Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Seismic Retrofit of a Previously Partially Retrofitted Heritage Hospital Building

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ABSTRACT

Built in 1913, building A of the Enfant-Jésus Hospital complex is located in Quebec City in a moderate seismic zone. The post-disaster facility was expanded with the construction of partially connected buildings B and C in 1929-1930 and underwent several modifications thereafter. When a major expansion was undertaken in 1995, a seismic retrofit of SABC building ensemble was implemented, which included the integration of new reinforced concrete shear walls and diaphragm strengthening. This rehabilitation aimed at improving the performance and behavior of the dual existing Seismic Force Resisting System (SFRS), featuring unreinforced brick masonry bearing walls and unreinforced brick masonry infill walls. The paramount constraints of maintaining the healthcare services during the construction work resulted in difficulties (phasing, noise, dust) preventing the global retrofit work envisioned in 1995 to be fully performed.

In 2015, the opportunity to fulfill the SABC building retrofit work left unfinished was provided by the beginning of a major transformation project of the Enfant-Jésus Hospital. However, the Codes and the State-of-Practice having significantly evolved between 1995 and 2015 – including a major raise in the seismic hazard for Eastern Canada – challenges were numerous. Performance-Based design and various analysis methods were used to model this complex building. The selected retrofit solution used various interventions simultaneously, such as shear walls, steel bracings, new concrete beams as diaphragms chords and collectors, horizontal bracings, PRF, etc. Complex detailing was necessary to achieve the proper clarity in the tender documents and constructability/phasing issues were thoroughly studied. Various constraints were integrated in the design such as the building's Heritage elements, and existing and new mechanical components.

The project's main challenge was to develop a structural retrofit solution tailored to the project specificities: build on an unfinished retrofit, keep the hospital fully operational during the construction work, preserve the heritage, and do not jeopardize the building's functionality. The work on site began in May 2022.

Keywords: Seismic retrofit, Performance-Based Design, Hospital, Healthcare, Building Heritage, Unreinforced Masonry

INTRODUCTION

The new Quebec City Hospital Complex project was announced in 2015, following studies identifying the high costs related with the proposed Project of expanding and rehabilitating the Hôtel-Dieu of Quebec City, which is the oldest hospital in America, north of Mexico. The relocation of the services was thereafter planned in a new complex to be constructed on the unused land of another existing hospital complex (Enfant-Jésus Hospital), in Quebec City. The new Hospital Complex project consists in the construction of seven new buildings either isolated or separated by expansion joints, of an underground parking structure, of several underground tunnels and of numerous retrofits in the remaining existing buildings. The total project cost estimate revolves around $2.3 billion Canadian Dollars. In this paper, the retrofit of the SABC building ensemble is discussed.

Existing buildings A, B, C and S currently house general surgery, radiology and the archives departments of the hospital. Buildings A, B and C are amongst the oldest buildings at the Enfant-Jésus Hospital. Built in 1913, 1929 and 1930 respectively, they have undergone numerous expansions and modifications over the years. The tower of building A was partly added in 1937 and additional floors were added in 1952. The construction of building S in 1995 included seismic retrofitting interventions for buildings A, B and C. Figure 1, present the complex construction stages of the SABC building ensemble.

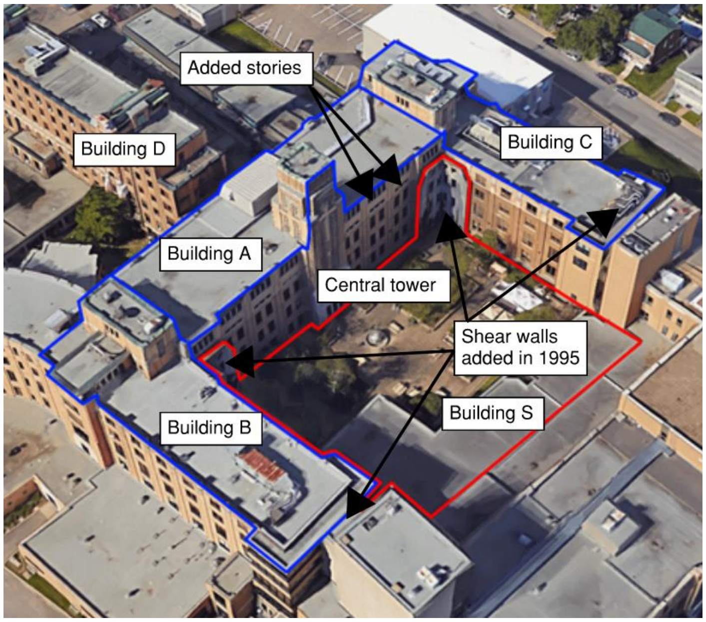


Figure 1. Construction stages of the SABC building ensemble

STRUCTURAL SYSTEM – PREVIOUS RETROFIT

Building A features six storeys' slabs and slabs on deck resting on steel beams supported by interior columns and a perimetric load-bearing unreinforced masonry brick wall. Its central Art Deco tower is ten storeys high and built out of reinforced concrete frames (beams, slabs and columns). Buildings B and C are five storeys high and are composed of reinforced concrete frames (beams, slabs and columns). Building S is mainly a two-storey underground reinforced concrete basement building featuring a one-storey above ground steel structure. Note that the low roof of building S is mostly occupied by a terrace and a green roof. Together, these four (4) buildings have functional links with the rest of the hospital complex.

