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SHAKE TABLE TEST RESULTS FOR A HALF-SCALE REINFORCED CONCRETE INDONESIAN HOUSE WITH AND WITHOUT ECONOMICAL BASE ISOLATION

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Abstract

This paper presents a qualitative evaluation of uni-axial shake table test results for a half-scale reinforced concrete house designed by the Indonesia Aid Foundation (IAF). The building is intended to provide a quality-controlled design by being precast at a factory and delivered to the site for assembly, thus providing a living area for a family of approximately six people. In addition, the house is to be base isolated on used car tires filled with sand to approximate more technical rubber bearing base isolators available for use in construction and seismic retrofit today. The base isolation system was extremely effective and did not allow shear force to be transferred into the reinforced concrete walls, resulting in virtually no damage.

Keywords: Earthquake; shake table; developing country; Indonesia; base isolation; concrete

1. Introduction

Indonesia experiences many moderate to large earthquakes as a result of its proximity to the subduction of the Australian tectonic plate under the Sunda plate, as well as many local faults that are strained as a result of these plates compressing [1]. Regrettably many homes in Indonesia are not well designed to protect their occupants during such seismic events. In Indonesia, as in many developing countries, many single (and multi) family homes are built of un-reinforced masonry block or stone and detailed inspection during construction is not fully enforced. In particular, the growing middle class in Indonesia prefers to build masonry or concrete homes rather than wood. Over the last decade numerous fatalities have occurred due to lack of shear resistance and/or instability of these types of houses during Indonesia's large earthquakes. For example, on May 27, 2006 a M6.3 earthquake occurred on Java, Indonesia, completely destroying 154,000 houses and damaging 260,000 houses, leaving an estimated 600,000 people without permanent shelter. The total number of people killed

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during this event was 5,176, and a substantial number of these deaths were a result of the unsafe residential construction [1].

This paper presents the qualitative results of shake-table testing of a half-scale reinforced concrete house. The specimen was designed and provided for testing by the Indonesia Aid Foundation. The house was designed to be constructed at a precast concrete plant in order to provide an inexpensive, yet quality-controlled home for Indonesian families. In addition to the precast concrete house the testing reported in the paper also considered the effectiveness of an inexpensive base isolation system based on the use of old tires.

Ideas for base isolation systems were conceptualized almost 100 years ago. Most base isolators used for engineered structures today are technical innovations that require significant engineering design and can be quite costly. Base isolation is generally used for structures in which it is not desirable to add a supplemental force resisting mechanism, i.e. historically significant structures, or when it is an economically viable option. The idea of using old car or truck tires as base isolation in developing nations has been around for some time with some preliminary studies [e.g. 2, 3]. However, to date tests at a reasonable scale have not been conducted. This paper includes the method and results used to test a ½ scale 50 kN (11 kip) reinforced concrete building on the uni-axial shake table at Colorado State University. The specimen was first tested with base isolation in place and later without the base isolation system.

2. One-Story Indonesian House Design

In Indonesia, as in many developing countries, houses typically consist of a single large room. The reinforced concrete house tested in this study was designed by The Indonesia Aid Foundation such that it can be brought to the site and bolted together using steel plates embedded in the concrete roof and walls. Figure 1(a) and 1(b) present the construction drawings for the half-scale house whose prototype dimensions were approximately 6 m ×4.5 m in footprint and consisted of conventional reinforcement as well as some bamboo reinforcement in the floor. Figure 1(b) shows the roof which is relatively flat with a slight pitch for rain. Although the roof appears in Figure 1(b) as concrete it was envisioned that this could be replaced in practice by a wood truss roof system with plywood sheathing. Concrete or clay tiles would provide roof covering which is consistent with current Indonesian architecture for these size houses. A metal roof would also be possible and be substantially lighter, but are not as popular in Indonesia. With this in mind, the RC roof was simply representative of the added seismic mass needed for dynamic similitude. Mass in a scale dynamic model varies as the square of the scale factor, so the mass of the model for a half-scale building should follow the scale law,

$$M_m = M_p / 4$$

Where M_m is the mass of the model and M_p is the mass of the prototype. The concrete roof provided the necessary added mass for dynamic similitude and represented a wood and tile roof to within an accuracy of 5%. The RC shear walls on the long side of the structure

provided the primarily lateral force resisting mechanism for the shake table test.

