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Architectural Retrofit of Building Structure: Architectural Strategies on the Construction Defect of Mid-Rise Building

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Abstract. Due to unsafe and unstable conditions, construction defects in mid-rise buildings have led to unfeasible occupancy. Building demolition is not a viable solution when architectural retrofit strategies can prevent demolition and reconstruction. These strategies are part of sustainable development, aiming to prolong building lifecycles and lifespans. New advanced materials in construction have facilitated the retrofitting of defective building structures. Carbon Fiber Reinforced Polymer (CFRP) and Ultra High-Performance Concrete (UHPC) serve different primary purposes; however, they work together to strengthen building structures. CFRP is effective for tensile strength, while UHPC is advantageous for compressive strength. This paper explains how architectural retrofit strategies can address building defects resulting from workmanship deficiencies that do not meet structural standards, such as improper moulding, concrete mixtures, and steel joint reinforcement. The research employs experimental techniques on a mid-rise building with structural defects to achieve feasible safety and sustainable development through preservation and improvement. Finally, this research explores new technologies and materials to implement retrofit strategies from an architectural perspective.

Keywords: Retrofit · Structural Defect · CRFP · UHPC

1 Introduction

Architectural retrofit in this research paper refers to sustainability by maximizing the use of a defective building without demolishing it and improving its structure. In early retrofitting, architects collaborate with civil engineers to preserve and enhance the building to meet structural and safety standards. The case study focuses on a seven-story (mid-rise) building in West Java, Indonesia, intended to serve as a new hotel. The main structure, including the foundation, columns, beams, and slabs, was constructed during the COVID-19 pandemic. It was designed by architects and engineered by civil engineers. The construction process was supervised by architects and civil engineers up to the foundation stage, adhering to the construction plan and standards. However, during the lockdown period, the subsequent construction progress from the first to the seventh story was not supervised, leading to workmanship deficiencies and construction defects.

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These defects halted construction progress and caused abandonment for several years (Figs. 1 and 2).

Fig. 1. Documentation of construction defects (left), horizontal assessment sample on slabs and documentation of structural assessment for beams and columns (middle and right).

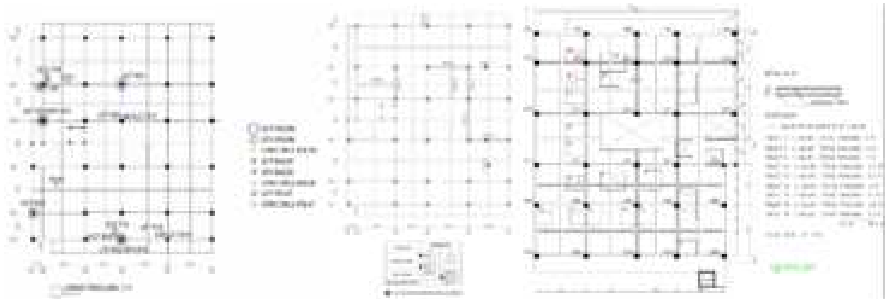

Fig. 2. Mapping Structural Defection of columns (left), beams (middle), slabs (right).

Based on concrete and steel reinforcement quality assessments of columns and beams, the mid-rise building had safety and stability issues. Many structural defects were in columns, including concrete erosion and cold joints. Column and beam eccentricity were not aligned and not perpendicular. Besides, the column and beam needed to be appropriately attached. The column dimensions were wider, from the second to sixth floors, than specified in the drawing plans. The plans showed steel reinforcement using hot-rolled deformed bars; however, mild steel round bars were used instead [1]. The gap distance between stirrup reinforcements for the columns was twice as long as specified in the drawing plans [1].

Moreover, the structural assessments indicated safety and stability issues with the beams in the mid-rise building. The beams exhibited different dimensions and forms, particularly between the second and sixth floors, where the difference in beam thickness ranged from 60 to 150 mm [1]. Beam reinforcement utilized mild steel round bars that did not adhere to the drawing plans; the stirrup reinforcement gaps were longer than specified [1]. Additionally, the condition of the beams showed numerous fractures, exposing their reinforcements. For slab problems, the concrete moulding was contoured, with height variations between 100 and 200 mm [2]. Additionally, the quality of the structural concrete in the columns, beams, slabs, and stairs did not meet SNI 2847:2019 national standards [2].