The foundations of buildings A, B and C are conventional and are supported by continuous or isolated footings. In Building S, 1500 mm thick mat foundations and specifically detailed walls ensures a more efficient distribution of seismic forces in the ground at the level of the shear walls.

The exterior envelope of buildings B and C is mostly composed of infill unreinforced masonry brick walls.

The construction project of Building S, which started in 1995 included new shear walls at A, B and C buildings to improve their seismic capacity. In doing so, and by providing diaphragms connections, the four (4) buildings became structurally linked under seismic loads. Thus, creating building ensemble SABC. However, the connection was not completed, as not all shear walls extend to the upper floors. It should be noted that not all connections from the walls to the diaphragms, that were envisioned during design, were built in this project. This was observed during an extensive surveys campaign and from comparison with the design drawings. Also, no strengthening was performed to improve the seismic behavior of the central tower.

The Seismic Forces Resisting System (SFRS) for the building ensemble is a combination of unreinforced masonry brick walls (both load bearing and infill), reinforced concrete frames and the reinforced concrete shear walls added in 1995. It should also be noted that the seismic forces at the two upper floors at building A are mostly transferred to the masonry walls, as the reinforced concrete shear walls do not reach these levels. This condition is deemed an irregularity according to NBCC 2015 [1] prescriptions.

The diaphragms, which are a key component in allowing the seismic forces to be conveyed to the vertical elements of the building's SFRS, are composed of different types of reinforced concrete slabs, supported by either steel beams or reinforced concrete beams. Note that the composition of the structure was not fully specified in the drawings for buildings A, B, and C, and that surveys were needed to confirm these information's. However, the connection of the diaphragms to the masonry walls could not be investigated and was considered to be inadequate.

In order to connect the existing diaphragms to the new shear walls, collectors beams were also built in 1995. These components were specifically designed to act as shear connectors between the existing structure and the new walls, and they consisted of reinforced concrete and steel beams anchored to the slabs. However, almost no diaphragm strengthening work was carried out in the 1995 project, to improve it's shear or flexural capacity, thus limiting the effectiveness of the global retrofit solutions.

CHALLENGES

Early in the design process, numerous assumptions had to be made as the available construction documents for building ensemble SABC offered limited insight on some of its structural details and on many structural modifications. Hence, to collect the missing information, several survey campaigns were carried out in close collaboration with the hospital managing body. These proved particularly complex in a pandemic context considering healthcare services were maintained. In some instances, access to certain areas of the hospital was impossible for the construction professionals since survey activities posed a high risk for the care of vulnerable patients.

While a proper level of understanding of a structure and its behavior is required to undertake a seismic retrofit project, the numerous construction phases of this building ensemble were challenging as it formed a complex structure. The design team had to review several drawings bundles, sometimes showing interventions that were either never or partially carried out. An extensive on-site testing campaign was also required to characterize the materials.

Another peculiar aspect to this project was the pursuit of a partially implemented seismic retrofit designed in 1995, at a time when state-of-the-art seismic design and engineering tools for lateral analysis did not have today's level of sophistication, especially in Quebec, where the seismic hazard was considered low. This proved to be challenging, as the design team might have opted for different orientations, from the outset, for resolving some of the issues.

DESIGN APPROACH

Performance Criteria

In the province of Quebec, the construction legal document is the Quebec Construction Code [2], which now adopts NBCC 2015 [1] prescriptions, with modifications. One such modification, is the inclusion of clause 10.4.1.3 that greatly impacts the projects involving existing buildings. This clause essentially requests that when a *post-disaster* building undergoes transformation, and with a threshold of more than 25% of all floor areas are stripped, the seismic capacity of the modified structure shall be improved to at least 60 % of the NBCC 2015 (2% in 50 years – 1:2475 years return period) requirements. This was the case for building ensemble SABC in the project. Considering the importance of the structure for the community, the following decisions were made regarding the performance criteria to be used:

- In reinforced concrete foundations systems: flexural reinforcing bars yielding under seismic loads (or loads resulting from the development of shear walls flexural capacity - capacity protected foundations) shall be accepted, provided that the maximum stresses evaluated does not exceeds by 30% the elastic limit ($\varepsilon_S < 1.3\ f_y / E_S$). These damages should only occur in localized areas of the foundations.
- In reinforced concrete foundations systems: concrete cracking due to flexural reinforcing bars yielding under seismic loads (or loads resulting from the development of shear walls flexural capacity - capacity protected foundations) shall be accepted ($\varepsilon_c < f'_c / E_c$). These damages should only occur in localized areas of the foundations.
- No damage to reinforced concrete gravity load resisting structures shall be accepted, except in diaphragms systems where small damages are accepted.
- Pounding between buildings shall not be accepted. Buildings drifts shall be increased by accounting for foundations rotations due to soil flexibility and by building's diaphragms flexibility when relevant. This criterion is especially important for *post-disaster* buildings, as damages resulting from building's pounding are highly non-linear and difficult to predict. Expansion joints shall be designed accordingly.
- Geotechnical stability to overturning shall be adequate and bearing stresses shall be less than the factored bearing strength.

