Table of contents

1 Overview

Canada covers an area of approximately 10 million square kilometres, similar to the continent of Europe. Its west coast lies on the Pacific ring of fire, where the country's largest historical earthquakes have occurred, with regions of moderate seismicity also present in the east of the country. Some of the country's most populated urban centres and historical buildings lie in regions of significant seismicity. This article is an introductory guide to the seismic design of buildings in Canada, focusing on the design approach and determination of forces, rather than detailing of seismic systems.

Canada uses its own national building code, which has developed organically over the previous century to include a modern, mostly prescriptive, limit-states structural design philosophy, following similar trends to code developments in other countries. This article refers mainly to National Building Code (NBC) 2015, currently in force, while including some of the notable updates in the recently published 2020 edition.

Earthquake effects govern the design of the lateral systems of buildings in regions of high or moderate seismicity, except for very tall buildings, which may still be governed by wind effects. Seismic hazard levels in the code have generally increased over time, as more earthquake sources were included, design return periods increased and effects such as long-duration shaking became recognised.

Currently there is a well-developed set of approved lateral systems in concrete, steel and low-rise timber, with key drives for future developments including:

- Widening the understanding and use of performance-based seismic design
- Advancing lateral systems for taller timber buildings
- Communicating and re-appraising earthquake performance expectations with policy-makers, clients and the public
- Use of damage assessment methods such as FEMA P-58 in the design process
- Introducing new low-damage technologies, including base isolation where appropriate.

Downtown Vancouver

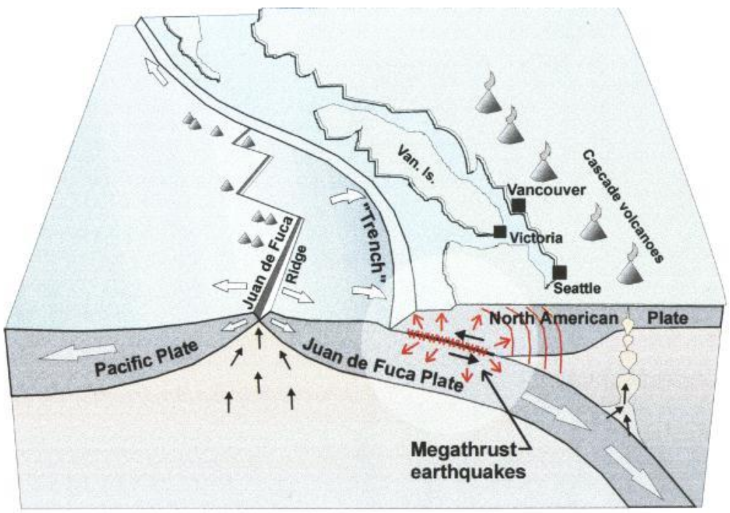
2 Definitions

Term	Symbol	Note
Site coefficient for spectral acceleration	F(T)	Coefficient representing the ground conditions, used to modify the elastic spectral response acceleration, S_a, to give the design spectral response acceleration, S(T).
Earthquake importance factor	I_E	Factor representing the importance category of the building, used to amplify the base shear and resultant forces, but not deflections or drifts.
Peak ground acceleration	PGA	Expressed as a ratio to gravitational acceleration.
Ductility-related force modification factor	R_d	Reduction factor representing the capability of a structure to dissipate energy through reversed cyclic inelastic behaviour, applied to the base shear calculated from an elastic analysis.
Overstrength-related force modification factor	R_o	Reduction factor accounting for the dependable portion of reserve strength in a structure, applied to the base shear calculated from an elastic analysis.
Seismic force-resisting system (SFRS)		Approved system to resist seismic forces, listed in the building code.
Site class		Class from A to F, based on the stiffness, strength and other properties of the ground.
Design spectral response acceleration for period T	S(T)	Acceleration used in design, expressed as a ratio to gravitational acceleration.
Elastic spectral response acceleration	S_a	Acceleration of single-degree-of-freedom model, calculated for 5% damping and excluding effects of ground conditions, expressed as a ratio to gravitational acceleration.
Period	T	Period of a mode of the structure.
Fundamental lateral period	T_a	Highest period of the structure, applying to equivalent static force procedure in the direction under consideration.
Base shear (equivalent static procedure)	V	Base shear determined using equivalent static force procedure in the direction under consideration.
Base shear (dynamic procedure)	V_d	Base shear determined using dynamic analysis procedure in the direction under consideration.
Total seismic weight	W	Seismic weight, including dead load, 25% of snow load, 60% of storage load and contents of tanks.

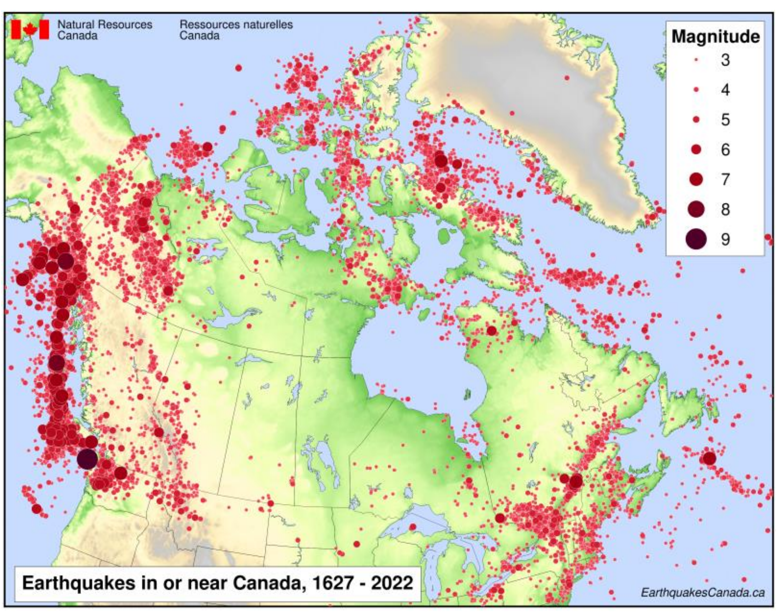
3 Local seismicity

The seismicity across the Canada varies significantly.

