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THE BEHAVIOR OF A NEW STEEL POST-TENSIONED CONNECTION FOR FRAMED STRUCTURES

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ABSTRACT
As the most effective mechanical and structural systems are usually the simplest, the development of a new method based on past experience can be very useful. The use of a cable as a tensile member and variations made in geometry of a connection via steel solid nodes to strengthen and to eradicate the weak points in a connection are among the main features of the present research. The combination of a post-tensioning method and the rigidity of a steel node with a semi-circle geometry have led to the clamping effect in the flanges. This Post-Tensioned Solid Node (PTSN) systemized approach to steel/concrete construction streamlines and transforms traditional design and construction processes. The present research, introduces a new type of PT connections using high strength post-tensioned cables wrapped around rigid quadrants of circles that provide for rigidity, strength, and self-centering of the connection. This new connection is experimentally validated under a cyclic loading condition. In addition, using nonlinear finite element analysis, performance of the connection is further assessed to investigate how various parameters influence the cyclic performance and failure modes of the proposed connection. To study the general behavior of this connection, an initial test has been conducted together with finite element methods before conducting more extensive research. This post-tensioned solid node steel connection is experimentally validated under quasi-static monotonic loading conditions. The experimental prototypes of the connection were subjected to concentrated loads at the end of a cantilever beam and were tested under different conditions of post-tensioning, various diameters and tensile strength for the cables. In addition, using a nonlinear FEM the performance of the connection was further assessed to investigate how various parameters influenced the cyclic performance and failure modes of the proposed typology.

KEYWORDS: steel connection; post-tensioned; finite elements; cyclic test.

INTRODUCTION
The inappropriate behavior of moment resisting steel frames in 1994 *Northridge* earthquake resulted in sudden failure in beam-to-column connections. As a result, various new configurations have been proposed for upgraded moment-resisting joints, including post-tensioned (PT) connections. *Shen* and *Astaneh-Asl* proposed a PT connection comprised of seat and top angles and PT strands (Shen J. and Astaneh-Asl A., 1999). They undertook monotonic and cyclic tests on the connection and reported a stable cyclic response and an appropriate hysteretic energy dissipation capability. As different alternatives to the weld connections, *Ricles* et al. (2001) proposed a PT connection with top and seat angles and *Christpoulos* et al. (2002) proposed PT energy-dissipating bar connections in moment frames.

Energy-dissipating devices used at the top and bottom of PT connections undergo damage subsequent to large cycles of deformation. As a result, they need to be replaced after a major seismic event, which has proven to be an operational and economic problem arising after large-scale earthquakes. To overcome this problem, *Rojas* et al. proposed a kind of PT friction-damped connection for moment resisting frames (2005). *Morgen* et al. (2003) and *Wolski* et al. (2006) also proposed other friction devices for self-centering moment-resistant frames. To prevent interaction with the floor diaphragm, these devices were positioned at the bottom flange of beams and were able to be replaced easily if necessary. Although the above post tensioning proposals were resulted in most cases in enhancing the energy-absorption capability of the connection, in many cases rigidity of the connection was traded off with the result of increasing the relative rotation of the connection.

The proposed PT connection
Configuration

The PT connection proposed in this study consists of two main parts: the top and bottom rigid quadrants (or nodes) (4 pieces), and the PT cables (2 pieces). This is shown schematically in Fig. 1 where the slotted quadrants provide for a moment resisting bearing for the beam and secure the PT cables in their place to apply the PT force before construction of the floor slab. As anticipated, radius of the quadrants is a determining geometric dimension. On one hand, it should provide for a minimum installation space and on the other hand, it is to supply maximum strength and stiffness for the connection. To maintain distance between the nearby quadrants on the flanges of various beams, a suitably sized box-shaped solid segment is placed between the quadrants. Although the connection is ordinarily designed with two cables, it is possible to contemplate accommodation of more cables with the number and diameter of the cables and the post-tensioning force depending on the design requirements.

