

PERFORMANCE OF BUILDING STRUCTURES DURING THE OCTOBER 15, 2006 HAWAII EARTHQUAKE

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ABSTRACT

This paper presents salient observations from a comprehensive site inspection program to determine the nature and extent of damage to hundreds of building structures affected by the magnitude 6.7 October 15, 2006 Hawaii Earthquake. Structural damage was identified at a limited number of buildings and consisted of classical shear cracking of short (captive) columns; failure of concrete beam/truss supports; shifting/cracking of foundation elements in low-rise wood-frame structures; cracking/displacement of concrete masonry block; shifting/partial collapse of unreinforced cement rubble masonry elements; and isolated failures of retaining wall anchors. Nonstructural damage was common and consisted of damage to suspended ceiling systems; damage to concrete masonry elements such as infill walls and column covers; minor cracking/spalling of concrete; and cosmetic damage to brittle wall finishes. Isolated structural and nonstructural damage resulting from soil failure/settlement was also observed. The observations indicate that structural damage typically relates to well known deficiencies in structural systems. Nonstructural damage was consistent with expectations given intensity of ground shaking.

KEYWORDS Earthquake, Structures, Performance, Damage

1. INTRODUCTION

At the request of a major property insurance carrier, a comprehensive site inspection program was initiated to determine the nature and extent of earthquake-induced damage to hundreds of insured buildings spread out over the islands of the State of Hawaii that had potentially been affected by a magnitude 6.7 earthquake. The site inspection program was initiated the day after the earthquake and continued for over a year and included airports, ports, hospitals, courthouses, schools, libraries, gymnasiums, stadiums, historical buildings, observatories, housing projects, resorts and hotels, water tanks, and transfer stations, among many other facilities. In all, over three hundred properties that encompassed many hundreds of buildings were inspected.

The detailed site inspections included 1) visual examination of the interior and exterior of building structures and surrounding areas, including a survey of condition of interior and exterior wall, ceiling, and floor finishes; 2) review of pertinent architectural and structural plans, where available; 3) discussions with property owners and representatives to determine their understanding of the damage and their experience during the earthquake; and 4) photo-documentation of representative conditions.

Each condition was evaluated considering the site-specific documentation, physical nature of the condition, expected response of the structure and components to earthquake ground motions, and structural, geotechnical, and material behavior of the structure and components. Damage was defined as an adverse, non-trivial, physical change in the safety, serviceability, appearance, or reparability of a component or portion of a structure. Distinction between structural and nonstructural (or cosmetic) damage was drawn using definitions consistent with FEMA Publication 306 (FEMA 306, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings: Basic Procedures Manual*). Damage is considered to be structural only when it results in a non-trivial, adverse change from its pre-earthquake condition in the ability of the structure to sustain load or resist future earthquake shaking. Nonstructural damage is all other damage that does not meet this threshold.

The numerous site inspections generated a large detailed knowledge base of not only the performance of these structures but also the correlation (or lack thereof) of the damage to site ground shaking and conventional expectations of damage. This paper presents the salient observations from the site inspection program.

2. OCTOBER 15, 2006 HAWAII EARTHQUAKE

A moment magnitude 6.7 earthquake centered off the northwest coast of the Island of Hawaii occurred on October 15, 2006 at 7:07 AM local Hawaii time. The earthquake epicenter (latitude 19.820 N, longitude 156.027 W) was located about 62 miles west of Hilo, at a focal depth of about 24 miles. The earthquake has been identified as the Kiholo Bay Earthquake, Puako Earthquake, and simply as the Hawaii Earthquake, which is the designation adopted in this paper. The Hawaii Earthquake was followed by a magnitude 6.0 event at 7:14 AM (local Hawaii time), which was centered offshore near the north tip of the Island of Hawaii at a focal depth of about 12 miles. Numerous aftershocks were recorded subsequent to the magnitude 6.0 earthquake. Additional details on the earthquake can be found in the EERI Special Earthquake Report (EERI 2006), Robertson, et al. (2006), and with the U.S. Geological Survey (www.usgs.gov).

