SELF-CENTERING SEISMIC-RESISTANT STEEL FRAME SYSTEMS: OVERVIEW OF PAST AND CURRENT RESEARCH

Richard Sause and James M. Ricles

Lehigh University

Maria E. Moreyra Garlock, Erik VanMarcke, and Li-Shiuan Peh

Princeton University

Judy Liu

Purdue University

Introduction

Conventional seismic-resistant structural systems use fully restrained joints that are designed so that inelastic deformations develop in the main structural members. Conventional earthquake-resistant systems provide acceptable life-safety and collapse-prevention performance, but the economic impacts of inelastic deformation and related damage can be significant.

New earthquake-resistant structural systems, called self-centering (SC) systems have been studied experimentally and analytically. These systems use gap-opening behavior at selected critical joints between main structural members, along with associated energy dissipation elements, to provide nonlinear softening behavior, ductility, and energy dissipation without significant inelastic deformation and related damage to the main structural members. Elastic restoring forces provided by post-tensioning at these joints return the structure to it original position, eliminating residual drift.

This paper provides an overview of past and current research on SC seismic-resistant steel frame systems.

Past Research on SC Systems

During the past 10 years, several major analytical and experimental studies on SC seismic-resistant systems have been conducted in the US and in other countries. This section summarizes past research conducted at Lehigh University, where the following systems have been studied: (1) unbonded post-tensioned precast concrete walls, (2) unbonded post-tensioned precast concrete moment-resisting frames, and (3) steel moment resisting frames with post-tensioned connections.

Unbonded post-tensioned precast concrete walls are constructed by post-tensioning precast wall panels across horizontal joints. The post-tensioning steel is not bonded to the concrete panels, but is anchored at the foundation and the top of the wall (Fig. 1(a)). At a selected level of earthquake loading, the horizontal joint at the foundation level decompresses due to the overturning moment and a gap opening behavior develops (Fig. 1(b)). Upon unloading, post-tensioning and gravity load cause the wall to return to its original position (i.e., to self-center) as shown in Fig. 1(c). Specific limit states in the lateral load versus lateral drift behavior are shown schematically in Fig. 2.

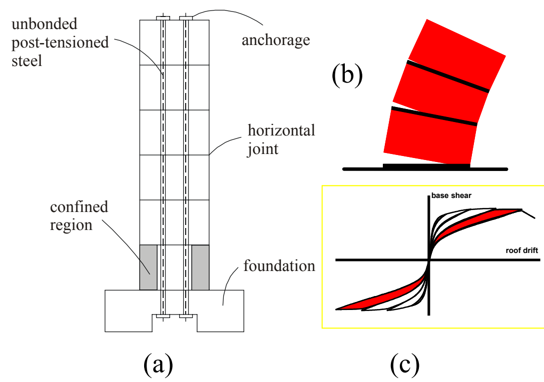

Fig. 1 Unbonded post-tensioned precast wall.

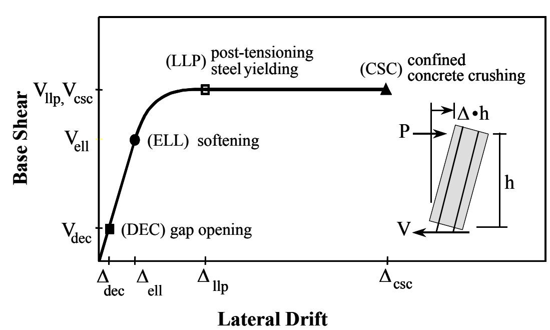

Fig. 2 Lateral load versus lateral drift for unbonded post-tensioned precast wall.

Research that developed analytical models, identified limit states, conducted nonlinear time history response analyses, and developed and validated performance-based design methods and criteria for unbonded post-tensioned precast walls is presented in [1-3]. A subsequent experimental study that validated the analytical models, validated the expected limit states, and identified an undesirable limit state is presented in [4].

Unbonded post-tensioned precast concrete moment-resisting frames are constructed by post-tensioning precast beams to precast columns using strands or bars that are not bonded to the concrete in the connection region. At a selected level of earthquake loading, decompression occurs at the beam-column interfaces and flexural gap opening occurs. Upon unloading, the post-tensioning causes the gaps at the beam-column interfaces to close, providing the frame with self-centering behavior. Research that developed analytical models, identified limit states, conducted nonlinear time history response analyses, and developed and validated performance-based design methods and criteria for unbonded post-tensioned precast moment-resisting frames is presented in [5-6].

Steel moment resisting frames with post-tensioned connections are constructed by post-tensioning steel beams to steel columns using strands that are post-tensioned after bolted top-and-seat angles are installed (Fig. 3(a)). The post-tensioning strands run through the columns, and are anchored against the column flanges (Fig. 3(b)). The strands compress the beam flanges against the column flanges to resist moment, while the angles and friction at the beam-column interfaces resist transverse shear force. Under seismic loading the angles yield and dissipate energy.

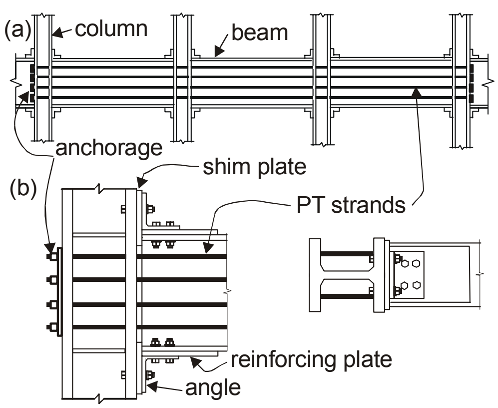

Fig. 3 Steel moment resisting frames with post-tensioned connections.

