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# Seismic retrofit and shaking table test of medical equipment in a hospital

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**ABSTRACT:** Due to the variety in the categorization of nonstructural components and medical equipment in a hospital, before embarking on seismic design, the critical and/or vulnerable nonstructural items should be identified and prioritized. In this study, consulting with the constructors and hospital facility managers, the procedures and accompanied tools including the screening criteria, simplified seismic evaluation form, design requirements and appropriate seismic restraints are proposed and recommended for the nonstructural components and equipment in a hospital. Furthermore, some critical and vulnerable medical equipment items were chosen for shaking table tests to verify the application of proposed simplified evaluation forms and recommended seismic restraints. Based on the modeled specimens of medical equipment, the test results revealed that restraint devices actually contribute to decrease displacement response, but it increases acceleration response of the equipment due to the impact effect. Besides, damages of adhesive layer between restraint devices and equipment or anchors at partition wall appeared under larger earthquakes. Based on the test results, the simplified evaluation form and seismic restraints were modified to be applicable for free-standing medical equipment, and further, the pull-out strength of partition wall and the adhesive strength of non-destructive devices were taken for the next research subjects for seismic design of medical equipment.

## 1 INTRODUCTION

Due to the interruption of traffic after earthquakes, it is necessary that medical equipment and medicine supplies of a hospital within the affected area should be self-sufficient for at least 72 hours. However, from the experiences of the Hanshin-Awaji earthquake in Japan (1995) and the Chi-Chi Earthquake in Taiwan (1999), medical equipment (e.g. medicine cabinets and X-ray machines) was damaged seriously, and hence it resulted to significant shortage of emergency medical capacities of hospitals. Currently, the Department of Health (DOH) in Taiwan has completed the simplified evaluation of seismic capacity, electrical and mechanical systems of DOH hospitals, but the specific seismic capacity of medical equipment has not yet been considered. For large hospitals, a lot of medical equipment is attached to different types of structures with miscellaneous attachment types. Therefore, both the efficiency and accuracy should be considered for the simplified evaluation of seismic capacity and simplified seismic design of medical equipment.

In this study, undertaken in cooperation with a large hospital (hereinafter referred to as N Hospital), an installation manual for nonstructural components in a hospital was developed and practical suggestions proposed for its integration with the construction plan to promote the seismic performance of nonstructural components in a new hospital building (under construction). The first step in this study is to define the selection criteria to identify the critical and seismic vulnerable nonstructural components, and then define the installation types to meet the operational requirement. The seismic vulnerability and associated seismic demand can be determined using developed simplified seismic evaluation and design programs, and further, the design parameters for anchors and some non-destructive seismic restraint devices can be calculated directly by the programs. In addition to the traditional attachments, auxiliary non-destructive seismic restraint devices were also proposed for general nonstructural components. Furthermore, some critical and vulnerable medical equipment items were chosen for shaking table tests to verify the application of proposed simplified evaluation and design forms as well as the recommended seismic restraints.

## 2 CRITICAL AND SEISMIC VULNERABLE MEDICAL EQUIPMENT

For the financial ability and efficiency, the first step is to identify the critical and seismic vulnerable items, which should be designed and installed under the consideration of seismic effect, from the numerous nonstructural components in a hospital. The critical medical spaces and the supporting mechanical and electrical systems should be selected first. According to SB 1953 (2001) and the survey questionnaire answered by head nurses and facility managers of the N Hospital, the critical medical spaces in the N Hospital included the Emergency room, Pharmacy, PET (Positron Emission Tomography) center, Haemodialysis room, Operating room, Dept. of nuclear medicine, Dept. of radiology, Dept. of radiation oncology, and Dept. of anaesthesiology.

