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# PERFORMANCE OF OFC'S IN EARTHQUAKES BY SHAKE TABLE TESTS

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## SUMMARY

Operational and Functional Components (OFC) are those elements in a building that are required for its normal function and operation. In recent earthquakes it has become clear that, in addition to the safety related aspects of the seismic performance of OFCs, the economic impact of the poor or marginal performance of these components can be very severe. A variety of shake table tests of different types of OFCs have been conducted at the University of British Columbia during the last six years. The most significant effort was a series of forty-nine shake table tests to determine the seismic performance of OFCs typically found in office environments. Examples of the OFCs tested include: bookshelves, file cabinets, a photocopier, fully furnished office work stations, communication racks, LAN rack, motor control centre, equipment seismic isolation and restraining systems, and other office equipment. Some of the OFC were tested with different dead load distributions, as it may is expected in usual office environments. The purpose of this paper is to present a summary of the shake table tests conducted and discuss the relevant results.

## INTRODUCTION

This paper describes the results from a series of shake table tests conducted on various Operational and Functional Components (OFC) of buildings. The purpose of these tests was to evaluate the performance and functionality of these OFC during severe shaking from simulated earthquakes. The objective of these tests was to determine how commercially available office equipment and other OFC would perform during different levels of strong shaking due to earthquakes. In order to evaluate this performance, the effects of combined bidirectional (vertical and horizontal) ground shaking on OFCs were investigated. Another objective of the testing project was to investigate the effectiveness of various restraining and base-isolating techniques for protecting office equipment in the event of an earthquake.

This study includes results from detailed analyses of the data collected during all shake table tests conducted. The information contained in this paper includes: a) results of analyses of recorded motions at different locations of the OFCs, b) frequency domain analysis of records to determine modal frequencies, amplification factors and damping estimates, and c) comparative studies of responses of various components.

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The tests were conducted by placing or anchoring the equipment (or **Test Articles**) on a shake table and subjecting them to prescribed excitations. The OFC were tested either separately or mounted to a rigid wall assembly. Because of the dimensions of the shake table and those of some OFCs, such as the work stations, it was not possible to test large assemblies of these components, and it was only possible to test single units. A workstation may be interconnected or attached to another workstation or other piece of office furniture so that the response of the whole assembly to strong shaking may differ from the response of a single unit. It can be assumed that testing of a single work station represents more severe conditions than testing a whole assembly, and the lateral forces acting on the restrainers of the unit can be expected to be larger than those acting on the restrainer of a multi-unit assembly. The shaking of the shake table during the tests was limited to two directions: East/West (EW) horizontal and vertical motions. Shaking in the other horizontal component or due to rotations of the shake table was simulated.

These studies were part of a collaborative research between Public Works and Government Services Canada (PWGSC) and the Earthquake Engineering and Structural Dynamics Research Laboratory (EQ Lab) of the Department of Civil Engineering at the University of British Columbia (UBC).

## OVERVIEW OF TESTS

A detailed work plan was developed jointly by UBC and PWGSC at the beginning of the testing project. The work plan included the selection of qualified personnel; facilities and equipment, the number of shake table tests to be performed, the selection of the location of measuring instruments and data acquisition parameters, and the determination of proper ways of documenting each test. Many common office equipments and various equipment seismic isolation and restraining systems were tested. Some of the OFC were tested with different arrangements of dead load that may be expected in an office environment. Other OFC were tested unrestrained, as well as, restrained using restrainers from different manufacturers.

### Description of Testing Facility

The earthquake motion simulations were performed with the shake-table at UBC's EQ Lab. The laboratory provides space for construction, assembly, and handling of relatively large structural models and heavy equipment. The shake table is controlled by a state-of-the-art Signal Processing Subsystem, driven by a Replication Multi-shaker Control Software, which is capable of replicating recorded earthquake shaking and other types of motions. The shake table is a 3 m (10 ft) by 3 m (10 ft) cellular structure made of aluminum, has a payload capacity of 156 kN (35,000 lb). The hydraulic actuator, used to produce motion in the East/West direction, can generate up to 156 kN (35,000 lb) of force and a maximum peak-to-peak displacement of 15.24 cm (6 inches). The other four actuators can produce motions in the vertical direction, each generating 89 kN (20,000 lb) of force.

### Description of Test Articles

The test articles were common office equipment, such as file cabinets, bookshelves, LAN racks, communication racks, library shelves, and photocopiers. Table 1 shows the dimension and supplier of the test articles included in the testing project.

**Table 1. Description of Test Articles**

| Test article | Height | Width | Length | Supplier and Location |
|---|---|---|---|---|
| **File cabinet** | 83" | 18" | 36" | PWGSC |
| **File cabinet** | 62" | 18" | 36" | PWGSC |
| **Book Shelf** | 72" | 12" | 33" | PWGSC |
| **Book Shelf** | 47" | 12" | 36" | PWGSC |
| **LAN rack** | 33" | 64" | 90" | Sustema Inc. of St. Laurent, Quebec |
| **Communication rack** | 24" | 31" | 85" | WCB in conjunction with Counter Quake Service Inc. of Victoria, B.C. |
| **Motor control centre** | 40" | 20" | 91.5" | Square D Company of Monroe, North Carolina. |
| **Seismic isolation platform** | 39" | 47" | | Tekton Inc. of Tempe, Arizona |
| **Seismic isolation platform (with caster base)** | | | | Tekton Inc. of Tempe, Arizona |
| **76" library shelving (5 level)** | 36" | 18" | 76" | Hi-Cube Storage Products |
| **66" library shelving (2 side shelving)** | 36" | 26" | 66" | Hi-Cube Storage Products |
| **Photocopier (on wheels)** | 48" | 30" | 48" | WCB in conjunction with Counter Quake Service Inc. of Victoria, B.C. |
| **Light fixture (12, 14 &16 gauge wires)** | | | | Canem West Services Incorporated in conjunction with M. Wang Engineering of Vancouver, B.C. |
| **Caster cups** | | | | M. Wang Engineering of Vancouver, B.C. |
| **Fastening devices** | | | | WorkSafe Technologies of Valencia, California. |
| **Fastening equipment** | | | | Terra Firm, Earthquake Preparedness Inc. of Vancouver, B.C. |

## DESCRIPTION OF INPUT MOTIONS

The driving signals for the shake table were developed using recorded accelerograms from past earthquakes and artificially generated waveform. To simulate two directions of ground shaking, horizontal and vertical, the shake table driving signals were developed in pairs, representing two of the three motions measured at a recording station. The pairs were used to develop sets of driving signals, which were identified as records A1 to A9. Table 2 includes information about the records, their site of origin, magnitude, year of earthquake and location were the measurement was made.