- High seismic hazard exists in the Pacific northwest, generated by the sliding of Pacific plate relative to the North American plate along the Queen Charlotte fault in Northern British Columbia, the subduction of Juan de Fuca plate under the North American plate west of Vancouver Island (Cascadia subduction zone) and seismicity within the North American plate. The rupture of a 500km long segment of the Queen Charlotte fault in 1949 was Canada's largest earthquake in recent history, with an estimated magnitude of 8.1.
- Moderate seismic hazard exists in the St Lawrence river and Ottawa river regions in Ontario and Quebec, as well as some of the less populated regions in the far north.
- Low or very low seismic hazard exists in the other regions of the country.



Cascadia subduction zone [Source: Natural Resources Canada]

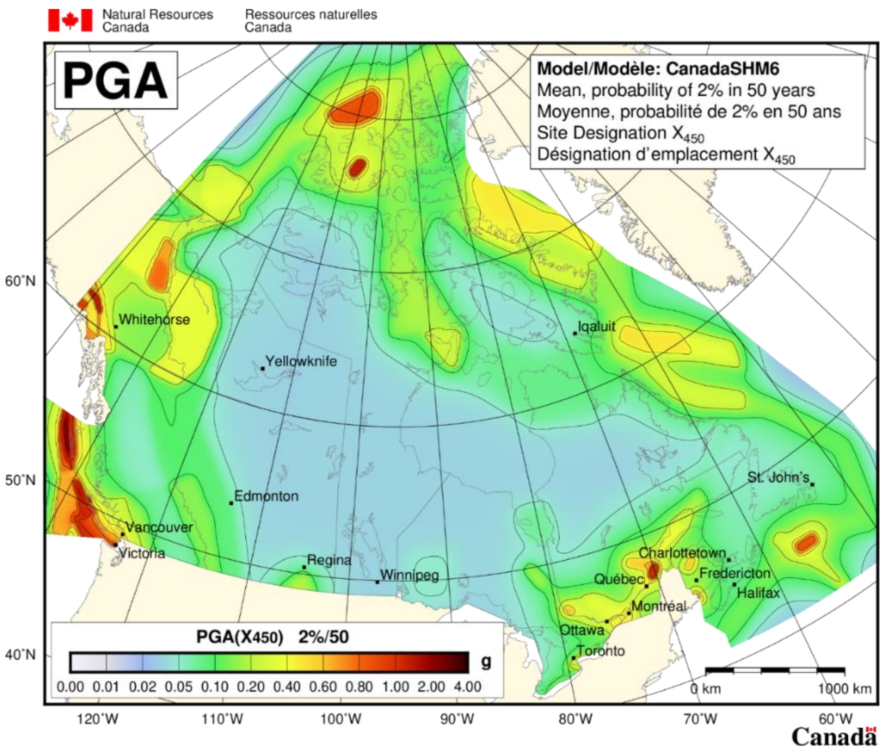


Historical earthquakes in Canada recorded between 1627 and 2022 [Source: Natural Resources Canada]

The current seismic hazard model is the 6th generation model, used to create the hazard values for NBC 2020. The 5th generation model was used for NBC 2015.

Zonation maps for each structural period are provided by Natural Resources Canada (NRCan) for reference, but are not used to read off hazard values in the design process. Instead, seismic data for use in design is provided for all locations across Canada using a web-based tool for data from the 6th generation seismic hazard model.

https://www.earthquakescanada.nrcan.gc.ca/hazard-alea/interpolat/nbc2020-cnb2020-en.php



Zonation map for peak ground acceleration, based on the 6th generation model [Source: Natural Resources Canada]

4 Regulatory framework and historical background

Loading requirements, including seismic actions, are contained within National Building Code of Canada (NBC), which is a model code then copied almost exactly into local provincial or municipal building codes or regulations, which govern structural design and practice in any jurisdiction. The adoption of the model code into the local legislation and regulations takes time, meaning that the local codes in force at any time lag behind the latest seismic guidance in the national code. The current national model code is NBC 2020, whereas the provincial codes (e.g. British Columbia Building Code, Ontario Building Code) are currently based on the previous national model code, NBC 2015.

The design of structures to resist the loading effects calculated in the building codes is contained in separate material codes – the concrete code A23.3, the steel code S16, the wood code O86 etc.

Design for earthquakes was first introduced into NBC in 1941. Key developments since then are described in detail in the paper *Evolution of seismic design provisions in the national building code of Canada*, summarised below:

- 1953 – Country divided into different seismic zones; effect of building stiffness indirectly introduced.
- 1965 – Importance factor and soil factor introduced.
- 1970 – Seismic hazards based on probabilistic analysis of known earthquake sources introduced, using 100-year hazard values, with load factors applied to earthquake effects to give ultimate effects for design.
- 1975 – Dynamic analysis and modal superposition of response spectrum analysis more ingrained in the code; structural ductility factor introduced, used to reduce the elastic response spectrum.
- 1985 – Hazards recalculated at 475-year return period (10% exceedance in 50 years)
- 1990 – Load factors reduced to 1.0; provisions for ductile detailing in material design codes expanded; drift limits introduced, varying for different importance categories. The 1990 code is a threshold between older, less ductile, design and modern, ductile, design.
- 2005 – hazard level increased to 2475-year (2% in 50 years); defined structural irregularities introduced and constraints placed on them; dynamic analysis the norm rather than the exception for all but short and regular structures.

Today, performance-based design using non-linear response history analysis is used for structures with systems or characteristics outside the prescriptions of the code, such as:

- Structures with severe irregularities
- Structures with seismic systems not defined in the code or exceeding the code height limit of a defined system
- Structures with base isolation or supplemental damping.

