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CYCLIC BEHAVIOR OF POST TENSIONED STEEL BEAM COLUMN CONNECTIONS WITH REDUCED LENGTH STRANDS

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Abstract: The use of posttensioning techniques in steel beam-column connections can improve the re-centering capability and reduce permanent deformation. Reliable finite element model can be used to investigate the load carrying capacity of the post tensioned (PT) steel beam column connection under cyclic loading, which is both time and cost saving. The optimum performance of the PT connection depends on several design parameters. Reducing the length of PT strands can be an option to minimize the overall cost without compromising the performance. This study considers five different strand lengths which may affect the performance of the connection during cyclic loading. A three-dimensional finite element model is developed in ANSYS and validated with experimental results. Difficulties that may arise during the validation stage due to the complexity in connection geometry, bolt pretension, gap opening/closing and contact behavior are discussed. Finally, the cyclic responses of those connections are examined in terms of stiffness, strength, energy dissipation capacity, and residual displacement.

1 INTRODUCTION

In the past earthquakes, traditional moment resisting frames suffered serious damages. Most of the buildings failed in the regions of beam-column connections in a brittle manner. After the hazardous behavior of steel moment resisting frames, concerns were raised among the researchers about the performance of those connections. As a result, partially restrained connections (PR), have been developed and attracted considerable attention over the past few years (Ricles et al. 2002). Fully restrained connections have shown poor hysteretic behavior and are found to be inefficient during strong earthquakes. Different techniques such as the use of flange reinforcing plate, bolted haunch brackets and the use of welded haunch brackets are also investigated by Fang et al. (2014) and Wolski et al. (2009). However, the damage of steel moment resisting frames under moderate to severe earthquakes is still inevitable.

Due to the permanent deformation of a steel moment resisting frame after a severe earthquake, it is almost impossible to repair it afterwards. In some cases, the cost involved in repairing the deformation is much higher and not economically feasible. To minimize or remove the permanent deformation, research has been done on some smart materials (i.e shape memory alloy) to evaluate its applicability. Shape memory alloys (SMAs) have shown good prospect to be used in steel moment resisting frames, bracing systems, isolation of structures and retrofitting purposes (Alam et al. 2007). However, the major concern is the cost. Shape memory alloy is expensive and large amount of material is needed for civil engineering applications. This high cost is due to its complex training process, manufacturing process and lack of proper behavior under dynamic loading (Alam et al. 2007). Alternatively, the structures can incorporate some energy dissipation techniques in such a way that the damage is confined within those elements. These elements undergo inelastic deformation while other structural components such as beams and columns remain essentially elastic, a concept similar to the use of partially restrained connection. However, the performance of partially restrained connections can be further improved by introducing post tensioning into the moment resisting frames (Ocel et al. 2004; Qiu and Zhu 2014; W. Wang, Fang, and Liu 2016; Wei Wang et al. 2015; Wolski et al. 2009). The connections have the ability to re-center and absorb energy during lateral loading and damaged components can be repaired afterwards. These connections use PT high strength steel strands to assemble beams and columns. Shim plates are used in the beam-column connection face to prevent localized stress. Depending on the mechanism of energy dissipation of the connection, different combinations of element have been studied (Vasdravellis, Uy, and Karavasilis 2012; Rojas, Ricles, and Sause 2005; Christopoulos et al. 2002). Recently, finite element models for PT steel connections were developed by Moradi and Alam (2016). The finite element modeling in the present study generally followed the guidelines and techniques provided by Moradi and Alam (2016). The results of sensitivity analyses and optimization study of PT steel beam-column connections were reported in (Moradi et al. 2015) and (Moradi and Alam 2017a), respectively. The effect of beam section was assessed by Moradi and Alam (2017b) in a study of the limit state behavior and lateral load drift response of PT connections.

The aim of this study is firstly to develop finite element models for our future studies, and secondly, to evaluate the performance of PT connections with a shorter length strand. A validation study followed by parametric studies has been done to understand the behavior of these connections.

