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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.

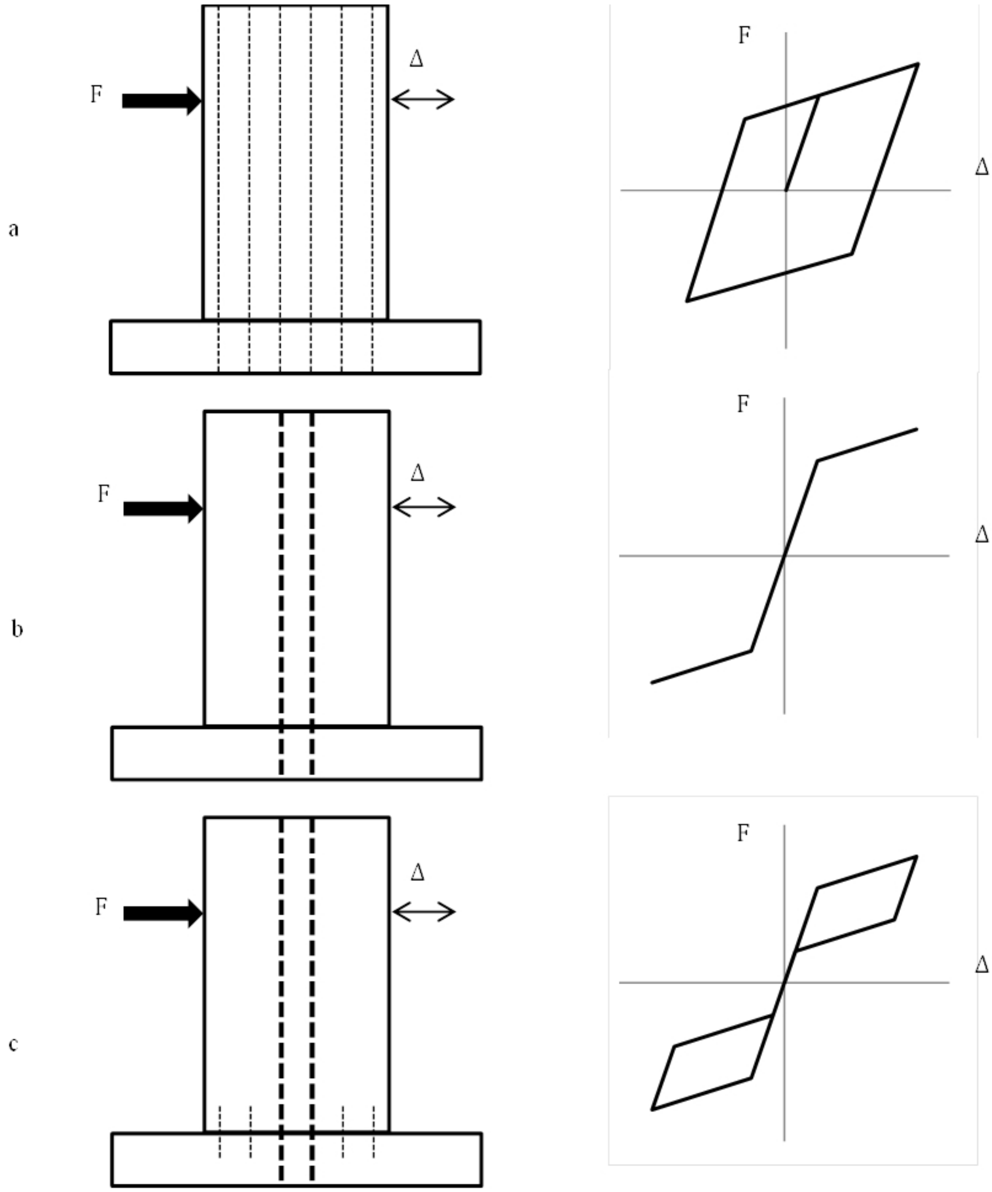

Fig. 1. (a) conventional cast-in-place wall; (b) unbonded post-tensioned wall; (c) unbonded post-tensioned hybrid wall.

