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Nonlinear Dynamic FEM Analysis of Unbonded Posttensioned Coupled Pendulum Shear Walls Linked with Elastic Energy Dissipating Connectors

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ABSTRACT

This paper outlines the progress of a research program that targets the development of a seismic design concept that is unrestricted by traditional material failure limit states. This design concept harnesses nonlinear system kinematics for the engineering of coupled unbonded post-tensioned shear (UPTS) walls. This research integrates geometric and elastic instabilities in the seismic design of systems towards achieving resilient and sustainable UPTS walls. The new wall concept is designated as pendulum UPTS walls, because, instead of rocking about the wall toes, it rotates about a fixed point on the wall due to an engineered curved path at the wall-base interface. Coupled UPTS walls are linked with shear connectors that dissipate energy via elastic instabilities even at low or moderate drift demands. The system of pendulum walls coupled with elastic shear connectors is self-centering and can resist lateral seismic loads without permanent damage. This paper presents nonlinear dynamic analysis results that validate the improved seismic performance of coupled UPTS pendulum walls linked by elastic energy dissipating connectors.

Introduction

A grand challenge in structural engineering is the development of lateral load resisting systems that can be used in achieving immediate occupancy and minimum economic losses following an extreme hazard. Research on rocking UPTS walls has clearly demonstrated that these systems fit well within this grand challenge because of their self-centering response under lateral loads [1]. Building on the assets of rocking UPTS walls, this research is investigating a new concept for engineering UPTS walls with improved lateral response [2]. This is achieved by incorporating the following synergistic concepts: (1) a UPTS wall with pendulum-type sliding/rocking response, and (2) using elastic energy dissipation devices as vertical shear connectors. The outcome is a damage-free self-centering system that is unrestricted by the typical material failure limit states.

Rocking UPTS systems are typically equipped with connectors to provide energy dissipation via yielding or friction mechanisms. Such connectors, however, have the disadvantage of residual deformations and require large deformations for activation. As an intriguing alternative, increased attention has been recently given to concepts that utilize elastic instabilities for energy dissipation and shock absorption. These systems usually consist of chains of multistable elements that are connected in series and respond to a common load in a progressive manner. When loaded under displacement control the elements display a negative stiffness due to geometric nonlinearity. The consecutive elastic snap-through of the repeating units results in a hysteretic force-deformation response. These systems can thus be used to elastically absorb and dissipate energy [5].

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Rocking UPTS walls are nowadays considered in high seismic regions provided they meet the experimental requirements of ACI ITG-5.1 [3] and the design requirements of ACI ITG-5.2 [4]. Pendulum UPTS walls represent a significant departure from rocking UPTS walls, because the base is formed in the shape of an arched surface and wall behavior is best characterized as an inverted pendulum without separation at the wall-base interface. Results from this research program meriting the advantages of pendulum UPTS walls over rocking UPTS walls are further discussed in this paper. This paper presents nonlinear dynamic analysis results for validating the improved seismic performance of coupled UPTS walls linked by elastic energy dissipating connectors.

Experimental Program for FEM Calibration and Validation

Uncoupled UPTS Walls

Experimental Setup

The experimental program for the FEM calibration and validation of UPTS walls was conducted using the test setup of Figure 1(a-c). The wall height, width and thickness are respectively, 16.0 ft, 10.0 ft, and 8.75 in. This set of dimensions leads to an aspect ratio of 1.6 and a slenderness ratio of 22. Based on these ratios, the wall can be classified as slender. Posttensioning (PT) forces were applied using four unbonded 5/8-in. steel threaded tendons. These PT tendons were arranged in a 2x2 pattern and each was initially post-tensioned to 7.5 kip ($0.25f_{pu}$), resulting in a total PT force of 30 kips. Further details of the experimental program are presented in [2].

