Earthquake Response Analysis and Simulation of Sensitive Hospital Equipment in the Philippines

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SUMMARY:

This paper presents a method that can analyze earthquake response of typical non-structural components in a hospital. Wheel-movable, free-standing and desk-mounted equipment typically found in emergency rooms, intensive care units and operating rooms were modeled and restraints were designed to minimize or eliminate rolling, sliding and overturning. The method utilizing rigid bodies subjected to inertial forces due to earthquake was introduced and validated using simple analytical computations and numerical experiments. Examples show that non-slip mats are effective in restraining equipment that are unlikely to overturn while the ¹/₄"-diameter bungee cord with optimal orientation or pre-tensioning significantly reduces the acceleration response of the equipment. Heavy equipment, like the 175-kg medical cabinet, may be restrained using bolts or 4-mm accessory cord. This study recommends that soft materials be attached to the equipment at points of possible collision with the wall in order to prevent further damage and large displacement of the equipment.

Keywords: earthquake, furniture, hospital, simulation

1. INTRODUCTION

Surveys and field investigations after strong earthquakes have reported that human injuries during strong earthquakes are mainly due to overturning furniture and falling objects. Therefore, attention must be made to not only structural elements but also non-structural components of a building. Non-structural components include, but not limited to, systems, elements, or components of the building that are not part of the structural load-bearing system but are subjected to the building dynamic environment, caused by, as an example, an earthquake. As designs for structural components of a building for seismic forces are readily available in structural codes, less attention has brought about for non-structural components.

When very strong earthquake strikes, the number of people expected to be in need of care and treatment demands that hospitals should not only be structurally sound but also the non-structural components and sensitive equipment in it must be properly restrained and functional.

Structural, as well as non-structural, components of the hospital building should be at the most minimal risk of damage. These non-structural components of the building also hinder the functionality of essential facilities, such as a hospital, in an event of an earthquake since medical equipment may be damaged due to overturning, sliding, rocking or collisions.

Hospitals should be the safest place to be at critical situations such as earthquakes. People's lives depend on its functionality. Even if the structural integrity of the hospital building is ensured, non-structural components—unsecured and unrestrained—has shown to be detrimental in injuries and casualties of people inside the hospital. These non-structural components are of great concern since many of these are medical equipment are used for treatment and without it, the hospital cannot perform its duties.

Despite these facts, little attention is paid to non-structural elements in the seismic design of structures. Non-structural elements are specifically significant to hospitals because the total cost of these is much higher than the cost of the building itself. However, damage of these can incur not only cause loss of property and money, but also further injury and loss of lives of people.

This study addresses this problem by investigating the response the typical furniture or equipment in a hospital during strong motion earthquakes. Hospital equipment to be considered are limited to those found in the Philippines. Furthermore, the hospital equipment to be considered are those likely to cause harm or injury to people (e.g. cabinets). Only desk-mounted and freely standing equipment will be considered. Not all non-structural equipment will be modeled. Non-structural components that need to be frequently moved are restrained in such a way that the restraint can be easily detached.

In this paper, engineering solutions for restraining or controlling hospital equipment movements, in order to minimize casualties to people or failure of equipment during earthquakes, will be presented. Standard mitigation procedures for non-structural components are developed.

2. METHODOLOGY

2.1 Theoretical Basis

For simplicity, earthquake forces are directly applied to the hospital equipment, which are treated as rigid bodies. To animate this systemof rigid bodies, appropriate forces must be taken into account. Forces that arise due to relative positioning of objects (e.g., contact, collision), object's velocity, connections (e.g., springs), and user-specified vector fields (e.g., gravity, other external forces) must be exerted on bodies properly. These forces, according to Newton's laws, induce linear and angular accelerations depending on the mass and mass distribution of the body, respectively.

Earthquake response is simulated in rigid body systems by exerting effective earthquake forces (inertial force) that are equal to the rigid body mass times the ground acceleration, acting opposite to the acceleration. In this paper, the accelerogram of the 1995 Kobe, Japan earthquake is used in the simulations.

2.2 Validation of the Simulation Program

The simulation program used in this study was tested to solvetypical dynamic problems expected of equipment during strong motion earthquakes. Results show that the program can reasonably estimate response when the idealized equipment *slides*, *overturns*, *falls-off* (as in projectile) and *collides* with other equipment. These results, however, are not reported in this paper.

