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AN OVERVIEW OF A NEW CANADIAN STANDARD ON THE SEISMIC RISK REDUCTION OF OPERATIONAL AND FUNCTIONAL COMPONENTS OF BUILDINGS

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ABSTRACT

Building components can be categorized into two main groups: structural and operational/functional. Structural components provide the load-carrying capacity of a building's structure such as beams, columns and walls. Operational and functional components, or OFCs, provide the operational and functional capacities for the building such as architectural components, mechanical and electrical systems and communication equipment, which are often referred to as non-structural components. In Canada, seismic provisions for the design and construction of building structures are well established. However, similar guidance for the seismic evaluation and upgrading of OFCs was not available until the publication of the CSA-S832 Guideline on the Seismic Risk Reduction of Operational and Functional Components of Buildings by the Canadian Standards Association (CSA) in 2001. Based on the feedback from the industry on the use of the 2001 Guideline, the latest knowledge on earthquake effects on OFCs and the new research findings, the Guideline has been further developed into a new Standard in 2006. This paper presents an overview of the new CSA Standard and its risk assessment methodology for OFCs.

Introduction

Building components can generally be categorized into two main groups. The first group includes the structural components such as beams, columns and walls that carry and transfer the load imposed upon the building's structure. The second group encompasses all other building components that provide the operational and functional capabilities for the building. These operational and functional components, or OFCs, also known as non-structural components can be divided into three sub-groups:

(i) Architectural components (external and internal),
(ii) Building service components (mechanical, plumbing, electrical, telecommunication, etc.), and
(iii) Building contents (common and specialized).

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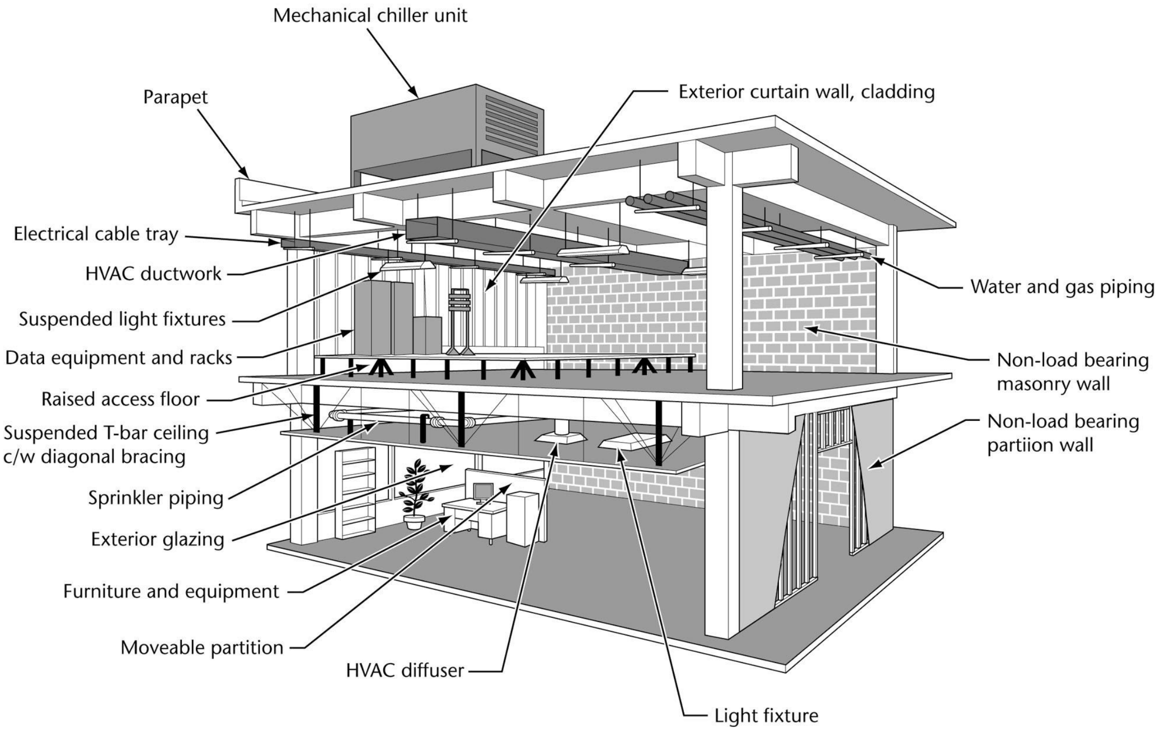

Figure 1. Operational and functional components of a building (CSA, 2006).