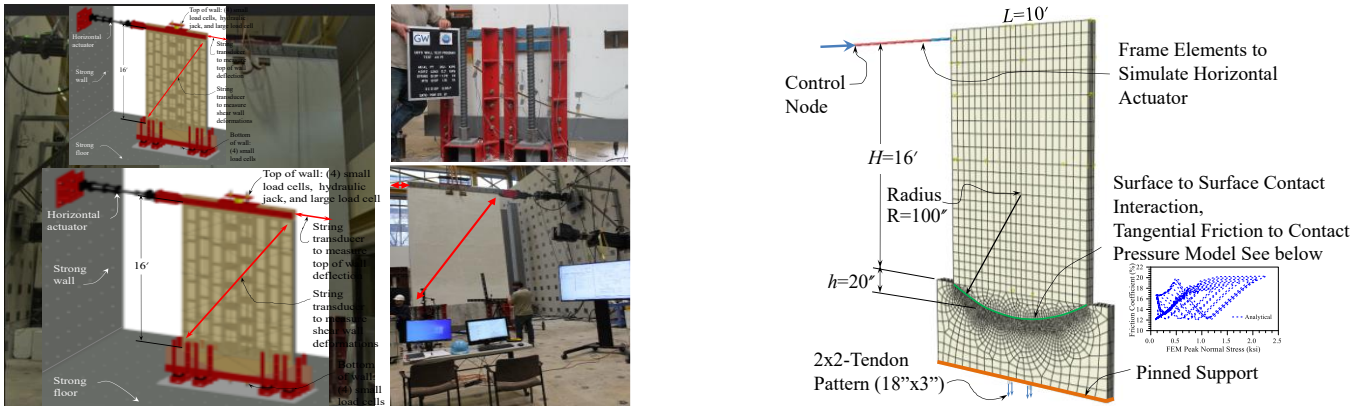


Figure 1. UPTS Pendulum Wall (a-c) Test Setup (d) 3D Finite Element Model.

Finite Element Model

The main objective of the finite element model (FEM) simulations was to numerically characterize the in-plane response of the test unit depicted in Figure 1(a) and to investigate the nonlinear dynamic response of coupled pendulum UPTS walls linked by elastic energy dissipating connectors. The in-plane response of pendulum UPTSs was conducted using the 3D FEM model depicted in Figure 1(d). Further details of the numerical program are presented in [2].

Summary of Experimental Results

Figure 2(a) substantiates that one of the main advantages in developing a pendulum response is that during the sliding process at the wall-base interface there is substantial energy dissipation capacity through friction. As such, the experimental results demonstrated that the use of high viscosity grease was necessary to reduce the friction coefficient and thus ensure that the wall remained in contact with the base. Results in Figure 2(b) show that during reversed cyclic loading there was a negligible increase in the PT force. This is of significant value to the design of UPTS walls because limiting the forces in PT tendons will evade yielding of the PT tendons and thus avoid setting strict drift limits in the seismic design of pendulum UPTS walls [4].

Elastic Energy Dissipation Connectors

The multistable cosine-curved dome (MCCD) system (see Figure 3) is a newly developed self-centering energy dissipation device based on elastic instabilities [5]. It consists of multiple cosine-curved domes linked in series, each exhibiting a tailorable elastic limit-point response (snap-through instability) with a negative stiffness region. The response of a system of linked units (MCCD) shows consecutive snap-through buckling events and an elastic hysteretic response with a self-centering capability as shown in Figure 3(b). The MCCD system's response was experimentally validated using 3D printed polymer prototypes and tested using the setup in Figure 3(a). The experimental response

along with the predicted response of a developed analytical model is shown in Figure 3(b) [5]. To facilitate analysis of structures implementing the MCCD damper, its sawtooth-shaped hysteretic force-deformation response is idealized as the flag-shaped (parallelogram) response shown in Figure 3(c) [6]. The idealized flag-shaped response of the energy dissipating connector was implemented in the finite element model of the coupled pendulum walls by using two parallel nonlinear springs (one bi-linear elastic and the other elasto-plastic) in series with a linear spring.