Research has shown that the lateral load response of properly designed and detailed post-tensioned rocking walls can be characterized by four distinct limit states, which are illustrated in Fig. 2. If tensile strain demands at the base of the wall under lateral loading are below the pre-compression strain due to post-tensioning and gravity loading, and are within the linear elastic region for the component materials, the lateral load response is similar to that of a conventional wall. As tensile strain demands exceed the pre-compression strain, the wall begins to lift off of the foundation because the wall panel-to-foundation joint is ineffective in tension, i.e. only the unbonded post-tensioning steel is effective in resisting tensile force across the wall-foundation interface. This is referred to as the decompression limit. As the gap along the wall-foundation interface propagates under increased lateral load demand, the lateral load response begins to appreciably soften due to second-order geometric effects (referred to as the effective linear limit). This softening elongates the periods of vibration for the structure, which tends to lower inertial force demands in the system for typical ground motions due to a reduction in transmissibility. From this point, the rocking wall continues to support additional loading until tensile strain demands in the post-tensioning steel reach yield. Following yielding, strain-hardening in the post-tensioning steel supports lateral loading at a greatly diminished stiffness. Failure of a well-designed wall, which resists buckling modes of failure, is marked by excessive damage in the compression toe of the wall or global instability.

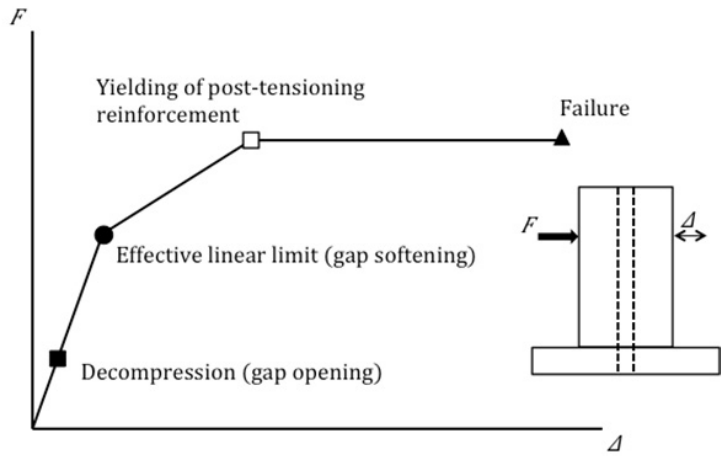

Fig. 2. Idealized monotonic lateral load response for post-tensioned walls.

3. Sustainable construction through damage-resistant seismic design and renewable materials

Until recently, much of the research on self-centering, seismic-resistant building systems (particularly in the U.S.) has been devoted to steel and concrete construction, whose industries have historically dominated the commercial and multi-family residential sectors. However, greater emphasis on sustainable construction practices, which has been motived by diminishing natural resources, rising construction costs, and concerns over the environmental impact of material harvesting and processing practices, has rejuvenated interest in renewable and readily available materials for building construction.

Seismic-resistant post-tensioned lateral force resisting systems that were developed for steel and concrete buildings are now being investigated for timber structures, as illustrated in Table 2, which presents a collection of recent studies on post-tensioned timber construction. In New Zealand, this technology has already made its way into practice with the construction of at least two post-tensioned timber buildings in 2011-2012 (Dekker et al. 2012; Holden et al. 2012).

Additional opportunities exist in other renewable materials as well. In Indonesia, for example, researchers are investigating laminated timber composites for structural applications that utilize abundant and fast growing native plant species, e.g. *Paraserianthes falcataria* and *Hevea brasiliensis Muell* (Awaludin et al. 2011, 2012a, 2012b, 2013a, 2013b). These species have been rarely used for structural applications due to their relatively low strength and stiffness, as compared to structural grade timber. However, their use in laminated veneer lumber (LVL), in which a built-up section is assembled by binding thin plies of the material with adhesive, is seen as a potential solution to diminishing timber resources. Made in a factory under controlled conditions, LVL has superior material uniformity compared to the base product and has been shown to provide a stronger, straighter section that is less susceptible to warping, twisting, bowing, or shrinking.

An important limitation to the widespread implementation of seismic-resistant post-tensioned construction is that the use of hydraulic rams for post-tensioning are not readily / economically available in all regions of the world, necessitating practical solutions that employ indigenous materials and adaptable construction practices. For example, design concepts such as hand-tensioned, spring-loaded rocking frames (currently being studied at Lehigh

University) may offer a cost-effective and practical alternative in developing regions where the full spectrum of construction technologies is not readily available, although more data is needed to validate these systems.

