
Assessing the cost, embodied carbon, and constructability of seismic retrofits

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ABSTRACT

Recent changes to the Canadian building code increased the design seismic hazard level in several locations, necessitating retrofits to achieve current performance expectations for older and structurally deficient buildings. Although many seismic upgrading solutions are discussed in the literature, few have addressed their impact on triple-bottom-line sustainability and ease of construction. This paper presents a framework to evaluate the upfront costs, embodied carbon, and constructability of retrofit strategies demonstrated using a case study reinforced concrete building with a hybrid wall-frame lateral system. Two retrofit strategies are compared, including adding planar shear walls to increase the building's lateral stiffness and using fluid viscous dampers to dissipate seismic energy. The building was analysed using the equivalent linear static method under the present-day design seismic hazard in Vancouver and Montréal, Canada. This analysis showed that the existing moment frame has insufficient shear and bending moment capacity and exceeds the allowable drift limits in both locations. The shear wall and viscous damper retrofits were designed to optimise material use and meet the code minimum requirements. Then, they are compared quantitatively for construction cost and cradle-to-gate embodied carbon. Finally, constructability was assessed qualitatively, considering the regional availability of materials and labour, construction scheduling and downtime, and local permitting requirements. The case study showed that the optimal retrofit strategy is highly dependent on the characteristics of the building under consideration, including its lateral system, configuration, location, and structural deficiencies. Overall, these results highlight the importance of considering cost, embodied carbon, and constructability in early-stage design decisions.

1 INTRODUCTION

Seismic design provisions in building codes and standards are often updated based on more reliable estimates of seismic hazard in a region. These updates may necessitate seismic performance evaluation of many existing buildings. The primary motivation for seismic upgrades to older or deficient structures is to improve performance and ensure life safety during an earthquake. However, there are economic and environmental implications associated with the choice of retrofit strategy. Research has shown that pre-emptive seismic upgrades produce less embodied carbon emissions than demolishing and rebuilding after an earthquake

(Aljawhari et al., 2024). From an economic perspective, proactive retrofits mitigate the financial burden on the government, individuals, and companies who may see increased insurance premiums or reductions in coverage. For example, a major earthquake in Vancouver, Canada, where portions of the building stock were designed to earlier code provisions and do not meet modern performance expectations, could cause \$128 billion in total losses and potentially lead to the collapse of the Canadian property and casualty insurance industry (Vines et al., 2025). The feasibility of retrofit implementation is also a notable factor, as it is directly linked to construction costs and the willingness of building owners to undertake seismic upgrades.

While many past studies have comparatively evaluated the structural performance of seismic retrofitting solutions, few have examined their relative impact on triple-bottom-line sustainability and ease of construction. This paper suggests a straightforward assessment method to compare the upfront cost, environmental impact, and constructability of different retrofit methods during schematic design. The procedure is demonstrated using a case study example comparing two different seismic retrofit strategies for a pre-Northridge reinforced concrete (RC) wall-frame structure. The first strategy involves the addition of planar shear walls to increase the lateral stiffness, while the second uses fluid viscous dampers to dissipate energy and RC jacketing to upgrade the moment frame (MF). Vancouver and Montréal, Canada, were chosen to represent high and moderate seismic hazard case study locations, respectively, to evaluate how seismic hazard level influences outcomes for retrofit cost, embodied carbon, and constructability. Section 2 provides a brief overview of similar frameworks proposed in the literature and their limitations. Then, the proposed assessment methodology is summarized in Section 3. Section 4 describes the case study example, structural modelling, and design of the retrofit strategies. Finally, the results of the assessment are presented and discussed in Sections 5 and 6, respectively.