The driving signals for the shake table were developed from the accelerograms by conditioning these motions (high-pass filtering and amplification of the signals). The high-pass filter was needed to ensure that the associated displacement did not exceed the stroke of the actuators, and amplification was used to match the peak acceleration of the filtered signal with that of the original records. A comparison of response spectra plots for the horizontal and vertical components indicated that the shake table was able to reproduce the same demands as the original ground motions at frequencies above 1 Hz for the horizontal motions, and at frequencies above 4 Hz for vertical motions. A comparison of response spectra plots for the vertical components indicated that the shake table spectra were mostly of the same shape but of lower spectral intensities than those for the original records, especially for frequencies below 4 Hz.

**Table 2. Description of Input Motions**

| Driving Signal | Recorded Site / Developer Origin | Earthquake Name | Year | Magnitude | Sensor Location and Horizontal Component | Sensor Location and Vertical Component |
|---|---|---|---|---|---|---|
| **A1** | 6 storey Sylmar County Hospital record | California Northridge earthquake | 1994 | 6.7 | N/S direction at east wall of the fourth floor of the Hospital building | U/D direction near the east wall of the building |
| **A2** | Kobe University record | South Hyogo Prefecture (Kobe, Japan) earthquake | 1995 | 7.2 | N/S direction on the Ground | U/D direction measured at ground floor |
| **A3** | Free field record at Sylmar County Hospital | California Northridge earthquake | 1994 | 6.7 | N/S direction on the ground at a distance away from the building | U/D direction in the free field |
| **A4** | 4 storey commercial building in Watsonville, California | California Loma Prieta earthquake | 1989 | 7 | Roof from the four storey building | U/D direction inside the building |
| **A5** | 7 storey hotel building in Van Nuys, California | California Northridge earthquake | 1994 | 6.7 | Roof on east wall in the E/W direction | U/D direction inside the building |
| **A6** | 13 storey building in Sherman Oaks, California | California Northridge earthquake | 1994 | 6.7 | Ground floor in the E/W direction | U/D direction measured at ground floor |
| **A7** | The artificially generated VERTEQ waveform | Developed by Bell Communications Research, Inc. (Bellcore) | 1995 | N/A | 50% of the record for seismic zone 4 (Uniform Building Code) | U/D direction of earthquake A4 |
| **A8** | The artificially generated VERTEQ waveform | Developed by Bell Communications Research, Inc. (Bellcore) | 1995 | N/A | 100% of the record for seismic zone 4 (Uniform Building Code) | U/D direction of earthquake A5 |
| **A9** | Joshua Tree Fire Station record | California Landers earthquake | 1992 | 7.3 | Ground floor in the E/W direction | Not simulated |

## TEST SETUPS AND TESTING PROCEDURES

The tests were classified into thirteen groups or sessions. Each of these sessions had similar experimental setup and testing procedures. This included building an I-shaped drywall assembly on the shake table for placing cabinets and bookshelves, restraining file cabinet and bookshelves to the wall, setting a library shelving and video cameras (see Figure 1). Other setups such as locating the communication rack, LAN rack, seven CPUs and monitors in different locations were also included in this project (see Figures 2, 3 and 4).

Every test in a session was referenced to the earthquake used for the shake table simulation and was catalogued with a unique code. Out of thirteen sessions, Session 3 is given as an example here (see Figures 1 and 2). The setup of Session 3 was used for Test T105, in which record A1 was used.

