17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan – September 27th to October 2nd, 2021

DESIGN FOR ENHANCED POST-EARTHQUAKE PERFORMANCE USING PROVISIONS OF THE 2020 NATIONAL BUILDING CODE OF CANADA

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Abstract

For the past three decades the National Building Code of Canada (NBC) seismic provisions have focused on a life safety approach to seismic design with an emphasis on ductile design, with seismic forces reduced using well-defined plastic yielding elements. Designers are required to use capacity design provisions and work away from the plastic hinge zone to protect the gravity system from damage that would affect its load carrying capability. Observances of buildings designed using a similar methodology in past earthquakes, such as the 2011 Christchurch, New Zealand earthquake, has shown that buildings designed this way can perform very well from a life safety standpoint, but the buildings may well be damaged beyond economic repair and may not be usable after a seismic event. The provisions in past editions of the NBC have tried to provide extra protection to buildings classified as “Post Disaster” and “High Importance” by requiring ductile seismic systems and higher forces than for Normal Importance buildings. Under past and present Canadian Code provisions High Importance and Post Disaster buildings have been required to have tighter drift limits and stricter limits on irregularity. The desire for improved seismic performance in these buildings is a hidden aim in these provisions; however, the Christchurch earthquake showed that these provisions do not necessarily mean that the buildings will be functional after a rare Code level seismic event. The successful post-seismic results for buildings after the 2016 Kumamoto, Japan earthquake and the robust seismic design exhibited by Japanese designers contributed to the Canadian Code being adapted to try to emulate some of these desirable results. For the 2020 edition of the NBC, new provisions were introduced for High Importance and Post Disaster buildings that require designers to account for two levels of seismic event: (1) a rare event in which ductility and hinging of plastic yielding zones can occur, and (2) a lower return period seismic event in which the seismic system and the gravity system must remain elastic. This paper will discuss these provisions and show how the design of a simple steel building in Vancouver would be modified by these provisions. Choosing the seismic system wisely and using systems such as tension-compression bracing will result in a more robust design than using systems such as tension-only bracing that yield or buckle early. Seismic systems that use high ductilities to reduce design forces to the level that yielding, or buckling would be expected to occur in even minor seismic events will also have more difficulty in satisfying the new seismic design provisions of the NBC. This paper shows how early yielding systems are modified by the new seismic design provisions of the NBC to provide better performance in both smaller and larger seismic events.

Keywords: Improved seismic design performance, Canadian, Codes,

1. Introduction

Prior to the 2020 edition of the National Building Code of Canada (NBC), the primary focus of the Code was life safety for all buildings, with buildings that needed to be operational after the earthquake designed for slightly higher forces. Ductile design principles are used extensively in the NBC to reduce forces and make seismic design more economical. Recent earthquakes in countries with modern building codes have shown that good seismic engineering through ductile design principles can reduce the death toll from earthquakes. However, concern was raised after recent earthquakes where the loss of life was reasonably small but damage to buildings and the economy was in the billions of dollars – while ductility was saving lives as intended, it was leaving areas hit by seismic events devastated. In the 2020 edition of the NBC,[1] enhanced seismic performance requirements were introduced to try to reduce property loss for lower return period earthquakes while still allowing the building to perform in a ductile manner under the design level event. These requirements involve performing a set of checks on a subset of buildings that are felt to be most critical to maintain functionality and occupancy immediately after an earthquake. In these checks, forces from a lower return period earthquake are imposed on a structural model of the building with the requirement that the building remain elastic. In the most recent editions of the NBC prior to the 2020 edition, seismic design was based solely on having the building behave in a ductile manner and designed solely for the 2% in 50-year Code design level event.

2. The Need for Enhanced Seismic Performance

Since 1953, when the National Building Code first started addressing seismic loading, the desire has been protection of life and life safety with the mantra that the occupants of the building should be able to exit safely after a major earthquake. Designers have worked to make their buildings more ductile so that rare and large earthquakes could be withstood without collapse. With ductile design the building might require demolition after the event; per Code, the structural engineer had done their job if the occupants got out safely. In this vein, structural research worked hard to get both the ductility factor R_d and overstrength factor R_o higher for a given system thus increasing the economy of the system, as illustrated in Figure 1. Figure 1a shows a resort hotel in Mexico in the town of Barra de Navidad – the hotel was operating when this photo was taken in 1983. Figure 1b shows the same hotel in 2003 – the hotel had been severely damaged in an October 1995 magnitude 7.3 event and eight years later it was still abandoned. The hotel’s bedrooms are in the concrete shearwall structure at the right and although the walls of this portion of the complex were heavily damaged, they do illustrate the concept of safe exit. The dining, bar, and administration structure at the left is designed with a concrete moment frame. The collapsed roof beams and floor structure did not provide safe exit. While most engineers feel that they have done their job well if people can exit the building safely, building owners want a structure that they can operate after the earthquake.