(a) (b) (c)

Performance-based design examples: (a) Ten-storey timber braced frame and CLT shear wall building in Vancouver, exceeding current code height limit for these systems [Credit: Fast + Epp]; (b) Tall concrete tower in Vancouver with gravity-induced lateral demand [Credit: Glotman Simpson]; (c) Base-isolated school in Vancouver, showing level of isolation plane [Source: *Base Isolation Seismic Upgrade of a Heritage Building at Lord Strathcona Elementary School*]

5 Basis of design

5.1 Performance requirements

The building code requires design at the 2% in 50 years hazard level (2475-year return period) and not exceeding an inelastic inter-storey drift of 2.5%. The implied performance level for normal importance buildings is the achievement of life-safety, meaning that occupants are expected to be able safely to leave the building and an evaluation of damage may be carried out, but repairs may not be economically feasible.

For high importance buildings (e.g. schools) and post-disaster buildings (e.g. hospitals), importance factors are applied to forces and drift limits are tightened, so as to reduce the expected damage under the design-level earthquake. For post-disaster buildings, the performance is expected to be closer to immediate occupancy, but explicit checks on damage to demonstrate this are not required.

Some low occupancy buildings are classed as low importance and the importance factor reduces the force level.

Importance category	Application	Importance factor, I_E	Drift limit
Low	Buildings representing a low hazard to human life in the event of failure.	0.8	2.5%
Normal	All buildings not categorised as low importance, high importance or post-disaster. Applies to most buildings.	1.0	2.5%
High	Buildings likely to be used as a shelter after a design-level earthquake, such as schools or community centres.	1.3	2.0%
Post-disaster	Buildings essential to the provision of services following a design-level earthquake and intended to remain largely operational, such as hospitals.	1.5	1.0%

No explicit checks are required for performance in more frequent earthquakes under NBC 2015. Under NBC 2020, however, new checks are introduced with the aim of limiting damage under more frequent earthquakes for tall and higher importance buildings.

The code does not require any assessment of actual levels of damage, for any type of building, although this can be requested by owners of important facilities.

5.2 Design principles

Seismic design in any material must conform with the following principles:

- Capacity design principles should be followed, by which defined elements are chosen to yield or otherwise dissipate energy during a design-level earthquake and are designed to have sufficient ductility or dissipative capacity to do so. All other elements are protected against yielding by increasing their strength to allow for the predicted over-strength of the yielding element.
- Structures shall have clearly defined load paths, including a clearly defined seismic force-resisting system (SFRS), which includes the yielding elements described above.
- All elements not considered part of the SFRS must be investigated and shown to be able to support their gravity demands while undergoing seismic deformation.
- Stiff elements that are not part of the SFRS shall be separated from all other elements of the building such that no interaction occurs during a design-level earthquake.
- The stiffness of other elements not part of the SFRS shall be accounted for in the design for any adverse effects on period or irregularity.

- Structural modelling shall be representative of the distribution of building mass and stiffness and shall account for cracking, the effect of finite size of members and joints, second-order effects and any other effects that influence the lateral stiffness of the building.

5.3 Defined irregularities

The defined irregularities play an important role in avoiding building designs that include geometries or characteristics which are known to induce failure during earthquakes, even when sufficient strength from a force analysis under theoretical loading has been provided.

The number and definition of irregularities continues to be refined in successive versions of the building code, as more research is carried out into failure-inducing characteristics of irregular buildings. NBC 2020 includes ten defined irregularities:

- Irregularity 1: Vertical stiffness irregularity (significant change in stiffness between floors)
- Irregularity 2: Mass irregularity (significant change in mass between floors)
- Irregularity 3: Vertical geometric irregularity
- Irregularity 4: In-plane discontinuity in SFRS
- Irregularity 5: Out-of-plane offset in SFRS
- Irregularity 6: Weak storey
- Irregularity 7: Torsional sensitivity
- Irregularity 8: Non-orthogonal systems
- Irregularity 9: Gravity-induced lateral demand
- Irregularity 10: Inclined columns (new in NBC 2020)

Some of the main restrictions based on these defined irregularities are:

- A weak storey (irregularity 6) is prohibited, except for very low hazard levels. For post-disaster buildings, there is no exception to this prohibition.
- In-plane and out-of-plane offsets (irregularities 4 and 5) are not permitted for tall or flexible concrete shear wall buildings, where the fundamental period is greater than 1.0s. Walls must also continue all the way to the foundations.
- In-plane and out-of-plane offsets (irregularities 4 and 5) are not permitted for wood buildings of more than four storeys.

5.4 Defined seismic force-resisting systems (SFRS)

NBC allows for the use of defined seismic force-resisting systems. Each defined system has a ductility factor (R_d) and an overstrength factor (R_o) defined in the code. The product of these values is equivalent to the single force-reducing factors used in other international codes. Use of systems not defined in the code is not prohibited, but extensive analysis and testing must be carried out to demonstrate that the system satisfies the basic behavioural principles of the capacity design approach and to determine safe and appropriate values of the reduction factors R_d and R_o.

Generally, R_d and R_o are used together as a combined reduction factor R_dR_o. R_d is used on its own to classify systems into different levels of ductility, which controls which specific design rules apply to the system. R_o is used on its own to indicate a minimum overstrength which may be used in the absence of calculated values in some design checks.

The table below describes some commonly used structural systems.

