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Seismic behavior of replaceable steel truss coupling beams with buckling restrained webs

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ABSTRACT

In order to facilitate the constructability and meanwhile ensure desirable seismic behavior, an innovative type of replaceable steel truss coupling beam with a buckling restrained web was conceived and studied. The buckling restrained steel web is designed and detailed as a fuse and a damper of the beam in which all inelastic deformations and damage are concentrated. Bolted connections between steel webs and beam chords, as well as pin connections between beam chords and adjacent reinforced concrete shear walls, are employed to minimize the post-event repair/replacement difficulties and expenses. To evaluate the seismic behavior, three large scale coupling beam specimens were constructed and tested under cyclic loadings. The effects of some configurations of the steel webs including welded edge stiffeners and slits on the seismic behavior were highlighted. The test results indicate that all three specimens failed in a ductile manner with a concentration of inelastic deformation at steel webs and thus exhibited desirable deformation and energy absorption capacities. The strength and stiffness of the proposed coupling beam can be enhanced by welding edge stiffeners to steel webs while the steel web with slits is susceptive to suffer significant buckling of flexural links, resulting in a relatively lower strength and ductility of the beam. To predict the load carrying capacity of the proposed coupling beam, a modified strip model to account for the beneficial effects of the buckling–bracing provided by precast reinforced concrete panels was developed. The analytical results were compared with the experimental results.

1. Introduction

Coupled shear wall systems, which consist of two or more in-plane shear walls interconnected with coupling beams, are frequently used in medium and high-rise buildings [1]. Due to the favorable coupling actions created by coupling beams, coupled wall systems resist overturning moments induced by seismic events partially through axial compression–tension couples across the wall systems rather than totally through the individual flexural actions of the walls, and thus they are efficient systems with great lateral stiffness and strength. Moreover, in contrast to conventional individual walls in which the dissipation of seismic energy usually concentrates at shear wall bases, properly designed coupled wall systems develop a means of dissipating energy mainly through large inelastic deformations of coupling beams over the entire height of the wall systems. Thus, the overall seismic responses of a coupled wall system largely depend on the type and details of the coupling beams used. However, previous earthquakes such as Wenchuan earthquake in China have demonstrated the vulnerability of conventionally reinforced concrete coupling beams with longitudinal flexural and vertical shear reinforcements subjected to seismic attacks [2,3].

To improve the seismic behavior of conventional coupling beams, some efforts have been made by providing special reinforcement layouts [4,5] or using steel and steel–concrete composite coupling beams [6–11] as substitutes in recent decades. Although pertinent experimental results showed that the aforementioned details offered coupling beams an improved performance over conventional beam types to some extent; however, each of them had some drawbacks to limit their wide use in practice. Diagonally reinforced concrete coupling beams proposed by Park and Paulay [4] have proved to be very complicated, if not impossible, to fabricate and construct. Steel and steel–concrete composite coupling beams have gradually gained acceptance as a viable substitute for reinforced concrete coupling beams in high seismic regions and have been studied by some researchers [6–11]. Their experimental results indicated that steel and steel–concrete composite coupling beams, similar to steel link beams in eccentrically braced frames, can provide excellent ductility and energy dissipating characteristics. However, special configurations of beam-to-wall connections are usually required and significant damage of the connections and coupling beams leads to very costly post-event repair. To further enhance the advantages of steel coupling beams, Fortney [12] studied a type of built-up

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steel coupling beam consisting of two outer beam sections embedded in wall piers and a replaceable central "fuse" section. However, some types of weld failures, block shear failure and bolt bearing failure were observed at the end of the Fortney's test.

In this study, an innovative type of replaceable steel coupling beam for coupled wall systems, as shown in Fig. 1, was conceived and studied. The proposed coupling beam is designed as a steel truss with a replaceable buckling restrained web. The buckling restrained web, which is confined by two precast reinforced concrete panels to avoid elastic and inelastic out-of-plane buckling, serves as a fuse and a damper of the beam where all deformations and damage are concentrated during medium and serious seismic events. That is to say, both beam chords and shear tabs for connections are intended to remain elastic when the buckling restrained web reaches its ultimate load to dissipate energy input. In the buckling restrained web, some gaps are set around the precast reinforced concrete panels to make the reinforced concrete panels provide only out-of-plane bracing to the web rather than resist lateral applied loadings. To facilitate the construction and post-event repair, the web is bolted to both top and bottom chords of the beam through fish plates while the ends of the beam chords are connected to the shear tabs by means of "real" pins, which allow free rotation of the chord members inside the beam plane. Then the shear tabs are welded on face plates with multiple steel angles embedded in reinforced concrete shear walls. If the wall boundaries are reinforced with steel structural columns, the shear tabs can also be directly connected to the steel columns. Compared with conventional steel coupling beams, the proposed steel truss coupling beam has the following noteworthy merits: 1) the installation and post-event repair of the beams are simple since bolted connections between steel webs and beam chords, as well as pin connections between beam chords and adjacent reinforced concrete shear walls, are employed; 2) the replaceable buckling-restrained web can achieve large inelastic deformation and thus can contribute to the energy dissipation capacity of the coupling beam; and 3) the strength and stiffness of the coupling beams can be easily adjusted by changing the configurations of the steel webs, facilitating the seismic design of overall structures.