Fig. 1a (left) – Resort hotel in Barra de Navidad, México, in 1983. Fig. 1b (right) – Same hotel seen in 2003, many years after heavy damage in an October 1995 earthquake. Moment frame structure at left did not permit safe exit.

2.1 The Challenge of Ductile Design

The concept of ductile design is to concentrate the yielding into specific sections of the building structure such that they can absorb energy and protect the remaining part of the structure. However, with the use of high R_dR_o values, there can be an early onset of damage in the building in these ductile areas during much less than design level earthquake events. The damage for the design level earthquake can be such that the building needs to be demolished.

The need for consideration of recovery in seismic design can be seen in three recent seismic events; all were about the same magnitude and all were close to an urban area, as shown in Table 1. The first of these occurred in 2010 when a magnitude 7.0 event essentially destroyed Port-au-Prince in Haiti – the area had not experienced an earthquake in more than 200 years and structural codes, especially seismic provisions, were seldom observed or enforced. The death toll was in some estimates almost a quarter of a million people. The economy already in difficulty was shattered. In 2017 – seven years after the event – 2.5 million people were still in need of aid and, in 2021, eleven years after the earthquake, recovery still remains slow.

Table 1 – Effects of Three Recent Earthquakes Near Urban Areas

Event	**Magnitude and Depth**	**Deaths**	**Damage**	**Codes**
Port Au Prince (Haïti) (January 12, 2010)	7.0 at 13kM	100,000 to 230,000	Extensive and many total collapses	Lax to non-existent and not enforced
Christchurch (New Zealand) (February 22, 2011)	6.2 at 5kM	185	Significant damage many buildings both new and old demolished	Heavily based on reducing forces by accounting for ductility
Kumamoto (Japan) (April 16, 2016)	7.0 at 10kM	48	Minor damage to engineered buildings	Robust design with ductile detailing

The second earthquake of interest is the magnitude 6.2 event in Christchurch, New Zealand, on February 22, 2011. This event was a moderate earthquake of short duration; however, it was close to the central business district and resulted in collapse of several buildings and brick façades. The central business district was barricaded off with only rescue and recovery personnel allowed in for several years. More than 1,300 buildings were subsequently demolished in the central business district and, in the surrounding suburbs, the number of demolitions approached the 10,000 mark. Many of the buildings that were demolished were sufficiently new that they had been designed to modern seismic codes. The cost of rebuilding Christchurch is estimated at $40 billion, and the event is expected to influence the New Zealand economy for decades. The huge societal costs of the Christchurch earthquake were observed by Canadians and Canadian Code writers, who felt that a different approach in the Canadian Code was needed if a similar fate was to be avoided in Canadian cities.

The third earthquake is the Kumamoto, Japan earthquake of April 16, 2016. As with the other two earthquakes, this event happened close to and partly under an urban area. Japanese seismic design is very robust and there was extraordinarily little damage to engineered building structures (Figure 2b); however, there were extensive landslides and castle walls built of unreinforced masonry were damaged (Figure 2a). There were 48 “direct” deaths in the Kumamoto earthquake and 170 “indirect” deaths from the earthquake. The direct deaths came from actions during the earthquake itself while the indirect deaths were from health issues caused after the earthquake. Several of the indirect deaths were caused by deep-vein thrombosis, better known as economy-class syndrome, from people sheltering in their cars after the earthquake. Other indirect deaths came from relocation of frail patients in hospitals that were temporarily without services. The speed of recovery and low damage to engineered structures in Kumamoto from a large shallow earthquake close to an urban area are goals for consideration in the Canadian Code.


Fig. 2a (left) – Castle in Kumamoto, Japan, in 2018 showing damage from the 2016 earthquake. Damage is mostly at the top of the stone block wall; the wooden castle above does not appear damaged. Fig. 2b (right) – Urban Kumamoto, where the skyline does not exhibit gaps for collapsed or missing buildings; businesses are open and there are no signs of damage.