2 REFERENCE PT CONNECTION

The experimental details of an interior PT beam column connection (Figure 1) from Ricles et al. (2002) is used as a basis for the verification of the finite element simulations. The connection consists of a column, beams, angles, shim plates, reinforcing plates, washer plates and bolts. The column and beam sections are W14×311 and W24×62, respectively. From the tested specimens by Ricles et al. (2002), herein specimen PC4 is modeled in ANSYS (Release 17.2). The connection incorporates four high strength post tensioning strands on each side of the beam web. The PT strands, with the ultimate strength of 1864 MPa, pass through the column flange parallel to the beam and are initially post tensioned by a force of 34% of their ultimate tensile strength.

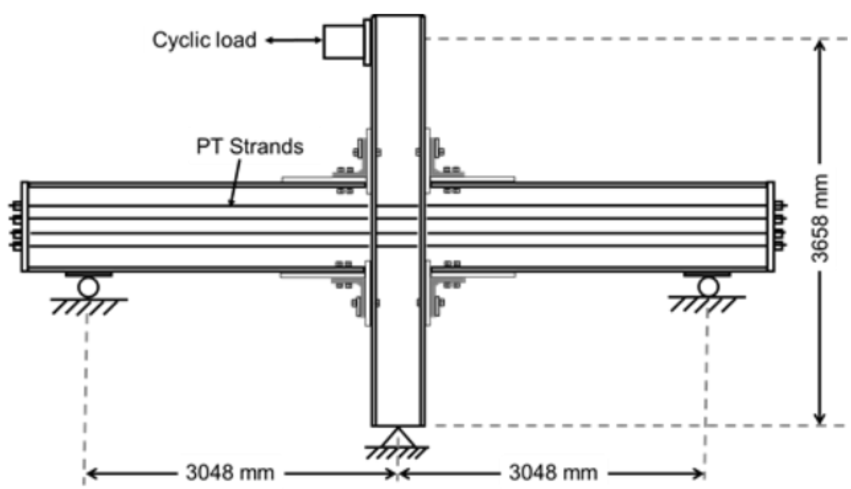


Figure 1: Schematic of PT beam column connection tested by Ricles et al (2002) (Adapted from Moradi, Alam, and Milani (2015)).

3 DEVELOPMENT OF FE MODELS

The finite element modeling in this paper generally followed the guidelines and techniques provided in Moradi and Alam (2016). Figure 2 shows the three-dimensional geometry of the developed model. Considering the symmetry condition, half of the total connection is modeled in order to reduce the computational time. The main challenges during the validation study are to overcome the convergence difficulties. The techniques found useful in solving the convergence difficulties are discussed in the following sections.

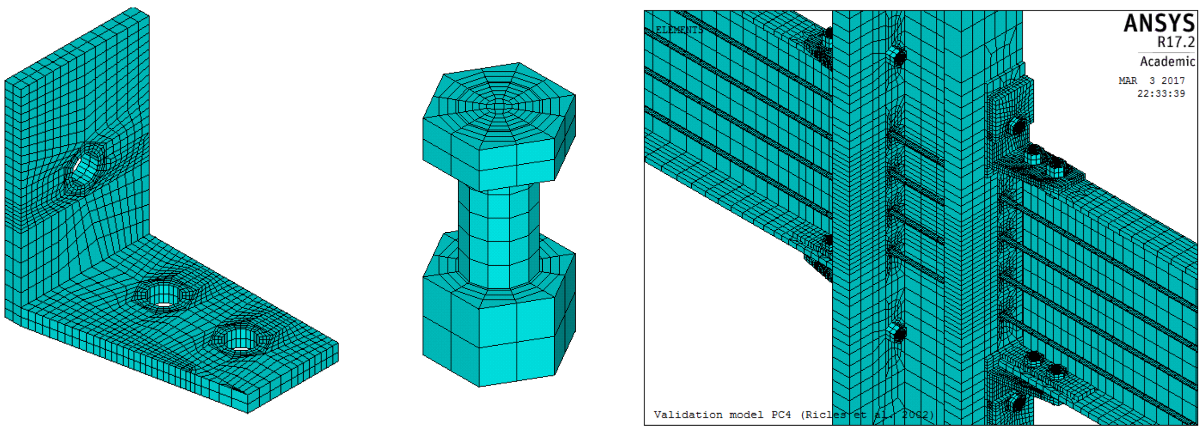


Figure 2: Developed FE model for experimental specimen PC4

3.1 Material Properties

For modeling the steel components of PT connection, a bilinear kinematic behavior is assigned, except for the steel angles for which a tri-linear stress-strain behavior is considered (Figure 3). The strain hardening parameter (alpha) is assumed to be 0.01 for beam web and flange, flange reinforcing plate, shim plate and bolts. The modulus of elasticity and Poisson’s ratio for all steel materials are assumed to be 200 GPa and 0.3, respectively.

