

Seismic Evaluation and Upgrading of Buildings

by D.E. Allen

This Update briefly reviews the main factors that determine the extent of building failure and loss of life during earthquakes. It also describes guidelines for evaluating and upgrading existing buildings with regard to earthquake resistance.

Requirements in Part 4 of the National Building Code of Canada (NBC) relating to earthquake-resistant design are written primarily for new buildings and cannot easily be applied to existing buildings. However, there are many older buildings with structural systems, components or materials that are not addressed by the NBC. Attempts to apply the Part 4 require-

ments to make these buildings earthquake resistant have often resulted in modifications that were invasive, impractical and expensive.

Several serious earthquakes in North America over the past decade or so highlighted these difficulties and indicated the dearth of information available to consultants for evaluating and upgrading buildings. To address this lack of information, the Institute for Research in Construction, working with partners throughout Canada, developed and published a set of three guidelines. Two of the three guidelines are referenced in Commentary K of the *User's Guide – NBC 1995 Structural Commentaries (Part 4)*, which provides guidance on the application of NBC Part 4 requirements to existing buildings.¹ The scope of the three IRC guidelines and a new CSA guideline now being prepared are described in this Update.

Earthquakes and Buildings

An earthquake is caused by a sudden grinding slippage between two parts of the earth's crust, which propagates motions in the surrounding ground. These ground motions, which occur in all directions, shake buildings and

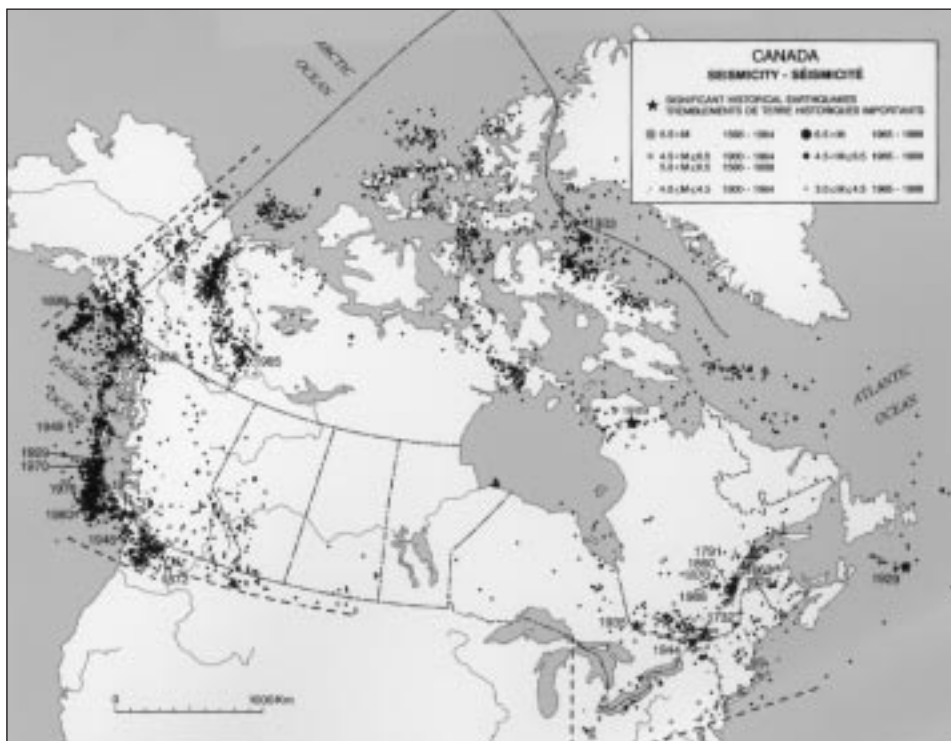


Figure 1. History of earthquakes in Canada

can lead to collapse or cause building components to fall, either of which can be life threatening. Buildings can also be damaged to the point where they are unusable or prohibitively expensive to repair.

