in the continuous horizontal beam. In a seismic event, the link's inelastic deformations provide the lateral system with ductility and energy dissipation while protecting the rest of the structure as long as capacity design principles are followed (AISC 2005). With the increased emphasis on performance-based design, structural systems capable of rapid repair are needed to facilitate return to occupancy following an earthquake. Researchers have begun to examine the possibility of using a bolted link design so that after a seismic event the damaged sections could be replaced (Stratan & Dubina 2004). Bolted links would also allow for cost effective designs of buildings located in lower seismic regions (Hines 2009).

The challenge with implementing replaceable links is the link connection, such that the

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links are simple to install and remove while able to withstand the expected inelastic shear and moment demands. One of the main performance related issues is related to premature failure of the welded area connecting the link to the column or end plate (Okazaki & Engelhardt 2007, Ramadan & Ghobarah 1995, Stratan & Dubina 2004). Past tests have shown that a number of specimens failed prematurely due to fractures at the interface (Ramadan & Ghobarah 1995) with further investigations finding that fillet welds promoted ruptures under cyclic loading (Dubina et al 2000). As a result, subsequent tests have avoided weld failures at the interface by over-conservative designs of connections in order to concentrate the study on the link behavior (Okazaki and Engelhardt 2007).

b) Unstiffened End   c) Parallel to Web

Effective Link Section

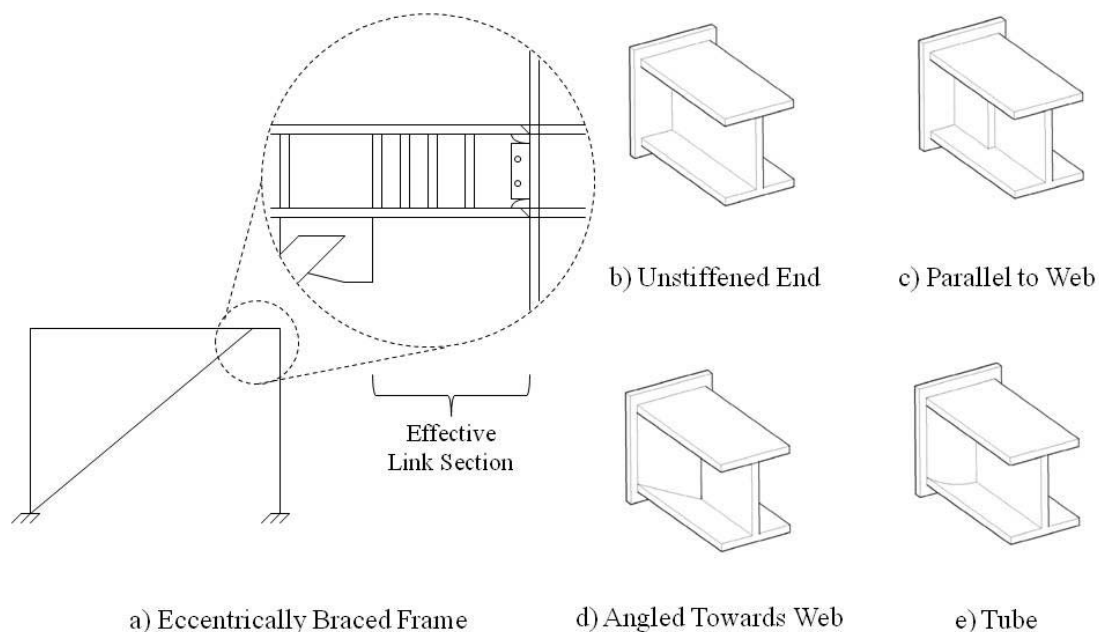d) Angled Towards Web   e) Tube

a) Eccentrically Braced Frame

Figure 1.   EBF link-to-column connection and considered link stiffener details.

In an effort to produce a workable and replaceable link, a design approach was sought that would minimize the chance of premature failure at the connections of the replaceable link. The objectives of the study were to develop connection details and conduct detailed numerical analyses to evaluate their effectiveness and select candidate details for large scale experimental validation, of which preliminary results are also presented.

