TECHNICAL NOTE

NewZ-BREAKSS: Post-tensioned Rocking Connection Detail Free of Beam Growth

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ABSTRACT

This technical note concisely presents the details of a post-tensioned rocking moment connection (PT-RMC) concept that could be implemented in steel plate shear wall (SPSW) and moment-resisting frame (MRF) systems, along with preliminary results from limited SAP2000 cyclic nonlinear static pushover and time-history analyses that verify its anticipated behavior. The partial research results presented here could be of benefit in ongoing discussions about practical implementation and design codification of PT-RMCs [aka post-tensioned energy dissipating (PTED) or self-centering moment-resisting (SC-MRF) connections].

Keywords: rocking connection; self-centering frame; steel plate shear wall; moment frame.

Post-tensioned rocking moment connections (PT-RMCs) in steel frames have been proposed by many researchers (e.g., Ricles et al., 2002; Christopoulos et al., 2002a, 2002b; Garlock et al., 2005; Rojas et al., 2005) as an alternative moment-resisting frame (MRF) connection that provides frame self-centering and limits hysteretic damage to designated energy dissipating elements during earthquakes. This connection, which is appealing for many reasons, requires careful and nonconventional floor diaphragm detailing to account for interaction effects of the PT frame with the gravity system. In particular, issues with PT frame expansion (Garlock, 2003), often referred to as "beam growth," arise associated with the opening of the rocking beam joint. Garlock and Li (2008) and Iyama et al. (2009) proposed some innovative floor slab diaphragm details for specific plan layouts to accommodate the beam growth that occurs in the PT frames relative to the other gravity frames in building structures and, more challengingly, when beam growth develops in both orthogonal plan directions. Apart from floor slab issues, in taller frames having larger columns, because columns must flexurally deform to accommodate beam growth at subsequent stories, the large stiffness of these columns may become overwhelming and prevent beam growth to the point where PT-RMC systems may not work properly.

Here, a type of rocking connection is proposed, inspired by a moment-resisting connection developed and implemented in New Zealand (Clifton, 1996, 2005; MacRae et al., 2007; Clifton et al., 2007; MacRae, 2008; MacRae et al., 2009), to achieve the advantages of a PT-RMC system without beam growth. This is done as part of an ongoing research project on steel plate shear walls (SPSWs) having rocking beam connections (e.g., Berman et al., 2010); consequently, the focus of this technical note is primarily on SPSW systems. However, while this technical note illustrates how a rocking connection of the type proposed here could be detailed for SPSW systems, it is presented with the understanding that, with minor changes, it could also be a workable solution for rocking MRF as a method to eliminate beam-growth issues, while providing in both cases the benefit of frame recentering while eliminating the need for special detailing of the diaphragm to accommodate beam growth.

NEWZ-BREAKSS ROCKING CONNECTION

For convenience, the proposed connection is called the "New Zealand-inspired—Buffalo Resilient Earthquake-resistant Auto-centering while Keeping Slab Sound (NewZ-BREAKSS) Rocking Connection." This proposed rocking connection is shown in Figure 1 for the particular detail that would be used in a self-centering SPSW system (the detail shown is for a ⅓-scale frame considered for possible testing).

In Figure 1, VBE is the vertical boundary element and HBE is the horizontal boundary element in keeping with the nomenclature used for conventional SPSW systems. The proposed rocking connection essentially eliminates the beam

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growth typically encountered in the previously researched connections that rock about both of their beam flanges by, instead, maintaining constant contact of the beam top flange with the column during lateral drift. Additionally, this connection provides a large moment arm from the rocking point to the centroid of the post-tension for maximizing the PT elongation desired for self-centering connections. However, in a given beam, because the top flange of the beam is in constant contact with the columns at both ends of the beam, as the frame drifts, when one of the rocking joint "opens" and induces PT elongation, the rocking joint at the opposite end of the beam "closes" and induces PT decompression. Thus, the two PT elements need to be anchored independently along the length of the beam as shown in Figure 1; if a single PT element was used to span across the entire beam and was anchored only to the columns, its net elongation would be zero over the full length of the beam. Note that the stress concentrations at the rocking point for this connection are not significantly different than for the condition for post-tensioned moment-resisting rocking steel frames, in that a flange reinforcement plate will also typically be needed to accommodate stress demands on the rocking beam flanges as shown in Figure 1.