2 LITERATURE REVIEW

Despite the inherent interdependencies between cost, environmental impact, and ease of construction, no studies were found that compared them simultaneously. Only one relevant publication was found that considered constructability, investigating the ease of incorporating friction dampers into existing concrete buildings (Rao et al., 1995). Fung et al. (2021) proposed a model for retrofits to shear wall buildings considering the upfront retrofit costs and the long-term economic implications of undertaking a retrofit versus leaving the building as is. Cavalieri et al. (2023) analysed upgrades for concrete buildings in Italy and found that using friction dampers had a much lower lifecycle environmental impact. Salgado et al. (2020) studied the environmental impacts of shear wall strengthening methods for 1970s concrete buildings in California; however, they did not consider cost or constructability. Clemett et al. (2022) developed a multi-criteria decision-making framework considering cost and carbon to find the best retrofit option for a school building, which was effective for their case study but is limited in scalability. Finally, two studies were found that investigated how viscous dampers can be used to decrease the environmental impact of structures (Lavan & Idels, 2023; Rodríguez-Castellanos et al., 2024). However, they relied on assumptions to estimate the embodied carbon of the viscous damper and did not conduct a life cycle assessment (LCA) of the device. This paper addresses gaps in the literature by proposing an assessment procedure to compare the performance of seismic upgrade methods in terms of upfront cost, embodied carbon, and constructability and by providing the results of a preliminary cradle-to-grave LCA of a viscous damper.

3 METHODOLOGY

Figure 1 illustrates the proposed assessment procedure for selecting the optimal retrofit. The focus of the proposed procedure is to compare the performance of each alternative based on upfront cost, environmental impact, and constructability. This approach assumes that each retrofit alternative is equally desirable in terms of seismic performance and architectural modifications. The structural analysis and design methods used are

left to the discretion of the designer and the regional code requirements. However, all retrofit strategies should be designed to satisfy the same structural safety requirements to facilitate comparison. The structural design and analysis methods used in the case study example are described in Section 4.

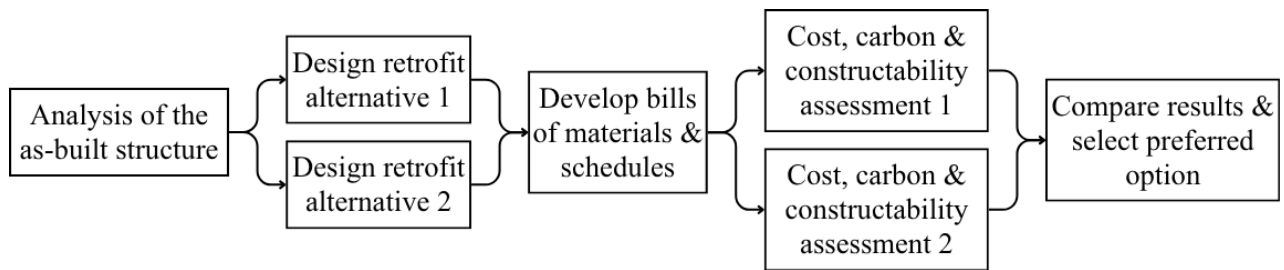


Figure 1: Flow chart illustrating the proposed procedure for evaluating and comparing the upfront cost, embodied carbon, and constructability of alternative retrofit methods.

3.1 Construction cost estimation

The first step in the proposed procedure is to develop a bill of materials and construction schedule to inform the cost estimate and LCA. A building information model was developed in Revit (Autodesk Inc., 2024) based on the schematic structural design to automate the generation of a bill of materials, including the concrete and reinforcing steel quantities. Non-structural materials were neglected because the probabilistic impacts of seismic loss due to an earthquake occurring during the life span of the upgraded building were not considered in this comparison. The works of González (2024) and Guerrero (2022) provide more context on estimating the environmental impacts of seismic damage in a New Zealand and Canadian context, respectively. The construction schedules were prepared by breaking each retrofit into a logical sequence of tasks and assigning durations to each. They included all activities for retrofit implementation, including concrete and reinforcement placement, formwork and temporary supports, demolition, and, for the damper option, procurement and installation of the viscous damper devices.

The cost estimates were developed in RSMeans (Gordian, 2024) using the location-specific unit rates for Vancouver and Montréal for materials, labour, and machinery. The cost of the viscous damper was provided by the manufacturer. Due to the non-disclosure agreement (NDA) with the damper manufacturer, the results were presented as normalised percentages relative to the highest-cost option to enable comparison while protecting confidential pricing data. The intent of this estimate was to capture the main cost drivers that differentiate the retrofit options, rather than develop a detailed tender-level estimate for construction. Additionally, the estimate was based on the upfront retrofit costs and did not consider how structural upgrades would influence future operational and maintenance expenses or seismic loss.

