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HIGH-PERFORMANCE SEISMIC RETROFIT METHODS IN MODERATE SEISMIC ZONES

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Abstract

Seismic retrofit of existing buildings located in moderate seismic zones is often triggered by local legislation when a building is being modified for other reasons. However, as opposed to in high seismic zones, the public often has little awareness of the risks posed by moderate seismic events. Developers are thus not willing to invest additional resources in seismic retrofit solutions even though they would ensure a better seismic performance of the structure and reduce repair costs after an earthquake. Due to a lack of familiarity, these new technologies are often perceived by clients as unnecessarily complicated and as a risk to the project budget and schedule. However, new technologies often allow for immediate benefits through reduced costs, reduced construction time and a less invasive intervention. To open the market to these new technologies, convincing arguments need to be presented to demonstrate that these benefits can be achieved reliably on a given project.

The current research project aims to contribute to the faster adoption of new technologies and a more rational selection of the type of retrofit of existing buildings in moderate seismic zones. This paper discusses the first phase of the project, where the workflow was defined and implemented in a front-end tool for two typologies of retrofit: shear walls and yielding-restrained braces (braces with friction dampers). Finally, a specific building example will demonstrate its application.

Keywords: seismic retrofit, moderate seismicity, yielding restrained braces, concrete frames, concrete shear walls

1. Introduction

Earthquakes have posed a significant threat to the built environment throughout humanity's recorded history, with many catastrophic events showing their potential impact. Consequently, seismic building codes and regulations have appeared and evolved in most jurisdictions with high to moderate seismicity over the last century. In Japan for example, one of the first countries to adopt seismic regulations, these were first explicitly addressed in 1924, following the 1923 Great Kanto earthquake. The later evolution of these regulations was also heavily influenced by subsequent large earthquakes [1]. While the evolution of seismic regulations not only in Japan but worldwide has resulted in modern buildings oftentimes having an adequate performance level, the same is not true for existing structures built before 1970's to 1980's or even more recently depending on the jurisdiction. In the last decade alone, earthquakes as the 2011 Christchurch or the 2010 Haiti events have resulted in tens of thousands of casualties and billions of dollars in damages, most of them associated with structures designed with no or inappropriate seismic considerations. These and other events have also demonstrated that the design earthquake is not necessary to severely damage older buildings, and that in most cases they would have survived with reasonable upgrades.

The seismic assessment and retrofit of existing buildings has therefore been a priority in recent decades for researchers, building authorities and private organizations alike. Knowledge continues to advance on topics like rapid seismic assessment methods; innovative materials including carbon fiber reinforced polymers; shape memory alloys or high-performance fiber reinforced concrete; retrofit solutions for specific structural systems such as adobe or earthen construction, which are used by approximately one third of the world population; and building typologies including masonry churches which have high historical and architectural value. Building authorities have been making every effort to keep up with these advances and to bring them into practice by issuing guidelines for the seismic vulnerability assessment and retrofit of buildings, by encouraging the assessment and retrofit of existing buildings, making it mandatory in some cases, and by evaluating and selectively retrofitting governmentally-owned building stock. A prime example of the efforts made in seismic evaluation is the bill passed by the state of Oregon (USA) in 2005 to develop a statewide seismic needs assessment, including the seismic safety survey of K-12 public school buildings and large community college buildings as well as hospital buildings with acute inpatient care facilities and fire stations [2]. Some private organizations have also invested in this assessment and retrofit effort, including a comprehensive seismic risk assessment of the buildings at the University of British Columbia Vancouver campus, where the risk to people, assets and core functions on campus under various earthquake scenarios was quantified and initial financial strategies for cost-effective mitigation were proposed [3].

