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SUSTAINABLE AND LOW COST ROOM SEISMIC ISOLATION FOR ESSENTIAL CARE UNITS OF HOSPITALS IN DEVELOPING COUNTRIES.

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Abstract

Historical and recent earthquakes have shown repeatedly that developing countries in South America suffer devastating effects. The use of modern building codes can limit damage to structures but non-structural elements and essential equipment in buildings remain at risk. In critical structures such as hospitals, sub-par performance of non-structural systems can lead to consequences as devastating as structural failures. For example, hospitals can lose their basic functionality, leading to dangerous conditions for their patients, and equally important is that they may not be able to provide urgently needed medical care to earthquake victims, just when medical care is needed most.

Passive seismic protection systems, such as base isolation, provide a good means of controlling the demand imposed by earthquake events. Base isolation systems have become quite common in developed countries like Japan, primarily due to their rapid development after the M7.2 Kobe earthquake in 1995. However, there are far fewer applications in developing countries due to economic considerations and other factors. The slow adoption of these protective systems in developing countries has provided the motivation for an innovative design in this project that uses cost-effective, recycled material, i.e. recycled tires, for isolating designated floors or rooms in health care facilities. There is a global need to develop safety standards for an economically viable protective system that can be implemented within new or existing structures to reduce the dynamic response and increase the performance of structures and their contents so that the overall risk is lowered.

The proposed system differs from what has been identified in the existing literature, since half of an entire tire is used and is configured to have adequate stability. It is difficult to define a rubber tire analytically because of its complex geometry and material nonlinearities. In this study, analyses were performed in detail using numerical methods. These analyses were used for comparison with experimental data from individual tire cyclic tests in order to obtain their mechanical properties, specifically stiffness and damping characteristics. The numerical and experimental validation of a complete prototype system have been performed. The proposed seismic protective system is intended for high functional value locations, such as hospital operating rooms and intensive care units, where the seismic risk imparts significant consequences on the functionality of the hospital during and in the aftermath of an earthquake event.

Keywords: hospital resilience; seismic isolation; critical facilities; seismic retrofitting hospitals

1. Introduction

Developing countries have a need for economically viable seismic protective systems that can improve the performance of structures such as housing, hospitals, schools and infrastructure. Passive systems such as base isolation have demonstrated to be an effective means of controlling the demand imposed by an earthquake, so that the overall risk is lowered [1, 2]. Developing countries are beginning to recognize the importance of considering structural control technology such as passive systems, but the initial cost may be a barrier to implementation.

This paper describes an environmentally sustainable and cost-effective system that can be used to reduce the seismic response of non-structural contents whether in existing or new structures. The isolation system is dubbed Recycled Tire Bearing (RTB) and is intended for isolation of an entire room in a critical facility.

Numerical analyses accomplished by finite element analysis (FEA) were employed to understand the behavior, the mechanical properties and stability of the system. Furthermore, an initial experimental phase consisting of quasi-static testing aimed at verifying the design structural integrity and stability, and provided the requisite validation of the FEA.

The proposed design of the RTB system is intended for critical rooms such as hospital operating rooms and intensive care units in developing countries where the seismic risk is high. As a case study, the retrofitted Miguel H. Alcívar Hospital located in the city of Bahia de Caráquez in Ecuador was selected in order to implement the proposed RTB system in operating rooms and intensive care units. This hospital was designed and subsequently retrofitted based on the Ecuadorian Construction Code [3], and detailed documents of the hospital were provided by ESPE University [4, 5] and the Ecuadorian Army Corps of Engineers [6] who were responsible for the design and construction. The structural system was assumed to remain elastic because the hospital was reinforced with heavy concrete shear walls to provide sufficient global strength. Given the added stiffness of this hospital after retrofitting, the acceleration demand imposed on the non-structural elements becomes of great concern, and therefore, the envisioned seismic protective system aids in mitigating the vulnerabilities of valuable contents of operating rooms and intensive care units.

2. Assessment of Non-Structural Elements and Concept of Seismic Isolation

Recent earthquakes have shown that even though modern codes have limited the damage to structural elements, non-structural elements have experienced damage and proven to be expensive to repair/replace [7, 8].

A study that focused on assessing the seismic hazard associated with non-structural elements in hospitals was conducted in Ecuador [9, 10]. The study considered two healthcare facilities: (1) the Regional Military Hospital in Guayaquil [11], which is part of the health network of Ecuadorian Armed Forces with a capacity of 81 hospital beds (see Figure 1), and (2) the Miguel H. Alcívar Hospital with a capacity of 120 hospitals beds, which was damaged during the 1998 earthquake in Ecuador [4, 5, 6, 10]. These two hospitals were evaluated using the U.S. Federal Emergency Management Agency (FEMA) [12, 13, 14] guides FEMA E-74 "Reducing the Risks of Nonstructural Earthquake Damage - A Practical Guide" and FEMA 396 "Risk Management Series, Incremental Seismic Rehabilitation of Hospital Buildings, Providing Protection to People and Buildings." The projected level of performance of non-structural elements and components was determined to be inadequate, potentially disabling these hospitals and exposing patients to undue risks during and after a significant earthquake. As an example of the evaluation, Figure 1 shows the risk to patients when a television monitor is in a precarious position and may fall.

