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SEISMIC PERFORMANCE OF OPERATIONAL AND FUNCTIONAL COMPONENTS (OFCS): FIELD OBSERVATIONS AND SHAKE TABLE TESTING

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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, in addition to the safety related aspects of the seismic performance of OFCs, the economic impact of the poor or marginal performance of them can be very severe. In this paper, a seismic risk assessment study conducted as part of a major project of the University of British Columbia called Joint Infrastructure Interdependencies Research Project (JIIRP) includes the evaluation of the performance of OFCs; a summary of the Seismic Risk Assessment considered for these components is presented first. The response spectra from the earthquake scenarios are used to compute floor response spectra (acceleration, velocity and displacement) in order to gain a better understanding of the demands experienced by OFCs. Secondly, a series of vibration tests were conducted on machinery and pipelines of actual buildings that are part of lifeline systems; the testing program included the evaluation of the dynamic properties of them using operational and forced vibration conditions. Then, a summary of a series of shake table tests of different types of OFCs conducted in recent years at the University of British Columbia is presented and the results are discussed. The results from field observations and laboratory tests are compared, and the similarities and differences between responses are discussed.

KEYWORDS: OFC, earthquake, behaviour, shake-table, instrumentation, field-tests

1. INTRODUCTION

Recent earthquake events, as the Wenchuan earthquake that struck the southwest China’s Sichuan province on May 12th , 2008 rises the concern that such natural hazards can change the lifestyle of an entire region, the death toll as of may 29 is 68,516 and 19,350 are still missing, http://www.chinaview.cn/08quake/. The problem that is to be solved is the strengthening of the resiliency of critical infrastructure; this is a major concern for Canada and the rest of the world. The task for Canada and other countries is to establish an action plan to guide the identification of risks, the implementation of protective safety measures, and the proper and effective response to disruptions of critical infrastructure.

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.

The Joint Infrastructure Interdependencies Research Project of the University of British Columbia is an effort to assess the impact of physical and temporal interdependencies among multiple infrastructure systems, during the development of large disaster events, since the impact of these interdependencies may be hidden on its temporal consequences. As part of this project a studied case was developed in order to develop a simulator. A Canadian university campus (Point Grey Campus of the University of British Columbia UBC) was selected as the studied case; seismic risk assessment was conducted, building and lifeline seismic damage was evaluated, and specialized buildings and facilities were investigated along with their OFCs, Martí, et. al. (2008).

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 three earthquake scenarios; a description for seismic behavior is presented by using the results of shake table tests and field vibration tests. Three important topics were taken into account for the methodology used 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. These topics will be addressed in this paper.

2. SEISMIC RISK ASSESSMENT METHODOLOGY (SRA)

The University of British Columbia has conducted a series of SRA studies in the Vancouver region, Thibert, 2008; this paper, as part of the JIIRP project, 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 behaviour was characterized through Risk Assessment Methodology, and the following steps were used for this research:

1) Seismic Hazard
2) Inventory of OFCs
3) Determination of dynamic properties and seismic performance of OFCs
4) Determination of demands using Floor Response Spectrum

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

2.1 Seismic scenarios

As part of the seismic hazard identification, a set of three seismic scenarios were proposed in the UBC Campus case. These scenarios were characterized with the following Instrumental Intensities: VIII, IX and X. Further explanation on these scenarios and the whole project is provided in Cook, 2000; Thibert, 2008.

The seismic characterization of Structures, Lifelines and OFCs can be achieved through Response Spectrum. OFCs are sensitive to displacement, velocity or acceleration; therefore relationships between Instrumental Intensities and those responses are needed. In this paper relationships between Intensity and Spectral Responses are obtained from Cook, 2000, NBCC 2005, Wald, 1999 and Thibert, 2008.

3. DYNAMIC CHARACTERISTICS OF OPERATIONAL AND FUNCTIONAL COMPONENTS

3.1 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. However highlights of these tests will be provided in this paper.

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.

3.1.1 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 using the ARTeMIS Extractor software, and further details can be found in the Earthquake Engineering Research Facility Report, EERF 07-08.

Table 1. Values of frequencies and dampings 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)	

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

3.2 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, table 4; a list of the maximum observed displacements and accelerations computed on the relay racks is presented in table 3. No damage was observed in the tested equipment.

