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IMPROVING THE DYNAMIC PERFORMANCE OF OFCs DURING EXTREME VIBRATION CONDITIONS

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ABSTRACT

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 their poor or marginal response has had safety related and severe economic impacts in the process of repairing and recovering the normal operations of buildings. It is, therefore, of great interest to find ways to improve the seismic performance on OFCs whose performance is sensitive to severe ground shaking. But, given the fact that OFCs in buildings are of many types and are usually present in great numbers, it is necessary to develop cost effective methods to evaluate the sensitivity of OFCs to severe shaking once they are installed in buildings, and to assess ways to improve the performance of existing ones. This paper is responsive to this need by presenting results of in-situ testing and using these results to estimate the expected performance of the OFCs investigated. The testing program included the evaluation of their dynamic properties using operational and forced vibration excitations. In addition, a series of OFCs' shake table tests that were conducted at the University of British Columbia with different support conditions are presented and discussed to complement the information obtained from the in-situ tests. The results from field observations and laboratory tests are compared, and the similarities and differences between responses are discussed. The effectiveness of a simple method to isolate the vibrations of OFCs is also included in the discussion. The paper shows how cost-effective in-situ tests can be used to understand the behavior of structures, OFCs, and support bearings.

Introduction

Recent earthquake events rises the concern that such natural hazards can change the lifestyle of an entire region. The problem that is to strengthen the resiliency of critical infrastructure; this is a major concern for Canada and the rest of the world.

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The amount of damage to the contents in a building has a significant effect on the impact of an earthquake to the overall population. Therefore it is of great importance to evaluate the risk of OFCs in buildings. But given the large amount of these components in any building; it is important to develop and implement cost-effective methods that permit a fast and reliable risk assessment of these elements. In this paper a risk assessment based on vibration and experimental testing is presented.

According to the Canadian Standards Association, (S832-06), the structural components are those basic components which are designed and constructed to carry and transfer all loads to the ground without total or partial collapse of the building. Operational and Functional Components can contribute to the structural integrity of the building, depending on their location, type of construction, and method of fastening, but these are not generally considered structural components. In this paper Non structural Components are defined as building services OFCs (mechanical, plumbing, electrical and telecommunications components); and Building Contents (common and specialized components).

This paper describes a methodology to evaluate the demands on OFCs for earthquake threats; a description for seismic behavior is presented by using the results of shake table tests and field vibration tests. Three topics were considered for the methodology in this paper:

1) Seismic Risk Assessment
2) Determination of Dynamic Characteristics and Seismic Performance of OFCs through shake table testing and field vibration tests
3) Floor Response Spectra

It is the intention of this paper to show briefly the whole procedure of determination of seismic demands of OFCs and two examples on how to modify the behavior of OFCs by using isolation supports or shock absorbers.

Seismic Risk Assessment methodology (SRA)

This paper is focused in reviewing and defining the seismic behaviour of OFCs that have been tested experimentally as well as in operational and functional conditions.

The seismic risk assessment of critical infrastructure includes the evaluation of lifeline systems as well as OFCs inside important buildings or facilities. Three steps were used for the inventory and the determination of dynamic properties and seismic performance of OFCs and structural elements:

1. Identify the important OFCs inside of buildings or facilities, that could affect the lifeline functionality, through the following activities:
   - Perform operational or forced vibration tests
   - Review experimental shake table tests
   - Process the data and characterize the dynamic properties and use mathematical models if possible.

2. Obtain relevant dynamic properties (for the building and the OFCs)
3. Compute the seismic behaviour through Floor Response Spectra under different scenarios

Dynamic characteristics of Operational and Functional Components (OFCs)

Operational and forced field testing on OFCs

Sixty seven measurements were performed with vibration equipment, using a set of 6 sensors with different capacities, a test hammer and a laptop computer. Specific details of these measurements and detailed information of the equipment used and the data processing can be found in (EERF 07-08).

Two different types of tests were carried out: operational (OP) and forced (F) vibrations. Mechanical and electrical equipment was tested under two operational conditions: equipment on and off. Pipelines were subjected to force vibration using a test hammer and a triaxial sensor. Pictures of two OFCs are shown in Figure 1.

Figure 1. equipment set up and measurement testing at some OFCs.