Earthquake ground shaking is quantified through global measures such as the modified Mercalli Intensity (MMI), or more commonly, its surrogate, the Instrumental Intensity; Community Intensity (commonly referred to as the Felt Intensity); and location-specific measures such as peak ground and spectral acceleration among other measures. These selected measures for the Hawaii Earthquake are discussed briefly in this section as these different measures assist in developing a global understanding of the earthquake event, developing expectations for structural and nonstructural performance, and evaluating the seismic performance of specific structures.

2.1. Instrumental Intensity (Modified Mercalli Intensity)

Figure 1 (left image) presents the isoseismal map of estimated instrumental intensities for the Hawaii Earthquake. The intensity varied from 5 to 8 across the Island of Hawaii, with the areas north of the epicenter typically experiencing the most severe shaking. Structural damage to well-built structures is typically not expected at ground shaking intensity levels below 8. Unreinforced masonry structures, poorly built structures, or structures in otherwise poor condition may sustain structural damage at a ground shaking intensity of 7. In general, structural damage to the building inventory is typically not expected to occur below a ground shaking intensity of 7. While site-specific response of structures is a combination of ground shaking at the site coupled with the characteristics of the structures at the site, in general, structural damage was observed to be confined to the intensity 7 and 8 areas, with the damage clearly attributed to seismically vulnerable design details (e.g., short columns, poorly anchored foundation systems) or material behavior (e.g., corrosion of embedded reinforcement, behavior of concrete masonry and cement rubble masonry).

The Community Intensity (or Felt Intensity) map for the earthquake, which is based on descriptions of human response and damage from individuals in the affected areas, was, in general, consistent with the Instrumental Intensity map seen in Figure 1.

2.2. Peak Ground Acceleration

Figure 1 (right image) presents the contours of peak ground acceleration for the Hawaii Earthquake. An analysis of particular ground motions indicated the strong motion duration to be on the order of 10 seconds. While contours of high peak ground acceleration are observed north-east of the epicenter, the physical response of building structures in that area in terms of lack of any conspicuous structural damage did not indicate even moderate levels of ground shaking in that area.

2.3. Spectral Acceleration

Figure 2 presents contours of spectral acceleration at 0.3 and 1.0 seconds. The data indicates that the energy

content of the recorded ground motions, in general, is concentrated in the lower-period range, with the spectral acceleration values for the horizontal components of the ground motions dropping sharply beyond a period of about 0.2 seconds.

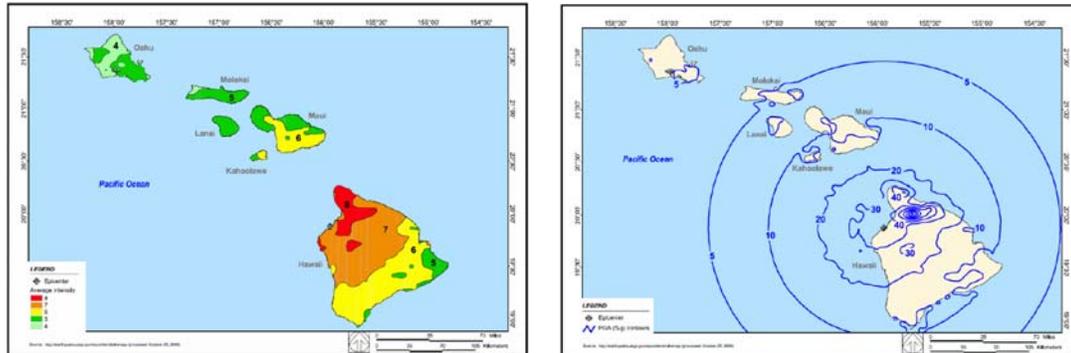


Figure 1. Instrumental intensity and peak ground acceleration (%g) contours (data source: USGS).