Fig. 1 – Military hospital dialysis room (Left side), example FEMA E -74 damage and television special brackets supports (Center, Right)

Passive systems such as base isolation have been developed and past events around the world have demonstrated the effectiveness of base isolation systems at reducing the level of response in a building compared to what would otherwise occur in its original configuration. It is assumed that de-coupling will be accomplished using an isolation scheme that makes the fundamental period of the isolated structure several times greater than the period of the structure without the isolation system [15, 16].

Base isolation systems or other seismic protective strategies have become quite common in developed countries. In Japan after the M 7.2 Kobe earthquake in 1995[17] and in Chile after the M 8.8 earthquake in 2010 [18], many facilities and single-family residential buildings were equipped with seismic protection devices. There are certain factors to consider when evaluating the feasibility of installing structural control systems particularly in developing countries like Ecuador. One of the main factors hindering the use of isolation systems is the high cost of acquisition and deployment, and such issue can significantly limit the implementation, especially in public buildings and residential housing. Some studies also indicate that the weight of the devices is another factor limiting their use [1, 2].

Generally, base isolation systems can be implemented at various levels, such as isolation of the entire structure, floor isolation or room isolation. The entire structural isolation provides a global solution; however, this system is expensive and does not provide vertical isolation, which could be needed for certain type of non-structural elements (e.g. ceiling and piping systems). Existing floor isolation systems [19] are relatively new and unproven technologies, and similar to the entire structure isolation, the devices employed in the system are expensive and do not provide vertical isolation. Given the economic factors and deployment issues, room isolation offers a viable alternative that allows for alleviating the high cost associated with entire-floor isolation, and can provide protection of medical equipment in locations of high value to the functionality of the hospital. Considering the above implementation impediments, the protection strategy that is proposed in this paper offers a low-cost alternative for hospital room isolation that can be deployed in developing countries.

2.1 Proposed Recycled Tire Bearing System

There is a global need to develop safety standards and economically viable protective systems that can be implemented within new or existing hospitals to reduce the overall earthquake risk associated with loss of functionality after an earthquake event. The slow adoption of protective systems in developing countries has provided the motivation for an innovative design that uses a cost-effective, recycled material, i.e. recycled automobile tires, for isolating designated rooms in health care facilities.

The Recycled Tire Bearing (RTB) system is designed to isolate critical rooms in health care facilities such as emergency rooms, essential care units, and recovery rooms (see Fig. 2). The proposed system consists of recycled tires cut through their diameter and inserted between the structural slab and a newly created floor surface. The arrangement of tires in this RTB system is symmetric in plane, with four half-tires covering an area of approximately 1.2 m x 1.2 m square. Each tire is compressed under the gravity load of a newly created floor surface and the room contents. Unlike conventional seismic isolation systems, the RTB system is able to deform both in the horizontal and vertical directions during an earthquake, thereby providing seismic isolation under horizontal and vertical floor motions. Also, potential vibrations caused by the RTB system during the normal operation of the isolated room can be eliminated by using bolts as a locking mechanism between the bottom slab and the newly-created floor surface. This locking mechanism, acting like a fuse, is designed to fail at a predetermined floor acceleration in order to activate the RTB system in the event of an earthquake as shown in Figure 3 (Right side). Considering that the uplift can introduce tensile stresses, the boundary condition or support of the tire is designed to allow uplift under tensile load.

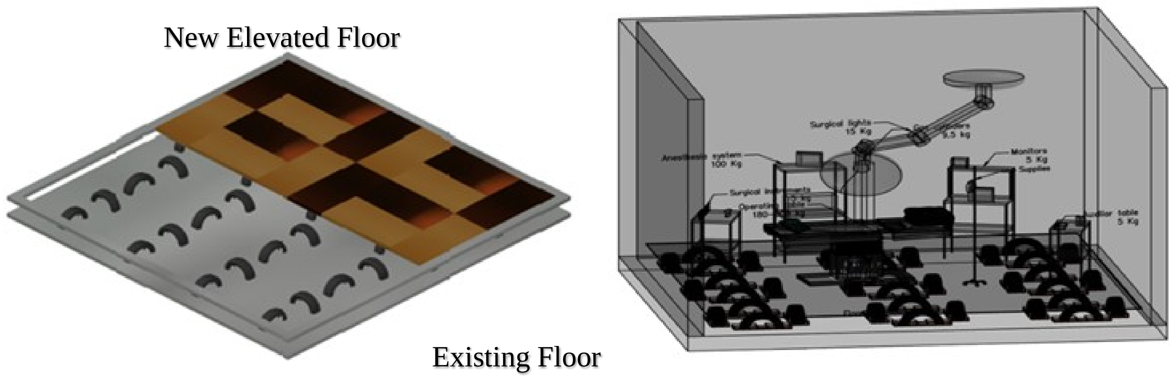


Fig. 2 – Illustration of the application of the RTB system in the operating room of a hospital

