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STRATEGIES FOR THE SEISMIC UPGRADING OF PAIRS OF BUILDINGS IN A HISTORIC PRECINCT

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ABSTRACT

This paper reports on a theoretical student design project to seismically upgrade buildings in a historic precinct of Wellington. The unique feature of the structural upgrading, heritage retention and adaptation, and new building interventions in the precinct was that all retrofitting designs were applied to pairs or clusters of buildings in order to develop new strategies for their seismic retrofit.

The tying of buildings together as part of retrofitting is rarely encountered in earthquake engineering practice but this can be an important retrofitting approach as shown by the following design outcomes and case-study example. The main finding from the architectural design and seismic retrofit of 70 clusters of two to three buildings was the diversity of the retrofitting strategies that were applied. Two primary categories of retrofitting were identified; tying existing buildings together, and tying existing buildings to new buildings, with each category incorporating several variants. This paper highlights the advantages of retrofitting clusters of buildings to prevent seismic pounding, and for other economic and architectural reasons.

INTRODUCTION

Most cities in seismically-active regions possess historic precincts comprising streets lined with buildings constructed before the widespread use of modern earthquake-resistant design techniques and materials. Often, unreinforced masonry constitutes the predominant load-bearing material and largely defines the inferior seismic performance of these buildings. This was witnessed most recently in the 2012 Canterbury earthquake sequence, New Zealand, and in the 2015 Nepal earthquake. Not only are the buildings in such precincts seismically vulnerable by virtue of their own materiality, structural configuration and inadequate detailing, but they are usually built very close to or against each other, or share boundary walls. While buildings within a block, away from street corners, may get some form of mutual support from adjacent buildings, the lack of horizontal separation, now a requirement of contemporary codes, means they are vulnerable to pounding from the buildings on either side.

When an individual building is seismically assessed, the presence of close neighboring buildings is taken into account by assessing the ‘Pounding Potential’ [1]. Due to their immediate proximity such adjacent buildings pose an unavoidable pounding threat to any retrofitted building. The retrofit solution of a single building may not prevent pounding but it can mitigate its consequences. Methods for such mitigation as listed by Cole et al [2] include insertion of structure to replace existing elements likely to be damaged by pounding, and increasing overall resilience to pounding. Unfortunately, rather than preventing damage, these approaches acknowledge its inevitability and seek to minimize it. They are also incapable of preventing damage to building contents and injuries to occupants as a result of colliding structural elements.

Given the inadequacy of much current practice with respect to pounding between buildings, this paper investigates the potential for retrofitting small clusters of buildings rather than just individual buildings. Where two or more buildings are tied together and retrofitted as a single building, not only is pounding eliminated but possible structural, architectural and economic synergies arise when adjoining building owners work together to solve a common problem.

For the purpose of investigating the potential for retrofitting clusters of buildings a research-through-design approach [3], was taken. The Cuba Street historic precinct in the city of Wellington, New Zealand, was selected by the three project partners, Wellington City Council, Heritage New Zealand, and Victoria University of Wellington School of Architecture as the location suitable for design investigations for integrated architectural and seismic retrofits. Seventy Master of Architecture students at Victoria University of Wellington were then tasked with designing theoretical schemes for retrofitting clusters of buildings, in order to protect lives and heritage architecture, and to redevelop and intensify site usage. The student designs were to anticipate what the full ten city block precinct would and should be like in 2035 and beyond. During this design process, students were allocated groups of adjacent sites to redevelop and were required to design retrofit schemes for the buildings on them, as clusters.

DESCRIPTION OF RESEARCH PRECINCT

The precinct is designated the Cuba Street Character Area in the Wellington City Plan and has a collective formal heritage status with Heritage New Zealand. Cuba Street has always been about retail, commerce and entertainment (Figures 1 and 2). From the turn of the twentieth century, most of the commercial buildings had shops on the ground floor and residential accommodation above. People still live in the late Victorian and Edwardian tenements, giving the street its lively urban character.

