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Contribution of pre-slacked cable braces to dynamic stability of non-ductile frames; an analytical study

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ABSTRACT

Frames with poor seismic details can reveal deteriorating hysteretic behaviors with stiffness and strength degradation, as well as pinching. All of these features can give rise to significant concerns in terms of lateral dynamic stability. In order to alleviate such undesirable behaviors, a Pre-Slacked Cable Brace (PSCB) is proposed by which post-yield stiffness of highly pinched non-ductile frames would be greatly improved with minimal increase on their lateral strength capacity. In the present study, an open-source time domain platform, called Macro-Simulink model, is derived by which different deteriorating hysteretic behaviors can be simulated under both quasi-static and dynamic excitations. Accuracy of the Macro-Simulink model is also verified through earlier experimental results. As a numerical assessment, contribution of the PSCB is examined for a representative non-ductile single story frame. Obtained results indicate that PSCB can improve lateral stability of the frame under mainshocks–aftershocks sequences as it completely removes strength degradation from hysteretic behavior of the whole system. This is achieved at the expense of a minor increase in the ultimate strength of the braced frame. As a result, PSCB would not impose significant additional demands on force-controlled components. Besides, PSCB has a pronounced contribution on self-centering capability of the braced frame. Obtained results also indicate that lateral stability of the vibrating systems with highly pinched hysteretic behavior might be quite vulnerable to aftershocks.

1. Introduction

According to the current understanding of structural behavior under seismic-induced excitation, a lateral load resisting system with maximal energy dissipation capability and minimal hysteretic deterioration is required to transfer all of the inertia forces to the ground. Learned from past earthquakes and earlier studies, non-ductile lateral load resisting systems with highly pinched and deteriorating hysteretic behaviors might be unable to provide a reliable load path. There are different sources through which undesirable hysteretic behaviors can be triggered. These include local/global buckling, low-cycle fatigue, crack opening-closing, reinforcement slip, crushing, etc. The majority of seismic provisions in the current seismic codes, such as AISC 341 [1] and ACI 318 [2], aimed to alleviate above mentioned sources. However, old or poorly detailed new structures are still susceptible to hysteretic deterioration during a major seismic event.

During the past 20 years or so, significant efforts have been devoted to achieve a better understanding about seismic behavior of non-ductile systems with deteriorating hysteretic behavior. For example, spectral displacements of SDOF systems with different deteriorating hysteretic behaviors have been obtained by Song and Pincheira [3]. They have noticed that undesirable effect of deteriorating behaviors is more pronounced for stiff and short period SDOFs. The same conclusion has been also made by Ruiz-Garcia and Miranda [4]. In addition, Miranda and Akkar [5] have examined seismic behavior of inelastic systems with negative post-yield stiffness. Obtained results have signified the detrimental effect of negative post-yield stiffness (strength degradation) on lateral stability of the considered systems. In addition, dominant effect of post-yield stiffness on collapse capacity has been pointed out by Ibarra and Krawinkler [6] and Adam and Jager [7]. For example, negative post-yield stiffness due to the *P*–delta effect can accelerate dynamic stability as suggested by Bernal [8] and Ibarra and Krawinkler [6].

Obtained results by Elkaday and Lignos [9] indicated that considering composite action in fully restrained beam-to-column connections would result in a connection behavior with enhanced

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post-yield stiffness and subsequently can lead to a higher system-level collapse capacity. In another study, it was revealed that post-yield stiffness not only governs dynamic instability but can also have noticeable effect on the residual deformation [10]. As indicated by Hatzigeorgiou et al. [11] and Christidis et al. [12], residual and maximum displacements are correlated. Therefore, it can be expected that systems with positive post-yield stiffness tend to reduce both maximum and residual displacements.

Using extensive small scale shaking table tests on steel moment frames with deteriorating connection behaviors, adverse effect of strength degradation and negative post-yield stiffness have been observed by Rodgers and Mahin [13]. A thorough discussion with regard to seismic performance of degrading hysteretic behaviors has been provided by FEMA P440A [14]. According to FEMA P440A, while deteriorating systems have less energy dissipation capability, maximum displacement demands (displacement spectrum) are not so sensitive to type of the hysteretic behavior, especially for flexible long period systems. This is not the case, however, for stiff structures. Therefore, while the decreased energy dissipation capability of systems with deteriorating hysteretic behaviors has some adverse effects, the main problem with such behaviors is due to their negative post-yield stiffness and the corresponding strength degradation.

As a result of the earlier findings, the main intention of the present study is to increase post-yield stiffness of systems with non-ductile hysteretic behaviors. This can be done by placement of an elastic element in parallel with the main deteriorating behavior. However, in this way, initial stiffness as well as yield strength of the vibrating system might greatly increase and larger demands would be imposed on the force-controlled components. Therefore in this study, a cable brace with a tuned initial slackness, hereafter called Pre-Slacked Cable Brace (PSCB), is proposed to improve post-yield behavior of non-ductile systems with deteriorating behaviors.