2.3 Modeling of Hospital Equipment

A digital layout of the Intensive Care Unit (ICU) based on the ICU of East Avenue Medical Center in Philippines is done. Hospital equipment located are modelled as precise as possible using appropriate combinations of basic objects like spheres, cylinders, cuboids (parallelepiped), planes and fixed points. Dimensions are based from manufacturers of medical equipment and from previous research (Inguito, 2011). An example of is shown in Figure 1. Moreover, material properties, including density, coefficient of static and kinetic friction, and coefficient of restitution are also used for the model.



Figure 1.Numerical model of a mechanical Ventilator

2.4 Modeling of Restraints Using Nonlinear Springs

2.4.1 Bolts

The specification of A307 bolts is used for restraining fixed and heavy equipment. It is because highstrength bolts are no longer needed and A307 bolts are the most economical bolts that can be used. Based on the National Structural Code of the Philippines (NSCP), the properties of A307 Bolts (NSCP 2010, Table 510.3.2) are as follows:

Fu = tensile strength (snug tight condition) =311MPa (45 ksi)

Fv = shear strength (snug tight condition) =169MPa (24 ksi)

This bolt will be modeled in the program using nonlinear springs. Figure 2(a) below is the force vs. elongation plot of the spring in tension and compression, replicating the A307 bolt.



Figure 2. Force-deformation/strain characteristics of (a) A307 Bolt and (b) different diameters of elastic cord, and (c) accessory cord used in analyses

2.4.2 Bungee Elastic Cords

Elastic cord, also known as bungee cord or shock cord is used in this study as restraint for deskmounted equipment. The nonlinear force-strain characteristic is shown in Figure 2(b).

2.4.3 Accessory Cords

Medium and heavy-weight equipment needs stronger cords for them to be restrained properly. Accessory cords are used for this purpose rather than bungee elastic cord because it has generally larger tensile strength. Figure 2(c) shows the tensile force-elongation plot for different diameters of elastic cord.

3. NONSTRUCTURAL MODELS

3.1 Medical Cabinet

A medical cabinet is a heavy equipment and may cause severe damage to people and equipment when not properly restrained. Furthermore, its contents are important for the continuous function of the hospital. As it is not sensitive to acceleration, what is analyzed is only the displacement response. Shown in Figure 3 are the 175-kg models for the said equipment restrained using A307 bolts mentioned in section 2.4.1. The response of the equipment subjected to the 1995 Kobe earthquake is shown in Figure 4.



(a) Unrestrained Cabinet (b) Restraint 1 (c) Restraint 2

Figure 3. Medical Cabinet



Figure 4. Position-time history plots of the restrained and unrestrained cabinet subjected to Kobe earthquake.

From these results, the first configuration of restraint is more effective. Therefore, it is better that the restraints are introduced at the sides of the medical cabinet rather than on its top.

3.2 Desk-mounted Equipment

Desk-mounted equipment are expected to be damaged due to impact along the borders of the desk/bench and due to falling from the table during a strong ground motion. Internal damage is also possible due to excessive acceleration response during a seismic activity.

The dimensions of the assumed model for the desk-mounted equipment are $0.3m \ge 0.2m \ge 0.2m$. It has a mass of 5 kg and is made up of iron. It also has four rubber pads at its base with kinetic and static friction coefficient of 1.08 and 1.5, respectively. It is mounted 1m above the floor. The mounting object is made to be immovable.



Figure 5. Equipment Restrained by a Bungee Cord

3.2.1 Application of Bungee Elastic Cord (Shock Cord)

For the model, a 6-mm $(\frac{1}{4})$ diameter cord is used with a tensile strength of 895 N (Figure 4). It is because cords with smaller diameter is tested but results show that it is ineffective. The endpoints of the cord are attached to the mounting object (i.e. desk).

It is 30% shorter for the purpose of pretension to hold the equipment in place. The restraint is modeled at different angles (75°, 60°, 45° and 30°) from the horizontal to be able to determine the optimum angle of orientation. Please refer to Figure 19 for the average acceleration-degrees plot.



Figure 6. Average Acceleration (m/s^2) – Angle (degrees) Plot

Figure 6 shows that increasing the angle of orientation of the restraints significantly increase the acceleration response of the equipment. This is true for all three major axes. With this, angle 30° and

 45° are being considered as the best angles. Also, the differences in the maximum displacement in the X and Y axis are insignificant (only 7-mm maximum). Meanwhile, in the z-direction, the difference is about 2cm. For this case, the 45° orientation is better than the 30° .