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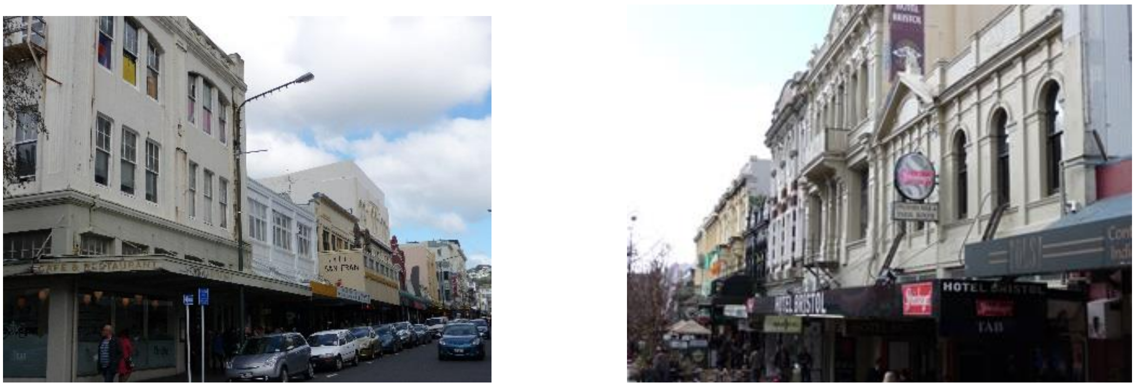
Figure 1: A map of Cuba Street prepared by Wellington City Council in 2013 showing heritage buildings (dark shaded buildings have a higher heritage classification) and earthquake-prone buildings (red dot). Earthquake-prone buildings are defined as having 33% or less seismic strength than that required for an equivalent new building.



(a) (b)

Figure 2: (a) Typical Cuba Street buildings in one block; and (b) buildings in another block with more interesting facades.

Many of the buildings in the street date from 1900-1940, after which city development largely passed them by. The result is a reasonably coherent streetscape of predominantly two to three-story buildings. There is a risk that if a large group of these buildings was lost, much of the existing character of a finely-scaled, much loved if slightly worn city precinct might also be lost. This project addressed the retrofitting and diversity of potential architectural redevelopment of all buildings along both sides of Cuba Street.

APPROACHES TO PREVENT POUNDING INCLUDING RETROFITTING CLUSTERS OF BUILDINGS

The severity of pounding during an earthquake depends on many factors and varies greatly between events. Cole et al [2] provide a list of building configurations that are vulnerable to pounding. They note how interior buildings in a uniform row may experience a degree of protection due to pounding at the expense of the more heavily damaged buildings at each end of the row. Rosenblueth and Meli [4] report that during the 1985 Mexico City earthquake, about 40% of damaged structures experienced some degree of pounding, and that pounding was responsible for a 15% collapse rate. A pounding damage survey of mainly low-rise buildings following the very short duration yet intense 2011 Christchurch earthquake showed that pounding caused significant damage or worse to up to 12% of the surveyed buildings [5]. Almost all were of unreinforced masonry construction. Pounding is clearly undesirable.

The strategy of retrofitting a cluster of buildings to overcome pounding and for other beneficial reasons has received little attention from the earthquake engineering community. For example, although the number of papers on pounding presented in World Conferences of Earthquake Engineering have increased to 16 in 2012, only a few acknowledge the approach of tying adjoining buildings together. During the same conferences many papers were presented on retrofitting, but in almost all cases buildings were considered in isolation from their neighbors. Mazuzawa and Hisada [6] reported on retrofitting two large hospital buildings by tying them together and then seismically isolating them. In another study, the feasibility of tying an old five-story building possessing one particularly vulnerable story to a new ten-story building was investigated [7]. The authors concluded that their strategy was successful in preventing the collapse of the old building, but that its structural performance was sensitive for different ground motions with comparable acceleration response spectra.

Treatment of clusters of buildings is recognized in Europe. De Porto et al [8] report that the Italian seismic code recommends an entire cluster of buildings is analyzed even if just part of it is damaged or vulnerable. Further, following the 2009 L'Aquila earthquake, the Italian authorities required owners of damaged buildings to present a single unified damage repair plan for their cluster of buildings before reconstruction funds were released. The authors describe the analysis and design interventions of heritage precinct area, yet although the buildings were considered as part of a cluster, none were reported as being tied together.

Seismic retrofitting guidelines have also displayed reticence with respect to pounding. For example, FEMA 547 [9] neglects to raise the subject. However, ASCE/SEI 41-13 [10] includes several clauses regarding adjacent buildings. Designers are to collect data on the separation or lack of it between buildings in order to investigate "interaction issues", but no advice is provided other than recommending that "consideration should be given to hardening those portions of the building that may be impacted by debris or other hazards from adjacent structures". ASCE/SEI 41-13 [10], in page 27, does acknowledge the retrofitting strategy of tying buildings together. Although missing from the list of eight permitted retrofit strategies, it could be considered to be included in “Other retrofit strategies approved by the authority having jurisdiction”. But more significantly, the strategy is explicitly mentioned in page 392 in Appendix A of the ASCE/SEI 41-13 [10]: “With separate structures in a single building complex, it may be possible to tie them together structurally to force them to respond as a single structure”.