Results from field testing

The recorded motions were signal processed to remove high and very low frequency components first. Linear trends were also removed from the records. Then the power spectral density (PSD) of each record was computed. The resulting PSD for each location and each orientation were also computed and documented, and a pre selection of frequencies was achieved through this process. Complementary analyses were performed using the ARTeMIS Extractor software (2008). The Enhanced Frequency Domain Decomposition (EFDD) method was used in order to estimate natural frequencies and damping in some OFCs, (Brincker et al 2000 and Brincker et al 2001). The frequencies chosen from the ARTeMIS software plots of the OFCs corresponded to the same frequencies identified previously. Three natural frequencies for the longitudinal, transversal and vertical components were obtained. Table 1 summarizes some values found, and further details can be found in the Earthquake Engineering Research Facility Report, (EERF 07-08).

Results from ambient vibration tests carried out in a health facility, as part of the study case was also performed and the frequency identified from ambient vibrations test conducted on a Health Facility was 2.2 Hz (0.45 sec), (Juárez and Ventura, 2008).

Table 1. Values of frequencies and damping from field tests for a set of OFCs.

Mode	**Frequency [Hz]**	**Damping Ratio [%]**	**Direction**	**OFC**
1	4.6	5.6	Transversal	**Electric Generator**
2	9.0	1.6	Vertical	
3	29.7	0.4	Longitudinal	
1	6.2	3.6	Transversal	**Boiler I**
2	23.5	0.3	Vertical	
3	29.7	0.3	Longitudinal	
1	5.0	10.0	Transversal	**Back up Pump**
2	21.7	2.9	Vertical	
3	94.7	0.4	Longitudinal	
1	1.9	Not Identified (NI)	Lateral	**Pump 7**
2	3.1	NI	Vertical	
3	10.0	NI	Longitudinal	
1	9.6	NI	Transversal (1)	**Air Medical Pipeline**
2	14.6	NI	Longitudinal	
3	17.9	NI	Transversal (2)	

Shake table testing (OFCs)

Two series of shake table testing were performed in 1996 (EERL 96-002) and 1998 (EERL 98-006) at the Earthquake Engineering Research Lab of the University of British Columbia; several building contents (OFCs) were tested under different ground motions. Some of the ground motions used were taken from actual earthquakes that were recorded on different floors in real buildings.

In project EERL 96-002 frequencies and seismic behaviour were obtained for two relay rack types; a list of the maximum observed displacements and accelerations computed on the relay racks is presented in (Juárez and Ventura, 2008). No damage was observed in the tested equipment.

Project EERL 98-006 conducted in the Earthquake Engineering Research Lab in UBC, tested a significant number of OFCs at different levels of earthquake motions.

Shake table testing with isolation or special supports

In 2008 a series of tests were conducted in UBC on OFCs that were isolated. Two conditions were tested: OFC alone and OFC and surcharge weight. In addition, a set of tests were conducted in order to compare the response of OFCs without isolation systems, (EERF 08-02, 2008).

For most of the tests the accelerations above the isolation systems were significantly less than the input accelerations. For those tests in which the displacement of the isolation system reached the maximum permissible displacement of the devices, the input acceleration was increased due to impacts of the moving parts of the isolation system. Although the high frequency content of the input accelerations was significantly reduced by the isolation systems, the displacements above the isolators were always greater than those from the corresponding input motions. Damping of the isolation systems increased when surcharge weight was added to the isolation systems. When the input motions were scaled up, the displacement capacity of the isolation systems was reached causing large acceleration values, (EERF 08-02, 2008).

An experiment to prove the vibration reduction of visco-elastic stripes was conducted at the earthquake Engineering Research Facility, using a steel table, a surcharge of 2,000 lb (2 steel plates of 1,000 lb), and a shaker. Several measurements were conducted to decide the thickness and configuration in which the visco-elastic supports were to be placed to reduce the vibration produced by a shaker (a sine sweep was generated). Figure 2 shows the configuration set up for the tests; two measurements were obtained, one on top of the surcharge plates, and other measurement on the table, where the visco-elastic stripes were supposed to have reduced the amplitude and the induced vibrations.

Figure 2. Set up showing the table, the surcharge and the shaker.