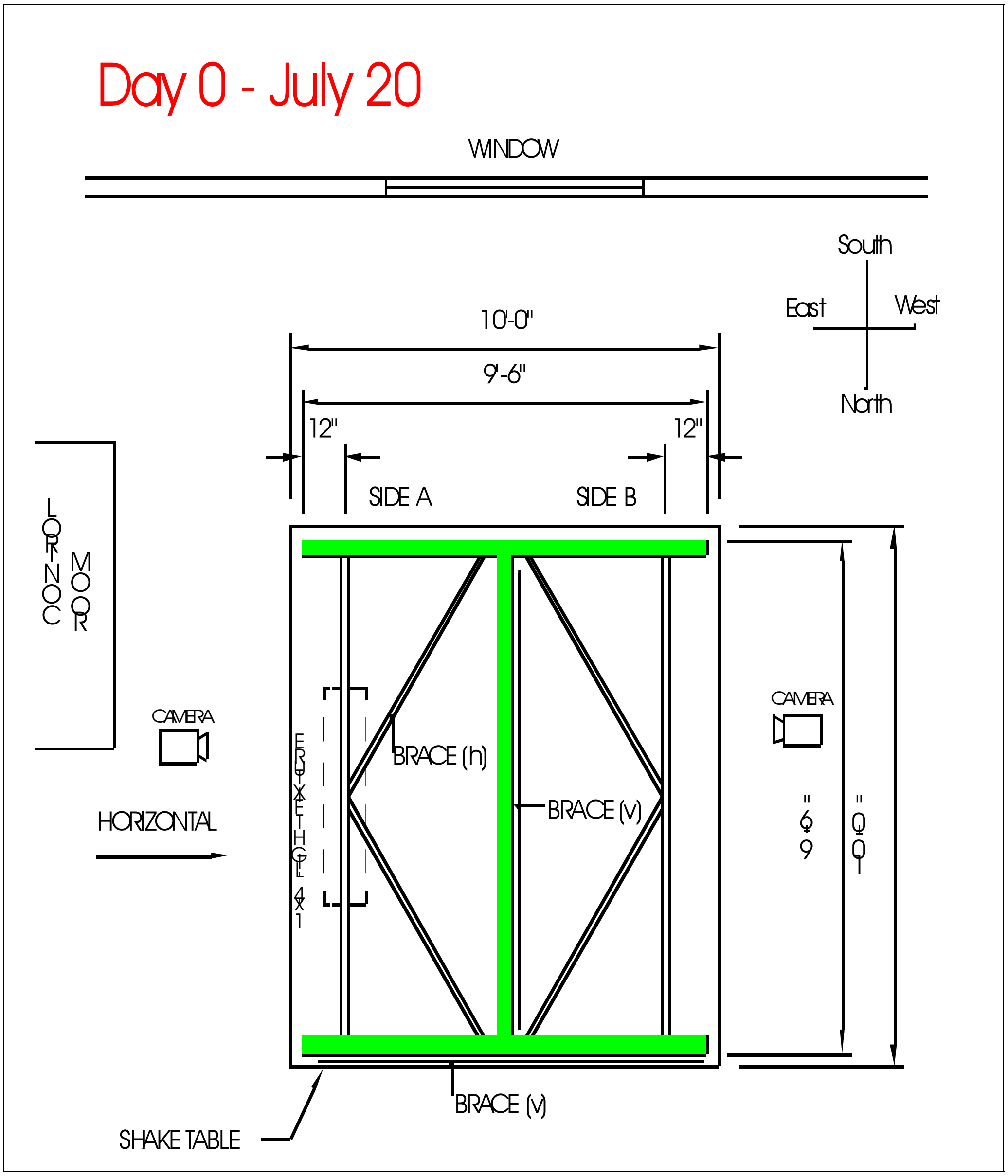


**Figure 1.** Setup of Drywalls Supporting Tested Equipment.

**Figure 2.** Large and Small Bookshelf Setup in Session 3, before test (top), and Shelving and Books Fallen from Large Bookshelf during Test T105 (bottom).