Main Factors that Determine Building Failure

Whether or not a building survives an earthquake depends primarily on how it behaves when subjected to the ground motions generated by the earthquake. The main factors that control this behaviour are discussed below.

Seismicity. This term refers to the expected seismic ground motions, which are determined by the magnitude of earthquakes and their frequency of occurrence in various regions of Canada (see Figure 1). For each location, the NBC specifies a magnitude of ground motion that has a 10% probability of occurring once in 50 years; it is this magnitude of shaking, categorized in terms of seismic zones ranging from 0 (low magnitude) to 6 (high magnitude), that a building must be designed to withstand.

Integrity. This term refers to the degree to which components of a building are interconnected and thus able to prevent the building from being shaken apart by an earthquake. The components that affect a building's integrity include not only the structural components (e.g., beams, columns, walls and foundations), but also those supported by the building structure (e.g., heavy partitions and equipment). For a building on firm ground in a location of low seismicity, lack of integrity is likely to be its only seismic deficiency, i.e., the only factor that could lead to damage or collapse.

Lateral strength/ductility. Horizontal shaking produces horizontal forces throughout the building that are transferred through the floors to the vertical structure and down into the ground. The critical property in terms of preventing failure is the vertical structure's ability to resist horizontal forces applied to each storey (i.e., its lateral strength).

Equally important in areas of medium to high seismicity, where very large earthquake forces can occur, is the ability of the vertical structure to yield under the forces (ductility) without coming apart, and to transfer force from overloaded components to other components (redundancy). Some building components, such as clay-tile

partitions in frame structures, have no ductility and may fail suddenly and explosively, releasing energy, which promotes collapse of the building.

Lateral stiffness. Lateral forces from an earthquake distort the vertical structure between floors, which can cause damage to building components attached to the structure (e.g., partitions and service lines) and render the building unusable. The lateral stiffness of the vertical structure controls distortion, which is critical in preventing the failure of attached components. Often this means that shear walls are required, as they are much stiffer under lateral forces than columns.

Building irregularities. A building without irregularities is one whose vertical structure is symmetrical in plan with continuous columns or walls from top to bottom so that earthquake forces are transferred directly to the ground. Some of the irregularities that can promote damage or collapse are shown in Figure 2.

Soft or unstable ground conditions.

Buildings on rock usually survive earthquakes much better than those with foundations on soft or unstable soil. Soft ground shaken by the rock below vibrates like a bowl of jelly, amplifying the seismic motion in the rock, and resulting in greater distortions and forces in the building. In the Saguenay earthquake of 1988, for example, the distorting frame structures impacted on concrete-block partitions, causing them to fracture and collapse.

Soft ground may also be unstable, and can liquefy (like quicksand) or slide during an earthquake, resulting in large ground distortions and severe damage to the building.

Seismic Evaluation and Upgrading of Buildings

The following guidelines are recommended to help structural consultants and building managers carry out seismic mitigation of buildings at minimum cost and disruption.

Screening Buildings for Seismic Evaluation

The IRC document, *Manual for Screening of Buildings for Seismic Investigation*,² is recommended as a tool to help property managers 1) determine which buildings need an engineering evaluation and 2) rank them with respect to their need for attention. The method is based on a rapid inspection (approximately an hour) of each building or its drawings. The inspector uses a form to

obtain a “score” for each building based on the following seismic risk factors:

- seismicity
- ground conditions
- type and age of construction (both of which influence integrity, strength and ductility)
- building irregularities
- use (e.g., hospital or office)
- presence of heavy or dangerous non-structural building components, which may fall, or building services lines and equipment, which may fail.

The manual provides:

- guidance on how to organize and carry out a seismic screening;
- information, or information sources (e.g., for ground conditions), needed to complete an evaluation;
- a consistent approach for use by inspectors.

This guideline should not, however, be used to conduct an engineering evaluation of a building.

