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Coreless self-centering braces as retrofitting devices in steel structures

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ABSTRACT

Conventional lateral resisting systems can provide sufficient strength and ductility for design based earthquakes, although the considerable residual deformation remaining in the plasticized regions undermines the resiliency of the structures. In order to resolve this problem, various self-centering systems have been proposed and tested in recent years, most of which are specified for new buildings and are not simply suitable for retrofitting applications. Moreover, the available self-centering systems are costly and complex to assemble, which can be considered as a serious barrier for practical application. To address these drawbacks, an innovative Core-Less Self-Centering (CLSC) brace is proposed, which is specified as a retrofitting device to be used in conjunction with conventional lateral resisting systems. CLSC braces are devices which can minimize residual deformations of existing buildings by combination of a nonlinear elastic behavior with the nonlinear inelastic behavior of the conventional resisting frames. A parametric study is conducted to find the most cost effective materials and at the same time, full self-centering behavior, using *OpenSees* software. During the second phase of study, an optimal design method is developed to achieve the most efficient configuration for the proposed braces among structural elements. In this regard, an iterative procedure is implemented on a 9-story steel plate shear wall (SPSW) building, which is retrofitted with CLSC braces, using Nonlinear Response History Analysis (NRHA), and the structural responses are evaluated. Results illustrate that the proposed brace not only is individually more economical, but also a wise placement of braces can enhance structural resiliency. The implementation of CLSC braces can significantly reduce repair costs of the whole structure, with minimal manipulation of the structural performance parameters.

1. Introduction

Conventional lateral force resisting systems are typically designed to provide adequate life safety for a design level earthquake. In this regard, large residual drifts of yielded elements lead to significant structural damage, which consequently can increase the cost of retrofitting or the replacement of both structural and nonstructural elements, such that the renovation of the whole structure will be more feasible [1]. These concerns imply a necessity for developing a system in which the structural damage of an earthquake is minimized and the building can be restored to its original condition with reasonable effort. Although these systems may slightly increase the cost of building construction, they can significantly reduce the life-cycle cost of the structure, particularly after prospective hazards [1].

Self-centering systems are devices which can re-center deformed structures to their initial shapes after the occurrence of a hazard. In recent decades, several self-centering systems have been proposed and developed [2–5]. A major group of these systems are post-tensioned (PT) elements which are implemented in beam-column connections [6–9]. The mechanism of re-centering in these connections is a push force induced by post-tensioned bars to the flexural gap openings. As the post-tensioned elements remain elastic, they need to be paired with energy dissipaters. Moreover, researches indicate that PT self-centering systems suffer from the challenge of finding secure gravity force paths in a building, due to their connection configurations [5]. Consequently, recent studies have led to the investigation of self-centering systems to overcome these disadvantages. Self-centering braces not only have solved the difficulties in transferring gravity loads, but can also be easily constructed and replaced by other seismic braced systems. In addition, the re-centering mechanism of self-centering braces is based on their axial realignment capacity when placed between two stories. This mechanism can be considered as a more effective action, in comparison with its rival mechanism which is a restoring force to close an infinitesimal opening between a beam and column connection. In this regard, several self-centering braces are introduced in which tensioning elements and energy dissipaters are provided within the brace [10–12]. A Self-Centering Energy Dissipative (SCED) brace was proposed and developed such that the energy dissipation and the re-centering ability were provided by friction pads and aramid fiber tendons, respectively [10]. A unique mechanism was provided in the brace to give additional elongation in the tendons whether the brace was in tension or compression. Inner and outer steel tubes were utilized to

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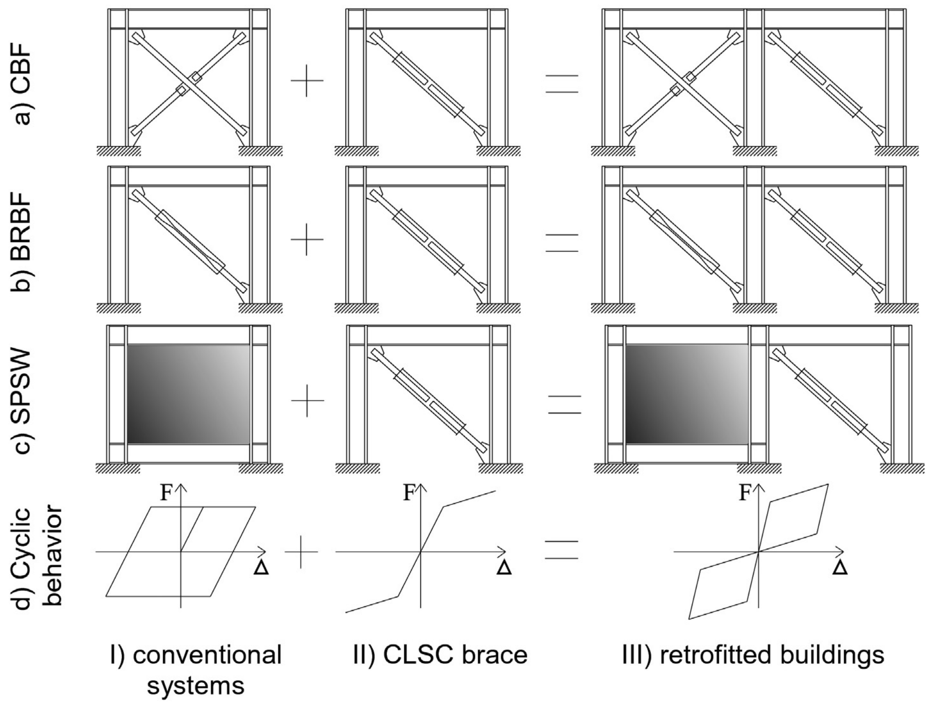