Another factor that must be considered is the space constraint. Desks are not made to be very wide. Angle 30° takes so much space than angle 45° . With this, it is better to choose angle 45° than angle 30° as the optimal angle.

3.2.1 Application of Non-slip Mats

A non-slip mat made of rubber is also used as restraint. This is to test whether non-slip mats are credible in significantly restraining desk-mounted equipment.

The result for the 45-degree angle is compared with the result from the result from the non-slip mat model. A simulation of the unrestrained desk-mounted equipment is also done. The displacement and acceleration response for the three cases are graphed and analyzed.



Figure 7. (a) Position-time and (b) Acceleration-time History Plots for the Desk-mounted Equipment.

From Figure 7, it can be deduced that non-slip mat is an effective restraint for the modeled equipment. It significantly decreased the displacement of the object without inducing very large acceleration response. However, it is important to note that the equipment has a large base and is unlikely to overturn. Further test must be done to determine the applicability of non-slip mat as restraint in objects with different dimensions.

Meanwhile, the bungee cord is a better restraint because of the lower acceleration response than the non-slip mat. It is also safer to use such restraint because it is attached to the equipment unlike the non-slip mat that is dependent only on friction.

The bungee elastic cord and non-slip mat is also tested for a 5.5 kg ECG Machine. Results show that the smallest diameter of the cord that is effective is 6 mm (1/4"). The non-slip mat is ineffective for the ECG machine. The equipment has a height to width ratio equal to 1.12 during the simulation for the application of the non-slip mat, the ECG machine slid, overturned and then fell to the ground.

3.3 Freely Standing

3.3.1 Mechanical Ventilator

The whole ventilator weighs 28 kg. The dimensions of the equipment are $0.52m \ge 0.62m \ge 1.68m$. The diameter of the accessory cord used as restraint is 4 mm (5/32").

Two models are done for this equipment. In the first model, the equipment is anchored at its center of gravity (0.82 m from the ground). In the second model, it is anchored on two points: 0.3 m above and 0.6 m below the center of gravity. Also in this model, a soft material is added at the back of the monitor to minimize the impact between the equipment and the wall. The impact factor is assumed to be 0.25 which is 50% of the default impact factor of concrete.



Figure 8. Design of Restraints for Mechanical Ventilator



Figure 9. Position-time history plots for Mechanical Ventilator

 Table 1. Average Acceleration – Model Relationship for Mechanical Ventilator

Model	Average Acceleration (m/s ²)		
	Х	Y	Ζ
Model 1	5.54	2.58	3.84
Model 2	4.49	2.08	3.95

It is observed from Figure 9 and Table 1 that both ways of restraining the mechanical ventilator are effective. However, the soft material is a necessity as the monitor bumps on the wall often times during the earthquake simulation. Also, model 2 is better, though it will cost more, because of the relatively smaller lower acceleration response when it is used. Also note that the accessory cord used for restraining this equipment has a 4-mm diameter only. The accessory cord proves to be a strong cord that can be used for many more freely standing equipment.

4. CONCLUDING REMARKS

This study analysed earthquake response of typical non-structural components found in emergency rooms, intensive care units and/or operating rooms of a hospital. The method utilizing rigid bodies subjected to inertial forces due to earthquake was used to model wheel-movable, free-standing and desk-mounted equipment and restraints were designed to minimize, if not eliminate, rolling, sliding and overturning.

Experiments have shown that non-slip mats are effective in restraining equipment that is unlikely to overturn (height/width ≤ 1.0 , regardless of weight) such as the defibrillator (h/w = 0.309). The bungee cord, on the other hand is a better restraint because of the resulting lower risk due to lower acceleration response of the equipment. The minimum diameter of the bungee cord that is recommended to be used for the 5-kg desk-mounted equipment and the ECG model is $\frac{1}{4}$ ". The bungee cord is made 30% shorter than the required length for the purpose of pretension to hold the equipment in place. The optimal orientation of the bungee cord is 45° for restraining desk-mounted equipment.

For heavy equipment, like the 175-kg medical cabinet used in this paper, it is suggested that bolts be used as fasteners. Bolts may also be used for bedside table by restraining its hind legs. A 4-mm accessory cord also proved to be strong enough to restrain other heavy equipment such as a mechanical ventilator and phaco machine.

Moreover, this study recommends that soft materials be attached to the equipment at points of possible collision with the wall. This is to prevent further damage on the equipment and reduce large displacement that may cause harm to other equipment or cause injuries to people.

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