The NZSEE Study Group guideline [11] provides considerably more advice to designers considering tying buildings together. After discussing the problem of pounding and the possibility of widening seismic joints, Section 13.3.8 Linking Buildings Together across Seismic Joints, gives the following advice: “Some buildings are comprised of several seismically separated structures often with completely inadequate seismic joints between them. Often these structures can benefit from the installation of linkage nodes between the separated structures that can transfer axial loads and seismic shears in a controlled manner. With careful design and detailing it is possible to achieve controlled “articulated” movement between buildings and to use the excess seismic strength of one building to assist in supporting its neighbor. Careful analysis is required particularly where neighboring buildings have quite different strengths, stiffness and building periods.”

CASE STUDY

Before introducing the student theoretical design project, a contemporary case-study illustrates retrofitting of a pair of buildings in practice. Buildings numbered 326 and 330 Lambton Quay, Wellington, were recently tied together and retrofitted (Figure 3).

Consisting of a basement and six stories, 326 Lambton Quay was constructed in the mid-1930s. The five transverse reinforced concrete frames that resist transverse loads were assessed at 25% New Building Standard (NBS) with the governing mechanism consisting of reinforcing bond through the joint and no account taken of pounding [12]. That is, their combined strength equaled 25% of that required by current regulations for an equivalent new building. The longitudinal walls achieved more than an acceptable 67% NBS. The New Zealand Building Act requires that buildings possess a level of structural strength equivalent to at least 33% NBS. 330 Lambton Quay with its basement and eight stories was constructed a few years later. Three riveted steel moment frames that provide transverse resistance were also assessed using a detailed analysis at a maximum of 40% NBS. Its longitudinal walls achieved over 67% NBS.

The fact that both buildings would pound each other was not included in either of the %NBS calculations. Nor did an analysis investigate the possibility of pounding benefiting one of the two buildings by dampening its response while the other building was damaged. This is supported by Cole et al [2] that no recommendations exist for design engineers wanting to model the floor-to-column collisions expected in the case-study buildings. Moreover, a recent study [13] of floor-to-floor pounding of adjacent five and eight storey frame buildings, subject to six strong ground motions, concludes that ‘the effect of collision of adjacent frames seems to be unfavorable for most of the [different configuration] cases and, therefore, the structural pounding phenomenon is rather detrimental than beneficial”.

The combined retrofit involved tying both buildings together to act as one during an earthquake. No longitudinal retrofit was required as the existing walls at 67% NBS were well over the minimum 33% NBS. Strength in the transverse direction is now provided by a new very stiff seismic frame to the rear of 330 (60% NBS for the combined building), the existing steel frames of 330 (assessed at 10% NBS) and an upgraded frame on the inside of the front façade of 326 (Figure 4). The construction of this frame necessitated a new steel beam and saw cuts through the mid-spans of the existing façade spandrel beams to increase deformation capacity. Two new columns acting as vertical beams in 330 deal with the slightly vertically-offset floors. Where horizontal transverse tie forces are transferred at the front of the buildings the steel tie is designed and detailed to yield before the new concrete column in 326 is damaged in torsion, bending and shear. A steel collector member picks up inertia forces from 326 and transfers them into the new seismic frame of 330. Tying the two buildings together does create a vertical irregularity in the form of a set-back above the roof of 326, however the existing steel frames of 330 are adequate for the increased response. Cattanach [12] notes how the wider footprint of the combined building plan leads to improved torsion performance.

Figure 3: Two buildings tied together. 330 Lambton Quay, Wellington, is the building to the left, and to the right, 326 Lambton Quay.

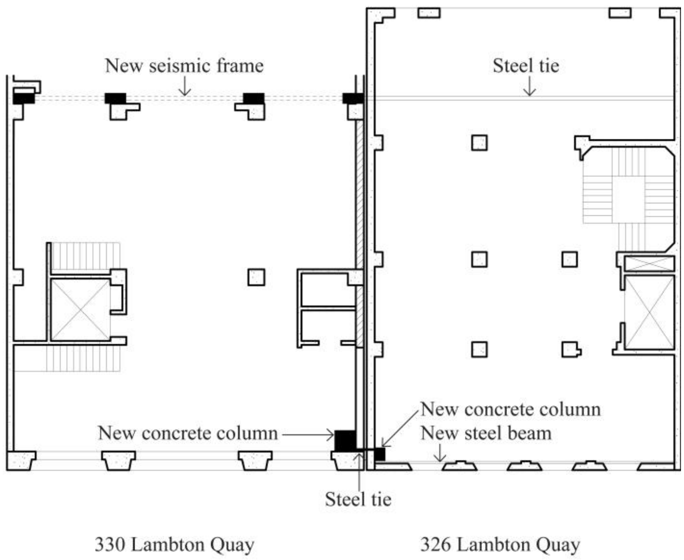


Figure 4: Simplified typical floor plans of 330 and 326 Lambton Quay, Wellington showing the main retrofit structure.