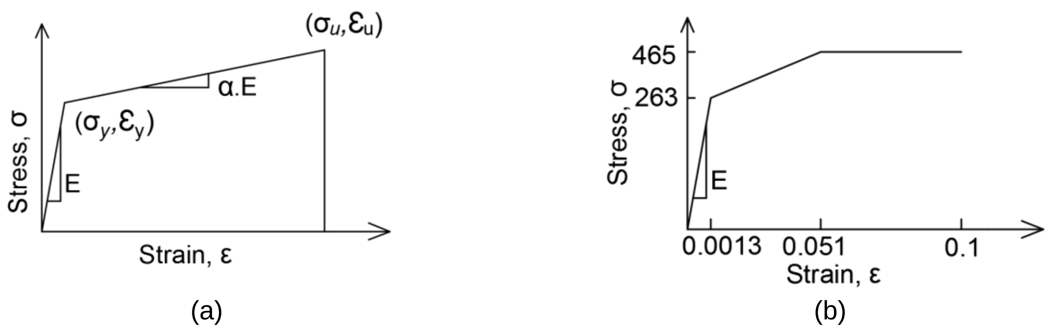


Figure 3: Material properties assumed for (a) all steel components, and (b) steel angles

3.2 FE Mesh and Contact

A different meshing approach has been used in this study from that used by Moradi and Alam (2016). A mesh only element (i.e. Mesh200) is used from the element library of ANSYS to have better control over the mesh density. This mesh element is used to extrude a low dimensional mesh to a higher dimensional mesh. The mesh density is controlled at the point of interest and where there is a higher possibility of stress concentration. Eight node solid homogenous elements (SOLID 185) are used afterwards to extrude the meshed area into a volume. The accuracy of the model can be increased by using finer mesh, however, it becomes computationally more demanding. Therefore, the selection of optimum mesh sizes is an important part of a finite element analysis. A mesh sensitivity analysis is conducted to choose the optimum amount of element which gives reasonable result and at the same time reduces the computation time. Contact surface is one of the most important parts of these kinds of models. The CONTA173 and TARGE170 elements which are very efficient for the surface to surface contact modeling, are used herein. Frictional coefficient for all contacts is taken as 0.4. Contact elements are defined between the column flange and shim plate, shim plate and angle surface, angle and beam flange, and reinforcing plate and beam flanges. Since, half of the total beam column connection is simulated in this study, the symmetry boundary condition is applied in the horizontal direction of this connection. The following properties recommended by Moradi and Alam (2016) are used to solve the divergence problem.

1. Gauss point detection is used to detect the location of contact.
2. Both initial geometric penetration (gap) and offset are excluded from the analysis.
3. The contact algorithm is set to penalty function

3.3 Analysis

Nonlinear static analysis with the unsymmetrical Newton-Rapson method is utilized to solve the convergence issue. Large deformations of solid elements are also permitted due to the geometric nonlinearity. To avoid convergence issue, small time steps are predefined using the “DELTIM” command. The pretension forces are applied to the bolts and strands. The amount of pretention forces is equal to the 70% of the tensile strength for bolts according to the ASTM specifications and Ricles et al. (2002). The loading sequence is determined to simulate the actual loading condition. At initial time steps pretension force in the bolt is applied which is about 230kN (Moradi, Alam, and Milani 2015). The PT forces in the strands are applied afterwards, the amount of which on each strand is about 88kN. The horizontal loading is applied on the top nodes of the column. The loading cycles applied on the column have the amplitudes of 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 1, 1.5, 2, 2.5, and 3%. As can be seen in Figure 4, the FE model predicts the PT beam-column connection behavior very well.