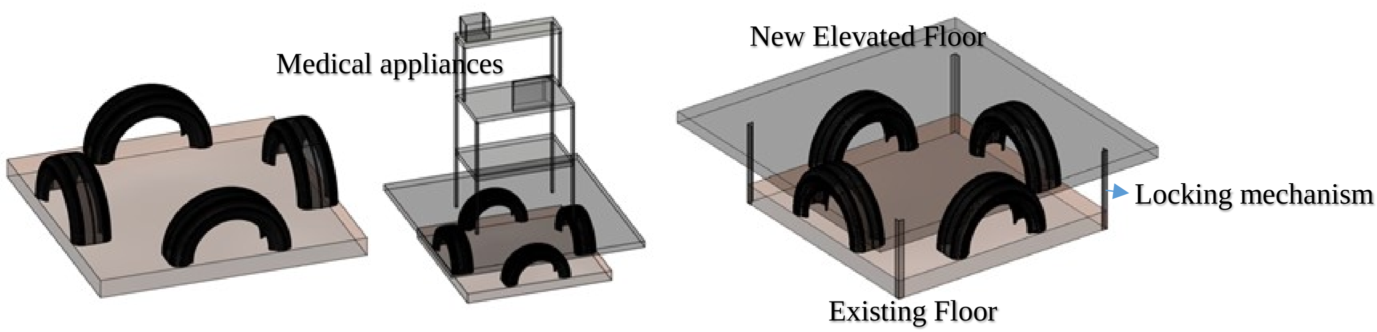


Fig. 3 – Illustration of the RTB (Left side), RTB with medical appliances and supplies (Center) and vertical locking mechanism (Right Side)

3. Numerical Modelling Using Finite Element Analysis

The analyses of the tire system were performed in detail using numerical methods, in this case the FEA program LS-DYNA [20]. A model was initially created to characterize the behavior of an individual tire in detail, considering its proposed shape in the RTB system, and full consideration of its very complex geometry in terms of non-uniform shape, variable thickness, and constitutive models for a number of materials (i.e., rubber, steel, nylon, and polyester). A computational model of the tire (shown in figure 5) that represents the physical problem was created including the geometry, materials, loading, and boundary conditions. Figure 4 shows samples of recycled tires R-13 with its constituents of steel cords, tire cross section pattern thickness of the tread, under tread, sidewall and body.

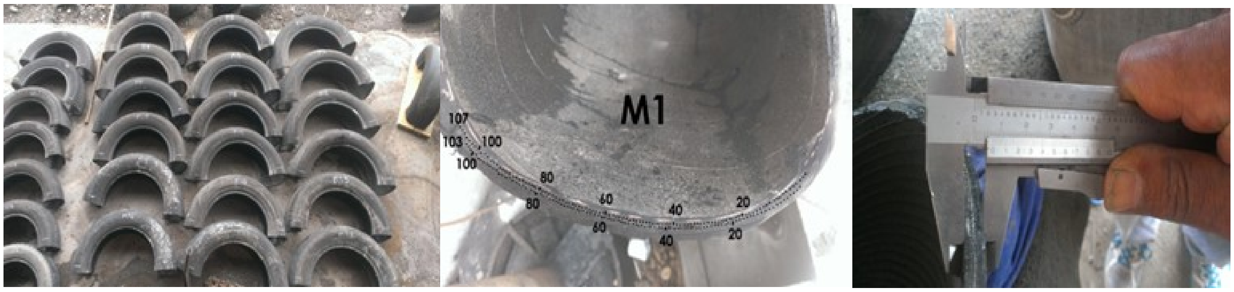


Fig. 4 – Samples of recycled tires, steel cords, tire cross section pattern thickness of the tread, under tread, side wall and body

The accurate determination of material properties of each constituent layer of the tire was an important factor in the successful development of the numerical model. The tire is made of various layers with distinct material properties, such as natural or synthetic rubber, nylon, and steel wires. Rubber components and cords represent the two main components of the tire. The tread, under tread, sidewall and body are non-linear hyperelastic materials and were modelled using the Mooney-Rivlin constitutive model [21, 22, 23]. The steel cords were modeled as elastic material and the nylon cords as elastic-plastic material. Considering the complexity of the tire geometry and constituent layers, the mesh was generated for each constituent layer or part. Beam and isoparametric 8-node solid elements in LSDYNA designated in figure 5 (right) as 5-6-7 and 1-2-3-4 respectively, were used to represent these two parts of the tire. The cords were generated using beam elements, and the rubber components such as tread, under tread, body and sidewall were also modeled with 8-node solid elements. Figure 5 shows the geometry, the various elements (designated by numbers 1 to 7) of the model, and the FE mesh [24, 25].

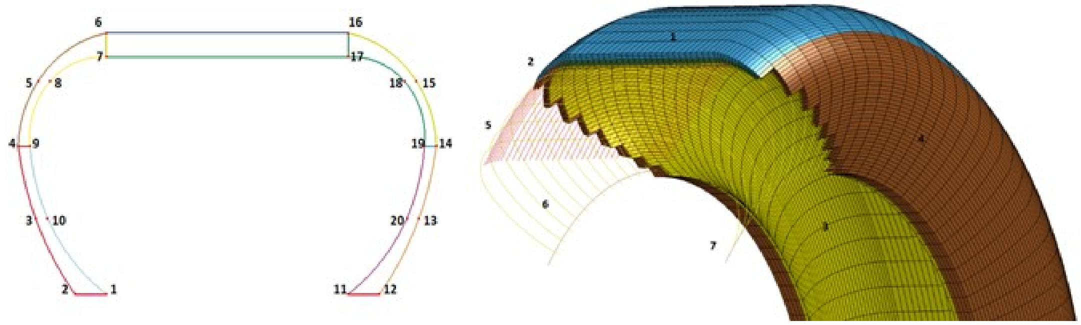


Fig. 5 – Geometry (Left) and FE Model - Tire components: 1. tread, 2. under tread, 3. body, 4. sidewall, 5. radial cords, 6. circumferential cords and 7 bead cords

The boundary conditions of the model follow the as-built prototype. During the horizontal cyclic tests and the initial numerical analyses, two different boundary conditions were considered as shown in Figure 6; A-A fixed-fixed and A-H fixed-roller.