System	Reduction factors			Source of ductility
	R_d	R_o	R_d R_o	
Shear walls with ductile detailing				
Concrete (not coupled)	3.5	1.6	5.6	Flexural yielding of walls
Concrete (not coupled) (lower level of detailing)	2.0	1.4	2.8	Flexural yielding of walls
Concrete (coupled)	4.0	1.7	6.8	Yielding of coupling beams
Concrete (coupled) (lower level of detailing)	2.5	1.4	3.5	Yielding of coupling beams
Timber (nailed plywood on studs)	3.0	1.7	5.1	Distributed damage in nailing
Moment frames with ductile detailing				
Steel	5.0	1.5	7.5	Flexural yielding of beams
Concrete	4.0	1.7	6.8	Flexural yielding of beams
Timber	2.0	1.5	3.0	Flexural yielding of beams
Braced frames with ductile detailing				
Steel (concentrically connected braces)	3.0	1.3	3.9	Buckling of braces
Steel (eccentrically connected braces)	4.0	1.5	6.0	Yielding of connecting header
Steel (buckling-restrained braces)	4.0	1.2	4.8	Axial yielding of steel core
Timber	2.0	1.5	3.0	Yielding of connections
Conventional construction (no special ductile detailing)				
Concrete shear walls or moment frames	1.5	1.3	1.95	Limited yielding of elements
Steel braced or moment frames	1.5	1.3	1.95	Limited yielding of elements

Height limits apply to some of the lower ductility systems or systems used in locations of high seismicity. There is no height restriction for some of the most ductile steel and concrete systems.

6 Ground conditions

The site class describes the ground conditions between A (hard rock) to E (soft soil). Soils which are liquefiable, highly sensitive clays or other unstable soils are classified as site class F and require site-specific evaluation by a geotechnical engineer.

The average shear wave velocity in the top 30m of soil is one of the parameters used to determine site class.

- Above 1500m/s → Site class A
- 760m/s to 1500m/s → Site class B
- 360m/s to 760m/s → Site class C
- 360m/s to 180m/s → Site class D
- Below 180m/s → Site class E

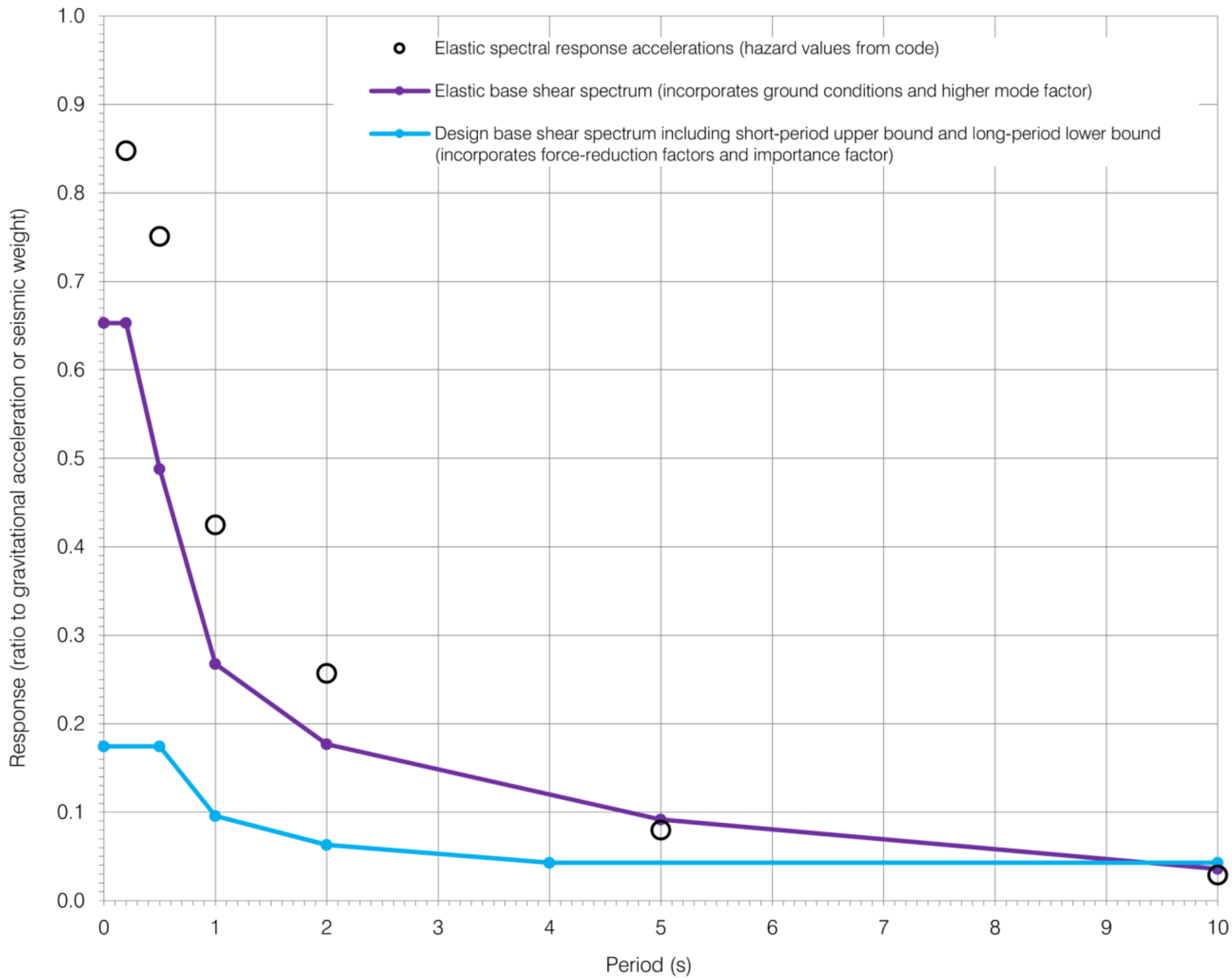
7 Design spectrum

The seismic hazard data in the code is provided as elastic spectral response accelerations, S_a, expressed as a ratio to gravitational acceleration, at the discrete periods of 0.2s, 0.5s, 1s, 2s, 5s and 10s and for an assumed damping of 5%. The hazard data is provided at the design level (2% in 50 years) as well as for shorter return periods.