When specifically looking at common retrofit practices for buildings, conventional options have generally relied on stiffening and strengthening structures, as well as improving their ductility by adding or strengthening existing walls, frames and foundations. However, these methods are often invasive and costly, requiring heavy demolition and reconstruction and long construction time requiring relocation of the building's occupants. Another downside of these methods is that by stiffening the building, seismic forces are increased, requiring additional strengthening of primary and secondary load carrying elements. A study conducted in Cali, Colombia, for example, investigated the modal properties of seven reinforced concrete buildings before and after seismic retrofit. It was found that the buildings' frequencies increased up to 200% when retrofitting with concrete shear walls, thereby increasing the applicable spectral acceleration of the Colombian Building Code in use by up to 26% [4].

To overcome these problems, high-performance alternatives have been developed. They rely, among other things, on dissipation of energy, isolation of the structure from the ground and increased ductility without adding stiffness. They were also developed to offer a better performance than their classic counterparts, which translates to a reduced cost of the retrofit when using life cycle assessments, less damage to buildings' non-structural components, and reduced downtime after a seismic event. While these high-performance systems have become common in high seismic zones worldwide, their adoption in moderate seismic zones has been slow.

2. Seismic retrofit in moderate seismic zones

Cities located in what can be considered moderate seismic zones have the potential to be classified as having high seismic risk. While somewhat counterintuitive, this can be explained by revisiting the definition of risk, as shown by Eq. (1). While the seismic hazard might only be moderate, the building stock can be highly vulnerable because of its age, construction methods and quality; these regions may indeed have higher risk than regions with higher seismic hazard due to the age of their building stock. Thus, Montreal for example, located in Eastern Canada, has been identified as the second-most at risk city in Canada, accounting for roughly one quarter of the relative seismic risk of all Canadian cities [5]. Similarly, a comprehensive study conducted for the New York metropolitan area concluded that this region is low-hazard, yet high-risk: considering its large population and its building stock composed largely of unreinforced masonry, even a moderate earthquake would have a significant impact on the lives and economy of the region [6].

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Exposure} \tag{1}$$

Unfortunately, the public has little awareness of the risks posed by seismic events in moderate seismic zones, and voluntary retrofits are rare. Seismic retrofit of existing buildings is thus often only triggered by local legislation, mostly when a building is being modified for another reason. While these regulations have been effective in getting buildings retrofitted, conventional retrofit schemes are still prevalent. When developers are required to invest in a seismic retrofit, they prefer conventional methods over new technologies. Based on a simple lack of familiarity, these new technologies are often perceived as unnecessarily complex and a risk to the project budget and schedule by clients.

Something similar can be said for practicing engineers, who are often extremely constrained by time and resources, especially in the initial schematic design phase of projects where the type of retrofit solution is often selected. They therefore tend to lean towards systems they are familiar with and shy away from the additional effort required for the design of high-performance systems, which as opposed to common construction often require non-linear analyses and may not be regulated in the same prescriptive manner by building codes. However, while this might be true for detailed design, simplified analysis methods exist even for high-performance methods. For example, it has been demonstrated that yielding-restrained braces (braces with friction dampers) can be designed with a conventional linear force-based method when certain conditions are met [12]. Similar simplified procedures exist for other systems as well.

Research and existing case studies have mostly focused on the advantages of innovative systems in the reduction of life-cycle cost of the building, or on better performance during and after an earthquake (i.e. less damage to structural and non-structural components and less downtime after the event), as shown in references [8] to [10]. While the findings are significant in high seismic zones, they are less effective in moderate seismic zones where more importance is given to immediate benefits. However, some researchers and practitioners have demonstrated that high-performance retrofit methods, which have become mature technologies, can have these immediate benefits, such as reduced cost and a faster and less invasive construction. A program on the use of high-performance technologies for the seismic retrofit of Canadian federal buildings in the province of British Columbia, for example, demonstrated the cost effectiveness of high-performance alternatives, comparing their up-front cost to conventional retrofit solutions. Furthermore, the study found that additional cost reductions could be achieved through the reduced disturbance of occupants of the buildings. High-performance retrofit techniques used included friction dampers, fluid viscous dampers, carbon fiber reinforced plastic, fiber reinforced cement and external prestressing [11]. The immediate advantages of high-performance solutions were also observed in moderate seismic zones, as shown for example by the seismic rehabilitation of the Ministry of Justice headquarters building in Ottawa, Canada. The use of friction dampers in braced frames allowed the dissipation of seismic energy, avoiding the expensive and time-consuming task of strengthening columns and foundations. The use of this system allowed a reduction in costs and the construction schedule when compared to a traditional retrofit option using shear walls [12].