Table 2. Recent developments in seismic-resistant post-tensioned timber construction.

Research Area	Reference(s)
Experimental tests of laminated veneer lumber hybrid moment-frame beam-column, wall-foundation, and column-foundation assemblies	Palermo et al. 2005, 2006a, 2006b, 2006c
Design/modeling of seismic-resistant post-tensioned timber buildings	Newcombe et al. 2008; Smith et al. 2008a, 2008b
Experimental tests of post-tensioned timber moment-frame beam-column assemblies with supplemental passive damping	Smith et al. 2011a
Experimental study regarding the demountability, relocation, and re-use of post-tensioned timber buildings	Smith et al. 2011b
Construction of the Carterton Events Centre Auditorium in Carterton, New Zealand using post-tensioned laminated veneer lumber rocking walls	Dekker et al. 2012
Construction of the NMIT Arts and Media Building in Nelson, New Zealand using post-tensioned laminated veneer lumber rocking walls	Holden et al. 2012
Experimental tests of post-tensioned laminated veneer lumber rocking walls coupled with plywood sheets	Iqbal et al. 2012
Experimental tests of post-tensioned timber frames for multi-story seismic-resistant buildings	van Beerschoten et al. 2012

4. Summary

Traditional approaches to seismic design of seismic resistant systems for building structures, while satisfying the objective of life-safety, often result in buildings that require extensive repair or that must be demolished after a significant seismic event. More recently, an alternative design approach has emerged that is intended to provide structures that remain damage free and self-center after an earthquake, requiring less (if any) repair after the seismic event. This alternative design approach is well-developed for steel and concrete building systems, and has more recently been studied for timber systems as well. Opportunities remain for continued evolution of improved sustainability through more widespread implementation of self-centering damage-resistant seismic design, implemented with an awareness of continued development of renewable materials, and also with a recognition of local construction methods.

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References

[1] American Concrete Institute (ACI) (2009) “Requirements for design of a special unbonded post-tensioned precast shear wall satisfying ACI ITG-5.1 (ACI ITG-5.2-09) and Commentary,” American Concrete Institute, Farmington Hills, MI.

[2] Awaludin, A., Sasaki, Y, Pradana, E, Danastri, D.A. (2011) “Mechanical properties of LVL Paraserianthes falcataria, *Technical Report*, Civil and Environmental Engineering Department,Universitas Gadjah Mada, Yogyakarta, August.

[3] Awaludin, A. (2012a) “Development of structural wall made from LVL Sengon (Paraserianthes falcataria): basic mechanical properties,” *Proceedings from the 1st International Conference on Sustainable Engineering Structures and Construction Materials*, Yogyakarta, September 11-13, 2012.

[4] Awaludin, A. and Suriani, E. (2012b) “Shear resistance of timber member to concrete foundation using lag screw fasteners,” *Proceedings from the 5th ASEAN Civil Engineering Conference*, Ho Chi Minh, Vietnam, October 25-26.

[5] Awaludin, A., Palaeowati, N., and Hariadi, S. (2013a) “Prediction of lateral resistance of timber joints with wood and bamboo dowel-type fasteners,” *Proceedings from the 3rd Engineering Annual Seminar*, Universitas Gadjah Mada, Yogyakarta, February 13.

[6] Awaludin, A., Pribadi, A., and Satyarno, I. (2013b) "Racking resistance of Paraserianthes falcataria wooden panels under monotonic load," *accepted to the 6th Civil Engineering Conference in Asia-Pacific Region*, Jakarta, August 2013.

[7] Dekker, D., Chung, S., and Palermo, A. (2012) "Carterton Events Centre Auditorium pres-lam wall design and construction," *Proceedings from the 2012 NZSEE Conference*, New Zealand, Paper No. 53.

[8] El-Sheikh, M.T., Sause, R., Pessiki, S., and Lu, L.W. (1999) "Seismic behavior and design of unbonded post-tensioned precast concrete frames," *PCI Journal*, Precast/Prestressed Concrete Institute, Vol. 44, No. 3, May/June, pp. 54-71.

[9] El-Sheikh, M.T., Pessiki, S., Sause, R., and Lu, L.W. (2000) "Moment-rotation behavior of unbonded post-tensioned precast concrete beam-column connections," *ACI Structural Journal*, American Concrete Institute, Vol. 97, No. 1, pp.122-131.