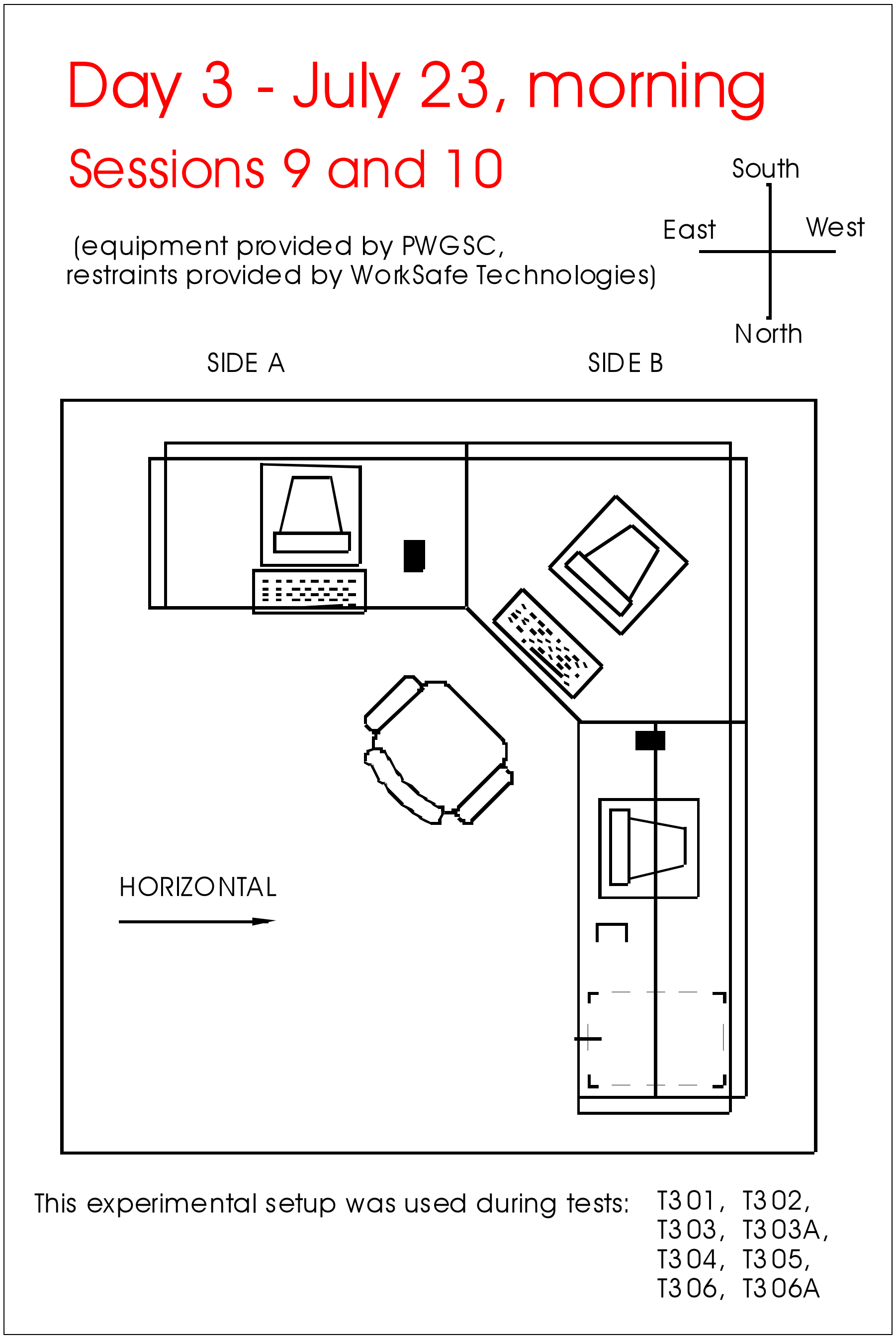


**Figure 3.** Setup of Office Cubicle and Tested Equipment for Sessions 9 and 10

**Figure 4.** Office cubicle setup for Sessions 9 and 10 before the test (top) and after the test (bottom)

For side A in Figure 1, the setup included restraining the 83x18x36 (large) file cabinet to the wall using fasteners and installing two lag to studs at the top; and restraining a 62x18x36 (small) file cabinet to the wall and installing lag studs at the top of the cabinet. A top heavy dead load was used for the file cabinets (restrained to dry wall). For side B, the setup included restraining the 72x12x33 (large) bookshelf to the wall and installing lag studs at two top locations. A 47x12x36 (small) bookshelf was restrained to the wall and shelf grip strips were used to restrain the books on the shelves. A top heavy uneven load was placed on the bookshelves (which were restrained to dry wall). Detailed descriptions of the test setup and the sessions are given in the report by Horyna et al. [1]. This report, and a companion report by Ventura [2] include detailed analyses of the data gathered during the tests and detailed analyses of the performance of the tested components.

## TEST RESULTS

In this project, a total of 49 shake table tests were conducted. The OFCs were tested unrestrained as well as restrained using various motion restrainers. In this study, damage to electronic equipment, such as CPU's or monitors did not imply that the equipment had lost its functionality. It only meant that the electronic equipment sustained severe impact or that its casting was damaged after the fall.

### Data analysis results from Shake Table tests

Tables 3.a and 3.b show the response values for each of the test articles considered in this investigation. These tables include peak values of acceleration and displacements of the shake table, as well as of the test articles. The peak values of response were obtained from the detailed analyses of records. The most important columns of this table are those for the results of the Dynamic Amplification Factors for acceleration and displacement, since they indicate the degree of amplification, or de-amplification, of the shake table motion transmitted to the test article. The results show how sensitive is each test article to either base acceleration or to base displacement, and help to better understand which test articles are acceleration-sensitive or displacement-sensitive.

### Results of Analysis of Selected Records

Tables 4.a and 4.b include general comments and observations made about selected sets of results. The comments refer to the information presented in the previous section.

