Engineering Structures 136 (2017) 54–67

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Slack free connections to improve seismic behavior of tension-only braces: An experimental and analytical study

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ARTICLE INFO

Article history:
Received 25 June 2015
Revised 2 January 2017
Accepted 4 January 2017

Keywords:
Tension-only brace
Slack free connection
Quasi-static test
Hysteretic behavior
Pinching

ABSTRACT

A passive mechanical device, called Slack Free Connection (SFC), is introduced by which hysteretic behavior of tension-only braces (TOBs) would be greatly improved in terms of energy dissipation capability. SFC has a mono-directional behavior such that it provides no constraint for the attached TOB under compression. As a result, the TOB can slide itself into the SFC experiencing no compressive force and subsequently no buckling or slackness. On the other hand, when the TOB tends to experience positive elongation, SFC locks itself and the attached TOB can carry tensile loads. This self-tensioning mechanism makes the TOB to be always taut during load reversals such that during the carried out tests, no buckling was observed for super-slender braces with slenderness of 765. Quasi-static cyclic tests as well as numerical simulations revealed that SFC can completely remove pinching from hysteretic behavior of the TOBs and significantly improve their energy dissipation capability. The energy dissipation would be provided through the tensile yielding of the TOB while the SFC would remain elastic. Finally, a tunable post-yield stiffness is proposed for the TOB-SFC system using a Wire Rope Brace (WRB) in parallel with the TOB-SFC system. Based on parametric studies conducted in this paper, even a minor positive post-yield stiffness can greatly reduce residual displacements as another benefit of the proposed system.

1. Introduction

Earlier case histories [1] and experimental studies [2,3] have revealed that Tension-Only Braces (TOBs) have poor seismic performance with highly pinched hysteretic behaviors. As a result, most seismic codes [4,5] have prohibited application of the TOBs (super-slender braces) for medium to tall buildings in seismic-prone regions. Consider a cross TOB system in which one of the TOBs has experienced plastic elongation during the forward inter-story drift. Once direction of the inter-story drift changes, the developed force in the yielded TOB eventually drops to zero and the TOB starts to slack (buckle) during the backward movement of the story. At the beginning of the next reversal, the slacked TOB cannot contribute to the lateral load bearing until it becomes straight again. This feature of the TOBs results in a highly pinched hysteretic behavior with minimal energy dissipation capability.

Some researchers have examined contribution of the TOBs as secondary elastic lateral load resisting systems [6,7]; others have tried to improve their seismic behavior by incorporating different damping devices. For example, Araki et al. [8] have implemented Shape Memory Alloy (SMA) in series with TOBs to achieve a reliable bracing system with self-centering capability. Similar techniques based on TOB-SMA combinations have also been investigated by others [9,10]. In such bracing systems, the tension-only brace is supposed to remain elastic and the SMA is responsible for the energy dissipation. In another study, Phocas and Pocanschi [11] have placed a hysteretic damper in series with a closed loop TOB configuration. Combinations of the TOB with friction dampers [12] and pressurized viscous dampers [13] have also been investigated reporting promising results. However, in a TOB-damper configuration, the whole dissipated energy would be localized in a small fuse (damper) such that even moderate inter-story drifts would lead to significant ductility demands on the fuse.

To address the aforementioned concern, special connections can be incorporated in the TOB by which hysteretic behavior of the TOB experiences little or no pinching and simultaneously the plastification develops along the full length of the tension-only element. There are some limited studies devoted to investigate such special connections. Tamai and Takamatsu [14] have proposed a self-tensioning connection based on a beveled washer, a pre-compressed spring, and a sliding wedge. When the tension-only brace tends to be compressed, the wedge slides beneath the bev-

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http://dx.doi.org/10.1016/j.engstruct.2017.01.009
0141-0296/

eled washer and prevents the TOB to slack. Based on their quasi-static cyclic tests, they have shown that hysteretic behavior of the TOB with the proposed connection has significant energy dissipation capability with no pinching. However, based on the experimental results by Tamai and Takamatsu [14], their proposed connection cannot reliably eliminate hysteretic pinching of the TOBs. During one of the load reversals, the restoring force of the pre-compressed spring was lost leading to a highly pinched cyclic behavior. Golafshani et al. [15] have analytically investigated behavior of a ribbed connection with which the connected tension-only element would remain taut during load reversals. However, they performed no experimental study on the proposed ribbed connection. In both of the abovementioned connections, the tension-only element is not constrained against compression and would slide into the connection. In contrast, when the tension-only element tends to be tensioned, the connection locks itself and makes the brace able to carry tensile forces. Such connections with the mono-directional behavior, if properly designed, guarantee an un-pinched hysteretic behavior for the TOB.

