DISSIPATIVE EMBEDDED COLUMN BASES FOR ENHANCED SEISMIC PERFORMANCE OF STEEL MOMENT RESISTING FRAMES

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1. SUMMARY

This paper presents an innovative design concept for embedded column base (ECB) connections. The developed ECB connection achieves a non-degrading hysteretic response. In the proposed ECB connections, the dissipative zone is shifted into the embedded portion of the steel column inside the reinforced concrete (RC) foundation. This is achieved by lowering the flexural strength of the embedded column portion by reducing the column flange width, by keeping the RC foundation elastic, and by decoupling the flexural behavior of the steel column from that of the RC foundation. A debonding material layer that is wrapped around the embedded column portion is used for this purpose. Nonlinear geometric instabilities of the embedded column portion are prevented because of the surrounding concrete, which realizes a stable energy dissipation mechanism. The proposed concept is validated through large-scale quasi static cyclic testing as well as complementary finite element simulations. These demonstrate that the dissipative ECB connections behave as intended. More specifically, the proposed dissipative ECB connections do not experience flexural strength deterioration of the connection up at least to 4 % rads and they minimize column axial shortening.

2. INTRODUCTION

First story fixed-end steel columns in moment resisting frames (MRFs) experience inelastic cyclic local buckling under earthquake shaking [1]. This, in turn, may trigger member instabilities (i.e., lateral torsional buckling) that often act synergistically with local buckling and compromise the load carrying capacity of steel columns [2]–[4]. Research studies with emphasis on fixed-end columns highlighted another instability mode associated with column axial shortening [2], [5]–[7], which is shown in Figure 1 for hollow structural steel (HSS) and I- or H-shaped steel columns. Consequently, this could impair decisions regarding the structural repairability and demolition due to vertical residual deformations [7], [8].

Motivated by field observations [9], [10] as well as complementary numerical studies [11], [12] the authors have developed a new concept that enables weak column base connections to provide energy dissipation during an earthquake rather than concentrating the inelastic deformations within the column portion above the footing. While similar work on exposed column bases has been conducted [13]–[16], the primary focus of this paper is on dissipative embedded column bases (ECBs) that are common in mid- and high-rise steel MRF construction at least in North America. In the subsequent sections, the primary concept development is presented along with its validation with large scale experiments and complementary finite element simulations.

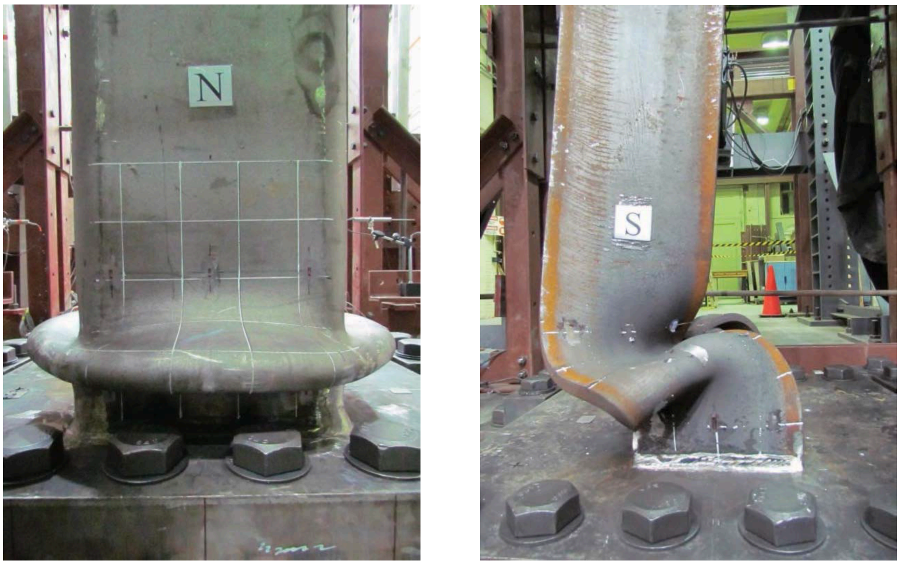


Fig. 1 seismic stability of steel columns with emphasis on axial shortening (images adopted from Suzuki and Lignos [6]).

