Development of dissipative embedded columns base connections for mitigating column axial shortening

Hiroyuki Inamasu[1[0000-0001-9224-3285]], Albano de Castro e Sousa[2],

and Dimitrios G. Lignos[2[0000-0003-0682-4660]]

[1] École polytechnique fédérale de Lausanne, Lausanne, Vaud, CH-1015, Switzerland (Current affiliation: Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan)
[2] École polytechnique fédérale de Lausanne, Lausanne, Vaud, CH-1015, Switzerland
dimitrios.lignos@epfl.ch

Abstract. This paper proposes an innovative design concept for embedded column base (ECB) connections featuring wide flange steel columns. The developed ECB connection achieves a non-degrading hysteretic response up to lateral drift demands associated with low probability of occurrence earthquakes. Column residual axial shortening due to local buckling is also minimized. 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 behaviour of the steel column from that of the RC foundation through the use of a debonding material layer wrapped around the embedded column portion. 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 testing as well as complementary finite element simulations. Both experiments and simulations demonstrate that the proposed 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.

Keywords: Dissipative embedded column base connections, Wide flange steel column, Large-scale cyclic testing, Column axial shortening, Local buckling.

1 Introduction

Seismic resistant steel moment-resisting frames (MRFs) are often designed with a fixed column base assumption. Steel columns with fixed bases may experience nonlinear geometric instabilities, such as local buckling, while MRFs undergo lateral deformations during an earthquake. These may induce (1) flexural strength deterioration and (2) column residual axial shortening [1–4]. Recent studies suggest that considerable column

axial shortening may result into building demolition in the aftermath of earthquakes [2, 5, 6].
Embedded column base (ECB) connections are frequently adopted in mid- and high-rise steel MRF buildings. In such a connection, a steel column is embedded into a reinforced concrete (RC) foundation. In the current seismic design standards, the RC foundation is designed to be stronger than the steel column [7, 8]. The axial and shear force demands of the column are transferred to the RC foundation through horizontal and vertical bearing [9]. The flexural demand of the column is largest near the surface of the RC foundation and diminishes with respect to the embedment depth [10–13].
Experimental studies on 'fixed' ECB connections suggest that they have an inherent flexibility due to the concrete bearing deformation as well as the deformation of the embedded column portion [10]. Recent numerical studies suggest that this flexibility reduces the column axial shortening under a given lateral drift demand [6, 14].
Motivated by the above, this paper proposes an innovative dissipative ECB connection concept, which is specifically tailored for wide flange steel MRF columns. The new concept achieves a non-degrading hysteretic response of the connection. The proposed concept is validated through large-scale quasi-static physical testing as well as complementary numerical simulations.

2 Dissipative ECB concept and Experimental validation

This section presents the experimental investigation of the proposed dissipative ECB concept. Figure 1 illustrates the overview of the proposed dissipative ECB connections. In the proposed concept, the embedded column portion should undergo deformations during an earthquake (i.e., the embedded portion is the dissipative zone) under flexure as depicted in Fig. 1. The RC foundation should remain elastic under bearing force demands (excluding cover concrete, which can be easily repaired). The column flange width inside the RC foundation is reduced to lower the flexural strength of the embedded portion. The flexural deformation of the dissipative zone should be decoupled from that of the RC footing to allow for the column deform freely. This may be achieved with a debonding material layer between the column and the RC foundation, which minimizes the friction between the two surfaces. The reduced flange portion may be filled with a soft material (e.g., styrofoam). The surrounding concrete prevents the formation of nonlinear geometric instabilities within the dissipative zone, thereby minimizing flexural strength deterioration under cyclic loading.
The effectiveness of the proposed dissipative ECB concept was investigated through large-scale quasi-static cyclic testing. Both conventional and dissipative ECB specimens were tested. Each specimen comprised of a cantilever steel column welded to a steel end plate, which was embedded into the RC foundation. The adopted column profile was IPE400 (web and flange local slenderness: h/t_w = 38.5, and $b_f/2t_f$ = 6.7, respectively). Each specimen was 2575 mm long including an embedment depth of 850 mm. The steel column was made of S355J2+M material (nominal yield stress of 355 MPa). The RC foundation was 1075 mm tall and had a footprint of 1885 x 685 mm. The conventional ECB specimen was designed according to [7, 8]. In the dissipative