Then, the architectural components and critical medical equipment for performance levels of life safety and operational activities in the critical medical spaces should be identified. The critical medical equipment items with higher vulnerability during earthquakes were chosen from the results of questionnaires and from criterion stated in ASCE7-05 (2005). In this study, a simplified evaluation form was established using MS Excel software to determine the seismic performance of any selected nonstructural items in the critical medical spaces. Users can get the evaluation results by inputting the characteristic parameters of the selected nonstructural components. The installation for items identified as 'seismic evaluation required' should be considered under the seismic effect. Figure 1 shows the identified nonstructural items to be installed under seismic consideration.

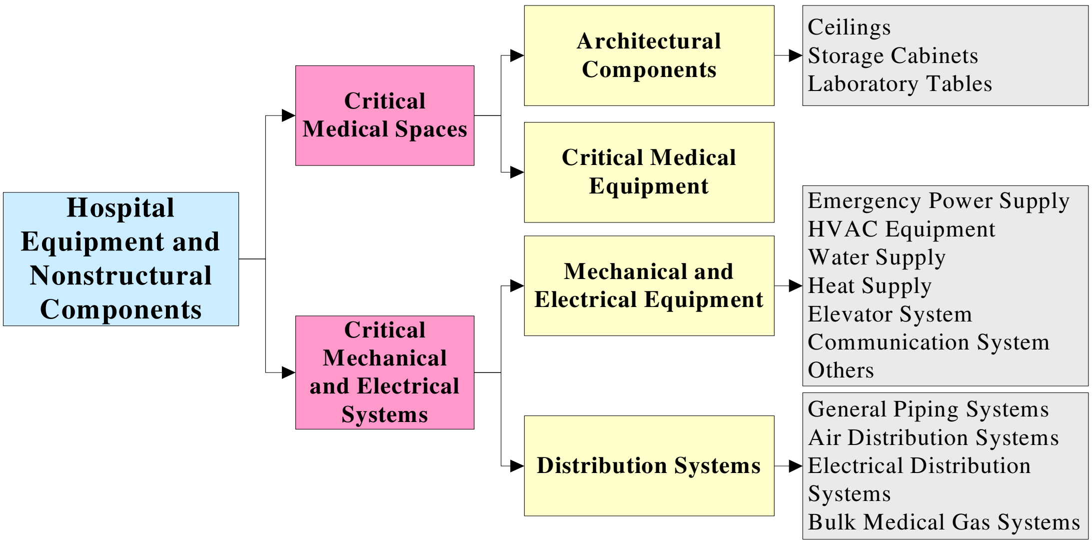



Figure 1: Identified nonstructural items to be installed under seismic consideration

## 3 SIMPLIFIED SEISMIC DESIGN PROGRAMS

In general, the installation types for nonstructural items are considered to meet the operational requirement. For seismic consideration, it is required to improve the seismic capacity of installation devices for nonstructural components, and meanwhile not obstruct the functionality of nonstructural components and equipment. The seismic restraint devices for general nonstructural components can be divided into four categories according to different installation types, as shown in Fig. 2, where the component can be rigidly mounted, vibration isolated, suspended or classified as portable ones.

Based on the *Seismic Design Code for Buildings* in Taiwan (2005) and other references, the seismic demand on attachments of nonstructural components and medical equipment can be automatically calculated by MS Excel software. In addition, as shown in Table 1, a simplified seismic design form for post-installed anchorage was presented according to ACI 318-02 (2002). Based on the determined design parameters (e.g. number of anchors at each support, anchor size, and embedded depth), the attachments of equipment can be designed to satisfy the specified seismic demands. However, the support of medical equipment may not be designed with bolt holes in advance and it may be impractical to drill holes in the shell of equipment. In this situation, additional non-destructive seismic restraint devices should be considered, and hence simplified seismic design forms for such devices for medical equipment were presented in this study. One example for the Z-shape stopper is illustrated in Table 2.