Figure 3 shows the PSD results from these tests. Amplitudes have been reduced by placing the visco-elastic stripes. The measurements without shock absorbers show that amplitudes are as high as 20, and only one frequency is observed around 11 Hz, which is the vertical period of the table. The measurement on the table, where the shock absorbers are placed, show an amplitude close to 1.6. A significant reduction of the vibration is achieved by adding mass to the system and a proper distribution of visco-elastic stripes in the whole system, the amplitude of the vibration was reduced more than 10 times.

Proposed methodology using Floor Response Spectra

The Floor Response Spectra Methodology was used in this research to compute the seismic response of OFCs at any given point in a building. The dynamic characteristics of one building at a study case and for some OFCs were determined. Time histories that match the seismic scenario response spectra were computed. In this paper a set of two SDOF system models of one building were considered. Elastic and elasto-plastic behaviour were also defined for the SDOF systems, so that non linear behaviour can be characterized. Three response spectra from the earthquake scenarios were selected; and a set of 9 modified time histories were obtained (Juárez and Ventura, 2008), and hence a set of linear and non linear floor response spectra were computed on the roof of the building that was modeled as a SDOF system; one simple reason for this, is that many OFCs in a building are placed either on the roof or the ground level, that is the case of the Health Facility considered for this paper.

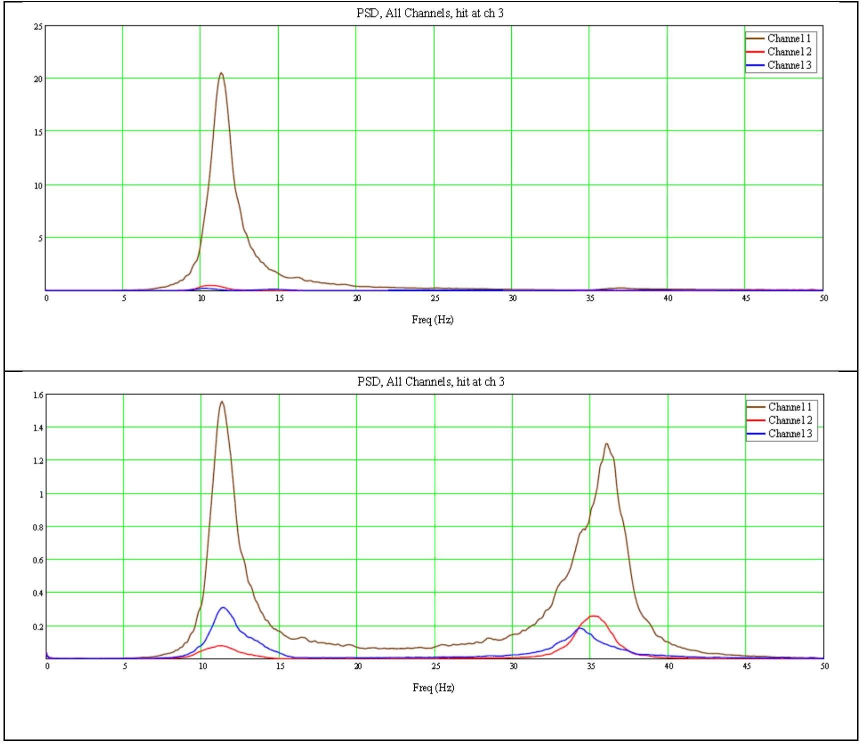

Figure 3. PSDs of two measurements.

It is evident that for a given ground motion, the motions at each floor of any building will be different from the base ground motion. With a computer model and time histories, a response spectrum can be developed at a given point within the building, and then computation of a floor spectrum for that point in the building using either the average or peak envelope or other such combination of all the spectra is then possible.

In many cases obtaining time histories for a given site may not be possible, and only the reference response spectrum for the site (seismic codes) could be available. With the basic computer model of the building, it is possible to generate a floor spectrum at any point, by adding at that point a series of SDOF systems of different periods with small masses that do not affect the overall building response, running a conventional response spectrum analysis of the overall model and then graphing the response for the different period elements, The Response Spectrum Proceedings, 2007.