While it is sometimes useful visually to plot a continuous spectrum using these acceleration data points, a continuous spectrum is correctly created only once the effects of ground conditions and higher mode behaviour have been incorporated.

Spectrum construction in codes based on NBC 2015 follows the following process:

- Determine the accelerations, S_a, at the site, excluding the effect of ground conditions, at discrete periods.
- Incorporate the effect of ground conditions by modifying the accelerations by soil factors F(T) to determine design spectral response accelerations, S, at discrete periods.
    - For site class C, soil factors are F(T) = 1.0 for all periods.
    - For site classes A and B, F(T) < 1 and the spectrum is reduced for all periods.
    - For site classes D, E and F, F(T) > 1 and the spectrum is increased for all periods except for short-period buildings in some locations.
    - In the next generation of codes, based on NBC 2020, the soil factor F(T) is removed and a design spectrum S(T,X) is calculated and provided directly for the location and the actual shear wave velocity using a web-based platform, where X is the shear wave velocity or other site descriptor.
- Incorporate the effect of higher mode behaviour by modifying the design accelerations by higher mode factors, M_v, at discrete periods. This then represents the values of elastic base shear as a ratio of seismic weight, for a normal importance building.
- Linearly interpolate between these data points to create the elastic base shear spectrum.
- Apply force reduction factors R_d and R_o, the importance factor I and upper and lower limits to create the design base shear spectrum.
    - $V = S(T_a)\ M_v\ I_E\ /\ (R_d\ R_o)$ x seismic weight
    - For most short-period buildings, the base shear is capped at 2/3 times the 0.2-second base shear.
    - For long-period shear wall buildings, the base shear has a lower limit equal to the 4-second base shear.
    - For long-period braced frame or moment frame buildings, the base shear has a lower limit equal to the 2-second base shear.

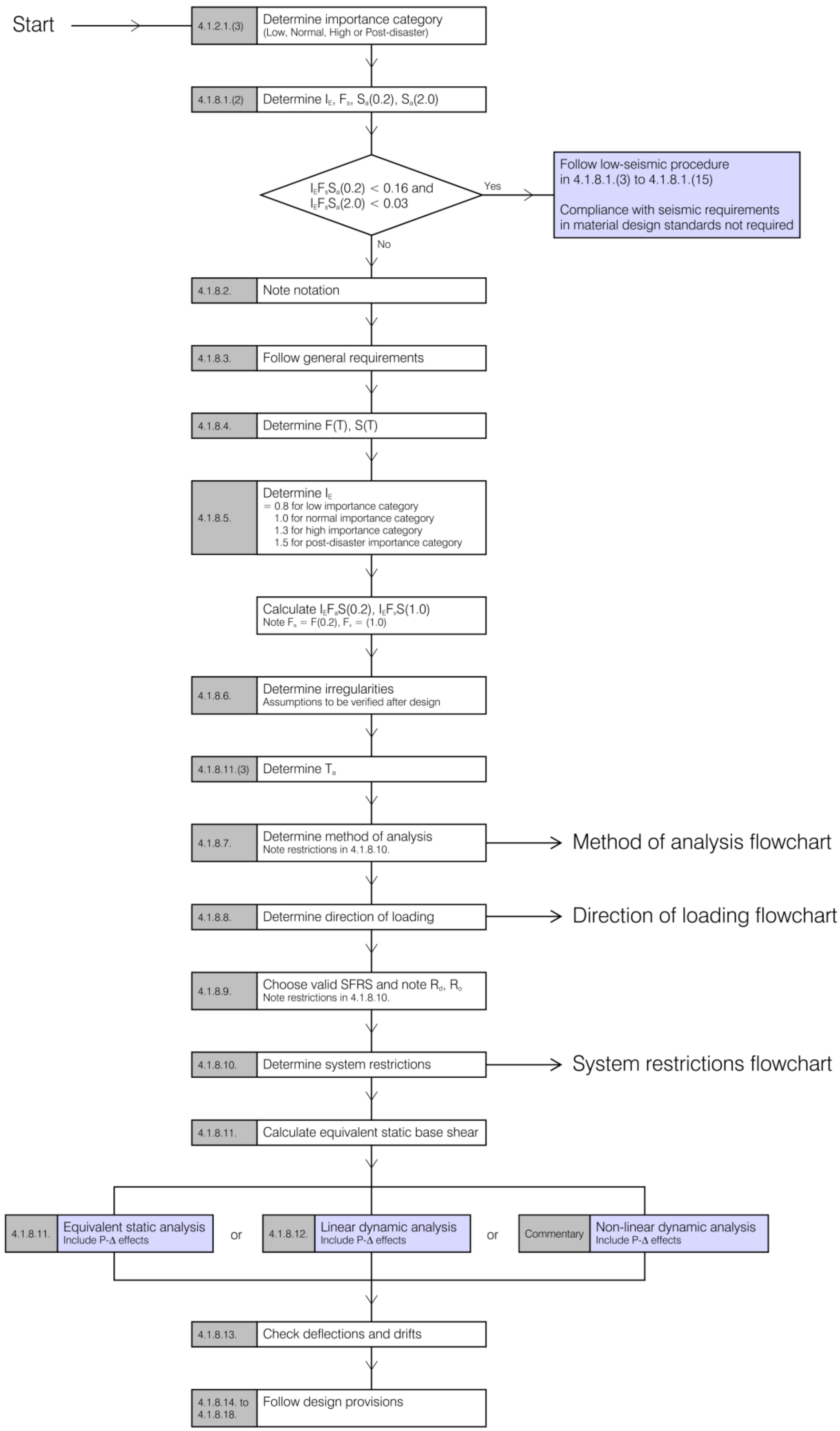


Example spectrum for Vancouver and site class B, for a normal importance concrete shear wall building with R_d = 2.0 and R_o = 1.4