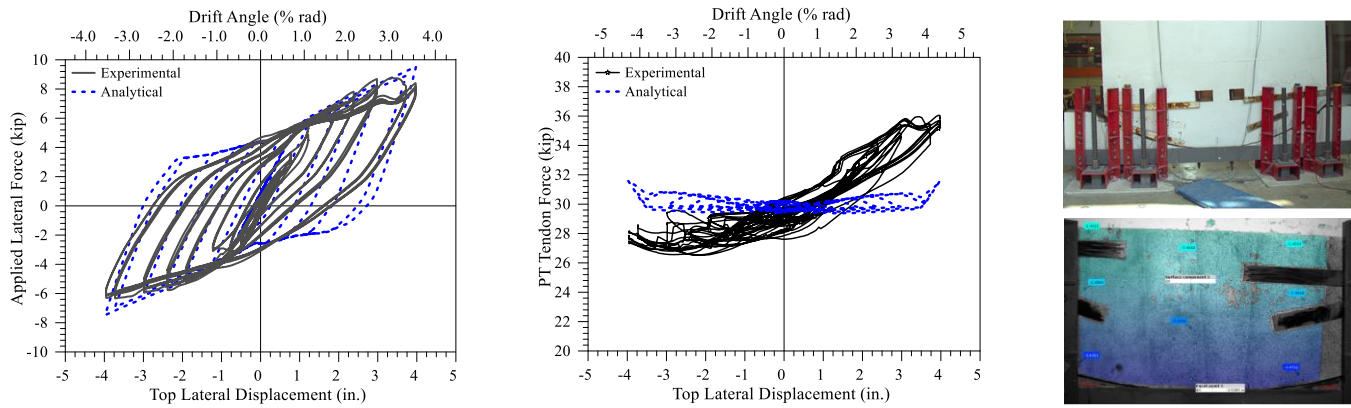


Figure 2. Summary of Experiment Results (a) Lateral Load-Deformation Response, (b) Axial Load-Deformation Response, (c) Comparison of Base Deformation at Peak response with Digital Image Correlation.

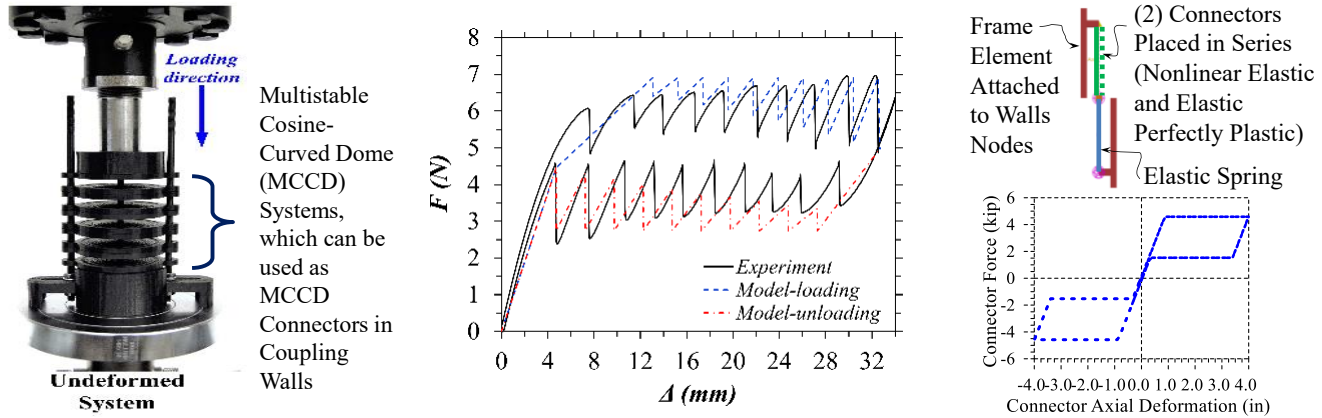


Figure 3. MCCD Elastic Energy Dissipator [5,6]: a) Test Setup, b) Experimental and Analytical Results, c) FEM Modeling and Idealized Flag-shaped Response of MCCD Connector.

Nonlinear Dynamic Analysis of Coupled UPTS Walls

Coupled Pendulum UPTS Walls 3D Finite Element Model

The 3D FEM model used for the nonlinear dynamic analyses is presented in Figure 4(a). The analyses were conducted using the program ABAQUS [7]. The dynamic load consisted of imposed ground base accelerations from the Northridge earthquake, see Figure 4(a). Three MCCD connector assemblies were considered for the coupled pendulum walls. Figure 3(c) shows the resulting idealized flag-shaped $F-\Delta$ response for each of the three MCCD damper assemblies. Placement of the three MCCD connectors in the 3D coupled wall FEM model is presented in Figure 4(a).

Simulation Results of Uncoupled and Coupled UPTS Walls

Figure 4(b) depicts the FEM model deformation at peak response. This figure shows that in both walls, the center of deformation nearly coincides with the center of their wall-base interface circular profile. This indicates that their main response is by gliding without separation at the interface. Figure 5(a) shows that the load-deformation response of these walls under dynamic load approximates well the response of the uncoupled wall under reversed cyclic loading. Likewise, Figure 5(b) shows that while the peak displacement was nearly the same in the two systems, the residual deformation in the coupled walls was significantly less (or even negligible) than for the uncoupled wall. In addition, Figure 5(a) shows the coupled walls were able to dissipate higher levels of energy. This is attributed to the presence of the MCCD connectors. Figure 5(c) shows that the MCCD connectors responded with nearly ideal self-centering characteristics and with significant energy dissipation capacity. This is relevant to the damage-free self-centering

response of coupled pendulum UPTS walls that are unrestricted by material failure limit states.