Table 2. Dynamic properties and geometry of two OFCs (Relay racks).

Component	Size	Frequency (Hz) X	Frequency (Hz) Y
Relay rack	19”	6.2	13.2
Relay rack	23”	6.9	14.3

Table 3. Performance of the Relay racks under different earthquakes and different conditions.

Test number	Payload (kg)	Stiffeners	Abs acc(g) max		Abs acc(g) min		Abs Disp (cm) max		Abs Disp (cm) min	
			19”	23”	19”	23”	19”	23”	19”	23”
4	150	Yes (4)	6.02	6.69	-8.07	-6.93	5.2	5.1	-5.3	-4.5
8	150	No	3.27	5.99	-3.45	-6.95	5.2	3.0	-5.0	-2.6
9	227	No	4.21	3.71	-3.75	-5.28	2.9	3.8	-3.0	-3.4

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; some tested articles and their details are shown in table 4. Observations about the dynamic behaviour of the OFCs and the ground motions used are presented in table 5.

Table 4. Tested articles and their characteristics.

Test article	Size	Id
File cabinet	83” (H) x 18” (W) x 36” (L)	Large file cabinet
Book shelf	72x12x33	Large book shelf
Lan rack	33x64x90	LR
Communications rack	24x31x85	CR
76” libarary shelving	36x18x76	Large LS
Photocopier on wheels	48x30x48	Ph

Table 5. Ground motion used, seismic performance and observations for different OFCs.

Test	Earthquake	Observations	Acc (g)	Disp (cm) @ the top
103	From the 6 storey Sylmar County Hospital record from the 6.7 Northridge, 1994 (4th floor)	Large bookshelf turned over Small bookshelf performed well	Shake table (ST) -1	ST 6 Large FC -11 Small FC 12.5
305	From the 7.2 Kobe, 1995 (on the ground)	Overturning of CPU’s 1 and 2 Monitor 1 was separated from its stand Some books feel off the shelf	ST -1 Work station -2	ST 8
306	From a 13th storey building in Sherman Oaks; 6.7 Northridge, 1994 (ground floor)	Monitor 1 fell off the desk Monitor 2 was overturned CPU’s 1 and 2 were overturned	ST -1 Work station 1.5	ST -5.8
306A	VERTEQ	CPU’s 1 and 2 were overturned Monitor 2 was overturned Falling books from the shelf	ST 2.1 Work station -4	ST 8
404	VERTEQ	The LAN rack moved to different positions	ST 2.5 Lan rack 0.8	ST 8

4. 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 UBC case and for some OFCs were determined. Time histories that match the 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, 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.

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.

4.1 Floor Response Spectra from the Seismic Hazard Assessment

The procedure to obtain the floor response spectra is listed below:

1. Response spectra (RS) for Instrumental Intensities VIII, IX and X were selected. These RS were developed in a previous research by Cook, 2000, and the RS are shown in table 6.

Table 6. Response spectra values for Instrumental Intensities VIII, IX and X (PSA)

T (sec)	**PGA**	**0.17**	**0.25**	**0.33**	**0.5**	**0.67**	**0.83**	**1**	**1.17**	**1.33**	**1.5**	**1.67**	**1.83**	**2**
VIII	0.25	0.5	0.51	0.52	0.41	0.3	0.21	0.19	0.18	0.16	0.13	0.1	0.08	0.07
IX	0.38	0.8	0.76	0.75	0.6	0.39	0.3	0.24	0.21	0.19	0.18	0.17	0.17	0.14
X	0.5	1.04	1	1.02	0.69	0.48	0.38	0.29	0.26	0.24	0.24	0.25	0.24	0.19

2. Three ground motions were selected for the given seismic hazard (Northridge, Loma Prieta and Cape Mendocino), table 7. These ground motions were selected with the recommendations presented by Clague, 2001.

Table 7. Ground motions selected for the Spectral matching.

