EXPERIMENTAL VALIDATION OF SELF-CENTERING STEEL MOMENT CONNECTIONS WITH WEB HYSTERETIC ELEMENTS

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1 ABSTRACT

Self-centering steel moment resisting frames have been developed as an alternative to conventional steel moment resisting frames aiming to eliminate structural damage and to minimize residual drifts under the design earthquake. In this paper, a new self-centering beam-to-column connection typology is proposed. The connection uses post-tensioned high strength steel bars to provide self-centering capability and a new energy-dissipation system consisting of yielding web hourglass pins which can be very easily replaced if damaged. The connection performance is experimentally validated under quasi-static cyclic loading. The experimental results show that the proposed connection exhibits stable self-centering behaviour and energy dissipation. The connection specimens are imposed to drift levels far beyond the expected design ones in order to identify all possible failure modes.

2 INTRODUCTION

Conventional ductile steel moment-resisting frames (MRFs) are currently designed to form a global plastic mechanism under strong earthquakes through the development of plastic hinges at the end of beams and at the base of the columns [1]. This design approach provides well known advantages such as acceptable behaviour able to protect human life, economy, low base shear force and controlled total floor accelerations. However, plastic hinges in structural members involve significant cyclic inelastic deformations and local buckling which result in difficult to inspect and repair damage as well as residual drifts. Therefore, conventional steel MRFs result in socio-economical losses such as damage repair costs and loss of building use or occupation after a major seismic event. In addition, they may result in building demolition due to the complications associated with repairing large residual drifts. Research efforts developed self-centering steel moment resisting frames (SC-MRFs) with post-tensioned (PT) connections [2]. SC-MRFs have the potential to eliminate inelastic deformations and residual drifts under strong earthquakes as the result of several features: softening force-drift behaviour due to separations (gap openings) developed in beam-to-column connections; re-centering capability due to elastic pre-tensioning elements (e.g., high strength steel bars) providing clamping forces to connect beam and columns; and energy dissipation capacity due to energy dissipation elements (EDs) which are activated when gaps open. When properly designed, these EDs can be easily inspected and replaced. In this paper, a new SC beam-to-column connection typology is proposed. The connection uses PT high-strength steel bars to provide self-centering capability and new EDs consisting of yielding web hourglass pins (WHPs) which can be very easily replaced if damaged. The connection performance is experimentally validated under quasi-static cyclic loading conditions. The experimental results show that the proposed connection exhibits stable self-centering behaviour and energy dissipation. The connection specimens are imposed to drift levels far beyond the expected design ones to identify all possible failure modes.

3 SC PT CONNECTION WITH WHP

3.1 *Structural details*

The proposed SC PT connection was designed to provide stable self-centering capability and increased energy dissipation with the aid of high strength steel bars and WHPs which do not interfere with the floor slab and are very easy to replace. Fig. 1 shows a 3D representation of the proposed connection. The figure represents the actual configuration of an exterior connection of a steel SC-MRF. Two high strength steel bars located at the mid-depth of the beam, one at each side of the web, are anchored to the exterior column flange and pass through holes drilled on the column flanges. The bars are post-tensioned and hence, clamp the beam to the column while providing self-centering capability. WHPs consist of two pairs of steel pins which are inserted in aligned holes drilled on the web of the beam and on strong supporting plates. The pairs of WHPs are symmetrically placed (close to the top and bottom beam flange) to provide increased lever arm and hence, increased internal moment resistance under cyclic connection rotations.

The WHPs are designed to have an hourglass shape to provide enhanced energy dissipation and fracture capacity [3]. Both sides of the beam web are reinforced with steel plates which increase the contact surface between the WHPs and the web. In this way, possible ovalization of the sides of the holes drilled on the web and the reinforcing plates under the high WHP bearing forces will be negligible and connection pinching behaviour can be avoided. The strong supporting plates are welded on the column flange. The connection also includes beam flange reinforcing plates to avoid excessive early yielding in the beam flanges under the high PT bars forces. In addition, the panel zone is strengthened with horizontal stiffeners and continuity plates along the web of the column.

