## PERFORMANCE BASED BUILDING

## Full paper

# STRUCTURAL STRENGTHENING FOR OPTIMIZING FLOOR SPACE DURING RETROFITTING OF HIGH-RISE OFFICE BUILDINGS

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## ABSTRACT

Re-life of aged buildings is frequently more cost-effective and time efficient than re-building. In developing a strong business case for re-life, a major challenge to be addressed is that of maximizing the rentable floor space which often puts a re-life project at a disadvantage. In increasing usable floor space, options available to the client include removal or adding floors and partitions, relocating services, cutting openings or extending floors and relocating lift wells etc. In these situations, innovative structural strengthening schemes could be implemented to strengthen the existing structure. Whilst there are decision-support tools reported in literature to cover other parameters in relation to re-life of buildings, they do not include evaluation of the optimizing of rentable floor space and corresponding structural strengthening needs.

The structural strengthening of existing buildings can be achieved using one of many upgrading techniques such as span shortening, externally bonded steel, fiber-reinforced polymer (FRP) composites, external post-tensioning systems, section enlargement, or hybrid strengthening systems. Each technique has specific advantages and disadvantages and the applicability to building materials such as concrete, steel, timber and masonry varies. This paper presents a decision support framework developed to compare and assess options available to the design team of a re-life project in optimizing rentable floor space. A matrix developed to map existing as well as innovative structural strengthening techniques to strengthening needs will also be presented with application examples from a case study in Melbourne.

**Key words: Re-life, optimization, strengthening, case study**

# 1.0 INTRODUCTION

Observation of commercial office buildings built 35 years ago shows that they are reaching the end of their original design life span (aging). Repair and maintenance expenditure is expected to increase due to the structural deficiency and functional obsolescence of aged buildings. In some situations, buildings cease to fulfill the expected services during their design life span due to the changes in office work environment, changes in procedures, changes in equipment design or because of poor initial design. A modern office block must be equipped to meet these changing trends; otherwise it will soon depreciate in value and loose its renting potential or market value [1]. The results of these factors point to an opportunity for an efficient "re-life" rather than demolition and "new-build" [2]. It is frequently more cost-effective and time efficient to refurbish than to re-build. Consequently, an increasing number of re-life projects are exploring the advantages of occupying older buildings [2].

In developing a strong business case for re-life rather than demolition and re-build, a major issue to be addressed is maximizing of rentable floor space, which often puts a re-life project at a disadvantage. In increasing usable floor space, options available to the client include removal or adding floors and partitions, relocating services, cutting openings or extending floors and relocating lift wells etc. In each case, innovative strengthening schemes have much to offer when considering upgrading the existing structure.

For a retrofitting project to be successful, the owner has to establish a suitable retrofitting plan of action. If a client makes inappropriate choices, the outcome may be a time and/or cost overrun and general dissatisfaction. Nowadays, a number of decision support tools are available to the owners to assess the current condition of their buildings with respect to deterioration, functional obsolescence, energy consumption and environment quality, before making a decision to retrofit their buildings. Those decision support tools also help to choose appropriate retrofitting actions and to estimate the cost. However, the available decision support tools do not cover the building structure. Consequently the "Floor space optimisation" strand of Re-life project funded by CRC for construction innovation is looking into the development of a management decision support tool that assists the owners in selecting an appropriate strengthening scheme during optimizing of floor space in a re-life project.

## 2.0 THE NEED FOR STRUCTURAL STRENGTHENING IN RE-LIFE OF BUILDING

Due to the increase in economical and environmental constraints, the current trend is to upgrade deteriorated and obsolete structures rather than replacing them with new buildings [8]. It is a significant challenge for engineers to satisfy the clients' requirements during retrofitting; specially optimizing the usable floor space. Usable floor space of existing building can be optimized by modifying the layout of an existing building such as removing or adding of floors and partitions, relocating services, cutting openings or extending floors and relocating lift wells etc. In these situations, innovative structural strengthening schemes could be implemented to strengthen the existing structure.