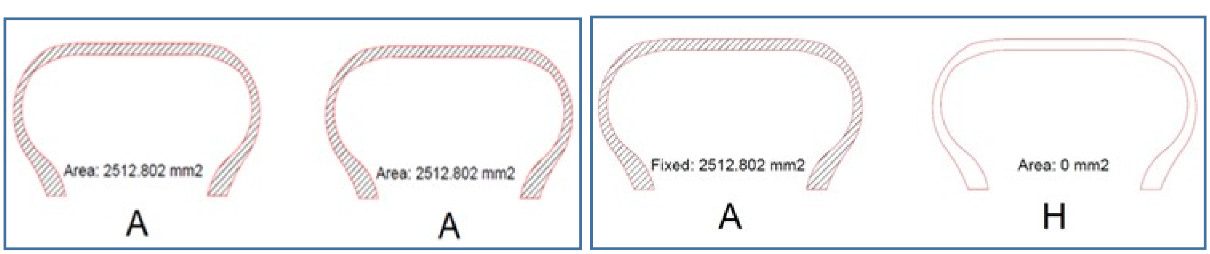


Fig. 6 – Boundary condition during the test and analytical analysis: A-A fixed-fixed and A-H fixed-roller

The force-displacement behavior from the analyses of a single tire is compared with test data. This testing provided validation to the model assumptions pertaining to the mechanical properties, boundary conditions, and further provided stiffness and damping characteristics. The numerical and experimental behavior of an individual tire under vertical and horizontal forces follow the hysteretic loops shown in Figure 7.

The maximum displacement, effective (secant) stiffness, energy dissipated per cycle, and the effective damping ratio were calculated for each test based on three loading cycles at the applied maximum force. Note that under horizontal load, the equivalent viscous damping provided by a RTB specimen, is of the order of 15% of critical damping, which is significantly higher than that of conventional isolation bearings. Figure 7 and 8 show a comparison between the numerical and experimental results under vertical and horizontal cyclic loading, respectively under a gravity load of 1.5 kN representing the tributary weight above the system in a typical hospital room.

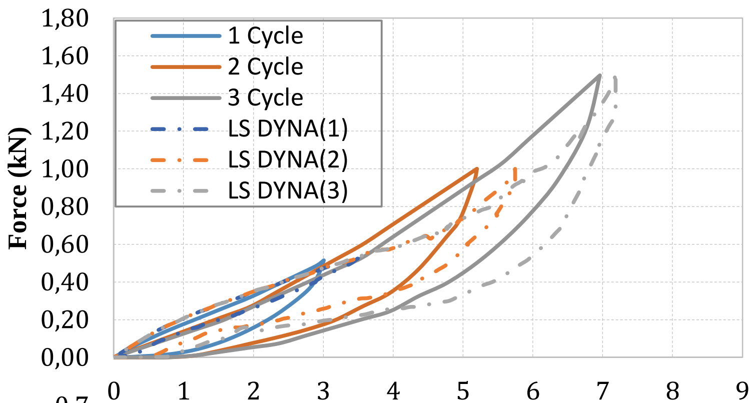


Fig. 7 – Component testing and FE modeling-vertical cyclic response

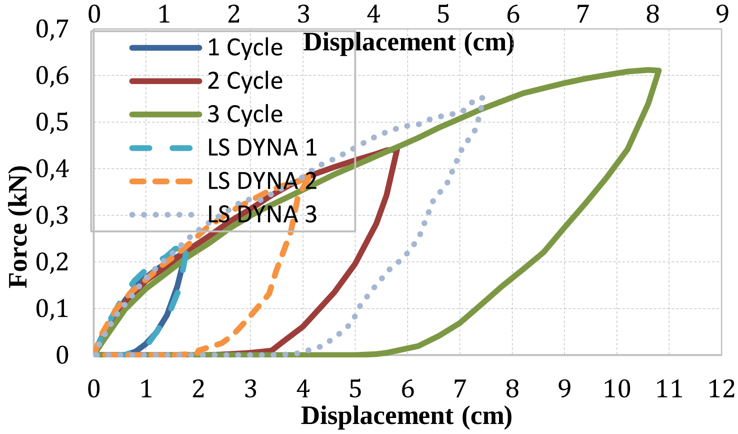


Fig. 8 – Component testing and FE modeling-horizontal cyclic response (gravity loading =1.5 kN)

Figure 9 shows the test results for different boundary conditions under vertical displacement control and horizontal force control. The results indicate that the effective lateral stiffness of the RTB system is significantly reduced by changing the boundary conditions from **A-A** to **A-H.**

