MITIGATION OF SEISMIC HAZARDS IN TILT-UP-WALL BUILDINGS

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SUMMARY

This paper presents results of a study that combines analytical and experimental investigations to provide guidelines for improved design of tilt-up-wall (TUW) structures under dynamic earthquake environments. An analytical model that accounts for the interaction among the structural components was used to study the response of typical TUW structures. Motions obtained from the analyses were used as input to the dynamic testing of full-scale TUW panels. The results indicate that panel/diaphragm interaction effects result in design moments for the panels and design forces at the panel to roof connections that are larger than those specified by current design procedures. This study was conducted under the sponsorship of the National Science Foundation.

INTRODUCTION

Tilt-up-wall (TUW) construction is a form of precast concrete construction used primarily for one- or two-story buildings, and in a few cases for multistory buildings. The centrally reinforced wall panels are cast in a horizontal position at the site and after curing for as little as two days can be tilted up and moved into place. The main advantage of TUW buildings is that they offer some economy with respect to other traditional types of construction. TUW construction has progressively increased during the last three decades throughout the United States, including seismically active areas. However, its structural integrity during seismic loading has been observed only to a limited degree. Damage to TUW buildings was reported in the great Alaskan earthquake of 1964 and in the San Fernando earthquake of 1971.

A joint task force of ACI-SEAOSC has recently completed a test program on slender wall panels (Ref. 1). Panels had varying height to wall thickness ratios of 30, 40, 50, and 60 and were subjected to both eccentric vertical loads and equivalent static lateral loads. Design guidelines based on the above equivalent static testing were provided.

The objective of the current 2-year research program was to modify the above design guidelines based on studying the response of tilt-up-wall buildings under dynamic earthquake environments. The scope of the research program included: (1) categorization of existing TUW construction in the United States, (2) analyses of typical TUW structures with variations in diaphragm systems and panel height-to-thickness ratios, (3) a plan for full-scale,

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component tests of representative TUW panels subjected to dynamic, out-of-plane earthquake motions, (4) development of mathematical models for the analysis of TUW structures, (5) evaluation of the effect of varying diaphragm stiffnesses on panel response, (6) evaluation of anchorage requirements, and (7) development of guidelines for mitigation of seismic hazards in TUW buildings (Ref. 2). Some of the pertinent results of this research project are reported in this paper.

EXAMPLE ANALYSIS OF A TUW STRUCTURE

One objective of the analytical phase of the program was to calculate and evaluate the three-dimensional response of a typical full-scale TUW building. The effect of interaction between various structural components was calculated. This step is complemented by an experimental program to investigate the response of typical full-scale TUW panels subjected to the calculated seismic interaction motions.

The typical one-story warehouse-type building shown in Figure 1 was selected for the analysis. The building consists of a wood roof diaphragm 300 ft long by 150 ft wide supported on four sides by 20 ft high concrete tilt-up wall panels. The panels were 5.5 in. thick with a height-to-thickness ratio (H/t) of 44. The critical orientation of the earthquake motion is perpendicular to the long dimension of the structure, as shown in Figure 1. The side walls undergo primarily bending deformations, while the diaphragm undergoes primarily shear deformations. Accordingly, the roof diaphragm was modeled as a deep shear beam and the TUW panels were modeled as flexural beams. Due to the assumed symmetry in both geometry and loading, only half of the building about the centerline of the long dimension was considered in the model (Figs. 2 and 3). The tilt-up side wall panels were represented by linear elastic uniform beam elements in this analysis (Fig. 3). To partially account for their nonlinear response, the effective bending stiffness of the panels was reduced to 25 percent of the gross section and a 5% damping ratio was used in this analysis. Previous analysis showed that the panel response would be highly nonlinear, and that the reduced bending stiffness is a reasonable compromise between the uncracked and fully cracked section.

The roof diaphragm segments were represented by nonlinear, inelastic, hysteretic shear springs and viscous dampers based on cyclic in-plane loading tests, both static and dynamic, that have been conducted on plywood diaphragms (Ref. 3). See Table 1 for these values.