Strengthening of an existing structure may also become necessary under the following circumstances:

1. When buildings are exposed to harsh environments such as de-icing salts, chemicals or air-borne salt spray, or have inappropriate details, the structures may experience significant deterioration in the form of steel corrosion, concrete cracks and spalls [4]. Such deterioration may result in structural inadequacies that adversely affect the structure or its members,

2. In situations where the building owners make decision to change the usage of a type of building depending on the business demand in the current market environment. As a result, the existing structure of a building may or may not be strong enough to withstand the new loading,

3. Structures constructed in early days may have been designed to carry loads that are significantly smaller than the current needs, possibly due to increase demand usage [4],

4. Structural inadequacies may arise due to errors in initial design or construction and changes of design standards.

By carefully implementing appropriate structural strengthening methods, re-life of buildings can be justified/achieved rather than adopting demolishment and re-building

## 3.0 Structural strengthening techniques

Selection of an appropriate strengthening method is dependent on the materials of construction. Structural elements of existing buildings are commonly constructed of concrete, steel, timber and masonry. Concrete is the most commonly used building material and widely used in the forms of in-situ concrete, precast concrete and post-tensioned concrete.

The structural strengthening can be achieved by section enlargement, external post tensioning, external bonded steel elements, bonded advanced fiber reinforced polymer (FRP) composites, span shortening, or a combination of these techniques [4,8]. No matter what strengthening technique is used, the ability to perform as an integrated system can be obtained only by providing an adequate bond between the existing member and the repair/reinforcement to ensure monolithic structural behaviour [8]. Stress concentrations resulting from added material should be investigated as they may cause a localized failure.

Unfortunately, there is no specification or design that covers all repair/upgrade scenarios and engineers, architects, and contractors must be innovative and thorough, in their design details, specifications, and applications.

## 4.0 Management support tools available for re-life projects

A good retrofitting action plan will lead to the success of a re-life project. If an asset owner makes inappropriate choices, the outcome may be a time and/or cost overrun and general dissatisfaction. With the aid of decision-making tools, it is possible to select the most suitable retrofitting action. A number of such tools have been developed for office buildings with TOBUS, MEDIC, EPIQR and INVESTIMMO being the most commonly reported in the literature [1,3,4].

The decision-making software tools, EPIQR (for apartment buildings) and TOBUS (for office buildings) have been developed for the assessment of retrofitting needs of buildings in European countries. The use of these tools can facilitate a quick and accurate diagnosis of the condition of the existing building in terms of its major area including construction, energy performance, indoor environmental quality, and functional obsolescence. The main advantages of using these tools are the ability to evaluate various refurbishments and retrofit scenarios, and cost of induced works, in the preliminary stages of a project [5,6].

In EPIQR and TOBUS, deterioration of building materials and components are described by the use of a classification system with four classes. The prediction of the period of passing into the next deterioration state is of high interest as this is directly connected to higher refurbishment costs. The prediction of qualitative deterioration states are important and correspond to key moments in the element's life where some refurbishment action has to be taken [5,6].

European countries have been used another software tool entitled MEDIC to predict the future degradation state of building. MEDIC is intended for use with EPIQR and is based on a subdividing of the building into 50 elements. MEDIC calculates the remaining life span of a building element not as a deterministic unique value but as a probability distribution. It can help the owner of a building to decide the most judicious moment to undertake refurbishment to achieve his short and long term financial needs [7].

Following the footsteps of EPIQR an TOBUS, a decision-making tool for long term efficient investment strategies in housing maintenance and refurbishment – INVESTIMMO has been developed in European countries. It has been aimed at evaluating housing maintenance and refurbishment options, which covers expectations of tenants, housing market, and quality of building upgrading and environmental impacts in addition to the factors identified in TOBUS [5].

From the review of literature, it was clear that these tools can be used to evaluate the general state of buildings with respect to some of the aspects of building re-life projects such as service life, functional obsolescence, energy consumption and environment impacts. However, no reported work presents a decision support tool, which can be used to compare and assess options available to the design team of a re-life project in optimizing rentable floor space.