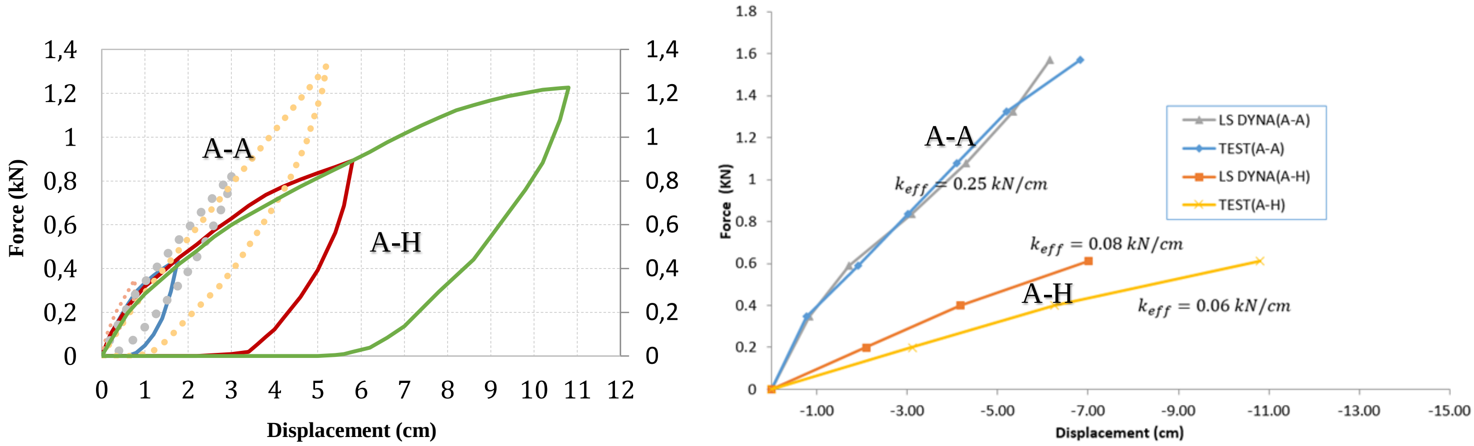


Fig. 9 – Component testing horizontal cyclic response fixed-fixed and roller-fixed boundary condition

Based on the test results shown in Tables 1 and 2, the tributary vertical load for an RTB is 6.0kN, considering that each half-tire carries 1.5 kN. The vertical deflection under this gravity load is approximately 7 cm. This is reasonable because it allows sufficient control of vertical movement before contact with the structural slab (bottoming out of the bearings) or separation (uplift) take place. For this level of tributary gravity load, the vertical effective isolated period $T_{v\text{-}eff}$ is 0.53 s and the horizontal effective isolated period $T_{h\text{-}eff}$ is 1.29 s (Model figure 10). The ratio of the vertical stiffness to the horizontal stiffness is 3.68. The horizontal effective isolated period is shorter than the traditional target of 2 s for base isolated systems [15]. However, the higher damping ratio provided by the RTB system is envisioned to provide a significant reduction of the floor response in comparison to the rigid floors.

Table 1 – Compression experimental test and (FE) ls dyna results

COMPRESSION EXPERIMENTAL TEST							(FE) LS DYNA RESULTS						
Type	Cycle	F_{vmax} kN	u_{vmax} cm	EDC (kN-cm)	k_{eff} (kN/cm)	β_{eff} (%)	Type	Cycle	F_{max} kN	u_{vmax} cm	EDC (kN-cm)	k_{eff} (kN/cm)	β_{eff} (%)
RCB	1	0.52	3.01	0.38	0.17	7.77	RCB	1	0.52	3.49	0.21	0.15	3.71
	2	1.00	5.20	1.14	0.19	6.97		2	1.00	5.75	0.96	0.17	5.32
	3	1.50	6.96	1.92	0.21	5.88		3	1.52	7.19	2.00	0.21	5.83

Variables that appear in Table 1 and 2: EDC = Energy dissipated per cycle; k_{eff} = Effective stiffness; β_{eff} = Effective damping; F_{vmax} = Vertical Force and u_{vmax} = Max; Vertical displacement; F_{hmax} = Horizontal Force and u_{hmax} = Max. Horizontal displacement.

Table 2 – Vertical and horizontal test and (FE) LSDYNA results – gravity loading =1.5 kN

VERTICAL AND HORIZONTAL TEST							(FE) LS DYNA RESULTS						
Type	Cycle	F_{hmax} kN	u_{hmax} cm	EDC (kN-cm)	k_{eff} (kN/cm)	β_{eff} (%)	Type	Cycle	F_{hmax} kN	u_{hmax} cm	EDC (kN-cm)	k_{eff} (kN/cm)	β_{eff} (%)
RCB	1	0.22	1.76	0.17	0.13	13.72	RCB	1	0.22	2.10	0.19	0.10	14.16
	2	0.44	5.80	1.27	0.08	15.84		2	0.44	4.17	0.92	0.11	14.45
	3	0.61	10.80	3.22	0.06	15.5		3	0.61	7.00	2.23	0.09	14.2

Figure 10 schematically shows a representative dynamic model of the RTB system [26]. The system can be idealized by a spring-mass system with three degrees-of-freedom: u_1, u_2 and θ. The values of the in-plane stiffness are shown in Table 2. Out-of-plane stiffness is assumed negligible. This vibration model of a spring-mass-system is used to determine the dynamic properties of the RTB for different values of mass, which represent the tributary weight of the RTB.