TABLE 1. PARAMETERS FOR THE ROOF DIAPHRAGM MODEL
1/2, 5/8 in. Plywood, Blocked (Fig. 4)

Diaphragm	Unit Weight, lb/ft^2	K_1*, kip/ft	K_2, kip/ft	F_1, kip	F_u†, kip
Soft (1/2")	20	1300	1300	24	240
Stiff (5/8")	20	1940	1940	30	300

*K_i = Initial stiffness of spring †F_u = Ultimate capacity of spring

TABLE 2. EARTHQUAKE INPUT MOTIONS AT BASE AND ROOF DIAPHRAGM

Case No.	Earthquake Input Motion at Base	Scaling Factor	Roof Diaphragm
1	1971 Castaic, N69W	1.80	Flexible
2	1971 Castaic, N69W	1.80	Stiff
3	1940 El Centro, S00E	1.25	Flexible
4	1940 El Centro, S00E	1.25	Stiff

The first 30 sec of both the N69W component of the 1971 Castaic acceleration record and the S00E component of the 1940 El Centro acceleration record were selected as the basis for the input ground motion to the TUW building analyses. These accelerations were scaled to the 0.40 g EPA level (Ref. 4) of highly seismic areas, such as Los Angeles, by multiplying by a uniform scaling factor of 1.8 and 1.25 respectively (Table 2).

RESULTS OF ANALYSIS

The analysis was performed using the STARS/III computer program (Ref. 5). The results indicate that the most critical response of the panels occurs in the panel midway between the two end walls (Figs. 5 and 6). As shown in Figure 5, the maximum dynamic moments induced in the panel are larger for the Castaic input (Cases 1 and 2) than for the El Centro input (Cases 3 and 4) where Castaic represents a near earthquake and El Centro represents a distant earthquake. Moreover, for each earthquake input, the maximum moments are influenced by the diaphragm stiffness. The maximum dynamic seismic moment was equal to (2.8 x equivalent static moment) and (2.28 x ultimate design moment), using current design methods (Ref. 6). The maximum input acceleration of 0.48 g was amplified to 0.62 g and 0.75 g at the roof level of soft diaphragms (Cases 1 and 3). However, a higher amplified acceleration of 0.87 g and 1.10 g was calculated at the roof level of stiff diaphragms (Cases 2 and 4).

The results of the analysis indicate that the connections at the panel-to-roof diaphragm level can be subjected to forces considerably higher than those obtained from equivalent static design methods. Also, the dynamic seismic moments at the midheight of the panel can be considerably higher than the design moments calculated by the current design methods. For the same EPA, the current design methods do not account for the different types of earthquake inputs (near or distant), or for different diaphragm stiffnesses. It is clear that these design methods need to be updated to account for these differences. The analysis also indicates that the roof diaphragm behaves like a linear shear beam for the middle sections. However, the portions of the diaphragm adjacent to the end walls have a pronounced nonlinear, hysteretic shear beam response and strongly influence the TUW panel response.

TUW PANEL TEST DESCRIPTION

Experimental Philosophy

The structural response of TUW buildings subjected to high seismic loads is nonlinear and involves interaction among many of the structural elements, such as the end walls, roof diaphragm, side walls, and wall/diaphragm anchorage. A substantial amount of the testing of reinforced concrete has been directed toward in-plane loadings. In TUW construction, the most important response is in the out-of-plane direction. The experimental philosophy used in this study was based on the development of full-scale, dynamic, component tests for TUW panels that use kinematic motions obtained from the previous analyses that account for the interaction among the different structural components. The kinematic input to the wall panel test was a ground motion at the base of the panel and a compatible roof diaphragm motion from the analyses at the top, where variations in the diaphragm stiffness characteristics are included.