2.2 Pre-2020 Provisions in the NBC for Critical Buildings

Starting with the 1965 edition of the NBC, there has been a realization that certain buildings need to be able to continue to operate after a seismic event. To this aim, an importance factor, I_E, was introduced that required increased forces to be used in the seismic design of those buildings along with tighter drift limits. This is shown in Table 2.

Table 2 – Importance classification and expected outcome for buildings in the NBC

Importance Classification	I_E	Example	Desired Outcome after 2% in 50-year event
Low Importance	0.8	Storage lockers, outdoor sculptures	Collapse Prevention
Normal	1.0	Office and residential buildings	Life Safety
High Importance	1.3	Schools and community centres	Emergency Shelter
Post Disaster	1.5	Hospitals, firehalls, ambulance	Continued operation

2.3 Provisions in the NBC to Influence the Design for Rapid Recovery

The National Building Code of Canada has several provisions to help the buildings most wanted to be occupied rapidly after an earthquake; to achieve that aim, the following provisions have been included in NBC 2020[1, 2]. While some of the provisions have been in the NBC from several previous editions of the Code, there has been a progressive drive to include more provisions to help buildings that are critical within the community to be able to be occupied soon or immediately after the event.

1) For ductile design of High Importance and Post Disaster buildings, an importance factor greater than 1.0 is used when computing the forces thus increasing the load that the Seismic Force Resisting System (SFRS) must be capable of resisting; this in turn results in yielding occurring only at higher level earthquakes and less damage for the design level earthquake.
2) For High Importance and Post Disaster buildings, there are restrictions on irregularities depending on the seismic risk category with the most restrictions in the highest seismic risk category.
3) The permitted drift limits for the design level event are more restrictive for High Importance and Post Disaster buildings than they are for Normal Importance buildings.
4) Non-structural elements (operational and functional components) must be restrained for higher forces for High Importance and Post Disaster buildings.
5) In the three highest seismic categories (SC2, SC3, and SC4) for Post Disaster buildings and the two

highest seismic categories (SC3, SC4) for High Importance buildings, there is a requirement to look at two earthquake levels: (1) the 2% in 50-year event for ductile design, and (2) a lower return period event in which the structure shall remain elastic.

6) For Normal Importance buildings in the highest seismic category (SC4) with a height above grade of 30m, it is a requirement to look at a seismic event of 2% in 50 years for ductile behaviour and an event corresponding to 10% in 50 years for elastic behaviour of structural members other than the ductile lateral load resisting system.

2.4 The Role of Irregularity in Enhanced Performance Seismic Design

One of the findings from past seismic events is that buildings that are regular perform better than those that have irregularities. The irregularities tend to concentrate the damage of the building into a specific area and are often difficult to analyze properly. Restricting the form of the building to prevent irregularities occurring is an important step to make the building perform better in response to earthquake loading.

Ten different irregularities are recognized by NBC, and the requirements for these vary depending on the seismic category and the building importance. Some irregularities such as weak storeys are only permitted in Normal Importance buildings in the very lowest areas of seismic activity. Weak storeys have been shown to be a particularly severe form of irregularity, and this type of irregularity has been responsible for many of the building collapses and fatalities in both Haiti and in several California events. Some irregularities such as soft storeys are banned outright in areas of higher risk, while other irregularities such as mass irregularity may be included in the design provided additional analysis is done to address irregularity. Buildings that are regular will behave better in seismic events than those buildings with irregularities and therefore regular buildings are more likely to exhibit improved seismic behaviour. With depressing frequency, post-earthquake photos show buildings with weak storeys that have failed in the event and often killed the occupants inside.

Table 3 – Irregularity restrictions for Buildings Less than 20m and Ts Less than 0.5 seconds

		High Importance				Post Disaster			
Type	Description	SC1	SC2	SC3	SC4	SC1	SC2	SC3	SC4
1	Vertical Stiffness				NP			NP	NP
2	Mass Irregularity								
3	Vertical Geometrical				NP			NP	NP
4	In-Plane Discontinuity				NP			NP	NP
5	Out-of-plane Offset				NP			NP	NP
6	Weak Storey		NP	NP	NP		NP	NP	NP
7	Torsional Sensitivity				NP			NP	NP
8	Non-Orthogonal				R			R	R
9	Gravity Induced Lateral Demand				NP			NP	NP
10	Sloped Column				NP			NP	NP

In Table 3, the “NP” entries are special “Not-Permitted” restrictions that apply to the building; many of these restrictions are only because the building is Post Disaster or High Importance. What we see from Table 3 is that irregularity is much more restricted in Post Disaster buildings than in High Importance buildings; these restrictions are more extensive than for Normal Importance buildings. We also see that the restrictions take place mostly in the higher seismic categories (SC3 and SC4). What some engineers are concerned about is that there are very few “work arounds” for buildings that architects are designing that violate the irregularity rules. Buildings that do not have irregularities do behave better in seismic events than buildings with irregularities.

