Journal of Constructional Steel Research 115 (2015) 329–345

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Toward buckling free tension-only braces using slack free connections

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ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form 25 August 2015
Accepted 28 August 2015
Available online 14 September 2015

Keywords:
Tension-only brace
Buckling free
Hysteretic behavior
Energy dissipation
Seismic behavior
Slack free connection

ABSTRACT

This study introduces a slack free connection (SFC) by which pinching would be removed from hysteretic behavior of tension-only braces (TOBs). SFC through its mono-directional behavior, eliminates undesirable pinching of the tension-only bracing and changes it to a reliable lateral load resisting system with high energy dissipation capability. A Matlab/Simulink-based model, called Macro-Simulink model, is developed to simulate hysteretic behavior of TOBs with or without SFC. Derived Macro-Simulink model is also able to account for hysteretic behavior of the frame. The frame itself can have either deteriorated or non-deteriorated hysteretic behaviors. The Macro-Simulink model is verified through different techniques including earlier experimental results, explicit finite element modeling, and other pre-verified analytical/numerical tools. It is observed that initial pre-tension load only affects initial stiffness of the TOB and has no contribution on its nonlinear hysteretic behavior. Obtained results of this study indicate that energy dissipation capacity of TOBs with SFC would be improved up to 6 times compared with that of conventional TOBs. Moreover contribution of SFC is more pronounced in the case of frames with highly deteriorated behaviors. As a result TOB with SFC can be considered for retrofit purposes as well.

1. Introduction

Tension-only elements have extensive applications in different structures, such as suspension or cable-stayed bridges, cable roofs of sport stadiums, and also as a pre-tensioning technique in pre-stressed concrete elements. Meanwhile, their applications in other structures with other roles are still gaining more attention. As a novel application, Samuel and Astaneh-Asl [1] have examined effect of cables in order to prevent progressive collapse of buildings. Cables are also important elements in some seismic protective systems mainly to transmit control forces from actuators or energy dissipating devices to the main structure. Kim et al. [2] proposed a rotational friction damper connected to tension-only braces to dissipate seismic-induced energies. In another study, Sophocleous and Phocas [3] have investigated contribution of an adaptable closed mechanism consisting of pre-tensioned tendons and hysteretic devices. A retrofit technique has been also proposed by Kurata et al. [4] in which an energy dissipating device is combined with cable braces. Moreover, there have been studies in the literature devoted to applications of TOBs in smart and active structures mainly as active tendons [5–12]. For instance, Zahrai and Hamidia [5] proposed an innovative compound system consisting of shape memory alloy (SMA) and external cables to retrofit existing typical structures.

According to current seismic codes of practice [13,14], the use of cables or very slender (tension-only) braces is prohibited in regions with high level of seismicity. While Tremblay and Filiatrault [15] have shown that TOBs experience no detrimental seismic impact load during load reversals, the main concern of current codes stems from presence of very large pinching in nonlinear hysteretic behavior of TOBs. The so called pinching highly reduces energy dissipation capacity of TOBs and consequently makes them undesirable elements for seismic applications. However, during the last 20 years, noticeable efforts have been directed toward seismic behavior of TOBs [16–24]. For example, Molaei and Saatcioglu [23] experimentally studied seismic retrofit of two RC frames using diagonal cables with and without prestressing. Based on the test results, they found that cable bracing significantly improves lateral strength and stiffness of the RC frames (about 1.5 and 2 times using single and double cables, respectively) and such method can be a proper retrofit alternative when drift control is concerned. However this technique failed to improve energy dissipation capability of the whole system. As depicted in Fig. 1, cable braces would experience huge sagging (global buckling) during cyclic loads. The sagging and inherent brittleness of cable materials were the main reasons of the low energy dissipation capability of the cable braces. Note that, most cables (wire ropes) are made from high strength steels with little plastic elongation capacity. In another study, Wang et al. [24] have experimentally examined behavior of TOBs on a two story steel frame. Again a pinched behavior was observed due to cyclic compression buckling of the braces.

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http://dx.doi.org/10.1016/j.jcsr.2015.08.048
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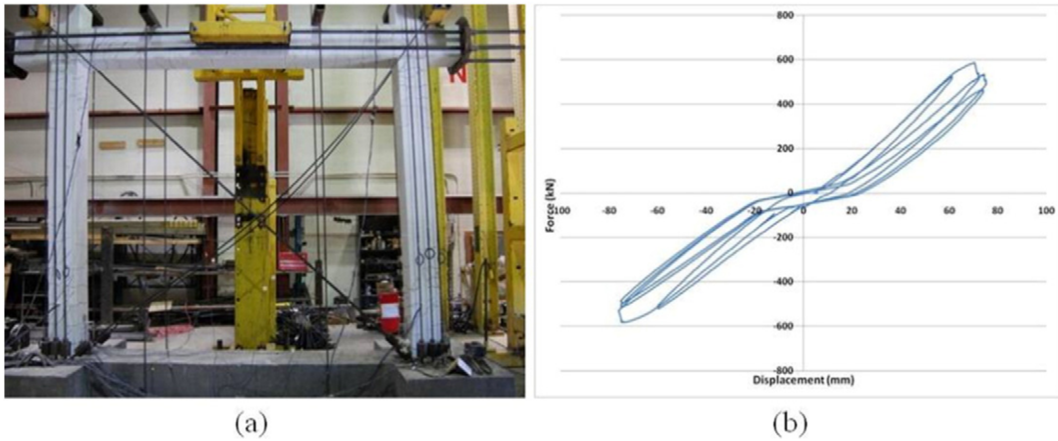