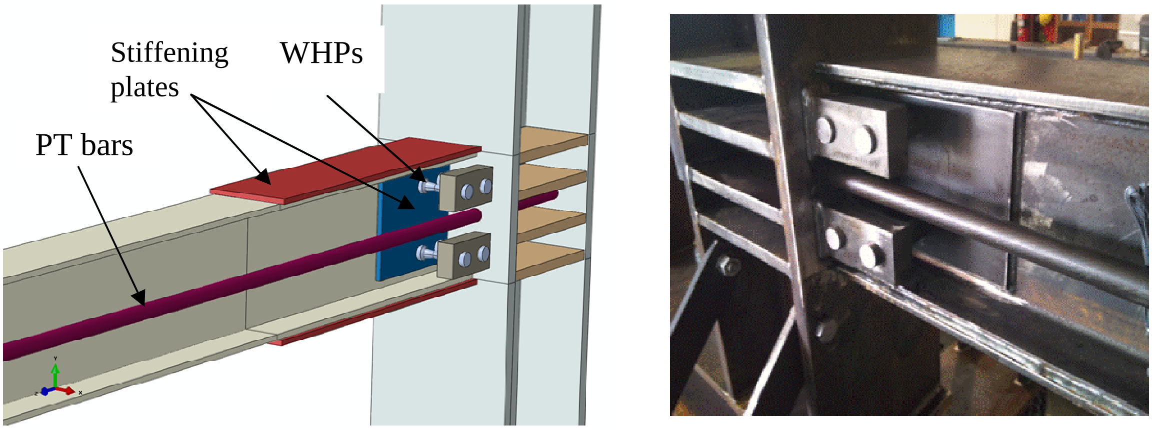


Fig. 1. Left: 3D representation of the proposed self-centering PT connection and Right: a photo of the connection in the Lab.

4 DESIGN OF PROTOTYPE SC PT CONNECTION WITH WHP

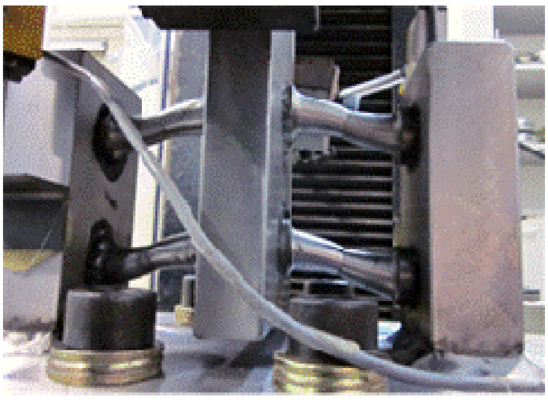
The design focuses on the exterior connection of the 4th floor of a prototype steel building [4]. This connection is designed as a self-centering PT connection with WHPs using the methodology presented in [3]. This methodology uses two major performance objectives and associated structural limit states, namely: (1) Immediate Occupancy (IO) under the design basis earthquake (DBE) by avoiding damage in beams and columns while permitting gap opening (it is assumed that damaged WHPs can be replaced without disturbing building occupation); and (2) Collapse Prevention (CP) under the maximum considered earthquake (MCE) by avoiding PT bar yielding and beam local buckling while permitting minor yielding in beams and columns. The MCE has intensity equal to 150% the intensity of the DBE.

The above performance objectives proposed in [3] may result in sudden loss of strength and stiffness due to undesirable failures related to beam local buckling or tendon yielding when the connection is deformed beyond the MCE drift limit. In this work, the details proposed by Kim & Christopoulos [5] are employed to avoid local buckling and form a ductile plastic hinge at the end of the flange reinforcing plate for drifts equal or higher than the MCE drifts. This design approach is slightly different than the one presented in Kim and Christopoulos [6] where the ductile plastic hinge is formed for drifts equal or higher than the DBE drifts.

