Seismic Retrofit of Existing Buildings: Innovative Alternatives

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Abstract

Recent earthquakes in Turkey (1999) and Taiwan (1999) demonstrated the power of nature and the catastrophic impact of such power upon urban cities. Casualties and damage associated with older buildings, which were designed and constructed using codes that are now known to provide inadequate safety, are far worse than that for newer buildings which have been designed and built in accordance with more stringent code requirements. On a universal scale, the stock of older buildings built before 1980's is believed to be many times more than the number of newer buildings in most urban cities. Relatively speaking, seismic retrofitting of buildings is still a new activity for most structural engineers. The retrofitting of a building requires an appreciation for the technical, economic and social aspects of the issue in hand. Changes in construction technologies and innovation in retrofit technologies present added challenge to engineers in selecting a technically, economically and socially acceptable solution.

Conventional upgrading techniques usually include the addition of existing walls and foundations and strengthening of frames. Most of these techniques often lead to costly consequences such as heavy demolition, lengthy construction time, reconstruction, and occupant relocation. Such costly, environmentally hostile and intrusive approach associated with conventional techniques often deters building owners from retrofitting building for improved earthquake performance.

An on-going program on the use of innovative technologies for the seismic retrofit of Canadian federal buildings in the Province of British Columbia has demonstrated the cost effectiveness of the innovative alternatives. During the past few years, Public Works and Government Services Canada (PWGSC) has demonstrated the successful and cost effective applications of emerging technologies such as passive damping device and advanced composed materials. The use of these innovative technologies in building retrofit projects was found to be far less intrusive to building occupants and offered savings in construction cost. Planned retrofit projects will consider the continued use of emerging technologies such as other types of passive damping device, external pre-stressing techniques and steel shear plates. Since no two buildings are the same, the challenge to structural engineers is to select the alternative solutions that are technically, economically and socially acceptable. The paper gives an overview of PWGSC's experience in the use of innovative technologies for cost effective seismic retrofit of existing buildings.

1. Introduction

Building code requirements for seismic lateral forces for high seismic areas in Canada have increased by as much as 100 per cent since the early 1970's. Improved design requirements and methods can be expected to reduce damage of newer buildings to acceptable levels in the event of a moderate to strong earthquake. However, older buildings, which were designed by codes that are now known to provide inadequate safety, are likely to be vulnerable to severe damage or collapse under strong seismic excitation. The recent earthquakes in U.S.A. (Northridge 1994), Japan (Kobe 1995), Turkey (Golcuk-Izmit 1999) and Taiwan (Chi-Chi 1999) revealed the fact that an earthquake does not necessarily have to be the "big one" to cause widespread destruction, especially among older buildings. Past earthquakes have also demonstrated that these older building would have survived, in most cases, with a reasonable upgrading.

In Canada, the stock of pre-1980's buildings is believed to be many times more than the number of newer building which were designed and built in accordance with the more stringent and recent codes. While substantial advances have been made in developing refinements to new codes (which are developed for new construction), relatively little effort has been given to take care of the existing and potential vulnerable old buildings. It has been said that "disasters do not happen to well-prepared communities". In an effort to prepare the communities for seismic events and to maintain sustainability of communities through better preparedness or readiness, the challenge to Canada's seismic protection community is how to improve the performance of existing building in a technically, economically and socially acceptable manner.

2. Seismic Hazard Mitigation Approach

The average age of PWGSC's buildings is over 40 years, i.e. many of these buildings could be vulnerable to moderate to strong earthquakes. An integral part of the PWGSC's seismic hazard mitigation strategy is to evaluate and apply innovative technologies such that these PWGSC buildings can be retrofitted in a cost-effective manner. Generally speaking, a building would go through a three-step process before consideration is given to seismic retrofit, namely screening, evaluation and retrofit.