# Table 3a. Data Analysis Results from Shake Table Tests

| Test Information | | | | Shake Table Motions | | | Test Article Motions | | | | | Dynamic Amplification Factors | | | Frequency Domain Analysis | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Code | Test Article Description | Test Name | Earthquake Record | PTD (cm) | PTA (g) | PTVf (cm/s) | PAD (cm) | PAA (g) | PAAf (g) | PAVf (cm/sec) | PArDf (cm) | DAFd | DAFa | Comments | Freq. (Hz) | FRF amplitude | Damping (%) |
| 1 | Large File Cabinet | T103 | A1 | 6.02 | 1.11 | 64.56 | 11.20 | NM | 4.81 | 129.18 | 15.60 | 1.9 | 4.3 | Large bookshelves turned over, small is fine. File cabinet has no damage | 6.66 | 0.46 | 3.42 |
| 2 | Small File Cabinet | T103 | A1 | 6.02 | 1.11 | 64.56 | 12.30 | NM | 4.60 | 112.30 | 9.66 | 2.0 | 4.1 | | 23.19 | 3.46 | 0.45 |
| 3 | Large File Cabinet | T104 | A2 | 5.05 | 1.04 | 52.24 | 7.73 | NM | 5.12 | 137.74 | 9.76 | 1.5 | 4.9 | Large bookshelves turned over. Other equipment has no damage. Test was cut short due to the shake table safety shut off | 16.67 | 1.32 | 0.67 |
| 4 | Small File Cabinet | T104 | A2 | 5.05 | 1.04 | 52.24 | 5.71 | NM | 4.66 | 120.38 | 4.78 | 1.1 | 4.5 | | 10.16 | 2.38 | 1.60 |
| 5 | Large File Cabinet | T105 | A1 | 6.03 | 1.10 | 64.56 | 0.94 | NM | 1.39 | 25.50 | 5.61 | 0.2 | 1.3 | Books and shelves of the large bookshelf fell out. No other damage. | 18.73 | 2.62 | 0.55 |
| 6 | Small File Cabinet | T105 | A1 | 6.03 | 1.10 | 64.56 | 0.37 | NM | 0.64 | 13.99 | 5.87 | 0.1 | 0.6 | | 19.37 | 5.34 | 0.54 |
| 7 | Large Book Shelf | T105 | A1 | 6.03 | 1.10 | 64.56 | 0.50 | NM | 1.67 | 17.93 | 6.02 | 0.1 | 1.5 | | 3.49 | 4.42 | 3.60 |
| 8 | Small Book Shelf | T105 | A1 | 6.03 | 1.10 | 64.56 | 0.22 | NM | 0.36 | 4.89 | 6.00 | 0.0 | 0.3 | | 13.66 | 9.44 | 0.79 |
| 9 | Large File Cabinet | T106 | A2 | 6.48 | 1.00 | 52.60 | 0.67 | NM | 1.16 | 19.83 | 6.16 | 0.1 | 1.2 | Shelves without books of the large bookshelf fell out. No other damage. | 17.55 | 4.24 | 1.06 |
| 10 | Small File Cabinet | T106 | A2 | 6.48 | 1.00 | 52.60 | 0.20 | NM | 0.74 | 9.93 | 6.22 | 0.0 | 0.7 | | 7.38 | 6.70 | 1.72 |
| 11 | Large Book Shelf | T106 | A2 | 6.48 | 1.00 | 52.60 | 0.46 | NM | 0.91 | 16.60 | 6.37 | 0.1 | 0.9 | | 17.79 | 4.34 | 1.34 |
| 12 | Small Book Shelf | T106 | A2 | 6.48 | 1.00 | 52.60 | 0.16 | NM | 0.35 | 5.29 | 6.25 | 0.0 | 0.4 | | 9.69 | 22.06 | 1.19 |
| 13 | Large File Cabinet | T107 | A1 | 6.04 | 1.10 | 64.42 | 0.78 | NM | 1.12 | 29.57 | 5.48 | 0.1 | 1.0 | No damage observed. | 18.66 | 3.08 | 0.66 |
| 14 | Small File Cabinet | T107 | A1 | 6.04 | 1.10 | 64.42 | 0.37 | NM | 0.67 | 13.37 | 5.91 | 0.1 | 0.6 | | 21.12 | 5.15 | 0.68 |
| 15 | Large Book Shelf | T107 | A1 | 6.04 | 1.10 | 64.42 | 0.43 | NM | 1.02 | 13.58 | 6.09 | 0.1 | 0.9 | | 21.04 | 3.53 | 0.60 |
| 16 | Small Book Shelf | T107 | A1 | 6.04 | 1.10 | 64.42 | 0.28 | NM | 0.46 | 6.03 | 6.02 | 0.0 | 0.4 | | 13.73 | 7.11 | 0.89 |
| 17 | Large File Cabinet | T109 | A1 | 6.03 | 1.09 | 64.39 | 4.44 | NM | 3.13 | 75.91 | 6.35 | 0.7 | 2.9 | Books from small bookshelf fell out. No damage observed. | 6.75 | 1.16 | 2.17 |
| 18 | Small File Cabinet | T109 | A1 | 6.03 | 1.09 | 64.39 | 7.88 | NM | 5.15 | 119.82 | 5.22 | 1.3 | 4.7 | | 20.09 | 0.69 | 0.70 |
| 19 | Large Book Shelf | T109 | A1 | 6.03 | 1.09 | 64.39 | 6.59 | NM | 4.81 | 115.48 | 7.89 | 1.1 | 4.4 | | 13.82 | 0.71 | 0.75 |
| 20 | Small Book Shelf | T109 | A1 | 6.03 | 1.09 | 64.39 | 0.90 | NM | 0.76 | 14.40 | 5.90 | 0.1 | 0.7 | | 6.59 | 4.28 | 1.58 |
| 21 | Large File Cabinet | T110 | A2 | 6.48 | 1.01 | 52.19 | 4.30 | NM | 3.40 | 73.28 | 5.87 | 0.7 | 3.4 | No damage observed. | 8.18 | 1.17 | 1.44 |
| 22 | Small File Cabinet | T110 | A2 | 6.48 | 1.01 | 52.19 | 5.91 | NM | 3.81 | 97.50 | 7.47 | 0.9 | 3.8 | | 14.45 | 1.68 | 0.76 |
| 23 | Large Book Shelf | T110 | A2 | 6.48 | 1.01 | 52.19 | 6.71 | NM | 3.58 | 81.85 | 10.55 | 1.0 | 3.5 | | 8.26 | 0.87 | 1.88 |
| 24 | Small Book Shelf | T110 | A2 | 6.48 | 1.01 | 52.19 | 0.87 | NM | 1.56 | 21.38 | 6.74 | 0.1 | 1.5 | | 14.37 | 3.00 | 0.79 |
| 25 | Large File Cabinet | T111 | A1 | 6.03 | 1.12 | 64.71 | 4.89 | NM | 3.41 | 104.23 | 7.83 | 0.8 | 3.0 | Books fell from both bookshelves. No other damage. | 6.59 | 0.81 | 1.85 |
| 26 | Small File Cabinet | T111 | A1 | 6.03 | 1.12 | 64.71 | 11.80 | NM | 3.89 | 100.69 | 10.11 | 2.0 | 3.5 | | 13.82 | 1.42 | 0.79 |
| 27 | Large Book Shelf | T111 | A1 | 6.03 | 1.12 | 64.71 | 1.65 | NM | 2.64 | 36.20 | 6.04 | 0.3 | 2.4 | | 2.38 | 2.74 | 6.19 |
| 28 | Small Book Shelf | T111 | A1 | 6.03 | 1.12 | 64.71 | 0.76 | NM | 1.02 | 15.95 | 6.18 | 0.1 | 0.9 | | 3.09 | 3.91 | 4.02 |
| 29 | Large File Cabinet | T112 | A2 | 6.47 | 1.02 | 52.46 | 5.15 | NM | 3.34 | 80.93 | 6.27 | 0.8 | 3.3 | One book fell off the large bookshelf. No other damage. | 15.72 | 1.18 | 1.06 |
| 30 | Small File Cabinet | T112 | A2 | 6.47 | 1.02 | 52.46 | 9.42 | NM | 4.01 | 105.48 | 7.94 | 1.5 | 3.9 | | 10.32 | 2.22 | 1.20 |
| 31 | Large Book Shelf | T112 | A2 | 6.47 | 1.02 | 52.46 | 1.01 | NM | 2.53 | 43.36 | 6.64 | 0.2 | 2.5 | | 14.45 | 2.29 | 0.77 |
| 32 | Small Book Shelf | T112 | A2 | 6.47 | 1.02 | 52.46 | 0.56 | NM | 0.95 | 15.52 | 6.45 | 0.1 | 0.9 | | 14.37 | 4.98 | 0.74 |
| 33 | Photocopier | T201 | A4 | 5.51 | 1.37 | 50.88 | NM | 0.90 | | 44.09 | 3.06 | 0.6 | 0.7 | No damage observed. | 14.29 | 1.79 | 0.95 |
| 34 | Photocopier | T202 | A3 | 5.63 | 1.06 | 53.66 | NM | 0.94 | | 54.27 | 2.97 | 0.5 | 0.9 | No damage observed. | 16.20 | 1.56 | 0.92 |
| 35 | Photocopier | T202A | A4 | 5.50 | 1.37 | 51.30 | NM | 1.32 | | 68.79 | 5.15 | 0.9 | 1.0 | No damage observed. | 14.29 | 1.09 | 0.64 |
| 36 | Large Library Shelf | T205 | A4 | 5.51 | 1.35 | 50.02 | 0.21 | NM | 0.39 | 8.12 | 5.23 | 0.0 | 0.3 | No damage observed. | 14.45 | 10.09 | 1.16 |
| 37 | Small Library Shelf | T205 | A4 | 5.51 | 1.35 | 50.02 | 5.24 | NM | 1.84 | 88.40 | 7.16 | 1.0 | 1.4 | | 17.39 | 1.56 | 0.76 |