In conclusion, new technologies have matured enough to allow for immediate benefits through reduced costs, reduced construction time and a less invasive intervention in certain cases, even in moderate seismic zones. However, to open the market to these new technologies, convincing arguments need to be presented to clients and other stakeholders by the practicing engineer to demonstrate that these benefits can be achieved on a given project. Thus, these engineers need a tool that allows for reliable, yet simple estimates of the impact of different retrofit techniques will have on schedule and cost of the project.

The current research project aims to contribute to the faster adoption of new technologies and specifically to a more rational selection of the type of lateral load resisting system (LLRS) selected for the retrofit of existing buildings in moderate seismic zones. This paper discusses the first phase of the project, where the workflow was defined and implemented in a front-end tool for two typologies of retrofit: shear walls and yielding-restrained braces (braces with friction dampers). Finally, a specific building example will demonstrate its application.

3. Workflow

The developed high-level workflow targets the schematic design phase of the project, its intended user being the structural engineer conducting the seismic analysis and design. It is assumed that this engineer has adequate experience in seismic design. The workflow's desired outcomes are metrics on key parameters (related to immediate benefits) for each studied LLRS with a reasonable level of accuracy and reduced calculation effort. The key parameters to be determined are (a) the quantities of the components of the new LLRS and (b) the retrofit needs for the existing structure, particularly the foundation. This information can then be used to calculate immediate costs and estimate the impact on the project schedule and disruption of building activities. This last step was excluded from the workflow since it is project-specific and needs to be investigated and agreed on with other stakeholders of that project. Note that a detailed analysis and design will be required for the retained retrofit. The high-level workflow can be simplified into the five steps listed below.

1. Collect building and site information
2. Perform initial assessment to validate if retrofit is required
3. Check permissible systems and select options for closer examination
4. Analyze selected options and determine minimum pass requirements
5. Compare metrics and present results to other stakeholders

The first step in any potential retrofit project is to collect basic information on the building and on the site. This step does not deviate from current practice: existing documentation, including structural drawings, architectural drawings and geotechnical reports, need to be studied. It is recommended to confirm this information with at least one site visit. Additionally, some destructive and non-destructive tests might be deemed necessary if the existing information is incomplete or unreliable. If the retrofit is tied to the change of use or modification of the existing structure, the associated structural changes need to be clarified. Special performance criteria that might have to be considered also need to be defined, even if the intent is not to carry out a performance-based design. In the Canadian context, for example, the performance criteria might refer to a mandatory percentage of code compliance for existing structures, and to an importance factor introduced in the National Building Code of Canada (NBCC) to increase the performance of high importance and post-disaster buildings. Special conditions of the building will also inform specific performance requirements to be considered: the risk of pounding to a neighboring building with a limited joint spacing or the necessity to protect unreinforced masonry partitions might warrant more restrictive drift limits than those prescribed by codes, for example.

The original structure then needs to be studied in some detail to determine if it requires retrofit. In moderate seismic zones, this assessment can typically rely on linear static procedures. The most time-consuming component of the assessment, required for most cases, will be the creation of a finite element model to determine the inter-story drifts. Engineering judgement is needed to determine the reasonable simplifications to this model. The capacity of the elements that make up the LLRS, the secondary systems and potential deficiencies also need to be assessed. Again, this step is well established in current practice and the workflow does not intend to change it, although as will be seen in the next section on the developed tool, some effort was made to increase the efficiency of steps one and two.