## 5.0 Proposed decision support framework

In order to develop a decision support tool for selecting the most appropriate structural strengthening scheme during optimizing floor space, the preliminary objective was to identify the clients' requirements and problems associated with structural strengthening. Through the review of literature and based on the experience, a list of issues, which may influence strengthening work has been compiled. Consequently, Delphi process was utilised to rank them based on the importance in refurbishment projects. The following issues were identified as important by the experts engaged in research/practice in the field of building refurbishment:

1. change of use of floors,
2. cutting openings in floors and extending floors,
3. relocate/renew services,
4. structural appraisal prior to refurbishment and
5. safety reliability issues in structural strengthening.

Through an extensive review of literature and industry practices, a set of structural strengthening techniques has been identified, which may be used to address the issues ranked high from Delphi studies. Upon identifying the issues and solutions, the methodology to develop the decision support tool was established which is shown in the figure 1.

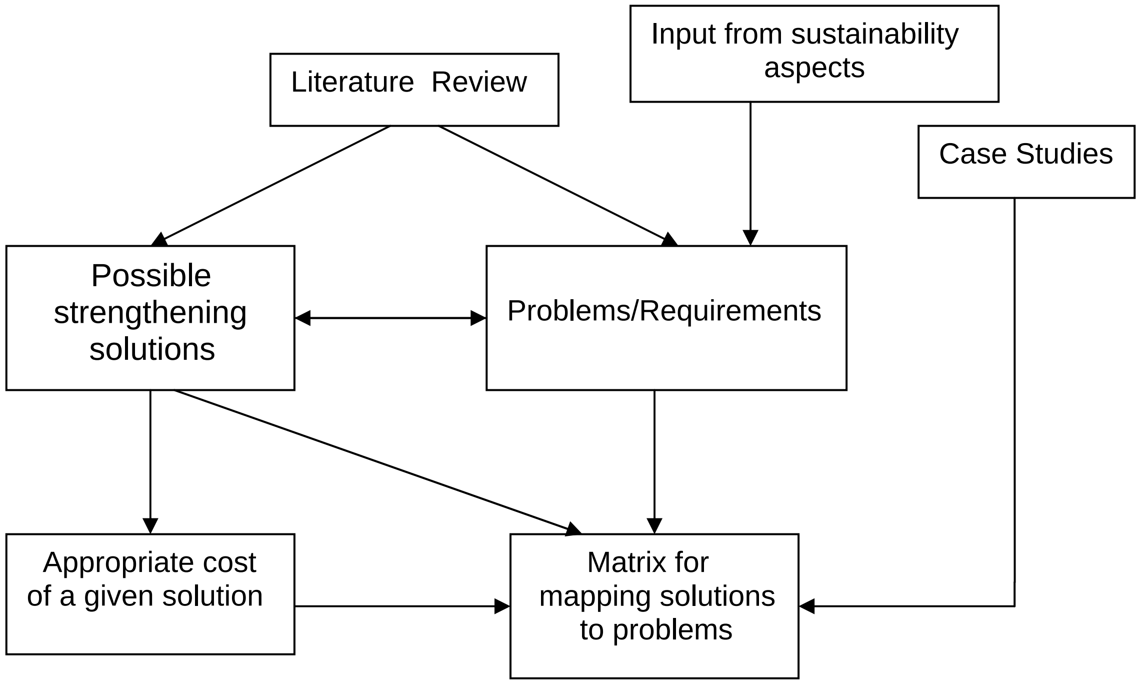


**Figure 1:** Framework for decision support tool

From the framework of decision support tool, it is clear that mapping solutions to problems/issues needs to be evaluated considering the approximate cost of possible strengthening options those can be used for a particular user requirement. The preliminary matrix of mapping structural strengthening solutions to the user requirements was developed and characteristics, issues, possible applications, application examples, companies/contractors, sample design calculations and approximate cost are included in each strengthening technique (Figure 2 / Table1).