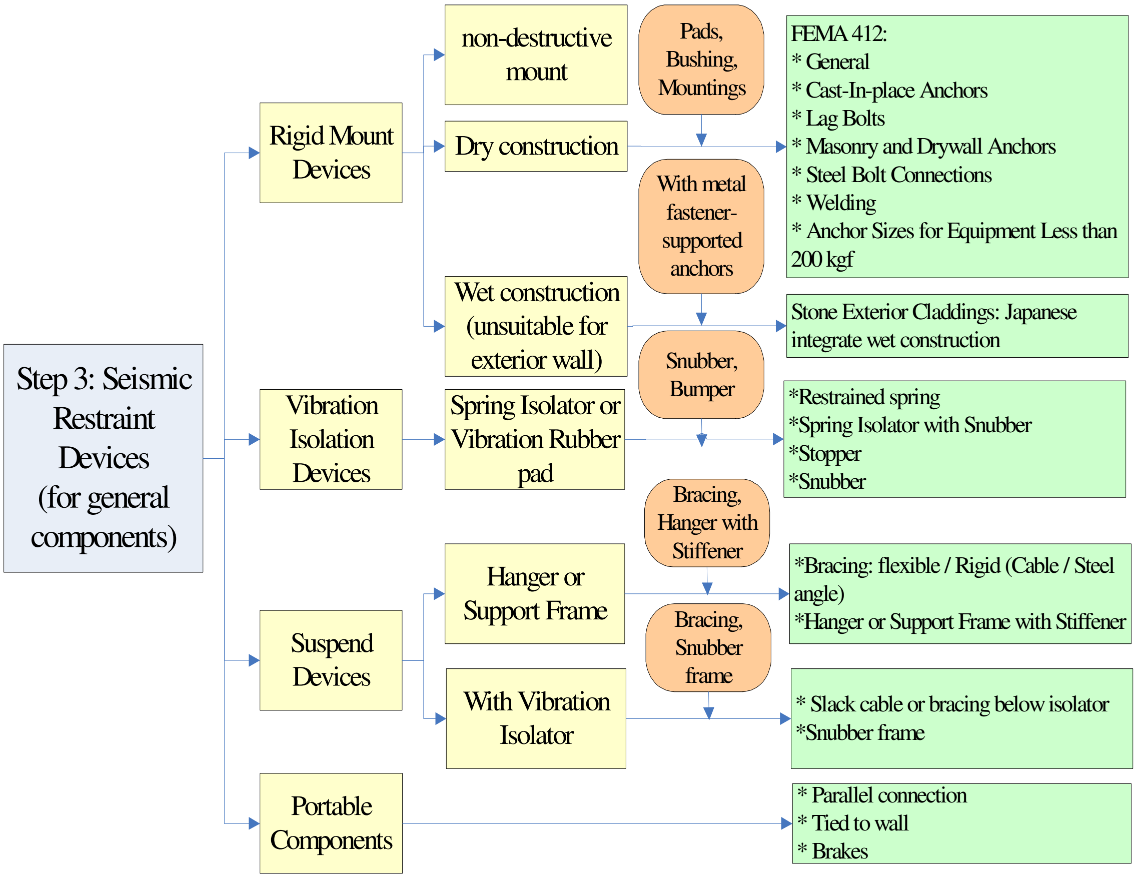



Figure 2: Seismic restraint devices for general nonstructural components

## 4 PULL-OUT AND SHAKING TABLE TESTS

Based on the survey questionnaires and simplified evaluation for medical equipment at each critical medical space in the N Hospital, all medical equipment can be classified into three categories according to its type of attachment, namely, freestanding items (e.g. safety cabinet), wheel movable items (e.g. medical trolley, micro-selectron, pharmaceutical refrigerator, mass infuser, hyperbaric oxygen capsule, dialysis machine), and desktop items (e.g. gamma counter). Meanwhile, more vulnerable medical equipment in each category was subjected to shaking table tests. In this study, as summarised in Table 3, Z-shape stoppers and some auxiliary non-destructive seismic restraint devices, such as brakes and adhesive belts (such as Thumb Lock), were proposed and designed for equipment according to its daily use. In addition, the tensile strength of adhesive and clasp belts were confirmed by pull-out tests as shown in Fig. 3. The test results show that most damages occurred at the adhesive layer between restraint devices and equipment or at the anchors on partition wall.