Table 1. Summary of concrete crushing test in 2023

No	Location	Compression Strength (Mpa)*	Smallest f'c (Mpa)	SNI 2847:2013 Chapter 5.6.5.4 Requirements		
				85% f'c design (Mpa)	75% f'c design (Mpa)	f'c design (Mpa)
1	Column – 1st floor (axis C/6)	38,09	13,07	21,17	18,68	25
2	Column – 2nd floor (axis E/3)	30,08				
3	Slab – 4th floor (axis 5–6/B-C)	19,46				
4	Column – 4th floor (axis F/3)	29,37				
5	Column – 5th floor (axis E/4)	25,46				
6	Beam – 2nd floor (axis 3–4/A)	29,07				
7	Beam – 3rd floor (axis 5–6/D)	19,13				
8	Beam – 3rd floor (axis 3–4/C)	42,52				
9	Beam – 4th floor (axis 3–4/D-E)	13,07				
10	Beam – 5th floor (axis 4–5/C)	21,54				
11	Beam – 5th floor (axis 5/B-C)	20,66				

(*continued*)

Table 1. (*continued*)

No	Location	Compression Strength (Mpa)*	Smallest f'c (Mpa)	SNI 2847:2013 Chapter 5.6.5.4 Requirements		
				85% f'c design (Mpa)	75% f'c design (Mpa)	f'c design (Mpa)
12	Beam – 7th floor (axis 3–4/A)	29,43				
13	Slab – 3rd floor (axis 4–5/B-C)	34,53				
14	Slab – 6th floor (axis 2–3/A-C)	24,85				
	Average	26,95				

Columns and beams in a mid-rise building's primary functions are supporting vertical forces from dead and live loads and lateral forces from wind, earthquake, and others. Thus, columns and beams need compression and tensile strength simultaneously. Standard materials like concrete reinforcement have coincident roles in a mid-rise structure's rigidity, durability, and strength. These structural defects reduced a mid-rise building's rigidity and durability, especially compression strength. From Table 1, some columns, beams, and slabs did not meet national standards for compression strength, with the smallest of 13,07 Mpa. The crushing test used the solid concrete area, not deteriorated concrete; thus, the compression strengths on the deteriorated area must be lower.

Retrofitting architecture is a sustainable method to enhance building performance by repairing its structure without demolition. The scope of this research is limited to addressing issues related to compression strength in columns and beams by utilizing new materials, such as Carbon Fiber Reinforced Polymer (CFRP) and Ultra-High Performance Concrete (UHPC). Researchers aimed to prevent structural defects and demolition by strengthening the main structure of the mid-rise building. These structural defects have opened up possibilities for utilizing new technologies and materials, such as CFRP and UHPC, to increase the compression strength of a mid-rise building.

2 Methodology

Four main mistakes during predecessor construction processes affected structural performance related to standard materials like concrete and steel reinforcement. These four main mistakes affected the structural performance of a mid-rise building, ultimately decreasing compression strength, as follows:

1. The concrete mixture was not evenly mixed, and the formwork was not evenly filled, which impacted the rigidity and durability of structural elements (deteriorated concrete in beams and columns) and decreased compression strength.

2. The joinery between columns and beams was without proper detachments or cold joints, which weakened shear forces and rigidity.
3. The dimensions of columns and beams were too wide, and their eccentricities were unaligned, which caused heavier structural dead loads and not straight vertical and lateral forces.
4. Steel reinforcement used different steel bars, and transverse reinforcements were not tied enough.