[10] Garlock, M., Sause, R., and Ricles, J.M. (2004) "Design and behavior of post-tensioned steel moment frames," *Proceedings from the 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, August, (Paper No. 2560, CD-ROM).

[11] Garlock, M.M., Ricles, J.M., and Sause, R. (2005) "Experimental studies of full-scale post-tensioned steel connections," *Journal of Structural Engineering*, Vol. 131, No. 3, pp. 438-448.

[12] Garlock, M.M., Sause, R., and Ricles, J.M. (2007) "Behavior and design of post-tensioned steel frame systems," *Journal of Structural Engineering*, Vol. 133, No. 3, pp. 389-399.

[13] Garlock, M.M., Ricles, J.M., and Sause, R. (2008) "Influence of design parameters on seismic response of post-tensioned steel MRF systems," *Engineering Structures*, Vol. 30, No. 4, pp. 1037-1047.

[14] Holden, T., Devereux, C., Haydon, S., Buchanan A., and Pampanin, S. (2012) "Innovative structural design of a three storey post-tensioned timber building," *Proceedings from the World Conference on Timber Engineering*, Auckland, New Zealand, July 15-19.

[15] Iqbal, A., Pampanin, S., Fragiacomo, M., Palermo, A., and Buchanan, A. (2012) "Seismic response of post-tensioned LVL walls coupled with plywood sheets," *Proceedings from the World Conference on Timber Engineering*, Auckland, New Zealand, July 15-19.

[16] Iyama, J., Seo, C.-Y., Ricles, J., and Sause, R. (2008) "Self-centering moment resisting frames with bottom flange friction devices under earthquake loading," *Journal of Constructional Steel Research*, Vol. 65, No. 2, pp. 314-325.

[17] Keller, W.J. and Sause, R. (2010) "Analysis and design of unbonded post-tensioned concrete rocking walls for the 2010 E-Defense four-story seismic-resistant post-tensioned concrete test structure," *ATLSS Report 10-04*, Center for Advanced Technology for Large Structural Systems, Lehigh University, Bethlehem, PA, 326 pages.

[18] Keller, W.J., Sause, R., and Seo, C.Y. (2010), "Preliminary design and pre-test numerical shake table simulations for an archetype self-centering building system utilizing post-tensioned concrete walls and frames, *NEES/E-Defense Collaborative Earthquake Research Program – 5th Planning Meeting*, Tokyo, Japan, Mar. 2, 83 pages.

[19] Kurama, Y. C., Pessiki, S., Sause, R., and Lu, L.W. (1999a) "Seismic behavior and design of unbonded post-tensioned precast concrete walls," *PCI Journal*, Precast/Prestressed Concrete Institute, Vol. 44, No. 3, May-June.

[20] Kurama, Y. C., Sause, R., Pessiki, S., and Lu, L.W. (1999b) "Lateral load behavior and seismic design of unbonded post-tensioned precast concrete walls," *ACI Structural Journal*, American Concrete Institute, Vol. 96, No. 4, July-August.

[21] Kurama, Y., Sause, R., Pessiki, S., and Lu, L.W. (2002) "Seismic response evaluation of unbonded post-tensioned precast walls," *ACI Structural Journal*, American Concrete Institute Vol. 99, No. 5, pp. 641-651.

[22] Lin, Y.-C., R., Ricles, J.M., Sause, R., and Seo, C.Y. (2009a) "Earthquake simulations on a self-centering steel moment resisting frame with web friction devices," *Proceedings from the 6th International Conference on Behavior of Steel Structures in Seismic Areas – STESSA 2009*, Philadelphia, PA, August 16-20, pp. 61-66.

[23] Lin, Y.-C., Ricles, J.M., and Sause, R. (2009b) "Earthquake simulations on a self-centering steel moment resisting frame with web friction devices," *Proceedings of the 2009 Structures Congress*, Austin, TX, April 30-May 2.

[24] Newcombe, M.P., Pampanin, S., Buchanan, A., and Palermo, A. (2008) "Seismic design and numerical validation of post-tensioned timber frames," *Proceedings from the 14th World Conference on Earthquake Engineering,* October 12-17, Beijing, China.

[25] Palermo A., Pampanin S., Buchanan A., Newcombe M. (2005) "Seismic design of multi-storey buildings
using laminated veneer lumber (LVL)," *Proceedings from the* 2005 *NZEES Conference*, New Zealand, March 11- 13.

