Numerical and experimental study of an innovative steel connection equipped with a yielding damper of the steel plate type

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ABSTRACT

Connections are recognized as the most critical components in structural systems for transferring loads and maintaining overall integrity under various static and dynamic loading conditions. Replaceable energy-dissipating structural fuses provide an effective means of protecting structures against earthquake forces. However, previous studies have identified two major challenges: the dependence of the cyclic performance of yielding fuses on beam-section dimensions and the risk of damage to primary load-bearing members. To overcome these limitations, this study proposes an innovative pin-jointed connection that converts beam rotation into yielding of a replaceable damper, thereby concentrating damage exclusively in a designated region. This mechanism protects the beam and column while simultaneously making the cyclic response of the connection independent of beam-section dimensions. First, the seismic behavior of three yielding mechanisms—flexural, shear, and ADAS dampers—was experimentally compared under cyclic loading. Owing to the superior performance of the ADAS damper, the numerical model of the connection was then validated, and a parametric study was conducted on 12 models by varying the damper's minimum width and thickness to systematically evaluate their effects on the seismic response. The results showed that the ADAS damper reached a final rotation of 0.08 rad and provided notably greater ductility and energy-dissipation capacity than the other specimens. Increasing the damper width and thickness enhanced the connection stiffness, maximum moment, and absorbed energy. Finally, the evaluation of beam-section dimensions showed that, when the force-transfer arm remained constant, changing the beam size had no significant effect on the cyclic response of the connection.

KEYWORDS

Steel Connection ،Yielding Damper ،Experimental Study ،Cyclic Behavior ،Energy Dissipation.

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1. Introduction

Steel beam-to-column connections play a fundamental role in seismic-resistant structural systems because they control force transfer and maintain structural integrity during earthquakes. Observations after the Northridge (1994) and Kobe (1995) earthquakes revealed that conventional steel connections could experience brittle failures due to insufficient ductility and limited energy dissipation capacity [1, 2]. Therefore, various energy dissipation systems have been proposed to improve seismic performance by concentrating plastic deformation in replaceable components. Previous studies have investigated different metallic dampers, including curved steel dampers, slotted dampers, TADAS, ADAS, rotational dampers, and other yielding devices, demonstrating their capability to enhance stiffness, ductility, and energy absorption while protecting primary structural members [3-7]. Although these systems have provided significant improvements, the development of a connection capable of simultaneously isolating damage, preserving elastic behavior of beams and columns, and maintaining stable cyclic behavior independent of beam dimensions remains an important research challenge.

The main objective of this study is to introduce a novel steel connection equipped with a pin mechanism that transforms beam rotation into controlled deformation of a replaceable yielding damper. The proposed mechanism directs nonlinear behavior into the damper element and reduces the possibility of damage in the main structural members. In this research, three yielding mechanisms, including flexural, shear, and ADAS dampers, are experimentally compared. Subsequently, a validated numerical model is developed to investigate the influence of ADAS damper geometry on seismic performance through a parametric study.

The configuration of the proposed connection and the load transfer mechanism are illustrated in Figure 1. The pin acts as the center of rotation, while the replaceable damper functions as the seismic fuse by absorbing earthquake-induced energy.

2. Methodology

The proposed connection was designed to control the damage location and transfer beam rotation into plastic deformation of the yielding damper. Unlike conventional connections where plastic deformation may occur in beams, columns, or welded regions, the proposed system utilizes a pin mechanism to isolate nonlinear behavior within a replaceable component.

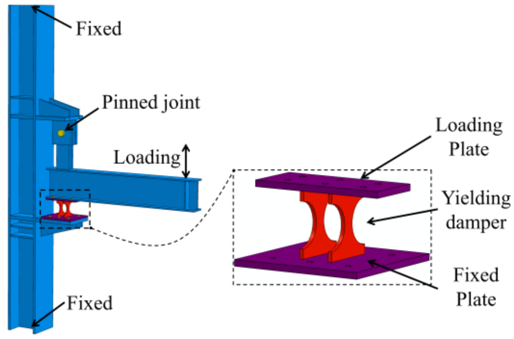

Figure 1. Schematic representation of the proposed pin-based steel connection and replaceable yielding damper mechanism.

Three experimental specimens were fabricated and tested under quasi-static cyclic loading. The specimens consisted of an IPB200 column and an IPE180 beam according to the strong-column weak-beam concept. A 20 mm diameter pin was used as the rotation center. The specimens were classified as M1, M2, and M3, representing flexural, ADAS, and shear yielding mechanisms, respectively.

The M1 specimen employed two horizontal steel plates designed to yield through bending action. The M2 specimen consisted of an ADAS damper with a total width of 90 mm, minimum width of 20 mm, and height of 100 mm. The M3 specimen included two steel plates designed to dissipate energy through shear yielding. All specimens were fabricated using identical materials and tested under displacement-controlled cyclic loading following FEMA 350 recommendations [8].

Based on the experimental evaluation, the ADAS specimen was selected for further numerical investigation due to its superior ductility and energy dissipation capability. A three-dimensional finite element model was developed in ABAQUS considering material and geometric nonlinearities. The numerical model was validated by comparing the simulated hysteretic response with experimental results. After validation, a parametric study was conducted on 12 models by varying the minimum width and thickness of the ADAS damper. The damper thicknesses of 4, 6, 8, and 10 mm and minimum widths of 9, 22.5, and 45 mm were investigated.