## Table 3b. Data Analysis Results from Shake Table Tests

| Code | Test Article Description | Test Name | Earthquake Record | PTD (cm) | PTA (g) | PTVf (cm/s) | PAD (cm) | PAA (g) | PAAf (g) | PAVf (cm/sec) | PArDf (cm) | DAFd | DAFa | Comments | Freq. (Hz) | FRF amplitude | Damping (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Test Information** | | | **Shake Table Motions** | | | **Test Article Motions** | | | | | **Dynamic Amplification Factors** | | | **Frequency Domain Analysis** | | |
| 40 | Large Library Shelf | T206A | A9 | 6.49 | 0.44 | 41.75 | 7.04 | NM | 0.17 | 2.31 | 6.20 | 1.1 | 0.4 | No damage observed. | 14.29 | 5.85 | 1.88 |
| 41 | Small Library Shelf | T206A | A9 | 6.49 | 0.44 | 41.75 | 6.16 | NM | 1.89 | 68.03 | 8.60 | 0.9 | 4.3 | | 20.01 | 0.39 | 0.57 |
| 42 | Large Library Shelf | T208 | A1 | 6.04 | 1.14 | 64.40 | 3.18 | NM | 2.21 | 49.15 | 5.76 | 0.5 | 1.9 | No damage observed. | 6.67 | 1.13 | 2.36 |
| 43 | Small Library Shelf | T208 | A1 | 6.04 | 1.14 | 64.40 | 8.14 | NM | 2.63 | 108.49 | 6.75 | 1.3 | 2.3 | | 9.45 | 0.96 | 1.25 |
| 44 | Work Station | T301 | A5 | 5.85 | 0.65 | 43.92 | NM | 0.80 | | 46.12 | 6.33 | 1.1 | 1.2 | Books from the shelf fell down. Side walls of the work station partially separated. No other damage | 5.16 | 2.28 | 2.49 |
| 45 | Work Station | T302 | A2 | 7.18 | 1.19 | 58.98 | NM | 0.82 | | 68.83 | 7.16 | 1.0 | 0.7 | One leg of the stand under monitor one was bent. | 15.80 | 1.44 | 0.79 |
| 46 | Work Station | T303 | A6 | 5.41 | 1.08 | 55.91 | NM | 0.99 | | 64.76 | 5.63 | 1.0 | 0.9 | No other damage. | 14.13 | 1.86 | 0.97 |
| 47 | Work Station | T303A | A8 | 7.93 | 2.25 | 78.00 | NM | 1.38 | | 83.25 | 9.65 | 1.2 | 0.6 | Only horizontal motions were simulated. Damage includes partial collapse of stand. Position of CPU 3, 4, and work station changed. | 9.53 | 2.50 | 1.45 |
| 48 | Work Station | T304 | A5 | 5.85 | 0.64 | 43.08 | NM | 1.78 | | 50.28 | 5.26 | 0.9 | 2.8 | Damages include dislocation of monitors two and three and overturning of CPU one. | 5.68 | 1.23 | 2.57 |
| 49 | Work Station | T305 | A2 | 7.30 | 1.08 | 59.13 | NM | 1.23 | | 76.64 | 7.00 | 1.0 | 1.1 | CPU one and two overturned. Monitor one separated from its stand. | 8.18 | 1.60 | 2.43 |
| 50 | Work Station | T306 | A6 | 5.41 | 1.06 | 56.60 | NM | 3.20 | | 65.72 | 5.50 | 1.0 | 3.0 | Monitor 1 fell off the desk. Monitor 2, CPU one and two were overturned. N/W side of the work station didn't suffer significant damage. | 7.30 | 1.57 | 1.94 |
| 51 | Work Station | T306A | A8 | 7.93 | 2.23 | 76.98 | NM | 3.69 | | 79.50 | 11.05 | 1.4 | 1.7 | Damages include overturning of CPU 1, 2, monitor 2 and falling books from the shelf. | 5.40 | 1.85 | 2.52 |
| 52 | Communication Rack | T307 | A7 | 3.96 | 0.82 | 41.21 | NM | 1.86 | | 77.32 | 4.66 | 1.2 | 2.3 | No damage observed. | 12.23 | 0.89 | 0.96 |
| 53 | Communication Rack | T307A | A8 | 7.92 | 2.44 | 80.77 | NM | 4.80 | | 182.39 | 15.54 | 2.0 | 2.0 | No damage observed. | 5.58 | 1.28 | 2.16 |
| 54 | Communication Rack | T308 | A7 | 3.96 | 0.81 | 41.40 | NM | 0.59 | | 62.46 | 4.66 | 1.2 | 0.7 | No damage observed. | 12.39 | 4.26 | 1.46 |
| 55 | Communication Rack | T308A | A8 | 7.93 | 2.44 | 79.62 | NM | 0.71 | | 76.14 | 7.70 | 1.0 | 0.3 | No damage observed. | 18.02 | 7.43 | 1.00 |
| 56 | Communication Rack | T308B | A8 | 7.92 | 2.44 | 77.83 | NM | 0.56 | | 42.84 | 4.67 | 0.6 | 0.2 | No damage observed. | 10.88 | 12.14 | 1.03 |
| 57 | Communication Rack | T308C | A8 | 7.92 | 2.22 | 78.56 | NM | 0.66 | | 36.79 | 6.47 | 0.8 | 0.3 | No damage observed. | 18.18 | 8.50 | 0.62 |
| 58 | Communication Rack | T309 | A7 | 3.97 | 0.80 | 41.05 | NM | 1.91 | | 112.50 | 6.51 | 1.6 | 2.4 | One CPU and metal weights fell from the communication rack. | 5.56 | 1.28 | 2.16 |
| 59 | LAN Rack | T401 | A8 | 7.95 | 2.02 | 78.66 | NM | 5.80 | | 159.48 | 9.31 | 1.2 | 2.9 | One CPU fell on the floor. Other displaced in the rack. | | | |
| 60 | LAN Rack | T402 | A8 | 7.94 | 2.69 | 78.68 | NM | 2.26 | | 48.59 | 4.62 | 0.6 | 0.8 | No damage observed. | | | |
| 61 | LAN Rack | T402A | A8 | 7.94 | 2.68 | 78.74 | NM | 1.24 | | 51.86 | 5.86 | 0.7 | 0.5 | No damage observed. | | | |
| 62 | LAN Rack | T403 | A8 | 5.37 | 1.54 | 70.95 | NM | 5.99 | | 130.48 | 8.40 | 1.6 | 3.9 | Three CPU and one monitor fell off the LAN rack. Table was cut short due to safety shut off. Tilting of the LAN rack observed. | | | |
| 63 | LAN Rack | T404 | A8 | 7.93 | 2.72 | 80.73 | NM | 0.86 | | 30.75 | 4.83 | 0.6 | 0.3 | The LAN rack moved to different position. | | | |
| 64 | MCC | T405 | A7 | 3.98 | 0.82 | 41.83 | NM | 3.37 | | 162.68 | 9.38 | 2.4 | 4.1 | Two bolts loosened up and deformation of the exterior metal sheet observed. | 9.77 | 0.84 | 1.58 |
| 65 | MCC | T406 | A8 | 7.95 | 2.80 | 79.59 | NM | 6.49 | | 398.31 | 38.54 | 4.8 | 2.3 | No damage observed. | 16.36 | 0.85 | 1.15 |