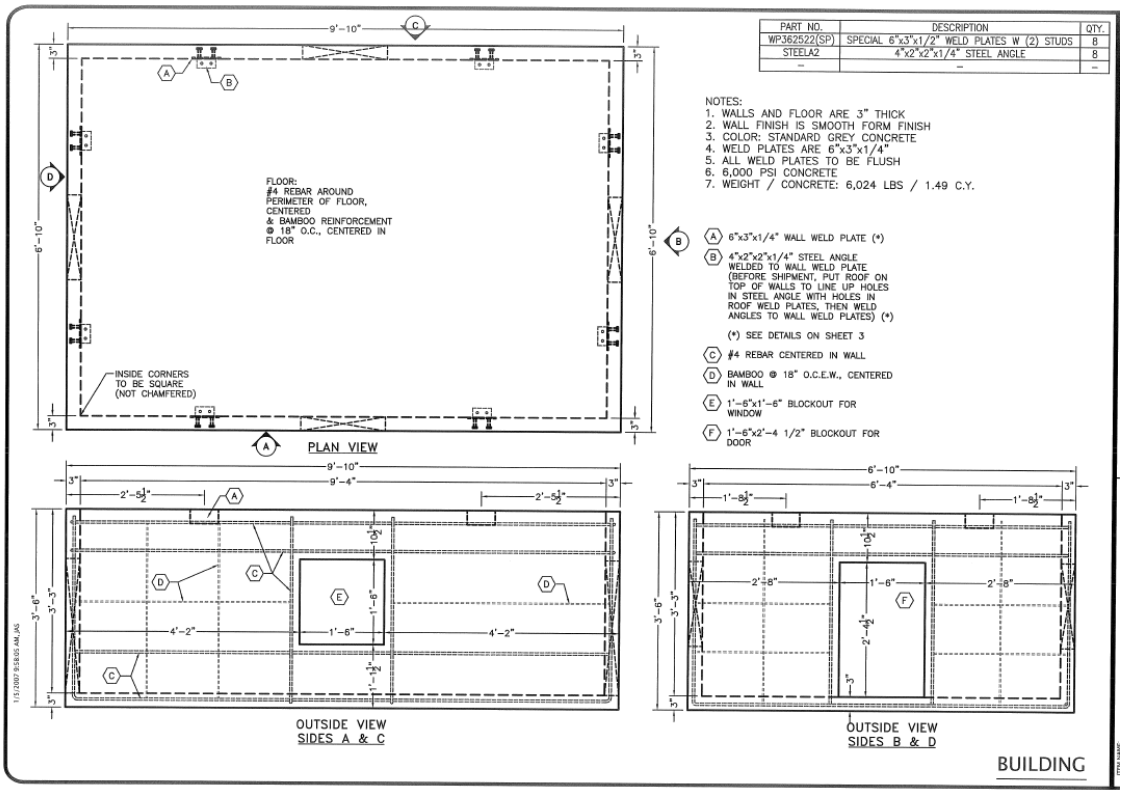

Figure 1(a). Construction drawings for walls and floor of precast concrete house model

The base isolation system consisted of used tires filled with sand. The tires used for testing were approximately 710 mm in diameter, generally of the size for small passenger trucks. This size was chosen to approximately achieve the dimensions needed for a half scale test, anticipating that prototype construction would utilize tires from larger commercial trucks. For prototype construction the tires would be placed in a shallow pit at the site and all regions around and in the tires would be filled with soil before the precast house was put in place. It was not possible to follow this exact procedure for testing the base isolation system on the shake table. Instead the tires (filled with sand) were "sandwiched" between layers of OSB (oriented strand board). The tires were attached to the OSB using a two part urethane adhesive. The OSB provided a surface to bolt the tires to the shake table and to the concrete house. In order to protect the shake table from damage caused by loose sand and to aid in cleanup the sand was placed in loosely filled bags before being placed in the tires. Figure 2 shows the layers of the base isolation system used in this study.