Fig. 1 illustrates some examples of OFCs (CSA 2006). Past earthquakes have shown that the majority of casualties and damage are due to the falling debris of OFCs. Buildings often became non-operational due to failure of building systems and equipment, and not because of structural damage. Fig. 2 shows the caving-in of office contents and the pulling out of anchorage for sprinkling pipe in an earthquake, both of which could have impact upon the operation and function of a building. The failure and falling debris of OFCs also create serious problems for search and rescue operations after the earthquake, resulting in additional increase in casualties.

(a) (b)

Figure 2. Failure of OFCs during earthquakes: (a) Caving-in of office contents and (b) Pulling-out of anchor for sprinkling pipe.

The 1988 Saguenay earthquake in Québec caused very little structural damage; A great majority of the injuries, property damage and economic loss was caused by the failure of OFCs. During the 1994

Northridge earthquake in California, several major hospitals had to be evacuated, not because of structural damage, but due to failure of emergency power systems, air control (heating and cooling) units, falling ceilings and light fixtures. Damage caused by the February 28, 2001 Nisqually earthquake near Seattle was also largely attributed to OFCs.

Recent earthquakes clearly demonstrated the tremendous impact of the failure of the OFCs of buildings upon life safety and economic losses related to functionality and property. A number of studies (see for instance Onur, Ventura and Finn (2005), FEMA (2003) and Comartin, et al. (2006)) have shown that the economic losses due to failure of OFCs and damage to the building contents far exceed the losses due to structural damage and can exceed 70% of the total economic losses in buildings.

The seismic protection community is realizing that the protection of a building must include both the building's structural components and its OFCs. Benefits of seismic protection of OFCs are tangible: direct improvement of life safety, better property protection, reduced economic and financial impact, and enhanced search and rescue operations.

Seismic Risk Reduction of OFCs

In the U.S., the seismic provisions for OFCs can be found in the International Building Code (IBC) issued by the International Code Council (ICC 2006) and in the ASCE-7-05 issued by the American Society of Civil Engineers (ASCE 2005). The 2006 IBC is expected to be adopted by most jurisdictions in the U.S., including California. IBC 2006 refers to ASCE-7-05 on the seismic requirements for OFCs.

In addition to these codes, there are industrial guidelines on the seismic restraint requirements for various OFCs commonly found in buildings. These guidelines provide detailed and often prescriptive requirements on the seismic restraint requirements of specific elements or systems. They generally refer to other codes and standards for detailed analysis. Here are some commonly referenced guidelines:

1) "Guidelines for seismic restraint for direct-hung suspended ceiling assemblies" (CISCA 2004)
2) "A Practical guide to seismic restraint" (ASHRAE 1999)
3) "Standard for the installation of sprinkler systems" (NFPA 2006).
4) "Seismic restraint manual: guidelines for mechanical systems" (SMACNA 1998).

In Canada, the National Building Code of Canada, NBCC, (NRC 2005) has been primarily developed for the design of structural components of new constructions. While the earthquake-resistant design of building structures reflects the seismic hazard levels in Canada, the design of nonstructural components (i.e. functional and operational) as required by NBCC, is partly based on empirical amplification factors of the seismic effects, which are not well documented. Also, evaluation and mitigation of seismic risk of OFCs for existing buildings are not addressed in the NBCC.

Based on the "Guideline for the Seismic Evaluation and Upgrading of Non-Structural Building Components" (PWGSC 1995), the Canadian Standards Association (CSA) published the "Guideline for the Seismic risk reduction of OFCs of buildings: CSA-S832-01" (CSA 2001), which was the first of its kind for the seismic risk reduction of OFCs. The guideline provided information and methodology to identify and evaluate seismic risks and to undertake appropriate mitigation strategies. CSA-S832-01 was based on the 1995 edition of the National Building Code of Canada (NRC, 1995).

