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SEISMIC RISK REDUCTION OF OPERATIONAL AND FUNCTIONAL COMPONENTS OF BUILDINGS: STANDARD DEVELOPMENT

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SUMMARY

Recent earthquakes clearly demonstrated the tremendous impact of the failure of the so-called non-structural components of buildings upon life safety and economic losses. These non-structural components are essentially the operational and functional components (OFCs) of a building. Quite often, a building sustained only minor damage to its structural elements but was deemed not safe to operate or occupy due to extensive damage to its OFCs. It has been well documented that the major cause of death and injuries in most earthquakes has been due to the failure of OFCs. National codes and guidelines were in place for the seismic design, evaluation and upgrading of building structures in Canada and other countries, similar documents did not exist for the OFCs of buildings. In 1997, the Canadian Standards Association (CSA) established a Technical Committee on "Seismic Risk Reduction", which was tasked to develop a new CSA Guideline on the seismic risk reduction of OFCs of buildings. This paper presents the salient features of the guideline and its further development into a national standard.

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, such as architectural elements, mechanical and electrical units, tele-communication systems and building contents. Such operational and functional components, or OFCs, also known as non-structural components, include:

(i) Architectural components (stairways, parapets, cladding systems, suspended ceilings etc),
(ii) Mechanical and electrical equipment (emergency power systems, fire protection systems, storage tanks, piping systems, radar and object-tracking devices, computer and building control systems, transformers etc), and
(iii) Building contents (office equipment, storage racks, file cabinets etc).

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Recent earthquakes clearly demonstrated the tremendous impact of the failure of the OFCs of buildings upon life safety and economic losses. More and more, the seismic protection community is realizing that the protection of a building must include a building's structural components as much as it's OFCs. Benefits of seismic protection of OFCs include improved life safety, better property protection, reduced economic and financial impact, and enhanced search and rescue operations.

SEISMIC HAZARDS OF OFCS

Earthquakes along the Pacific rim, such as India, Japan, Taiwan, and U.S.A. during the past 20 years demonstrated the power of nature and the catastrophic impact of such power upon urban cities. Impact of failure of OFCs include: majority of injuries due to falling debris of OFCs, buildings being non-operational due to failure of building systems and equipment, and serious problems for search and rescue operations after the earthquake, resulting in an increase in casualties.

In Canada, the 1988 Saguenay earthquake, the strongest event in Eastern North America recorded within the last 50 years, caused very little structural damage. A great majority of the injuries, property damage and economic loss was caused by the failure of functional and operational components in buildings.

Failure of equipment and the debris caused by falling objects could critically affect the performance of vital facilities such as emergency command centers, fire and police stations, hospitals, power stations and water supply plants. For example, during the 1994 Northridge earthquake in California, several major hospitals had to be evacuated, not because of structural damage, but due to failure of non-structural components such as emergency power systems, air control (heating and cooling) units, falling ceilings and light fixtures.

For the Nisqually (Seattle-Olympia) earthquake in February 2001, a large portion of the estimated $2 billion dollar loss was attributed to damage to non-structural components such as parapets, chimneys, URM wall sections, ceiling systems and light fixtures.

STANDARDS AND GUIDELINES

In the US, seismic provisions for OFCs can be found in NEHRP (National Earthquake Hazard Reduction Program) by the Building Seismic Safety council [1] and the Uniform Building Code (UBC) by the International Conference of Building Officials [2]. In Canada, there are the National Building Code of Canada [3] and the Canadian Standards Association's Guideline [4] with provisions governing the seismic requirements of OFCs. There are also industrial guidelines on the seismic restraint requirements of various OFCs of a building.

Standards

Under the NEHRP and sponsored by the Federal Emergency Management Agency (FEMA), several reports (FEMA 302, 303, 310, 74) have been developed on the seismic provisions for OFCs in new buildings and on the evaluation and rehabilitation of OFCs in existing buildings. The UBC is probably the most widely used code in the US for seismic design. Seismic provisions for both the structural and non-structural components are specified in the UBC.