Screening

Screening entails assessing buildings to ascertain their level of seismic risk following a simplified procedure whose main objective is to determine if the building should or should not be subject to a more detailed investigation (i.e. step 2). The widely used methodology for seismic screening in Canada is given in "Manual for Screening of Buildings for Seismic Investigation, 1993"[1], developed by the National Research Council's (NRC) Institute for Research in Construction. Its purpose is to establish numerically a Seismic Priority Index (SPI), i.e. ranking, which results from the addition of a Structural Index and a Non-Structural Index.

Major factors to determine the screening score are building location, soil conditions, type and use of the structure, obvious building irregularities, presence or absence of non-structural hazards, building age, and building importance and occupancy characteristics. The bench mark for the screening is the 1990 edition of National Building Code of Canada, or NBCC 1990 [3]. For a building that was built in compliance with NBCC 1990, its SPI is expected to be equal to 2.0. The priority for a more detailed evaluation is "low" for SPI less than 10, "medium" for SPI between 10 and 20 and "high" for SPI greater than 20. PWGSC used a cut-off value of 12 for SPI, i.e. detailed evaluation is proposed for buildings with a SPI value of greater than 12.

Evaluation

In the evaluation process, a detailed investigation is performed on buildings with medium to high priority as a result of the screening exercise. NBCC 1995 and NRC's "Guideline for Seismic Evaluation of Existing Buildings, 1993" [2] provide adequate guidance for the performance evaluation of existing buildings. The objective of a performance evaluation is to identify the vulnerability of the structural and non-structural systems and their components to seismic loads.

In carrying a detailed evaluation for stone masonry structures, PWGSC's "Guidelines for seismic assessment of stone masonry structures"[4] can be used. Existing guidelines from NRC and Federal Emergency Management Agency address the most commonly found brick masonry construction but do not include the special types of structures and construction materials found in heritage stone masonry buildings. PWGSC's guidelines provide analytical methods and criteria for assessing the seismic adequacy of stone masonry structures.

Retrofit

Seismic retrofit becomes necessary if it is shown that, through a seismic performance evaluation, the building does not meet minimum requirements up to the current building code and may suffer severe damage or even collapse during a seismic event. Seismic retrofitting of buildings is a relatively new activity for most structural engineers. The retrofitting of a building requires an appreciation for the technical, economic and social aspects of the issue in hand. Changes in construction technologies and innovation in retrofit technologies present added challenge to engineers in selecting a technically, economically and socially acceptable solution.

Conventional upgrading techniques usually include the addition and/or strengthening of existing walls, frames and foundations. Adopting these recommendations often leads to heavy demolition, lengthy construction time, reconstruction, and occupant relocation with all the associated direct and indirect costs. It is often the indirect costs, the environmentally hostile approach, and the inconvenience associated with conventional techniques that deter building owners and custodians from committing to seismic retrofit.

In less than a decade, much progress has been made in developing innovative structural and non-structural hazard reduction measures in buildings. Advanced composite materials and new technologies have been extensively researched and, to a lesser extent, applied in seismic retrofit projects. As most building codes, including the NBCC, are moving from prescriptive to objective based, more flexibility in meeting stated performance requirements is allowed and encouraged. The use of innovative technologies lends itself well into adopting the new code development criteria.

3. Seismic Hazard Mitigation Technologies

During the past 10 years, a significant amount of research has been conducted into developing hazard reduction technologies for building structures such as damping devices, advanced composite materials, building isolators and external prestressing. Through its technology development and transfer program, PWGSC identifies, evaluates and adapts seismic technologies and tools, which are technically, socially and economically acceptable. Result of the successful technology transfer is that several such innovative technologies have been used or are being considered for use in the seismic retrofit of several federal buildings in the Province of British Columbia, which is the most seismic active zone in Canada. While passive damping device such as friction dampers and viscous dampers reduces the overall seismic demand upon the structural system of a building, the use of carbon fibre reinforced plastic, fibre reinforcement cement or external prestressing improves the performance of individual structural elements such as columns, beams and walls.