Once it is determined that the studied building indeed needs to be retrofitted, the next step is to compile a list of all possible retrofit options, either strengthening the current system or introducing a new one. Building codes usually identify limiting conditions for the use of different types of LLRSs that need to be considered in this step. Examples of these limiting conditions include the building height, its intended use or a factor that accounts for the site's specific seismic hazard. With the list of possible retrofit strategies, the engineer needs to limit the choice of further studied options based on his experience and the project specific characteristics.

For each specific retrofit strategy identified for further study, the next step is to determine minimum pass requirements, quantifying the key parameters that are the desired outcomes of the workflow. This is the step where time efficiency is critical and where approximate results are acceptable. Key considerations that will allow this to be achieved are listed below.

- A finite element model of the existing structure was already created in step 2 of the workflow for most cases.
- Linear analysis or simplified methods are to be used, even for high-performance retrofit solutions.
- Acceptance criteria for each retained system need to be established. This refers to design checks that potentially govern the design of the system, and that have an influence on the key parameters to be determined. As an example, drift limits could be one acceptance criteria for most systems. The system only needs to be designed to pass these acceptance criteria.

Each typology of LLRS requires the development of a specific workflow to achieve this time-efficient preliminary design. Section 4 will describe how specific workflows were developed and applied for the Canadian context for concrete shear walls and yielding-restrained braces.

Finally, metrics for the different studied options are compared and discussed with other stakeholders of the project to inform the selection of the retained retrofit option.

4. Front-end tool

The workflow described in the previous section, including specific workflows for retrofits using concrete shear walls or yielding-restrained braces, were implemented in a tool for the Canadian context based on the 2015 edition of the NBCC [13]. A series of spreadsheets were developed to be used in conjunction with the finite element models of the building. It was assumed that the studied system is orthogonal, the same type of LLRS is used in for the retrofit in both directions and that it the building has no major irregularities (except for allowances made for torsional sensitivity). The following sections will describe some of the specifics for each step of the workflow.

4.1 Collect building and site information

To achieve the first step of the workflow, an input sheet was created where the user is prompted to define the building's and site's information, First, the project's basic information is recorded, including its name, address and the latitude and longitude. Next, seismic hazard values obtained from National Resources Canada [14] and the soil class are recorded. The percentage of code compliance to be achieved is also recorded. In Quebec, for example, existing buildings are permitted to be retrofitted to 60% of the code requirements. Finally, basic building characteristics are entered. These include the importance factor, above ground height, above ground number of stories, maximum and typical free story height, maximum wall length (if applicable), typical grid spacings, average plan area and typical dead and snow loads, as well as the existing type of LLRS. Some space is left for the user to record system specific information that will be required to determine if the building requires retrofit, including dimensions of beams and columns in concrete moment frame buildings.

4.2 Initial assessment

For the analysis of the existing structure, the tool assumes that the modal response spectrum method (or dynamic method) prescribed by the NBCC is used. However, since the base shear obtained needs to be calibrated to the base shear obtained from the equivalent static force procedure, a sheet was developed where this equivalent static base shear is first calculated based on the information of the input sheet. The user is only asked to add the relevant output from the finite element model, specifically the natural period, the seismic weight (which is compared to an automatically calculated estimate), the maximum B ratio (ratio of the maximum to average story displacement to determine torsional sensitivity), and the base shear from the uncalibrated dynamic method.

With these additional inputs, the code required calibration factors for forces and displacements are calculated. Finally, the user needs to input the drift ratios for each floor, calculated using the dynamic method, again without calibration, and the spreadsheet will calculate the calibrated drifts and will compare to allowable code limits. Additional space is left for system-specific checks, should they be required.

4.3 Permissible systems

The information recorded in the input sheet is sufficient to determine the allowable systems based on NBCC code restrictions for all the LLRS types. They are listed on a separate sheet, including steel, concrete, timber, masonry and cold-formed structures, identifying if they are allowable or not. A category of high-performance structures was also added to the list. Although there are no code restrictions on their use and they will always appear as allowable options, they were included for completeness and to ensure they are considered when selecting the systems to analyze further.