Whether it is the NEHRP/FEMA or the UBC, the design provisions are generally expressed in terms of empirical formula for both the seismic design force and displacement (or relative displacement) requirements for the OFCs. Similar approach is used in both codes in expressing the design lateral seismic forces in terms of empirical formula using a seismic parameter (in relation to the seismic zone, type of soil, location and type of the OFC etc.), an importance factor (which depends on the occupancy category or performance requirements) and the weight of the OFC. Provisions on the allowable displacements are generally associated with the relative displacement of two connection points on separate structural components or buildings. Maximum lateral deflections are commonly expressed in terms of percentage of the storey height.

In Canada, the National Building Code of Canada (NBCC) has been primarily developed for the design of structural components of new construction. While the design of building structures for seismic effects reflects the Canadian seismic hazard, the design of nonstructural components (i.e. functional and operational) as required by NBCC, is based on some empirical amplification factors of the seismic effects, which are not documented. Evaluation and mitigation of seismic hazard of operational and functional components for existing buildings are not addressed in the NBCC.

In 2001, the Canadian Standards Association (CSA) published the “Guideline for the Seismic risk reduction of OFCs of buildings: CSA-S832”, which is currently being further developed into a Standard. The guideline provides information and methodology to identify and evaluate seismic hazards and to undertake appropriate mitigation strategies and techniques. CSA-S832’s seismic risk assessment methodology can be used to determine the seismic risk rating of each OFC in terms of its vulnerability and consequence of failure. While the guideline is applicable to both new and existing building construction, its use in ranking/prioritizing OFCs in need of seismic retrofit is most effective and efficient. Details of the CSA guideline are given later in this paper.

Guidelines

There are industrial guidelines on the seismic restraint requirements for various OFCs of a building. These guidelines provide more detailed and often prescriptive requirements on the seismic restraint requirements of specific elements or systems. These guidelines generally refer to other codes and standards for detailed analysis.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE [5] published a comprehensive guide on the seismic restraint of HVAC, plumbing and electrical systems. In its comparison of code forces between the 1997 UBC, 1997 NEHRP and 1995 NBCC, it was found that the codes have similar forces for the rigidly mounted boiler on grade but rather different forces for (a) rigidly mounted boiler on roof and (b) vibration-isolated pump on grade or on roof. In all cases, the 1997 UBC requires higher seismic forces than the 1997 NEHRP. The 1995 NBCC seismic design forces are comparable to the 1997 NEHRP requirements for the rigidly mounted boiler but with lower design forces for the vibration-isolation pump.

Details on seismic restraint (bracing systems) for pipes, ducts and conduits are given in the “Seismic restraint manual, guidelines for mechanical systems” which was published by the SMACNA (Sheet Metal and Air Condition Contractors’ National Association) [6]. The manual gives only prescriptive specifications for seismic restraint of mechanical systems. Isolated ducts and fire sprinkler systems are not covered in the SMACNA manual.

Most codes refer to the NFPA’s (National Fire Protection Association) [7] “Standard for the installation of sprinkler system” for seismic restraint requirements of rigidly mounted sprinkler systems. Prescriptive requirements in terms of the size, the spacing and the attachment specifications of the bracing system are tabulated in the NFPA standard. The standard also provides guidance on piping between buildings or seismic joints.

CSA-S832 GUIDELINE ON SEISMIC RISK REDUCTION OF OFCS

In 1997, the Canadian Standards Association (CSA) established a Technical Committee on "Seismic Risk Reduction", which was tasked to develop a new CSA "Guideline on the seismic risk reduction of OFCs of buildings, CSA-S832". The guideline was based on the "Guideline for the seismic evaluation and upgrading of non-structural buildings components" published by the Public Works and Government Services Canada, PWGSC in 1995 [8]. The PWGSC guideline was developed mainly for office buildings.

The new CSA Guideline covers most occupancy types included in the National Building Code of Canada. The Guideline provides guidance on:

(1) Recommended procedure for conducting risk assessment of OFCs in new and existing buildings,
(2) A risk assessment methodology to determine the seismic risk rating for each OFC,
(3) Analytical methods to determine the degree of seismic deficiency and to ascertain the level of mitigation required, and
(4) Mitigation prioritization and techniques.

The CSA-S832 guideline introduced a new parametric methodology for assessing the seismic risk of OFCs. The risk is defined as the product of the OFC's vulnerability and the consequence of the failure of the OFC. For new building construction, 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 OF OFCS

The recommended approach to risk assessment is to determine the seismic risk rating for each OFC and establish a ranking based on numerical risk rating scores. The seismic risk rating is determined as the product of the OFC's seismic vulnerability (probability of failure) and the consequences of failure (probability of resultant death, injury, or loss of building functionality) if failure/malfunction occurs.