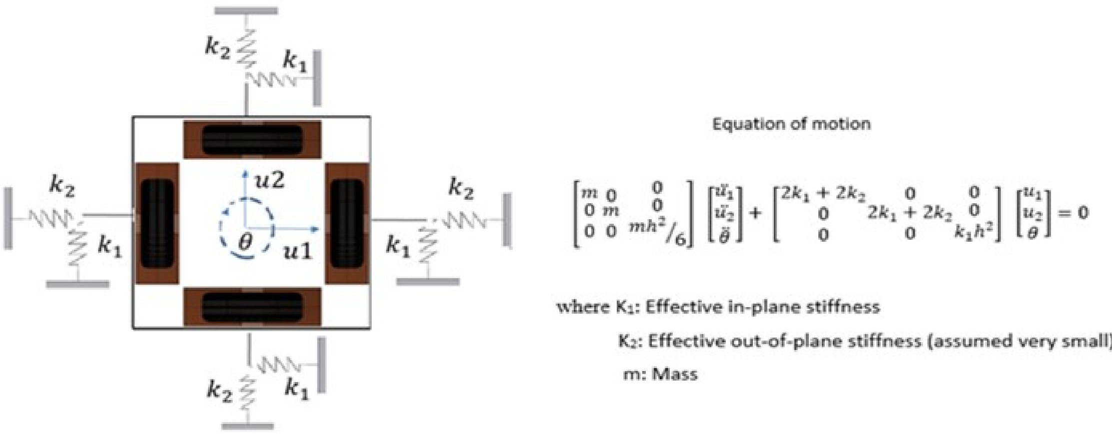


Fig. 10 – Dynamic model of RTB

4. Case Study Hospital

The proposed RTB design is intended to be used in priority locations of hospital operating rooms and intensive care units in developing countries where the seismic risk is high. The hospital has critical medical equipment and complex mechanical and electrical systems, which must have guaranteed functionality because the hospital cannot operate without them. Undoubtedly, one of the worst impacts resulting from earthquake hazard is the effect on healthcare infrastructure, principally hospitals. For example, Ecuador suffered major earthquakes in 1987 and 1998 that severely damaged hospitals such as the José María Velasco Ibarra and Miguel H. Alcívar hospitals, as shown in Figure 11. Non-structural elements in these hospitals suffered major damage [4]. These hospitals were not adequately built for the country's seismic hazard and consequently they were not operational after the earthquakes. The number of deaths resulting from the earthquakes was probably higher than it would have been had the hospitals been designed or retrofitted to provide seismic resiliency.

After the 1998 earthquake, the Ecuador Ministry of Public Health embarked on a program to retrofit hospitals by means of jacketed columns and concrete shear walls, with the intent of strengthening these structures. The primary goal of this strengthening was to increase the strength of the building beyond the design code level that will create a quasi-elastic response of the structure. However, this retrofitting strategy will lead to high floor accelerations in an earthquake event and adversely affect the response of the non-structural elements inside the facilities.

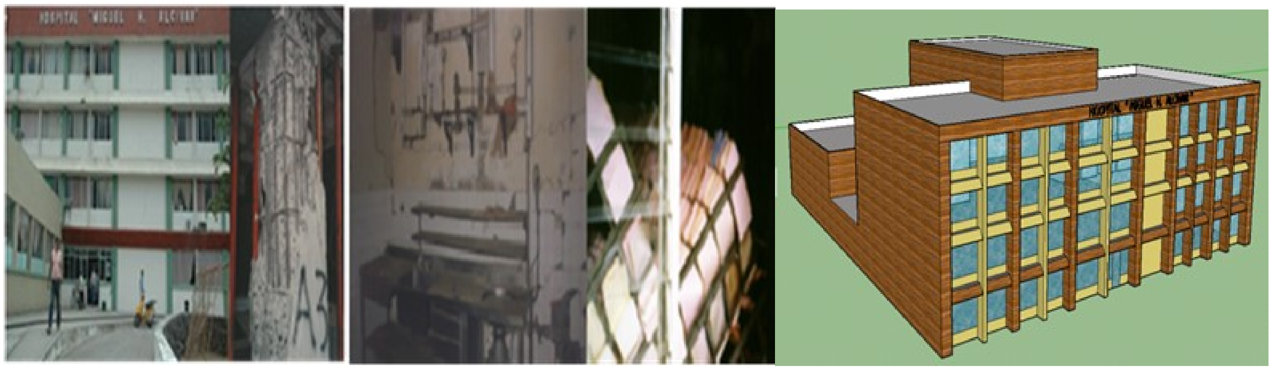


Fig. 11 – Structural and non-structural damage of Miguel H. Alcívar hospital during the1998 earthquake in Ecuador (Courtesy of R. Aguiar)

The Miguel H. Alcívar Hospital in Ecuador was selected as a case study in order to verify the implementation of the RTB system in essential care units and was analyzed using SAP 2000 [27], as illustrated in Figure 12. A linear time-history dynamic analysis was used to evaluate the structure under design level ground motions of FEMAP695 Far Field Ground Motion Set [28]. The fundamental period of the building is 0.44 s.