The project was initiated by the owner of 330 upon discovering that his building was on the cusp of being considered earthquake prone and in need of retrofitting. Based upon advice from his structural engineer and quantity surveyor, he established that there would be very significant financial savings to both owners if the buildings were tied together [14]. The owner of 326 agreed, and it was decided that the costs of the seismic retrofit be apportioned equally between buildings. All other costs, including architectural and services reinstatement and alterations were covered separately by each building owner. Individual legal ownership was maintained for both buildings and insurance issues during construction were eased by both buildings having the same insurer. The fact that the buildings are tied together is noted on their legal documents. The strategy of tying the buildings together was very cost-effective, eliminating pounding and improving torsion response.

As noted in a previous section it is rare for buildings to be tied together as a retrofit solution. In this case study, the owners were motivated to take this step by significant financial savings and the elimination of pounding. If retrofitting involving adjacent buildings being tied together is to become more widespread several educational initiatives are needed. Building owners need to be aware that this is an option. Then, when briefing consultants on a retrofit design, owners can request a feasibility study of potential synergies of tying buildings together. Architects and structural engineers also need their awareness to be raised. When tasked with retrofitting single buildings subject to potential pounding from adjacent buildings, they should look outside their immediate sites and consider possible architectural and economic benefits of tying buildings together. The success of the case study was largely due to the same structural engineer analyzing both buildings, and during that process realizing the financial savings of tying them together. If preliminary findings, after input from a quantity surveyor, indicate financial benefits for both building owners, that would be the time for building owners to begin discussions. The conclusion of initial positive discussions signals the time to introduce other stakeholders and advisors. Early involvement of the local building authority and insurers is advisable. The owners might decide to insure with the same company to overcome potential stumbling blocks. Legal advice to protect both parties and to work towards a successful resolution would be also sought at this stage.

Further country-specific research is necessary to underpin any attempts to promote the strategy of tying buildings together. A publication containing case studies would be helpful. In particular, attitudes of the insurance industry and the legal profession need to be discerned and solutions to potential impediments found and disseminated. Also, legislation regarding the treatment of earthquake-prone buildings needs consideration. For example, with the passing of the New Zealand Building (Earthquake-prone Buildings) Amendment Act 2016 [15], earthquake-prone building owners have specific time periods within which to reduce seismic hazard. This legislation that requires action from every owner provides added motivation for them to cooperate with their neighbours when considering retrofit.

HISTORIC PRECINCT RESEARCH METHOD

In this theoretical project, the students designed redevelopment of every building and site for the whole length of Cuba Street working with clusters of buildings. They responded to the incremental intensification of the city over time triggered by seismic upgrading and its associated major investment. They investigated different ways of adapting and reusing heritage building fabric and integrating seismic retrofitting. They documented existing buildings in detail and assessed their existing conditions and undertook cultural heritage assessments to define the existing building fabric and structure and heritage values. This was followed by a seismic retrofit design for redevelopment of a cluster of buildings. Throughout the project the students were supported by practicing architects and structural engineers. More information about the design process is available in [16].

Regarding the level of retrofit, although Wellington City Council recommends upgrading to a minimum of 67% NBS [17], the retrofitting designs undertaken here were to 100% NBS. The higher standard of retrofitting is recommended as it future-proofs buildings against future code changes that may require higher levels of seismic strength. Students sized their retrofitting structure using the preliminary structural design software RESIST [18]. They also made two assumptions regarding the strength and deformation capacity of the existing structures. First, they assumed (correctly in some cases), that the seismic resistance of an existing structure could be neglected. While in practice the establishment of an existing building's seismic strength is the first step in a retrofit design, the skill level of the students and the limited time available for the project meant that this atypical and conservative assumption was adopted. Secondly, the students assumed that the deformation capacity of existing structural elements were adequate to ensure gravity load-bearing during an earthquake. In acknowledgement of the shortcoming of this assumption, students chose structural systems with lateral stiffness compatible with those of the existing structures. It was understood that any inadequate deformation capacities would be remedied later by limiting deformation demands, or by providing saw cuts or confinement.

PROJECT OUTCOMES

Following research into the history and multi-scaled urban context of Cuba Street, the project involved theoretical integrated structural and associated architectural upgrading of the historic buildings to extend their lives for at least another twenty years. The existing buildings were subject to intensification of occupancy and architectural modifications to ensure their on-going viability and future relevance. Students upgraded and extended buildings to improve their urban or interior design, and their functional or financial performance. Some poor quality buildings that were run down and had been badly altered over the years destroying their heritage qualities were demolished and new buildings designed in order to intensify the occupancy of the precinct. Synergies arose when two or more buildings, existing or new, were considered together rather than as isolated structures. It was assumed that adjoining buildings were either jointly owned, or that their owners had agreed to having them tied together as per the earlier case study.