The vulnerability factor, V, considers the effects of six vulnerability parameters: OFC restraint, impact/pounding, OFC overturning, OFC flexibility and location, characteristics of ground motion and building characteristics. Each of the first four OFC-related parameters was assigned rating scales (RS) and weight factors (WF) while the last two parameters were related to building and site/ground motion characteristics (RB and RG respectively).

Vulnerability rating score

The followings summarize the vulnerability parameters and the evaluation of the vulnerability rating score, 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/(2vF))
RS = 10 if (h/d) is greater than (1/(2vF))

Where h is the distance from support or restraint to the center of gravity or top of the OFC, d is the horizontal distance between the OFC supports, v is the zonal velocity ratio for the location of the building and F is the foundation factor.

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, RG
RG = 0.1 if vF is less than 0.10
RG = 0.5 if vF is greater than 0.1 and less than or equal to 0.3
RG = 1.0 if vF is greater than 0.30

Note that RG depends upon the characteristics of ground motion and soil condition, and is expressed as the product of the zonal velocity, v, and the foundation factor, F. as defined in the NBCC 1995.

Building characteristics, RB
RB = 1.5 for frames structure
RB = 1.0 for other structure types

Note that RB is based on the predominant type of lateral force resisting system of the building structure.

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

$$V = RG \times RB \times \Sigma(RS \times WF) / 10$$

Consequence rating score
The consequence rating score, C, considers the effects of two consequence parameters: life safety and functionality of the building. Each of these parameters was assigned rating scales (RS) from 1 to 10 or from 0 to 10 as follows:

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

Note that the life safety parameter reflects the impact on life safety from malfunction or failure of OFC during and immediately after the earthquake. The occupancy factor, N, is defined as the product of area (occupied area exposed to risk in metre square), occupancy density (persons per metre square) and duration factor (average weekly hours of human occupancy divided by 100, and is equal to or less than 1.0) and is as defined in the NBCC 1995.

Functionality – required for post-disaster functions or for immediate occupancy after the earthquake
RS = 0 if no applicable or if breakdown greater than one week is tolerable
RS = 1 if breakdown between 1 week and 1 day is tolerable
RS = 5 if the building is to be used as post-disaster facility according to NBCC 1995
RS = 10 if fully functional immediately after earthquake is required.

The consequence rating score, C, is equal to the summation of the two consequence effects, i.e. $C = \Sigma(RS)$.

Seismic risk rating score
The seismic risk rating score, R, is the product of the vulnerability rating score, V, and the consequence rating score, C, i.e. $R = V \times C$.

CSA-S832 recommends the following categories of seismic risk rating levels:
(1) Low risk if R is equal to or less than 15
(2) Moderate risk if R is greater than 15 but less than or equal to 50
(3) High risk if R is greater than 50

Remarks

An OFC with a low seismic risk rating may be considered a low priority for mitigation. An OFC with moderate seismic risk rating warrants mitigation; priority for mitigation of OFCs should take into account the ranking of all OFCs under consideration and the short- and long-term mitigation strategies for the building. For an OFC with a high seismic risk rating, immediate mitigation action should be considered.

Forms for seismic risk assessment of OFCs are given in the Guideline. The forms include all the parameters and the associated values for a quick assessment of the seismic risk of individual OFCs using multi-choice approach and simply calculations. Alternatively, the users can develop a spreadsheet to automate the computations and to create a database of the OFCs assessed. The database can later be used to rank the OFCs in accordance with its seismic risk rating score.

The CSA seismic risk assessment methodology is applicable to both new and existing buildings. It can be used to screen OFCs under consideration and to prioritize OFCs for detailed analysis and/or mitigation. Use of the methodology is simple, the rationale for the methodology is clear and the resulting seismic risk ratings are generally repeatable. Other approaches involve either subjective judgment (which may not be repeatable), prescriptive requirements with lack of clearly defined rationale or detailed analysis procedures, which may not be required for OFCs with moderate to low seismic risk ratings (i.e. not cost effective).