3.2 Life cycle assessment

The process-LCA of the retrofit strategies was informed by the Canadian best practice guidelines (Bowick et al., 2022), chosen based on the location of the case studies. Figure 2 shows the scope of the LCA, which includes the cradle-to-gate impacts of the retrofit implementation (A1 to A5) and the end-of-life impacts associated with any demolition to components of the as-built structure required (C1 to C4). The assessment considered the superstructure and foundations, with the concrete and reinforcement strength and quantities based on the schematic structural design. Material quantities, transportation distances, construction processes, and waste disposal were based on the same bill of materials and construction schedule used for the cost estimate.

For the case study example, the embodied carbon of the retrofits was calculated using One Click LCA (2024) based on the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). The impact of the viscous damper devices was calculated separately in openLCA (GreenDelta

GmbH, 2024) using the ecoinvent and worldsteel 2020 databases, then added to the relevant results from One Click LCA manually. The material flows and processes for the devices, including the steel and damping fluid, were converted into environmental impacts using the Intergovernmental Panel on Climate Change 2021 global warming potential method. Due to an NDA with the manufacturer, the specific materials used in the damper were generalised. Future studies using the proposed approach should be based on the LCA tool and environmental impact database best suited to their region. The case study example only considered one endpoint environmental impact indicator for demonstration purposes: global warming potential (GWP), which is a measure of embodied carbon reported in kilograms of carbon dioxide equivalents (kg CO₂-eq). The LCA could easily be extended to include other endpoint indicators without impacting the methodology of the proposed procedure.

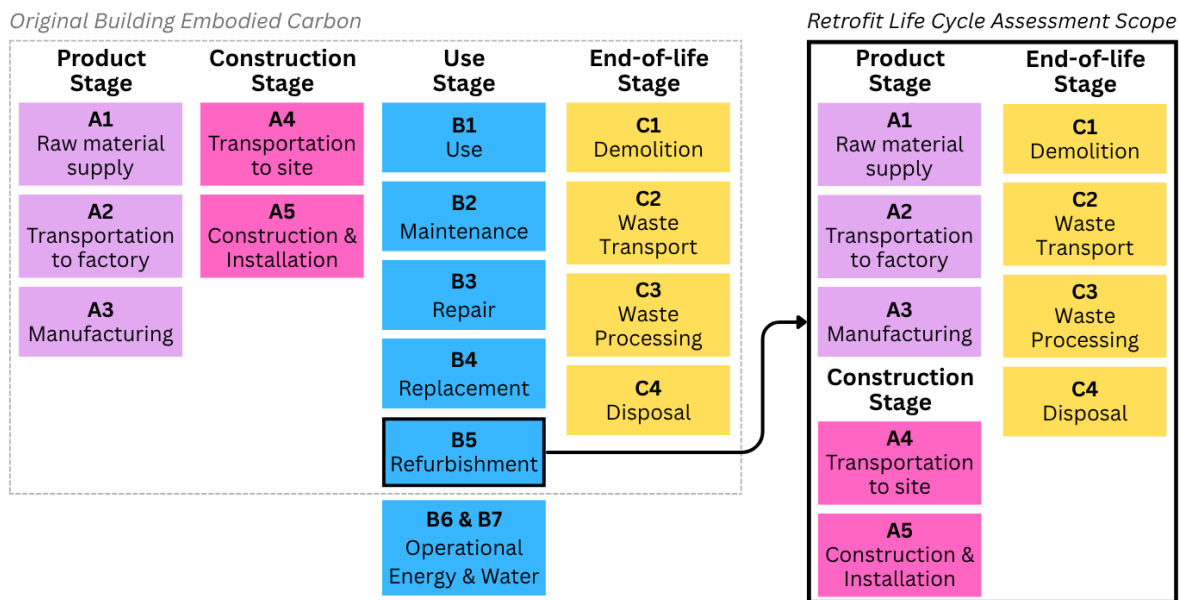


Figure 2: Life cycle assessment stages considered for the retrofits, as indicated by the black solid line.

3.3 Constructability assessment

Constructability was evaluated using a combined quantitative and qualitative approach. The construction schedules were used to identify the activities most likely to result in downtime due to reduced occupancy or temporary loss of functionality, including demolition, shear wall and footing construction, and column and beam RC jacketing. Then, the duration of the critical activities was compared quantitatively for each strategy based on the number of days of downtime. A qualitative review was used to assess factors not captured on a preliminary construction schedule. This included the availability of skilled labour, proximity of material sources, equipment and access constraints, and permitting requirements. Permitting was identified as a notable consideration because the Canadian code does not offer a prescriptive pathway for lateral systems containing supplemental energy dissipation devices. Together, the quantitative schedule estimates and the qualitative review provided a practical basis for comparing the ease of construction of each retrofit strategy.