As the existing SFRS offers low resistance to lateral forces due to the highly unpredictable behaviour of masonry walls under cyclic loads, which is attributable to the brittle nature of the materials, the variability observed in their integrity and their construction quality. Furthermore, the load-bearing masonry had a dual role as it supports vertical loads and must also resist lateral forces, which constrains this system to very small displacements. In fact, an **inter-storey drift limit of 0.3%** was selected to ensure adequate behavior of the masonry walls under earthquake loads. This limit was selected using ASCE 41-17 [3] and the work of authors such as Wilding and Beyer [4] and a thorough study of the wall's composition and materials, see Figure 2 for an example of the masonry walls composition. This drift limit also protected infill masonry brick walls from displacement-induced seismic loads. This design performance criteria was of paramount importance to achieve a solution offering the required level of protection.

Figure 2. Building A unreinforced masonry brick load-bearing walls composition

Structural Analysis and Design

The partially retrofitted building ensemble SABC was modelled numerically using a fixed base (FB) CSi ETABS model [5], see Figure 3 that illustrate the initial model used for the seismic assessment. Multi-modal response spectrum analysis was then performed to assess the general performance and behavior of the structure. The masonry walls, both load-bearing and infill, were studied using multiple approaches, such as shell finite elements and by considering the diagonal compression struts assumptions, and upper and lower bounds properties as described by ASCE 41-17 [3], TMS402 [6] and Eurocode 6 [7]. The shear walls were modelled using shell elements and their expected level of damage and cracking was studied to ensure proper load transfer by performing pushover analysis. The existing reinforced concrete frames were studied, and their level of damage and cracking was also thoroughly studied as these loads bearing components are of paramount importance for the building stability and to maintain its operations and they are expected to remain essentially in the elastic range. The various diaphragms and their connections to the SFRS components were also evaluated. This proved to be a complex task and is further discussed in the following section.

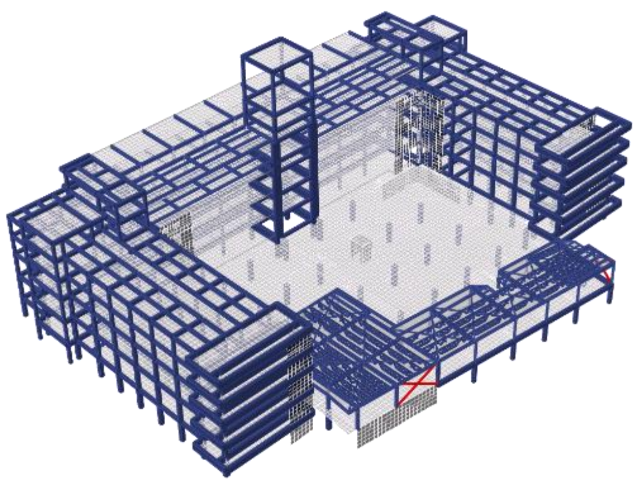


Figure 3. Initial model used for the seismic assessment; masonry walls are not shown for simplicity purposes

From this study, several SFRS shortcomings were identified which led to the design of a global retrofit solution, as described in the following sections. As the project significantly evolved since its beginning, several refinements were implemented in the FB numerical model to optimize the solution and to adapt with construction stages.

Diaphragms

As a complex structural ensemble, a particularly challenging aspect of the seismic assessment was the analysis and evaluation of the existing structural diaphragms. First, the construction methods used to build the SABC were numerous over the last century, and this resulted in the study of several conditions such as:

- In the original Building A part (1913), structural reinforced concrete slabs on steel beams, encased in concrete, were found.
- In the buildings B and C (1929-1930), reinforced concrete beam, slabs and “floretyles” system were used. Theses two buildings were built without a structural separating joint with Building A.
- The original added Central Tower (1953) reinforced concrete beams and slabs were built. Also, for the two storeys added to the original Building A, prefabricated reinforced concrete “Siporex” slabs on steel beams were used.
- In the Building S project, that featured retrofit work (1995), collectors from the existing diaphragms of Buildings A, B and C were added to connect with the new reinforced shear walls that provided a new SFRS. One existing level was also retrofitted with replacing the prefabricated slabs with slabs on deck and steel horizontal bracings.
- Building S (1995) featured structural flat slabs with drop panels. Also, a one-storey level diaphragm is structed with a steel deck roof and steel horizontal bracings.

When analyzing theses diaphragms under seismic lateral loads, reductions of the in-plane properties in the two main local axes were applied. This allowed for a proper consideration of the in-plane shear in the modeled shell elements of the diaphragm and for axial loads to be transferred to chords and collectors’ elements. The desired behavior was ultimately achieved by adding different property modifiers to all the beams, even to the one that were not considered or detailed as seismic force collectors.

A dynamic analysis was performed using a lower bound - upper bound design approach. This was especially deemed necessary as the existing diaphragms featured various thicknesses, construction joints and connection detailing. It was thus difficult to properly evaluate its shear capacity at some locations. This approach also aimed at assessing a realistic diaphragm rigidity. Iterations were performed until convergence with the expected yielding rupture mechanisms were obtained between the governing components in the diaphragm., These mechanisms ranged from:

- Reinforcing steel bar yielding in tension.
- Concrete shear cracking. At some area, only the concrete and low shear strength was considered.
- Construction joints shear friction.
- Shear connectors (between slabs and beams) yielding.
- Tenson/Compression yielding in horizontal bracings.
- Discontinuities in reinforcing bars. Shear friction theory (without reinforcing steel bar for dowel action but with monolithic values) was used. This assessment was made from the understanding of the design team that shear friction needs to be satisfied at any diaphragm locations, but that it does not commonly govern when reinforcing bar are provided. CSA A23.3 Standard provide information’s, although limited, about shear friction theory [8].