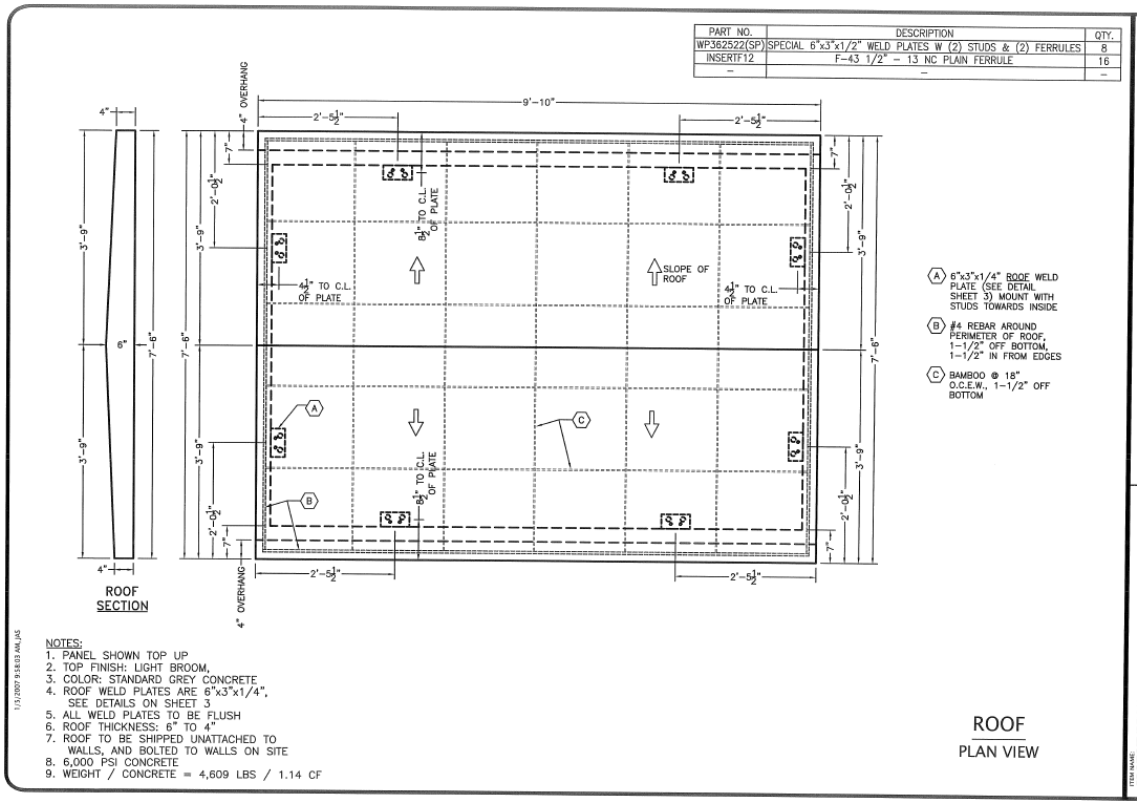

Figure 1(b). Construction drawings for roof of precast concrete house model

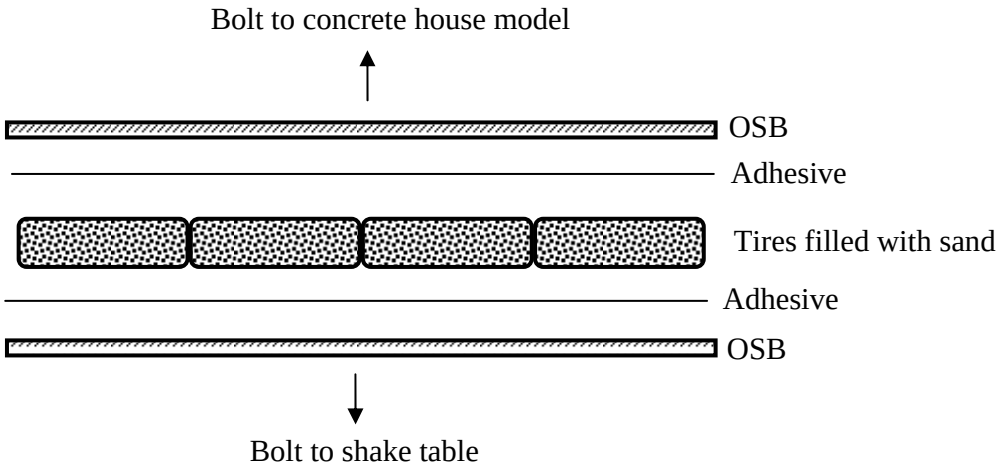

Figure 2. Schematic of technique for mounting base isolation to shake table

3. Experimental Setup

3.1 Base isolated building

In order to install the base isolation system on the shake table, the bottom layer of OSB was bolted to the shake table. The tires were then bonded to the layer of OSB. When the tries were in place they were filled with sand in loosely filled sand bags. The top layer of OSB was bolted to the bottom of the concrete house, then the adhesive was spread on the top surface of the tires and the house and top layer of OSB were put in place simultaneously. In order to preserve dynamic similitude, mass corresponding to the floor and bottom half of the walls was added to the interior of the structure before the roof was added. As mentioned, the concrete roof shown in Figure 1b that was originally designed to go with the concrete house, was changed in favor of a wood framed roof after the concrete house and roof had already been cast. Because the test was intended to evaluate the shear resistance of the walls of the structure, there was no compelling reason to model the wood framed roof as part of the test since such a large amount of mass would need to be added for dynamic similitude. Testing was conducted with the concrete roof, but the results are indicative of what would be expected with a wood framed roof. Figure 3 shows a picture of the concrete house and roof with base isolation on the shake table.

Figure 3. Model concrete house on shake table before testing

Before testing, the structure was instrumented with several displacement gages. Gages to record the horizontal displacement were placed so as to measure the motion of the shake table, the motion of the OSB layer directly above the tire-based isolation system, and the motion of the top of the wall of the concrete house. A gage was also oriented vertically to record any uplift motion. This gage measured the uplift at the level of the upper layer of

OSB at one end of the structure. A schematic of the gage placement is shown in Figure 4(a).

3.2 Fixed-base building

After testing with the base isolation system in place, the isolation system was removed and the concrete house model was bolted directly to the shake table. For testing of the fixed base building only the horizontal motion of the table and the horizontal motion at the top of the concrete wall was recorded. The placement of these gages is shown in Figure 4(b).