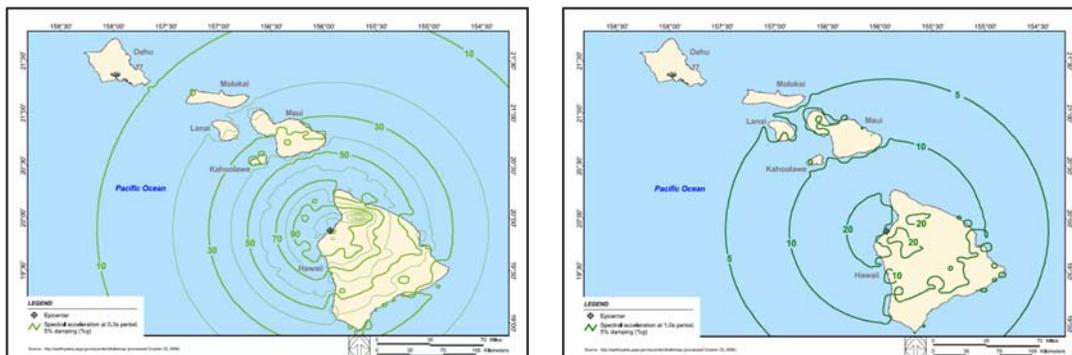


Figure 2. Spectral acceleration contours: (left) 0.3 seconds and (right) 1.0 seconds (data source: USGS).

3. STRUCTURAL DAMAGE OBSERVATIONS

This section focuses on the various types of structural damage that was observed during the site inspection program. Structural damage to other building structures that were outside the scope of this program has been reported in the literature (EERI 2006, Robertson, et al., 2006).

Structural damage was identified at a limited number of buildings and consisted of 1) classical shear cracking of short columns; 2) failure of concrete beam/truss supports; 3) shifting/cracking of foundation elements in low rise wood-frame structures; 4) cracking/displacement of concrete masonry block; 5) shifting/partial collapse of unreinforced cement rubble masonry elements; and 6) isolated failures of retaining wall anchors. Examples of these failures are presented next.

3.1. Shear Cracking of Short Columns

A large percentage of engineered building structures inspected exhibited a typical architectural detail wherein the infill wall (typically constructed using concrete masonry units) between the concrete-frame columns would stop short of the upper beam to leave space for windows. This detail, in effect, results in a classic short column situation wherein the irregularity in the strength and stiffness brought on by the infill wall results in the story deformation being essentially localized in the short columns spanning between the top of the infill wall and the beam above. Not surprisingly, shear cracking of such columns was observed at many structures. Examples of such damage are as shown in Figure 3.



Figure 3. Classical shear cracking of short columns.

3.2. Failure of Concrete Beam/Truss Supports

Another frequently observed condition consisted of failure (cracking and spalling) of a wedge of concrete under the bearing area of a beam or truss as seen in Figure 4. The exposed failure surface often exhibited corrosion of the embedded reinforcement indicating that the connection was in a compromised state prior to the earthquake and the additional earthquake loading was sufficient to aggravate the condition. In some instances, the beam/truss had to be temporarily shored until permanent repairs could be made.



Figure 4. Cracking/spalling at bearing area of beam/truss. Note corrosion of embedded reinforcement.

3.3. *Shifting/Cracking of Foundation Elements*

A significant percentage of low-rise wood-frame residential construction in Hawaii adopts a typical detail with the elevated first floor supported on a post-and-pier system, with the framing below the floor consisting of toe-nailed braces in two directions, and each individual post supported on a concrete block, which in turn is supported on a shallow concrete foundation block. There is often no positive connection between the post and the supporting blocks, and typically no shear walls exist in the foundation framing system. This particular detail is susceptible to sidesway and many instances of shifting/rotation of the post or foundation blocks were observed along with splitting of the posts and braces. In some cases, the structures had to be laterally supported to mitigate risk of additional damage during aftershocks or under sustained loads. Examples of such damage are as shown in Figure 5.



Figure 5. Shifting (left image) and cracking (right image) of foundation elements.

3.4. *Damage to Concrete Masonry Unit Blocks*

Concrete masonry unit (CMU) blocks are a preferred material of construction in Hawaii, often used as shear walls, infill walls (with or without grouting and reinforcement), and covers on concrete columns among other uses. Cracking and in-plane and out-of-plane displacement of CMU blocks was observed as seen in Figure 6.



Figure 6. Examples of cracking and shifting of CMU block walls.

3.5. *Shifting/Partial Collapse of Unreinforced Cement Rubble Masonry Elements*

Some historical buildings and others exhibit the use of cemented rubble masonry (referred to as CRM and typically composed of local stone with mortar of widely varying quality). Typical uses include walls, columns, chimneys, and miscellaneous architectural features. A wide range of damage to such elements ranging from shifting of stones to partial collapse of walls was observed as seen in Figure 7. The Hulihee Palace experienced severe damage to its cement rubble masonry walls as seen in Figure 7 (right image).