[26] Palermo A., Pampanin S., Fragiacomo M., Buchanan A., Deam B. (2006a) "Innovative seismic solutions for multi-storey LVL timber framed buildings, *Proceedings from the World Conference on Timber Engineering*, Portland, August.

[27] Palermo A., Pampanin S., Buchanan A. (2006b) "Experimental investigations on LVL seismic-resistant wall and frame subassemblies," ECEES, *Proceedings from the 1st European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland, September 3- 8.

[28] Palermo A., Pampanin S., Buchanan A., Fragiacomo, M., and Deam, B. (2006c) "Code provisions for seismic design of multi-storey post-tensioned timber buildings," ECEES, *Proceedings from the International Council for Research and Innovation in Building and Construction – Working Commission W18: Timber Structures*, Florence, Italy, August.

[29] Peng, S.-W., Ricles, J.M., Sause, R., and Lu, L.W. (2000) "Experimental evaluation of a post-tensioned moment connection for steel and composite frames in seismic zones," *Proceedings from the 6th ASCCS Conference on Steel and Concrete Composite Structures*, Los Angeles, pp. 721-728.

[30] Perez, F. J., Pessiki, S., and Sause, R. (2004a), "Seismic design of unbonded post-tensioned precast concrete walls with vertical joint connectors," *PCI Journal*, Precast/Prestressed Concrete Institute, Vol. 49, No. 1, January-February.

[31] Perez, F. J., Pessiki, S., and Sause, R. (2004b), "Lateral load behavior of unbonded post-tensioned precast concrete walls with vertical joints," *PCI Journal*, Precast/Prestressed Concrete Institute, Vol. 49, No. 2, March-April.

[32] Perez, F. J., Pessiki, S., and Sause, R. (2007) "Analytical and experimental lateral load behavior of unbonded post-tensioned precast concrete walls", *Journal of Structural Engineering*, American Society of Civil Engineers, Vol. 133, No. 11, November.

[33] Perez, F.J., Pessiki, S., Sause, R., "Experimental Lateral Load Response of Unbonded Post-tensioned Precast Concrete Walls," *ACI Structural Journal*, Vol. 110, No. 6, November-December 2013, pp. 1045-1055.

[34] Ricles, J.M., Sause, R., Garlock, M., Peng, S.W., and Lu, L.W. (2000) "Experimental studies on post-tensioned seismic-resistant connections for steel frames," *Proceedings from the 3rd International Specialty Conference on Behavior of Steel Structures in Seismic Areas – STESSA 2000*, Montreal, pp. 231-238.

[35] Ricles, J.M., Sause, R., Garlock, M.M., and Zhao, C. (2001) "Post-tensioned seismic-resistant connections for steel frames," *Journal of Structural Engineering*, Vol. 127, No. 2, pp.113-12.

[36] Ricles, J.M., Sause, R., Peng, S.-W., and Lu, L.W. (2002) "Experimental evaluation of post-tensioned steel connections," *Journal of Structural Engineering*, Vol. 128, No. 7, pp. 850-859.

[37] Rivera, M., Pessiki, S., and Sause, R. (2013) "Experimental and analytical evaluation of multi-story unbonded post-tensioned hybrid concrete walls," *ATLSS Report*, Center for Advanced Technology for Large Structural Systems, Lehigh University, Bethlehem, PA.

[38] Rojas, P., Garlock, M., Ricles, J., and Sause, R. (2005a) "Use of post-tensioned friction damped connections for seismic retrofit of steel moment resisting frames," *International Journal of Steel Structures*, Vol. 5, No. 3, pp. 265-276.

[39] Rojas, P., Ricles, J.M., and Sause, R. (2005b) "Seismic performance of post-tensioned steel moment resisting frames with friction devices," *Journal of Structural Engineering*, Vol. 131, No. 4, pp.529-540.

[40] Roke, D., Sause, R., Ricles, J., Seo, C.-Y., and Lee, K.-S. (2006a), "Self-centering seismic-resistant steel concentrically-braced frames," *8th U.S. National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, San Francisco, April.

[41] Roke, D., Sause, R., Ricles, J.M., and Gonner, N. (2009a), "Damage-free seismic-resistant self-centering steel concentrically-braced frames," *STESSA 2009, Proceedings from the 6th International Conference on Behavior of Steel Structures in Seismic Areas*, Philadelphia, PA, August 16-20, pp.3-10.