The location of the PT anchor point along the beam will depend on the strain demands of the PT elements at the maximum target drift. The anchor location should be provided to ensure that the PT strains remain elastic up to that drift demand. Either steel or fiber-reinforced polymer (FRP) tendons or rods could be used, depending on the level of PT strain anticipated. One other notable characteristic with the proposed detail is that because one joint closes, the recentering capability of the PT at the closing joint diminishes as the PT element is "relaxed"; if, at certain drifts, the initial elongation of the PT tendon or rod is overcome, the PT element will become fully relaxed and only the PT element at the opening joint will contribute to recentering the frame. Thus, the opening joint will always contribute to frame recentering, while the closing joint may or may not contribute depending on whether the PT element loses its pretension at the maximum target drift level. In the example presented subsequently, eventually, at large drifts, only the opening joint contributes to frame recentering (the closing joint eventually does not contribute after the PT element at that joint has lost its pretension). However, preliminary results show that this phenomenon has been found to be of no significant detrimental effect on structural behavior and can be accommodated by design.

To better understand the behavior of the proposed detail, the moment relationship along the length of the beam was obtained from first principles based on the free body diagram shown in Figure 2 using a capacity design approach for a self-centering SPSW. Here, it is assumed that the boundary frame and PT remain elastic and only the web plate yields. Note that vertical HBE reactions develop as shown in Figure 2, which is resisted by a shear tab connection as shown in Figure 1. However, for clarity, the shear tab detail is not shown in the free-body diagram illustrated in Figure 2.

In Figure 2, V_i is the story shear force, W_{bx} is the web plate horizontal yield force resultant along the length of the HBE, W_{by} is the web plate vertical yield force resultant along the length of the HBE, $P_{HBE(VBE)}$ is the horizontal reaction at the rocking point of the yield force resultant of the web plate acting on the VBE, P_s is the PT force, P_{sVBE} is the horizontal reaction of the post-tension force at the rocking point, y is the distance from the HBE neutral axis to the centroid of the PT, d is the depth of the HBE, R is the length of the radius corner cut-out of the web plate, and L is the clear span of the HBE. Note that the subscripts 1 and 2 indicate

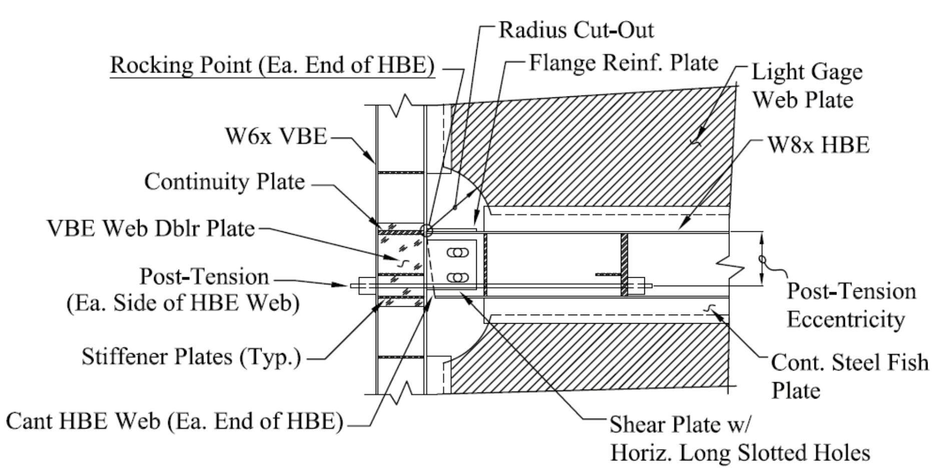

Fig. 1. Self-centering SPSW rocking connection.