Friction Damper

Friction damper, consisting of specially coated steel plates being bolted together, is usually part of a steel brace system that is mounted within a column-beam frame. The commonly used friction damper systems are in the form of an X (friction damper being at the middle of the X) or a diagonal (friction damper being along the diagonal) inside a rectangular column-beam frame. Such a friction damper system is attached to the structural frame through connections at the column-beam joints.

Friction damper system's function is similar to that of a shock-absorbing system in a car. Earthquakes release energy through ground shaking motions, which induce seismic loads to a building structure. Friction dampers absorb the earthquake-induced energy (or load) when the steel plates slide against each other at pre-determined slip load, i.e. dissipating the earthquake-induced energy through friction-generated heat energy. Adding friction dampers to an existing building increase the seismic load carrying capacity of the building structure by means of reducing the demand of seismic resistance capacity upon the building's existing load carrying elements.

Friction damper system has been used in one federal building [Figure 1] and is currently being installed in a second federal building [Figure 2] in British Columbia. Use of friction damper system for a third federal building is under consideration.

Fluid Viscous Damper

Similar in function to that of friction dampers, fluid viscous damper is another type of passive device that can be used in the seismic retrofit of existing buildings. Retrofitting an existing building with viscous dampers results in reduction of seismic demand upon the structural elements of the existing building. In a building retrofitted with velocity dependent viscous dampers, the damper force is out of phase with the hysteretic or drift demands in the structural system. In other words, the damper delivers zero force to the lateral system at maximum drifts and delivers maximum force to the lateral system when the structure passes through the gravity state during dynamic response to earthquake input. In summary, the viscous dampers provide the maximum damping effect when the lateral movement of the structural system is at its highest velocity, i.e. in passing through the gravity or initial state.

The first use of fluid viscous dampers on a federal building in British Columbia is being proposed and under consideration.

Carbon Fibre Reinforced Plastic

Advanced composite materials such as carbon fibre reinforced plastic (CFRP) is much stronger and lighter than steel. The inherent non-corrosive characteristic of CFRP makes CFRP reinforcement a very effective alternative to steel reinforcement for reinforced concrete structures, especially when reinforcement corrosion is a main concern for the performance and durability of the structure. Analytical and experimental results have shown that, wrapping structural components (such as columns, beams and walls) with CFRP sheets improve their strength and ductility without adding stiffness to the elements. Ease of installation, which is similar to putting up wall papers, makes the use of CFRP sheets a very cost-effective and efficient alternative in the seismic retrofit of existing buildings.

CFRP has been used on one federal building [Figure 3], is currently being used in a second federal building and will likely be used in a third federal building in British Columbia.

Fibre Reinforced Cement

Past and recent earthquakes have exposed the vulnerability of un-reinforced masonry (URM) and the consequence of URM's failure. Common practice of retrofitting URM walls is either by replacing the URM walls with lighter construction or by adding an structural overlay onto the URM walls. The latter method often increases the stiffness of the wall elements, which in turn attract higher loads in the event of an earthquake.

Fibre reinforced cement, or FRC, comprises of a high strength fibreglass grid or mesh and a thin layer of fibre reinforced cement. Adding a FRC overlay onto an URM wall enhances its strength and ductility performance without increasing its stiffness. FRC can transform an URM into a reinforced masonry wall with improved structural performance under an earthquake.

FRC has been used in one federal building [Figure 4]. Use of FRC for a second federal building is under consideration.

External Prestressing

Most common deficiencies, i.e. failure, found in older reinforced concrete columns are due to lack of confinement, insufficient lateral reinforcement and inadequate reinforcement splicing. Providing steel or concrete jacketing to deficient columns not only improves the strength but also increases the stiffness of the column. Increasing the columns' stiffness is not desirable as the stiffened columns now attract, or are subjected to, higher seismic loads. One alternative would be wrapping the column with CFRP sheets. A second alternative would be wrapping the column with individual cable strands, which are prestressed to exert active pressure against the column section.