4 CASE STUDY EXAMPLE

A 10-storey reinforced concrete (RC) residential building was analysed as a case study. It was constructed in 1972 and has a hybrid lateral system with planar shear walls in the Y-direction and a MF in the X-direction. The total gross floor area of the superstructure is 9,362 m². A detailed description of the structure and as-built drawings can be found in Miranda & Bertero (1991).

4.1 Modelling

4.1.1 As-built Structure

The seismic evaluation of the case study structure was conducted using the equivalent static force procedure based on the current code (Canadian Commission on Building and Fire Codes, 2020) and that at the time of construction, NBCC 1970 (Associate Committee on the National Building Code, 1971). A linear static finite element model was developed using ETABS version 20.2 (Computers and Structures, Inc., 2022). Stiffness modifiers were applied per the provisions of the Canadian concrete code to reflect cracked-section behaviour (CSA, 2019a). Although nonlinear static or dynamic analyses are typically used in research, the linear static method was chosen to reflect common industry practice for regular mid-rise buildings in Canada.

4.1.2 Seismic Retrofits

Table 1 summarizes the configurations analysed as part of the example case study. The first retrofit method involved adding planar shear walls. Although wall cores are typically more efficient, placing planar walls along the building's central corridor minimized layout changes and retained all perimeter glazing. Similar to the analysis of the as-built structure, the shear wall design was done using a linear static model. The walls were sized to withstand 100% of the NBCC 2020 design level earthquake at each location, neglecting the capacity of the existing MF based on the provisions of the Canadian concrete code (CSA, 2019a). Pad footings for the added shear walls were designed schematically to resist overturning based on assumed soil properties for each case study location. Upgrades to the floor and roof diaphragm were not considered because the reinforcement detailing for the as-built case study structure was not included in the structural plan set. Future research should investigate how diaphragm updates will influence the cost, embodied carbon, and ease of construction the retrofit strategies considered in this study to address this limitation.

Table 1: Summary of the four retrofits analysed in the example case study.

Retrofit Method	Location	Scenario ID	Intervention
Shear wall strengthening	Vancouver	SW-VAN	Add planar shear walls with mat foundations
	Montréal	SW-MTL	Add planar shear walls with mat foundations
Viscous damper & RC jacketing	Vancouver	VD-VAN	Add viscous dampers, RC column and beam jacketing, foundation upgrades
	Montréal	VD-MTL	Add viscous dampers, RC column jacketing, foundation upgrades

The second retrofit strategy included adding viscous dampers to dissipate energy and RC jacketing to increase the capacity of the existing MF. The linear static model of the as-built structure was converted into a non-linear dynamic time history model with eleven ground motion records, chosen based on similarities to the case study sites (Ancheta et al., 2013). The ground motion data were scaled to reflect the sites seismic hazard. The viscous damper configuration and RC jacketing design were optimized via parametric analysis. The damper properties were provided from the manufacturer and were modelled as links based on the Maxwell Model of Viscoelasticity. The dampers were configured diagonally across the bays and steel braces were sized per the Canadian code (CSA, 2019b) based on the maximum damper force from the model using grade ASTM 500 steel. The reaction force on each end of the damper-brace assembly acts at an angle to its connection to the MF, increasing the column axial load and creating higher beam end moments. RC column jacketing was used to increase the capacity of the existing members to meet this demand. Additionally, this

addressed the inadequate reinforcement detailing in the as-built structure by improving confinement. Similarly, jacketing the bottom and sides of the beams improved their shear and bending resistance.

4.2 Structural Analysis and Design

4.2.1 Case study building

Figure 3 compares the base shear coefficient calculated using the equivalent linear static method and the seismic hazard in the current code with that in effect at the time of construction. The minimum base shear capacity required in 1970 is nearly half of current expectations in both locations. This indicates that the building's lateral system is likely significantly under-capacity and would not meet modern performance standards during the design level earthquake. The existing shear walls in the Y-direction were found to be adequate at both case study locations, with maximum drifts close to 1.1%. In contrast, the MF in the X-direction was deficient, with maximum inter-storey drifts reaching 4.3% and 3.1% in Vancouver and Montréal, respectively, exceeding the 2.5% code limit for normal importance structures.