This research used the experimental method directly applied to the defective structural building that focuses on four main problems by enhancing column compression strengths, beam compression strength, column-beam joinery, and beam-slab joinery. Defects building data consists of mapping of structural defects on drawings and compression strength evaluation [3]. Based on structural defects mapping and evaluation, research continued to analyze the most efficient retrofitting methods and mark off on drawings. After drawings, the application for retrofitting methods for this mid-rise building uses Carbon Fiber Reinforced Polymer (CFRP) and Ultra-High Performance Concrete (UHPC):

1. Strengthening columns use grouting, UHPC to fix concrete problems, wrapping, and CFRP to fix weak ties for transverse reinforcements and smaller steel bars.
2. Strengthening beams utilise injecting methods using UHPC and stripping using CFRP.
3. Column-beam joinery uses column shoe methods with UHPC.
4. Beam-slab joinery using chemical anchor with UHPC and steel anchor.

At the end of this experimental method, researchers evaluate the methods by measuring compressive strengths using samples for concrete crushing tests. After the UHPC and CRFP applications, the evaluation aims to measure the compression strength alterations (Fig. 3).

Fig. 3. Retrofitting Methods for structural defects of a mid-rise building

1

3 New Advanced Materials for Retrofit Architecture: Carbon Fiber Reinforced Polymer (CFRP) and Ultra-High Performance Concrete (UHPC)

Retrofit architecture prolongs the building lifecycle and promotes sustainable development goals. It involves planimetric and volumetric changes and the exclusion of deteriorated building elements [4]. Meanwhile, retrofit actions have proven to provide significant environmental benefits and enhance building energy and environmental performance through a lifecycle approach [4]. Preserving the architectural appearance is one of the many advantages of retrofit architecture, as it avoids architectural obstruction and reduces the need for new materials by strengthening existing elements [5].

The use of advanced materials plays a prominent role in retrofit architecture. In the early stages, building design reconstruction requires existing and structural drawings to determine retrofit strategies [3]. Meanwhile, the condition of the building reveals several damages, both structural and material, that necessitate a material and structural assessment [3]. Conducting a structural assessment for existing buildings is essential for developing retrofitting strategies. Structural components must be evaluated, including assessments of material quality and reinforcement [3]. Also, load and force analysis aims to understand building durability and stability's tensile and compressive strength [3]. Only one structural defect can lead to building failure; thus, addressing structural defects requires several phases for strengthening and improvement, including [3]:

1. Unloading is placing supports for parts of the building at risk of collapse.
2. Substrate treatment involves dismantling loose materials from columns, beams, and slabs, cleaning the restoration area, and injecting epoxy into cracks.
3. Column strengthening can use the jacketing technique to enhance stiffness and stability.
4. Beam strengthening utilises binding and wrapping with Carbon Fiber Reinforced Polymers (CFRP).

CRFP has the benefit of augmenting tensile strength for building structures. Using CFRP in buildings has increased compressive strength, preventing cracking and premature shear failure [6]. Combining CFRP with steel wire mesh or wire rope restraints has enhanced the elements' compressive strength and ductility [6]. CFRP comprises polymer matrices, such as thermoplastic or thermosetting materials [7]. The advantages of these materials include being lightweight, having high impact resistance, and being easily moulded into different concrete shapes [7]. CFRP materials for reinforced concrete have a significant effect on increasing load-carrying capacity and stiffness [8]. Thus, CFRP performs well when wrapped around the two lateral sides and soffit of structural elements [8].

On the other hand, UHPC has the benefit of intensifying compressive strength. Structural defect concrete reinforcement in field experiments utilizes UHPC (Ultra High Performance Concrete) and UHPFRC (Ultra-high-performance fibre-reinforced concrete).
3
UHPC is a composite material that provides compressive strength and rehabilitation for existing concrete structures [9]. UHPC increases the strength of fractured and defective concrete reinforcements [10]. It has successfully improved deteriorated and fractured

beams [10]. Furthermore, UHPC effectively strengthens fractured and rotten concrete structures [10]. Additionally, adding steel wire mesh along with UHPC layers has reinforced beam structures [9]. The rough surface (S-R) technique ensures joint strength and increases stiffness in existing structural buildings [10]. UHPC layers enhance the strength of reinforced beams [10, 11]. They also reduce the compressive impact caused by fractures, resulting in higher durability under compression [11]. During experiments on concrete fractures, the application of UHPC has strengthened reinforced concrete [11]. Ultra-high-performance fibre-reinforced concrete (UHPFRC) is widely used for beams and plates, as it can reduce fracture effects and increase column stiffness [12]. UHPFRC has successfully decreased fracture effects and enhanced column stiffness [12].