that the force components shown are of different magnitude. In particular, it is assumed that the web plate below the HBE flange is thicker than the web plate above the HBE. By static equilibrium at sections 1 to 5 (points of applied load changes), the moment distribution along the length of the HBE is determined as follows:

$$M_1 = P_{s1VBE}\left(\frac{d}{2}\right) - P_{s1}\left(\frac{d}{2L}x + \frac{y}{L}x\right) + P_{s2}\left(\frac{y}{L}x + \frac{d}{2L}x\right) + \left(\omega_{by1} - \omega_{by2}\right)\left(\frac{L}{2}x - Rx\right) + \left(\omega_{cx1} + \omega_{cx2}\right)\left(\frac{dh}{4} - \frac{d^2}{4} - \frac{dR}{2}\right) + \omega_{bx1}\left(\frac{2dR}{L}x - dx\right) + V_i\left(\frac{d}{4}\right) \tag{1}$$

$$M_2 = P_{s1VBE}\left(\frac{d}{2}\right) - P_{s1}\left(\frac{d}{2L}x + \frac{y}{L}x\right) + P_{s2}\left(\frac{y}{L}x + \frac{d}{2L}x\right) + \left(\omega_{by1} - \omega_{by2}\right)\left(\frac{L}{2}x - \frac{x^2}{2} - \frac{R^2}{2}\right) + \left(\omega_{cx1} + \omega_{cx2}\right)\left(\frac{dh}{4} - \frac{d^2}{4} - \frac{dR}{2}\right) + \omega_{bx1}\left(\frac{2dR}{L}x - \frac{d}{2}x - \frac{dR}{2}\right) + \omega_{bx2}\left(\frac{d}{2}x - \frac{dR}{2}\right) + V_i\left(\frac{d}{4}\right) \tag{2}$$

$$M_3 = P_{s1VBE}\left(\frac{d}{2}\right) + P_{s1}\left(y - \frac{d}{2L}x - \frac{y}{L}x\right) + P_{s2}\left(\frac{y}{L}x + \frac{d}{2L}x\right) + \left(\omega_{by1} - \omega_{by2}\right)\left(\frac{L}{2}x - \frac{x^2}{2} - \frac{R^2}{2}\right) + \left(\omega_{cx1} + \omega_{cx2}\right)\left(\frac{dh}{4} - \frac{d^2}{4} - \frac{dR}{2}\right) + \omega_{bx1}\left(\frac{2dR}{L}x - \frac{d}{2}x - \frac{dR}{2}\right) + \omega_{bx2}\left(\frac{d}{2}x - \frac{dR}{2}\right) + V_i\left(\frac{d}{4}\right) \tag{3}$$

$$M_4 = P_{s1VBE}\left(\frac{d}{2}\right) + P_{s1}\left(y - \frac{d}{2L}x - \frac{y}{L}x\right) + P_{s2}\left(\frac{y}{L}x + \frac{d}{2L}x - y\right) + \left(\omega_{by1} - \omega_{by2}\right)\left(\frac{L}{2}x - \frac{x^2}{2} - \frac{R^2}{2}\right) + \left(\omega_{cx1} + \omega_{cx2}\right)\left(\frac{dh}{4} - \frac{d^2}{4} - \frac{dR}{2}\right) + \omega_{bx1}\left(\frac{2dR}{L}x - \frac{d}{2}x - \frac{dR}{2}\right) + \omega_{bx2}\left(\frac{d}{2}x - \frac{dR}{2}\right) + V_i\left(\frac{d}{4}\right) \tag{4}$$