**Table 4.a. Results of Analysis of Selected Records**

| Test Article | EQ Rec. | Code | Description | Comment |
|---|---|---|---|---|
| Photocopier (Ph) on wheels | A3 | 34 | restrained to wall | 1. Vertical accelerations for the restrained and unrestrained article are of the same order.<br>2. FRFmax happens at closely spaced frequencies (~14.29Hz, ~16.20Hz). The damping ratios at these frequencies are close to each other (~0.92%, ~0.94%). The Amplification factor of the photocopier is high, because the frame of the photocopier is a rigid steelwork with a low structural damping.<br>3. The wall flexibility may have some effect on the measured motions of the restrained photocopier. |
| | A4 | 33 | unrestrained | |
| | A4 | 35 | restrained to wall | |
| Communication Rack (CR) | A7 | 52 | restrained to floor | 1. Since CR onto table and restrained to floor (CR-52) is more rigid than CR placed on table without restraints (CR-58), the FRF amplitude for CR-52 is less than that for CR-58 ( ~0.89 vs. ~1.28). Damping ratios are as follows: for CR-52 0.96% and for CR-58 2.16%.<br>2. Influence of the Seismic Isolation Platform (SIP): For CR-54 the FRF from record A7 is higher than for CR-52 (4.24 cm and 0.89 cm, respectively). A similar situation happens for the record A8: For CR-55, which was placed on SIP, the FRF is larger than that for CR-53 without SIP and restrained to the floor (12.14 cm and 1.28 cm, respectively).<br>3. Influence of bungee chords restrain: The bungee make CR-55 more rigid than CR-56. Thus, the FRF amplitude for CR-55 is less than the FRF for CR-56 (7.43 cm and 12.14 cm). Removal of the bungee (CR-56) does not change the damping factor too much (for CR-56: ~1.03%, and for CR 55: ~1.0%).<br>4. Because of the geometry and similar stiffness of the rack in both principal directions, a strong-coupled response is observed in the recorded motions. Significant vibration in two mutual perpendicular directions can be clearly appreciated in the records. |
| | A7 | 54 | onto the SIP | |
| | A7 | 58 | removed from SIP and placed on table without restraints | |
| | A8 | 53 | restrained to floor | |
| | A8 | 55 | lifted onto the SIP | |
| | A8 | 56 | lifted onto the SIP, the bungee was removed from the inside of SIP. | |
| | A8 | 57 | lifted onto the SIP, the bungee was removed from the inside of SIP | |
| Large File Cabinet (LFC) | A1 | 1 | Two top shelves of the FC filled with weights | 1. LFC and SFC have certain common properties and peculiarities such as that both have large length to width ratios. Since the members of the LFC and SFC (frame, chassis) can have different types of connections (welded, riveted, bolted, etc.), these may significantly affect the response of the units<br>2. The torsional rigidity of both LFC and SFC units is relatively small.<br>3. Influence of the wall restraint. The displacement of LFC-1 is larger than that for LFC-5 (11.20 cm for T103 and 0.44 cm for T105). This can be explained by the fact that the rigidity of LFC-5 is higher than that for LFC-1. The same can be said for SFC-6 and SFC-2 (0.37 cm for T103 and 12.3 cm for T105).<br>4. Wall restrains vs. Floor restraints. Restraining the cabinets to the wall provides more rigidity to the whole system than restraining it to the floor. Measured displacements at the top of LFC-13 and LFC-17 are 0.78 cm and 4.44 cm, respectively (T109, T111). Since LFC-13 was restrained to the wall, while LFC-17 was restrained to the floor, the former is more rigid than the later. For SFC-14 and SFC-18 the peak displacements are 0.37 cm for T107 and 7.88 cm, for T109. It seems that it is more effective to restrain these types of systems at the top than at bottom.<br>5. A comparison of displacements at the top and at mid height of LFC and SFC shows that these systems deform mainly in bending. The estimated damping coefficients, however, have a significant scatter. |
| | A1 | 5 | FC restrained to wall | |
| | A1 | 13 | Leave FC empty and restrained to wall | |
| | A1 | 17 | FC restrained to floor | |
| | A1 | 25 | | |
| | A2 | 3 | Two top shelves of the FC filled with weights | |
| | A2 | 9 | FC restrained to wall | |
| | A2 | 21 | FC restrained to floor | |
| | A2 | 29 | | |
| Small File cabinet (SFC) | A1 | 2 | Two top shelves of the FC filled with weights | |
| | A1 | 6 | FC restrained to wall | |
| | A1 | 14 | Leave FC empty and restrained to wall | |
| | A1 | 18 | FC restrained to floor | |
| | A1 | 26 | | |
| | A2 | 4 | Two top shelves of the FC filled with weights | |
| | A2 | 10 | FC restrained to wall | |
| | A2 | 22 | FC restrained to floor | |
| | A2 | 30 | Leave FC restrained to floor | |

