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Force distribution analysis of self-centering coupled-beams for moment-resisting-frames without floor elongation

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ABSTRACT

The self-centering (SC) coupled beam (CB) is an innovative system that can avoid floor elongation. The internal force distribution of SC-CBs is also different with conventional posttensioned (PT) connections. This paper first presents a non-uniform factor (Ω) for measuring the uneven force distribution at the beam ends of SC-CBs. Theoretical formations of the factor Ω are driven using structural analysis. Sensitivity analysis for a one-story one-bay frame is conducted to identify the significant parameters for the mitigation of uneven force distribution in the SC-CBs. The frames are also modelled in OpenSees where material and geometrical nonlinearities are taken into account. The numerical results for Ω match well with the theoretical values. A prototype six-story building is designed to evaluate the influence of three design parameters on the Ω value at different stories. Nonlinear dynamic analyses of five moment-resisting frames using SC-CBs with different combinations of design parameters indicate that the decreasing axial stiffness ratio of the upper beam component to the lower beam component can significantly mitigate the uneven force distribution at the two beam ends. Based on those analytical results, a simple regression equation is proposed for predicting the factor Ω.

1. Introduction

Unlike traditional welded or bolted moment-resisting frames (MRF) with significant seismic damage, self-centering (SC) MRF are considered to be damage-resistant structures under seismic excitation [1,2]. Recently SC-MRF have been widely studied [3], taking into account the systems' advantages such as flexible joint strength and stiffness, SC capacities and cost effectiveness. Nonetheless, the systems are achieved by gap-opening and gap-closing at beam-column interfaces, resulting in displacement incompatibility between floor diaphragm and lateral load-resisting bays. Special connection configuration and design are needed for the issues associated with slab damage in actual applications.

Some researchers have developed slab systems to avoid floor damage. Garlock et al. [4] adopted collector beams to transfer the lateral loads of structures to the lateral load-resisting system. The relationship between collector beam strength and stiffness must be reasonably designed to prevent interference with the gap opening to deal with collector beam yielding. Chou et al. [5] and Lin et al. [6] attached the floor slab to the beam at only one moment-resisting bay and allowed the floor slab to slide separately over other beams in Fig. 1a. As a result, axial forces of the beam fixed with the slabs became significantly greater, the actual loading at the region of separated slabs and beams is also unknown. As shown in Fig. 1b, Kim et al. [7] proposed detailing along the boundaries of the slabs that allow deformation. The slab sliding length is expected to be calculated to accommodate the likely displacements. Chou et al. [8,9] experimentally analysed the two novel slab schemes in PT connections subjected to static cyclic loads, showing how the slab systems affect the SC behaviour of PT connections. But in engineering practice, it is still difficult to use the above construction details in the two horizontal directions of larger frames without slab damage.

Other researchers have focused on investigating new beam-to-column connections to avoid floor damage because of floor elongation. A sliding-hinge joint connection was proposed [10–12] to satisfy these requirements. The top flange of the beam was pinned to the column to avoid floor elongation. Mander et al. [13,14] experimentally investigated the joint viability in rigid structural steel beam-to-column connections. The use of high-force-to-volume devices fitted directly into beam-column connections provided a damage avoidance design structural connection. Khoo et al. [15,16] proposed the SC version of the connection by incorporating friction-damping ring springs to reduce joint elastic strength and

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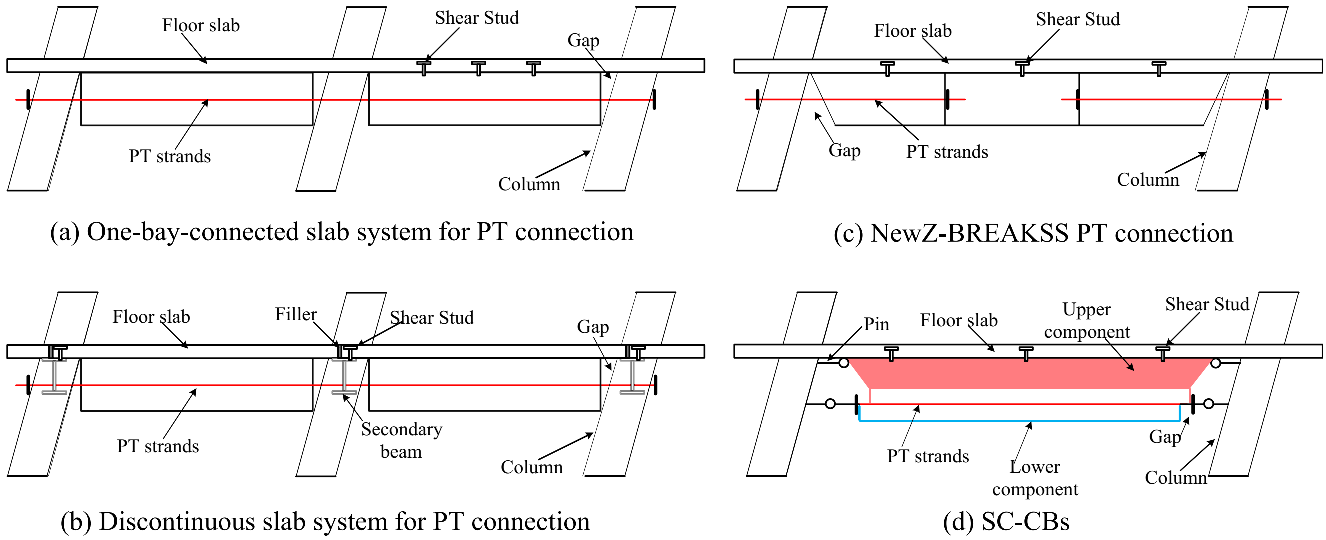