3. CONCEPT DESCRIPTION AND EXPERIMENTAL VALIDATION

Figure 2a depicts the proposed dissipative ECB connection. The embedded portion of the column should dissipative the energy during earthquake loading. The reinforced concrete (RC) foundation should remain elastic when the column flange bears on the footing. The column flange within the embedded portion is reduced to lower its flexural strength. The decoupling of the flexural behavior of this portion from that of the RC foundation enables the column itself to deform freely. This is accomplished with a debonding material that wraps around the embedded portion of the steel column prior to its installation and casting of the footing. This material minimizes friction between the steel and concrete interfaces. In such a concept, the surrounding concrete provides lateral stability to the embedded column web and flanges, thereby preventing the formation of local buckling and enabling instability-free hysteretic behavior under cyclic loading. More details regarding the concept are presented in Inamasu et al. [17].

The concept validation was accomplished with a large-scale experimental program that featured both conventional and dissipative ECB specimens. These featured a cantilever steel column welded to a steel end plate, which was embedded into the RC foundation. The column cross section featured an IPE400 made of S355J2+M steel. The ECB specimen length was 2575mm long. The embedded depth was 850mm. Figure 2b illustrates one of the test specimens after the completion of the installation in the test setup. The concrete footing was 1075mm tall and had a footprint of 1885 x 685 mm. The conventional ECB specimen was designed according to the AISC seismic provisions [18]. Each test specimen was subjected to a unidirectional standard symmetric cyclic loading protocol [19] in displacement control through a 1000kN servo hydraulic actuator. Lateral bracing was provided to the test specimens (see Figure 2b) through horizontal beams as the intention was to characterize only the planar behavior of the ECB connections.

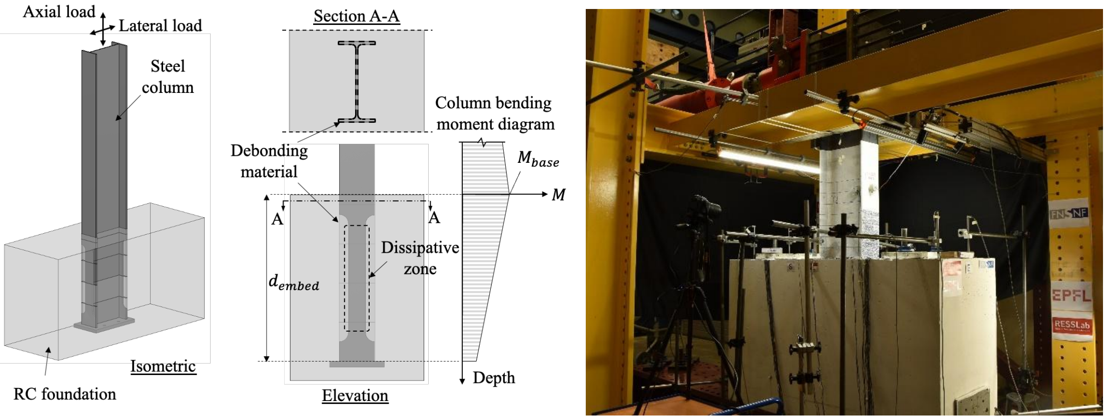
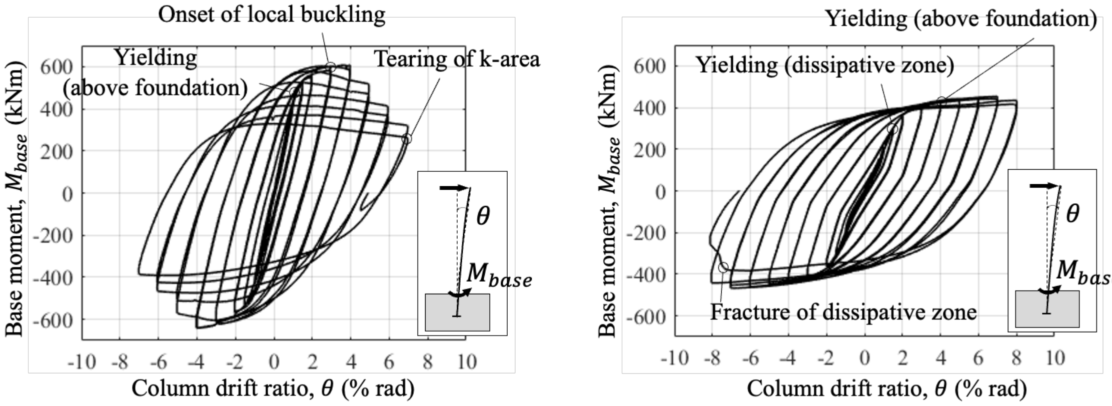


Fig. 2 Overview of dissipative embedded column base concept (Inamasu et al. [17]).