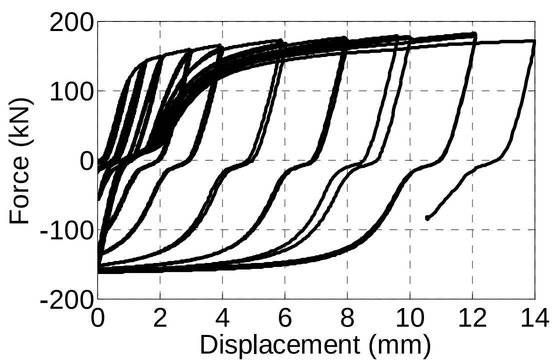
The design of the connection is based on story drifts equal to 0.64% under the FOE, 1.6% under the DBE and 2.4% under the MCE. These drifts are significantly lower than those used in previous works based on the IBC 2% drift limit under the DBE due to the strict serviceability drift limits imposed by the EC8 under the FOE. The FOE has intensity equal to 40% the intensity of the DBE. PT bars are designed to avoid yielding for $\theta_r \leq 0.07$ rad. This value eliminates the possibility of strand yielding since beam shortens (and the stress in the PT bar is reduced) due to the plastic hinge formation for drifts higher than the 2.4% MCE drift.

5 WHP COMPONENT TESTING

Component tests on the WHPs were conducted in order to assess their energy dissipation capacity and ductility under cyclic loading. Two pins were tested in order to reproduce the behaviour of the WHPs in the proposed SC connection typology. The supporting plates were welded on a fixed plate and the plate simulating the web of the beam was attached to the actuator applying the load. The thicknesses of the plates were equal to the thicknesses of the corresponding components in the connection tests described later. The induced displacement history was chosen to be consistent with that used for the connection tests, i.e., the required displacement of the pins due to the imposed connection rotation in the actual tests was calculated and applied as the component testing displacement history. The WHPs were designed in order to guarantee a stable and ductile hysteretic behaviour and to maximize the energy dissipation capacity during a seismic event. The hourglass geometry of the pins was calibrated in order to be consistent with the bending-moment diagram. In this way, a more efficient energy dissipation capability is ensured. Moreover, probable associated pinching effects are avoided. Fig. 2a shows the WHPs at ultimate deformation levels during the component tests. This deformation corresponds to a connection rotation of about 0.06 rad. The pins were capable of sustaining repeated large inelastic cycles without fracturing prior to an imposed displacement corresponding to 7% drift. Fig. 2b plots the force-displacement cyclic relationship achieved by the WHPs. The pins provided a force equal to 160kN. It is evident that the developed geometry resulted in a highly-dissipative system with good hysteretic behaviour and high ductility levels.



a)



b)

Fig. 2. a) Ultimate deformation and b) hysteretic force-displacement loop of the WHPs.

6 LARGE-SCALE CONNECTION TESTS

6.1 *Test setup*

The test setup is schematically shown in Fig. 3. The 250UB37 beam was connected to a strong 310UC158 column. Two additional steel members were welded to the column to form a truss system in order to minimize the column deformations (the 310UC158 horizontal member and the 200UC52 diagonal member). The whole system was bolted on the strong floor. The imposed displacement history was applied vertically by a 2000kNcapacity and 250mm-stroke hydraulic actuator. The actuator was positioned at a distance of 1800mm from the beam-column face and thus was able to impose a joint rotation equal to 7%, much larger than the target rotation of 2.4%, corresponding to the MCE level.

6.2 *Specimens*

Two specimens representing the proposed SC post-tensioned connection were designed according to the procedure described in Section 4. Due to laboratory limitations, the specimens were designed at a 0.6 scale with respect to the original dimensions of the prototype building. The resulting beam and column sizes and relevant details of the connections are summarized in Table 1.