The historic qualities of the host buildings were respected to greater or lesser degrees in the student design proposals. The variation in scope and approaches of the heritage retrofitting designs underlined the flexibility of adaptive reuse of heritage building fabric. Highlighting the potential future value of heritage building fabric, the best examples of these architectural design approaches are documented in the project summary publication [19]. The architectural implications of retrofitting the structure of a heritage building are too extensive to be ignored despite a general perception that retrofitting is solely or primarily structural. Several distinct approaches to the upgrading of, adaption of heritage building fabric, and integration of architectural and structural work that were observed in the student work and extend the taxonomy introduced by Ostwald [20] are described below.

Indifference - where seismic retrofitting is perceived as completely or primarily an engineering problem with the consequential implications ignored. This approach is particularly evident in minimal cost solutions to minimum standards. The retrofitting is indifferent to the aesthetic qualities of the underlying building and the impact of the finished result.

Invisibility - typically applied to architecture recognized as having high heritage value. With an invisible approach to seismic retrofitting new structure is carefully threaded through an existing building in a manner that allows it to be concealed. Parts of the building may be removed and new structure placed within. Structural expression is suppressed. A concern with the original qualities of the building dominates.

Separation - direct controlled relationships occur between new seismic retrofitting and the existing building. New materials and structural systems are visually expressed as specifically designed work layered over the existing structure. Visual distinction is created between existing and new layers of work. Original structural and architectural elements are left as untouched as possible, or undergo minor restoration. New structure is expressed and contrasted with the old as a carefully orchestrated juxtaposition of new against old, as a legible new layer of work.

Dialogue - where seismic retrofitting treats the existing building fabric as the site of a complete redesign. Structure and architecture are adapted, altered and added to, to create a hybrid old-new architecture that balances conservation principles [21] with the need to find contemporary uses to save the building from demolition. Free and often radical change of existing built fabric occurs to meet new and different circumstances. Structure may be partially expressed and exposed and partially hidden as required by both the existing structural performance and opportunities created by the hybrid building that results. Radical surgery and major additions may be required to address building deficiencies and the needs of its contemporary uses. Opportunistic and innovative in its architectural approach, this tactic works critically from and with the historic qualities of the existing building, augmenting these to create identifiably new work, and give a future to a building no longer meeting contemporary needs.

The range of approaches to seismic retrofitting demonstrates an awareness that there are different ways that seismic retrofitting irrevocably changes a building. Detailed knowledge of the existing architectural and structural fabric and the possible structural and architectural synergies is critical to the success of a seismic retrofit. This knowledge is potentially invaluable to an engineer embarking on a seismic retrofit design, and may change the way that an engineering design occurs.

Regarding the seismic retrofitting designs of the building clusters, the research-through-design approach generated a wide diversity of retrofit design strategies. The strategies that were adopted are classified and summarized into two broad categories, each containing several subcategories, as follows:

Tie Two or More Existing Buildings Together

This was the most commonly adopted strategy where one or more heritage buildings were adjacent, and no new building was planned. In many cases retrofit structure, either new moment or braced frames or shear walls, was evenly distributed between buildings (Figure 5a). In these instances the amount of horizontal structure necessary to tie the buildings together was minimized. New structure, such as the beams of moment frames could pass between the two buildings, helping to tie them together (Figure 5b).

The architectural impact of the retrofit structure of this strategy is similar to most current practice where adjacent individual buildings are retrofitted without consideration of their neighbors. Given that no one building is privileged this is a good solution where both buildings are owned separately. Potential synergies may be limited to the increased scale of the overall retrofit construction, thereby reducing cost, the elimination of pounding and providing better torsion performance.

More architecturally-interesting schemes concentrated retrofit structure in just one building. This meant (when just two buildings were tied together) that most of the structural intervention, including potential foundation work was confined to one building with relatively minor structural work required to the other (Figure 5c). This strategy creates architectural opportunities, including expressing the new structure in one building and concealing it in the other. If primary retrofit structure, like moment frames, is to be restricted to one building, it would typically be inserted into the taller building. Then, in at least one direction, the taller building supports the shorter building. Note that if moment frames are used in unreinforced masonry buildings it may be necessary to saw cut walls parallel to the frames to provide deformation compatibility between frames and the walls.