Analytical and experimental studies have shown that columns retrofitted with external prestressing exhibited improved performance in terms of strength and ductility. The improved performance is mainly due to the additional concrete confinement and supplementary shear reinforcement provided by the external prestressing system.

The first use of external prestressing [Figure 5] in a federal building in British Columbia is being proposed and under consideration.

4. Seismic Hazard Mitigation: Innovative Alternatives

During the past few years, PWGSC has demonstrated the successful and cost effective applications of innovative technologies in a number of seismic upgrading projects on federal buildings. These retrofit projects have three things in common: older buildings in need of a structural upgrading, performance evaluation using refined analysis method and use of innovative technologies with cost-effective results.

Harry Stevens Building - Friction Dampers

Harry Stevens Building in Vancouver was built in 1963 with an area or 6,243m^2. The building type is reinforced concrete structure with URM in-fill walls. The building has two above-grade floors and a basement.

Initial recommendations for the seismic retrofit of the Harry Stevens Building called for a conventional upgrading approach, which included the strengthening of existing shear walls, addition of new shear walls and partial foundation upgrading to accommodate added shear walls. This approach was found to be both cost excessive and intrusive. The construction cost of this upgrade was estimated to be around C$1,400,000. Indirect cost due to phased relocation of tenants was calculated at about C$650,000, i.e. the total cost would have been $2,050,000.

To achieve cost savings while meeting equivalent seismic safety requirements, PWGSC decided to consider the use of friction dampers in this building. Evaluation of seismic performance using refined analysis confirmed that this technology would be suitable and cause minimum interruption to business operations. Both diagonal and X-braced friction dampers were used and staggered over the entire building. These friction dampers absorb the energy released/transferred from the earthquake through the ground to the building structure, thus reducing the load that the building structure would otherwise be subjected to during an earthquake. In this particular case, foundation upgrading was not required due to sufficient energy dissipation in the upper stories. Figure 1 shows one of the X-braced friction dampers installed in the building.

The project was completed with the tenants being allowed to remain on site during the upgrading. The total cost of the structural upgrading was approximately C$810,000, compared to $2,050,000 if the conventional retrofit approach were adapted.

Standards Building - Fibre Reinforced Cement

Standards Building in Vancouver was built in 1963 with an area of 1,562m^2. The building type is a mixed structure of reinforced concrete and steel with URM in-fill walls. The building includes two above-grade floors and an attached two-story high garage.

Initial recommendations for the seismic retrofit of the Standards Building were to (a) add steel braces and (b) to replace the URM walls with new shear walls. The construction cost of this upgrade was estimated to be around C$410,000.

In order to meet equivalent performance and cost-effectiveness requirements, it was decided that the existing URM walls be strengthened instead of replaced. The building was eventually upgraded incorporating conventional techniques (new steel braces on the two floors) and innovative technologies (FRC on URM walls within the garage area). Multi-layered FRC was used to transform (strengthen) existing non-load bearing URM block walls to load bearing shear walls which were connected to the steel framing. Figure 4 shows the upgraded masonry block wall in the front, with the original URM block walls visible in the background. The structural upgrading cost was $180,000 using innovative technologies.

Port Alberni Federal Building - Carbon Fibre Reinforced Plastics

Federal Building in Port Alberni, a reinforced concrete structure, was built in 1960 with an area of 2,400m^2. Port Alberni is situated in one of the highest seismic zones of Canada

Initial recommendations for the seismic retrofit of the building were to (a) eliminate short columns by in-filling window openings, (b) building new wall panels on first floor and the basement floor to provide continuous load path for the walls, and (c) to strengthen deficient columns by either enlarging the columns or steel jacketing the columns. Column strengthening either by enlarging the column section or steel jacketing was found to be costly and intrusive, i.e. building needed to be vacated to carry out the work. The construction cost of this upgrade was estimated to be around C$438,000. Indirect cost due to partial relocation of tenants was calculated at about C$102,000, i.e. the total cost would have been $540,000.