$$M_5 = P_{s1VBE}\left(\frac{d}{2}\right) + P_{s1}\left(y - \frac{d}{2L}x - \frac{y}{L}x\right) + P_{s2}\left(\frac{y}{L}x + \frac{d}{2L}x - y\right) + \left(\omega_{by1} - \omega_{by2}\right)\left(\frac{L^2}{2} + Rx - \frac{L}{2}x - LR\right) + \left(\omega_{cx1} + \omega_{cx2}\right)\left(\frac{dh}{4} - \frac{d^2}{4} - \frac{dR}{2}\right) + \omega_{bx1}\left(\frac{2dR}{L}x - dx + \frac{dL}{2} - dR\right) + \omega_{bx2}\left(\frac{dL}{2} - dR\right) + V_i\left(\frac{d}{4}\right) \tag{5}$$

where h is the story height; ω_c and ω_b are the force per unit length of the horizontal and vertical components of the yielded web plate along the height and length of the VBE and HBE, respectively (Berman and Bruneau, 2008; Sabelli and Bruneau, 2007); x is the distance from point C along the length of the HBE; and P_{s1VBE} is the horizontal reaction at the rocking point, which is a fraction of P_{s1} and calculated as follows:

$$P_{s1VBE} = P_{s1}\left(\frac{h-y}{h+\frac{d}{2}}\right) \tag{6}$$

In addition, V_i, the story shear force assumed to be applied equally at each end of the frame for the condition considered, is given by:

$$V_i = \frac{1}{2}\left(t_1 - t_2\right)F_{yp}\left(L - 2R\right)\sin 2\alpha \tag{7}$$

where t_1 and t_2 are the thickness of the web plate below and above the HBE, respectively; F_{yp} is the anticipated yield strength of the web plate; and α is the angle of inclination of the tension field of the web plate with respect to a vertical axis. Note that for use with multistory frames, the additional lateral story shear force at each HBE level due to multistory PT frame stiffness would have to be considered for preciseness in calculating the HBE demands. These equations would be considerably simpler for the case of a self-centering moment-resisting frame because there would be no contribution from the yielding SPSW web plate in the preceding equations, but rather a small contribution due to the type of energy dissipation element introduced in the connection (to reflect the schemes considered in research on PTED or SC-MRF).

SAP2000 ANALYTICAL MODEL COMPARISON

To verify the behavior of the proposed rocking connection and the hysteretic response of SPSWs having NewZ-BREAKSS connections, cyclic nonlinear static pushover analysis was first conducted using the computer program SAP2000 (CSI, 2009). The analytical model used consisted of a single-bay, single-story frame with a bay width of 20 ft and story height of 10 ft. The SPSW web plate consisted of a 16 gage steel plate with assumed expected yield strength of 46.8 ksi. A total of eight ½-in.-diameter grade 270-ksi steel tendons were provided at each end of the HBE with a distance of 6 in. below the neutral axis of the HBE to the centroid of the tendons (here, it is assumed the tendons would be placed equally along each side of the HBE web in a grouping of 2 × 2). An initial post-tensioning force of approximately 20% of the assumed yield strength of the PT was provided. The depth of the HBE was taken to be 18 in., representing the use of a W18 beam section.

A strip model was used for the SPSW web plate (Sabelli and Bruneau, 2007). Because the hysteretic behavior of SPSW relies on yielding of the web plate through diagonal tension field action, the web plate was modeled by using a series of tension-only strips. Each of the strips was assigned an axial plastic hinge model assuming an elastic perfectly plastic response to account for nonlinear hysteretic behavior. The thickness of the web plate was provided to ensure that the boundary frame and post-tension elements remained elastic. A combination of nodal joint constraints and SAP2000 gap link elements was also required to properly model the rocking joint behavior.