ECB specimen, the column flange width of the embedded portion was reduced to 88 mm. As such, yielding occurred within the dissipative portion. A 3 mm thick butyl rubber tape was adopted as a de-bonding material layer.

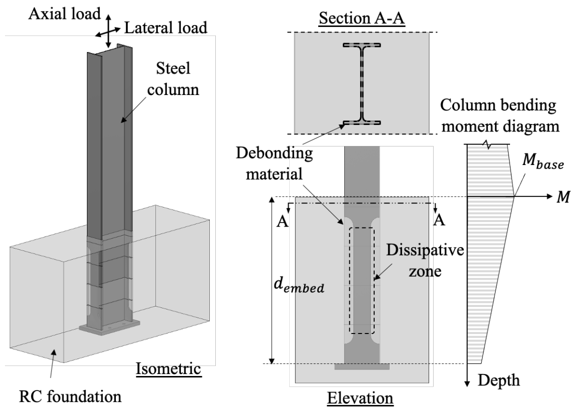


Fig. 1. Overview of the dissipative embedded column base (ECB) connection concept.

Each cantilever specimen was subjected to a standard symmetric cyclic lateral loading protocol [15]. The specimens were restrained against out-of-plane lateral movement. The column drift ratio is defined as the relative column top lateral displacement with respect to the RC foundation centre line divided by the cantilever height of the column. Figure 2 compares the deduced base moment – column drift ratio relations between the conventional and dissipative ECB specimens. The conventional ECB specimen had an elastic rotational stiffness of 4.86e4 kNm/rad. During 1 % rad cycles, flexural yielding was observed. While prior to 4 % drift amplitude, the hysteretic behavior was stable, the post-peak response was dominated by local buckling. Column axial shortening was also evident in this case. Figure 3a shows the observed deformation at the peak of the third excursion of the 5 % rad drift amplitude. Considerable inelastic column deformation was concentrated above the foundation. Eventually, the test was terminated when ductile tearing was observed within the local buckling region.

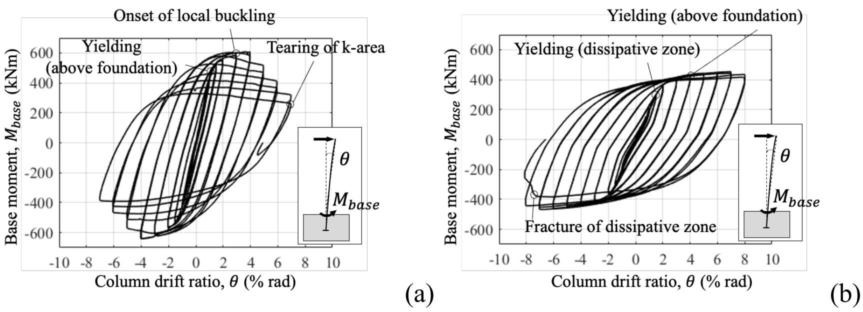
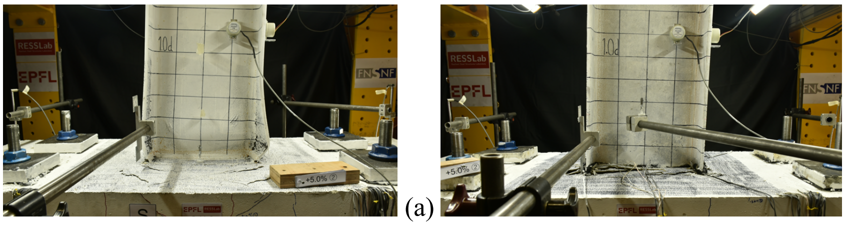


Fig. 2. Comparison of base moment – column drift ratio relations between (a) conventional and (b) dissipative ECB specimens.