Because of the extremely high price of medical equipment, it was modelled by square pipe and steel plate for the shaking table test, except medical trolley, mass infuser and electrical stimulator.

According to the *in situ* survey, the size, weight and support types of test specimens were actually modelled from the prototype of medical equipment. The modelled specimens for the other selected medical equipment are illustrated in Fig. 4.

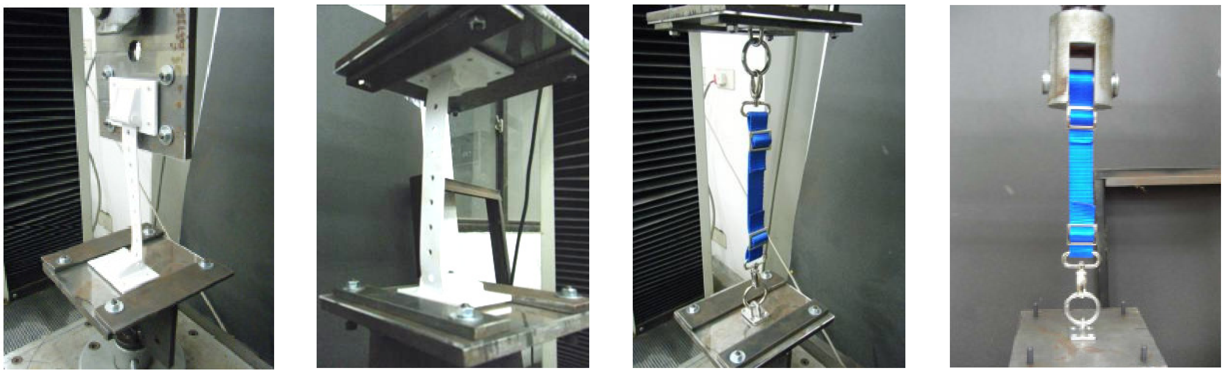


Figure 3: Tensile tests for Thumb Lock and clasp belts

(a) gamma counter

(b) hyperbaric oxygen capsule

(c) micro-selectron

(d) pharmaceutical refrigerator

(e) dialysis machine

(f) safety cabinet

Figure 4: experimental specimen for the selected medical equipment for shaking table tests

The input excitation that is compatible with the Required Response Spectrum (RRS) as specified by AC-156can be determined from the time histories of floor response acceleration at ChiaYi Potz Hospital in Chi-Chi Earthquake. The amplitude of input time histories was scaled linearly to the design earthquake with PGA of 0.32g. The N Hospital is a 10-story building, and most of critical medical equipment is located from B1F to 3F, therefore, the RRS for shaking table tests were classified into two groups with z/h=0 and 1/3, respectively, according to their location. The time histories of the input excitation as well as the comparison between RRS and TRS for the case of z/h=1/3 is illustrated in Fig. 5.