This study is devoted to introduce a mono-directional connection, called Slack Free Connection (SFC). SFC should be able to reliably work even during large displacement demands. Plastification of the TOB with SFC (TOB-SFC) would be uniformly distributed along the full length of the TOB enabling the system to sustain large inter-story drifts. Hysteretic behavior of the TOB with SFC has no pinching with significant energy dissipation capability. The used TOB in this system should be made of steel with a pronounced plateau at the yield stress and enough plastic strain capacity (in the range of 6% or more). Since the plastic strains would be developed along the full length of the TOB, high strength and less ductile steels can also be used. Moreover, the TOB should have some minimal compressive capacity to be able to push itself into the SFC. In the current study, conventional super-slender steel rebars are adopted as the tension-only elements. Moreover, a secondary elastic Wire Rope Brace (WRB) is also proposed to regulate post-yield stiffness of the framing system.

2. Slack Free Connection (SFC)

The main components of the proposed SFC are schematically illustrated in Fig. 1. These include the threaded arm, the mono-direction locks, and the housing. Using a coupler (threaded sleeve), the TOB would be connected to the threaded arm. When the TOB tends to experience compression, the threaded arm would push itself into the housing. This inward movement leads to a finite rotation of the mono-directional locks opening them. As a result, the threaded arm can easily push itself into the SFC. Upon the inward movement, the mono-direction locks tend to be closed due to the attached pre-compressed soft springs. Once direction of the inter-story drift changes the threaded arm tends to pull itself out of the housing. After a minor outward movement (slip), the mono-direction locks would be locked and further outward movement of the threaded arm would be restrained. The maximum possible slip (outward movement of the threaded arm) is equal to the thread spacing along the threaded arm which is denoted by the parameter MSL^* (maximum slip length) in Fig. 1(b).

Expected behaviors of the SFC and cross TOB with and without SFC during a half-cycle lateral loading are shown in Figs. 2 and 3, respectively. Note that the soft springs are always under compression even in the case of closed mono-direction locks.

From Fig. 3 it can be observed that TOB2 without SFC remain inactive during the both loading and the unloading phases. On the other hand, if TOB2 is equipped with the SFC, it can start its contribution during the unloading phase after a small slip. If TOB2 starts to carry load before the load in TOB1 drops to zero, there would be no pinching in the overall hysteretic behavior of the cross TOB. From Fig. 3 it can be noticed that if the MSL^* of the SFC is selected to be smaller than axial yield elongation of the TOB, or alternatively, if projection of the MSL^* along the horizontal direction, i.e. MSL, is selected to be smaller than lateral yield displacement of the TOB, pinching would be completely removed from the overall hysteretic behavior of the cross TOB-SFC system.

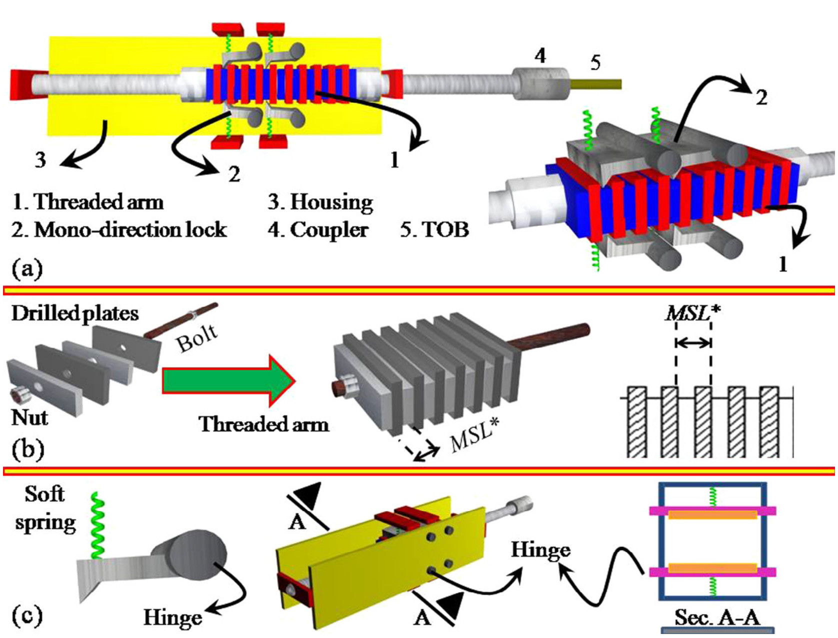

Fig. 1. (a) The main components of the SFC: details of (b) the threaded arm and (c) the mono-direction lock.