4.4 Analyze selected options

4.4.1 Concrete shear walls

The sheet developed for concrete shear walls is applicable to three levels of ductility: ductile, moderately ductile and conventional construction shear walls, both for normal and squat shear walls. The parameters that will allow the user to quantify the immediate impact of retrofitting a given building with shear walls are the number of walls, the wall thickness and the total length of wall. Furthermore, the total base shear and the axial load at the extremities of the walls will allow the user to determine the need to retrofit the foundations. Drift ratios will not only establish if the selected configuration is code-compliant, but also to inform the potential behavior of non-structural elements. These are the sought outputs of the workflow.

Two design parameters are considered critical to quantify the length of wall required in each direction for a given thickness: the building's drift and the maximum allowable shear force in the wall as prescribed by the NBCC. The following simplifications, deemed appropriate in the schematic design phase, were made:

- All walls are continuous over the height of the building.
- All walls have the same thickness.
- All walls use the same concrete strength.
- Approximately the same wall length will be used in both directions of the building.

As a first step, the minimum thickness per code regulations is established. The user is also allowed to input a project-specific minimum thickness, in which case the maximum value will govern. Next, the minimum amount of shear walls in each direction is estimated by comparing the base shear from the equivalent static method to the maximum allowable shear in the walls for each allowable system. At this stage, different iterations of the finite element model need to be performed to obtain results from the dynamic method, each one using a different quantities of shear walls. This minimum length of walls required is used to inform the selection of characteristics of these iterations. Each iteration is performed without calibration, that is, the results are only dependent on the building's mass and stiffness, as well as the spectral accelerations and soil class used. The results are thus applicable for all systems, and the implementation of the iterations is time efficient. The calibration to account for the importance factor, overstrength and ductility force-reduction factors and equivalent static base shear are performed in the spreadsheet. The spreadsheet will also make allowances for possible torsional effects unknown at this stage and the overstrength and inelastic effects that need to be accounted for when designing for shear.

With these results, the retained iteration based on the drift and shear checks is selected. As a last step, the maximum axial load at the wall ends due to seismic loading is extracted from the model and recorded on the sheet, where it is calibrated. These values can be used by the user to determine if foundation reinforcement is required.

4.4.2 Yielding-restrained bracings

It has been demonstrated that yielding-restrained braces can be designed using linear static methods, using ductility- and overstrength-related force modification factors of R_d=5.0 and R_o=1.1, respectively [6]. The parameters that will allow the user to quantify the immediate impact of retrofitting a given building with yielding-restrained braces are the number of braced bays and the slip loads of the friction dampers. The slip load will not only determine the size of the required braces and connections, but also influence the seismic load transferred to the foundation level, and therefore the need to retrofit them. Similarly to shear walls, drift ratios will determine code compliance and the expected behavior of the building and its components.

The main parameter that is critical to quantify the number of braces required is the dampers' slip load and the system's drift. With the input information already collected in the tool, the storey shear forces are established based on the equivalent static method. The user is prompted to input the desired slip load for each floor, and the minimum number of braced bays in each direction are then calculated based on the typical bay geometry in each direction, previously defined in the tool. It should be noted that using the equivalent static storey shear forces is a conservative approach, with the level of conservatism increasing for taller buildings. However, since high-rise buildings in moderate seismic zones tend to be governed by wind and not seismic forces, this approximation was deemed appropriate for a preliminary design. Finally, a finite element model is created to confirm the expected drifts and compare them to acceptable limits.

5.5 Compare metrics and present results

The final step in the process is to compare the metrics and present the results. For concrete shear walls, the presented metrics are the base shear, the total length of walls, the total volume of concrete, and the total surface area. For yielding-restrained braces, the metrics are the base shear, the total number of braced bays and the slip loads. It is then up to the engineer and other stakeholders to assess the cost, the impact on the schedule and the level of operation's disruption of each studied method, as well as the likelihood of the building requiring further retrofit of foundations or other elements of the structure.