Each level and each different construction of the ensemble was analyzed with different properties and modifiers, if deemed necessary, to capture the possible damages and cracking that could occur. Different iterations were conducted so this by-step analysis was similar to a progressive collapse study to ensure a proper load distribution if failure was detected in a particular location.

This investigation was achieved by generating both equivalent static and response-spectrum analyses (RSA) measuring the contribution from each natural mode of vibration to indicate the likely maximum shear stresses in the diaphragm by finite-elements analysis as shown in Figure 4. An axial load, and shear flow analysis through designated collector beams was also performed.

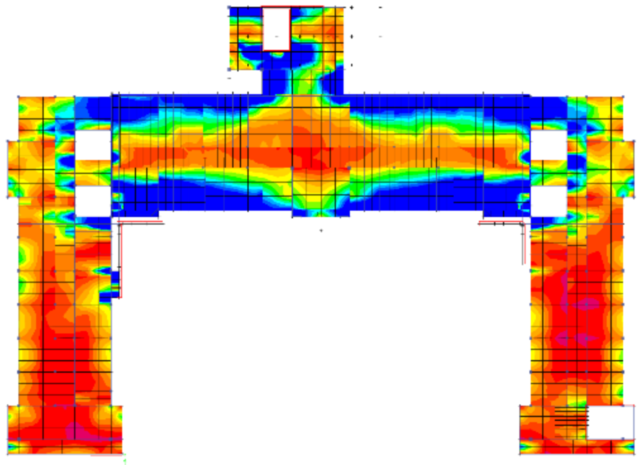


Figure 4. Example of a numerical analysis of building ensemble SABC diaphragm axial stresses

Based mainly on the results from the RSA and on engineering judgment from the study of the available existing drawings, multiple seismic performance deficiencies were identified in the existing diaphragm. Specifically:

- Collectors' beams needed to be strengthened in tension unless their axial load could be diminished. Also, as the building presented some torsional behavior, the lateral flexural and shear strength of the exterior element, that is not supported by a lengthy slab, had to be upgraded. This deficiency was likely not captured in the original retrofit design in 1995, as the simplified methods used probably could not predict this behavior. This also reduced the contribution of the L shaped exterior shear walls.
- In plane shear was too important where the existing diaphragms met the added shear walls and local rupture could be expected.
- Significant tension in chords showed that the flexural capacity of diaphragms showed insufficient strength and reinforcing bar yielded.
- The roof of building A presented numerous joints as it was built with prefabricated slabs. This was shown to significantly reduce the expected strength of this diaphragm.
- Load transfer from the central tower to the roof was too significant.

RETROFIT

Implemented retrofit solution

The retrofit solution envisioned at the early stage (seismic study phase) of the project, although aiming for the same performance objectives as described herein, did not include the project details (partitions' layout, envelope, M&E coordination) and the evolution of the project's scope. It was determined, from the first seismic assessment report, that the building's diaphragm chords and collectors, as well as the vertical system, needed to be reinforced. Concrete beams, floor strengthening interventions and new shear walls were planned to allow for a proper, continuous load path. However, an opportunity to improve and optimize the retrofit solution for the SABC building surfaced when the Client chose to demolish and rebuild the adjoining Building D. Figure 5 highlight in green the extent of both existing and new SFRS in building ensemble SABC, for simplicity purposes, slabs and masonry walls are not highlighted.

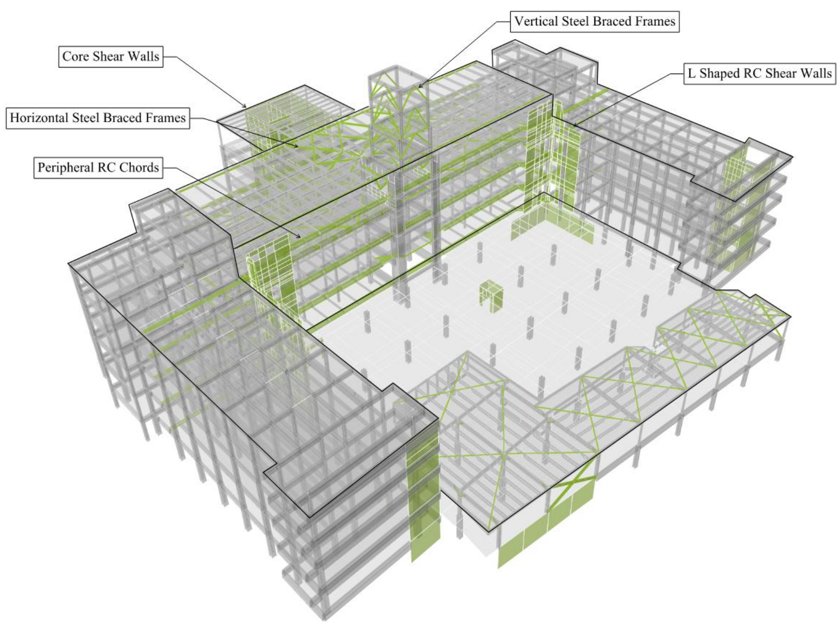
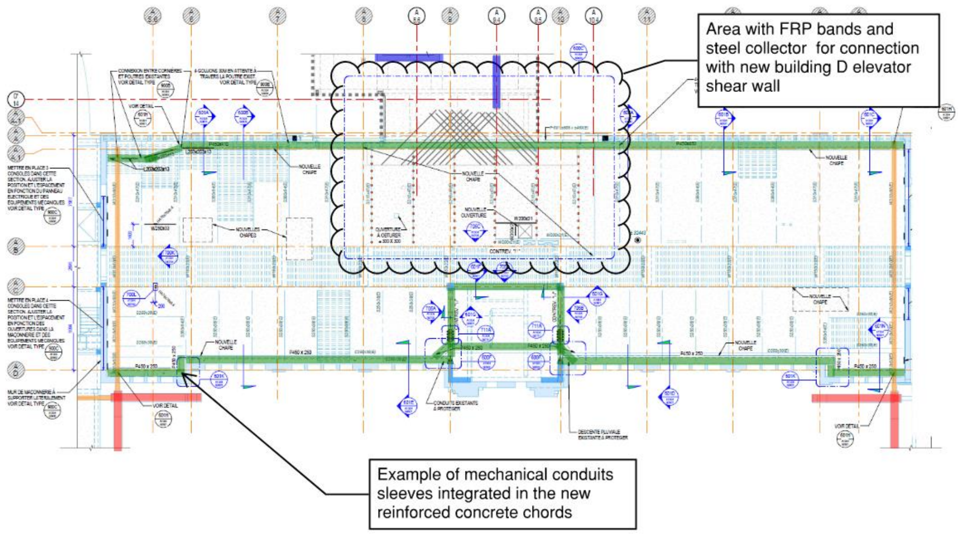