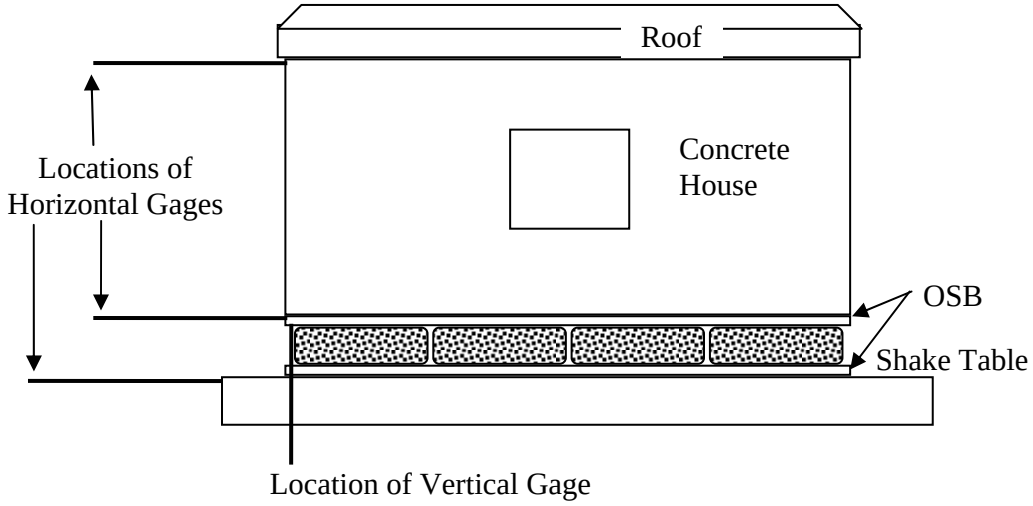

Figure 4(a). Gage placement for base-isolated building tests

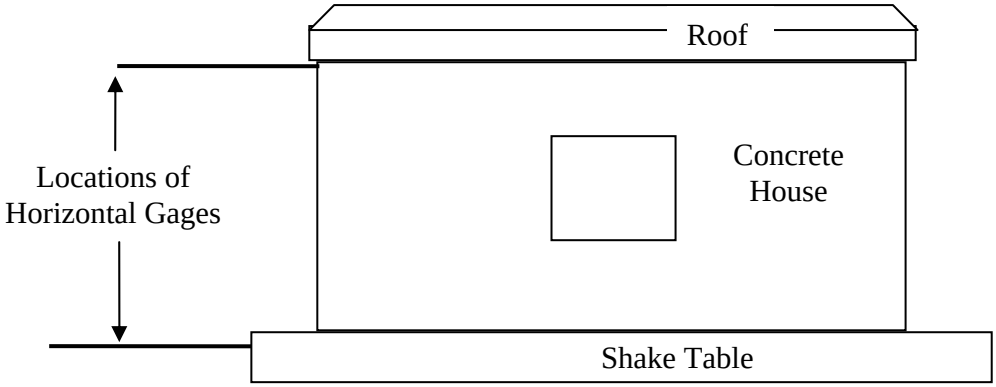

Figure 4(b). Gage placement for fixed-base building

4. Testing Procedure

4.1 Earthquake records

The primary earthquake record used for testing was the Bay of Plenty earthquake record

from New Zealand. This record was chosen due to difficulty in finding a record of ground displacement from Indonesia that had been previously processed for engineering use. A New Zealand record was selected because New Zealand is also subject to earthquakes caused by subduction. The earthquake record was scaled to simulate earthquakes with a range of different peak ground accelerations. After the structure had performed very well during most of the New Zealand records, it was subjected to earthquake records recorded during the Northridge earthquake in California. This record was used because it represents a particularly severe loading scenario known as a near fault event. At the beginning and end of testing the structure was also subject to white noise record in order to determine the natural frequency of the structure, and allow for the identification of shifts in the natural frequency due to damage. The same sequence of earthquake records was used for both the base isolated and fixed base tests. The sequences of testing are shown in Table 1.

Table 1. Testing sequence for base isolated and fixed base tests

Base Isolated Building	**Fixed Base Building**
White Noise	White Noise
Bay of Plenty, NZ 0.05g	Bay of Plenty, NZ 0.05g
Bay of Plenty, NZ 0.20g	Bay of Plenty, NZ 0.20g
Bay of Plenty, NZ 0.40g	Bay of Plenty, NZ 0.40g
Bay of Plenty, NZ 0.70g	Bay of Plenty, NZ 0.70g
Bay of Plenty, NZ 1.0g	Bay of Plenty, NZ 1.0g
White Noise	Northridge 0.46g
Northridge 0.12g	Northridge 0.87g
Northridge 0.46 g	Bay of Plenty, NZ 1.30g
Northridge 0.87g	Bay of Plenty, NZ 1.50g
Bay of Plenty, NZ 1.30g	White Noise
White Noise	

4.2 Base isolated building

Testing of the base isolated building followed the sequence shown in Table 1. Before testing began all existing cracks and large voids on the surface of the structure were marked with a black marker. After the completion of each earthquake record the structure was inspected for signs of damage. Any new cracking was marked with a colored marker. Data from the test sequence is discussed in later portions of this paper.