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2.5 NBC 2020 Code Requirements for Seismic Performance Checks

To address the concern that buildings that are critical to remain operational after an earthquake, NBC 2020 introduced requirements to require High Importance and Post Disaster buildings to have a second level of evaluation to make sure that, under smaller and therefore less rare events, the seismic system remains elastic. These requirements are shown in Table 4. Table 4 also shows that NBC 2020 has tighter drift limits for High Importance and Post Disaster buildings for these smaller lower-level events.

Table 4 – Seismic Requirements in NBC 2020 for evaluation of Elastic Response

Importance	Importance Factor for ductile design event.	Elastic Behaviour required at lower-level Earthquake using forces corresponding to R_dR_o=1.3	Elastic Response Earthquake Required in these seismic categories	Maximum Inter-storey Drift under 2% in 50-year event any Seismic Category	Maximum Inter-storey Drift under lower-level event using I_E=1.0 R_dR_o=1.3
Post Disaster	I_E=1.5	5% in 50 years (1 in 1000 years)	SC2, SC3, SC4	0.01h_s	0.005h_s
High Importance	I_E=1.3	10% in 50 Years (1 in 475 years)	SC3, SC4	0.02h_s	0.005h_s
Normal Importance >30m in height	I_E=1.0	10% in 50 Years (1 in 475 years)	SC4	0.025h_s	No separate drift requirement
Normal Importance <=30m in height	I_E=1.0	Evaluation for seismic effects is only required under the ductile design level event (2% in 50 years)	N/A	0.025h_s	Evaluation under lower return period seismic event not required.

While the desire is to have the building exhibit elastic behaviour and hence have minimal damage after the lower-level event, it is expected that buildings that behave elastically under the lower-level event will behave well in the design level event as ductility requirements are still necessary albeit for a lesser ductility demand for this level of earthquake. A good response under lower and larger events improves the resistance of the building to smaller events and hence the ability of the community to recover quickly after a seismic event of small or large magnitude.

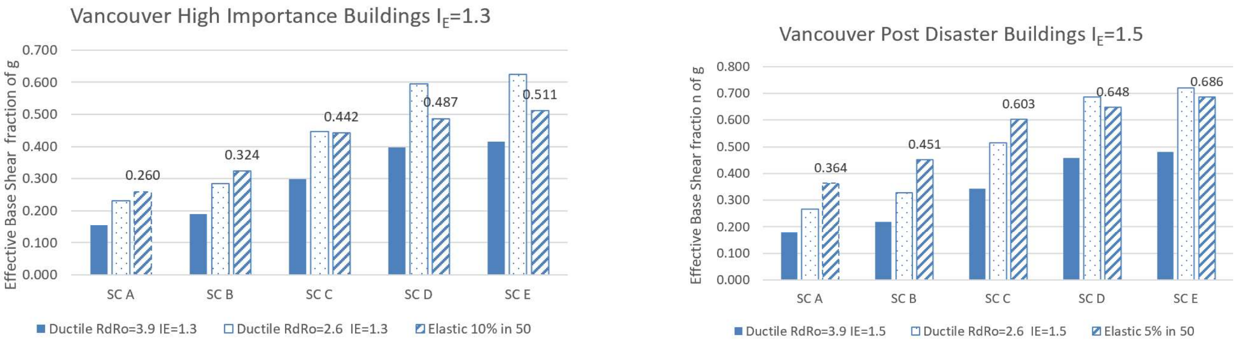


Fig. 3 – Effective base shear for low period buildings in Vancouver with different foundation conditions comparing the force for ductile design with the force for elastic design for both High Importance and Post Disaster buildings. The hatched bars are the effective base shear to be used for elastic design.