Description of Specimens

The specimens tested were representative of typical TUW elements found in the United States. The TUW specimens were 4 in. thick, 3 ft 6 in. wide, and 12 ft to 20 ft high, and were fabricated using typical materials. The wall panel parameters are given in Table 3. A total of 10 specimens were fabricated at H/t ratios ranging between 36 and 60. The H/t ratio of 36 has been established by the SEAOSC Yellow Book (Ref. 7) as the approved standard. The ratio of 60 represents an upper limit that has been used in the lower seismic zones. Two different reinforcing steel ratios ranging between 0.2% and 0.6% were used.

TABLE 3. WALL PANEL PARAMETERS

Parameter	Value
Unit weight of concrete (w), pfc	150
Compressive strength of concrete (f'_c), psi	$3000 \leq f'_c \leq 4000$
Grade of reinforcing steel	60
Capacity reduction factor (ϕ)	1.0
Panel thickness (t), in.	4
Reinforcement ratios (ρ), percent	0.20 to 0.60
Earthquake ground motion input	Based on ATC Effective Peak Accleration of 0.4 g
End eccentricities (e), in.	t/2 + 3-1/2 in.
Ledger load	200 lb/ft

Tests by the ACI-SEAOSC Slender Wall Committee (Ref. 1) indicated that changing the ledger weight did not significantly change the static response of the walls. Therefore, one representative level of 200 lb/ft overburden mass was used to simulate ledger load.

Since the experimental program was budgeted for only ten wall specimens, a sequential design process was adopted, whereby the specimens were designed, fabricated, tested, and analyzed in four groups. The first three groups consisted of two specimens each, while the fourth group consisted of four specimens. The sequential design process maximized the usefulness of the specimens. The first group consisted of the highest H/t ratio of 60, with a maximum and minimum of reinforcing steel, and represented the most likely condition for failure. Therefore, this group helped guide the design of the subsequent specimen groups, and so forth.

Test Set-Up and Instrumentation

The TUW panels were installed in a test fixture that allowed the base and top of the wall to be moved independently in the out-of-plane direction by servocontrolled hydraulic actuators (Fig. 7). The specimen rested on a low friction support (shown as rollered in the figure) that allowed the base of the wall to be displaced by the hydraulic actuator. The vertical overburden load was applied to the ledger through attachment rods that maintained a precise relationship between the vertical load and the center of the specimens. The basic instrumentation consisted of load cells, velocity transducers, and displacement sensors (string potentiometers), as shown in Figure 8.

The data from each instrument were recorded on magnetic tape in digital form for subsequent processing and archiving. Additional data were recorded in the form of still photographs, motion pictures, and observer notes or test logs.

Test Modes and Sequences

Each wall panel was subjected to a sequence of dynamic input motion pairs, or motion sets, that consisted of a compatible pair of kinematic motions, one for the base and one for the top of the wall (Table 2). The kinematic input to the base and top of the wall specimens was delivered by a high-pressure hydraulic actuation system that is controlled by displacement. This method of control provided the most reliable system for command and measurement. The dynamic testing started with motion sets of the lowest intensity and progressively proceeded to motion sets with higher intensity levels of motions. The results of the test program are documented in a report to be published.

CONCLUDING REMARKS

The analyses results indicate that typical TUW buildings can be adequately analyzed using lumped parameter models. The analyses show that dynamic seismic response for highly seismic areas can exceed design values obtained by equivalent static methods. At the time of writing this paper, the tests have not been completed. Accordingly, the final guidelines will be published in a separate report.