Considered Connection Detail

End Stiffener Selection
Link-to-column EBF connections have been detailed similarly to pre-Northridge beam column moment connections and were subject to similar potential performance issues (AISC 2005). Pre-Northridge moment connections typically utilized an end tab to hold the beam in place during construction before field welding the beam to the column. The chosen end detail for the replaceable links was an end-plate connection, which has been in use for beam connections and is a familiar design concept (Murry and Summer 2003). In order to provide for practical and

economic fabrication, fillet welds rather than complete joint penetration welds were desired. However, prior testing has shown that weld failures could occur under cyclic loading for fillet welds (Dubina et al 2000, Okazaki & Engelhardt 2007, Ramadan & Ghobarah 1995). In order to utilize fillet welds, modifications to the end region were needed to minimize failure at or near the welds. The general approach was to shift plastic strains away from the welds in the area of link-to-end plate connection by introducing end stiffeners.

Typical web stiffeners are placed perpendicular to the web with the aim of preventing web buckling. However, the end stiffeners used for the replaceable links were introduced to reduce inelasticity at the ends of the link. Containment of the stiffeners to between the link flanges was desired so as not to further increase the required depth. Three general options were considered as illustrated in Figure 1: stiffeners parallel to the web, angled from the flange ends toward the web and curved, utilizing sections of hollow structural shapes. The rationale for the latter two options was for gradual transition.

Link Selection

The end stiffener designs were investigated for a short, intermediate, and long link as defined by the ratio of eV_p/M_p, where e is the link length, V_p is the plastic shear and M_p is the plastic moment (AISC 2005). Short shear dominated links are considered when the ratio is less than 1.6, long flexure dominated links for ratios over 2.6 and intermediate links for values in between. In the analysis the links were 1350 mm (53 in) in length and designed using the following wide flange shapes of relatively similar depths as detailed in Table 1; W12x96, W12x35, and W12x22 as short, intermediate and long links respectively.

Table 1. Link designs.

	Short Link, W12x96, $eV_p/M_p < 1.6$	Intermediate Link, W12x35 $1.6 < eV_p/M_p < 2.6$	Long Link, W12x22 $eM_p/V_p > 2/6$
End Plate Thickness, mm (in)	38 (1.5)	38 (1.5)	38 (1.5)
Web Stiffener Thickness, mm (in)	16 (0.63)	9.5 (0.38)	9.5 (0.38)
Web Stiffener Spacing mm (in)	337 (13.3)	224 (8.8)	152 (6)

Numerical Model

Numerical link models were developed using Abaqus finite element software (Abaqus 2006). Non-linear material and geometry were utilized for the analyses of the numerical link models. A structured mesh was used with 8-node linear bricks, with reduced integration and hourglass control. Once the model geometry was obtained, the strain at key nodes along and near the flanges were recorded and used for convergence in mesh refinement. A mesh was applied with at least four elements representing each plate thickness to effectively model strain