(a) (b)

Fig. 3. Comparison of inelastic deformations observed at the third 5 % rad excursion; (a) conventional and (b) dissipative ECB specimens.

Figure 2b shows the hysteretic behavior of the dissipative ECB specimen. The elastic stiffness was 2.66e4 kNm/rad, which is nearly half of that from the conventional ECB. This is attributed to the presence of the de-bonding material layer. In this case, flexural yielding within the dissipative zone occurred during the 1.5 % rad drift amplitude. During the 2 % rad drift amplitude, the concrete cover near the web started cracking. During the 4 % rad cycles, the base moment exceeded the flexural yield strength of the unreduced section, indicating that the column above the foundation experienced mild flexural yielding. Local deformations due to bearing were also observed in the column flange after 4 to 5 % rad. Until the first cycle of the 7 % rad drift amplitude, no degradation in flexural strength was observed (see Fig. 2b). The maximum attained moment was 467 kNm. Referring to Fig. 3b the inelastic deformation was mostly concentrated within the dissipative zone. The ultimate failure mechanism was crack initiation due to ultra-low cycle fatigue, within the dissipative zone, as intended. The post-test inspection suggests that the observed concrete spalling between the column flanges was limited within the concrete cover thickness. The test results demonstrate that the proposed concept is successfully validated.

3 Finite element analysis of dissipative ECB connections

Complementary continuum finite element (CFE) simulations were performed with the commercial finite element analysis software ABAQUS (version 6.14-1) [16] . Details regarding the CFE model are summarized in [17]. The proposed CFE model for dissipative ECBs is validated with the experimental data discussed in Section 2. Figure 4a depicts a comparison of the base moment – column drift ratio relations. Figure 4b illustrates a comparison of the deformed shape between the simulated and the experimental results of the dissipative ECB. The proposed modelling approach successfully reproduces the moment – rotation response of the dissipative ECB connection up until fracture initiation within the dissipative zone. Moreover, the cumulative plastic strain (PEEQ) distribution in Fig. 4b suggests that the primary dissipative mechanism within the ECB connection is captured fairly well.

The developed CFE model is used to further investigate the performance of the dissipative ECB connections. A refined configuration was first developed that featured stiffeners between the column flanges at the RC foundation surface. This is found to be effective to prevent the observed column flange local deformation due to bearing, which was observed in the test program. Details of the refined configuration can be found in [17].