ACKNOWLEDGEMENTS

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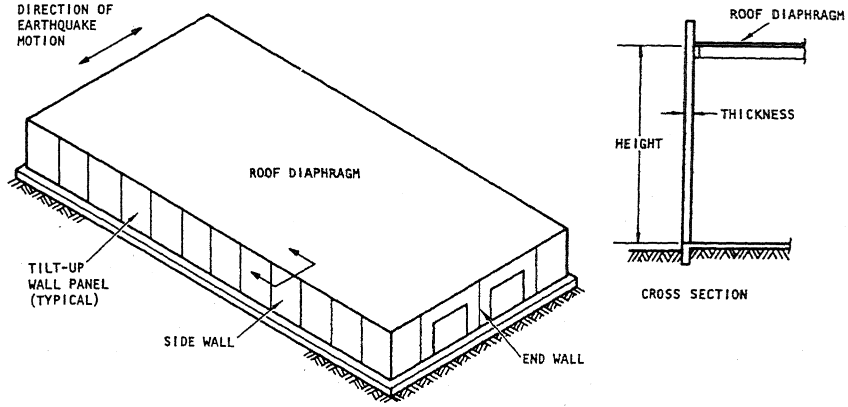


FIGURE 1. ONE-STORY TILT-UP-WALL BUILDING WITH A WOOD DIAPHRAGM ROOF

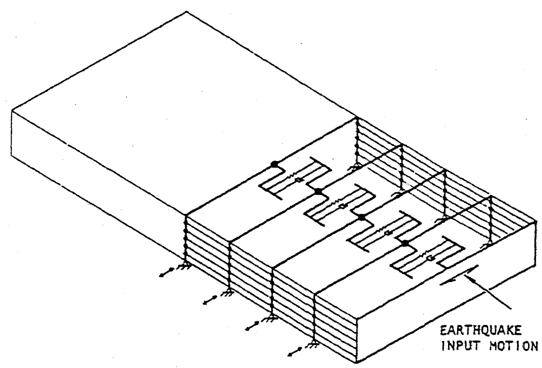


FIGURE 2. LUMPED PARAMETER MODEL FOR HALF BUILDING

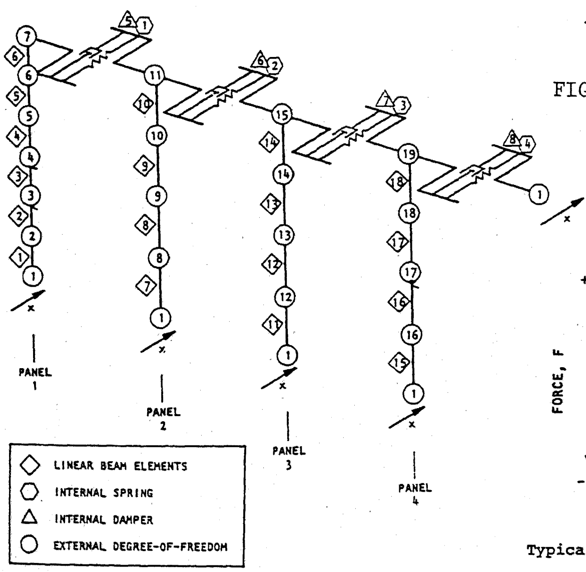
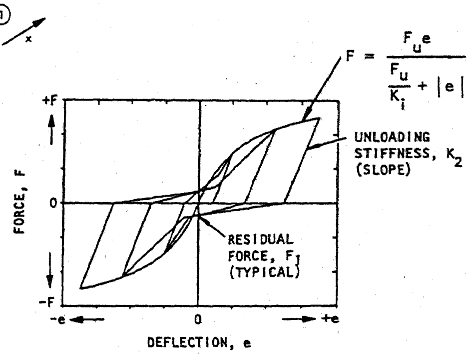