2. Experimental program

The main objectives to be achieved in this research program are: 1) to verify the applicability of the proposed replaceable steel truss coupling beam with a buckling restrained web for coupled wall systems; 2) to investigate the seismic behavior of the proposed coupling beams in terms of strength, stiffness, ductility and energy absorption capacity; 3) to evaluate the effects of some configurations of the steel webs including edge stiffeners and slits on the seismic behavior; and 4) to provide a rational analytical model to predict the strength of the proposed coupling beam.

2.1. Specimen design

Three replaceable steel truss coupling beam specimens called as SCB1–SCB3 were constructed and tested under cyclic loadings. Each specimen included two reinforced concrete shear walls connected using a steel truss coupling beam to represent a floor-level subassembly at a hybrid coupled wall structure. The test beam prototype has a span of 1800 mm and a depth of 1200 mm, which is common in reinforced concrete frame-core wall structures for tall office buildings with typical wall openings and story heights. Due to the geometric and strength constraints of existing laboratory conditions, tests were conducted on 2/3-scale coupling beam specimens having a clear span of 1200 mm and a distance between centerlines of beam chords equal to 650 mm, and the design strength of the coupling beam specimens was controlled by their replaceable steel web with measured dimensions of 720 mm (length) × 470 mm (depth) × 3.8 mm (thickness). As stated previously, the strength of the proposed coupling beam can be easily adjusted by changing the thickness of the web if necessary.

The details of the specimens are shown in Fig. 2. Since the proposed coupling beams can be replaced after test, reinforced concrete walls and beam chords were reused during the tests. The dimensions and reinforcement layouts of the reinforced concrete walls are included in Fig. 2c. The reinforced concrete walls, as well as the shear tabs with multiple steel angles for the pin-connections between beam chords and adjacent reinforced concrete shear walls, were designed and detailed according to the Chinese code for seismic design of buildings [13] to ensure the full development of capacities of coupling beams. Three steel angles with a flange width of 50 mm and a thickness of 6 mm were adopted in each beam-to-wall connection. Concrete filled steel tubes, which were composed of square steel tubes with a cross section of 150 mm (width) × 150 mm (depth) × 10 mm (thickness) and infill concrete with a target compressive strength of 55 MPa, were employed for the top and bottom chords of the coupling beams. The replaceable thin steel webs were bolted to the chords using 25 mm thick fish plates and slip-critical high strength bolts with a diameter of 16 mm, and the potential premature elastic and inelastic out-of-plane buckling of the webs was to be inhibited by a couple of precast reinforced concrete

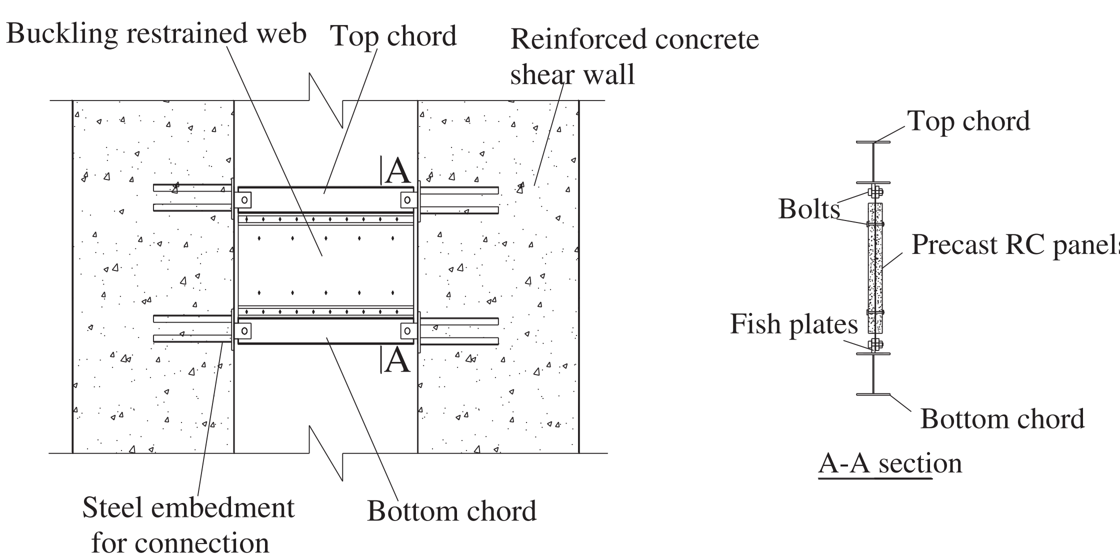

Fig. 1. Proposed steel truss coupling beam with a buckling restrained web.