5. Example application

The studied building is located in Montreal, a moderate seismic zone. It was constructed in the 50s and has nine stories and one basement. Because of its use, the building is considered a post-disaster (or high importance) building. The original structure did not have a well-defined LLRS: it was composed of concrete columns, flat slabs, exterior beams and interior beams in just one direction. For the presented example, however, it was assumed that the existing LLRS is composed of concrete moment frames in both directions. The structure was retrofitted using steel braces with friction dampers around the year 2000. A total of 88 dampers were installed, with slip loads of 400 and 500kN. The existing structure was not further retrofitted. The retrofitted building was analyzed by non-linear dynamic analysis using eight different seismic records and its adequacy was confirmed. Thus, the retained retrofit strategy serves as a benchmark for the simplified method presented here. In the following sections, the different steps of the simplified workflow will be described.

5.1 Building and site information

Basic input information on the building's geometry and characteristics was obtained from existing structural drawings. A geotechnical report was available, allowing the identification of the local site conditions (soil class C, very dense soil and soft rock). With the location of the site, the seismic hazard values, i.e. the spectral accelerations at different periods and the peak ground acceleration were obtained from Natural Resources Canada.

5.2 Initial assessment

For the initial assessment, a finite element model of the existing structure was created as shown in Fig. (1), where the longitudinal and transversal direction of the building will be identified with X and Y respectively. The building was simplified by disregarding the basement and using typical interior and exterior column sizes per floor. For the beams, one size of interior and one size exterior beams per direction per floor were used. In practice, this meant that the same beam sizes were used for all diaphragms except the roof, where beams were smaller. Some secondary beams and columns, not aligned with the main building grid, were not considered. Since the results are easily scaled and adjusted based on code requirements in the spreadsheet, the process becomes streamlined without any iterations to the analysis.

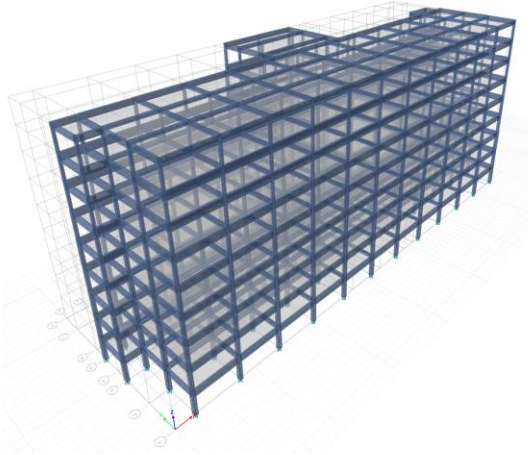
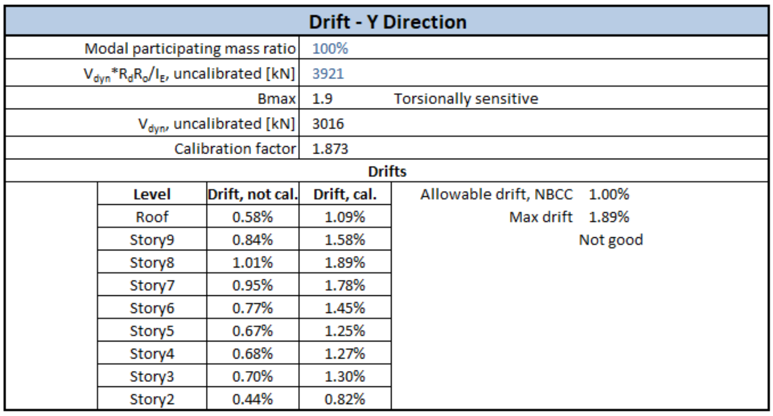


Fig. 1 – Simplified finite element model of the existing building

The initial assessment showed that the original building's inter-story drifts are above the acceptable limit of 1% in both directions, with maximum values of 1.15% and 1.89% in X and Y respectively. Thus, it was demonstrated that the building requires retrofit. It was also not deemed necessary to explore if the structural elements can resist the imposed seismic forces at this stage. Fig. 2 shows, as an example, the drift output in Y as recorded by the tool.