For the current example, the designed SPSW is used to avoid abstract complexities in keeping the problem parametric. Additionally, the boundary frame members are assumed rigid here such that PT force losses due to HBE axial shortening can be ignored, because this has a negligible impact on the results and keeps the conceptual illustration manageable. Ongoing research accounts for those effects that are secondary for the purpose of this technical note. However, the formulations developed earlier are applicable regardless of whether PT force losses are considered. Only the P_{s1} and P_{s2} terms in the moment equations are affected and would need to consider PT force losses due to axial shortening of the HBE due to the axial compression forces along the length of the HBE shown in Figure 2.

The comparison of the formulations developed describing the moment distribution along the HBE and also the system hysteretic response with the NewZ-BREAKSS connection is shown in Figure 3. It is observed that the proposed rocking connection provides recentering capability as observed by the hysteresis plots. A maximum displacement of approximately 3.6 in. was reached corresponding to a drift of 3%. The corresponding maximum base shear was approximately 256 kips. Note that because the boundary frame was modeled as rigid, this will lead to nearly simultaneously yielding of the web strips, which translates into the bilinear hysteresis loops observed (versus multilinear hysteresis loops that would be representative of a progression of web plate strip yielding, which would be observed in a boundary frame with flexibility).

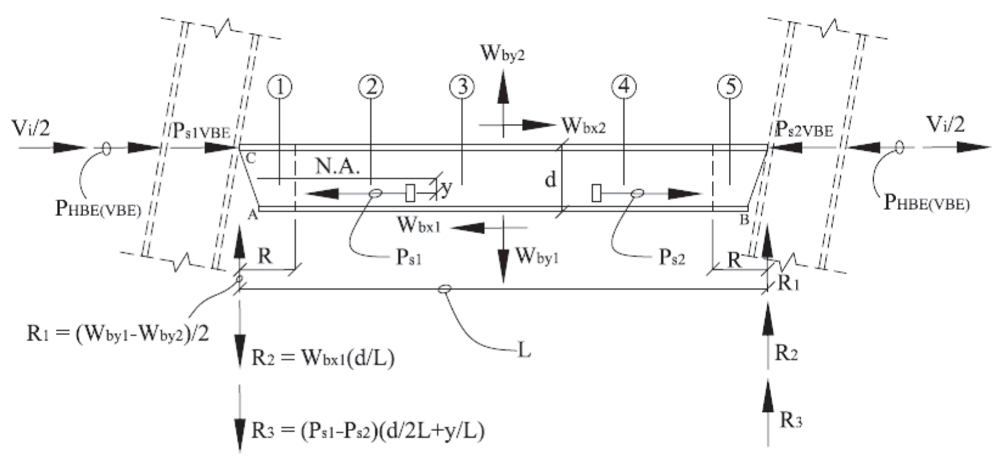

Fig. 2. Free-body diagram on HBE for rightward drift.

Additionally, the moment distribution obtained from the theoretical and analytical models are comparable. Note that the moment diagram shown is for a rightward 3% drift condition. From observation of the moment distribution, it can be seen that the PT force at the "opened" joint results in a vertical "step" in the moment diagram at the PT anchor location, as observed in Figure 3. The PT at the "closed" joint—for the condition shown—has become fully relaxed at this particular drift, and therefore no vertical step in the moment diagram is present at that location (which would not be the case otherwise).

Second, SAP2000 nonlinear time-history analysis was performed to verify the performance of the self-centering SPSW system with the NewZ-BREAKSS rocking connection under a more realistic loading environment due to a ground motion excitation. The same model was used as that for the cyclic nonlinear static pushover analysis, but a total frame tributary seismic weight of 350 kips was considered. For illustrative purposes only, the SAC LA14 ground motion was used as the ground motion input and is shown in Figure 4. The LA14 record is taken from the M6.7 Northridge earthquake record and is part of the Los Angeles suite of historical earthquake recordings, which were scaled to match the 10% in 50-year earthquake hazard for Los Angeles, California, as part of the 1997 SAC Joint Venture Project.