Floor Response Spectra from the Seismic Hazard Assessment

The procedure to obtain the floor response spectra is listed below, (Juárez and Ventura, 2008):

1. Response spectra (RS) for Instrumental Intensities VIII, IX and X were selected.
2. Three ground motions were selected for the given seismic hazard (Northridge, Loma Prieta and Cape Mendocino).
3. The facility or building was modeled as a SDOF System. Linear and non-linear behaviour were considered by selecting two behaviours for the SDOF system: Elastic and Elasto-Plastic behavior.

SDOFS behaviour	W	T	ξ	Vb
Elastic	49,000 kN	0.45 sec	5 %	NA
Elasto-Plastic				0.6 x W

4. A frequency band of 1 to 100 Hz was selected for the spectral matching, RSPMATCH was used to produce a set of new ground motions.
5. A total of nine ground motions were computed. As an example, Northridge ground motion was use to produce a ground motion that matched the response spectra of Instrumental Intensity VIII; the same procedure was performed for Loma Prieta and Cape Mendocino ground motions.
6. The 9 ground motions were applied to the SDOF systems, and new time histories were computed on the roof of the SDOF systems. Therefore 18 time histories were obtained: 9 for linear behaviour and 9 for non-linear behaviour.

Floor Response Spectra (FRS) Results

In Figure 4, the left figure shows the resulting FRS for the Elastic SDOF systems; peak accelerations of up to 8.5 g were reached for frequencies around 2 and 4 Hz. The calculated FRS's were obtained for a 2 % damping, as most of the equipment and contents are made of steel.

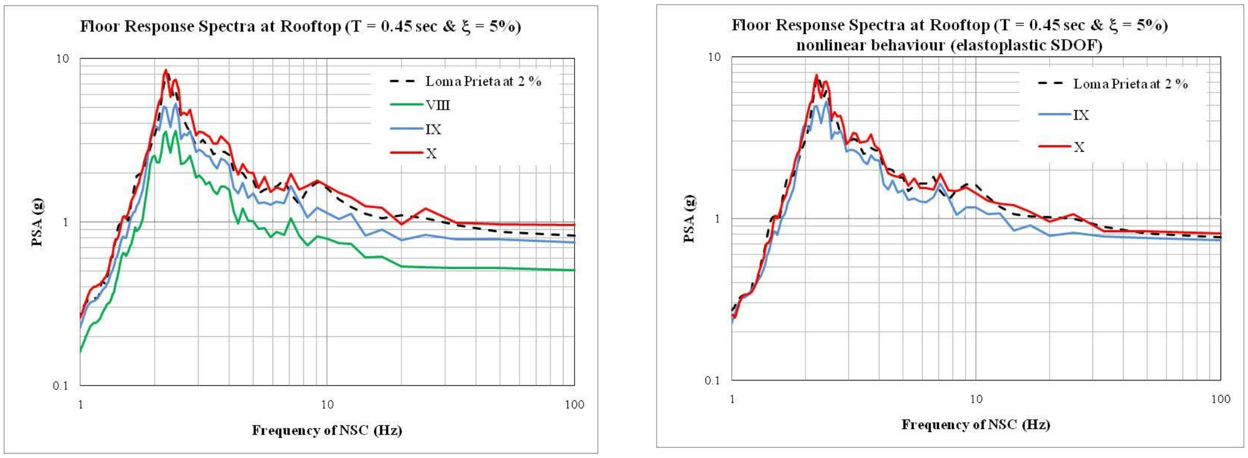

Figure 4. FRS for thre II: Elastic SDOFS (left) and Elasto-plastic SDOFS (right).

Nevertheless, in some cases the supports of OFCs are specialized mechanical supports that provide more than 10 % of the critical damping. For the Elasto-Plastic SDOF system the corresponding FRS is shown at the right-hand side of figure 2. Intensities IX and X were the only ones provoking a non linear behaviour.

Seismic behaviour of OFCs

The seismic behaviour of OFCs could be characterized with their dynamic properties and the results from the floor response spectra. In Table 2, a collection of important OFCs is shown, with frequency, damping values, and the corresponding acceleration that the OFC will experience using the calculated Floor Response Spectra. For these results it should be noted that no damage to OFCs was associated to the acceleration values. In the case of the Relay Racks that were part of a Shake Table testing, no damage was found even though accelerations at the top of the test articles were as high as 8 g's. The values obtained in Table 2 were based on specialized equipment, with large masses and special supporting springs and vibration pads.