distribution throughout the depth as shown in Figure 2d. Boundary conditions were applied to restrain all translation and rotation at one end and all translation and rotation except the axial translation at the other end such that no axial forces developed in the link. Initial imperfections were introduced by applying 2% of the first two buckling modes onto the model prior to imposing any end deformations.
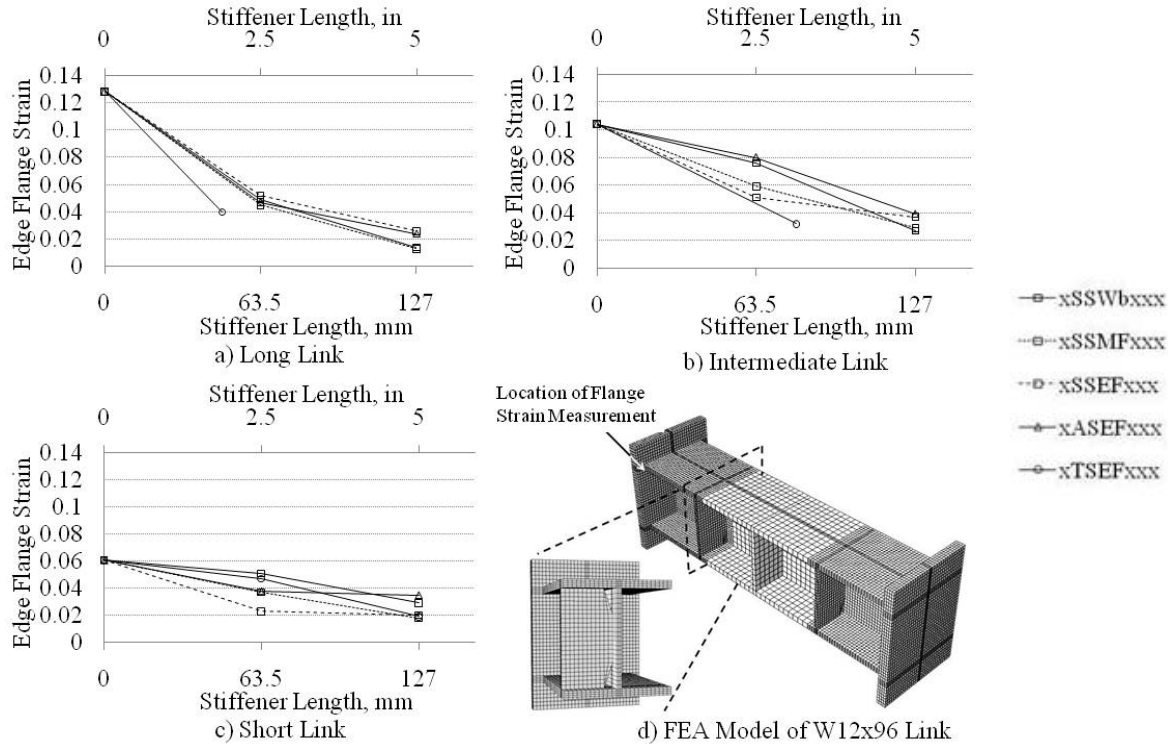


Figure 2. Strain in Flange at End of Link.

The analyses used material properties based on strain hardening properties for A572 Grade 345 MPa (Gr. 50) steel (Kaufmann et al 2001). The material properties and the modeling approach were validated by analyzing the hysteretic behavior of previously published experiments on W10x33 and W16x36 links (Okazaki et al 2004). The first set of analyses subjected the links to a monotonic displacement of 137 mm (5.4 in), corresponding to link rotation of 0.10 rad. This rotation was chosen to surpass the expected link rotation of 0.08 rad for short links (AISC 2005). This monotonic analysis was initially used to evaluate the end stiffener effectiveness in reducing stains at the link-to-flange interface. Later analyses would use the link-to-column cyclic loading sequence (AISC 2005) of applying increasing cyclic deformations on selected cases.

Different cases of link-to-end stiffener connections were investigated and are referred to using the following 8 character designation: the first character refers to short (S), intermediate (I), and long (L) links followed by the end stiffener configurations as none (NS), straight (SS), angled (AS) and tube (TS). Three locations of the start of the end stiffener relative to the web were at the web (Wb), mid flange (MF), and flange edge (FE). The last component of the designation is the length of the end stiffener in mm with 68mm (2.5 in) and 126mm (5 in) considered. For example, Figure 1c using a 68 mm (2.5 in) stiffener on a short link would be

referred to as an S|SS|Wb|068.