With feedback from the industry on the use of the 2001 Guideline and the publication of the NBCC 2005 (NRC 2005), the CSA-S832-01 Guideline has been revised and published in 2006 as a Standard (CSA 2006). The new CSA-S832-06 Standard's seismic risk assessment methodology is fully compatible with the seismic provisions defined in NBCC 2005 and can be used to determine the seismic risk rating of each OFC in terms of its vulnerability and consequences of failure. While the Standard is applicable to both new and existing building constructions, its use in ranking/prioritizing OFCs in need of seismic retrofit is most effective and efficient.

CSA-S832-06

Highlights of the CSA-S832 Standard include:

1) Guidance on defining performance objectives,
2) Procedures on seismic risk reduction for new and existing buildings,
3) Methods for determining seismic adequacy,
4) Considerations for determining OFC problems and mitigation options and priorities,
5) Methodology for conducting a seismic risk assessment, and
6) Information sections in the Annexes, including sample applications of the assessment methodology.

The Standard introduces a parametric methodology for assessing the seismic risk of OFCs. The risk is defined as the product of the OFC's vulnerability and the consequences of the failure of the OFC. For new building constructions, the methodology can be used as a preliminary evaluation tool for the seismic design of the restraint requirement of OFCs. For existing buildings, the methodology can be used to rank and prioritize the OFCs in need of detailed analysis and seismic retrofit.

Seismic Risk Assessment

The recommended approach to risk assessment is to determine a seismic risk index for each important OFC and establish a ranking based on numerical risk values. The seismic risk index, R, is determined as the product of the OFC's seismic vulnerability index, V,(related to the conditional probability of failure given the occurrence of a design-level earthquake) and the consequences of failure index, C, related to the likelihood of deaths and serious injuries (life safety) and loss of building functionality if failure/malfunction occurs.

Vulnerability index

The vulnerability index, V, considers the effects of six vulnerability parameters:

1) OFC restraint,
2) impact/pounding,
3) OFC overturning,
4) OFC flexibility and location,
5) characteristics of ground motion, and
6) building characteristics.

The first four parameters are specifically related to the OFC and the risk rating, RS, can be assessed directly using engineering documents and/or on-site inspection in existing facilities. The relative importance of each parameter in affecting the OFC's vulnerability is reflected by its weight factor (WF). The last two parameters are related to the building and site/ground motion characteristics (RB and RG respectively). The following sections summarize the vulnerability parameters and the evaluation of the vulnerability index, V.

OFC Restraint, WF=4

RS = 1 for fully restrained condition
RS = 5 for partially restrained or questionable restrained condition
RS = 10 for no restraint condition.

Impact/pounding effect, WF=3

RS = 1 for adequate gap
RS = 10 for inadequate or questionable gap.

OFC Overturning, WF=2

RS = 0 if OFC is fully restrained against overturning
RS = 1 if (h/d) is less than or equal to (1/(2FaSa(0.2))
RS = 10 if (h/d) is greater than (1/(2FaSa(0.2)).

Where h is the distance from the support or restraint to the center of gravity or top of the OFC, d is the horizontal distance between the OFC supports, Fa is the acceleration-based site factor and Sa(0.2) is the 5% damped spectral response acceleration value at a period of 0.2s, at the location of the building – Fa and Sa are defined in the NBCC 2005 (NRC, 2005).

OFC flexibility and location, WF=1

RS = 1 for stiff or flexible OFC on or below ground floor
RS = 5 for stiff OFC above ground floor
RS = 10 for flexible OFC above ground floor.

Stiff OFCs are defined as those having a fundamental period for the OFC and its connection less than or equal to 0.06s. Flexible OFCs have a fundamental period greater than 0.06s.

The combined effects from the above four OFC-related parameters can be determined as the sum of the product between RS and WF, i.e. **Σ(RS x WF)**.

Characteristics of ground motion, factor RG

RG depends upon the characteristics of both the ground motion and soil conditions. As such, RG has been expressed as 80% of the product of Sa(0.2) and the acceleration site factor, Fa, i.e., RG = Fa Sa(0.2) / 1.25.

Building characteristics, factor RB

Table 1 can be used to determine the value of RB of a building in terms of its fundamental period. If the building's period is not known, RB can be determined in terms of the building's structural system and height, as shown in Table 1. Note that RB is based on the predominant type of lateral force resisting system of the building structure.