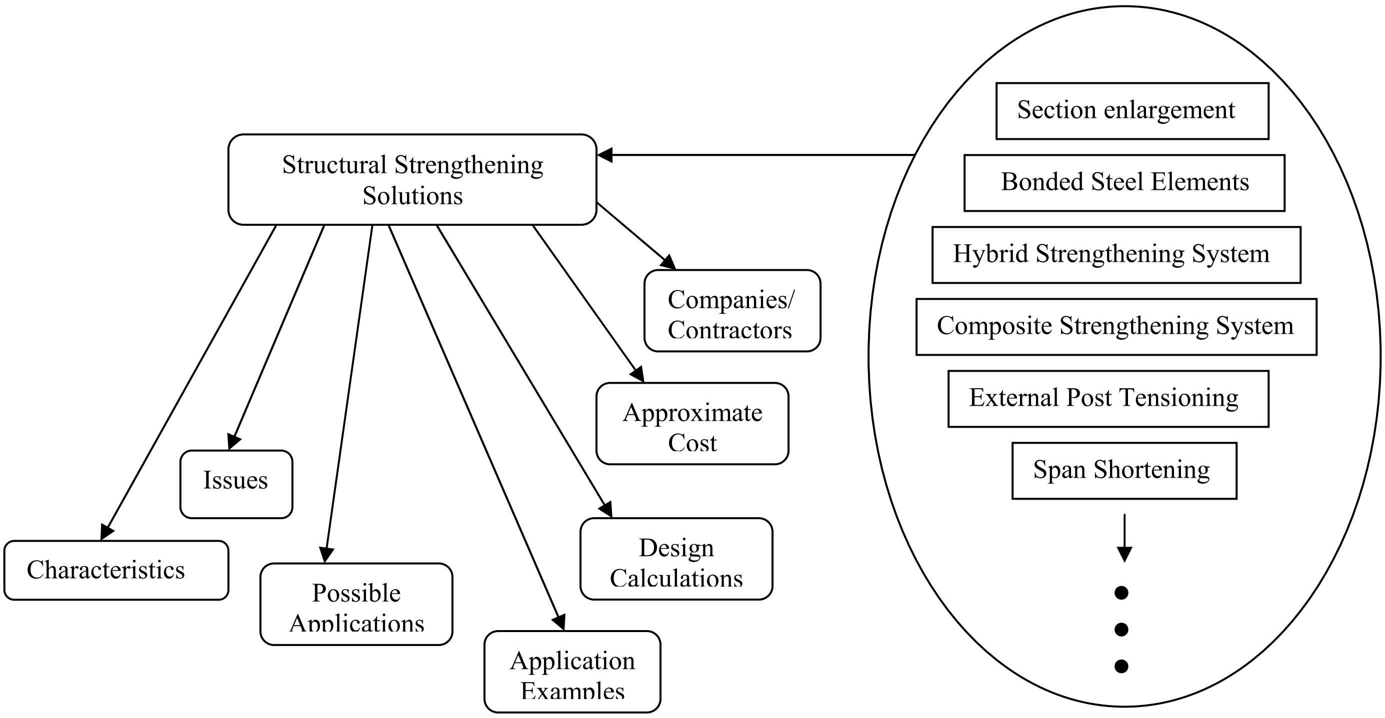


**Figure 2:** Preliminary matrix of mapping structural strengthening solutions to the user requirements

| | Structural Strengthening Solutions | Application Projects | Characteristic | Possible Applications | Issues Associated | Companies |
|---|---|---|---|---|---|---|
| 1 | **Externally bonded composite system**<br><br>**- Fiber Reinforced Polymer (FRP)**<br><br>**- Hardwire® Steel Reinforced Polymer (SRP)** | • Utility tunnel at a University in South Florida<br><br>• Restoration of swimming pool roof structure, Kalmthout, Belgium | • speed and ease of installation<br>• lower cost<br>• aesthetic appeal<br>• light weight<br>• non-corrosive<br>• excellent fatigue behaviour<br>• non-conductive<br><br>• can be used for flexural, shear, and axial (confinement) upgrading and crack control<br><br>• due to thin profile, r/f can be easily run in two directions for two way slabs<br><br>• allow for carpet, tile, and other flooring finishes to be installed over the system without any significant change in floor elevation | • concrete slab, beam, column and wall<br><br>• wooden beam, column<br><br>• masonry | • can damage the externally bonded composite<br><br>• problematic in flooring applications when used on cracked concrete slabs as these cracks may allow reflective cracking throu' polymer topping. | • VSL International Ltd<br><br>• Structural Preservation System (USA)<br><br>• Edge Structural Composites (USA)<br><br>• C.A. Lindam Companies (USA)<br><br>• Watson Bowman Acme Corp. (USA) |
| 2 | **Section Enlargement** | | • relatively easy method<br><br>• not good in harsh environment. Possible corrosion of embedded reinforcing steel.<br><br>• can increase load carrying capacity or stiffness<br><br>• additional concrete can be placed in the form of an overlay or jacket | • concrete columns, beams, slabs and walls | • Increase the weight of existing structure. Using lightweight concrete, additional weight can be minimised | • VSL International Ltd<br><br>• Structural Preservation System (USA) |