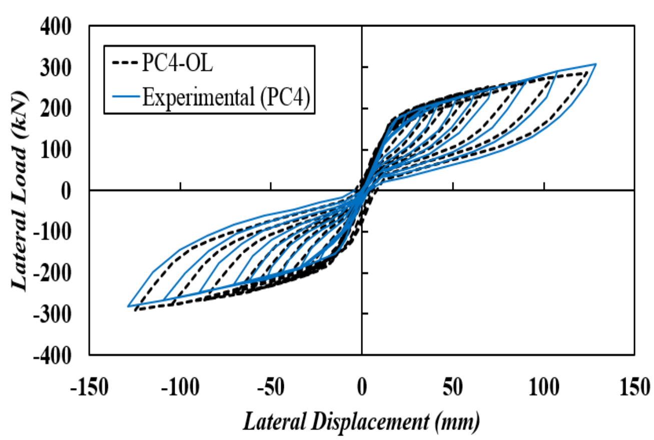
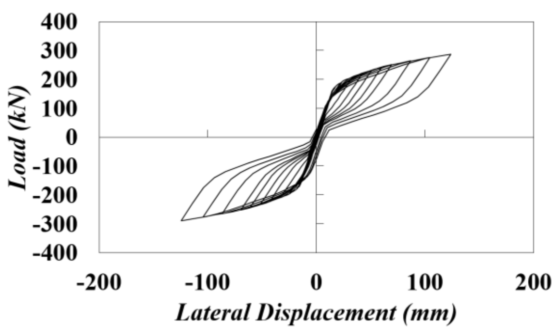


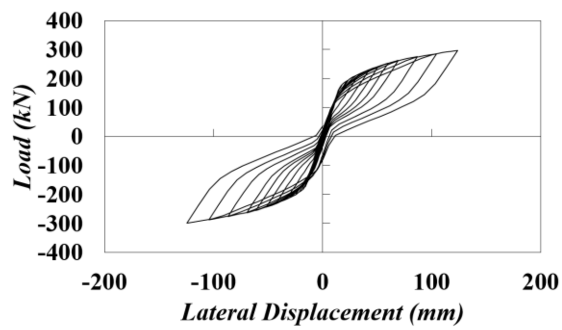
Figure 4: Analytical model vs experimental response (Ricles et al. (2002))

4 PARAMETRIC STUDIES

In order to examine the effects of PT strand length, specimen PC4 from Ricles et al. (2002) is modeled and analysed considering four different length other than the original specimen (PC4-RL1, PC4-RL2, PC4-RL3, and PC4-RL4). Table 1 lists these models alongside the response parameters. The post tensioning strand length considered in this study are 1019 mm (PC4-RL1), 1528 mm (PC4-RL2), 2038 mm (PC4-RL3), 2292 mm (PC4-RL4), and 3057 mm (PC4-OL). In Table 1, K_i, M_d and M_{max} indicate the initial stiffness, decompression moment, and maximum moment capacity, respectively. The lateral load displacement response is compared with the validated model (PC4-OL). The results show that the initial stiffness increases with the decrease in PT strand length. Due to the increase in initial stiffness, the decompression moment and maximum moment capacity increase (Figure 5). That means, for connections with shorter length, decompression starts at earlier displacements, leading to a larger gap opening between beam and column at large drifts. For the specimen, PC-RL1 (PT strand length is one third of the original length), stiffness increased by about 20% compared to the specimen PC4-OL (PT strand is equal to the original length). For the other specimens, the increase is about 3-6%.



(a)



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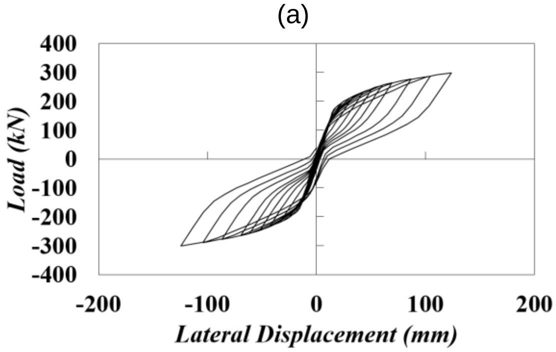

