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Sustainable seismic design

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Abstract

Traditional design of a seismic resistant system for a building structure has often relied on structural damage as the intended response of the structure to limit the increase in lateral force and to dissipate energy. The goal of this traditional design approach was life-safety, i.e. to prevent building collapse. Following this approach, a major seismic event can cause significant damage to the structure. This in turn requires extensive repair, or if the damage is severe enough, for the structure to be demolished. More recently, an alternative design approach has emerged that is intended to provide structures that remain damage free and self-center (i.e. exhibit no residual drift) after the earthquake. This paper describes this alternative approach, and discusses opportunities for improved sustainability through damage-resistant seismic design and renewable materials.

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Keywords: Earthquake; seismic design; post-tensioning; sustainability

1. Introduction

Traditional design of a seismic resistant system for a building structure has often relied on structural damage (e.g. yielding of steel, non-linear compression response of concrete, etc.) as the intended response of the structure to limit the increase in lateral force and to dissipate energy. The goal of this traditional design approach was life-safety, i.e. to prevent building collapse. Following this approach, a major seismic event can cause significant damage to the structure. Two inherent limitations of this approach are: (1) the required nonlinearity or softening of the lateral force resisting system is caused by damage; and (2) residual lateral drift after a major seismic event. This in turn requires extensive repair, or if the damage is severe enough, for the structure to be demolished. The need for extensive repair or demolition is inconsistent with sustainable design and construction practices.

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To address the limitations of traditional approaches to seismic design, over the past twenty years a considerable amount of research has been devoted to developing self-centering, seismic-resistant building systems that offer recoverable energy-dissipation mechanisms and damage-free softening of lateral load response. As an example of the previous work in this field, Table 1 presents a collection of relevant studies performed by researchers at Lehigh University. Included in the table is the type of lateral force resisting system studied, as well as a list of publications that provide the details of each study. The common element in each of these systems is the use of post-tensioning to allow gap opening at specified locations in the lateral force resisting system under the action of seismic loading in a manner that leads to softening of the structural system. Thus softening is obtained by overcoming the prestressing force, and not through damage.

These post-tensioned seismic-resistant building systems are a distinct departure from the conventional ductile design approach, in which the structural system survives seismic excitation through controlled damage. By utilizing damage-free mechanisms to achieve the desired building response characteristics (e.g. geometric softening of lateral load response through gap opening at beam-column and/or wall-foundation joints; and energy dissipation through relative movement along frictional interfaces or viscoelastic deformations), these systems are not only resistant to structural collapse (enforcing the life safety performance objective), but they also have the potential to significantly improve sustainability and to lessen the economic impact of a seismic event by reducing infrastructure damage.

Table 1. Lehigh University research on post-tensioned seismic-resistant building systems.

Lateral Force Resisting System	Publications
Post-tensioned concrete rocking walls	Kurama et al. 1999a, 1999b, 2002; Perez et al. 2004a, 2004b, 2007, 2013; ACI, 2009; Keller and Sause, 2010; Rivera et al. 2013
Post-tensioned concrete moment-frames	El-Sheikh et al. 1999, 2000; Keller et al. 2010
Post-tensioned steel moment-frames	Garlock et al. 2005, 2007, 2008; Ricles et al. 2000, 2001, 2002; Peng et al. 2000; Rojas et al. 2005a, 2005b; Seo et al. 2005, 2009; Iyama et al. 2008; Lin et al. 2009a, 2009b
Post-tensioned steel rocking frames	Roke et al. 2006, 2009a, 2009b; Sause et al. 2006a, 2006b, 2006c, 2009a; 2009b, 2010

2. Illustration of a post-tensioned lateral force resisting systems – concrete walls

Fig. 1 illustrates in general how damage-resistant post-tensioned seismic systems work. The example shown in the figure is for a concrete wall, but similar responses are obtained from the other structural systems as well. Fig. 1 shows a schematic of a conventional cast-in-place reinforced concrete wall, an unbonded post-tensioned concrete wall, and an unbonded post-tensioned hybrid concrete wall. Also shown is the expected base shear-lateral drift of each wall. The conventional reinforced concrete structural wall (Fig. 1(a)) is a cast-in-place concrete wall, without post-tensioning, and with detailing to provide stable hysteretic behavior. Mild bonded steel reinforcement in the wall extends across the wall-foundation interface and is anchored in the foundation. Under the action of lateral load, the wall softens due to yielding of steel reinforcement and nonlinear stress-strain response of concrete (i.e. damage). Upon reversal of lateral load F, the wall will not necessarily return to zero drift position. Instead, upon removal of the lateral force, the wall can exhibit a residual drift.

Fig. 1(b) shows an unbonded post-tensioned wall (similar to the precast walls with post-tensioning for self-centering studied by Kurama et al. and Perez et al.). These walls exhibit self-centering behavior but they do not have any mild steel reinforcement crossing the horizontal joint between the wall and the foundation. Therefore, these walls undergo large drift without dissipating any excitation energy as illustrated in Fig. 1(b).

An unbonded post-tensioned hybrid concrete wall, illustrated in Fig. 1(c), includes unbonded post-tensioning, and also bonded longitudinal web reinforcement for energy dissipation. The lateral load-deflection response of the hybrid wall is a combination of the energy dissipation as in traditional structural walls, and self-centering as in unbonded post-tensioned precast concrete walls. In an event of seismic excitation, use of unbonded post-tensioning provides the wall with self-centering capacity and the mild steel reinforcement is designed to dissipate energy.