4 Result and Discussion

4.1 Retrofitting a Mid-Rise Building: Columns and Beams

Retrofitting columns and beams face similar problems for deteriorated concrete, weak ties of transverse reinforcements, unaligned eccentricity, and thicker concrete cover. Deteriorated concrete on columns and beams has lessened compression strength, rigidity, and durability. Preserving hard concrete and dismantling porous or deteriorated concrete were beneficial to minimise construction waste [13] and reduce energy needs [14]. The first step is removing deteriorated concrete in columns and cutting letter U fractures in beams. The practical technique is grouting Ultra-High Performance Concrete (UHPC) on the remaining parts of hard concrete in columns, injecting UHPC in beams, and utilising UHPC rather than standard concrete due to the project's need to recover structural defects. UHPC are composite materials to strengthen concrete fractures and structures by adding compressive strength [8, 9]. Meanwhile, standard concrete used for existing structures faced durability and compression problems (Fig. 4).

Fig. 4. Retrofit Applications using UHPC for columns and beams.

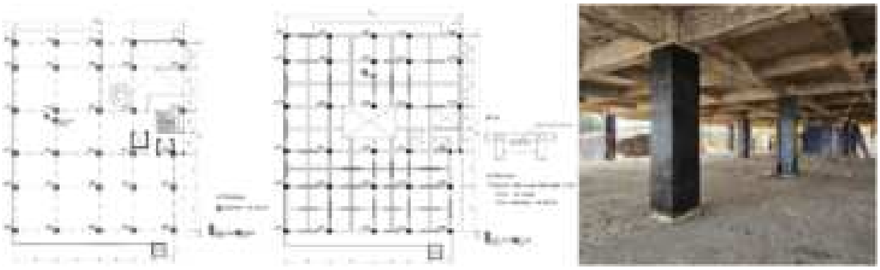

Fig. 5. Retrofit Applications using CRFP for columns and beams

Furthermore, weak ties and substandard transverse reinforcement have weakened columns' compression strength and beams' shear strength. While choosing retrofitting methods for beams and columns, researchers consider two challenges: dead loads from unplanned thicker concrete cover and their unaligned eccentricity. Due to those challenges, retrofitting columns and beams should be light but have ductility. Jacketing and wrapping techniques are two techniques to fix weak ties and substandard transverse reinforcements. The jacketing technique is transverse reinforcement outside columns and beams. It enhances stiffness and stability in columns [4] and shear strength in beams. Unfortunately, using jacketing techniques adds too much dead load from massive steel loads.

The wrapping technique utilises Carbon Fiber Reinforced Polymers (CFRP) made of lightweight materials. CFRP enhances tensile strength for building structures by preventing cracking and shear failure, as well as increases compressive strength by adding load-carrying capacity and stiffness [6]–[8]. In this case, CRFP wrapping is the most effective technique after UHPC grouting and injection to amplify ties of transverse reinforcement rather than the jacketing technique. CRFP techniques for this case are wrapping around columns and stripping along beams. Before doing this, the architect team prepared drawings for wrapping column locations and stripping beam locations (see Fig. 5).

4.2 Retrofitting a Mid-Rise Building: Joinery Columns – Beams and Beams – Slabs

Retrofitting joinery strategies aim to improve cold joints in columns-beams and non-proper detachment beams-slabs. Incorrect casting method caused cold joints that reduced durability, were prone to shear or tensile forces, and lessened load capacity – compression strength. Accordingly, column shoes manage column-beams joinery on every storey of the building. Column shoe technique uses Ultra-High Performance Concrete (UHPC) on each based column for binding purposes. On the side, a method enhances beam stiffness from lateral forces by binding slabs with beams. The existing condition showed no ties between slabs and beams. The most effective technique to enhance beam-slab stiffness is the chemical anchor. Chemical anchors use UHPC to tie up, and steel is for anchors. Thus, beams–slabs use drilling techniques to inject UHPC and insert anchors (Figs. 6 and 7).