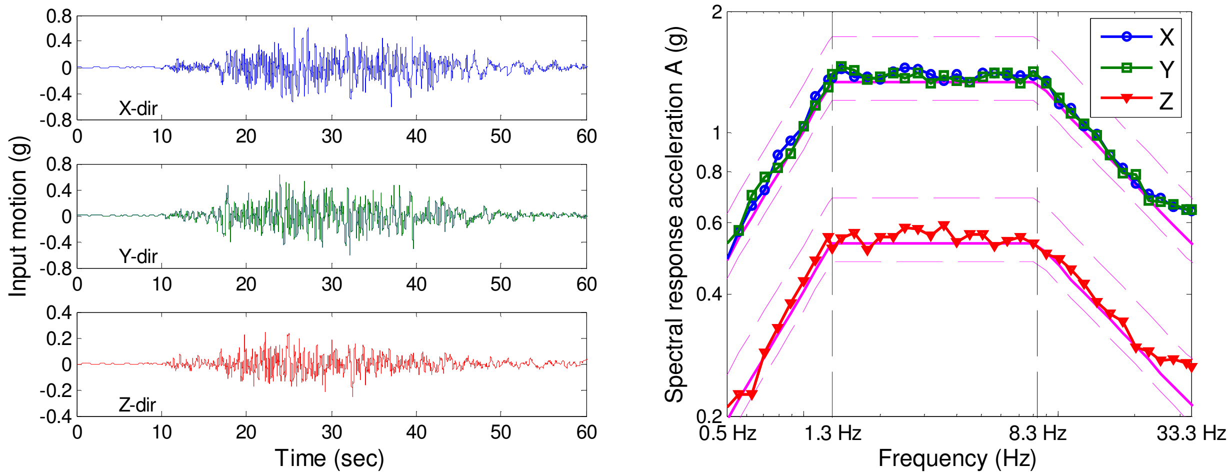


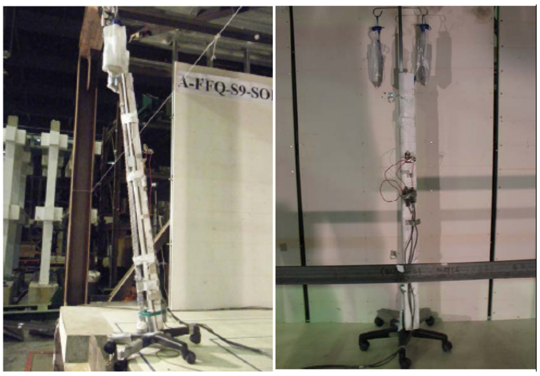

Figure 5: Time histories of input excitation and the comparison between RRS and TRS (z/h=1/3)

For the equipment items without seismic restraint devices, most responses in shaking table tests were quite consistent with the response identified by the simplified evaluation form (i.e. fixed well, rocking, sliding or overturning). The general observation for the shaking table test is illustrated in Fig. 6. Based on the test results, it can be observed that seismic restraint devices efficiently decreased displacement responses and possibilities of overturning or bumping with other items. However, restraint devices would inevitably increase the acceleration responses of equipment items. Take dialysis machine and mass infuser as examples, as shown in Fig. 7, Thumb Lock or belt devices can decrease the amount of sliding displacement, but result in a sharp increase of response acceleration because of the impact force. To reduce impact force and to avoid resonance of internal components in medical equipment, using ductile restraint devices or adding energy-dissipating devices (such as rubber pads) are suggested. In addition, the fundamental frequencies of medical equipment with restraint become generally higher than those without any restraint (Fig. 8).

## 5 CONCLUSIONS

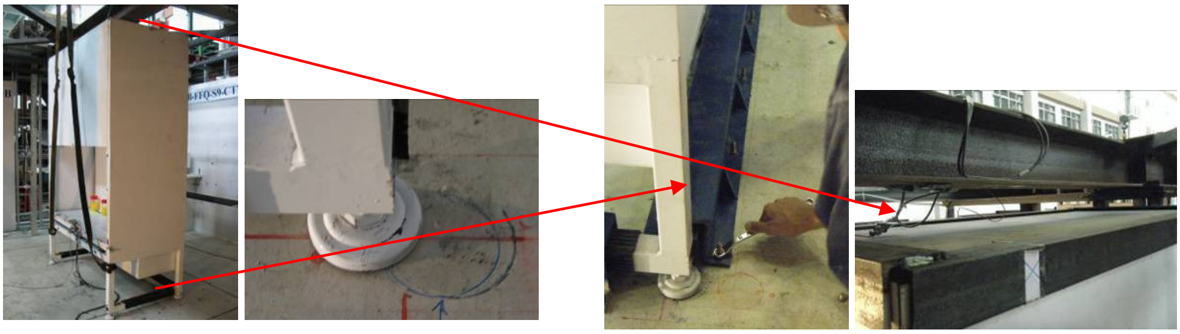
In cooperation with the N Hospital, the survey questionnaire for the critical categories of medical equipment after a catastrophic earthquake was answered by head nurses. Basic features of critical medical equipment in nine medical spaces in the N Hospital were identified, and could be classified into three attachment types, i.e. wheel movable, freestanding, and desktop ones. Vulnerable items among the critical equipment were then identified by simplified evaluation forms. The simplified design forms were presented for non-destructive seismic restraint devices as well.