4.3 Fixed-base building

Test procedures for the fixed base structure were very similar to those for the base isolated

structure and are omitted for brevity.

5. Shake Table Test Results

5.1 Base isolated building

During testing of the base isolated building two somewhat unexpected phenomena were encountered. The first phenomenon was rocking of the structure on the base isolation. It had been anticipated that the tires in the base isolator would undergo substantial shear deformation. In fact, although a white line was painted vertically on the treads of one tire in order to facilitate the observation of shear deformation, very little shear deformation was observed. Rather the structure appeared to be rocking due to rigid body rotation. The axis about which the structure was believed to rotate is shown in Figure 5. The rocking motion manifested itself in the data collected through significant motion recorded by the gage used to measure uplift. Because the structure was moving as a rigid body this motion did not cause damage, however the energy dissipating properties of the rubber tires were not being fully activated. The total response at the top of the walls, the deformation of the concrete house, the deformation of the isolator, and the uplift of the structure due to the New Zealand 100% earthquake record are shown in Figure 6. Figure 6(d) shows the substantial uplift recorded during the test.

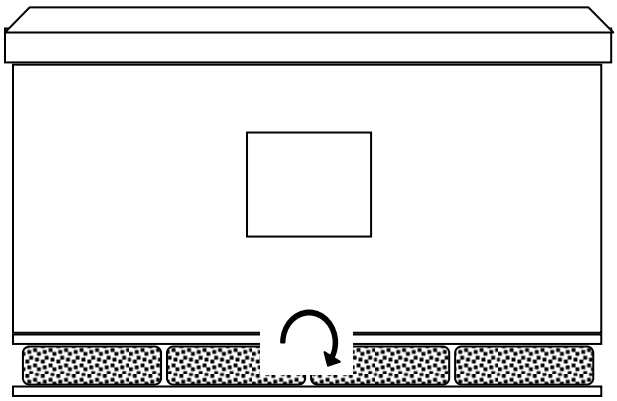

Figure 5. Axis of rotation for concrete house with base isolation

Figure 6(d) also shows the other phenomenon that was witnessed during the series of tests, permanent settlement of the sand in the isolator. During all but the smallest earthquakes, permanent settlement of the structure was observed. This settlement was not entirely unanticipated, however it was surprising that settlement continued to occur as testing proceeded through many earthquake records. The total amount of settlement, approximately 25mm could be eliminated in practice with compaction equipment, but is not necessarily an issue. The presence of permanent settlement interfered with attempts to remove the components of horizontal movement that resulted from rigid body rotation rather than deformation of the structure or isolator. For this reason the horizontal responses shown

in Figure 6 include not only the shear deformation of the isolator and concrete house, but also the effects of rigid body rotation of the structure.