| 3 | **External Post-tensioning** | • Two-span steel truss bridge (48-48m) over River Aare at Aarwangen, Switzerland<br><br>• Pier 39, Parking Structure San Francisco, USA<br><br>• Double-tee stems on an overpass located on the premises of a University in Washington. Damaged due to overheight truck. | • Possibility of controlling and adjusting the tendon forces, inspecting corrosion protection and replacing tendons.<br><br>• can be used for both reinforced and prestressed concrete<br><br>• minimal additional weight to the repair system<br><br>• ecconomical<br><br>• requied less time to complete<br><br>• can be used for flexural , shear and axial (confinement) upgrading | • Applicable for structural steel, composite steel-concrete, timber and masonry structures. e.g. building with masonry walls, girders in buildings, roof structures, circular structures such as silos, reservoirs and large masonry chimneys.<br><br>• great success to correct excessive deflections and cracking in beams and slabs, parking structure and cantilever members.<br><br>• due to minimal additional weight of repair system, this is effective and ecconomical for long span beams<br><br>• existing concrete structures against fatigue and cracking | • vulnerable to corrosion, fire and vandalism. However, improved ductility & fire proofing can be achieved by placing reinforcement in ducts that can grouted after stressing of tendon. Protection can also be achieved by encasing the post tensioning system in concrete or by using shotcrete.<br><br>• Externally bonded bars can be damaged by traffic. However, that can be prevented by installing the system in grooves made in existing member.<br><br>• requies access to sides and sometimes ends of member | • VSL International Ltd<br><br>• Structural Preservation System (USA)<br><br>• C.A. Lindam Companies (USA) |