Figure 5. Numerical Etabs model featuring the implemented retrofit solution for building ensemble SABC

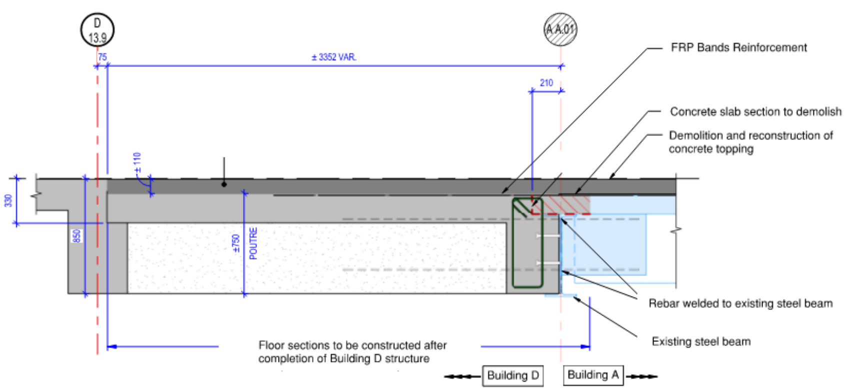
Indeed, the projected Building D was set to feature a block of elevators located close by the junction with pavilion SABC, allowing for the AGVs (robots transporting medical equipment) to serve all floors. Because of the site geotechnical conditions, the new building D would stand on a massive concrete mat, thus providing an opportunity to transfer seismic loads to the ground. It was therefore decided to structurally divide the new Building D – right after the elevators block - and have the floors located towards building SABC fixed to the latter. This floor area (subsequently designated as the AGVs core) was hereafter designed to maximize its rigidity, adding a shear wall at the interface of the SABC and D buildings, and it became a key component of the SABC building's seismic retrofit system, notably reducing significantly inter-storey drifts.

For the opportunity to be fully grasped, the connexion between the AGVs core and the SABC ensemble was required to transfer huge shear stresses at each floor level. Achieving that required to develop both connexion details and floor strengthening methods, using creativity, steel elements, FRP bands and cement grout (Figure 6 illustrate several diaphragm strengthening solutions and the global design intention). The final solution allowed for a load transfer at the interface that fully balanced the global SFRS, providing just enough stress relief for the existing shear walls (added in 1995) and their connexions to attain the required performance level (60% of the current NBCC-required capacity). The use of FRP bands to "stitches" the new shear walls core to building SFRS was seen as an innovative method that required discussions and design with technical support from providers. As the literature does not cover extensively this method, other solutions such as steel connections with existing steel beams, used in parallel with the FRP bands, were implemented and provided ductility if needed during an extreme event.

In Figure 6, in red are the 1995 L-shaped shear walls, in orange the 1995 added diaphragm collectors' beams, in green are the new peripheral reinforced concrete chords implemented in the studied project and in blue are the shear walls from the new building D elevator core implemented in the project.



(a)

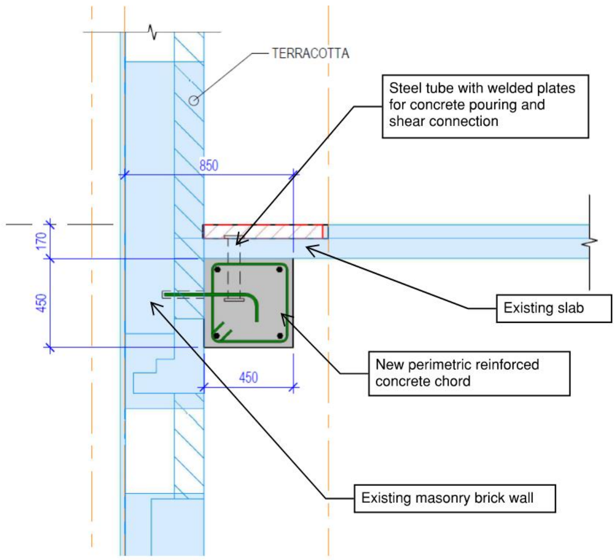


(b)

Figure 6. Diaphragms retrofit solutions (a) Global implemented solution; (b) FRP Bands construction details