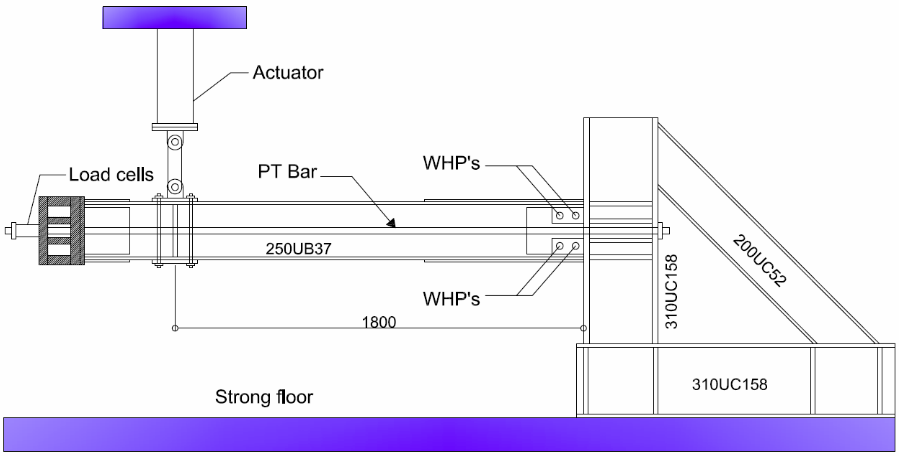


Fig. 3. The test setup

The two specimens were identical except that four longitudinal stiffeners were welded on the web and four 27mm-holes were drilled on the flanges of the second specimen, according to Kim & Christopoulos [5]. The details of this configuration are shown in Fig. 4. The purpose of this configuration is to eliminate local buckling effects on the beam web or flanges. Instead, a plastic hinge is intentioned to be formed at the end of the reinforcing plate. In this way, sudden failures and local instabilities are avoided and a ductile ultimate failure mode under large inelastic drifts is ensured.

Specimen:	**SC-WHP1**	**SC-WHP2**
Beam section	250UB37	250UB37
Column section	310UC158	310UC158
Initial post-tension	500	500
Length of reinforcing plates	700	700
Longitudinal stiffeners	NO	YES

Table 1. Specimen details

6.3 *Material properties*

The beam and column were made of F_y=300Mpa steel, while the yield strength of the reinforcing plates, stiffeners and pin-supporting plates was $F_y=350Mpa$. The post-tensioned bars were made of high-strength steel, with nominal yield strength equal to 930MPa and a fracture stress limit equal to 1060MPa. The pins were made of 1020 grade carbon steel with nominal yield strength of 500MPa. This type of steel was chosen in order to achieve the required strength provided by the WHPs to the connection, while keeping the sizes of the pins relatively small. Also, this specific material was the most suitable for fabricating the hourglass shape of the WHPs.