According to the results of questionnaires and simplified evaluation forms, nine vulnerable medical equipment items were chosen for shaking table tests. Non-destructive seismic-restraint devices were also proposed for each equipment item. Test results revealed that restraint devices actually contribute to decrease displacement response, but also increases acceleration response of the equipment. Besides, damage of the adhesive layer between restraint devices and equipment, and anchors into partition walls, appeared under larger earthquakes. Therefore, the pull-out strength of anchors in partition walls, and the adhesive strength of non-destructive devices, might be the next research subjects for seismic design of medical equipment.



(a) mass infuser: free standing (left) and fixed on floor (right)

(b) pharmaceutical refrigerator: free standing (left, with resulted sliding) and fixed on floor (right, no sliding)



(c) sliding response of safety cabinet without any seismic restraint

(d) proposed seismic restraint device for safety cabinet: stoppers on both bottom (left) and top (right)

(e) failure of Thumb Lock: pull out of expansion anchor (left, for micro-selectron), loosen belt (middle, for micro-selectron), and failure of adhesive layer attached on the table (right, for gamma counter)

(f) failure of clasp belts: pull out of expansion anchor (left, for dialysis machine), loosen belt (middle), and failure of adhesive layer (right)

Figure 6: Observation of the shaking table tests

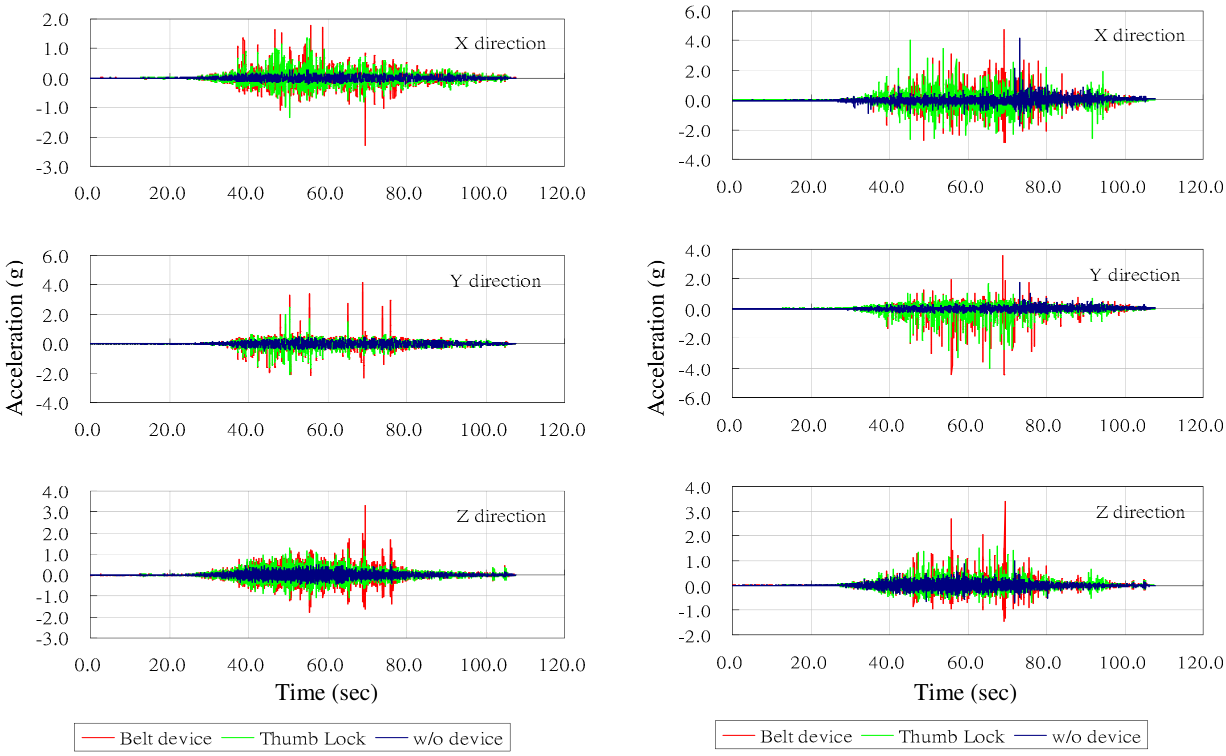



Figure 7: Acceleration Responses of Dialysis machine (left) and Mass Infuser (right)

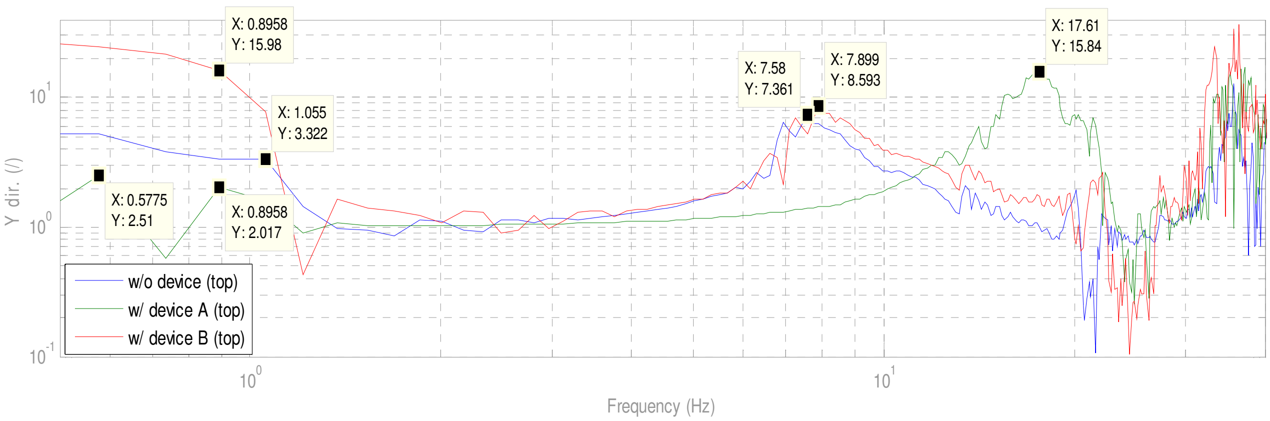



Figure 8: Transfer functions at top of Safety Cabinet

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ACI 318-02: Building Code Requirements for Structural Concrete, American Concrete Institute, Detroit, 2002.

ASCE7-05: Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Reston, VA., 2005.

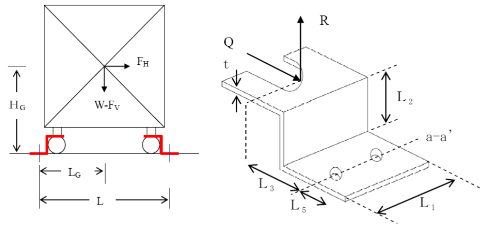
SB 1953 Regulations, Title 24, Part 1, California Building Standards Administrative Code, Chapter 6, OSHPD, 2001.