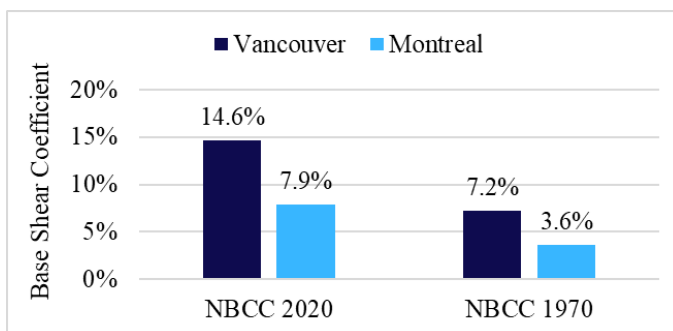


Figure 3: Base shear capacity required by the current code (NBCC 2020) and that at the time of construction (NBCC 1970).

Table 2 presents the ratio of demand to capacity for each structural member, with values below one indicating that the member is insufficient to withstand the applied loads. The existing shear wall lateral system in the X-direction was found to be adequate based on the design level earthquake of the current code; however, the MF in the Y-direction was under capacity. Moreover, a review of the original detailing identified ties with 90-degree hooks in all MF columns, which do not provide sufficient confinement. The interior columns, which are not part of the lateral system, experience increased end moments during an earthquake due to relative inter-story displacement. The demand on these columns from lateral displacement was calculated based on the provisions of the Canadian concrete code (CSA, 2019a).

Table 2: Capacity demand ratios of the members of the as-built structure in Vancouver and Montréal.

Capacity/Demand	MF Columns	Non-MF Columns	Beams
Vancouver	0.60	0.85	1.13
Montréal	0.79	0.95	2.0

4.2.2 Shear wall retrofit

For the case study retrofit in Vancouver, four new 350 mm thick, 35 MPa shear walls were added in the X-direction along gridlines D and E (Figure 4). Each wall spanned two bays, requiring the removal of twelve internal columns per level. Figure 5 show an example of the reinforcement detailing from the base to level three. The reinforcement layout was changed approximately every three levels to optimize material

efficiency; however, savings were achieved due to the high seismic hazard. Strength governed the design, resulting in a maximum inter-storey drift of 0.75%, well below the 2.5% code limit.

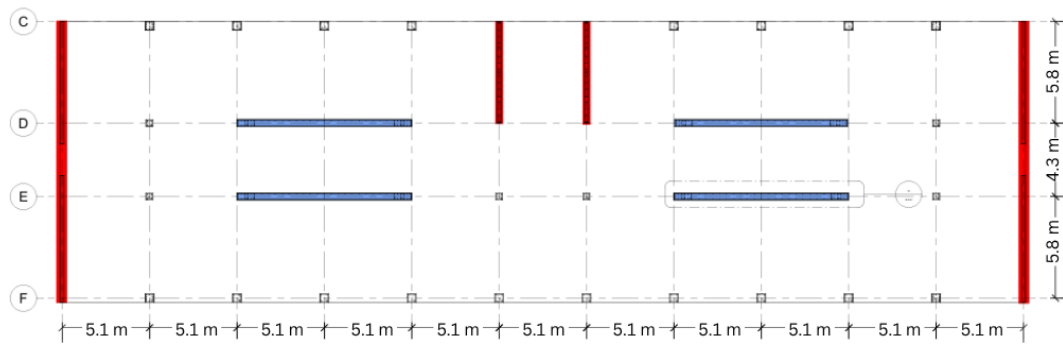


Figure 4: Shear wall layout for the case study in Vancouver based on the as-built structural drawings of the existing building, where red and blue indicate the existing and added shear walls, respectively.

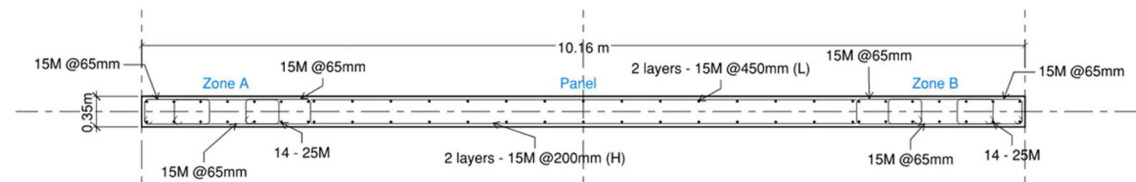


Figure 5: Example of shear wall reinforcement detailing for the Vancouver case study.