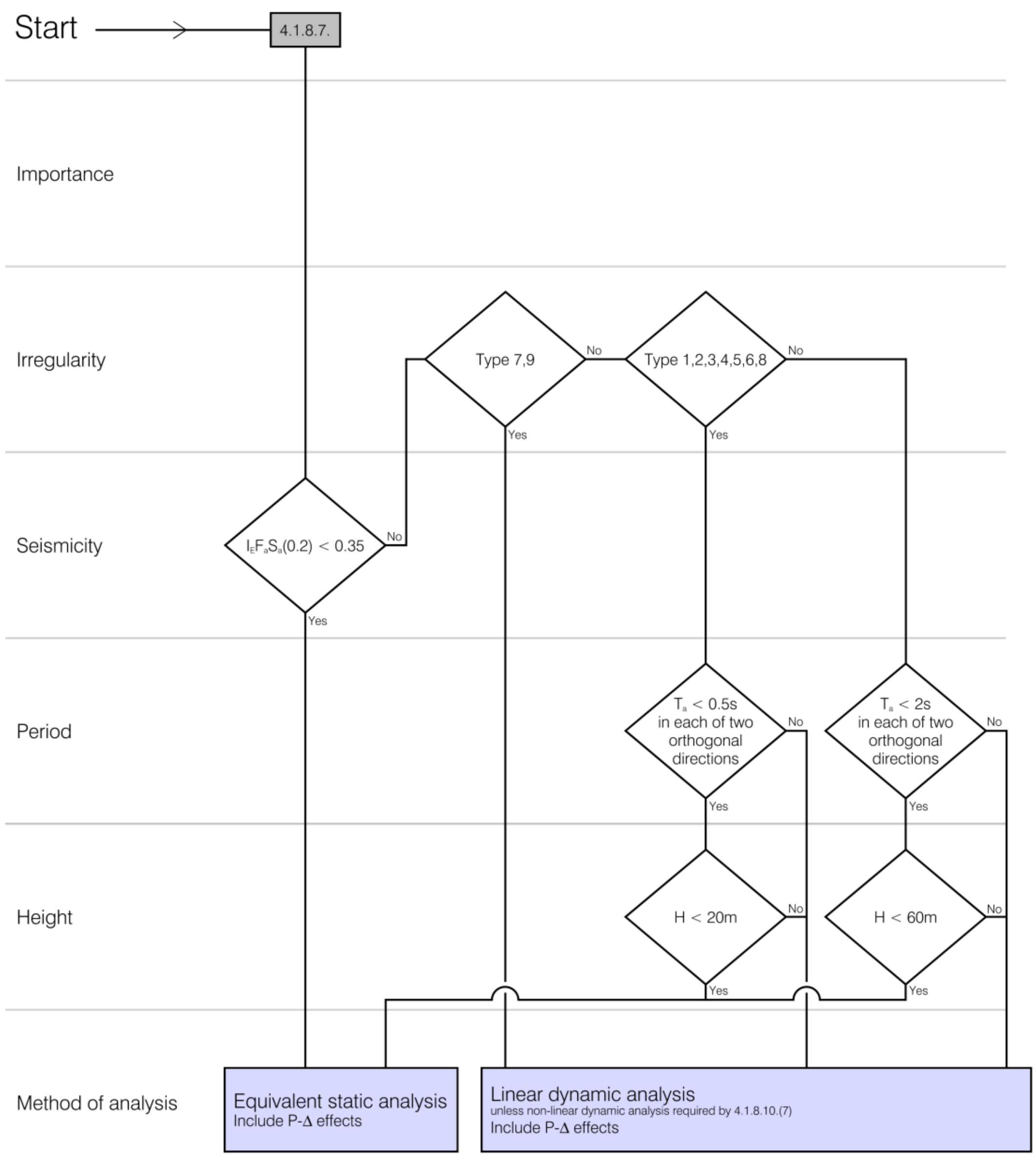
8 Analysis and design process

The code provides the following analysis and design process:

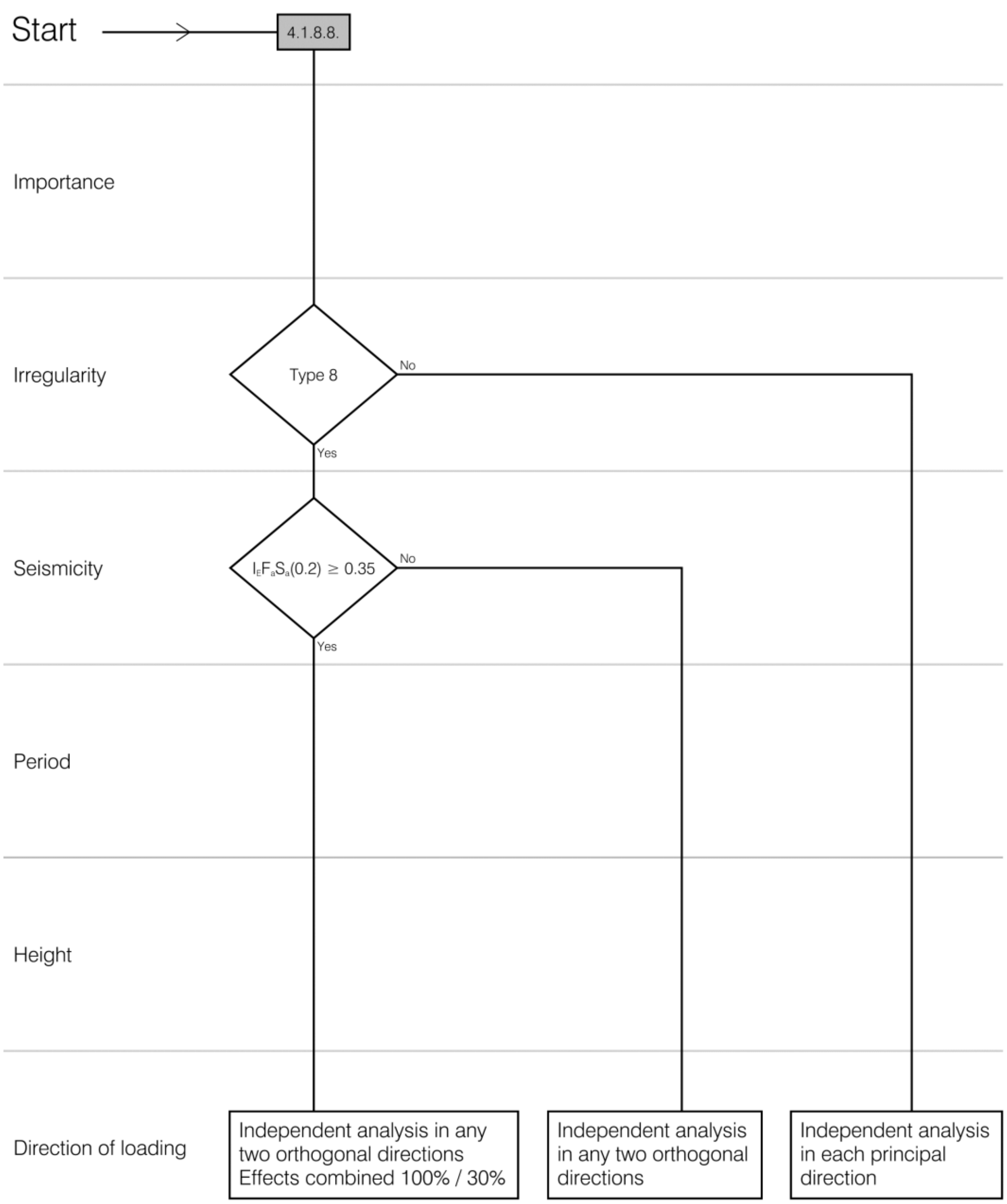
- Check if low-seismic procedure applies.
    - In regions of very low seismicity, a simplified procedure is allowed to be used.
- Determine hazard spectrum at location of building.
- Determine importance category, importance factor and drift limit.
- Determine irregularities.
    - The code provides a detailed definition for each irregularity and explicit checks for whether it is present.
- Determine period.
    - The fundamental period of the structure is determined either from an empirical formula or from a structural analysis model. If a structural analysis model is used, the predicted fundamental period is capped a twice the period calculated from the empirical formula.
- Determine method of analysis.
    - The dynamic procedure (typically modal superposition) is required unless the building is short and regular or at a site with a very low seismic hazard.
- Determine direction of loading requirements.
    - Where the building lateral system is laid out orthogonally, it may be analysed in the two orthogonal directions independently. Except for at very low seismic hazard, if the lateral system is not laid out orthogonally, then analysis is carried out in any two orthogonal directions and the results added in a 100% (direction 1) + 30% (direction 2) combination.
- Choose valid SFRS.
    - Only defined seismic force-resisting systems may be used. Each system has defined force-reduction factors R_d and R_o.
- Determine height limitations based on hazard level.
- Determine system restrictions.
- Calculate equivalent static base shear.
- Determine seismic forces using either equivalent static, dynamic or non-linear method.
    - When using the equivalent static method, the base shear is distributed up the building as seismic loading in a traditional triangular weighted distribution.
    - When a dynamic method is required, as for most buildings, the building is analysed in each mode and the results combined using SRSS. Critically, if the resulting base shear is less than either 80% (for a regular building) or 100% (for any other building) of the equivalent static base shear, then the base shear from the dynamic method and all the corresponding forces and deflections are scaled up such that the base shear equals 80% or 100% of the equivalent static base shear. This is a guard against the dynamic analysis deviating too far from minimum long-established requirements from a simplified behaviour model.
- Check drifts.
- Design SFRS, foundations and diaphragms.
- Check gravity system under seismic deformation.


Start
4.1.2.1.(3) Determine importance category
(Low, Normal, High or Post-disaster)
4.1.8.1.(2) Determine I_E, F_s, $S_a(0.2)$, $S_a(2.0)$
$I_EF_sS_a(0.2) < 0.16$ and
$I_EF_sS_a(2.0) < 0.03$
Yes
Follow low-seismic procedure
in 4.1.8.1.(3) to 4.1.8.1.(15)
Compliance with seismic requirements
in material design standards not required
No
4.1.8.2. Note notation
4.1.8.3. Follow general requirements
4.1.8.4. Determine F(T), S(T)
4.1.8.5. Determine I_E
= 0.8 for low importance category
1.0 for normal importance category
1.3 for high importance category
1.5 for post-disaster importance category
Calculate $I_EF_aS(0.2)$, $I_EF_vS(1.0)$
Note F_a = F(0.2), F_v = (1.0)
4.1.8.6. Determine irregularities
Assumptions to be verified after design
4.1.8.11.(3) Determine T_a
4.1.8.7. Determine method of analysis
Note restrictions in 4.1.8.10.
Method of analysis flowchart
4.1.8.8. Determine direction of loading
Direction of loading flowchart
4.1.8.9. Choose valid SFRS and note R_d, R_o
Note restrictions in 4.1.8.10.
4.1.8.10. Determine system restrictions
System restrictions flowchart
4.1.8.11. Calculate equivalent static base shear
4.1.8.11. Equivalent static analysis
Include P-Δ effects
or
4.1.8.12. Linear dynamic analysis
Include P-Δ effects
or
Commentary Non-linear dynamic analysis
Include P-Δ effects
4.1.8.13. Check deflections and drifts
4.1.8.14. to 4.1.8.18. Follow design provisions