The diaphragm chords were reinforced by building peripheral reinforced concrete beams at each floor level, anchored to the structure and the building's envelope (see Figure 6 and 7). This beam and the diaphragm strengthening were carefully designed and coordinated with the M&E team and the architect, accounting for sleeves openings for the heating cabinets and the geometry of the building outline. To ensure constructability, round steel tube sections were added through drilled holes in the slab to the new perimetric reinforced concrete beams below. This ensured that the concrete could be poured by the top floor. As this construction method was envisioned early in the design process, steel plates were also welded to create giants custom shear connectors and ensure a composite behavior between the existing slabs and the new peripheral reinforced concrete beams below. The details of this innovative solution are illustrated in figure 7 and this required the use several conservatives' assumptions, as the use of this method could theoretically yield the development of significant shear connection capacities. It should be noted that the authors did not find scientific data that supported extensively this method and instead relied on engineering judgment and existing accepted design methods.

Diaphragms collectors' components were also either added or retrofitted by adding steel plates.



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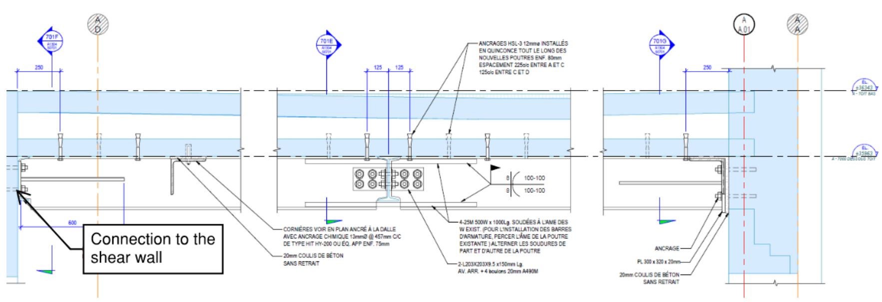


(b)

Figure 7. Diaphragms retrofit solutions (a) New peripheral reinforced concrete chords; (b) New added collectors beams

Retrofitting the whole SABC building also required extending the shear walls built in 1995 and tying them to the upper level, which had apparently not been possible at the time of their construction, due to the maintained floor usage.

The Central Tower retrofit required vertical steel bracings, preferred for their low weight and the allowance for transferring, in plan, the vertical loads.

At the main roof level, the diaphragm was strengthened with horizontal steel bracings to ensure a continuous load path that was not possible through the existing prefabricated "Siporex" reinforced concrete slabs. Additionally, the roof diaphragm retrofits interventions were designed to horizontally transfer the loads going down from the tower to the new and/or reinforced SFRS elements. Figure 8 illustrate the new horizontal bracings layout at the roof.

It should be noted, as both existing buildings B, C and S featured thick slabs, "floretyles" floors with continuous steel reinforcements detailing and peripheral beams, only few diaphragms strengthening interventions were required and they were mostly used to transfer in-plane shear at specific locations.

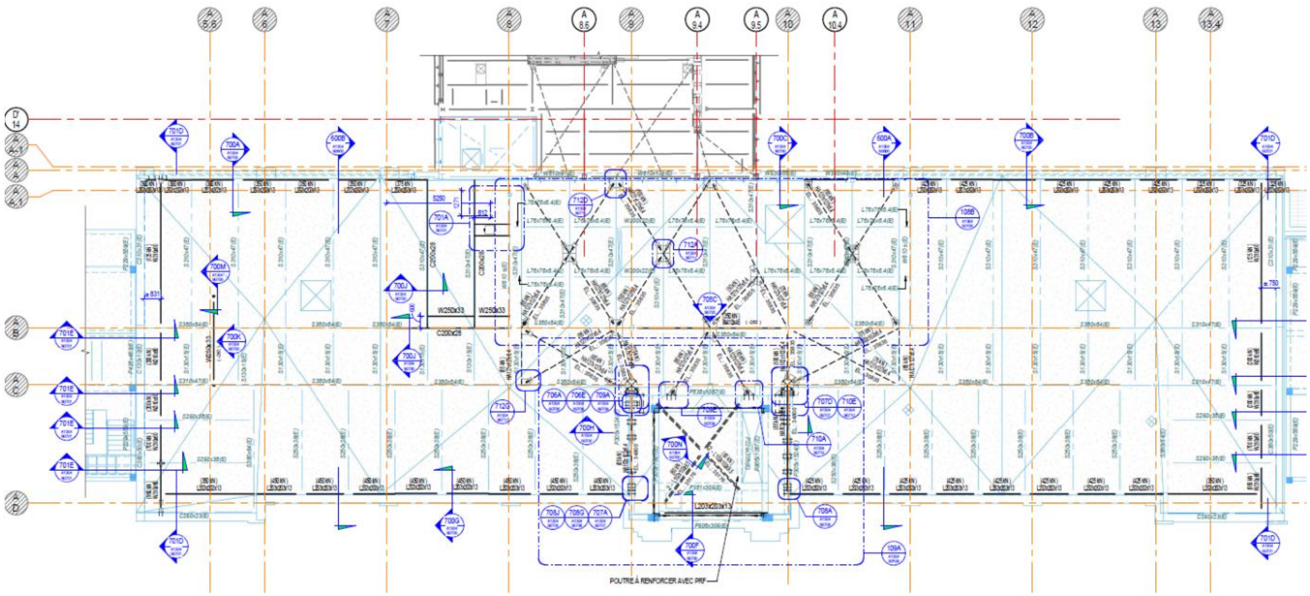


Figure 8. New horizontal bracings at roof location

Globally, the solution was tailored to the very specificities of the buildings, and maximized the opportunities offered by the surrounding buildings and the previous reinforcements performed on the structure.