Figure 3 shows the effective base shear for low period buildings in Vancouver with different foundation conditions (Site Classes A to E, noted SC A to SC E) comparing the force for two different ductile designs (for 2% in 50-year event) with the force for elastic design (for lower-level earthquakes, 5% and 10% in 50-year events) for both High Importance (I_E=1.3) and Post Disaster (I_E=1.5) buildings. The solid bars are the effective base shear for inelastic ductile design using R_dR_o=3.9 (ductile concentric brace bays) while the hatched bars are the force that is used for elastic design for lower-level earthquakes. What is immediately apparent is that when using an earthquake that has a lower return period the building needs to be designed for higher loads and it might be thought that the elastic design requirements are going to totally dominate the design; however, there are several factors that will help reduce the dominance of the elastic loading. What is seen in Figure 3 is that for Vancouver in all cases there is a considerable increase in the base shear forces for elastic design over inelastic design if R_dR_o=3.9 is used but the base shear forces are reasonably close if R_dR_o=2.6 had been used for the ductile design. A quick take on this would be that if the goal is to make the elastic design more of a check and less of a governing criterion, the design might need to start with a system that has lower R_d values; however, as will be noted in the next section and the examples there are other factors that will affect how easily the elastic design checks can be carried out particularly related to the choice of ductile system.

In NBC 2020 a series of performance checks were introduced to seismic design protocols for a select group of buildings that are particularly desirable to have perform well. This group includes Post Disaster buildings, High Importance buildings, and taller Normal Importance buildings that if damaged can close off a large area of an urban area to limit the risk of injury should they collapse. The procedure outlined in NBC 2020 is all buildings are designed using the normal ductile design procedures that designers are familiar with using the normal 2% in 50-year probability of exceedance event (1:2475-year event). For this event, the building should perform in a ductile manner. Importance factors and restrictions on irregularity are applied to High Importance and Post Disaster buildings to help them perform better than Normal Importance buildings for both smaller and larger events. Following the ductile design, a select group of buildings as outlined in Table 4 – predominantly High Importance and Post Disaster buildings in higher risk seismic areas – are required to go though additional checks. These checks involve determining the forces from a lower return period event (5% in 50-year or 10% in 50-years depending on the importance classification) usually via an analysis of a model of the structure. The intent is that for the lower return period event the structure should remain "elastic". To help protect the gravity system and non-structural elements there is also a deflection check required for the lower return period event for those buildings that are High Importance and Post Disaster.

In NBC 2020 the forces for the lower-level events are calculated using R_dR_o=1.3. There are several factors that help make the structure that being designed comply with the requirements:

a) The spectrum for the computation of base shear for loading from the 10% in 50-year or 5% in 50-year events will be less than the spectrum in the 2% in 50-year event.
b) The effects of accidental eccentricity need not be considered if the building is not torsionally sensitive. For High Importance and Post Disaster buildings, the requirement that the building not be torsionally sensitive is already in the Code irregularity design provisions.
c) For High Importance and Post Disaster buildings, when evaluating for elastic behaviour under a seismic event with an intensity less than the 2% in 50-year event, one does not include the importance factor when computing the forces for analysis.
d) When computing the elastic behaviour, it is not required to consider the resistance factors when considering the onset of inelastic action (Ø factors are set to 1.0).
e) It is acceptable to continue to use the "cut-off equations" for buildings with periods less than 0.5 seconds provided the building is not a site class F.

However, despite these helping clauses, it is noted that when using very highly ductile systems such as R_d=5.0 moment frames the lower-level event checks will govern. It will be shown in the summary of examples later in this paper that rather than choosing systems such as tension-only concentric braces as the building system the designer will be guided to choose tension-compression braces perhaps using R_dR_o=2.6 for the inelastic system.

2.6 Defining "Respond Elastically" for Steel Structures

An object behaves "elastically" if the object can resist a distorting force and return to its original size and shape when that force is removed, to do this requires that no plastic deformation occur in the object. The "objects" of interest in this discussion are buildings and these have both structural and non-structural components. As structural designers we have the greatest influence on the structural system of the building and under NBC 2020 designers are to evaluate the buildings under lower-level events and to make sure that under these defined lower-level events the structure remains "elastic". However, "elastic behaviour" is not defined in the Code. The intent is that the material standards should define what elastic behaviour is. The material standards are released a year prior to the release of the NBC 2020 and the need for defining elastic behaviour was not defined in S16-19[3]. While the definition of "elastic" is easier to achieve in steel than for wood or concrete buildings it still results in some issues. For example, does "elastic buckling" mean that the structure remains elastic after buckling has occurred? For elastic buckling we are less concerned about the member that is buckling and more concerned about the behaviour of the connecting plates that will undergo plastic hinging deformation as the compression brace buckles. Laboratory studies on brace bays such as those done by Robert Tremblay[4] show that elastic buckling can lead to large offsets of the brace that will result in failure of wall finishes and inelastic damage to the connecting plates. Therefore, elastic buckling should not be thought of as "elastic". In determining the buckling capacity for serviceability checks the resistance factor (Ø) is set equal to 1.0 so that when we calculate buckling capacity we do so by C_r/ Ø.