In Montréal, two 350 mm thick, 25 MPa shear walls were added along gridline E, reducing drift to 0.53%. The shear walls governed the design, resulting very little demand on the columns. Since Montréal has a much lower seismic hazard than Vancouver, significant material savings were achieved by reducing reinforcement at higher stories with lower demands. The capacity-demand ratios of the columns and beams in Vancouver and Montréal after the seismic upgrade, are summarised in Table 3.

Table 3: Capacity-demand ratios of structural members after the shear wall retrofit.

Scenario	MF Columns	Non-MF Columns	MF Beams
SW-VAN	1.78	4.27	2.18
SW-MTL	3.12	7.06	2.6
VD-VAN	1.17	1.76	1.14
VD-MTL	1.3	4.9	1.58

4.2.3 Viscous damper and RC jacketing retrofit

In Vancouver, the optimal retrofit configuration had 24 viscous dampers with a velocity exponent of 0.4 and a damping coefficient of 2,200 Ns/m. The dampers were oriented diagonally across the bays and distributed across levels two to four. The maximum damping force was approximately 1,300 kN with a stroke of ± 52.1 mm, within the device limits shown in Table 4. RC jacketing improved the axial and flexural strength of the columns, as well as confinement. For levels one to three, four 30M longitudinal bars and 10M closed ties spaced at 200 mm were added around the existing columns and the cross section was increased to 800 mm square, governed by the minimum cover requirements in the code. Similarly, the beam sections were increased to 750x750 mm with eight additional 25M longitudinal bars and 10M ties spaced at 200 mm. The quantity of longitudinal reinforcement decreased with demand for the beams and columns; however, the

added ties and cross section were consistent. The interior columns that are not a part of the MF were originally undersized; however, the upgrades reduced the demand within their capacity. These upgrades reduced the maximum inter-storey drift from 4.30% in the as-built structure to 1.84%.

Table 4: Viscous damper design parameters in Vancouver and Montréal.

Viscous Damper Design Parameter	Vancouver	Montréal
Velocity exponent	0.4	0.5
Damping coefficient (N s/m)	2,200	1,450
Maximum piston force capacity (kN)	1,500	1,000
Maximum stroke capacity (mm)	± 75	± 75

In Montréal, only four viscous dampers at level two were needed, reflecting the lower seismic demand than in Vancouver. The retrofit reduced X-direction drift to 1.48%, below the 2.5% code limit. The demands on the damper were lower relative to the Vancouver case study, with a maximum reaction force of 658.33 kN and stroke of ± 42.75 mm. This reduced the extent of the MF upgrades required; however, the column sections were still enlarged to 800 mm square given that the minimum cover requirements governed. For levels one to four, four 25M longitudinal bars and 10M ties spaced at 200 mm were added. While the column deficiencies resemble those found in Vancouver, the MF beams are adequate and do not need any RC jacketing. Table 3 lists the updated capacity-demand ratios for the damper retrofit at the Vancouver and Montréal case study sites.

5 ASSESSMENT RESULTS

5.1 Retrofit cost

Figure 6 shows the distribution of material and construction costs for each retrofit strategy in Vancouver and Montreal. In all scenarios, concrete and reinforcing steel contributed a significant portion of the costs. The shear wall retrofits required more extensive demolition and foundation work, which increased RC and formwork costs considerably. Damper retrofits reduced structural demolition and foundation intervention; however, they introduced additional costs for damper procurement and specialised installation. In Vancouver, the RC required for jacketing to strengthen the MF members was nearly as much as required for the shear wall retrofit.

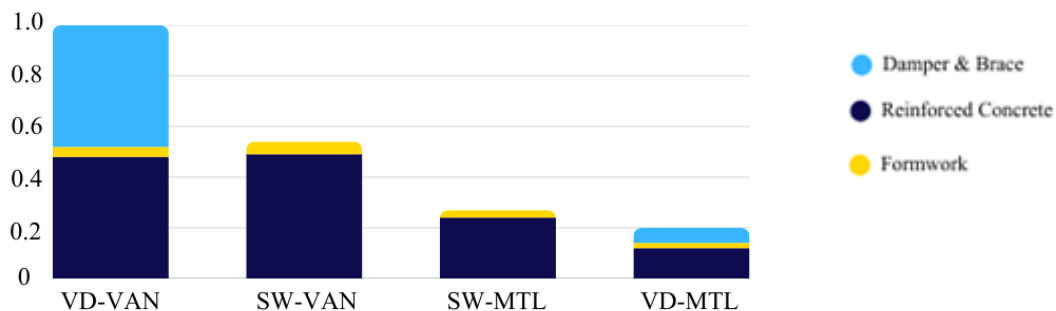


Figure 6: Retrofit cost distribution, normalized relative to the highest cost.