[42] Roke, D., Sause, R., Ricles, J.M., and Gonner, N. (2009b), "Design concepts for damage-free seismic-resistant self-centering steel concentrically-braced frames," *Proceedings from the 2009 Structures Congress*, Austin, TX, April 30-May 2.

[43] Sause, R., Ricles, J., Roke, D., Seo, C.-Y., and Lee, K.-S. (2006a), "Self-centering seismic-resistant steel concentrically-braced frames," *Proceedings from the 5th International Conference on Behavior of Steel Structures in Seismic Areas – STESSA 2006*, Yokohama, Japan, August pp. 85-90.

[44] Sause, R., Ricles, J., Roke, D., Seo, C.-Y., and Wolski, M. (2006b), "Self-centering steel frame systems," extended abstract, *4th NEES Annual Meeting*, Washington D.C., June.

[45] Sause, R., Ricles, J., Roke, D., Seo, C.-Y., and Lee, K.-S. (2006c), "Design of Self-Centering Steel Concentrically-Braced Frames," *4ICEE, 4th International Conference on Earthquake Engineering*, Taipei, Taiwan, October.

[46] Sause, R., Ricles, J.M., Lin, Y.-C., Seo, C.-Y., and Roke, D. (2009a), "Performance-based design of self-centering steel frame systems," *Proceedings from the ACES Workshop: Advances in Performance-Based Earthquake Engineering*, Corfu, Greece, July 4-7.

[47] Sause, R., Ricles, J.M., Lin, Y.-C., Seo, C.-Y., Roke, D.A., Chancellor, N.B., and Gonner, N. (2009b), "Validating performance of self-centering steel frame systems using hybrid simulation," *Proceedings of the 3rd International Conference on Advances in Experimental Structural Engineering*, San Francisco, CA, October 15-16.

[48] Sause, R., Ricles, J.M., Lin, Y.-C., Seo, C.-Y., Roke, D.A., and Chancellor, N.B. (2010), "Self-centering damage-free seismic-resistant steel frame systems," *Proceedings of the 7th International Conference on Urban Earthquake Engineering (7CUEE) & 5th International Conference on Earthquake Engineering (5ICEE),* March 3-5, Tokyo, Japan.

[49] Seo, C.Y. and Sause, R. (2005) "Ductility demands on self-centering systems under earthquake loading," *ACI Structural Journal*, American Concrete Institute, Vol. 102, No. 2, March-April.

[50] Seo, C.-Y., Lin, Y.-C., Sause, R., and Ricles, J.M. (2009), "Development of analytical models for 0.6 scale self-centering MRF with web friction devices," *Proceedings from the 6th International Conference on Behavior of Steel Structures in Seismic Areas – STESSA 2009*, Philadelphia, PA, August 16-20, pp. 849-854.

[51] Smith, T., Pampanin, S., Fragiacomo, M., and Buchanan, A. (2008) "Design and construction of prestressed timber buildings for seismic areas," *New Zealand Timber Design Journal*, Vol. 16, No. 3, pp. 3-10.

[52]Smith, T., Pampanin, S., Buchanan, A., and Fragiacomo, M. (2008) "Feasibility and detailing of post-tensioned timber buildings for seismic areas," *Proceedings from the 2008 NZSEE Conference*, New Zealand, Paper No. 53.

[53] Smith, T., Wong, R., Newcombe, M., Carradine, D., Pampanin, S., and Buchanan, A. (2011a) "The demountability, relocation and re-use of a high-performance timber building," *Proceedings from the 9th Pacific Conference on Earthquake Engineering*, Auckland, New Zealand, April 14-16, Paper No. 187.

[54] Smith, T., Pampanin, S., Carradine, D., Buchanan, A., Ponzo, F., Di Cesare, A., and Nigro, D. (2011b) "Experimental investigations into post-tensioned timber frames with advanced damping systems," *Proceedings from the 2011 ANIDIS Conference*, Bari, Italy, September.

[55] van Beerschoten, W., Palermo, Carradine, D., and Law, P. (2012) "Unbonded post-tensioned timber gravity frames for multi-story buildings," *Proceedings from the 2012 ASEC Conference*, Perth, Australia, Nov. 28-Dec. 2.