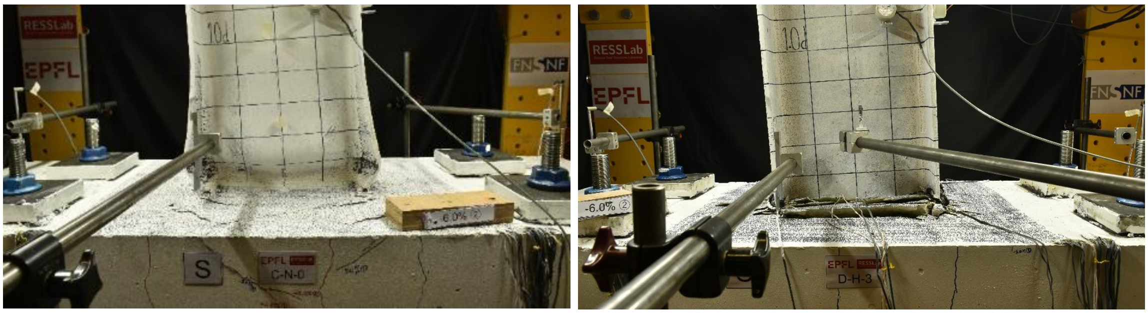
Figure 3 illustrates the experimental results for the conventional (see Figure 3a) and one of the dissipative (see Figure 3b) ECB connections. The former experienced flexural yielding and local buckling near the base above the concrete footing as depicted in Figure 4a. The onset and progression of local buckling caused cyclic deterioration in flexural strength of the steel member. Mild cracking was also observed in the footing. The application of loading stopped once ductile tearing occurred in the k-area within the local buckling region. Conversely, the dissipative ECB specimen exhibited a non-degrading hysteretic behaviour till about 8% rad lateral drift demands (see Figure 3b). As such, there was no sign of visual damage in the steel member as well as the RC foundation (see Figure 4b). The concrete inside the footing remained elastic as witnessed from the cuts that were done with a diamond saw after the end of the testing program [17]. The ultimate failure mode of the test specimen featured fracture due to ultra-low-cycle fatigue within the reduced flange of the embedded steel column portion. Referring to Figure 3b, the elastic stiffness of the dissipative ECB connection is comprised of two linear stages. Both of which can be derived analytically as suggested in Inamasu et al. [17].



(a) (b)

Fig. 3 Comparison of base moment – column drift ratio relation between (a) conventional and (b) dissipative ECB specimens.

Overall, the test results demonstrated that the proposed concept was successfully validated. The behaviour of a wider range of dissipative ECB connections was further explored with continuum finite element simulations. A summary of those is presented in the next section.