End Stiffener Effect on Strains at End of Link

The amplitudes of link strain at the end of the flange are shown in Figure 2 for the different stiffener arrangements and for the various stiffener lengths. The longer the end stiffener, the higher the reduction in plastic strain, indicating an increased end stiffener length positively affected strain reduction. The largest decrease in strain was observed for the long links, which were dominated by flexure at the ends of the link. The link end moments caused yielding and flange buckling near the link-to-column interface. The short links where dominated by shear deformations and thus the end stiffeners had less effect on reducing flange strains. The long links exhibited an average 80% decrease in strain while the short links exhibited an average 50% decrease.
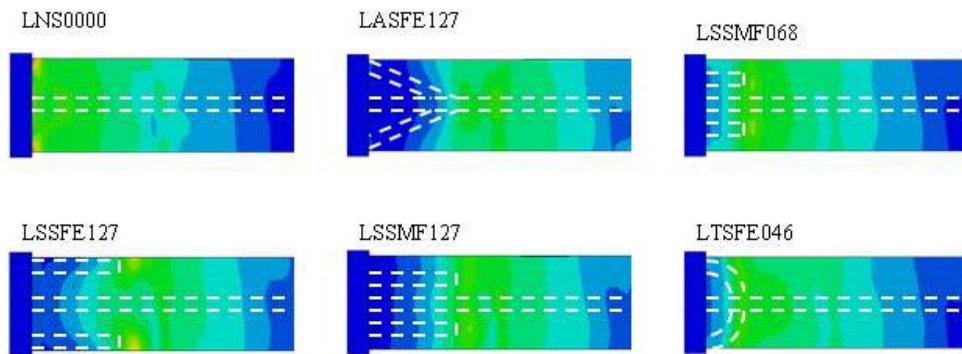
a) Stiffener Configurations for Long Links
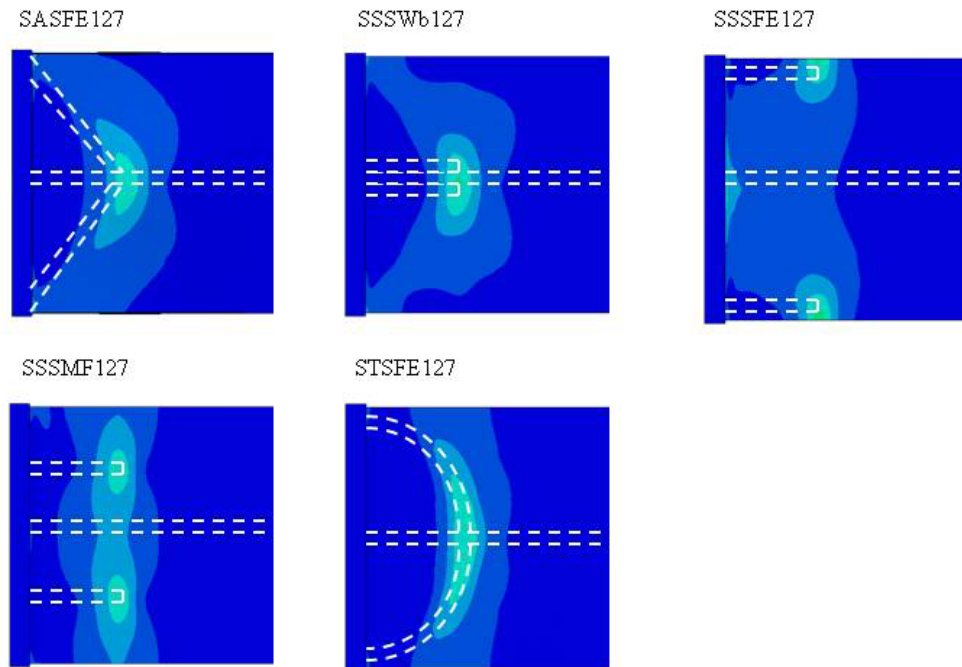
b) Stiffener Configurations for Short Links

Figure 3. Flange Strain in Tension Flange.