In order to meet equivalent performance and cost-effectiveness requirements, it was decided that the deficient columns be strengthened by means of wrapping the columns with CFRP. As the columns had adequate shear strength but were weak in flexural strength, the columns were wrapped full-height with one ply of CFRP. The Port Alberni Federal Building was the first application of CFRP for the seismic upgrade of reinforced concrete columns in western Canada. Figure 3 illustrates the application of CFRP sheets onto the column. The structural upgrading cost was $310,000 using innovative technologies.

Pump House Building – Friction Dampers and Carbon Fibre Reinforced Plastics

The Pump House building is situated at the Esquimalt Graving Dock site in Victoria. Built in 1924 with additions in 1940 and 1970, the building is a 2-storey reinforced concrete moment frame with interior and exterior brick masonry walls. The building has a mezzanine floor and is built on top of a large basement service cavern. As a recognized heritage structure, the rehabilitation solution must meet the requirement of heritage conservation. Any proposed solution must also not interfere with the Pump House' operation, i.e. the facility is to remain fully operational during construction.

Due to the two imposing conditions, the only practical solution appeared to be a combination of installing passive damping device such as friction dampers for the moment frame and wrapping the brick walls with CFRP sheets. The proposed non-intrusive solution for the structural framing of the main nave was accepted both by the heritage committee and by the facility's owner/operator. Figure 2 shows a rendering of the main nave of the building with friction damper systems.

Surrey Taxation Centre Building – Fluid Viscous Dampers

The Taxation Centre building in Surrey is a 2-storey steel frame structure with concrete and masonry walls. Basement walls are made of reinforced concrete and masonry blocks. Reinforced concrete shear walls are situated within the building, typically around stairways along the perimeter and three rectangular core areas. The building was built in 1977 and has a total area of about 25,000 m^2.

Main structural deficiencies include discontinuous shear walls, deteriorated concrete and URM walls, inferior connections between steel members and between steel frame and shear walls and inadequate foundation at shear walls. Two seismic retrofit solutions were proposed: one with a conventional approach meeting a life-safety performance requirement and one using innovative technologies of passive damping meeting a higher performance (i.e. immediate-occupancy) requirement. The main difference between the two proposed solutions is that the conventional approach adds wall panels to make the shear walls continuous while the innovative approach uses viscous dampers at selected locations such that discontinuous walls will not be utilized as shear walls. The estimated total construction costs for the conventional and innovative approaches are $4,391,000 and $2,787,000 respectively, a 35% difference.

4. Conclusion

In order to mitigate the seismic risk associated with older buildings, PWGSC is currently developing strategies and implementation plans for the well being of federal buildings. An integral part of the overall seismic risk reduction program is to evaluate and apply innovative technologies such that the federal buildings can be retrofitted in a cost effective manner. During the past few years, PWGSC has demonstrated the successful application of innovative technologies in a number of seismic upgrading projects on federal buildings. The proper use of these emerging technologies in building retrofit projects has been proven to be far less intrusive to building occupants and cost effective. Potentially great savings can be realized by reduction in construction cost and by avoidance of tenant relocation and associated productivity losses.

References

[1] Institute for Research in Construction (NRC/IRC). "Manual for Screening of Buildings for Seismic Investigation". National Research Council of Canada, Ottawa, Ontario. 1992.

[2] Institute for Research in Construction (NRC/IRC). "Guidelines for Seismic Evaluation of Existing Buildings". National Research Council of Canada, Ottawa, Ontario. 1993.

[3] National Research Council of Canada (NRC). "National Building Code of Canada (NBCC 1995)". Ottawa, Ontario. 1995.

[4] Public Works and Government Services Canada (PWGSC). "Guidelines for Seismic Assessment of Stone Masonry Structures". Hull, Quebec., 2000.

Figure 1 Harry Stevens building: X-braced friction damper

Figure 2 Pump House building: rendering of installation of friction dampers

Figure 3 Port Alberni Building: CFRP application on a column