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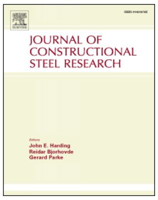

Behavior of post-tensioned connections with stiffened angles under cyclic loading

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ABSTRACT

Post-tensioned (PT) connections are used in steel moment resisting frames to eliminate structural damage and minimize residual drifts under seismic loads. A steel post-tensioned connection with top and seat angles has recently been developed. The angles act as energy dissipation devices in PT connections. In this research, stiffeners are added to the top and seat angles to improve the energy dissipation capacity of post-tensioned connections. Numerical analysis is performed and some relations are proposed to predict the behavior of post-tensioned connections with stiffened angles. The analysis results show that adding stiffeners to the connection angles increases the connection resistance at high inter-story drift angles. Moreover, stiffeners help concentrating the more residual deformation in the top and seat angles and increase the energy dissipation capacity of the connection. According to the results, we obtain modification factors as a function of angle and stiffener geometry in derived relations to predict the total connection moments under applied loading.

1. Introduction

Steel moment-resisting frames (MRFs) are designed to provide adequate ductility during earthquake excitements and dissipate seismic energy due to plastic deformations. Welded beam to column connections (pre-Northridge connections) were commonly used for steel moment resisting frames before the Northridge earthquake. The widespread damage to MRFs during the 1994 Northridge earthquake showed that these typical beam–column connections had inherent vulnerabilities at their beam-to-column welds. The complete penetration groove welds at top and bottom beam flanges that were fractured before deformation of plastic hinges in the beams [1].

The design approaches were modified by the Federal Emergency Management Agency (FEMA 350–351) [1,2] to provide stable plastic hinges in the beam without weld fractures. Many studies were performed to improve the cyclic behavior of beam–column connections in MRFs. Examples of such researches were done by Tremblay and Filiatrault [3] on reduced beam section (RBS) connections, Uang et al. [4] on rehabilitated connections with welded haunches, Engelhardt and Sabol [5] on reinforced connections with cover plates and Shiravand and Deylami [6] on restrained connections with side plates.

However, the inadequate performance of welded connections due to local buckling and yielding of beams led to utilize bolted beam-to-column connections. Many efforts have been made to improve bolted connections behavior under seismic loadings. Ricles et al. [7,8] developed post-tensioning approaches for steel bolted-connections. In post-tensioned connections, the angles are used as energy dissipation devices. Beams and columns remain elastic and the replaceable elements (angles) dissipate earthquake energy by inelastic deformations.

Ricles et al. [7–8] and Garlock et al. [9–11] carried out experimental studies on PT connection behavior. They investigated the effects of angle parameters on the energy dissipation capacity of PT connections. Typical geometry and idealized moment–rotation behavior of a PT connection with top and seat angles are displayed in Fig. 1.

Post-tensioned (PT) connections consist of bolted top and seat angles with post-tensioned strands. The transverse beam shear is tolerated by two angles and friction at beam–column interface. The strands are restrained at the ends of beam against column section and restore forces of connection. When the connection is subjected to moment, the post-tensioned strands clamp the beam firmly to the column and the beam flanges are in compression. When applied moment exceeds the moment capacity of the connection, force is released at the beam–column interface by angles. This process of releasing compression is called decompression. After decompression occurs, the gap at the beam–column interface is opened. As it is shown in Fig. 1(a), a PT connection shows flag-shaped response. θ_r is relative rotation between beam and column.

Christopoulos et al. [12–13] performed studies on a PT connection which used the combination of high-strength steel post-tensioned bars and confined energy dissipation bars to yield in tension and compression. The results showed that under high drifts, the system

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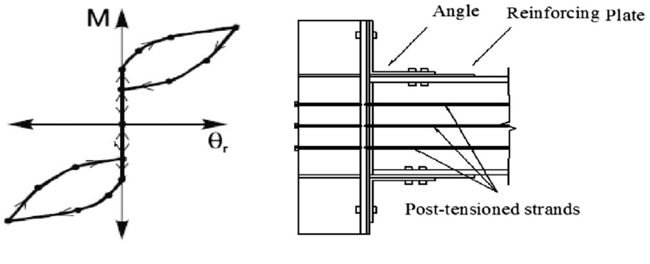

(a) (b)

Fig. 1. (a) Moment–rotation behavior [9], and (b) a typical PT connection.

returns to its initial condition and no damage observed in beams and columns.

Rojas et al. [14] studied a PT connection for a steel moment resisting frame with post-tensioned friction damped connections (PFDC) to increase the energy dissipation capacity. The results represented that the response of a PT frame exceeds that of a frame with a rigid connection and also good strength, ductility and energy dissipation observed.

Wolski et al. [15] performed an experimental study on connections with top and seat angles combined with post-tensioned strands which indicated that such post-tensioning concentrates inelastic deformation on angles. They concluded that the combination of post-tensioned strands and energy dissipating devices results in self-centering behavior by eliminating residual drifts of system.