Record	**Earthquake**	**Date**	**Magnitude (M_w)**	**Type**	**Depth (km)**	**Hypocenter (km)**	**Duration (sec)**	**PGA (g)**
1	Northridge	1994/Jan/17	**6.7**	Crustal	18	45	40	0.21
2	Loma Prieta	1989/Oct/18	**6.9**	Crustal	18	65	40	0.16
3	Cape Mendocino	1992/Apr/25	**7.1**	Crustal	10	54	44	0.18

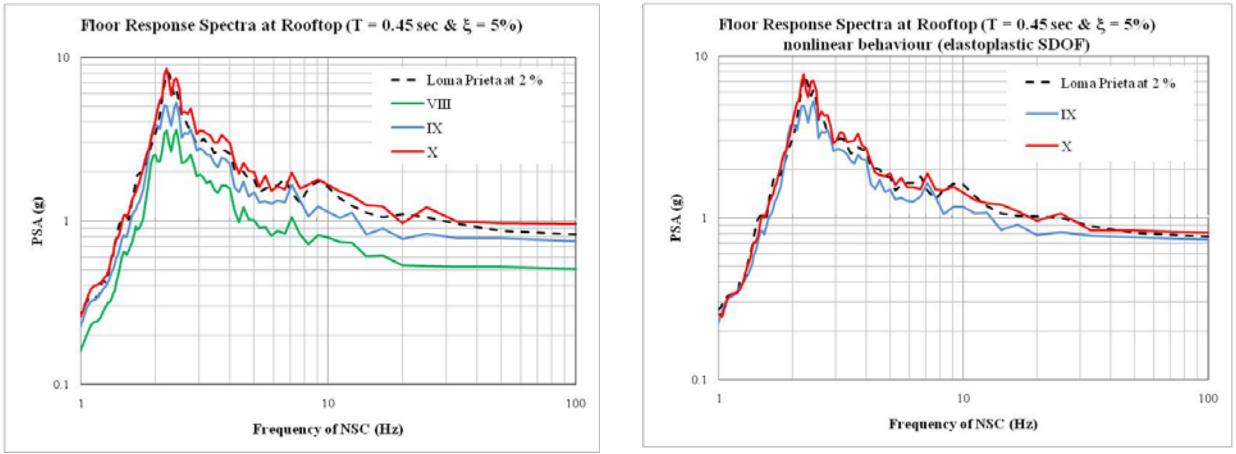
3. The facility or building was modeled as a SDOF System. Linear and non-linear behaviour were considered by selecting two behaviours for the SDOF system: Elastic and Elasto-Plastic behavior.

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.

4.2 Floor Response Spectra (FRS) Results

In Figure 2, the left figures show 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. 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.



Loma Prieta **Loma Prieta**

Figure 2. FRS for II VIII, IX and X at the rooftop of : Elastic SDOF system (left) and Elasto-Plastic SDOF system (right).

5. 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 8, 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, tables 2 and 3, 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 8 were based on specialized equipment, with large masses and special supporting springs and vibration pads.

Table 8. Level of acceleration in g for several OFCs using three levels 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 9 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 9 were determined for OFCs that had no special anchorage elements, and based on regular equipment found in offices.

Table 9. 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	will overturn @	2+	8
Monitors	will overturn @		
Books	will fall from shelf @		
LAN rack	will move to different positions @	2.5	8

6. 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.

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.

The floor response spectra is also a powerful tool to compute the accelerations, velocities or displacements that the OFCs will experience in the event of an earthquake of such intensities (VIII, IX or X). Nevertheless we should be aware of the limitations in the tools that we are using to predict damage in buildings, in OFCs and in Critical Infrastructure.

The following observations and remarks were made during the process of this research:

6.1 General building behavior

1. For medium to tall buildings, a P-Δ effect study should be carried out to investigate the variations of the response due to these effects.
2. The soil conditions will also affect the behaviour of the building and the amount of energy induced to the components.

6.2 Floor Response Spectra

3. The selection of the frequency band for the spectral matching is important. In this paper the selected band was 1 to 100 Hz, in order to cover for the whole population of buildings in a studied area.

4. The matching should be made taking into account the elastic behavior of the building, as well as the damage that the predicted ground motion will inflict to the structure, and hence the variation of the natural period of the building.

6.3 Oncoming research

The first part of this research has been accomplished, by defining the methodology to create Floor Response Spectra (FRS) for important buildings; and part of the research is also to classify the importance of some buildings for an overall population. The second part would be to have a good inventory of important OFCs and building contents; in order to provide accurate ways to define their seismic behaviour.

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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