Design and modelling of the connections

Steel to concrete connections were used extensively for the retrofit of the reinforced concrete structure of the central tower and to connect horizontal bracings with the structure of the roof. Being of unusual configuration, reinforced concrete frames were connected to vertical and horizontal steel braced frames by the means of geometrically intricate steel plates, gussets, and adhesive anchors. As shown in Figure 9, these connections were modeled in 3D to obtain the proper level of understanding of the complexity of the work from the contractors during the call of tender.

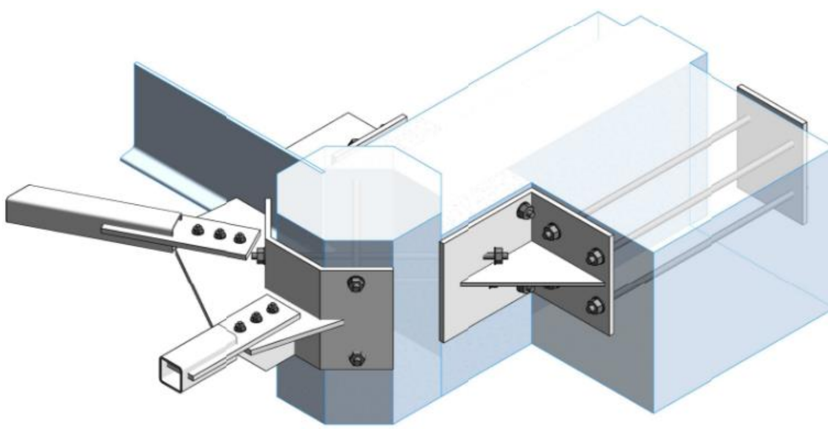
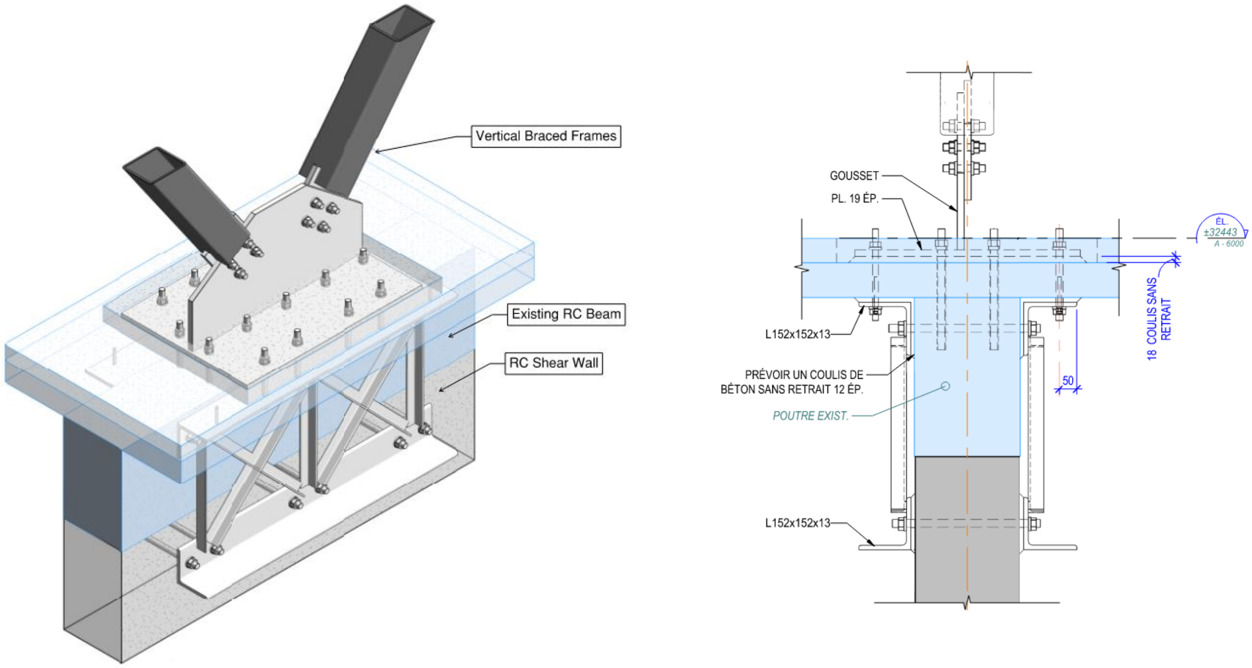


Figure 9. Horizontal steel braced frames connected to a hexagonal RC column.

Following capacity design principles, the connections were designed to withstand essentially elastic forces which proved to be one of the main technical challenges of the project. The reason being that there was little shear or tension capacity in the reinforced concrete, as the original construction did not have the proper reinforcing bar detailing or concrete geometry to ensure modern CSA A23.3 Standard prescribed Annex D requirements [8]. Solutions to this problem involved the use of “sandwich” steel plates for bearing and secondary steel structures that assured redundant force transferring mechanisms. As an example, Figure 10 depicts such instance where a narrow existing reinforced concrete beam, that was not properly detailed for such loads, was strengthen with steel trusses to transfer forces from the upper vertical braced frames to new lower reinforced concrete sections directly.