Seismic Evaluation

Engineering evaluations can be done using IRC’s *Guidelines for Seismic Evaluation of Existing Buildings*.³ This document can provide the means for conducting consistent and cost-effective engineering evaluations of all buildings except small buildings falling within the scope of Part 9 of the NBC. It can be applied to most buildings where the prevention of collapse and loss of life is the primary concern, e.g., apartment and office buildings. It can also be used to evaluate post-disaster buildings such as hospitals; however, additional requirements must be met to ensure that the building can be used for post-disaster services.

This publication enables a quick evaluation using a checklist of potential deficiencies based on life-threatening failures during past earthquakes, mainly in California and Alaska. Some of the

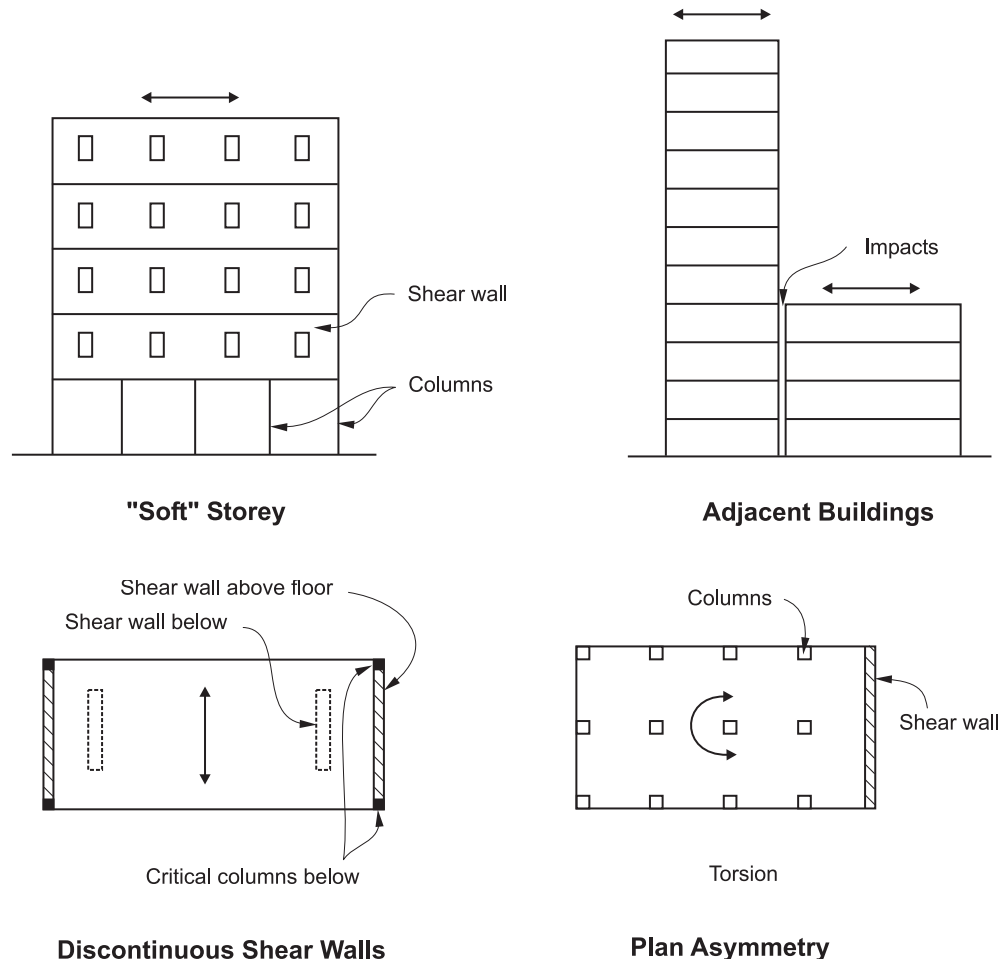


Figure 2. Seismic irregularities in buildings

items on the checklist require only a “back-of-the-envelope” calculation, followed, if necessary, by a more detailed evaluation of items that are uncertain or borderline. This procedure provides a way of determining a building’s deficiencies and ranking them at minimum cost.