Fig. 1. Conceptual scheme of retrofitted frames with CLSC brace.

provide this feature. Recently, another brace was developed based on the same unique mechanism, namely, the Self-Centering Buckling Restrained Brace (SC-BRB) [12,13]. SC-BRB consists of a BRB that works in conjunction with pre-stressed Shape Memory Alloy (SMA) rods to provide adequate energy dissipation and re-centering ability. Some other braces were designed based on the special features of the SMA wires [14]. Although SMA rods acquire the super elastic characteristic which results in an excellent self-centering ability, mass application of SMA materials is still costly. On the other hand, the aramid fiber tendons not only are more economical, but also possess an appropriate failure elongation capacity, leading to an excellent self-centering capability. Moreover, the SMA rods have inherent residual deformations, while the behavior of aramid fiber tendons is perfectly elastic and having no residual deformations results in better self-centering features.

From a retrofitting perspective, utilizing self-centering systems with PT connections is not feasible. This is mainly because of the challenges associated with the construction and the assemblage of these systems. In other words, implementation of these systems in existing buildings needs a fundamental modification in the existing connections, which in most cases is impossible. On the other hand, up to now, all the proposed self-centering braces consist of two main parts: an energy dissipater providing adequate ductility and a re-centering mechanism, which reduces the residual deformation induced by the energy dissipation part. As far as retrofitting perspectives are concerned, the application of this kind of brace is not necessary, since in an existing building, lateral force resisting systems already play energy dissipating role. As a consequence, the aforementioned braces not only should provide re-centering force to compensate for residual deformations of the main lateral resisting frames, but they should also assimilate a re-centering force to eliminate the residual deformations of their own energy dissipater parts. To address these drawbacks, a self-centering brace should be suggested having no energy dissipation capacity, but rather be capable of re-centering the existing residual deformations due to conventional lateral resisting systems. With this in mind, a new form of self-centering brace is proposed, namely, Core-Less Self-Centering (CLSC) brace, in which the dissipater part is eliminated. In addition, to enhance the workability and cost efficiency, the re-centering ability is induced by aramid cables, which are an available and economical material.

1.1. Research objective

In this research, the main goal is to introduce a new form of self-centering brace, which is appropriate for retrofitting existing buildings to enhance the resiliency. Fig. 1 clarifies the conceptual idea of how the brace works as a retrofitting member in a frame. As illustrated in Fig. 1(I), conventional lateral force resisting systems show a cyclic behavior which potentially acquire a sufficient energy dissipation capacity. From another side, a desirable option from the resiliency perspective is to reduce residual deformations, without any influence in energy dissipation capacity. Consequently, the self-centering brace does not have any additional energy dissipation part, the desired cyclic behavior is shown in Fig. 1(II). By superimposing the intrinsic behavior of the main lateral resisting systems on CLSC brace ideal behavior, Fig. 1(III) would be a desired cyclic behavior of retrofitted buildings. In fact, by tuning the characteristics of CLSC brace in retrofitted frames, as shown in Fig. 1, residual drifts could be minimized in existing buildings. From the retrofitting perspective, when a new device is going to be added to an existing frame, architectural limitations should be considered. In this regard, spans adjacent to the existing lateral resisting systems are feasible choices for the placement of the new devices, however CLSC brace could also be applied in other spans.

In this study, CLSC brace is developed and its behavior is studied. Research procedure is conducted as follows: First, the mechanism and structural behavior of CLSC brace is discussed and design equations governing its behavior are outlined. Next, an analytical model is employed using *OpenSees* software [15] to calibrate the modeling parameters, conducting a parametric study and highlighting the expected features of CLSC brace. Afterwards, an analytical study is directed to assess the effects of CLSC brace on the cyclic behavior of one-story frames, laterally resisted by Buckling-Restrained Braces (BRBs) and steel plate shear walls (SPSWs). Finally, in order to find the optimal layout of CLSC braces in a 9-story building, an optimization method is