Drift - Y Direction		
Modal participating mass ratio	100%	
$V_{dyn}*R_dR_o/I_E$, uncalibrated [kN]	3921	
Bmax	1.9	Torsionally sensitive
V_{dyn}, uncalibrated [kN]	3016	
Calibration factor	1.873	

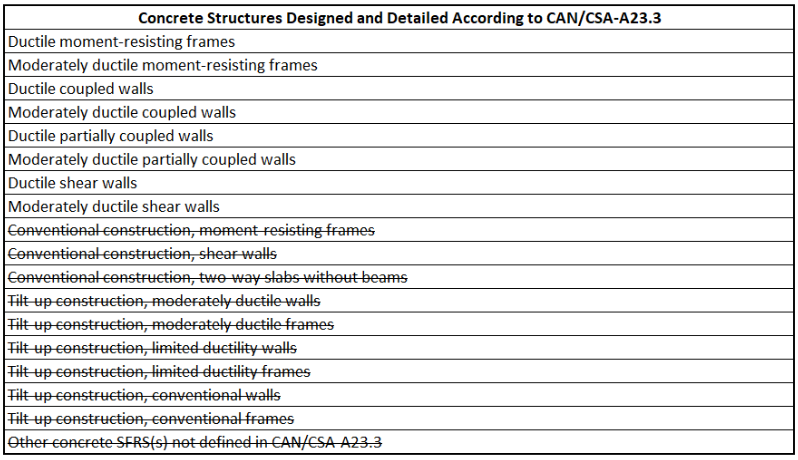
Drifts

Level	Drift, not cal.	Drift, cal.		
Roof	0.58%	1.09%	Allowable drift, NBCC	1.00%
Story9	0.84%	1.58%	Max drift	1.89%
Story8	1.01%	1.89%		Not good
Story7	0.95%	1.78%		
Story6	0.77%	1.45%		
Story5	0.67%	1.25%		
Story4	0.68%	1.27%		
Story3	0.70%	1.30%		
Story2	0.44%	0.82%		

Fig. 2 – Drift in Y as presented by the tool

5.3 Permissible systems

No additional input information is required to identify the permissible system. Fig. 3 shows, as an example, the allowable concrete LLRSs identified by the tool. For this example, the retained systems were moderately ductile shear walls, as a common retrofit strategy, and yielding-restrained braces as the high-performance option.



Concrete Structures Designed and Detailed According to CAN/CSA-A23.3
Ductile moment-resisting frames
Moderately ductile moment-resisting frames
Ductile coupled walls
Moderately ductile coupled walls
Ductile partially coupled walls
Moderately ductile partially coupled walls
Ductile shear walls
Moderately ductile shear walls
~~Conventional construction, moment-resisting frames~~
~~Conventional construction, shear walls~~
~~Conventional construction, two-way slabs without beams~~
~~Tilt-up construction, moderately ductile walls~~
~~Tilt-up construction, moderately ductile frames~~
~~Tilt-up construction, limited ductility walls~~
~~Tilt-up construction, limited ductility frames~~
~~Tilt-up construction, conventional walls~~
~~Tilt-up construction, conventional frames~~
~~Other concrete SFRS(s) not defined in CAN/CSA-A23.3~~