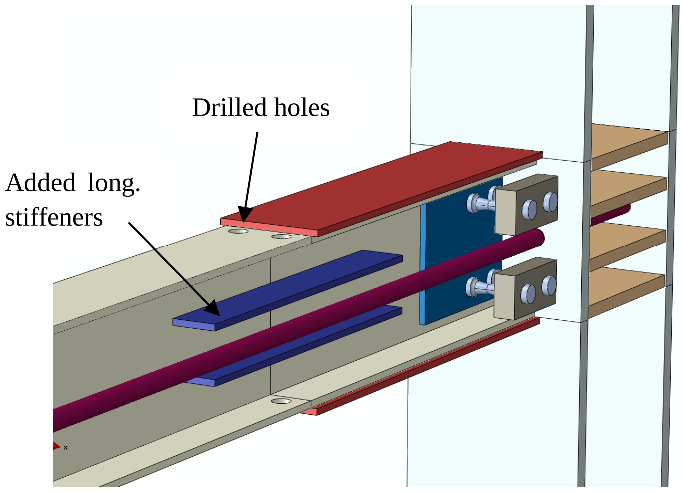


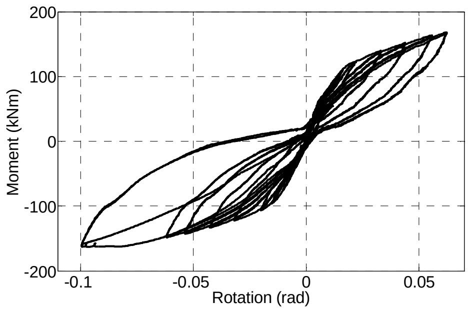
Fig. 4. Details of the second specimen

6.4 *Experimental results*

The specimens were loaded under displacement-controlled conditions, according to the AISC loading protocol [7]. The cyclic hysteretic response of the two specimens is shown in Figs. 5 in terms of the respective moment-rotation loops. It is shown that the specimens had a full self-centering capacity up to rotations equal to 0.05 rad. In fact, no damage in any part except the WHPs was observed up to this rotation levels. This rotation is considerably larger than the specified target rotation of 0.035 rad, which is set as the required rotation capacity of a connection for Ductility Class High (DCH) structural design concept in Eurocode 8. Nevertheless, the connections were loaded to excessive drift levels in order to identify all possible failure modes. A final cycle of 10% drift was imposed for this purpose. It can be seen from Fig. 5 that after the last large imposed displacement the connection lost its self-centering capability and a permanent deformation was present at the end. The failure modes were different in the two specimens. The failure mode of specimen SC-WHP1 was the local buckling of the beam which took place immediately after the end of the reinforcing plates on the beam flanges. The buckling initiated at the web and propagated to the flanges. This failure caused a significant drop in the stiffness of the connection. The specimen SC-WHP2 had a different failure mode than the first one. The reinforced with the longitudinal stiffeners web did not show any evidence of local buckling, and the behaviour was stable and ductile. However, the failure has occurred due to local buckling of the beam flanges at the contact regions with the column. It has to be noted that the design procedure adopted for the detailing of the specimens, and especially that for the determination of the length of the reinforcing plates on the beam flanges, is rather conservative, as it was proved by the experimental behaviour. In fact, local buckling in specimen SC-WHP1 has occurred at considerably larger drift levels than those intended by the design procedure.

7 SUMMARY AND CONCLUSIONS

Two specimens representing a new steel post-tensioned connection were designed and tested under cyclic quasi-static loading. The proposed connection configuration is equipped with a set of hourglass-shaped steel pins acting as energy dissipaters under earthquake loading. The specimens were loaded to drift levels far beyond the expected design ones in order to identify all possible failure modes. The connections performed well showing full self-centering capacity up to drift levels equal to 0.05rad. Under the design earthquake drift levels, damage was mainly concentrated to the energy dissipation pins which can be easily replaced after a seismic event. In large drifts, the failure modes were mainly the local buckling of the beam web and flanges immediately after the end of the reinforcing plates and the local yielding in the beam due to bearing forces at the contact regions with the column flange. The experiments demonstrated the adequacy of the adopted detailing method to avoid local buckling failure at large drift levels.



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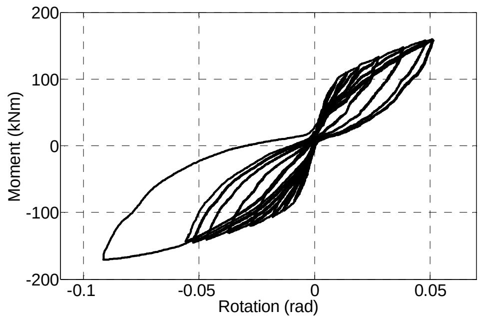

b)

Fig. 5. Moment-rotation hysteresis loop for specimens a) SC-WHP1 and b)SC-WHP2.

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ΠΕΡΙΛΗΨΗ

Ένα σχετικά πρόσφατο πεδίο έρευνας αποτελούν τα μεταλλικά πλαίσια με συνδέσεις που έχουν την ικανότητα να επανέρχονται στην αρχική τους θέση. Για το σκοπό αυτό τοποθετείται ένα σύστημα από προεντεταμένα καλώδια υψηλής αντοχής, τα οποία αγκυρώνονται στα δύο εξωτερικά υποστυλώματα του πλαισίου. Οι δυνάμεις προέντασης παρέχουν τη δύναμη επαναφοράς του πλαισίου στη αρχική του θέση ύστερα από μία σεισμική καταπόπνηση. Στην παρούσα εργασία, προτείνεται μία καινούρια τυπολογία αυτο-επαναφερόμενης σύνδεσης δοκού-υποστυλώματος. Στη σύνδεση τοποθετείται ένα σύστημα μεταλλικών στοιχείων που σκοπεύουν στην απορρόφηση σεισμικής ενέργειας μέσω ανελαστικής (υστερητικής) κάμψης. Τα στοιχεία αυτά είναι εύκολο να αντικατασταθούν ύστερα από μια έντονη σεισμική καταπόνηση, καθιστώντας την κατασκευή βιώσιμη. Η συμπεριφορά της σύδεσης εκτιμήθηκε πειραματικά υπό κυκλική καταπόνηση. Τα πειραματικά αποτελέσματα έδειξαν ότι η προτεινόμενη σύνδεση διαθέτει σταθερή αυτο-επαναφερούμενη συμπεριφορά και ικανοποιητική ικανότητα απορρόφησης ενέργειας. Τα δοκίμια φορτίστηκαν σε πολύ υψηλότερα από τα αναμενόμενα επίπεδα παραμόρφωσης έτσι ώστε να εξεταστούν όλες οι πιθανές μορφές αστοχίας.