For "elastic behaviour" of moment frames the elastic section modulus, S, rather than the plastic section modulus, Z should be used and for elastic behaviour, the moment resistance of a beam would therefore be F_yS with no Ø factor applied. Table 4 shows steel seismic systems grouped into typical configurations.

Table 4 – Seismic Requirements for Elastic Response Steel Structures

System	Definition of Elastic Response
Tension-Only Concentric Brace Frames	No buckling of the compression brace for the lower-level earthquakes. This means using a kL/r of less than 200. However, brace bay can be considered tension only under the 1:2475-year event.
Tension-Compression Concentric Brace frames (CBF)	No buckling of the compression brace for the lower-level earthquakes.
Eccentric Braced Frames	No yielding of the yielding element for the lower-level earthquakes.
Moment Frames	No yielding of the moment frame beams, columns or panel zones for the lower-level earthquakes. When determining stress, the elastic section modulus (S) should be used rather than the plastic section modulus (Z).
Steel Plate Shear Walls	No yielding of the tension field shear resisting element for the lower-level earthquakes.
Truss Yielding System	No yielding of any of the truss elements for the lower-level earthquakes.

The definition of elastic behaviour in concrete is more complex, however it involves the limiting of stresses in the concrete and while some cracking might occur it is desired that the cracks close up after the earthquake has finished. Furthermore, even some reinforcing steel yielding can occur (in vertical steel in shear walls), however the steel must return to its original length due to building self-weight after the earthquake with no residual deformation of the wall.

2.7 Building Strength and Ductility into Seismic Designs

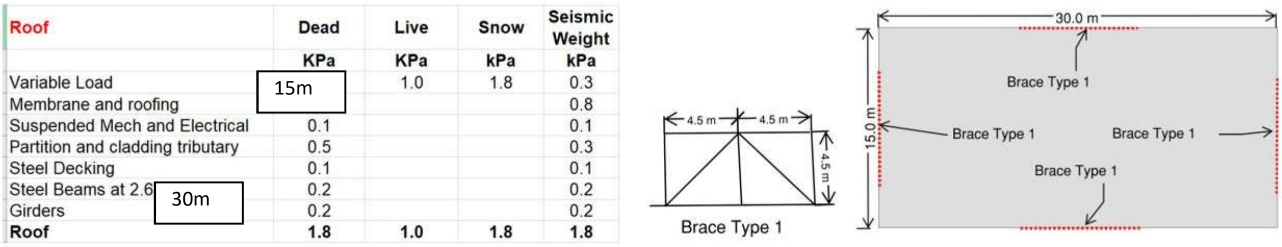
It is possible to build both strength and ductility into structural designs and this is illustrated by Japanese structural design which exhibits both the strength to resist earthquakes in an elastic way and is detailed in a ductile way to so that the members can perform inelastically should the earthquake result in forces that exceed the ability of the building to resist seismic forces in an elastic manner. Figures 4a and 4b show the bracing and connection details for a parking garage in Nagasaki, Japan. The garage is built of exposed galvanized steel, allowing the member thickness and connections to be observed and measured. Figure 4b shows one of the connections for the braces.

Fig. 4a (left) – Outside view of the Nagasaki Harbour Medical Center parking garage shows the extensive use of concentric braced frames. Fig. 4b (right) – Detail of one of the connections.

Taking the measurements of the brace sizes and making approximations of the structure weight and area it is estimated that this building would undergo a 1g lateral force prior to elastic buckling of the braces. This extremely high resistance for elastic behaviour means that the building would be expected to be undamaged under smaller seismic events and the ductile detailing would allow for good behaviour under events larger than this. Several other factors in its design would make this building behave well under seismic events including the use of several frames in each direction giving the building redundancy and the bolted connections that have multiple planes of bolts resisting the loads.

3. Example

Several examples were worked in reference [4] for High Importance and Post Disaster buildings in Vancouver on various soil types. One of these examples is shown in Figure 5. The basic shape and configuration of this example is a single storey 15m x 30m building. Many High Importance and Post Disaster buildings in Canada such as schools, ambulance stations, and firehalls are one and two storeys and constructed from structural steel.