**Table 1:** Matrix of mapping solutions to problems (Contd.)

| | Structural Strengthening Solutions | Application Projects | Characteristic | Possible Applications | Issues Associated | Companies |
|---|---|---|---|---|---|---|
| 4 | **Bonded steel element** | • Quatier des Celestines, a 19th century building in Namur | • Steel element can be steel plates, channels, angles or built-up members<br>• steel elements can be bonded with epoxy adhesive. In addition to epoxy, mechanical anchors can be used to ensure steel element will share loads in case of adhesive failure.<br>• can improve shear and flexural strength | • Steel plate bonded to tension face of concrete beam can increase flexural capacity, flexural stiffness and in deflection and cracking decreases<br>• Steel plate bonded to side of the member can improve shear strength of concrete beam.<br>• install structural steel beams on the underside of structures and steel brackets at column heads.<br>• long-term solution for structures subjected to aggressive environment | • influence to corrosion and fire.Suitable corrosion protection system and fire protection system can be used.<br>• due to their restrictive length, steel elements need to be spliced which complicate the design and construction operation<br>• existing reinforcement can be damaged while placing the anchors. Considerable site work is required to accurately locate existing reinforcement.<br>• Expensive false work is required to maintain the steel work's possition during bonding.<br>• Adding strengthening material under existing structure may redue the usable headroom | • VSL International Ltd<br>• Structural Preservation System (USA)<br>• C.A. Lindam Companies (USA) |
| 5 | **Span Shortening** | • Shortened span in Parking Garage | • reduce the force in overstressed beam<br>• increase the load carrying capacity<br>• best material for this application is steel, which is quick to install. | | • result in loss of space and reduced headroom.<br>• New footing for new column is expensive less expensive approach is to install diagonal braces that extend from the bases of existing columns | |
| 6 | **Hybrid strengthening method**<br>eg. steel/CFRP | • Strengthening of a roof system of an elementary school in New Jersey. They wanted to install skylight on existing roof slab.<br>• Transformation of former school building to library<br>• Roof structure of warehouse at Brussels in Belgium (due to calculation error,capacity of main supporting beams are not suficient) | • less expensive<br>• aesthetically pleasing<br>• fast application | • slab with opening<br>• rib slabs | | • Structural Preservation System (USA) |

**Table 1:** Matrix of mapping solutions to problems (Conti…)

| | Structural Strengthening Solutions | Application Projects | Characteristic | Possible Applications | Issues Associated | Companies |
|---|---|---|---|---|---|---|
| 7 | **Removing existing concrete and casting with lightweight concrete overlay (with steel wire mesh or steel bar)** | • Baltimore's historic Hippodrome Theater renovation -France | • increase bending capacity by increasing effective depth of existing bottom r/f<br>• at support, embedded steel steel r/f in overlay increase the bending capacity<br>• r/f in overlay limits cracking of overlay | • concrete slab and beam | • adequate surface preparation is required to ensure the bond between overlay and existing structure<br>• overlay replace existing topping and therefore small increase in dead load, which offset by using lightweight concrete. | • Structural Preservation System (USA) |
| 8 | **Hardwire** | • Baltimore's historic Hippodrome Theater renovation -France | • hardwire made of ultrahigh strength steel wires twisted together to form reinforcing steel cords wires bonded to existing structures with epoxy adhesive<br>• hardwire works as additional r/f to provide tensile strength | • reinforced and prestressed beams, girders, and slabs to provide additional flexural strength.<br>• can be used on sides of beams and girders to provide additional shear strength.<br>• can be used on structural elements to increase their capacity. | | • Structural Preservation System (USA) |
| 9 | **Hardwire steel belt with polymer flooring system** | • Leading national home improvement warehouse<br>• multi-story warehoue/ distribution facility for a large automative parts distributor in illionis | • hardwire does not replace today's polymer flooring system. However, additon of hardwire dramatically strengthens retrofitflooring design capabilities.<br>• combination of polymer flooring with these thin steel belts creates a system with the ability to increase structural capacity, blast resistance and general toughness of concrete<br>• ability to integrate with multiple polymer and cementitious materials | • heavy trafficked warehouses, manufacturing slabs, elevated slabs, slabs on pile construction, and slabs that are structurally deficient from improper design or construction<br>• viable solution where emission and odors are an issue. | | • Structural Preservation System (USA) |
| 10 | **Replacing existing wire system with encapsulated monostrand post tensioning system** | • Parking Garage in New York | • existing structure to be post tensionned system<br>• time and cost effective | | | • Structural Preservation System (USA) |
| 11 | **Epoxy mortar** | • Timber floor in a castle | • can be used to strengthen old timber structures. excellent material to repair wood because it has strong bond to wood and MOE is nearly equal to wood. | • Timber - A large groove was sawed on top side of the beam. Steel r/f has been placed in these groove. Then grooves are filled wth epoxy mortar. | | |

**Table 1:** Matrix of mapping solutions to problems

The matrix for mapping solutions to problems will be validated with three case studies which are the current building refurbishment projects: Council House 1 of Melbourne City Council (CH1) at little Collin Street in Melbourne, Health building at George Street in Brisbane and Sydney Law Court building at Macquarie street in Sydney. Since this is an on-going research, work reported herein discusses the case study of CH1 building in Melbourne.