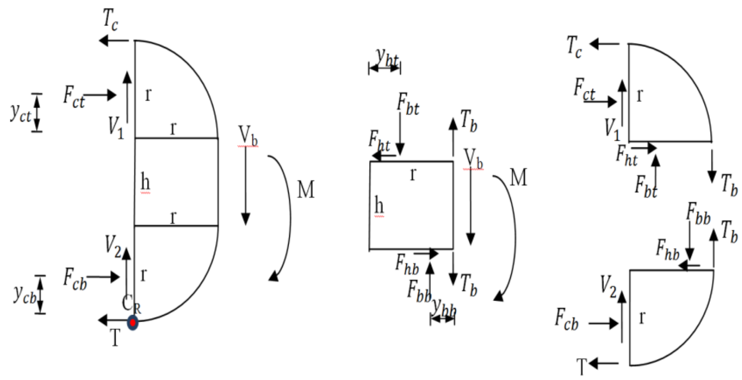

Fig.1 : Detail of free-body diagram and the proposed PT connection.

As it appears, the proposed connection eliminates the need for any on-site welding to joint up beams and columns. Behavior of the connection can be described using the free-body diagram shown in Fig.1. In this figure, normal and tangential components of the contact forces are shown. Also, the cable force changes from T_c at the top to T_b at the beam to T at the bottom of the connection. As seen, the system is 5 times indeterminate externally and 6 times internally. A determining point during lateral behavior of the above system is when the bearing stress between the quadrant and column face becomes zero at the topmost level. In this situation, distribution of the compressive bearing stress is triangular at the top, and trapezoidal at the bottom, with the same slope. Therefore, points of application of F_{ct} and F_{cb} are known. Besides, if it is assumed that in this case $V_1 = V_2 = V_b/2$ and T is the known initial pretension of the cable (assuming that the contact surface between the quadrant and the column face is rigid relative to the cable), then the increased cable tension, T_c, and the maximum bearing stress at the lowest point of contact, σ_c, both at the column, obtained from following equations. By summing moments about the beam center of rotation C_R, maximum compressive stress at the lowest point of contact, will be:

$$\sigma_c = \left[\frac{(V1+V2)C^2}{I_c} + \frac{F_{ct}(y_{ct}+h+r-y_{cb})+F_{cb}y_{cb}C}{I_c}\right] \quad (1)$$

In which, I_c is moment of inertia of the column. This equation can be expressed in the simpler form.

$$\sigma_c = [V_bC-M-V_br+T_c(h+2r)]C/I_c \quad (2)$$

Where C is equal to the distance over the depth of the beam between the centroids of the contact areas between the beam flanges and column (i.e., C= h). Since σ_c is sufficient to produce initial yielding, from the horizontal equilibrium, we will denote it as T_c.

$$F_{ct} + F_{cb} - T - T_c = 0 \qquad (3)$$

$$F_{ct}(y_{ct}+h+r-y_{cb})+F_{cb}y_{cb}+T_c(h+2r)+M+V_br = 0 \qquad (4)$$

We can calculate F_{ct} and F_{cb} for any assumed value of y_{cb} and y_{ct}.

$$F_{ct}= -[T_c(h+2r)+M+V_br]/[y_{ct}+h+r-2y_{cb}] \qquad (5)$$

$$F_{cb}=T+T_c+[(T_c(h+2r)+M+V_br)/(y_{ct}+h+r-2y_{cb})] \qquad (6)$$

The forces F_{ht} and F_{ct} are in horizontal equilibrium with the post-tensioning force (T_c) in the top quadrant, then:

$$F_{ht}+F_{ct}-T_c=0 \qquad (7)$$

$$F_{ht}=T_c-[(T_c(h+2r)+M+V_br)/(y_{ct}+h+r-2y_{cb})] \qquad (8)$$

The analytical study of Sec. 2 shows that, having a strong column, the decisive parameters of the proposed connection are: the plastic moment of the beam, the ultimate capacity (or the diameter) of the cables, and the pretension force ratio. These parameters are related to each other through Eqs. (1-5). Varying the parameters the moment-rotation curve of the connection can be determined analytically (Sec. 2), experimentally (current section), and numerically (Sec. 4) tasks followed by a comparison of the results. Also, stiffness, strength, and ductility of the connection are compared with a conventional moment resisting joint connecting the same beam and column under the same load. A test set-up consisting of a 1.5~3.0 meter long cantilever column bearing a variable length beam at the middle of its height is considered. The testing load is applied vertically at the end of the cantilever (Fig.2).