It is observed in Figure 4 that recentering under dynamic ground motion loading occurs for the given earthquake record as observed by the hysteresis plots. A maximum displacement of approximately 4 in. was reached, corresponding to a drift of approximately 3.4%. The corresponding maximum base shear was approximately 262 kips.

Note that a different hysteretic behavior would be obtained for a moment-resisting frame having the NewZ-BREAKSS rocking connections and would depend on the type of energy dissipation elements used in conjunction with the rocking beams (per the references cited earlier). Typically, those energy dissipation elements are weaker than the web plate of an SPSW but are able to dissipate energy in a repeatable manner. However, regardless of the different energy dissipation mechanism, the favorable characteristic of no beam growth would remain.

CONCLUSION

The NewZ-BREAKSS rocking connection provides the advantage of essentially no beam growth, thus mitigating damage to the floor diaphragm and beams while keeping

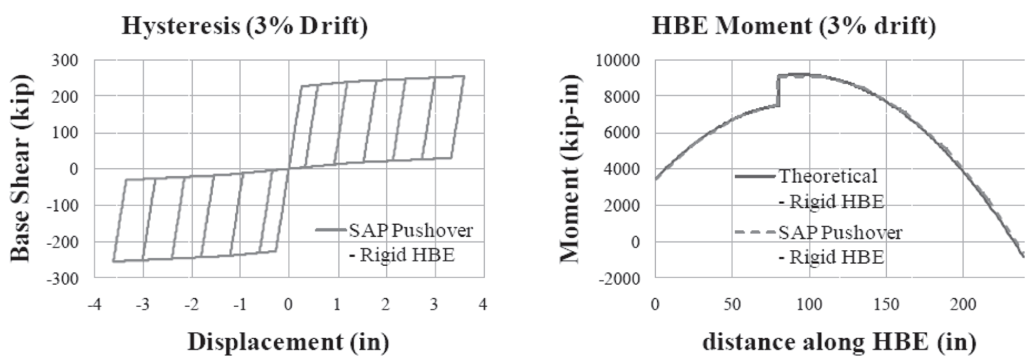

Fig. 3. SAP2000 pushover analytical versus theoretical comparison.

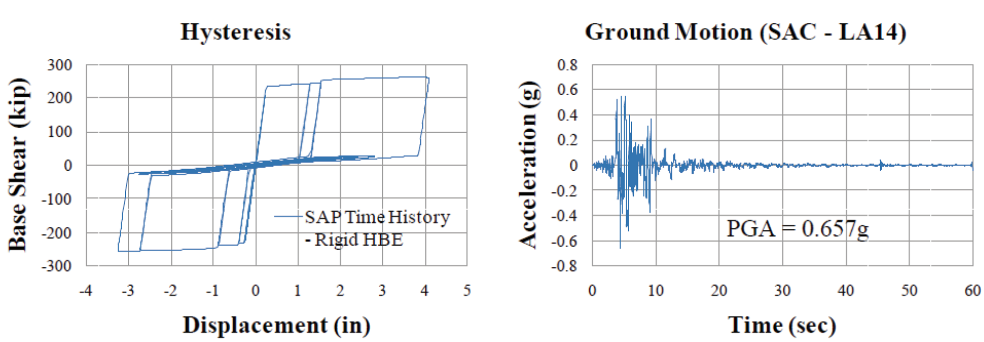

Fig. 4. SAP2000 nonlinear time history.

the desirable benefits of PT frames—namely, self-centering after an earthquake and limiting inelastic deformations to replaceable elements while the surrounding boundary frame remains elastic. Analytical modeling for use with self-centering SPSW systems was presented. Preliminary results from SAP2000 cyclic nonlinear static push-over and time-history analyses indicate that the NewZ-BREAKSS connection could be a viable option for self-centering systems. Future research is needed to further validate the connection, including experimental work to investigate its behavior and self-centering characteristics in a physical model.

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