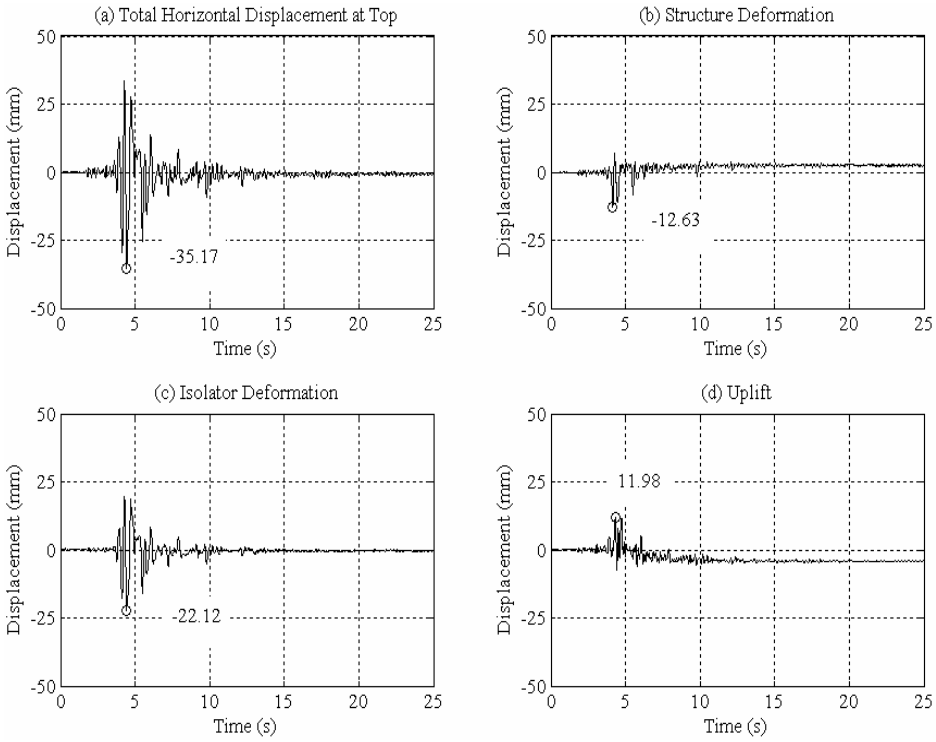

Figure 6. Response quantities for base isolated building New Zealand 100% earthquake record

Figure 7 shows the response spectra for the M6.2 Bay of Plenty, New Zealand earthquake at several different scalings and one spectra of the Northridge earthquake. The dashed vertical line represents the approximate natural period of the base isolated concrete structure including the rocking motion.

The base isolated structure showed very little evidence of damage following the full series of tests. Short hairline cracks were observed in the vicinity of the window openings in the side of the structure.

5.2 Fixed base building

The fixed base building also performed very well during testing. Unlike the base isolated building after testing with the series of earthquake records listed in Table 1, there were some signs of damage for the fixed base building. Figure 8(a) shows the cracks in the concrete of the southeast corner of the building that were present before any testing occurred. These cracks most likely occurred during transportation. Figure 8(b) shows the same corner of the building, and the growth of cracks the occurred during testing without the base isolation system. These cracks did not grow during testing with the base isolation scheme in place.

Figures 9(a) and 9(b) show a similar comparison for the southwest corner. Damage in the fixed base structure was largely concentrated on the southern end of the structure. Despite the growth of cracks, the structure was in reasonably good shape following testing.

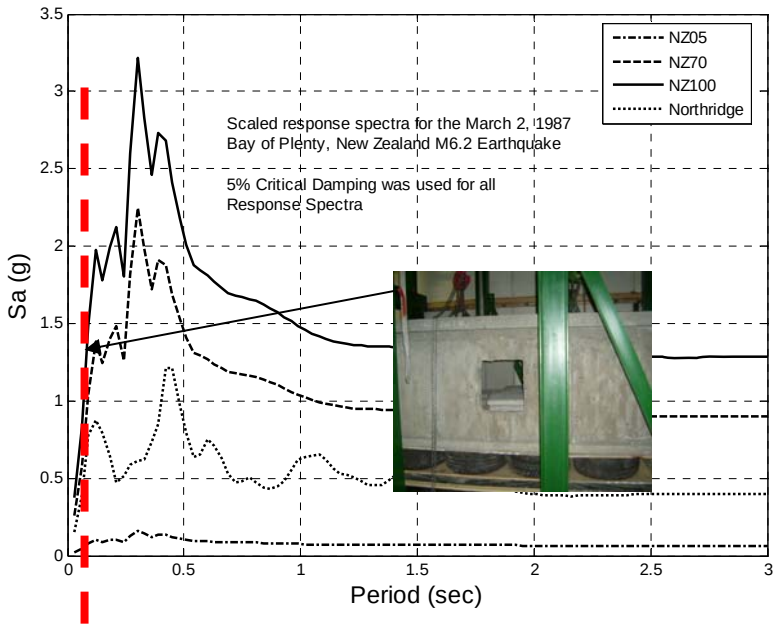

Figure 7. Response spectra for base isolated building for several earthquake records