Seismic Design Code and Commentary for Buildings, 2005 Edition, Construction and Planning Agency, Ministry of Interior Affair, Taipei, Taiwan (in Chinese), 2005.

**Table 1: Simplified seismic design form for anchorage**

| No. | | 03 | 05 |
|---|---|---|---|
| Equipment Name | | Safety Cabinet | Refrigerator |
| Evaluate Results | Y: seismic design required; N: not required | Y | Y |
| | Response of equipment | Rocking | Rocking |
| Horizontal seismic force (kgf) | | 166.3 | 216.0 |
| Vertical seismic force (kgf) | | 83.2 | 108.0 |
| Number of total attachments | | 3 | 2 |
| Number of attachments at short side | | 1 | 1 |
| Number of anchor bolts at one attachment | | 2 | 3 |
| Spacing of anchor bolts at one attachment (inch) | | 5 | 2 |
| Size of anchor bolt (M8, M10 …) | | M8 | M8 |
| Embedded depth of anchor bolt (inch) | | 2 | 2 |
| Concrete strength $f'_c$ (psi) | | 2000 | 2000 |
| Maximum shear force at one attachment (kgf) | | 55.44 | 108 |
| Maximum tensile force at one attachment (kgf) | | 139.8 | 276.8 |
| Maximum normal force at one attachment (kgf) | | 523.7 | 462.9 |
| $(V/V_a)^{5/3}+(N/N_a)^{5/3}$ | | 0.4 | 0.63 |
| Seismic capacity of attachment | | OK | OK |

**Table 2: Seismic design form of non-destructive seismic restraint devices (Z-shape stopper)**




| No. | | 03 | 05 |
|---|---|---|---|
| Equipment Name | | Safety Cabinet | Refrigerator |
| Width L1 (cm) | | 130 | 125 |
| Height L2 (cm) | | 12 | 15 |
| Distance L3 (cm) | | 7 | 6 |
| Distance L5 (cm) | | 2.5 | 4 |
| Height of mass center: $H_G$ (cm) | | 350 | 106 |
| Distance $L_G$ at short side (cm) | | 38 | 38 |
| Distance L at short side (cm) | | 76.5 | 77 |
| Allowable bending stress of stopper ($kgf/cm^2$) | | 2400 | 2400 |
| Size of anchor bolt (M8, M10,…) | | M8 | M8 |
| Thickness of stopper plate (cm) | | 0.15 | 0.19 |
| Tensile force for each bolt (kgf) | | 265.6 | 230.6 |
| Tensile force for each bolt (kgf) | | 27.7 | 36.0 |
| $(V/V_a)^{5/3}+(N/N_a)^{5/3}$ | | 1.00 | 0.41 |
| Seismic capacity of attachment | | OK | OK |
| Design results | Thickness of plate (cm) | 0.2 | 0.2 |
| | Bolt / embedded depth | M8/ 2in. | M8/ 2 in. |

**Table 3: Proposed seismic restraint devices for the medical equipment**

| Medical Equipment | Bearing | seismic restraint devices A | seismic restraint devices B |
|---|---|---|---|
| safety cabinet | adjustable glides | top/bottom stoppers | bottom stoppers |
| pharmaceutical refrigerator | iron casters | against the wall / Thumb Lock | against the wall |
| medical trolley supporting defibrillator | rubber casters | diagonal braking trolley/ defibrillator restrained by Thumb Lock | diagonal braking trolley / defibrillator restrained by plastic clasps and cable |
| micro-selectron | medical equipment casters | against the wall / Thumb Lock | Braking casters |
| mass infuser | hooded ball casters | Thumb Lock | alternative devices (metal clasps and cable) |
| dialysis machine | hooded ball casters | Thumb Lock | alternative devices (metal clasps and cable) |
| gamma counter | rubber glides | Thumb Lock | angles and rubber pads |