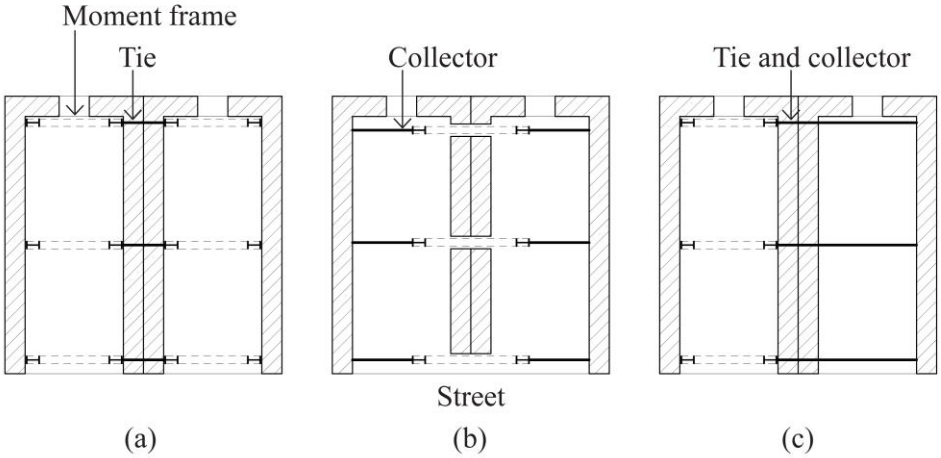


Figure 5: Plans of two adjacent idealized URM buildings showing moment frame retrofit structure in the transverse direction. In (a) and (b) the retrofit structure is evenly distributed in both buildings, and in (b) the frame beams tie the two buildings together. In (c) the primary retrofit structure is located in just one building. Diaphragm and wall face-loading upgrade structure is not shown.

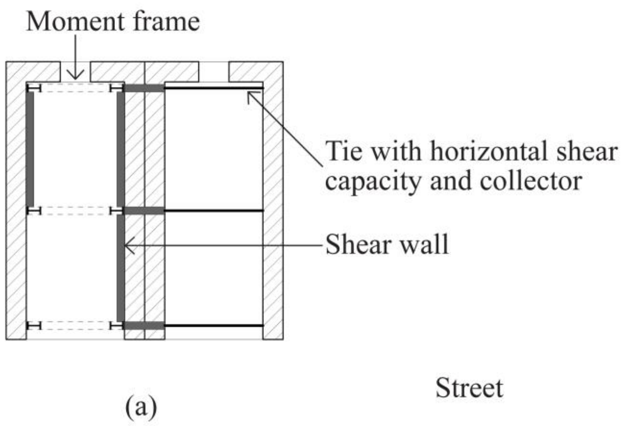


Figure 6: Plans of two adjacent idealized URM buildings showing moment frame retrofit structure in the transverse direction and shear walls in the longitudinal direction. In (a) transverse and longitudinal retrofit structure for both buildings is placed in just one building, and in (b) the longitudinal retrofit structure is evenly distributed in both buildings. Diaphragm and wall face-loading upgrade structure, essential for adequate performance, is not shown.

Other retrofit configuration combinations include new primary structure placed in only one building and supporting both buildings for both directions, parallel to and orthogonal to the street (Figure 6a). Alternatively, the new structure might provide resistance in just one direction, say parallel to the street, and in the other orthogonal direction resistance might be provided by new structure in both buildings (Figure 6b). The approach taken impacts on the demands placed on the existing and upgraded floor and roof diaphragms as they perform their roles of resisting inertia forces from existing construction and transferring them to the retrofit structure. These demands, including effects of any podium redistribution of seismic forces, require special attention by the structural engineer and would include consideration of the sensitivity of performance to diaphragm stiffness and strength.

Unequal suspended floor levels are frequently encountered. This condition necessitates strong columns or short walls which effectively function as vertical beams to transfer forces between the stepped diaphragms (Figure 7). This occurs irrespective of whether the new vertical structure is distributed evenly or not throughout both buildings. Care is required to ensure that horizontal forces can be reliably transferred from floor diaphragms and tie and collector members into any new vertical members.

Tie Existing Buildings to New Buildings

This opportunity arises where there is an open area behind a building fronting the street, or an adjacent site between or besides buildings becomes available following the demolition of an inferior historic building. Numerous variants of this strategy are possible depending on architectural ideas as well as structural requirements. The most common option is for the new building, assuming it is at least as high as the adjacent existing heritage building, to provide some or all of the retrofit needs of the existing building(s). The existing building is therefore subject to a minimal amount of intervention and the new building designed to address existing deficiencies. By having new construction support that which exists, it is also possible to open-up the existing architecture. Small confined spaces, typical of heritage masonry buildings can be enlarged as is often required, to accommodate new uses (Figure 8a).