Roof	Dead	Live	Snow	Seismic Weight
	KPa	KPa	kPa	kPa
Variable Load		1.0	1.8	0.3
Membrane and roofing				0.8
Suspended Mech and Electrical	0.1			0.1
Partition and cladding tributary	0.5			0.3
Steel Decking	0.1			0.1
Steel Beams at 2.6	0.2			0.2
Girders	0.2			0.2
Roof	**1.8**	**1.0**	**1.8**	**1.8**

Fig. 5 – Single storey example with metal deck on steel beams.

The single storey example has simple concentric frame bracing, and one can design the bracing using the loads determined under a variety of design options, importance criteria and ductility factors and produce Table 5 showing the results of this design comparison.

Table 5 – Brace sizes for the single storey example – Site Class C Vancouver NBC 2020 & S16-19

	Shear Load for Ductile Design (kN)	Shear Load for Elastic Design Check (kN)	Brace Size (Most efficient brace size by area that meets S16-19 axial capacity and detailing requirements)	**Elastic Design Check OK?**
Normal Importance Tension Only R_d=3.0 CBF	155	0	HSS 89x89x4.8	Not Required
Normal Importance Tension Only R_d=2.0 CBF	232	0	HSS 64x64x4.8	Not Required
Normal Importance Tension-Compression R_d=3.0 CBF	155	0	HSS 102x102x6.4	Not Required
Normal Importance Tension-compression R_d=2.0 CBF	232	0	HSS 114x114x6.4	Not Required
High Importance Tension Only R_d=3.0 CBF	201	176	HSS 89x89x4.8	No
High Importance Tension Only R_d=2.0 CBF	302	176	HSS 76x76x4.8	No
High Importance Tension Compression R_d=3.0 CBF	**201**	**176**	**HSS 114x114x6.4**	**Yes**
High Importance Tension Compression R_d=2.0 CBF	**302**	**176**	**HSS 127X127x6.4**	**Yes**
Post-Disaster Tension Only R_d=3.0 CBF	232	240	HSS 89x89x6.4	No
Post-Disaster Tension Only R_d=2.0 CBF	349	240	HSS76x76x6.4	No
Post-Disaster Tension Compression R_d=3.0 CBF	**232**	**240**	**HSS 114x114x6.4**	**Yes**
Post Disaster Tension Compression R_d=2.0 CBF	**349**	**240**	**HSS 127X127x6.4**	**Yes**

The results of the brace size comparison in Table 5 for the single-storey example shows that there is not a high penalty when the second criteria of evaluating under a lower-level event, provided the ductile design is performed using a brace system that is tension-compression instead of just designing as tension-only. The brace sizes shown in Table 5 all satisfy the detailing requirements of S16-19 from the standpoint of force resistance and detailing with minimum kL/r and b/t values appropriate for the R_d value being used. Figure 6 shows the two extremes of the design for the brace bays; on the left is a Normal Importance building brace designed with R_d=3.0 and a tension-only system. By NBC it is not necessary to demonstrate that this brace remains elastic under a lower return period seismic event and indeed we would expect to see buckling of the brace in even small seismic events. Design objective for this building would be safe exit. On the right is the brace for same building if the building was designed as a Post Disaster building. The brace size at HSS 127x127x6.4 is considerably larger than the HSS 64x64x4.8 that works for the tension-only Normal Importance building. The Post Disaster building design shown in Figure 6b works in a ductile fashion for forces that are 50% higher than the 2% in 50-year event and works elastically under the 5% in 50-year event. Figure 6 shows the range of results that meet NBC 2020 and S16-19 requirements for the sample building; they also show the range of outcomes that are possible for the building from safe exit for the Normal Importance building to continuous operation if the building is classified as Post Disaster. To design the building for better seismic outcomes means that the designer needs to select the braces to be larger and more robust. The High Importance results for this sample building are similar to the Post Disaster results as the buckling resistance of the brace is similar in both cases (124 kN in the case of High Importance and 170 kN in the case of Post Disaster and the most efficient brace size to solve this load is an HSS 127x127x6.4 in both cases. If the building is classified as Post Disaster with seismic risk of SC3 or SC4 or is High Importance with seismic risk of SC4 the use of tension-only braces does not produce results that are compatible with the requirements of NBC 2020.