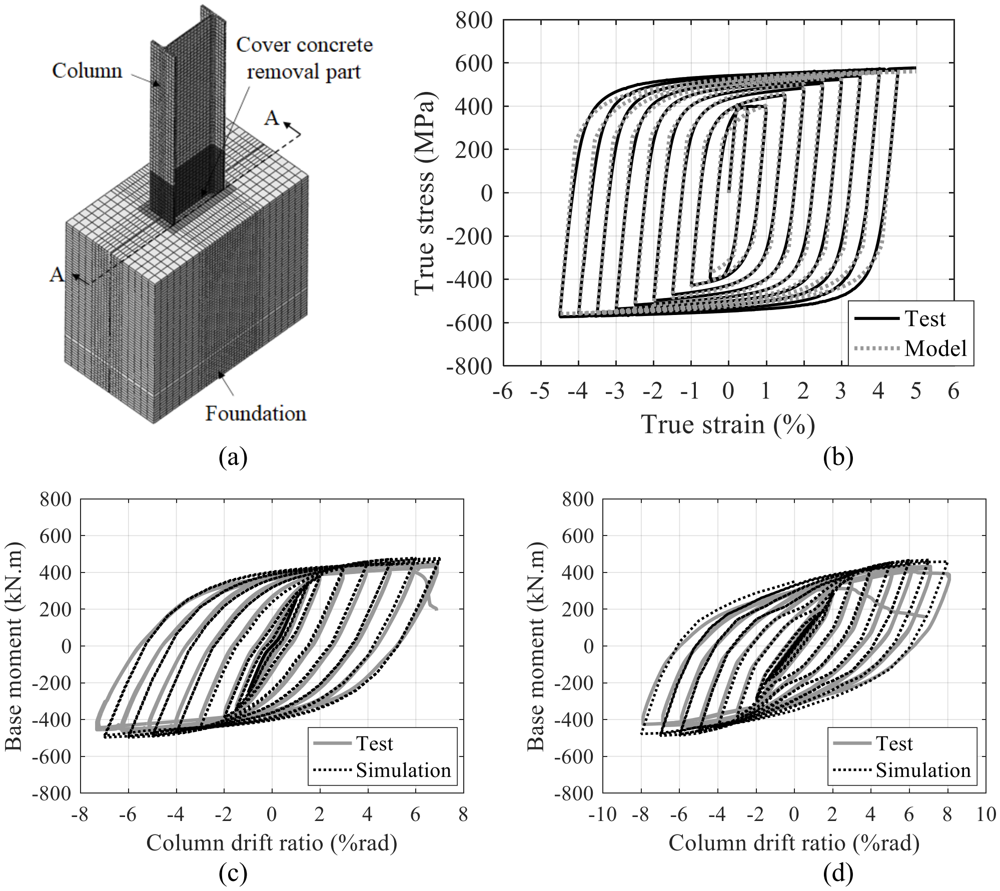


(a) (b)

Fig. 4 Damage patterns at lateral drift demands of 6% rads between (a) conventional and (b) dissipative ECB specimen (image from Inamasu et al. [17]).

4. COMPLEMENTARY FINITE ELEMENT STUDIES

This section summarizes in brief complementary finite element simulations that were conducted to further exploit the proposed concept. The simulations were carried out in the commercial finite element analysis program ABAQUS [20]. Figure 5a illustrate the finite element model specifics. The concrete foundation was modeled with linear solid elements (C3D8R) whereas the steel column was modeled with quadrilateral solid elements (C3D20R) both of which employ reduced integration. The steel material plasticity was considered with the updated Voce and Chaboche (UVC) model as proposed by Hartloper et al. [21]. The model was calibrated to cyclic data from round coupon samples based on the procedures discussed in [21], [22]. A sample calibration at the material scale is shown in Figure 5b. Further details regarding the finite element model specifics are presented in [23]. The proposed model of the dissipative ECB was validated to the acquired test data described in the previous section. Figures 5c and d illustrate sample comparisons for two of the tested dissipative ECB specimens. The comparisons suggest that the accuracy of the developed finite element model is noteworthy. Complementary finite element simulations were carried out with the same model to exploit the influence of loading history, bidirectional effects, the local slenderness, the axial load ration as well as the boundary conditions. These studies are documented in detail in Inamasu and Lignos [23].

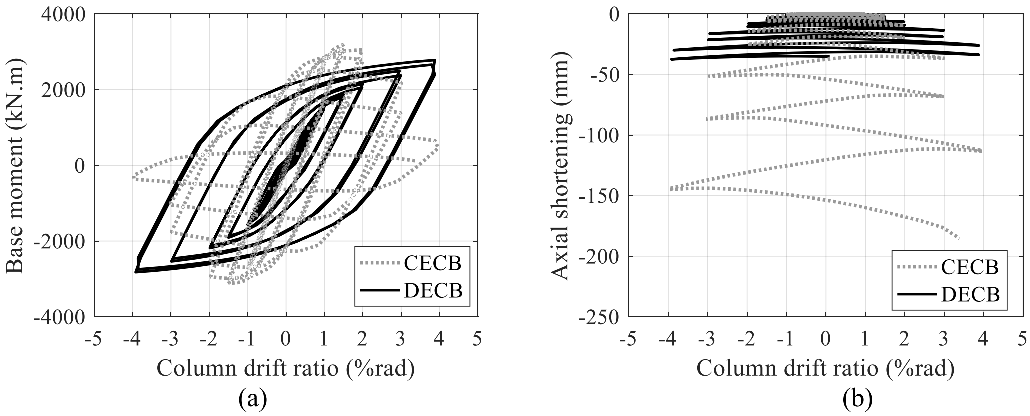


(a) (b)

(c) (d)

Fig. 5 Finite element model specifics and validations with experimental data (adopted from [23]).