If an existing building is of unreinforced masonry there may be a need for new vertical structure to resist wall face-loads, and new or upgraded diaphragms are likely to be needed at roof and suspended floor levels. If the existing building possesses sufficient strength in one direction, due to say boundary masonry walls orthogonal to the street, then the new building might need to provide strength only in the other direction (Figure 8b).

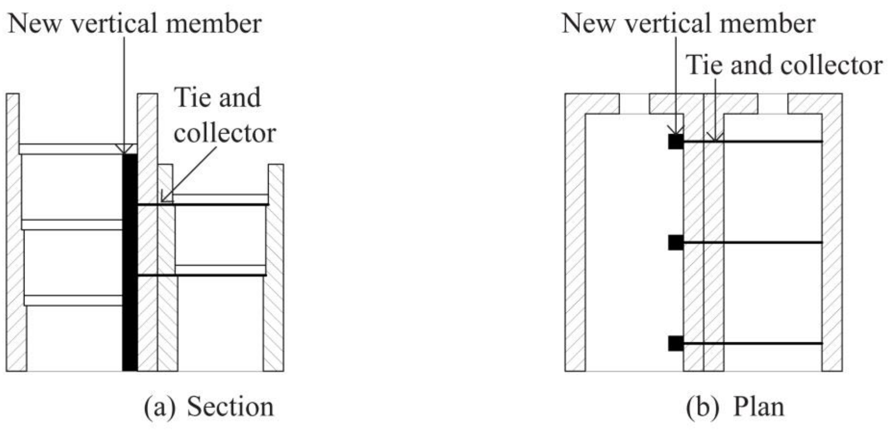


Figure 7: Two idealized and retrofitted URM buildings showing the vertical structure required to transfer forces from the diaphragms of one building to those of the other where the diaphragms are at different levels. The primary retrofit structure and upgraded diaphragms are not shown.

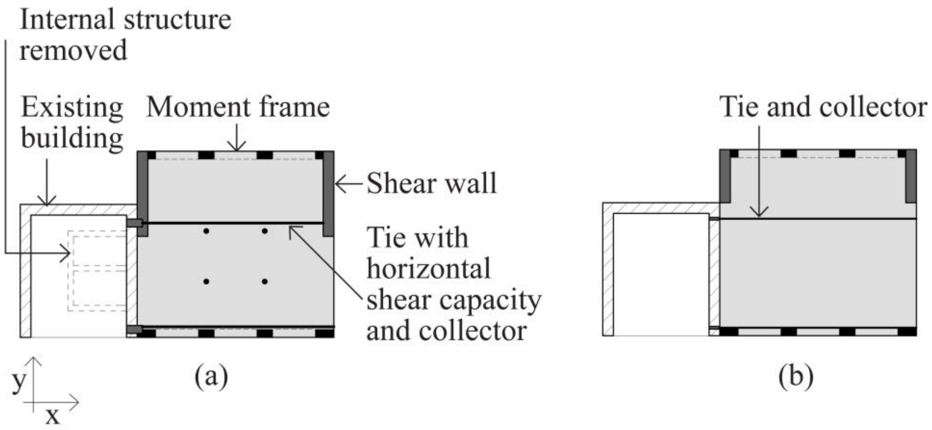


Figure 8: Plans of an idealized existing and new building joined together. In (a) structure in the new building is adequate for both buildings in both directions, while in (b) the existing building has sufficient strength in the y- direction but is supported by the new building in the x-direction.

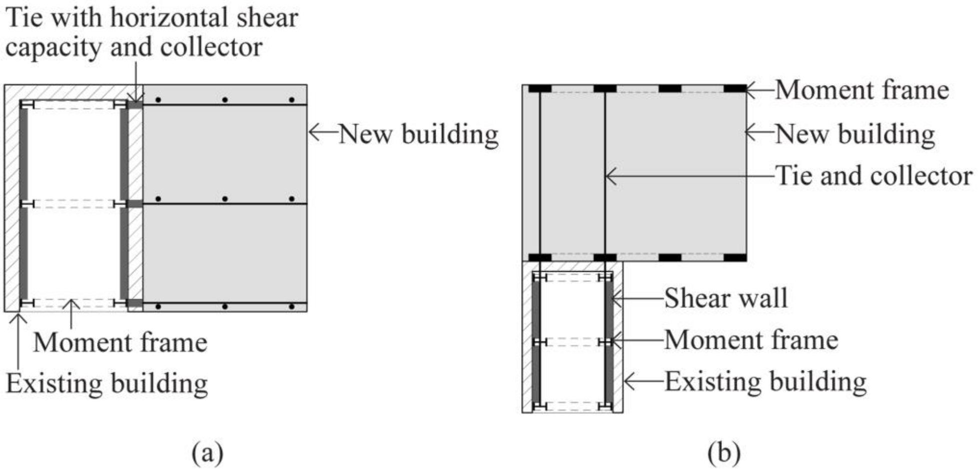


Figure 9: Plans of an existing and new building tied together. In (a) the existing building retrofit structure resists forces in both directions for both buildings, while in (b), retrofitted shear walls in the existing building resist forces for both buildings but each building has its own new moment frames in the other orthogonal direction.