For the most part, the criteria used for the structural evaluation of an existing building must follow Part 4 of the NBC. However, the NBC-specified seismic load is reduced by 40% for existing buildings because of the large cost associated with structural intervention compared to the small extra cost of achieving seismic safety in new construction. When the calculations show that the building components are not able to withstand this reduced (40%) seismic load, they should, under most circumstances, be upgraded and designed for the full seismic load specified by the NBC.

A special procedure is included for the evaluation of unreinforced masonry buildings with wood floor and roof structures, a form of construction no longer permitted by Part 4 of the NBC in earthquake-prone regions.

A new standard on the seismic evaluation of existing buildings, including post-disaster buildings, is being developed in the United States.⁴ It will contain an updated checklist that takes into account

the experience gained from recent earthquakes in Mexico, the United States and Japan. Of special concern are welded steel moment frames, many of which fractured during the Los Angeles earthquake of 1994 (see Reference 5 for guidance). In order to be able to apply this new standard in Canada, however, adjustments will have to be made to the U.S.-based criteria.

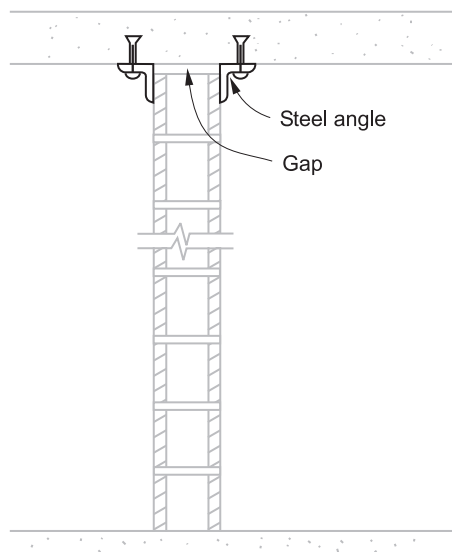
Seismic Upgrading

The IRC document, *Guideline for Seismic Upgrading of Building Structures*,⁶ describes various seismic retrofits and provides guidance on making the right choices for specific projects.

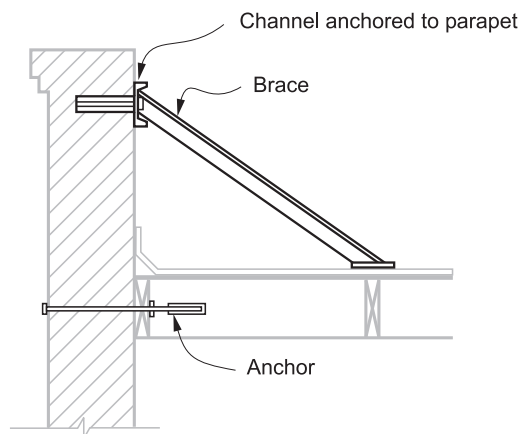
Most of the retrofits are conventional construction techniques, and include:

- anchoring masonry and other heavy components to the building structure (Figure 3);
- placing connectors between existing structural components;
- connecting new structural components (members, overlays, and infills) to existing components (Figure 4); and
- building new sub-systems such as shear walls, bracing systems or additional foundation elements, and connecting them to the existing structure (Figure 5).

Special retrofits include the addition of damping devices to reduce distortions and forces due to earthquakes; the addition of