3. Results and Discussion

The experimental investigation demonstrated that the proposed connection mechanism was able to successfully redirect nonlinear deformation from the primary structural members toward the replaceable yielding dampers. The presence of the pin mechanism provided a controlled rotation center and modified the conventional force transfer path in the connection. As a result, plastic deformation was mainly concentrated within the energy dissipation components, while the beam and column remained protected from significant damage.

The flexural yielding specimen (M1) showed stable behavior during the initial loading cycles and remained within the elastic range up to approximately 0.005 rad rotation. With increasing deformation, the yielding plates experienced combined flexural and axial effects, which increased the load-carrying capacity of the connection. However, the development of cracks near the connection region of the damper caused a reduction in performance, and final failure occurred at approximately 0.07 rad rotation. This behavior indicates that although flexural yielding mechanisms can provide acceptable ductility, stress concentration at connection regions may limit their ultimate deformation capacity.

The ADAS specimen (M2) exhibited the most desirable seismic response among the investigated configurations. The specimen maintained stable hysteretic behavior after yielding initiation, and plastic deformation developed gradually along the height of the ADAS plates. This deformation distribution prevented premature localization of damage and resulted in wider hysteretic loops. The specimen achieved a final rotation of 0.08 rad, demonstrating a higher deformation capacity compared with the other investigated mechanisms. Furthermore, the stable cyclic response of the ADAS damper resulted in greater energy dissipation and a higher equivalent viscous damping ratio.

In contrast, the shear yielding specimen (M3) provided the highest initial stiffness and ultimate moment capacity due to its relatively rigid configuration. However, excessive stiffness limited the development of large plastic deformations. The occurrence of stress concentration and out-of-plane instability in the yielding plates reduced its ductility, and the loading process was terminated at approximately 0.03 rad rotation. These results highlight that high strength alone is not sufficient for seismic applications, and parameters such as ductility, deformation stability, and energy dissipation capacity should also be considered.

The comparison of hysteretic responses confirmed that the ADAS mechanism provides a more balanced performance between strength and ductility. Therefore, the M2 configuration was selected for numerical investigation. The finite element model developed in ABAQUS successfully reproduced the experimental cyclic behavior. The differences between numerical and experimental results were 4.4% for initial stiffness, 3.5% for ultimate strength, and 3.1% for cumulative energy dissipation, indicating good agreement between the model and experimental observations.

The validated numerical model was subsequently used to investigate the influence of ADAS damper geometry on connection performance. The parametric study showed that increasing the minimum width and thickness of the damper increased the hysteretic loop area and improved cumulative energy dissipation. This improvement was attributed to the increase in plastic section modulus and the larger volume of steel participating in the yielding process. In addition, increasing damper dimensions enhanced the elastic stiffness and maximum moment capacity of the connection.

Although increasing damper dimensions improved strength-related parameters, the design of the yielding element should be carefully controlled to ensure that damage remains concentrated within the damper and does not transfer to the beam or column. The stress distribution results at the final rotation level confirmed that the main structural members remained below their yielding limits, while the ADAS dampers fully entered the plastic range. This behavior verifies the effectiveness of the proposed system as a replaceable seismic fuse.

Finally, the effect of beam cross-section variation was examined by replacing the IPE180 beam with an IPE220 section while maintaining the same force transfer arm. The numerical comparison showed nearly identical hysteretic responses, ultimate capacity, and energy dissipation characteristics. This finding indicates that the seismic response of the proposed connection is primarily controlled by the yielding damper properties and the pin-to-damper geometry rather than the beam cross-sectional dimensions. Therefore, the proposed system provides a flexible approach for seismic design in which the desired performance can be achieved through controlled damper design.

4. Engineering Implications of the Proposed Connection

The proposed connection introduces a damage-control strategy for steel beam-to-column connections by separating the energy dissipation mechanism from the primary structural members. Unlike conventional connections where plastic deformation may occur in beams and lead to difficult repair procedures, the proposed pin-based system transfers beam rotation into a replaceable yielding damper. This mechanism allows seismic damage to be concentrated in the fuse element while maintaining the elastic behavior of the beam and column. The results indicate that the cyclic performance of the connection is mainly controlled by the yielding damper characteristics and the force transfer geometry.

Therefore, the desired seismic response can be achieved through appropriate damper design rather than increasing beam dimensions. Moreover, maintaining the pin-to-damper distance provides consistent cyclic behavior for different beam sections. Further studies considering frame-level behavior, dynamic loading, and low-cycle fatigue effects are recommended to evaluate the practical applicability of the proposed system.

5. Conclusions

This study introduced a novel steel beam-to-column connection equipped with a pin mechanism and replaceable yielding damper. The proposed system was developed to concentrate seismic damage in a replaceable component while preserving the elastic behavior of primary structural members. Based on the experimental and numerical investigations, the following conclusions can be drawn:

- Among the investigated yielding mechanisms, the ADAS damper provided the best seismic performance, achieving a final rotation of 0.08 rad, a ductility index of 32, and the highest equivalent viscous damping ratio.
- Although the shear yielding mechanism provided higher initial stiffness and strength, its limited deformation capacity reduced its overall seismic efficiency compared with the ADAS configuration.
- The validated finite element model accurately reproduced the experimental cyclic response and demonstrated that plastic deformation was concentrated within the yielding damper while the beam and column remained elastic.
- Increasing the thickness and minimum width of the ADAS damper improved stiffness, moment capacity, and cumulative energy dissipation due to the increased amount of material involved in plastic deformation.
- The proposed connection showed independence from beam cross-sectional dimensions when the force transfer arm was maintained, providing the possibility of controlling seismic performance through damper design rather than beam size.

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