Fig. 1. (a) Cable braced RC frame and (b) hysteretic behavior of the cable brace [23].

Some researchers tried to improve behavior of TOBs through pre-tensioning technique. Obtained results, however, were not persuasive and no noticeable improvement has been observed [18,20–23]. Recently Tamai and Takamatsu [25] proposed a non-compression rod bracing with a special washer/wedge connection. In their proposed connection, the wedge slides between the beveled washer and this would prevent rod buckling. Obtained results were quite encouraging as pinching was eliminated and energy dissipation capability of the rod brace was significantly improved.

It seems that pinching can be removed from hysteretic behavior of TOBs through some mono-directional self-tensioning connections. In order to have an insight into behavior of pre-tensioned TOBs and improve the pinched hysteretic behaviors, current study is carried out in five correlated parts,

I) A Matlab/Simulink [26] based analytical model, called Macro-Simulink model, is derived to investigate nonlinear hysteretic behavior of frames braced with X-shape TOBs with or without pre-tension loads. The frame itself can be either pinned frame or a moment resisting frame.
II) A simple mechanical device, slack free connection (SFC), is proposed through which pinching would be eliminated from cyclic behavior of TOBS. SFC has both requirements, namely mono-directional and self-tensioning characteristics.
III) Derived Macro-Simulink model is extended to account for contribution of the SFC on hysteretic behavior of the TOBs.
IV) The Macro-Simulink model is verified by available experimental results as well as pre-validated tools, such as SAP 2000 [27], and explicit finite element modeling in Abaqus [28].
V) Hysteretic behaviors of different frames braced with X-shape TOBs with and without SFC under quasi-static displacement-controlled excitation are compared to evaluate contribution of the proposed SFC.

2. Analytical model for frames braced with pre-tensioned TOBs

Before developing a mathematical model, monotonic and cyclic behavior of pre-tensioned tension-only braces (TOBs) should be first reviewed. Consider two pre-tensioned TOBs with X-shape configuration, as shown in Fig. 2. Both TOBs contribute to lateral stiffness of the structure, as far as they are both in tension. This is true only in terms of lateral stiffness as pre-tensioning has no effect on ultimate strength of the X-shape bracing. TOBs would lose the initial pre-tension load during load reversals of high ductility demands. Besides, nonlinear cyclic behavior of such elements is highly pinched. Obviously, the analytical model should be able to account for above mentioned features as well as hysteretic behavior of the frame itself. Considering the frame shown in Fig. 2, the lateral static equilibrium equation can be written as,

$$F + (P_0 - \Delta P)\cos\theta = (P_0 + \Delta P)\cos\theta + P_f \quad (1)$$

$$F = P_f + 2\Delta P\cos\theta \quad (2)$$

$$\Delta P = K\prime_{TOB}\cos\theta u \quad (3)$$

$$F = P_f + 2\left(K\prime_{TOB}\cos^2\theta\right)u \quad (4)$$

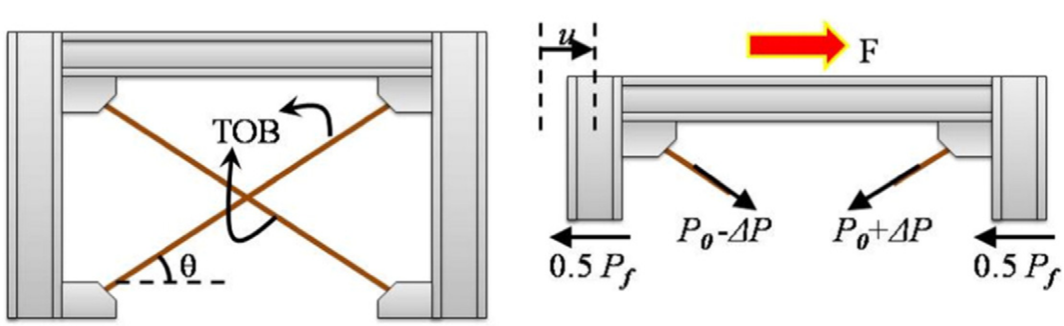

Fig. 2. A typical frame braced with X-shape pre-tensioned TOBs.