The difference between the various end stiffener details was generally small except for the tube stiffener, which appeared to be the most effective. Configuration LTSFE046 in Figure 3a resulted in a significant strain reduction for its length, but could not be practically extended further into the link than 46 mm (1.9 in). The tube stiffener could only extend as far as the radius allowed, which in turn was limited by the width of the flange. Due to the width of the flange in short links, stiffener geometry played a greater role in the strain distributed as shown in Figure 3b. Stiffeners in links SASFE127 and SSSWb127 reduced strains at the end plate above the web, but not as much at the flange edges. With link SSSFE127 the reverse occurred, with strains were decreased at the edges but increased in the center. In general, the stiffener configurations best able to reduce strains along the flange to end plate connection were the tube and angled stiffeners.

Stiffener Effect on Effective Link Length

Across the various links considered, the use of stiffeners reduced strain along the web at the link connection to different degrees. Angled and tube stiffeners, which connected to both the end plate and web, reduced plastic strains at the ends and in many cases resulted in complete elastic behavior. This immobilization of the link end effectively reduced the length of the link, as the plasticity was concentrated to areas between the end stiffeners. Straight stiffeners that were not connected to the web had a more gradual transition from the plastically deformed web to the end connection as illustrated in Figure 4. The strains at the web-to-end plate connection rapidly decreased and even the short 64 mm (2.5 in) stiffeners were found to be sufficient to develop near elastic behavior for the shear dominated links.
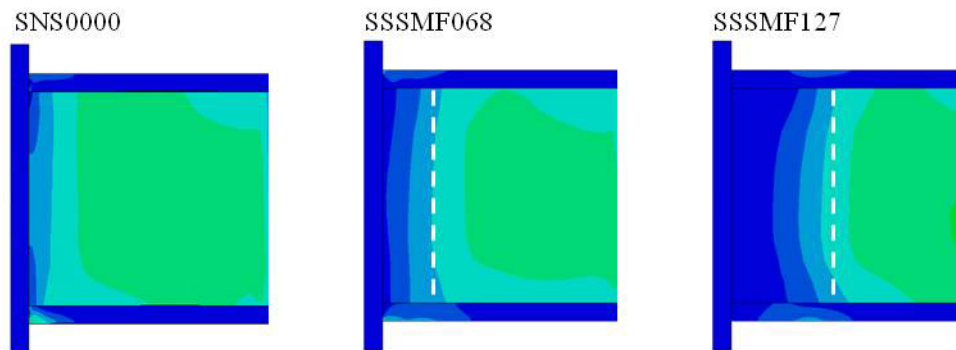

Figure 4. Plastic Strain in Short Link Web.

The reduction in plasticity of the web implies a reduced length of the link that is expected to deform. With the length of the link reduced, the ratio eV_p/M_p, which is used to differentiate between short and long links, needed to be recalculated. For these links the total length of stiffeners was subtracted to determine an effective length. While this can be appropriate for the tube and angle stiffeners, such an assumption is an approximation for the straight stiffeners. In the cases considered, the links (by intent) remained within their initial categories, even after considering the reduction in effective length, i.e. a W12x22 is a long link at 1350 mm (53 in) and at 1090 mm (43 in) after the stiffener length was subtracted. Since the use of an end stiffener influences the effective deformable length, care must be taken in the design for end stiffener implementation. Reducing link length within the frame increases the link rotation for the same building drift. The relationships between the shear rotation γ_p and the overall frame drift γ_p,

outlined in the provisions commentary (AISC 2005), also needs to consider the effective length of the link instead of the original link length.

Implementation Considerations

      The inclusion of end stiffeners at the ends of links has been shown to reduce strains at the flange and web. With the exception of the tube stiffener the use of the 127 mm (5 in) end stiffeners resulted in greatest decreases in flange and web strains. The benefit of the longer stiffeners was the shift of plastic strain further from the connection interface. While the tube stiffeners were effective in the intermediate and long links the practical implementation of this configuration was found to be limited. The tube radius could only be as large as half the flange width, which in turn limits the influence along the link length. However, for wide flange sections that have sufficiently wide flange, the tube stiffeners distributed the plastic strain effectively while reducing the strains at the end plate connection.