A variation of this strategy is the reverse of that above. Retrofit structure of an existing building may be designed to support both existing and new construction (Figure 9a). Like the addition of a light-weight conservatory to an existing house, the lateral stability, strength and stiffness of the conservatory is provided by the host building. The retrofitted structure of the existing building might also provide sufficient strength for both it and the new attached construction perhaps in just one, rather than both directions (Figure 9b).

Where there is a vacant lot between two heritage buildings it is possible to connect both buildings to a new central building. If the existing buildings possess sufficient strength perpendicular to the street, and if the strength requirements parallel to the street for all three buildings are met by the new building, retrofitting interventions to the existing are minimal and confined to wall face-load and diaphragm upgrading (Figure 10a). This design tactic requires the new architecture to negotiate the structural and architectural condition of the two adjacent buildings. The existing buildings will determine the new floor levels and the size and location of the primary structural elements within the new building. It will require comparatively strong structure to retrofit the two 'saddlebag' buildings. The two existing buildings remain relatively intact with minimal changes and consequences directly from the seismic retrofitting, however diaphragm upgrading including ties to connect to the diaphragms of the new building can be expected.

Any differences in floor levels will require new vertical structure as explained previously. Once again, this strategy can be reversed. It is possible to retrofit one or both existing buildings so that the new central building ties them together but doesn't need any lateral load resistance itself (Figure 10b). This strategy is attractive if the new building is intended to be as transparent as possible.

Each of these strategies implies a certain desired architectural outcome for the cluster that can only be realized by close integration of the retrofit structure with all other architectural elements and requirements.

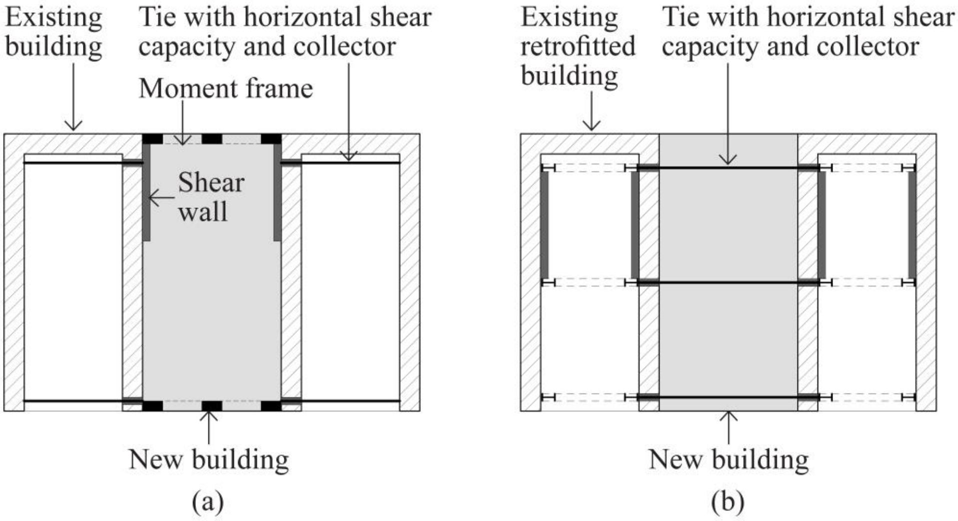


Figure 10: Plans of two existing buildings with a new building between them. In (a) the structure in the new building is adequate for all three buildings, while in (b) the new building has no lateral load-resisting structure and relies on the retrofit structure of the existing buildings.

CONCLUSIONS

Where there are either very narrow or no separation gaps between adjacent buildings requiring seismic retrofit, an important potential design strategy is to tie the cluster of buildings together to eliminate pounding and have them perform seismically as a single building. This approach, which is acknowledged by leading retrofit guidelines, yet rare in practice, solves the problem of pounding, may improve torsion, and can offer economic and architectural advantages.

Through this precinct-wide research-through-design approach many different approaches for retrofitting clusters of buildings which always included at least one historic building were explored. Two primary categories of cluster retrofit strategies emerged from the study; namely, tying existing buildings together, and tying existing buildings to new buildings. These categories and variations within each are described and illustrated. They show a range of strategies for retrofitting clusters of buildings that is worthy of consideration.

ACKNOWLEDGMENTS

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