Table 1. Building Characteristics, Factor RB.

	Period (T), s			
	0<T≤0.2	0.2<T≤0.5	0.5<T	
Number of Storeys	1 – 2	3 – 4	5 and up	Steel Moment Resisting Frame
	1 – 2	3 – 5	6 and up	Concrete Reinforced Moment Resisting Frame
	1 – 2	3 – 7	8 and up	Concrete Shear Wall
	1	2 – 4	5 and up	Braced Frame
Site Class A	1.0	1.1	1.2	Hard rock
Site Class B	1.0	1.2	1.3	Rock
Site Class C	1.1	1.2	1.3	Very dense soils and soft rock.
Site Class D	1.2	1.3	1.4	Stiff soil.
Site Class E	1.3	1.4	1.5	Soft soil.
Site Class F	1.5	1.5	1.5	Other.

*Note: Site Classes are defined in Table 4.1.8.4.A of the NBCC 2005.

The vulnerability index, V, can be determined using the following relationship:

$$\mathbf{V = RG \times RB \times \Sigma(RS \times WF) /10} \qquad (1)$$

Consequence index

The consequence index, C, considers the effects of two consequence parameters:

1) life safety and
2) functionality of the building.

Each of these parameters is assigned rating scales (RS) from 1 to 10 or from 0 to 10 as follows:

Life safety

RS = 1 for threat to very few persons (N is equal to or less than 1)
RS = 5 for threat to a few persons (N is between 1 and 10)
RS = 10 for threat to many persons (N is equal to or greater than 10).

The life safety parameter reflects the impact on life safety from malfunction or failure of the OFC during and immediately after the earthquake. The occupancy factor, N, is defined in the NBCC 2005 as the product of the occupied area exposed to risk in m^2, the occupancy density (number of persons per m^2) and the duration factor (average weekly hours of human occupancy divided by 100, equal to or less than 1.0).

Functionality – required for post-disaster functions or for immediate occupancy after the earthquake

RS = 0 if not applicable or if duration of breakdown greater than one week is tolerable
RS = 1 if breakdown between 1 week and 1 day is tolerable
RS = 5 for a post-disaster facility according to NBCC 2005
RS = 10 if full functionality immediately after the earthquake is required.

The consequence index, C, is equal to the summation of these two consequence rating scores, i.e. C=Σ(RS).

Seismic risk index

The seismic risk index, R, is the product of the vulnerability index, V, and the consequence index, C, i.e.

R = V x C (2)

Remarks

OFCs shall be ranked in accordance with the risk indices, with priority for mitigation being given to the OFCs with a higher risk index. For OFCs with equal, or nearly equal, risk indices, priority for mitigation shall be given to the OFCs with a higher consequence index.

For an OFC with a risk index less than or equal to 16, mitigation is optional due to the limited anticipated benefits of seismic risk reduction.

Application of the Seismic Risk Assessment

Detailed sample applications of the seismic risk assessment methodology are given in the CSA-S832 Standard on how to reduce the seismic risk of OFCS housed in buildings. For illustrative purposes, sample evaluation of OFCs for a building located in Victoria, British Columbia is given here. Fig. 3 shows the building and the OFCs considered in the sample calculations of the Standard.