As shown in Fig. 1, PSCB has a nonlinear-elastic behavior through which post-yield stiffness of the whole braced system would increase up to a predefined non-negative value. The proposed PSCB does not contribute to the initial lateral stiffness of the frame. In this way, the initial stiffness and yield strength of the braced frame would remain the same as those of the unbraced frame. More details about the PSCB and its mathematical formulations would be discussed in the subsequent sections. It should be clarified that the term "cable", in this study, is a general term and can be referred to different tension-only elements which have negligible flexural rigidity. These include wire ropes (such as 7×19 cables), glass or carbon fiber cables, etc.

Cable bracing is not a new technique and the topic has been studied by many researchers. Shalouf [15], for example, has examined contribution of pre-stressed cable brace for half-scale non-ductile RC frames with masonry infills. As depicted in Fig. 2, while cable bracing increases the lateral post-yield stiffness, it also results in significant increase in lateral yield strength and initial stiffness of the frame which might be undesirable from capacity design point of view. Besides, the pre-stressed cables have yielded at moderate drift demands (about 1%) and resulted in a negative post-yield stiffness at larger drift demands. In another study, Yang et al. [16] have demonstrated that wire rope bracing with suitable configuration can improve post-yield stiffness of non-ductile systems. In their study, unreinforced masonry walls were strengthened with multiple inclined wire ropes and promising results have been observed from quasi-static cyclic tests. Cable braces have been also proposed in cooperation with different energy dissipating devices [17–19].

The idea of cable bracing with initial slackness is also not new. Using wire rope braces bundled with a central cylindrical member,

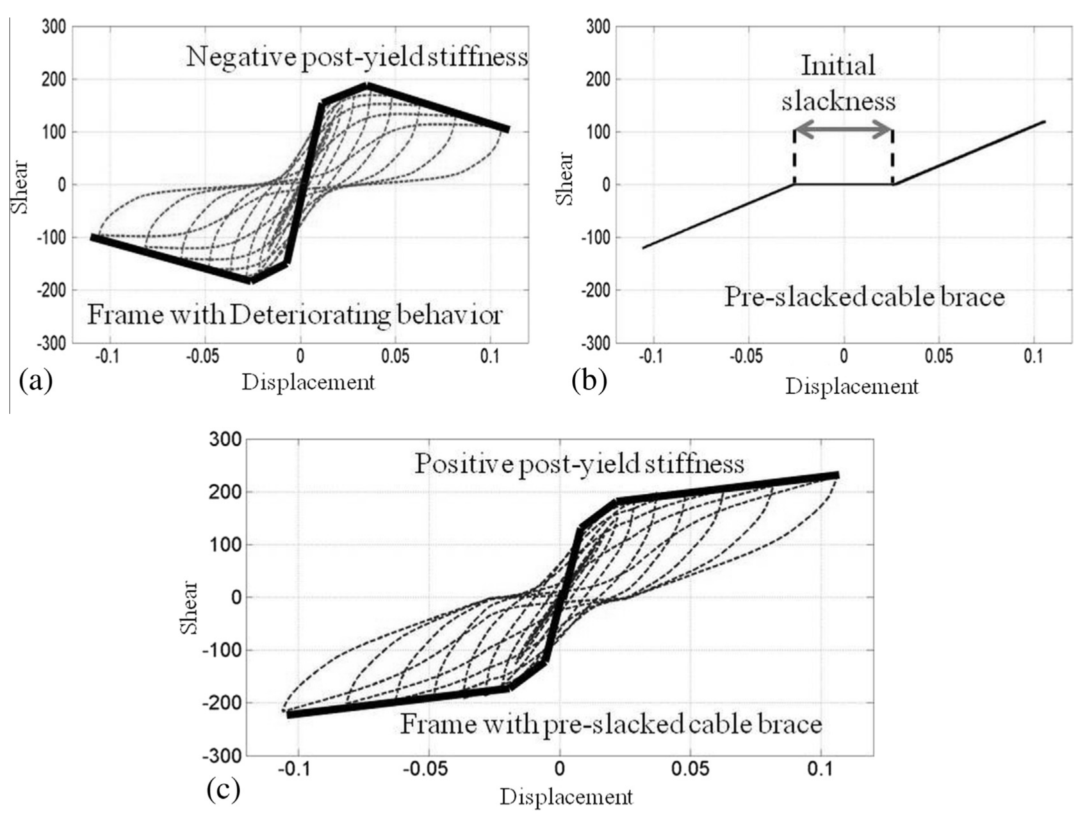

Fig. 1. Improvement of seismic behavior of non-ductile systems through pre-slacked cable brace.