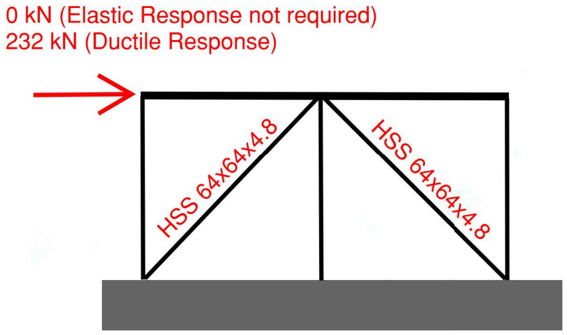


Fig. 6a Normal Importance Design Using
R_d=3 Tension only Braces
Expected Outcome: Life Safety

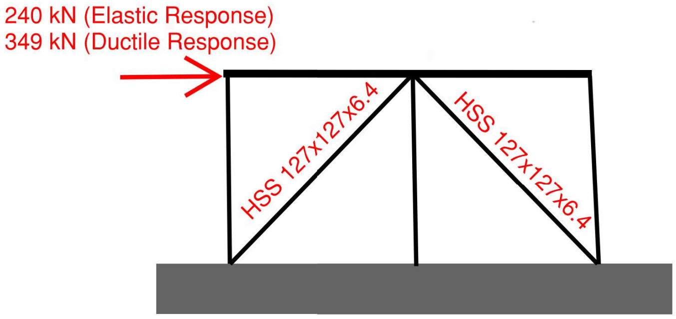


Fig. 6b Post Disaster Design
Using R_d=3 Tension Compression Braces
Expected Outcome: Continuous Operation

4. Conclusions

There is a definite need for certain buildings such as hospitals, firehalls, and schools to recover quickly after a moderate or significant seismic event. The past practice of considering safe exit and an undefined level of damage control does not necessarily help the building to achieve a state of immediate occupancy or full functionality. The building code has been gradually adopting provisions that limit the irregularities on buildings, especially those that are High Importance or Post Disaster. Provisions introduced with NBC 2020 that require certain buildings to remain elastic under a smaller event than the 2% in 50 years ductile design level event is one way of ensuring that the buildings that are desired to have immediate occupancy and fast return to functionality behave well (in the case of NBC behave elastically) for small and moderate earthquakes. While this might increase the cost of the building marginally in some cases, it did not do so in the sample problem if tension-compression bracing was used as a starting point. Providing a low-level earthquake check will significantly reduce the cost of repair of the building under the effects of small and moderate earthquakes.

Some systems such as tension-only brace systems are less likely to meet the requirement of no buckling under the lower return period event and in cases where it is necessary to satisfy the elastic behaviour under a lower return period event it would be desirable to start with tension-compression brace system. It is also more likely that starting the ductile design with a ductility factor, R_d, of 2.0 instead of higher ductility factors will help make the elastic design check be just a check instead of a redesign.

For High Importance and Post Disaster buildings in areas with seismic hazard, the aim of immediate occupancy or return to continuous operation and full functionality of the building is best achieved by:

a) Designing and building seismic systems that are both robust and ductile.
b) With an importance factor, I_E, of greater than 1.0 one is designing the ductile response of the building under ductile design to be able to resist higher forces than a Normal Importance building. This improves the life safety provisions for the building and reduces the extent of damage.
c) Limiting the drift so that the non-structural elements and the gravity system is protected by requiring it to undergo smaller compatible displacements.
d) Evaluating the building with two levels of seismic events and stating performance objectives (tight deflection control under both design level event and the lower-level earthquake check and the SFRS remaining elastic in the performance level event).
e) Eliminating irregularities that have been shown in past significant seismic events to be very damaging.
f) Designers will find that using Rd values of 2.0 and using systems that do not have premature failure such as tension-only brace systems, will result in less redesign when doing an elastic design check at the "lower level or performance level earthquake."

The provisions of NBC 2020 are intended to make certain buildings in Canada respond better to a seismic event. While this creates a bit more work for the engineer, and possibly requires some marginally larger members in the building, it will result in buildings performing better in seismic events. Canadians would love to see their cities recover as quickly after a seismic event as was demonstrated in Kumamoto after the 2016 earthquake.

5. Acknowledgements

The authors acknowledge the use of the proposed seismic provisions of NBC 2020. At time of writing this paper, the provisions were still under review by NBCC and had not been adopted into NBC 2020. They are expected to be officially adopted into Code at the end of 2021. The reader is cautioned that these provisions are not currently recognized as the Code in effect. The authors wish to thank members of the Standing Committee on Earthquake Design (SCED) who provided positive input and constructive criticism to the preparation of this paper.

6. References

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