Fig. 3 – Allowable concrete LLRSs as presented by the tool

5.4 Analyze selected options

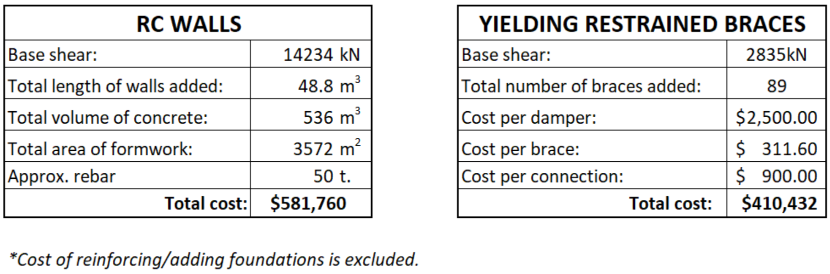
For concrete shear walls, a moderately ductile system was selected. The tool identified that the minimum required wall thickness based on the building's characteristics was 300mm, and that between 19 and 44 meters of walls would be required as a minimum to pass shear capacity checks. Based on this information, it was decided to create 12 different iterations, varying the number of walls in each direction from two to five walls, and examining two configurations for each case to assess how unfavorable placement of the walls could affect the results. The length of each wall was equaled to the typical grid spacing in that direction (7.1m in X and 5.4m in Y). For each iteration, the natural period, the base shear, the maximum interstorey drift and the parameter *B* were extracted. The base shear and the drift were obtained from the uncalibrated dynamic method, as explained in Section 4.4. The tool then calibrated all results, from which the iteration with four shear walls in each direction was retained. For this iteration, drifts were below the allowable limit even with an unfavorable location of the shear walls. The length of walls in each direction was also identified to be appropriate to pass shear requirements, with a total wall length of 49m. For the selected iteration, the base shear was 14 200kN in each direction, and the maximum axial load at wall extremities was 22 500kN.

For the yielding-restrained braces, the only additional input required was the desired slip load in each direction, with which the number of dampers in each floor and in each direction was established from the automatically-calculated storey shear forces. The targeted slip loads were between 400 and 600kN, and it was estimated that a total of 89 braces would be needed, with slip loads varying between 400 and 600kN. At the first level, it was estimated that a total of six dampers per direction were required. Steel brace sizes were pre-designed based on the slip load values, and a numerical model confirmed that drifts were below allowable limits.

5.5 Compare metrics and present results

Finally, the obtained results were compiled for easy discussion with other stakeholders. For both methods, the base shear was presented. For concrete shear walls, the required total length of new walls, volume of concrete, area of formwork and rebar was estimated. For the yielding-restrained braces, the approximate number of braced bays required, and the damper slip loads were indicated. While not part of the workflow, the direct cost of the installation of these elements was estimated for each case (in Canadian Dollars), demonstrating that the use of yielding-restrained braces is indeed cost effective in this case, see Fig. 4.

The actual retrofit of the building using yielding restrained braces was validated with a non-linear time history analysis. It used 88 dampers with slightly lower slip loads than the ones obtained in the initial assessment. In conclusion, the detailed assessment results are consistent with the initial estimates.



RC WALLS	
Base shear:	14234 kN
Total length of walls added:	48.8 m^3
Total volume of concrete:	536 m^3
Total area of formwork:	3572 m^2
Approx. rebar	50 t.
Total cost:	**$581,760**

YIELDING RESTRAINED BRACES	
Base shear:	2835kN
Total number of braces added:	89
Cost per damper:	$2,500.00
Cost per brace:	$ 311.60
Cost per connection:	$ 900.00
Total cost:	**$410,432**

**Cost of reinforcing/adding foundations is excluded.*

Fig. 4 – Cost comparison of both studied methods

6. Conclusions

This paper discusses structural retrofit in moderate seismic zones and the specific challenges to the adoption of newer, high-performance systems when compared to more traditional options. It then proposes a workflow to overcome some of these barriers, specifically affecting the engineers, and describes how this workflow was implemented for the Canadian context for one specific base building type, as well as one traditional and one high-performance retrofit option. Finally, the use of the tool was further illustrated with one specific building example.

It was demonstrated that the workflow and tool allow the determination of approximate retrofit schemes with simple and simplified procedures. The time investment required to identify allowable systems and to reach the conclusions is reduced compared to stand alone analyses and appropriate in the context of the schematic design phase. The metrics obtained with the procedure are used to inform other project stakeholders of the possible implications of using each system. Stakeholders can then use these findings to determine the immediate impact of each studied option and its risk and opportunities on the project's budget, schedule, as well as the expected disruptiveness on the project's operations.

7. Acknowledgements

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