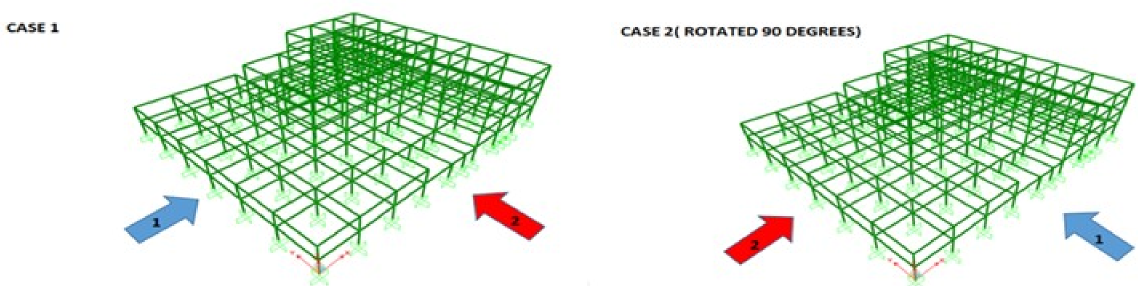


Fig. 12 – Illustration of the incremental dynamic analysis implemented in a surgery room- Miguel H. Alcívar Hospital

For each analysis, the absolute acceleration of the floor and the first floor relative displacement response spectra were obtained in each direction. The median floor spectrum acceleration for 15% damping in the horizontal directions (Figure 13) shows that at the effective horizontal isolation period of 1.29 s, and the associated equivalent viscous damping ramping ratio of 15% the acceleration demands at the top of the isolation plane remain under 0.30 g beyond which the medical equipment is considered to become nonfunctional [7]. Figure 14 shows that the associated median spectral displacement remains under 10 cm. This can be accommodated by leaving gaps between the perimeter of the top isolation plane (the elevated floor) and the surrounding walls.