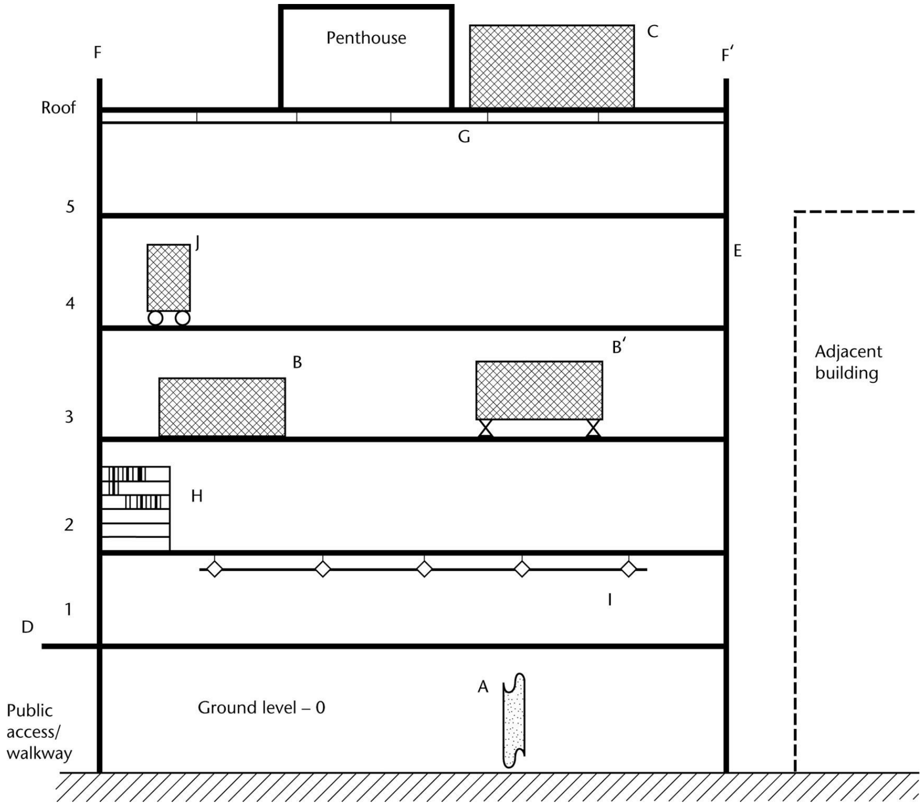

Figure 3. Building and OFCs under consideration in sample evaluation.

For the purpose of this example, it is assumed that the building was designed and built in 1977 in accordance with the 1975 NBCC. The building has six stories (plus one basement level not shown) and consists of reinforced concrete moment frames in both directions to act as the lateral and vertical load resisting system. The structure is founded on a stratum of stiff soil (Site Class D). The following OFCs are included in the assessment:

A. *Free-standard sculpture* - no connection; overturning ratio h/d=3.5.
B. *Electrical generator* – connections are rigid-mount brackets fastened directly to the floor, the capacity of the connections is doubtful, the generator is not located near any walls or other equipment, and continuous power should be supplied from the generator; overturning ratio, h/d=0.5.
C. *Electrical generator* – same generator and characteristics as OFC “B”, except connections are new vibration-isolated mounts with vertical and lateral stops fastened directly to the follow; connections are considered adequate to fully restrain the generator against overturning; overturn ratio h/d=0.5.
D. *Rooftop chiller* – connections are rigid-mount brackets fastened to a structural steel support frame supported by the roof slab and are considered very weak due to excessive rusting; chiller is located very close to the penthouse wall, so the gap is considered questionable; overturning ratio h/d=0.3.
E. *Canopy* – located over the main entrance; fixed and supported by the building structure with connection details that are considered adequate for all loading.
F. *Curtain wall* – the wall system is suspended from the ceiling floor slab with fully fixed connection details and is attached to the floor slab below with connection details that permit vertical slips; connections appear robust; movement/expansion gaps around glazing units are considered inadequate; the connections are considered to fully restrain the system against overturning; overturning ratio h/d=0.1

Results of the seismic risk reduction for the above OFCs are given in Fig. 4.

Project: Sample application for Victoria, BC	**Assessed by: DNS**	**Date: 18 April 2005**	**Floor/level: N/A**
Characterization of ground motion: $F_a = 1.02$ $S_a(0.2) = 1.2$ $RG = F_a \bullet S_a(0.2)/1.25 = 0.98$ $1/(2\ F_a \bullet S_a(0.2)) = 0.408$	Structure type = concrete moment frame Number of storeys = 6 Building characteristics (RB) = 1.4 $RG \times RB = 1.372$	Page 1 of 2	Room/area: N/A