      With the use of a 127 mm (5 in) end stiffener the overall difference between the performances of various stiffener configurations, observed in the numerical analyses, were relatively small. As a result practical implementation governed the selection of stiffeners for experimental implementation. For a bolted end plate connection, the straight stiffeners allowed access for bolting, whereas the tube and the angled web created an inaccessible portion to the web. Consequently, the most practical implementation of the end stiffeners was found to be the straight stiffener configuration.


Preliminary Experimental Results

      Large scale experiments have been initiated, starting with the W12x22 long links. The test setup is shown in Figure 5a and was based on the link column frame lateral system that is intended to utilize the replaceable links (Dusicka and Iwai 2007). The test setup was 4 m (12 ft) high with pin connections at the top and bottom of the W14x145 columns. Lateral deformation of the columns was induced by a 980 kN (220 kip) capacity actuator attached to a load transfer beam. The mechanism that formed was resisted by the link, located at column mid-height. Reverse cyclic deformations were imposed following the link deformation protocol of EBF links (AISC 2005). Link rotations were measured across the entire link, as the end stiffener regions, and between the end stiffeners.

      Two experimental results are shown for long links constructed from W12x22 in Figure 5b at approximately the same level of deformation. The case without stiffeners (LNS0000) exhibited significant strain and flange buckling at the ends of the link, which culminated in a failure mode characterized by flange fracture. The fracture occurred at the root of the fillet weld connecting the flange to the end plate. With the introduction of end stiffeners (LSSWb127), the plastic strains shifted away from the end connection. Flange buckling was minimized at the mode of failure moved into fracturing of the web.

      The hysteretic response from the experiments is compared to the numerical prediction in Figure 6 for both cases. The numerical model corresponded closely to the experimental results up until failure. Since the model did not attempt to predict ultimate failure, the analyses were artificially taken to 0.10 rad. The long link with no end stiffeners (LNS0000) reached a link rotation of 0.04 rad, which was double the required link rotation of 0.02 rad. The long link with end stiffeners located at the web (LSSWb127) and fabricated from the same W-section achieved