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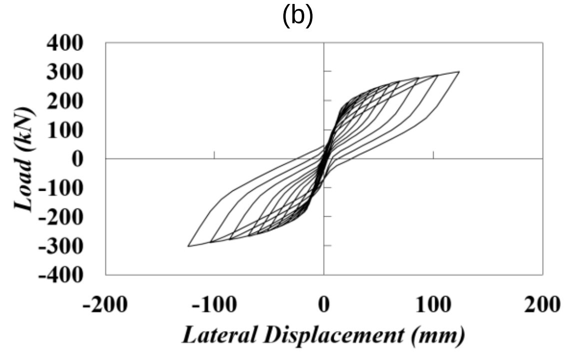

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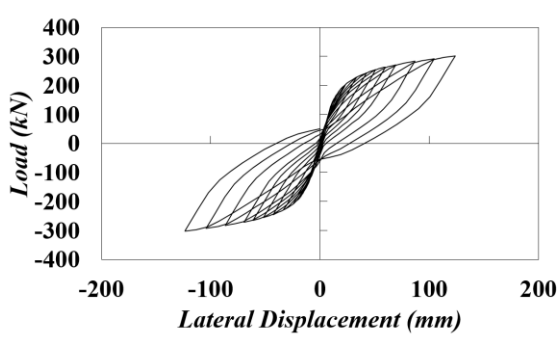

(e)

Figure 5: Analytical response of specimens (a) PC4-OL, (b) PC4-RL1, (c) PC4-RL2, (d) PC4-RL3, and (e) PC4-RL4

When the post tensioning strand length reduced from 3057 mm to 1019 mm (approximately a 33% decrease), the maximum decompression moment increased from 218.6 kN-m to 240.12 kN-m. The moment capacity of PT connection also increased due to the reduction of strand length. The amount of increase in the moment capacity of PC-RL4, PCRL3, PC-RL2 and PC-RL1 is 3, 4, 4, and 5.4%, respectively.

Table 1: Response values observed at 3% drift

Specimen	PT strand length (mm)	K_i (kN/m)	M_d (kN-m)	M_{max} (kN-m)
PC4-RL1	1019	12792 (1.27)*	247.12 (1.16)	514.17
PC4-RL2	1528	11291 (1.12)	238.05 (1.12)	509.03
PC4-RL3	2038	10998 (1.09)	220.08 (1.04)	507.47
PC4-RL4	2292	10906 (1.08)	218.97 (1.03)	504.63
PC4-OL	3057	10578 (1.05)	218.6 (1.03)	487.58

*Ratio between FE analysis results and experimental results

5 SUMMARY AND CONCLUSION

Five different three-dimensional FE models for the PT steel connections with top and seat angles were developed and analyzed in this study. The cyclic performance of different configurations was evaluated based on initial stiffness, decompression moment and maximum moment capacity. The findings and observations from the finite element analyses are summarised below:

- The results of the FE analyses were sufficiently consistent with the experimental results. Therefore, this model can be used further to examine the self centering behavior with different parameters.
- The length of post tensioning strand can be minimized provided that the limit states associated with its cyclic behavior are prevented before reaching an ultimate capacity.
- Based on parametric studies, a decrease in PT strand length by 33% (from 3057mm to 1019mm) resulted in 20% higher initial stiffness, 13% higher decompression moment, and 5% higher moment capacity. However, PT connection with reduced strand length shows poor self centering behavior under cyclic loading. Because, shorter length induced higher stress on PT strand and caused early yielding of steel strand. Therefore, length reduction of steel strand without affecting the performance of the connection is not a viable alternative to consider.

The FE models developed herein will be used by the authors for a series of future studies. The FE study can also be extended by introducing different energy dissipation mechanisms. The limitation of this study is that, the analysis cannot capture the material fracture, fatigue behavior of steel angles, dynamic loading rate effects, and out of plane movement of the connection components. Future research can focus in implementing these important aspects in finite element modeling. It can be concluded that, the length reduction of PT steel moment resisting frames is not possible without any effect on the self-centering capability of the connection. Therefore, introduction of advanced materials to improve the existing connection with much less cost can be the future scope of research in this field.

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