				Vulnerability index, *V*													Consequences index, *C*								Risk index, *R*	Element characteristics, *RE*, min	Retrofit index, *RI*
				Restraint			Impact/ pounding		Overturning			Flexibility and location					Life safety			Functionality (tolerable downtime)							
	Quantity	Performance objective	Value	Full restraint	Partial restraint	No restraint	Adequate gap	Inadequate or questionable gap	Fully restrained	$h/d \le 1/(2\ F_a \bullet S_a(0.2))$	$h/d > 1/(2\ F_a \bullet S_a(0.2))$	OFC on or below ground floor	Stiff OFC above ground floor	Flexible OFC above ground floor	$RE = \Sigma(RS \times WF)$	$V = RG \times RB \times (RE)/10$	$N \le 1$	$1 < N < 10$	$N \ge 10$	> 1 week	> 24 h ≤ 1 week	Post-disaster	Functional	$C = \Sigma(RS)$	$R = V \times C$	$Min(RE)$ $(8 \le Min(RE) \le 12)$	$RI = 1.087\ (RE - Min(RE))$
OFC description				($RS \times WF$)			($RS \times WF$)		($RS \times WF$)			($RS \times WF$)					RS			RS							
A — sculpture	1	LS	100K	4	20	$\boxed{40}$	$\boxed{3}$	30	0	2	$\boxed{20}$	$\boxed{1}$	5	10	64	8.8	$\boxed{1}$	5	10	$\boxed{0}$	1	5	10	1	8.8	8	70
B — generator	1	CO	25K	4	$\boxed{20}$	40	$\boxed{3}$	30	0	2	$\boxed{20}$	1	$\boxed{5}$	10	48	6.6	$\boxed{1}$	5	10	0	1	$\boxed{5}$	10	6	40	12	39
B′ — generator	1	CO	25K	$\boxed{4}$	20	40	$\boxed{3}$	30	$\boxed{0}$	2	20	1	$\boxed{5}$	$\boxed{10}$	12	1.6	$\boxed{1}$	5	10	0	1	$\boxed{5}$	10	6	10	12	0
C — chiller	1	CO	75K	4	20	$\boxed{40}$	3	$\boxed{30}$	0	$\boxed{2}$	20	1	$\boxed{5}$	10	77	11	$\boxed{1}$	5	10	0	$\boxed{1}$	5	10	2	21	12	71
D — canopy	1	LS	5K	4	$\boxed{20}$	40	$\boxed{3}$	30	0	2	$\boxed{20}$	1	$\boxed{5}$	10	48	6.6	1	$\boxed{5}$	10	$\boxed{0}$	1	5	10	5	33	12	39
E — curtain wall	1	LS	2K	4	$\boxed{20}$	40	3	$\boxed{30}$	$\boxed{0}$	2	20	1	$\boxed{5}$	10	55	7.6	1	$\boxed{5}$	10	0	$\boxed{1}$	5	10	6	45	12	47

(Continued)

Figure 4. Sample seismic risk assessment (Victoria - before mitigation).

For OFCs with a seismic risk index less than or equal to 16, mitigation is optional due to the limited benefits of risk reduction, as stated earlier. For OFCs with a risk index greater than 16, the decision to reduce the seismic risk should also include consideration of the OFC's retrofit ability expressed by its retrofit index, RI (right most column of table in Fig. 4). The retrofit index, RI in percentage, is an indicator of the amount of retrofit that can be done for a given OFC in order to reduce the seismic risk to its lowest possible value considering the given building structure and site vulnerability. The higher the value of RI, the more the seismic risk can be reduced, i.e. the more effective the risk reduction measure will be. In other words, an OFC with a high risk index R but a very low RI value (say 10%) may not warrant a seismic reduction effort, as the major parameters contributing to the high risk are not related to the vulnerability of the component itself.

Suggested mitigation actions are given below for the five OFCs evaluated and results of these actions on the risk index are given in Fig. 5.

A. Sculpture - Provide properly detailed connection at base of the sculpture or affix sculpture to the structural wall; limit public access around the sculpture.
B. Electrical generator – Install new connections; limit access to generator area.
C. Electrical generator – Limit access to generator area.
D. Rooftop chiller – Install new strengthened connections; relocate chiller to a new location on roof to eliminate possibility of impact/pounding.
E. Canopy – Install additional connections (e.g., braces) to reduce overturning effects.
F. Curtain wall – Install new connections to accommodate anticipated structural movements.