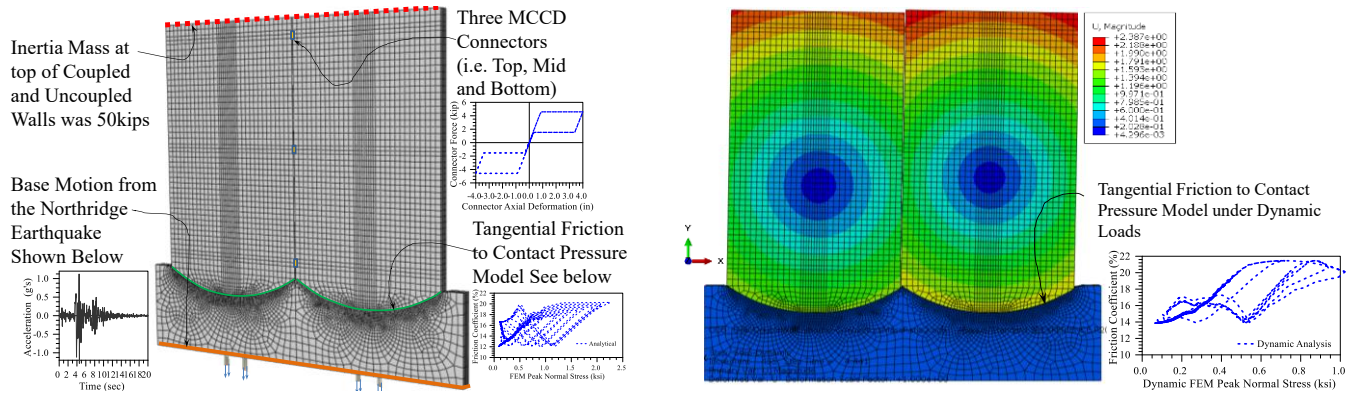


Figure 4. 3D-Finite Element (a) FEM Model, (b) System Deformed Shape with Connectors at Peak Response

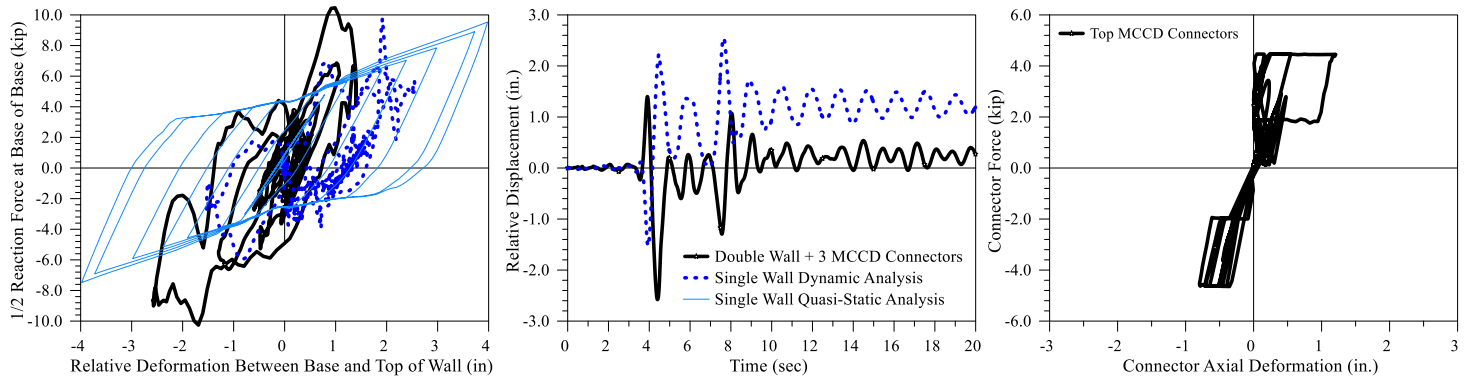


Figure 5. Dynamic Analysis Results: (a) Left Wall Relative Deformation vs. Time History, (b) Left Wall Reaction Force vs. Relative Deformation, (c) Top Connector Load Deformation Response.

Conclusions

Finite element analyses demonstrate that coupled pendulum UPTS walls with MCCD connectors can improve the response of these systems under seismic loads, leading to a system that is damage-free and self-centering. In addition, the system kinematics are optimized to increase the system's energy dissipation capacity. Constructing the footing interface in the shape of a circular profile allows the UPTS walls to dissipate energy through friction, while the MCCD connectors provide self-centering energy dissipation through elastic instabilities. As such the system investigated in this research can lead to the development of a design concept that is unrestricted by material failure limit states.

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