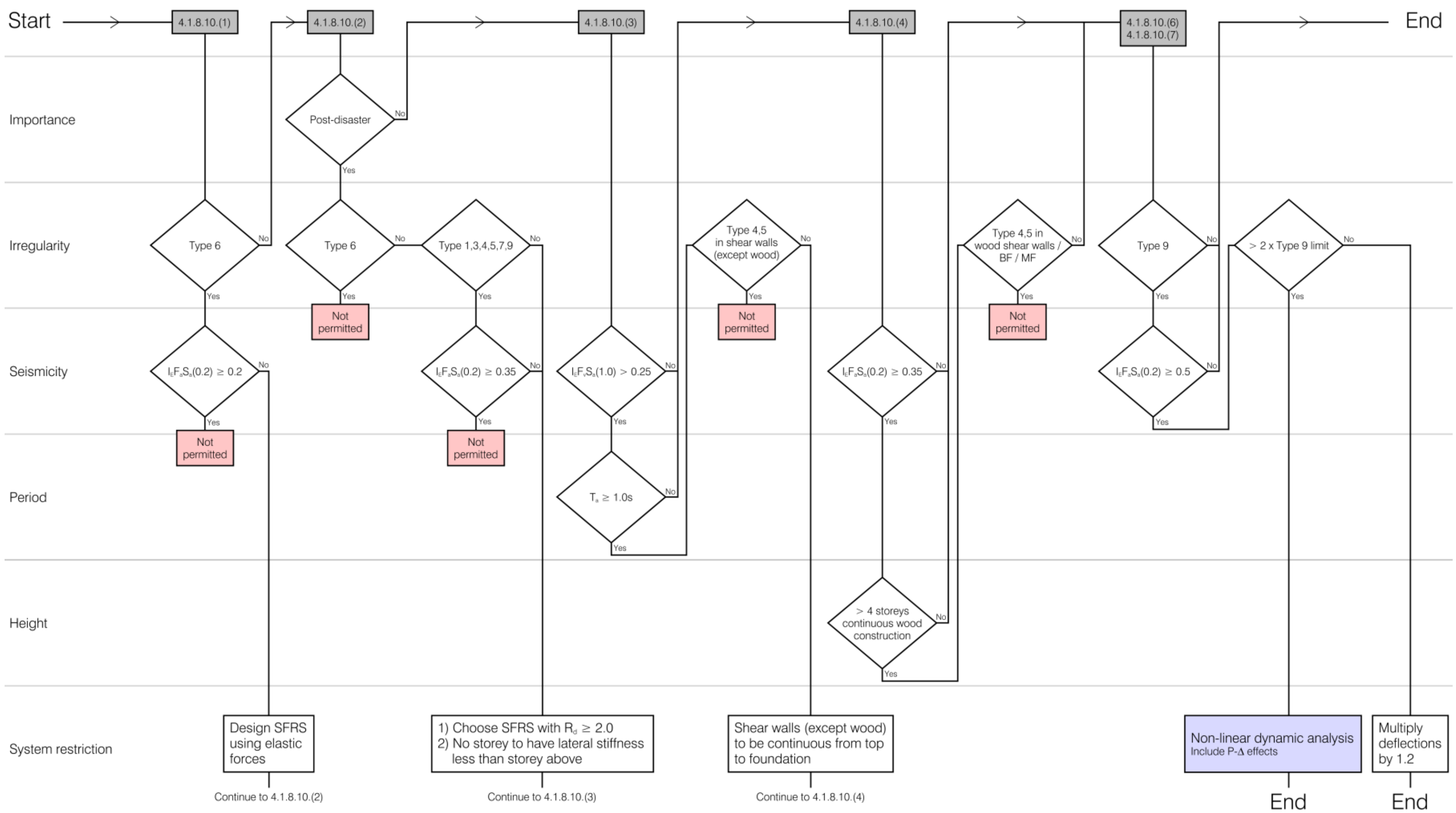
Method of analysis flowchart



Direction of loading flowchart



System restrictions flowchart



9 Safety verifications

While a complete description of the safety verifications for seismic design in the various systems is beyond the scope of this article, the following describes basic principles, which derive from the capacity design approach.

9.1 Drift

The seismic drift of the building is calculated without applying force-reduction factors or the importance factor. The design is checked to ensure that the maximum inter-storey seismic drift is within the limits noted earlier in this article.

9.2 Yielding elements of the SFRS

Yielding elements of the SFRS are designed for forces which include the force-reduction factors, such that they are expected to yield and undergo significant inelastic deformation.

Examples of yielding elements include: flexural reinforcement in concrete shear walls, concentric steel braces, fuse elements of eccentrically braced steel frames, the steel core of buckling-resistant braces and beam ends in moment frames.

The actual capacity of the yielding elements is always larger than the seismic design forces, because of material factors used in the design or because the demand is controlled by a different action, such as wind. The ratio of the actual capacity of a yielding element to its seismic design force is referred to as the seismic overstrength.

9.3 Non-yielding elements of the SFRS

Non-yielding elements of the SFRS are designed for forces which include the force-reduction factors but are then amplified by the seismic overstrength value of the yielding elements. This is to ensure that the non-yielding elements, which have an undesirable failure mechanism, do not ever fail before the intended energy dissipation occurs in the yielding elements.

Examples of non-yielding elements of the SFRS include: shear reinforcement in concrete shear walls, columns and beams in braced frames, columns in moment frames, foundations and diaphragms.

9.4 Gravity frame

The gravity frame is designed to support gravity loads when subject to the seismic drift of the building. The imposed drift induces additional forces in columns, beams and slabs, as well as degrading the capacity of some elements (such as concrete slab punching around columns) under cyclic motion.

10 References

National Building Code of Canada 2015

National Building Code of Canada 2020

Commentaries to National Building Code of Canada 2015 – Commentary J – Seismic design

CSA A23.3-19 Design of concrete structures

CSA S16-19 Design of steel structures

CSA O86-19 Engineering design in wood

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