Figure 7. Damage to cement rubble masonry elements.

3.6. Failure of Retaining Wall Anchors

Failure of the anchors (tie-backs) in a retaining wall forming a transfer station was observed. The retaining wall had rotated in the earthquake, resulting in the failure of the anchors themselves and/or of the connections between the anchors and the wall. The failure was manifested as opening of a lateral gap in the asphalt surface of the parking lot atop the retained soil.

3.7. Differential Movement

Differential movement between adjacent structural elements was observed at a few locations and typically manifested as damage to connections and expansion joints. Where appropriately designed, the expansion joints were able to accommodate the differential movement. Examples of typical damage are presented in Figure 8.



Figure 8. Damage due to differential movement of elements.

3.8. Structural Damage Associated with Geotechnical Failures

Isolated instances of structural damage were observed that were directly related to geotechnical failures in the form of liquefaction of the underlying soils. Figure 9 presents an example wherein liquefaction of hydraulically placed fill resulted in foundation movement and associated structural damage. Other instances of geotechnical failures, such as failure of steep banks or abnormal settlement of loose fill, were observed were structurally benign.



Figure 9. Evidence of sand ejecta (left), structural damage due to shifting of building foundation (right).

4. NONSTRUCTURAL DAMAGE OBSERVATIONS

Nonstructural damage was common and consisted of damage to ceiling suspension systems; concrete masonry unit elements such as infill walls and column covers; cracking/spalling of concrete; and damage to brittle wall finishes. Figure 10 presents examples of some of the nonstructural damage observed.



Figure 10. (Top left) ceiling tiles and suspension system; (top right) infill wall damage; (bottom left) spalling of concrete cover over corroded rebar; (bottom right) lateral displacement of concrete water tank roof.

Damage to suspended ceiling systems with acoustic tile or drop-in panels was observed at many locations. The damage, in general, included shifting and dropping of tile and other ceiling fixtures, especially at the room

perimeter, as well as damage to the T-bar suspension system and perimeter closure angle. The damage, in general, resulted from lack of adequate seismic restraints for the suspension system (e.g., lack of diagonal bracing wire and compression struts, or inadequate connection between the T-bar framing and perimeter angles).

Damage to CMU nonstructural elements such as infill walls and column covers was observed at many locations. The damage, in general, included cracking of mortar joints between blocks, cracking through the face of the blocks and, in some instances, local spalling of the block. Damage to the perimeter mortar or flexible sealant joints between CMU infill walls and adjoining columns/beams was also observed at many locations.

Cracking and spalling of concrete elements was observed at many locations. The spalling typically resulted from long-term corrosion of the embedded steel reinforcement; the earthquake shaking dislodged the concrete cover and exposed the previously concealed pre-existing conditions.

Concrete water storage tanks exhibited a typical design detail wherein there is no positive connection between the tank wall and base pad or tank roof. Relative movement of the tank wall with respect to the base pad and tank wall was observed at many locations. While leaks were observed at a few locations, in general, the movement was not enough to impair the functionality of the tanks.

5. OVERALL ASSESSMENT

The buildings inspected as part of this site investigation program covered a wide range of structures in terms of building types (wood-frame, concrete-frame, steel-frame, shear wall, portables, concrete tanks, etc.), year of construction, applicable building code requirements (if any), and general condition of the structures. As such, many of the structures likely fall short of current standards for seismic design and are susceptible to earthquake-induced damage, potentially severe, in future major earthquakes on the islands. This moderate earthquake exposed the weaknesses in these structures and should serve as a warning for property owners (or their risk managers) to consider structural risk evaluations and appropriate risk mitigation measures. In general, damage to the structures was more than would be expected given only the characteristics of the ground shaking; however, coupled with the structural vulnerabilities of the particular buildings, the observed damage is consistent with the levels of ground shaking across the islands.

This site inspection program highlights the need and usefulness of such programs in not only assessing the response of structures to a recent earthquake but also pro-actively pre-earthquake inspecting properties in order to develop a knowledge base from where appropriate risk mitigation measures can be developed and adopted to, hopefully, limit the physical and monetary damage resulting from earthquake events across the world.

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