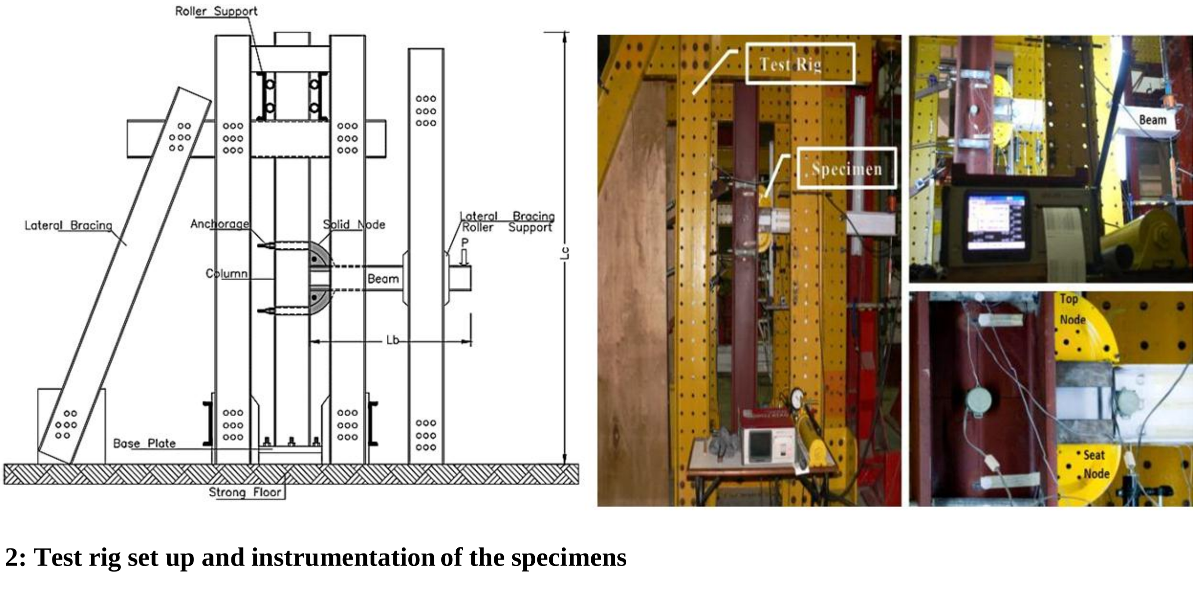

Fig. 2: Test rig set up and instrumentation of the specimens

CONCLUSIONS

In this paper a new post-tensioned moment-resisting connection, called the PTSN connection was presented for seismic applications. Equations were developed for the main internal forces induced in the connection with certain simplifying assumptions. Monotonic experiments on five specimens of the proposed connection confirmed its suitability for practical usage. A more extensive part of the research was focused on nonlinear finite element analysis of a larger number of samples of the connection. The failure modes of the connection were detected to be shear failure of the column web in the connection zone, bearing failure at the toe of the quadrant-column or quadrant-beam contact area, slippage at the same area, cable failure in tension, and bending failure due to plastic hinge formation at the junction of the beam and the quadrant segments, with the last one being the desired ductile failure mode. In the numerical analysis, effects of plastic bending capacity of the beam, tensile capacity of the cables, and the pretension ratio on the failure modes were investigated. It appears that the connection possesses higher stiffness and consequently less lateral displacement compared to moment-resistant frames. Moreover, the cyclic behavior of the PTSN connection was analyzed and its advantages over the common moment-resisting and some other pre-tensioned connections were illustrated comparatively. Finally, based on the mentioned analysis and tests, certain recommendations were made regarding ductile design of the proposed PTSN connection.

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