Figure 8(a). Cracking present before any shake table testing was conducted (south east corner)

Figure 8(b). Cracking present at the end of fixed base testing (south east corner)

Figure 9(a). Preexisting cracks on the south wall of the structure

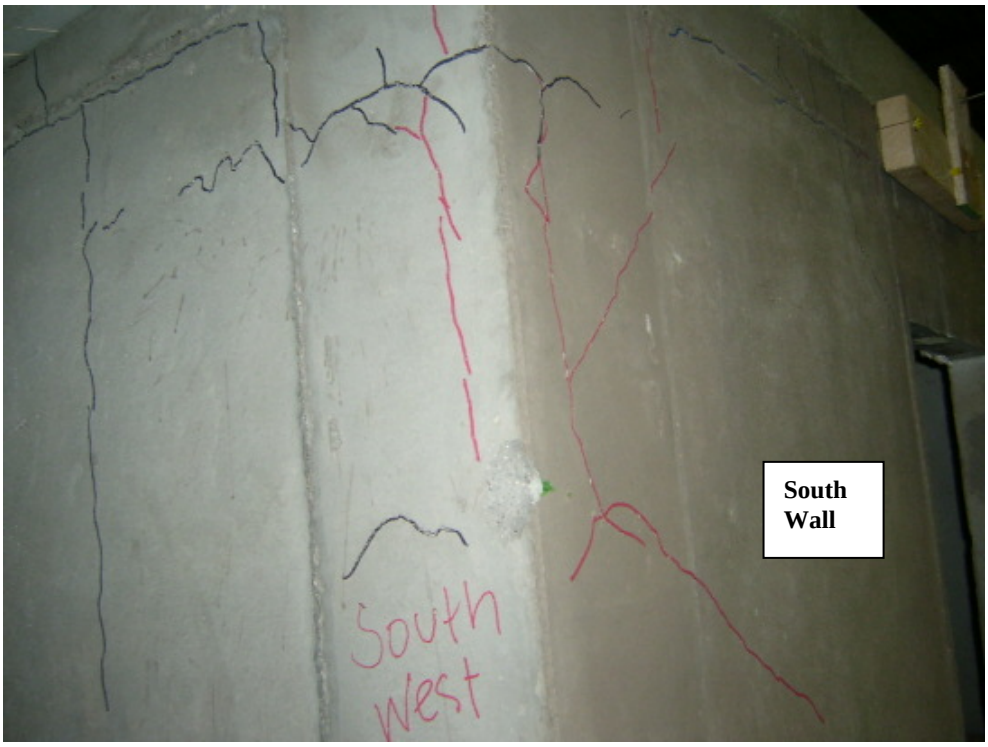

Figure 9(b). Cracking present after fixed base testing (south west corner)

6. Conclusions

In this paper qualitative results from shake table testing of a half-scale model precast concrete house were presented. The house performed very well under severe earthquake loadings both with and without the presence of a low cost base isolation system constructed from used vehicle tires. The base isolation system was observed to protect the structure very well. However, rather than deforming in pure shear the tires in the base isolation system caused the building on top of the tires to rotate in a rigid body fashion. This rigid body motion did not damage the structure, however it also did not take full advantage of the damping potential of the tires. The rocking motion along with settlement of the sand used to fill the tires was effective for seismic protection of the structure. Qualitatively the base isolation system was very effective as only a few hairline cracks were observed after testing. The structure also performed well with a fixed base, however substantial crack growth was observed during the tests.

Based on observations made during this study used tires appear to have significant potential as a low cost base isolation system for residential construction in developing countries. Further exploration of this concept should investigate ways to prevent the rocking motion observed in this study so as to activate the full damping and shear deformation potential of the tires. The potential for settlement in the fill soil as well as the response with

different types of fill soil should also be considered.

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