FIGURE 3. BEAMS, SPRINGS, AND DASHPOTS FOR HALF MODEL



Typical cyclic load-deflection diagram for model

FIGURE 4. LOAD DEFLECTION MODEL FOR WOOD DIAPHRAGMS

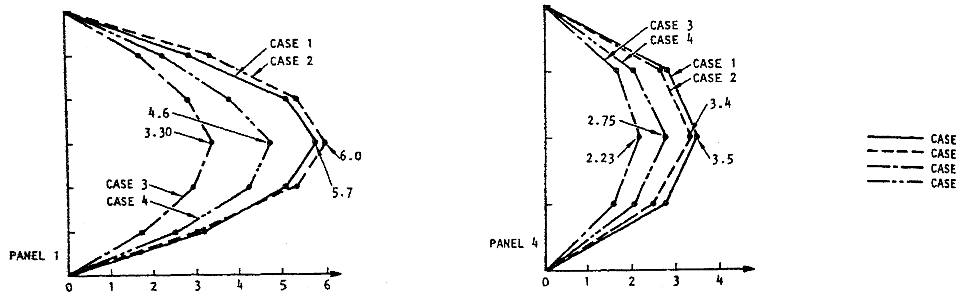


FIGURE 5. PANEL MAXIMUM MOMENTS (KIP-FT/FT) AND CORRESPONDING TIME

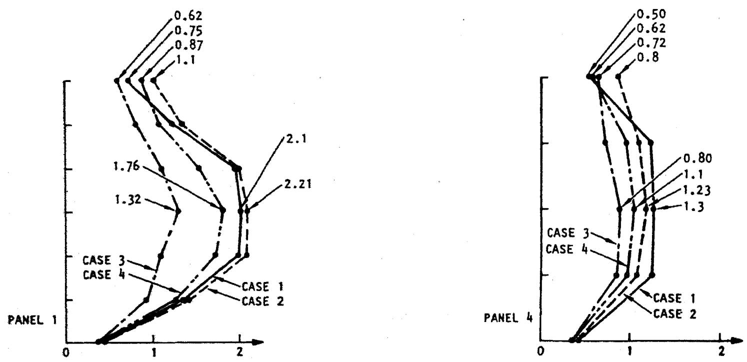


FIGURE 6. PANEL MAXIMUM ACCELERATIONS (G) AND CORRESPONDING TIME

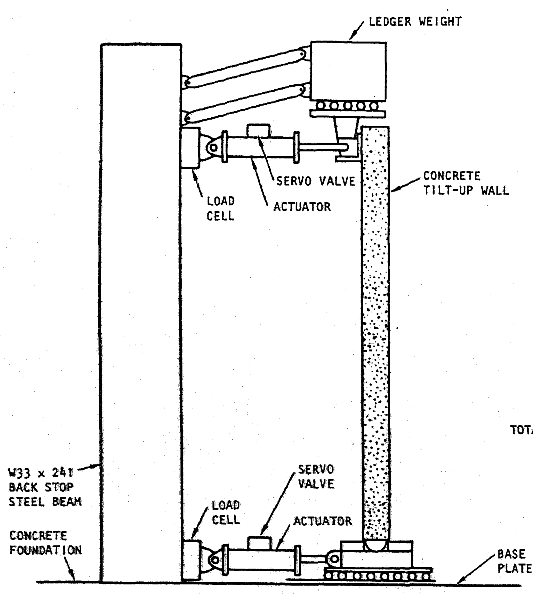


FIGURE 7. TEST SET-UP FOR DYNAMIC TESTING OF WALL PANELS

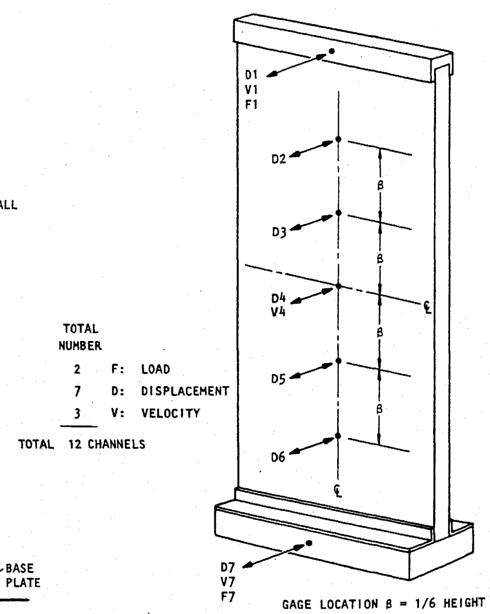


FIGURE 8. WALL INSTRUMENTATION