**Table 4.b. Results of Analysis of Selected Records**

| Test Article | EQ Rec. | Code | Description | Comment |
|---|---|---|---|---|
| Large Book Shelf (LBS) | A1 | 7 | Restrain BS to wall | 1. The FRF plots for data from tests for LBS and SBS (Codes 7,8) do not show well-defined peaks.<br>2. The effects of the two types of restrains (Snap Strap Nets and shelf grip strip) on the recorded data are practically the same, although the actual observed behavior of the two systems was different. By restraining the LBS to the wall and adding to it the Snap Strap Nets (T107, 0.43 cm) makes this unit slightly less rigid than when restraining it to the wall and adding the shelf grip strip (T105, 0.50 cm).<br>3. Restraining of the LBS to the wall and adding to it the Snap Strap Nets makes this unit more rigid than when it is restrained to the floor (T107, T109, 0.44 cm and 6.59 cm). |
| | A1 | 15 | | |
| | A1 | 19 | Restrain BS to floor | |
| | A1 | 27 | | |
| | A2 | 11 | | |
| | A2 | 23 | | |
| | A2 | 31 | | |
| Small Book Shelf (SBS) | A1 | 8 | Restrain BS to wall & add shelf grip strip | |
| | A1 | 16 | | |
| | A1 | 20 | | |
| | A1 | 28 | Restrain BS to floor & remove Snap Strap Nets | |
| | A2 | 12 | Restrain BS to floor & add shelf grip strip | |
| | A2 | 24 | | |
| | A2 | 32 | Restrain BS to floor & remove Snap Strap Nets | |
| Large Library Shelf (LLS) | A4 | 36 | Restrain LS to floor | 1. The displacements of the LLS at the top and the mid height are 0.21 cm and 0.73 cm, respectively (Test 206, A4). The displacement of the SLS at the top is 5.24 cm. Similar results are observed in the results for Test 205, A4.<br>2. There is not much dispersion of results for the estimates of damping coefficients (Codes 36-43). |
| | A4 | 38 | | |
| | A9 | 40 | | |
| | A1 | 42 | Restrain LS to floor with a top heavy load | |
| Small Library Shelf (SLS) | A4 | 37 | Restrain SS to floor | |
| | A4 | 39 | | |
| | A9 | 41 | | |
| | A1 | 43 | Restrain SS to floor with a top heavy load | |
| Workstation (WS) | A5 | 44 | Restrain LS to floor | 1. The E-W motion of the Shake Table produces not only for E-W and N-S motions of the workstation. Accelerations in the two perpendicular directions have peak values of the same order (Test 301, A5: N-S and E-W accelerations are 0.77 cm/sec$^2$ and 0.76 cm/sec$^2$, respectively). This means, that this workstation has such a structure that is characterized by a complex vibration response.<br>2. The recorded E-W horizontal acceleration time history shows a longer duration of significant shaking than the corresponding N-S acceleration. This indicates that the damping properties in the two directions are not the same. |
| | A5 | 48 | | |
| | A2 | 45 | | |
| | A2 | 49 | | |
| | A6 | 46 | | |
| | A6 | 50 | Restrain LS to floor with a top heavy load | |
| | A8 | 47 | | |
| | A8 | 51 | | |

## SUMMARY AND CONCLUSIONS

A series of 49 shake table tests on various functional and operational components, OFC, and office equipment were conducted in this study. The information obtained from the tests included damages observed on OFC and digital data recorded from sensors mounted on the tested equipment. A comparison of shake table input motions with original accelerograms was conducted during the analysis of data from the testing. The shake table motions were considered as good representations of the recorded motions in the frequency range of interest.

All test articles can be grouped in three main types based on their dynamic behavior:

1. Articles with large vertical and small horizontal dimensions. They have a number of fastening connections. All of them are characterized by a low torsional stiffness (Large and Small File Cabinets, Communication Rack and LAN Rack, Large and Small Book Shelves.). In order to ensure their good performance, it is recommended that OFCs in this group be anchored to a wall and that a rigid chassis be used to prevent undesirable torsional motions.

2. Articles with large horizontal dimensions, small vertical dimensions and large torsional stiffness (i.e., workstations). Seismic isolation supports may be used to improve their seismic performance.

3. Articles with small dimensions in both horizontal directions. All these articles have a stiff frame (i.e., photocopier and computer). As a recommendation, this group must be anchored to the floor.

The analyses of the recorded data indicated that the damping of the tested OFCs is generally low (les than 2%). But the damping was found sensitive to the level of shaking.


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