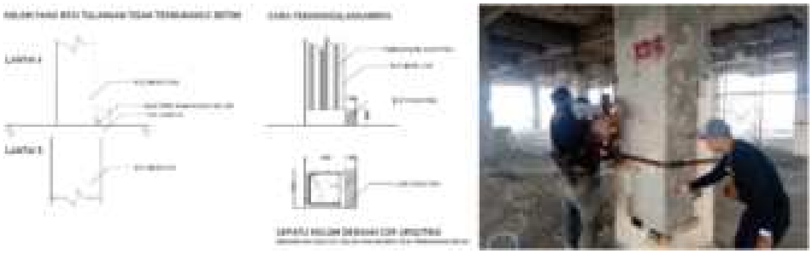

Fig. 6. Retrofit Strategies of Construction Defect of Mid-Rise Building using UHPC for columns shoes and CFRP for wrapping columns.

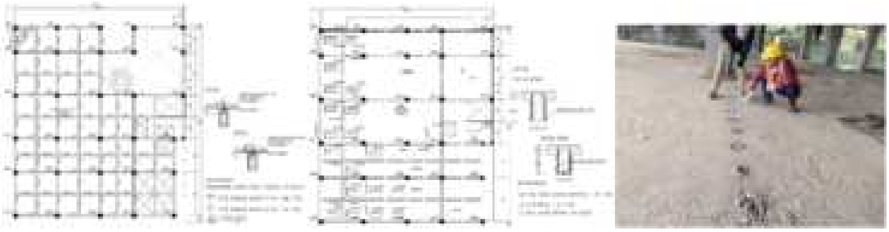

Fig. 7. Retrofit Strategies of Construction Defect of Mid-Rise Building using UHPC for beam-slab injections and CFRP for wrapping the bottom side of beams.

4.3 Compression Stress Evaluation After Applying UHPC and CRFP

After retrofitting columns, beams, and joinery, Ultra-High Performance Concrete

Table 2. Compression test after retrofitting

No	Information	Sample Test (Cm)	Weight (Gr)	Load (Kn)	Compression Strength	
					Kg/Cm^2	Mpa
1	After grouting with UHPC	15	12.300	700	484,44	47,70
2	After grouting with UHPC and wrapping with CFRP	15	12.400	1.020	708,82	69,51

(UHPC) and Carbon Fiber Reinforced Polymer (CFRP) have successfully escalated the compression strength of columns and beams. Columns and beams in a mid-rise structure get lateral and vertical forces that need compression and ductility strength to achieve building durability, rigidity, and strength. The evaluation of retrofit architecture has shown that UHPC intensifies compression strength to 47,70 Mpa. Although CFRP is effective for tensile strength, it has jacked up compression strength to 69,51 Mpa (Table 2).

5 Conclusion

Retrofitting defects in a building can be successful while comprehending the structural problems and choosing the right retrofitting strategies, including technique and material selections. The retrofit strategies of a mid-rise building have minimised construction waste and building demolition by selecting and preserving suitable existing structural materials. Dismantling deteriorated concrete gave space for Ultra-High Performance Concrete (UHPC) replacement—some techniques to apply UHPC on existing structures, such as grouting and injecting. UHPC increases compressive strength and is advantageous for addressing fractures in beams, slabs, and columns.

Furthermore, using Carbon Fiber Reinforced Polymer (CFRP) is the most effective and efficient way to solve cold joints, substandard steel bars, and lack of ties for transverse reinforcements. These structural problems negatively impacted the building by weakening compression and shear/ lateral strengths. CFRP's lightweight and high ductility is beneficial, adding compression strength for columns and beams. Ultra High-Performance Concrete (UHPC) and Carbon Fiber Reinforced Polymer (CFRP) in a seventh-story building strengthen and stiffen the building structure. Finally, the mid-rise building does not require demolition and reconstruction; retrofit architecture has helped sustain the building's life cycle.

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