Fig. 1. Conceptual kinetic diaphragm of conventional PT connections and SC-CBs.

stiffness losses. The SC behaviour of the joint not only required large-sized ring springs for improving SC properties, but also needed to be carefully designed and accurately implemented. Inspired by the aforementioned connection. As shown in Fig. 1c, Dowden et al. [17,18] developed a beam-to-column joint that rocks about the top beam flange only and is referred as the NewZ-BREAKSS posttensioned (PT) rocking connection. One characteristic of the joint was that two PT elements needed to be anchored independently at the two beam ends to achieve the elongation of the PT strands. The other characteristic of the joint was that the SC capability of PT strands would diminish when the joint closed. The NewZ-BREAKSS connection has less SC capability due to the two characteristics. The experimental results suggested the connection cannot entirely avoid the separation at the top flange location of the beam [19].

Recently, Darling et al. [20] proposed a novel SC coupled beam (CB) that eliminates deformation incompatibility with the gravity framing system and can be shop-fabricated, as shown in Fig. 1d. Maurya et al. [21–23] experimentally conducted five two-third scale SC-CB specimens. The beam is composed of two coupled components, a W-section/outer tube assembly and an inner tube. A yielding steel core plate restrained by the grouted restraining tube of the beam is used as a hysteretic damper to dissipate energy. The specimens were shown to undergo 5%–6% story drift without any observable damage in the beam and column structural elements. Lin et al. [24,25] also developed a steel SC-CB module for avoiding beam growth using a similar sliding configuration. The new PT beam technology is considered as a more cost-effective non-tearing floor SC system. The assemblage of the beam always results in an elongation of the tensioning elements whether the applied force on the frame pulls to the left or pushes to the right. On the other hand, the required elastic elongation of PT elements used in the joint is lower than that of SC brace frame when the structures are subjected to lateral loads at equal amplitudes. Therefore, composite polymer materials could be replaced by traditional metallic high-strength steel to produce the restoring force in the beam.

The experiment results for SC-CBs [26] suggested that the relative distribution of beam end moments was not even when the frame was subjected to lateral loads. Therefore, the internal force transfer mechanism of the system is different from that of conventional PT frames. This illustrates the need for an investigation of the uneven force distribution of SC-CBs in order to facilitate the design of the frames using SC-CBs in a seismic region. This work presents a theoretical formulation to explain the force transfer mechanism of the SC-CB. Sensitivity analysis is conducted to identify the significant parameters on the mitigation of uneven internal force at the two beam ends based on the above equations. Static cyclic analyses of a one-story MRFs using the SC-CB are then conducted to validate the theoretical results. Five six-story MRF using SC-CBs with different combination of design parameters are used to investigate the variation trends of the significant parameters on uneven internal force under both the design and maximum considerable levels of nonlinear dynamic analysis. A simple regression expression is derived to predict the non-uniform factor for design procedure based on the numerical results.

2. Configuration and behaviour of SC-CBs

As shown in Fig. 1d, SC-CBs consist of two coupled components (upper component and lower component) compressed together by PT strands. The fabrication and pre-stress process of SC-CBs can be completed in the factory. The gap-opening behaviour of SC-CBs happens at the corresponding bottom beam flange location and would not cause floor elongation. By comparing the conceptual diaphragm of conventional PT connections and SC-CBs in Fig. 1, the gap mechanism of SC-CBs is achieved by introducing additional stocky pin connections and tubes locating below the W-section. The special configurations will increase steel consumption of the beams. However, the actual economic cost of two systems in structural engineering should be rigorously estimated considering the advantages and disadvantages associated with on-site labor cost, pretension construction difficulties and the feasibility of composite floor diaphragm.

The schematic drawing of the friction damped SC-CBs proposed by the authors is shown in Figs. 2–4. The bottom flange of the W-section is cut off and then the outer tube is welded to the bottom web of the W-section, which is referred as the W-section/outer tube assembly. The posttensioned strands are affixed to free-moving end plates. The pretension force can be applied in the factory, compressing end plates tightly to the W-section/outer tube assembly and inner tube to form an integral unit. The W-section/outer tube assembly and the inner tube are pinned to the columns separately and constitute the upper component and the lower component of the SC-CB respectively. The pin-connected members