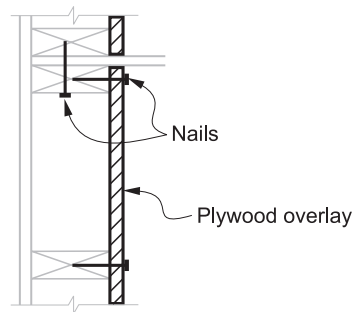


Masonry Partition

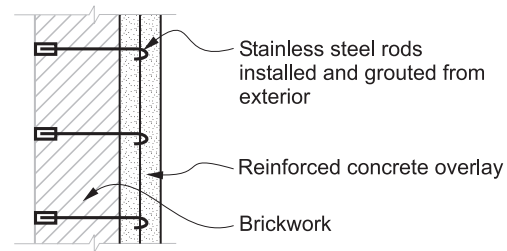


Masonry Parapet Support

Figure 3. Lateral support and anchorage added to masonry walls

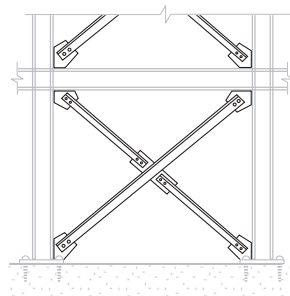


Plywood Overlay

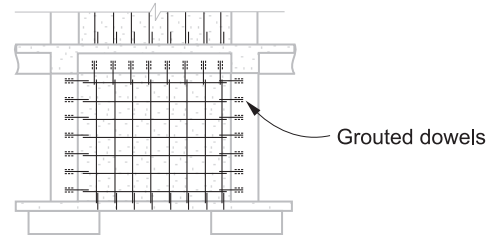


Reinforced Concrete Overlay

Figure 4. Overlays added to walls



New Bracing



New Shear Wall

Figure 5. New shear walls or bracing

flexible bearing pads between the foundation and the superstructure (base isolation) to reduce the transmission of horizontal ground motions to the structure; and soil-stabilization techniques, such as vertical gravel drains, to prevent soil liquefaction.

The choice of retrofits and their location in the building depends not only on correcting structural deficiencies (see “Main Factors that Determine Building Failure” above) but also on the following issues.

Accessibility. This refers to the ease or difficulty with which the contractor is able to gain access to the building components in order to carry out the retrofit. The major considerations are as follows:

- type, quantity and location of retrofits;
- need for scaffolding, cranes or other special equipment; and
- space available to perform the work.

The more difficult the access, the greater the cost and disruption, and the less choice there is with respect to retrofits. Foundation upgrading is particularly expensive because access is usually very difficult; however, it can

often be avoided by incorporating other elements, such as shear walls or bracing, into existing frames.

Disruption. If the building must be used during the upgrading, disruption becomes a major consideration. For this reason, seismic retrofits are best carried out during a major renovation, when the building is scheduled to be unoccupied. If this approach is not an option, retrofits must be carried out in stages, shifting people and operations, or undertaking work outside business hours, all of which increase the cost. Alternatively, exterior retrofits (bracing or foundation systems) are less disruptive than interior retrofits. In the case of hospitals, for example, exterior retrofit would likely be the preferred approach.

Building function. New structural components, such as shear walls or bracing, can negatively affect the layout of the building (and hence traffic flow), daylight, or aesthetics. For this reason, moment frames may be preferable to bracing or shear walls in certain locations.

Aesthetics/heritage value. The preservation of a building's aesthetics and its heritage value is especially challenging.

The engineer must work closely with the owner, the architect, the contractor and any specialists (e.g., a heritage consultant) to select a retrofit approach that best addresses and resolves all these issues.

New Guideline for Non-Structural Components

A new document, *Guideline for Seismic Risk Reduction of Operational and Functional Components of Buildings*,⁷ which deals with the seismic evaluation and upgrading of non-structural building components, is now being prepared by the Canadian Standards Association. It will recommend procedures and criteria to mitigate seismic risk at minimum cost and disruption.

A separate guideline on non-structural building components is needed because non-structural retrofits can often be carried out as part of a regular maintenance program with little disruption to building activities. In areas of low to medium seismicity, the failure of non-structural building components during an earthquake often poses a greater risk than structural failure. The 1988 Saguenay earthquake, in which most of the damage was due to the failure of concrete-block partitions, is a recent example of this.

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Dr. D.E. Allen is a guest research officer in the Building Envelope and Structure Program at the National Research Council's Institute for Research in Construction.

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