The moment-rotation (M-θ_r) behavior of a well designed post-tensioned steel connection, where θ_r is the relative rotation between the beam and column (Fig. 4(b)), is characterized by gap opening and closing at the beam-column interface under cyclic loading. The initial stiffness of the connection is the same as that of a welded moment connection before the gap opens at decompression (when θ_r equals zero before event 1 in Fig. 4(a)). With continued loading, the tension angle of the connection yields (event 2), with full plastic yielding of the tension angle at event 3. Upon unloading (event 4), the angles will dissipate energy (between events 4 and 8) until the gap between the beam flange and the column face is closed by the post-tensioning force at event 8.

Research that developed analytical models, identified limit states, and conducted nonlinear time history response analyses for steel moment resisting frames with post-tensioned connections is presented in [6-8]. Experimental studies that validated the expected behavior and limit states are presented in [9-10]. A study of steel moment resisting frames with post-tensioned connections that uses friction elements in place of the steel angles in the connections to dissipate energy is presented in [11].

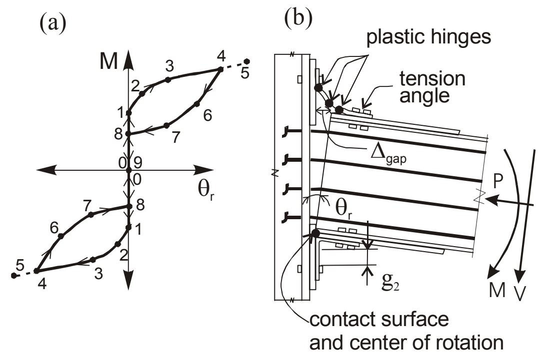

Fig. 4 Behavior of post-tensioned steel connection.

Past Research Findings

The major findings of past research [1-11] show that SC systems have the following attractive features: (1) economy, since the structural member size and complexity are similar to those of conventional seismic-resistant systems; (2) reduced damage, since SC systems can be designed to resist the design basis earthquake without significant damage; (3) initial lateral stiffness that is similar to that of conventional seismic-resistant systems; (4) controlled lateral force demands, due to a softening lateral force versus lateral drift behavior under earthquake loading; (5) lateral force versus lateral drift behavior that softens without significant inelastic deformation of the main structural members, and, therefore, without the resulting structural damage and residual drift, since the softening behavior is created by the opening of gaps at selected critical joints; (6) ductility capacity that can be quite large and is not fully controlled by material ductility; and (7) energy dissipation under seismic loading which is not a result of damage to main structural members, but is produced by energy dissipation elements that are easily replaced.

Current Research Project

A current research project, involving Lehigh, Princeton, and Purdue Universities, focuses on self-centering steel moment resisting frames (SC-MRFs) and self-centering steel concentrically-braced frames (SC-CBFs). The project goals are: (1) to develop fundamental knowledge of the seismic behavior of SC-MRF systems and SC-CBF systems, (2) to use the research facilities of NEES to conduct integrated design, analysis, and experimental research, and (3) to develop performance-based, reliability-based seismic design procedures. The overall project goal is self-centering steel frame systems that are constructible, economical, and structurally damage-free under the design basis earthquake.

Past research on SC-MRFs has identified research needs in the following areas: (1) interaction between an SC-MRF and the floor diaphragms, (2) improved energy dissipation elements for SC-MRF beam-column connections, (3) a SC column base that will provide axial force and moment resistance along with softening behavior without damage, (4) parametric studies of the SC- MRF system for various buildings, (5) design procedures with clearly specified performance objectives and reliability concepts, (6) large-scale experiments on complete SC-MRFs, and (7) pseudo-dynamic or hybrid pseudo-dynamic testing of SC-MRFs with realistic seismic input.

The SC-CBF system is new. The research needs are numerous, and include: (1) PT systems and connection concepts, (2) analytical models, (3) laboratory studies to evaluate promising PT systems and connection concepts and to validate analytical models, (4) parametric studies of the performance of the SC-CBF system for various buildings, (5) design procedures with clearly specified performance objectives and reliability concepts, (6) large-scale experiments on complete SC-CBFs, and (7) pseudo-dynamic or hybrid pseudo-dynamic testing of SC-CBFs with realistic seismic input.

To achieve the project goals, nine experimental and analytical research tasks will be conducted:
Task 1: Develop reliability-based seismic design and assessment procedures for SC systems.
Task 2: Develop SC-CBF systems.
Task 3: Further develop SC-MRF systems.
Task 4: Develop energy dissipation elements appropriate for SC-MRF and SC-CBF systems.
Task 5: Develop sensor networks for damage monitoring and integrity assessment of SC systems.
Task 6: Design prototype buildings.
Task 7: Perform nonlinear analyses of SC-MRF and SC-CBF prototype buildings.
Task 8: Conduct large-scale laboratory simulations of SC-MRFs and SC-CBFs.
Task 9: Collaborate on 3-D large-scale laboratory simulations of SC-MRFs and SC-CBFs.

Conclusions

A new family of earthquake-resistant structural systems, called self-centering (SC) systems, with the potential to eliminate damage to main structural members under the design basis earthquake has been studied experimentally and analytically. Past research has demonstrated the attractive features of these systems. A new research project, part of the NEES research program is further developing self-centering steel moment resisting frames and initiating development of self-centering steel concentrically-braced frames. The overall project goal is self-centering steel frame systems that are constructible, economical, and structurally damage-free under the design basis earthquake.

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