Figure 6 illustrates comparisons between the behavior of a dissipative ECB connection (termed DECB) featuring a W30x148 steel profile and its conventional embedded column base counterpart (termed CECB). The comparisons are based on two performance indicators, i.e., the base moment and column axial shortening versus the column drift ratio.



(a) (b)

Fig. 6 Comparisons of the hysteretic response of conventional and dissipative ECB connections; (a) base moment versus column drift ratio; (B) axial shortening versus column drift ratio (adopted from [23]).

Figure 6a demonstrates that steel columns in dissipative ECBs become resilient to local buckling even at relatively large lateral drift demands (i.e., 4% rad) relative those in conventional ECBs where local buckling may occur even at modest lateral drift demands (i.e., 2% rad). Consequently, column axial shortening is minimal in the former compared to the latter as shown in Figure 6b. This aspect is important from a repairability standpoint in the aftermath of earthquakes as structural repairs within the local buckling region are challenging and costly. Moreover, residual axial shortening could be a driving reason for building demolition in addition to residual drifts [8], [24].

5. CONCLUSIONS

This paper presents the development of a new concept for embedded column bases (ECBs) that are traditionally designed as strong relative to the respective column strength. The new concept defies the current paradigm by introducing a dissipative zone within the embedded portion of the steel column to the reinforced concrete footing. The paper highlights the primary features of the proposed concept along with its experimental validation at the Structures Laboratory of EPFL. The experiments demonstrated that the dissipative ECB connection is characterized by a non-degrading hysteretic behavior even at 8% rad. The ultimate failure mode is ductile fracture initiation and propagation due to ultra-low-cycle fatigue. Complementary finite element analyses of other column sizes and foundations demonstrate the efficiency of the proposed concept on making the steel columns resilient to local buckling even at large lateral drift demands. Column axial shortening is also minimized, which is an important local engineering demand parameter that controls structural repairability and demolition in the aftermath of earthquakes.

6. ACKNOWLEDGMENT

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ΕΓΚΙΒΩΤΙΣΜΕΝΕΣ ΣΥΝΔΕΣΕΙΣ ΕΔΡΑΣΗΣ ΥΠΟΣΤΥΛΩΜΑΤΩΝ ΜΕ ΔΥΝΑΤΟΤΗΤΑ ΑΠΟΡΡΟΦΗΣΗΣ ΕΝΕΡΓΕΙΑΣ ΓΙΑ ΒΕΛΤΙΣΤΗ ΣΕΙΣΜΙΚΗ ΣΥΜΠΕΡΙΦΟΡΑ ΜΕΤΑΛΛΙΚΏΝ ΠΛΑΙΣΙΩΝ

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ΠΕΡΙΛΗΨΗ

Στο άρθρο παρουσιάζεται μία καινοτόμα ιδέα σχεδιασμού εγκιβωτισμένων συνδέσεων έδρασης μεταλλικών υποστυλωμάτων καμπτικών φορέων με δυνατότητα απορρόφησης ενέργειας υπό σεισμική διέγερση. Οι συνδέσεις αυτές επιτυγχάνουν ευσταθείς βρόγχους υστέρησης ακόμα και σε μεγάλες ανοιγμένες μετατοπίσεις ορόφων (π.χ., 4% rad). Η περιοχή απορρόφησης ενέργειας βρίσκεται στο τμήμα του υποστυλώματος το οποίο είναι εγκιβωτισμένο μέσα στο θεμέλιο οπλισμένου σκυροδέματος. Αυτό επιτυγχάνεται με την απομείωση της καμπτικής αντοχής του εγκιβωτισμένου τμήματος του υποστυλώματος με ελεγχόμενη κοπή μέρους των πελμάτων του καθώς και με τη χρήση στρώματος υλικού αποκόλλησης (debonding layer) το οποίο τυλίγεται γύρω από το εγκιβωτισμένο τμήμα του υποστυλώματος. Ο τοπικός λυγισμός στο τμήμα αυτό αποτρέπεται λόγω της παρουσίας του περιβάλλοντος σκυροδέματος, το οποίο παρέχει πλευρική εξασφάλιση στον κορμό και στα πέλματα του υποστυλώματος. Η συμπεριφορά των ανωτέρων συνδέσεων πιστοποιήθηκε με πειραματικές δοκιμές ανακυκλιζόμενης φόρτισης καθώς και με χρήση συνεχών πεπερασμένων στοιχείων.