Hadianfard et al. [16] made numerical studies on the effects of angle geometry on a PT connection behavior. The results showed that the energy dissipation capacity and post-yielding stiffness of a PT connection increase by increasing the angle thickness or decreasing the angle gage length. Moradi and Alam [17] performed finite element studies and simulated the cyclic behavior of PT connections with top and seat angles which previously were tested by Ricle et al. [7]. They verified the results of numerical simulation of PT connections with top and seat angles against experimental results.

Based on previous works, it can be seen that the energy dissipation capacity increases by increasing the angle thickness. The increase of thickness leads angles to yield in higher resistant moment of connection. Hence, instead of increasing thickness, we propose adding stiffeners to the top and seat angles. In this research, finite element models of PT connections with stiffened angles are developed to find out the stiffeners effects on energy dissipation capacity. Nonlinear analysis is applied and moment–rotation hysteresis curves of models are derived. Moreover, analytical relations are suggested based on equilibrium equations and numerical simulation results. The total moment of the PT connection is estimated through finite element analysis and proposed relations. Modification factors are obtained for a typical angle and stiffener which are used in this study. The results show that these factors depend on angle and stiffener geometry and can be calculated for other angle/stiffener geometries by numerical or experimental researches.

2. Development of analytical relations

Fig. 2 illustrates the deformation of a PT connection with stiffened angles. The gap opening at the beam–column interface controls the behavior of connection. The free-body diagram of a PT connection with stiffened angles is shown in Fig. 3.

The decompression moment, the moment which causes gap opening, is estimated as the equation below [11]:

$$M_d = d_e \frac{T_0}{2} \tag{1}$$

Where T_0 is the initial post-tensioning force of strands (shown in Fig. 3) and d_e is equal to the distance over the depth of the contact areas between beam flanges and column ($d_e = 2d_c$). Decompression and gap opening at the beam–column interference cause strands elongating and producing an increase in strand forces. The total post-tensioning force in a PT connection can be considered as follows [11]:

$$T_t = T_0 + 2d_c\left(\frac{k_s k_b}{k_s + k_b}\right)\upsilon_r \tag{2}$$

In this equation k_b and k_s are the axial stiffness of the beam and strands, υ_r is the relative rotation between beam and column.

To investigate the behavior of the PT connection with stiffened angles, firstly, the common PT connection with top and seat angles is considered as shown in Fig. 4(a). The simplified model of a-deformed angle for per unit width is considered to study the angle behavior at ultimate limit state (Fig. 4(c)). As the connection is subjected to the moment, gap at beam–column interface starts to open and leads angles to deform up to three plastic hinge zones are generated during plastic mechanism (Node A, B and C in Fig. 4(b)). Moments and forces produced in angle during plastic deformation at ultimate limit state are shown in Fig. 4(c) and the equilibrium equations are used to determine these forces.

Considering the moment equilibrium of column leg (AB) and beam leg (BC) for the deformed angle, following equations can be derived:

$$M^1_{AB} + M^1_{BA} + V^1_a \Delta_{gap} - T^1_a g = 0 \tag{3}$$

$$M^1_{BC} + M^1_{CB} - V^1_a L = 0 \tag{4}$$

where M^1_{AB},M^1_{BA}, M^1_{BC} and M^1_{CB} are moments per unit length at nodes A, B and C, respectively, g and L are the distance between the filet

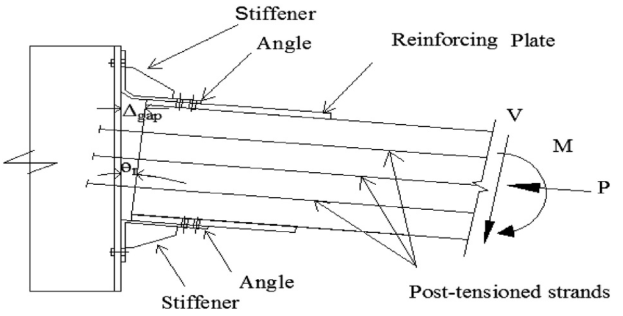

Fig. 2. Deformation of a decompressed PT connection with stiffened angles.

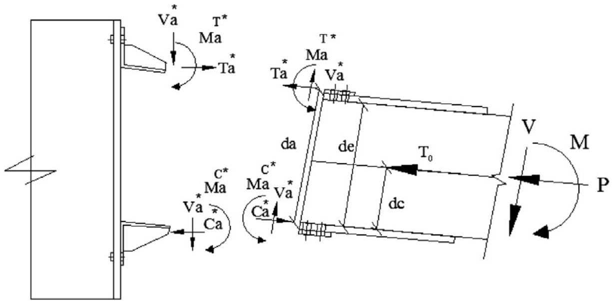

Fig. 3. Free-body diagram of a PT connection with stiffened angles.