(a) *(b)*

Figure 10. Steel truss used as a force transferring mechanism: (a) 3D view, (b) Section view

Considering that steel to concrete connections geometry had important implications on the existing structure, and that concrete anchoring was the technical challenges, steel connections were exceptionally designed by the Engineer of Record, as common practice in Quebec is instead to attribute this responsibility to the steel fabricator. This was to ensure proper communication during the tender process for the steel fabricator and to fully control the design. Methods such as the Whitmore section were used for theses design to follow state-of-the-art practical approaches [9].

On-site Construction Work

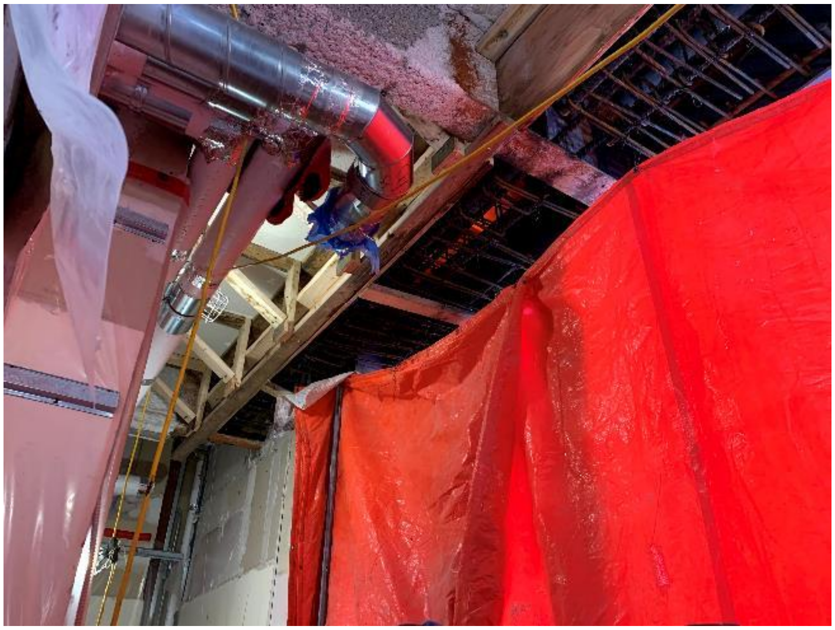
As maintenance of clinical services was vital, the retrofit project was ineluctably staged by story as the Hospital could sometimes only afford one inoperative floor at a time to maintain adequate services. Restrictive measures were imposed to the construction activities to minimize disturbance to neighboring environment. Among those figured dust containment and drilling vibration limits as care was given nearby to patients. Figure 11 shows a collector beam installed in such conditions.

Retrofitting the 5^{th} story of wing A revealed to be particularly complex. Being dedicated to mechanical infrastructures serving multiple wings and with a clear height of only 1700 mm, this floor presented constraints of space that had to be worked around. For the reinforced concrete chords beams constructed on the periphery of the floor, extensive coordination was necessary with MEP as the beams would interfere with existing mechanical services. The latter had to be temporarily moved for the implementation of the activities necessary for seismic reinforcement.

Figure 11. Collector Beam in B wing

Figure 12 illustrate others retrofit interventions undertaken since the beginning of the construction phase of the project.

(a)



(b)

Figure 12. Retrofit interventions at building ensemble SABC (a) New elevator core shear walls (b) Construction of new peripheral reinforced concrete chords

CONCLUSIONS

This project featured numerous challenges that can be categorized under three themes: information (getting it right, and understanding the structure), technical (assessment of the existing structure, and development of a retrofit solution meeting the performance objectives), and operational (constructability and phasing).

To answer those challenges, the retrofit solution was developed following a rigorous approach that encompassed a thorough study of the available drawings, a survey campaign allowing for a good understanding of the structure. Technical solutions tailored to the specificities of the structure and the non-structural elements were then developed in accordance with the performance objectives of the project, notably the inter-story drift ratios required to protect the existing loadbearing masonry walls. The solutions were developed considering the requirements for maintaining the hospital in service, notably the phasing.

Along the way we observed that the partially implemented seismic retrofit designed in 1995, with exterior L shaped shear walls, was a sophisticated, complex solution for the time, but its associated dynamic response might not have been fully understood. It demonstrates the advantage of using numerical modelling techniques, and today's state-of-the-art practice for assessing the dynamic behavior of buildings.

Three elements were identified that could benefit from further investigations / studies:

- At some reinforcing bar discontinuities in the diaphragms, Shear friction theory (without reinforcing steel bar for dowel action but with monolithic values) was used. This assessment was made from the understanding of the design team that shear friction needs to be satisfied at any diaphragm or reinforced concrete locations, but that it does not commonly govern when reinforcing bar are provided. This statement could be clarified or further studied.
- The use of FRP bands, on top of an existing slab, below a topping, is seen as an interesting innovative method to provide shear connection. Our literature review however resulted in the conclusion that it had not been studied or tested extensively under cyclic loading, which would be an interesting topic for future research.
- The use of custom shear steel connectors, for concrete pouring and composite action between the new chords and diaphragms, could result in significant shear connection capacities, even in thin slabs. Our literature review however resulted in the conclusion that it would be an interesting topic for future testing, to verify the adequate behavior of the assembly.

ACKNOWLEDGMENTS

The authors are grateful to Quebec Infrastructure Society (SQI) for their confidence with CIMA+ during the project.

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