Project: Sample application for Victoria, BC	**Assessed by: DNS**	**Date: 18 April 2005**	**Floor/level: N/A**
Characterization of ground motion: $F_a = 1.02$ $S_a(0.2) = 1.2$ $RG = F_a \bullet S_a(0.2)/1.25 = 0.98$ $1/(2\ F_a \bullet S_a(0.2)) = 0.408$	Structure type = concrete moment frame Number of storeys = 6 Building characteristics (RB) = 1.4 $RG \times RB = 1.372$	Page 1 of 2	Room/area: N/A

				Vulnerability index, V													Consequences index, C								Risk index, R	Element characteristics, RE, min	Retrofit index, RI
				Restraint			Impact/ pounding		Overturning			Flexibility and location					Life safety			Functionality (tolerable downtime)							
OFC description	Quantity	Performance objective	Value	Full restraint (RS × WF)	Partial restraint	No restraint	Adequate gap (RS × WF)	Inadequate or questionable gap	Fully restrained (RS × WF)	$h/d \le 1/(2\ F_a \bullet S_a(0.2))$	$h/d > 1/(2\ F_a \bullet S_a(0.2))$	OFC on or below ground floor (RS × WF)	Stiff OFC above ground floor	Flexible OFC above ground floor	$RE = \Sigma(RS \times WF)$	$V = RG \times RB \times (RE)/10$	$N \le 1$ (RS)	$1 < N < 10$	$N \ge 10$	> 1 week (RS)	> 24 h ≤ 1 week	Post-disaster	Functional	$C = \Sigma(RS)$	$R = V \times C$	$Min(RE)$ $(8 \le Min(RE) \le 12)$	$RI = 1.087\ (RE - Min(RE))$
A — sculpture	1	LS	100K	$\boxed{4}$	20	40	$\boxed{3}$	30	0	2	$\boxed{20}$	$\boxed{1}$	5	10	28	3.8	$\boxed{1}$	5	10	$\boxed{0}$	1	5	10	1	4	8	22
B — generator	1	CO	25K	$\boxed{4}$	20	40	$\boxed{3}$	30	0	2	$\boxed{20}$	1	$\boxed{5}$	10	32	4.4	$\boxed{1}$	5	10	0	1	$\boxed{5}$	10	6	26	12	22
B′ — generator	1	CO	25K	$\boxed{4}$	20	40	$\boxed{3}$	30	$\boxed{0}$	2	20	1	$\boxed{5}$	10	12	1.6	$\boxed{1}$	5	10	0	1	$\boxed{5}$	10	6	10	12	0
C — chiller	1	CO	75K	$\boxed{4}$	20	40	$\boxed{3}$	30	0	$\boxed{2}$	20	1	$\boxed{5}$	10	14	1.9	$\boxed{1}$	5	10	0	$\boxed{1}$	5	10	2	4	12	2
D — canopy	1	LS	5K	4	$\boxed{20}$	40	$\boxed{3}$	30	$\boxed{0}$	2	20	1	$\boxed{5}$	10	28	3.8	1	$\boxed{5}$	10	$\boxed{0}$	1	5	10	5	22	12	17
E — curtain wall	1	LS	2K	4	$\boxed{20}$	40	$\boxed{3}$	30	$\boxed{0}$	2	20	1	$\boxed{5}$	10	28	3.8	1	$\boxed{5}$	10	0	$\boxed{1}$	5	10	6	23	12	17

(Continued)

Figure 5. Sample seismic risk assessment (Victoria - after mitigation).

Effective mitigation measures are reflected in the reduction of the seismic risk indices, R, and the values of the retrofit indices. Note that OFC B' requires no specific mitigation due to its low seismic risk (R = 10) and retrofit index (RI = 0%). Details of the risk assessment methodology and the full sample calculations can be found in the CSA-S832-06 Standard (CSA 2006).

Conclusions

Recent earthquakes have shown that most casualties, injuries and economic losses have been caused by the falling debris of buildings' OFCs. While seismic provisions for the design and construction of building's structural elements are rather well established, similar guidance on the assessment and protection of OFCs in new and existing constructions is lacking. The Canadian Standards Association has published in 2006 the new Standard CSA-S832-06 which provides guidance on both the assessment and the mitigation of seismic risks associated with a building's OFCs. The Standard's seismic risk assessment methodology is compatible with the seismic provisions of the 2005 National Building Code of Canada and is applicable to new and existing buildings. The effectiveness of the methodology has been demonstrated through sample calculations.

Acknowledgments

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