5.2 Retrofit embodied carbon

Table 5 shows the environmental impact of the viscous dampers and each retrofit, including the embodied carbon intensity, which is a common metric used for comparative LCAs and is normalized to the gross floor area of the superstructure. For each scenario, RC was the main driver of environmental impact. The dampers only accounted for a small share of total global warming potential, approximately 5% in Vancouver and 3% in Montréal. The viscous damper and RC jacketing retrofit performed considerably worse in Vancouver than in Montréal, with 322.7% higher GWP. This was due to the significant MF upgrades required to withstand the larger damper reaction forces at a higher seismic hazard level. In contrast, the GWP of the shear wall retrofit was only 130.3% higher in Vancouver. Finally, the cradle-to-gate (A1-A3) impacts of the structural materials used for retrofitting accounted for 90% or more of total emissions in each scenario.

Table 5: Lifecycle carbon emissions distribution for the retrofits in Vancouver and Montréal.

Retrofit Embodied Carbon	Viscous Damper (kg CO ₂ -eq/unit)	Total Retrofit (kg CO ₂ -eq)	Total Intensity (kg CO ₂ -eq/m ²)
SW-VAN	-	289,666	30.9
VD-VAN	671	292,874	31.3
SW-MTL	-	125,766	13.4
VD-MTL	413	69,292	7.4

5.3 Retrofit constructability

The shear wall retrofit construction schedules in Vancouver and Montréal were 46% and 38% longer than those for the corresponding damper retrofits (Figure 7). The substantially longer timeline was due to structural demolition, excavation for the added footings, and concrete curing. The viscous damper retrofits avoided major wall-foundation work and extensive demolition. However, they still required significant shoring, formwork, concrete placement for jacketing, in addition to the device installation time. Permitting processes differed between strategies in accordance with the regional requirements. Viscous dampers are considered as an alternative solution and generally require peer review for permitting. This can introduce scheduling risk that may offset some on-site construction time savings (Moehle, 2024). In contrast, the design of the shear wall retrofit is based on prescriptive code provisions, typically allowing for a more straightforward permitting process.

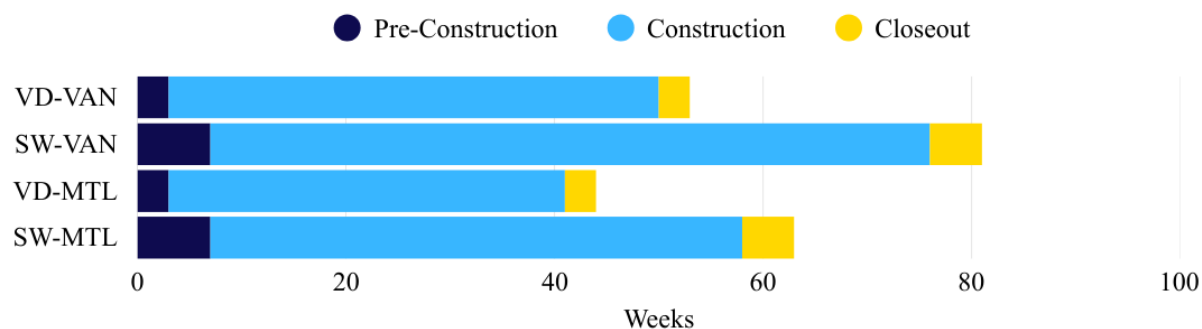


Figure 7: Construction timelines for the shear wall and damper retrofits in Vancouver and Montréal.