## 6.0 Case study - CH1 building in Melbourne

This study includes refurbishment of a high-rise commercial building approximately 35 years old. It comprises of seven office levels and four car park levels, of which two of the car park levels are underground. The structure of car park composes of reinforced concrete slab supported on secondary and primary beams and concrete encased steel columns. The office levels have reinforced concrete flat slab supported on concrete encased steel columns. The design team of the building has proposed three preliminary design options to satisfy the client's needs. The research team is currently analyzing those options and developing possibilities to maximize the floor space which could be included in the options proposed by design team. Strengthening of existing structure of the building due to the optimization of floor space is required and those data will be used to validate the matrix of mapping solutions to problems. Mapping of Structural work involved in CH1 building –option 3 with the strengthening techniques is shown in Table 2.

## 7.0 Conclusions

A framework for a decision support tool for selecting a structural strengthening scheme during building refurbishment has been presented. Issues perceived to be important by practitioners and experts in the field have been identified through the Delphi process. A matrix of structural strengthening needs and corresponding solutions have been presented. Mapping of the matrix to a current building refurbishment project has been given.

A major focus of the Re-Life project funded by the CRC for construction innovation is integrating of research in four major areas impacting on decision making in relation to building refurbishment: waste minimization, project management, structural strengthening and floor space optimization and evaluation of residual life. The current focus of the research team is to integrate outcomes of the four areas to develop an integrated decision making model for building refurbishment.

A most important attribute of the integrated model would be its dynamic nature, with provisions for inclusion of innovative strengthening schemes, construction practices etc. as they emerge.

| | Floor levels | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | | C2 | | C3 | | C4 | | L1-L6 | | L7 | | L8 | |
| | Structural work | Strengthening Technique | Structural work | Strengthening Technique | Structural work | Strengthening Technique | Structural work | Strengthening Technique | Structural work | Strengthening Technique | Structural work | Strengthening Technique | Structural work | Strengthening Technique |
| Structural work involve | New Lift (in new extension) | Nil | New Lift (in new extension) | Nil | New Lift (in new extension) | Nil | New Lift (in new extension) | Nil | New Lift (in new extension) | Nil | New Lift (in new extension) | Nil | New Lift (in new extension) | Nil |
| | New Ramp (in new extension) | Nil | New Ramp (in new extension) | Nil | New Ramp (in new extension) | Nil | Opening in existing slab | Hybrid Strengthening system | New extension of slab (Near comm. Bank) | Nil | Relocate the activity spaces | Hybrid Strengthening system | | |
| | | | Opening in existing slab for new stair | Hybrid Strengthening system | Opening in existing slab for new stair | Hybrid Strengthening system | New stair | Hybrid Strengthening system | Opening in existing slab for attrium | Hybrid Strengthening system | Relocate the activity spaces | Hybrid Strengthening system | | |
| | | | Change of use from carpark to shops | Composite Strengthening system | Change of use from carpark to shops | Composite Strengthening system | | | Opening in existing slab for ducts | Hybrid Strengthening system | Opening in existing slab for attriums | Hybrid Strengthening system | | |
| | | | Removed columns | Hybrid Strengthening system | Openings in existing slab for voids | Hybrid Strengthening system | | | Relocate the toilets | Hybrid Strengthening system | | | | |
| | | | | | Removed columns | Hybrid Strengthening system | | | Suspended ceiling replace with open grid system | Nil | | | | |

**Table 2:** Mapping of Structural Strengthening Techniques with the Structural work involved in CH1 building – option 3
C1-C4- four carpark levels, L1-L8-seven office levels and roof level

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