Table 2. Level of acceleration in g for several OFCs using three leves of Instrumental Intensity.

OFC or Component	**Freq (Hz)**	**ξ (%)**	**II VIII acc (g)**		**II IX acc (g)**		**II X acc (g)**		**Earthquake**
			Linear	**Non Linear**	**Linear**	**Non Linear**	**Linear**	**Non Linear**	
Electric Generator	4.6	5.6	0.79	0.79	1.18	1.17	1.54	1.53	Northridge
			1.20		1.73	1.7	2.26	1.86	Loma Prieta
			2.97		4.56		5.48	1.65	Cape Mendocino
Boiler I	6.2	3.6	0.83		1.32		1.63	1.6	Northridge
			0.86		1.34	1.25	1.63	1.54	Loma Prieta
			1.55		2.15		2.89	1.48	Cape Mendocino
Pump 7	1.9	NA	2.87	2.87	4.35	4.28	5.52	5.27	Northridge
			2.23		3.24	3.2	3.12	2.95	Loma Prieta
			0.19		0.17		0.21	5.18	Cape Mendocino
Pump (ground floor)	5	10	0.52		0.8		1.05		Northridge
			0.50		0.78		1.02		Loma Prieta
			0.51		0.76		1.01		Cape Mendocino
HT RG Pipeline	23	NA	0.58		0.87	0.84	1.07	0.95	Northridge
			0.53		0.83	0.81	1.2	1.07	Loma Prieta
			0.59		0.77		1.05	0.75	Cape Mendocino
Air Medical Pipeline	9.6	NA	0.81		1.17	1.08	1.45	1.27	Northridge
			0.79		1.14	1.16	1.66	1.43	Loma Prieta
			1.12		1.67		2.13	0.92	Cape Mendocino
Relay Rack	6.5	NA	0.79		1.31	1.27	1.69	1.6	Northridge
			0.83		1.30	1.35	1.56	1.51	Loma Prieta
			1.43		2.10		2.77	1.41	Cape Mendocino

Table 3 shows a seismic performance, at least at a limit state, for a collection of OFCs; the values computed for these contents were part of a shake table testing. According to the values obtained from the floor response spectra, the associated floor acceleration values would be 0.45 g (VIII), 0.60 g (IX), and 0.8 g (X). It should be noted that the seismic performance also depends on the natural frequencies of the contents. The values obtained in Table 3 were determined for OFCs that had no special anchorage elements, and based on regular equipment found in offices.

Table 3. Seismic behaviour of building contents, accelerations and displacements.

Content	Seismic behaviour	Floor Acc (g)	Floor Disp (cm)
Large bookshelf	It will turn over @	1	6
CPU **Monitors** **Books**	will overturn @ will overturn @ will fall from shelf @	2+	8
LAN rack	will move to different positions @	2.5	8

Conclusions and final remarks

The seismic demands of OFCs attached to a building may be different than those for the main building structural elements. In some cases these demands may be significantly higher. It is important to evaluate the seismic demands and the capacities of those systems that are important to critical infrastructures. As an example, consider a Water Station, as an important part of the Water System; and the pumps that provide pressured water to the health facility system (Hospital) within a studied case. In this example, if the pumps got damaged due to the level of shaking, the water system will be non-functional, and hence the considered population would be out of water and the Hospital will fail to provide service to injured people. It also shows that isolation devices or shock absorbers might help reduce induced vibrations during operational or earthquake demands.

This study shows the value of vibration field and experimental testing as part of a program to assess the seismic risk of operational and functional components in buildings. Therefore the understanding of the dynamic behavior of OFCs is crucial to establish a proper seismic risk assessment methodology. But given the vast amount of components in any building, it is important to implement testing methods that are fast, economic and reliable.

The methodology has been developed through the years Miranda and Taghavi, 2003 developed a database for the adequate organization, storage and easy retrieval of information related to the seismic performance of NSCs and contents on commercial buildings. ATC-58 takes into account the performance of NSCs in the overall estimation of the seismic performance of buildings.

In this research, the physical supports of OFCs define the different levels of seismic capacity of these components. From a civil engineering point of view the capacity would be limited to their physical collapse (overturning, fall or high level of motion), regardless of the operability conditions of the equipment.

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