6 DISCUSSION

6.1 Trade-offs between cost, carbon, and constructability

The combined comparison showed strong location dependence, which reflects how the regional hazard level interacts with the existing lateral system and drives the scale of retrofit intervention. In Vancouver, the shear wall retrofit was the lower-cost option, at 54% of the damper retrofit cost, and produced 1.5% lower embodied carbon; however, constructability was significantly worse. The added walls required additional demolition and new foundation construction, which extended the schedule by approximately 25 weeks. In comparative assessment in Montréal resulted in a different outcome. The damper retrofit offered the best performance across all three criteria, costing 11% less than the shear wall retrofit, producing 34% less GWP, and reducing construction time by five weeks. These results indicate that hazard level strongly influences the amount of added reinforced concrete needed to upgrade the moment frame, which dominates upfront cost and embodied carbon estimates.

The outcome in Vancouver is noteworthy because dampers are often associated with favourable structural performance in high-seismicity regions, yet the damper retrofit was not beneficial in terms of environmental impact. This finding is likely tied to the specific characteristics of the case study building and the assumptions adopted. The existing MF was notably deficient and the damper forces increased demand on the frame members and connections, which required substantial local strengthening. By contrast, the shear wall retrofit was designed so the new walls could resist the full lateral demand, reducing the demand on the existing frame. As a result, the relative performance of the damper retrofit in Vancouver should not be generalised. Instead, it should be interpreted as a case-dependent outcome that highlights how existing system capacity and chosen strengthening details can control the relative performance of the retrofit strategies in terms of upfront cost, carbon, and constructability.

6.2 Other considerations

This study developed an early-stage assessment procedure intended to compare retrofit options across three key parameters. A case study was used to demonstrate the procedure, rather than to identify conclusive trends or benchmarks between retrofit strategies and cost, embodied carbon, and constructability. Notably, the case study example only considered one damper configuration and one method of upgrading the MF, RC jacketing. Other configurations, types of supplemental energy dissipation devices, or approaches to strengthening the MF, like fibre-reinforced polymer (FRP) wrapping, could alter the outcome. In addition, the design was completed at the schematic level and did include detailing of the damper-brace-to-MF connection, which may influence the cost and environmental impact (Rodríguez-Castellanos et al., 2024). Additionally, the shear wall retrofit was designed using an equivalent linear static procedure, which is inherently conservative. Therefore, the estimates of material quantities from the structural design using this method may also be conservative relative to a design using non-linear dynamic analysis. Finally, the scope chosen has a notable impact on the cost and embodied carbon estimates. The assessments focused on retrofit implementation and did not consider how upgrading the structure influenced economic or environmental loss, including the impacts of post-earthquake repair, demolition, or replacement. Extending the scope of the assessment procedure could change the outcomes and identify strategies that reduce damage and improve reparability, particularly for buildings in higher seismicity regions. Overall, these limitations reinforce that the results are most appropriately interpreted as a case-based comparison that demonstrates a practical evaluation framework, rather than as an absolute ranking of alternative retrofit strategies.

7 CONCLUSIONS

This paper demonstrated an early-design stage assessment procedure to compare alternative retrofit strategies for cost, embodied carbon, and constructability. A case study of a 1970s RC wall-frame structure assumed to be located in Vancouver and Montréal is evaluated under the seismic hazard levels prescribed in NBCC 2020. In Vancouver, the shear wall retrofit strategy produced the lowest cost and embodied carbon but had a longer construction duration. In Montréal, the viscous damper retrofit was best in terms of cost, embodied carbon, and construction time. The quantity of reinforced concrete required for the upgrades governed for all factors. A novel contribution of this study is that it completed a cradle-to-grave LCA of the viscous damper devices, rather than relying on simplified or assumed relationships to estimate their embodied carbon. Future work will develop an Environmental Product Declaration supported by a full ISO-compliant LCA.

Overall, the case study illustrated how cost, embodied carbon, and constructability can vary with retrofit strategy and hazard level. The results support a clear practical implication: designers should not select retrofit strategies based solely on structural performance. Instead, they should evaluate cost, embodied carbon, and constructability together early in design to enable more informed and actionable retrofit decisions. However, additional research is required before drawing general trends. Future studies should apply the proposed assessment procedure to buildings with different layouts, heights, lateral systems, and locations to strengthen the applicability of conclusions for a broader range of structural configurations and hazard levels. In addition, further work should examine how changes in viscous damper design choices, including device layout, quantity, and connection detailing, influence the cost, embodied carbon, and constructability outcomes. These extensions would support more robust comparisons, inform future code development, and assist practitioners with retrofit strategy selection in early design stages.

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