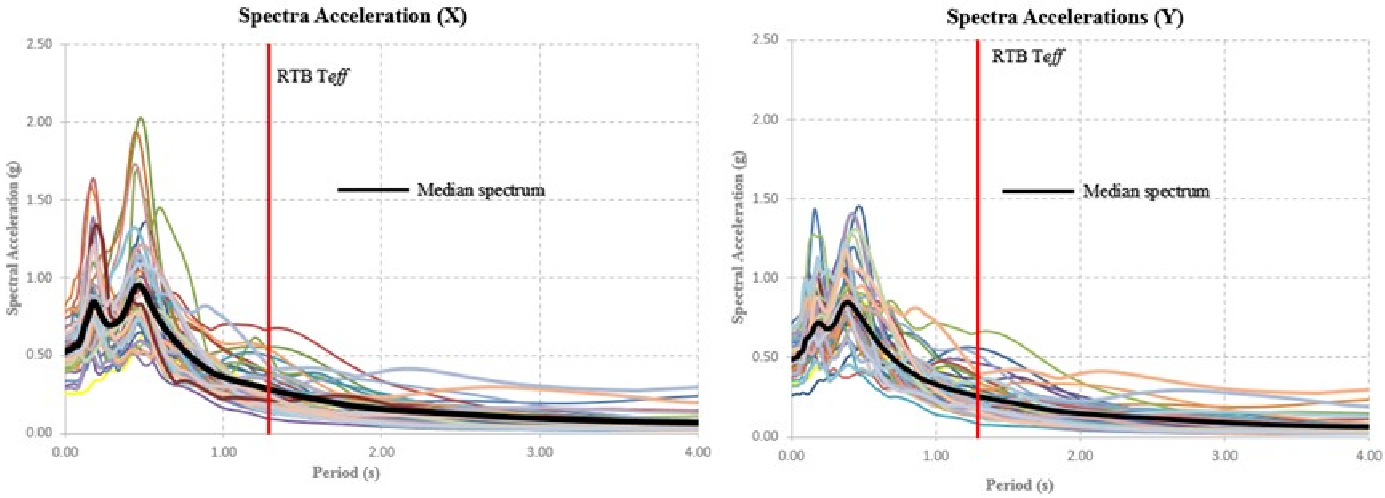


Fig. 13 – First Floor Acceleration Response Spectra for 15% Damping

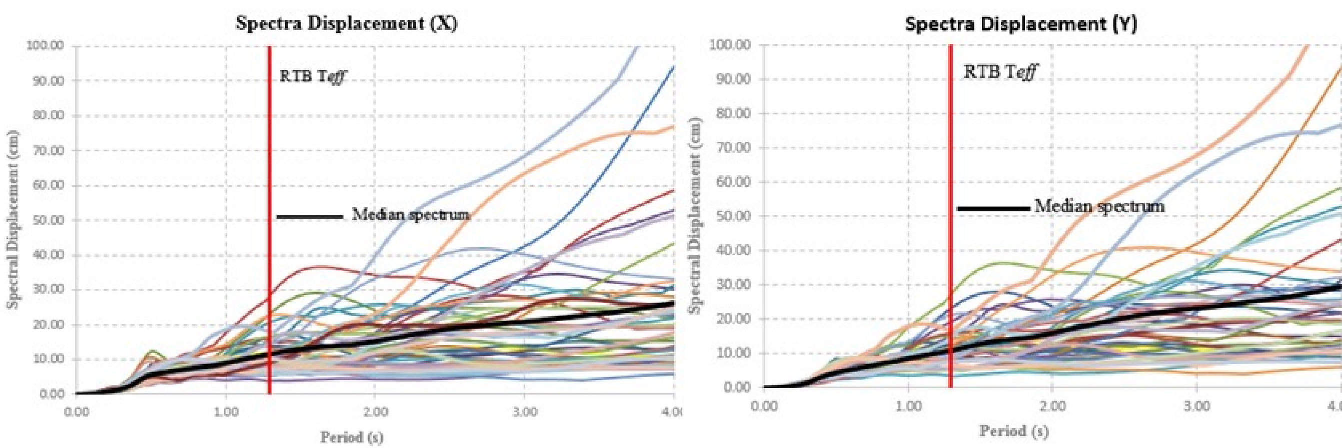
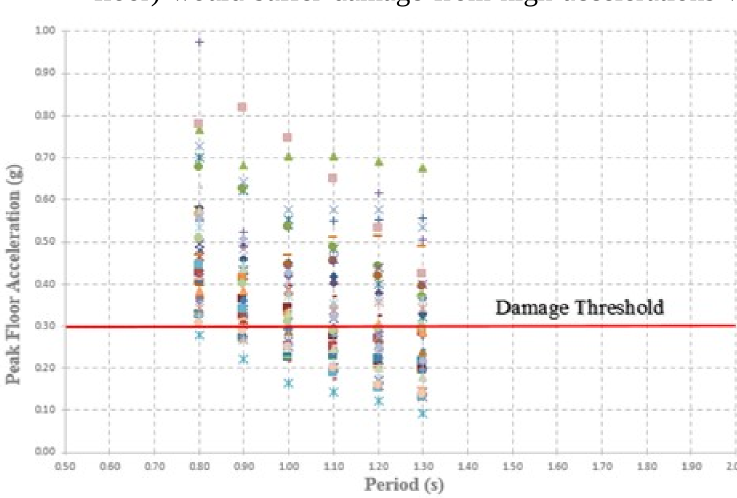
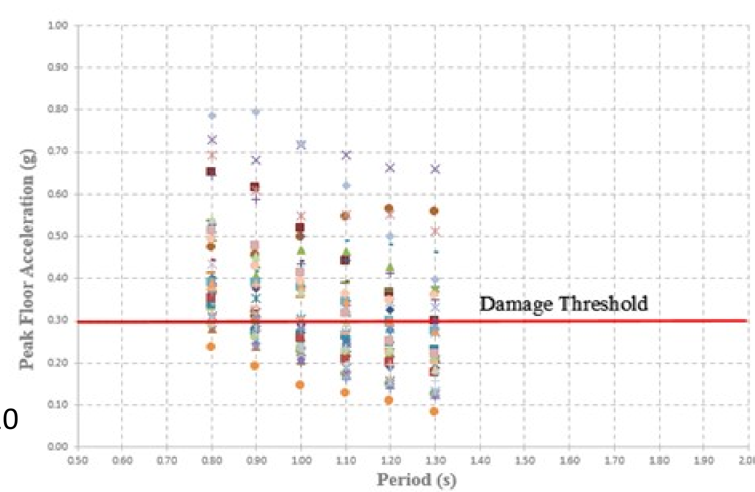


Fig. 14 – First Floor Displacement Response Spectra for 15% Damping

Figure 15 shows the number of instances that the peak floor acceleration is greater than 0.30 g for different effective periods of vibration. At the effective period of the RTB system (T =1.29 s), a floor acceleration of 0.30 g was surpassed 14 times in the x direction, which is 32% of the earthquake scenarios. In the y direction, 0.30 g was exceeded 13 times, or in 30% of the earthquake scenarios. The period without floor isolation would cause serious damage to the diagnostic equipment and its operation will be impaired. The median spectrum in (Figure 13) indicates that non-structural elements with a short period (i.e. rigidly fixed to the floor) would suffer damage from high accelerations while those isolated by the RTB would be protected from





damage.

Fig. 15 – Peak floor acceleration in X (Left) and Y direction (Right)

5. Seismic Testing

As illustrated in Figure 16, the final stage of this project includes seismic testing on a complete prototype system consisting of four RTB bearings on the six degrees-of-freedom shake table at the University at Buffalo to evaluate the seismic performance of the RTB system (Fig 17), and validate the numerical models. The specimen is rigidly connected to the shake table. The dynamic response of the RTB system will be recorded by accelerometers and string potentiometers. The experimental procedure consists of system identification and seismic testing of isolated structure. This experimental work was in progress at the time of writing.

Fig. 16 – Seismic test RTB

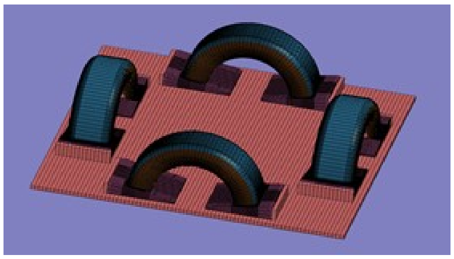


Fig. 17 – (FE) Model RTB

6. Conclusions

This paper describes a novel method of protecting hospital rooms and their contents from severe earthquake damage so that critical facilities can remain operational after an event. A first generation Recycle Tire Bearing (RTB) isolation system is proposed, modeled and analyzed using numerical methods, and then its performance was validated by experimentation, using a full-scale prototype. This study focuses on static, dynamic and shake table testing to evaluate the proposed isolation system.

Finite element models using LS-DYNA were able to predict well the results of the cyclic tests. The results of vertical and horizontal cyclic tests provided basic effective stiffness and damping properties, and demonstrated that the proposed RTB isolation system is a low cost and holds promise for isolating rooms in health care facilities to improve safety and reduce the risk of damage to equipment. The RTB system can be considered as a viable strategy for improving the seismic response of non-structural elements in targeted rooms of short period hospital facilities in developing countries.

The RTB system has relatively high damping and low horizontal effective stiffness, which would significantly reduce the transmission of floor acceleration to non-structural elements. Without response modification technology, the accelerations levels would probably cause serious damage to critical medical equipment and treatments in a hospital structure would be seriously affected during and in the aftermath of an earthquake.

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