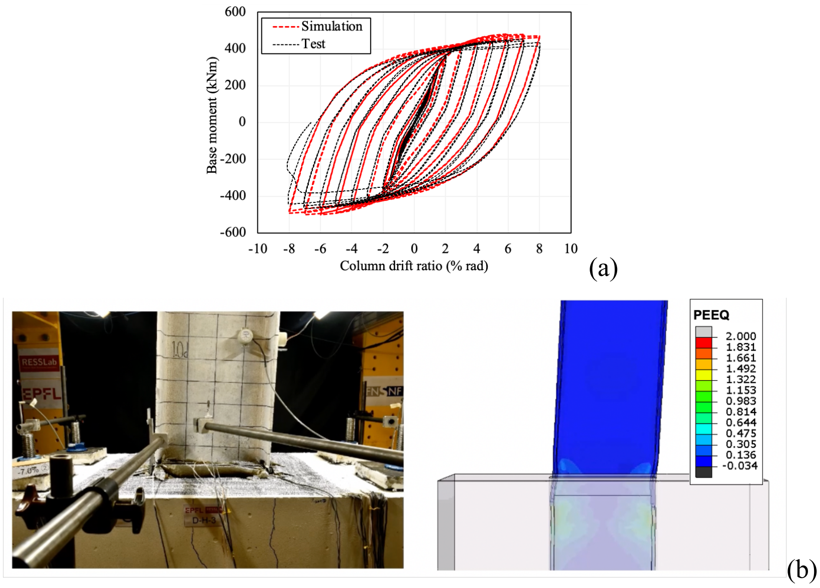


Fig. 4. Validation of the developed continuum finite element model for dissipative ECB connections: (a) base moment – column drift ratio relation; and (b) deformed shape (colour contour indicates the distribution of cumulative equivalent plastic strains, PEEQ).

The performance of the dissipative ECB connection under coupled axial load and lateral drift demands is also examined. The CFE models for conventional and dissipative ECB connections are compared. For both models, a W30x173 cross section is employed. The column height is 4000 mm. The embedment depth is 1400 mm in both cases. A constant compressive axial load of 20 % of the column axial yield resistance is applied to the column. The flexibility of the top end boundary condition due to the presence of fully restrained beam-to-column connections is also considered. Other examined aspects relate to the influence of the loading history with emphasis at earthquake-induced collapse [18].

Figure 5 compares the base moment – column drift ratio relations and the axial shortening – column drift ratio relations between the conventional and the dissipative ECB connections when subjected to a collapse-consistent protocol that depicts duration characteristics in the structural response. Referring to Fig. 5a, in the conventional ECB, there is significant flexural strength deterioration due to the early onset of local buckling. As such, axial shortening is intensified in this case (see Fig. 5b). On the other hand, the dissipative ECB connection does not experience any flexural strength deterioration for the same loading history, thereby minimizing column axial shortening (see Fig. 5b). The observed axial shortening in this case is attributed to the accumulated inelastic straining within the dissipative zone.

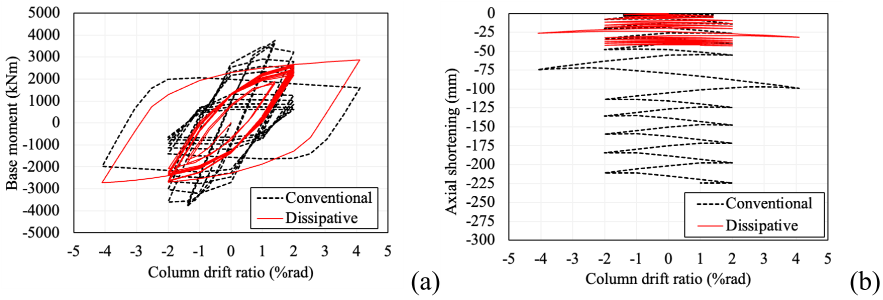


Fig. 5. Comparisons of the hysteretic response of conventional and dissipative ECB connections; (a) base moment – versus column drift ratio; (b) axial shortening versus column drift ratio.

4 Summary

This paper summarizes the development of an innovative design concept for embedded column bases (ECBs). A dissipative zone is realized within the embedded portion of the steel column inside the reinforced concrete (RC) foundation. This is achieved by reducing the column flange width of the embedded column portion, by keeping the RC foundation elastic under bearing stress demands, and by decoupling the flexural behaviour of the steel column from that of the RC foundation through the use of a debonding material layer wrapped around the steel column. The proposed concept was validated by means of large-scale physical tests as well as complementary continuum finite element (CFE) simulations. The experimental results suggest that the dissipative ECB successfully prevents local buckling in the column cross section above the RC foundation and enables a stable hysteretic response till a lateral drift demand of 7 % rad. The CFE simulations indicate that dissipative ECB connections do not experience any flexural strength deterioration up to at least 4 % rad in the presence of compressive axial load. Column axial shortening is reduced by 80 % relative to the conventional ECB case. More details regarding the research work presented herein is summarized in [17, 19].

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