a link rotation angle of 0.07 rad, a significant increase in deformation capacity. The shift in the failure mode was successful in improving the deformation capacity of the link.
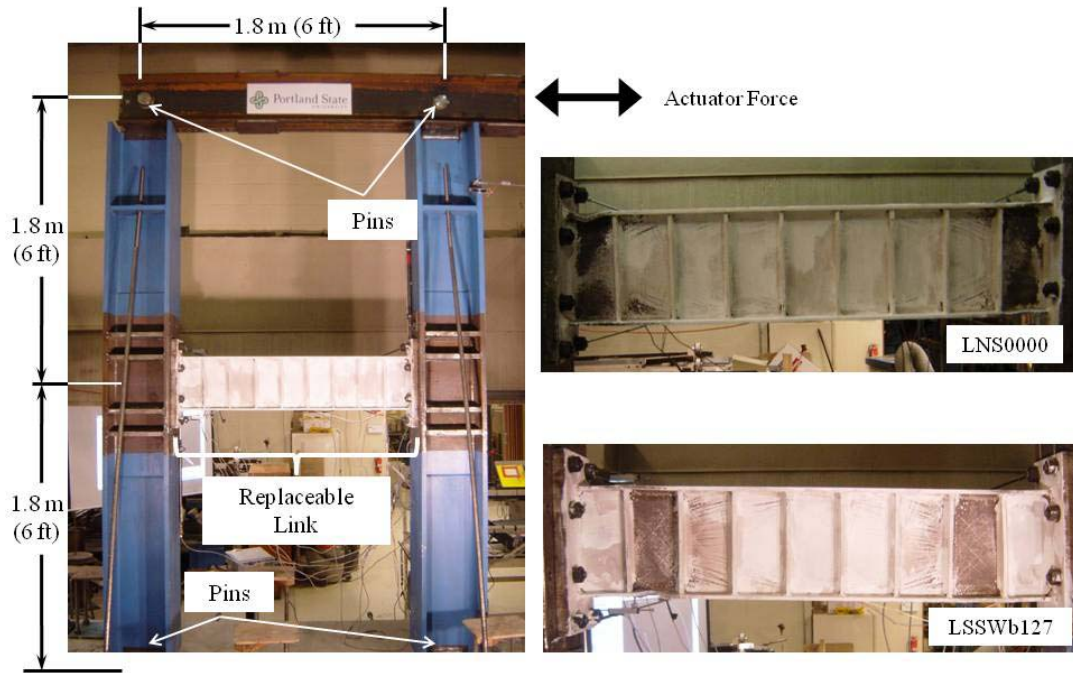
a) Experimental Test Apparatus   b) Links LB and L1 at 0.04 rad
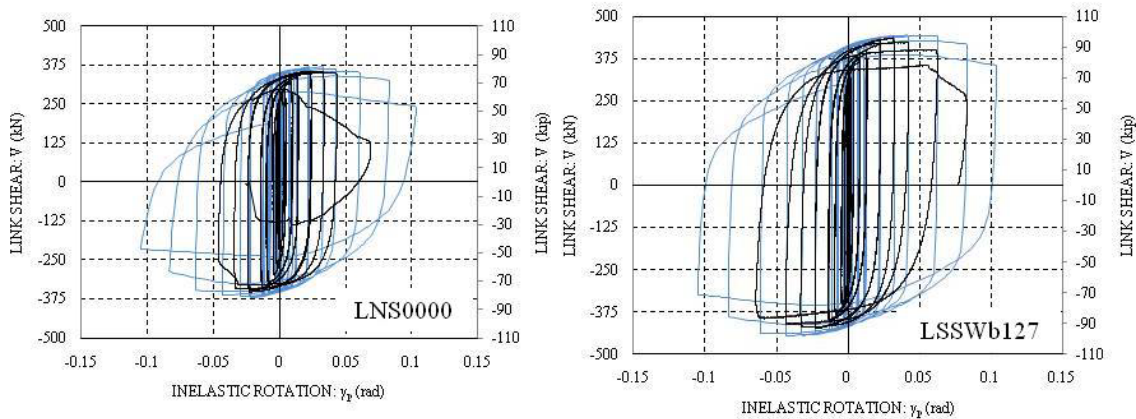
Figure 5. Test Setup and Deformed Links.

Figure 6. Comparison of Experimental and Numerical Cyclic Response.

The shear force capacity of the link also increased for the stiffened link. This increase in shear was caused by the shortening of the effective length of the link, which in turn increases the

shear required to mobilize the plastic end moments. Assuming the ends to be completely constrained by the end stiffeners, the effective link length decreased to 1092 mm (43 in). This increase in shear was expected and observed in both the numerical as well as the experimental results.

These initial results from the link experiments have shown the analysis capable of producing reliable information and more importantly tests have validated the end stiffener approach in the long links tested thus far. Future experiments will consider an end stiffener that is not connected to the web and will also consider the end stiffener effect for short shear dominated links.

Conclusions

Connection details were developed for replaceable link connections with the intent of limiting plastic strain at the link-to-end plate connection and thereby minimizing undesirable failure modes. Reducing the plastic demand at the location of welds was achieved through end stiffeners that shifted the plastic strain away from the welded link ends. Detailed nonlinear numerical analyses were used to evaluate straight, angled and tube end stiffeners for short, intermediate and long links. The tube stiffeners were found to have performance advantages as well as practical limitations, especially for long links. Straight end stiffeners of up to 127 mm (5.0 in) long parallel to the web were found to be both practical and effective in reducing plastic strains at the link-to-end plate connection.

Link configurations implementing bolted end plates and links with straight stiffeners are being investigated using large scale cyclic experiments. The initial results indicate that the use of end stiffeners on flexural links effectively shifts the failure mode away from the welded connections and increases the link deformation capacity.

Acknowledgments

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