FROM CSA-S832 GUIDELINE TO CSA-S832 STANDARD

The 2001 edition of CSA-S832 guideline is currently undergoing revisions to refine the risk assessment methodology and to reflect the proposed seismic provisions in the new NBCC 2005. In accordance with the simplified analytical method in the NBCC 1995, the lateral inertial force, V_p, is defined as:

$V_p = v\ I\ S_p\ W_p$ for architectural components, and

$V_p = v\ I\ C_p\ A_r\ A_x\ W_p$ for mechanical and electrical components.

where

v = zonal velocity for the location of the building
I = seismic importance factor for the building, varying from 1.0 for normal use buildings, 1.3 for schools to 1.5 for post-disaster buildings.
S_p = horizontal force factor for architectural components, varying from 0.7 to 6.5.
W_p = weight of part or portion of the structure

C_p = seismic coefficient for components of mechanical and electrical equipment, varying from 0.7 to 1.5.
A_r = response amplification factor to account for attachment type for mechanical and electrical equipment, varying from 1.0 (for components that are both rigid and rigidly connected and for non-brittle pipes and ducts) to 1.5 (for components located on the ground that are flexible or flexibly connected except for non-brittle pipes and ducts) to 3.0 (for all other cases).
$A_x = 1.0 + (h_x/h_n)$, which is the amplification factor to account for the location of the mechanical or electrical components within the building.
h_x = height (location) of the component above the base of building
h_n = height of the building above its base

As per the simplified analytical method in the proposed seismic provisions in NBCC 2005, the lateral inertial force, Vp, is defined as:

$V_p = 0.3\ F_a\ S_a(0.2)\ I_E\ S_p\ W_p$ for architectural, mechanical and electrical components.

where

F_a = acceleration based site coefficient.
$S_a(0.2)$ = spectral response acceleration value at 0.2s.
I_E = importance factor of the building.
$S_p = C_p\ A_r\ A_x / R_p$ (value of S_p is between 0.7 and 4.0.)
C_p = element or component factor
A_r = element or component force amplification factor
A_x = height factor = $1.0 + (2h_x/h_n)$
R_p = element or component response modification factor

The CSA Technical Committee's current tasks include refinement of the seismic risk assessment methodology and the revision of the methodology in accordance with the differences in seismic provisions between the NBCC 1995 and the NBCC 2005.

SUMMARY

Earthquakes, the inevitable natural hazards, can cause devastating disasters to our built environment. While the design, evaluation and upgrading of a building's structural components against seismic hazards have been well established, the evaluation and mitigation of operational and functional components is a relatively new activity for the seismic protection communities. During the past few years, significant progress has been made towards the understanding of seismic behavior of operational and functional components in terms of field observation and research efforts. Standards and guidelines, such as the CSA-S832 "Guideline for the seismic risk reduction of operational and functional components of buildings" provide guidance to engineers and designers in relation to mitigating the seismic risk associated the building's operational and functional components. To reflect the technology advancement, standards and guidelines need to continue to evolve in order to be able to provide the state-of-the-art guidance in safeguarding the operational and functional components of a building.

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REFERENCES

1. Building Science Safety Council. "NEHRP Recommended provisions for seismic regulations for new buildings and other structures: parts 1 & 2". National Earthquake Hazards Reduction Program. Washington, D.C. 2000.
2. International Conference of Building Officials (ICBO). "Uniform Building Code". Whittier, California. 1997.
3. National Research Council of Canada (NRCC). "National Building Code of Canada (NBCC 1995)". Ottawa, Canada. 1995.
4. Canadian Standards Association (CSA). "Guideline for Seismic Risk Reduction of Operation and Functional Components for Buildings, CSA-S832-2001". Rexdale, Ontario. 2001.
5. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE). "A practical guide to seismic restraint". Atlanta. U.S. 1999.
6. Sheet Metal and Air Condition Contractors' National Association Inc. (SMACNA). "Seismic restraint manual, guidelines for mechanical systems". Chantilly, Va.
7. National Fire Protection Association (NFPA). "Standard for the installation of sprinkler systems: chapters 4 – 6.4.3". NFPA, Quincy, Mass.
8. Public Works and Government Services Canada (PWGSC). "Guideline for the seismic Evaluation and Upgrading of Non-Structural Building Components". PWGSC. Ottawa, Canada. 1995.