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Structural Behavior of Reinforced Concrete Beams Retrofitted with Carbon-Efficient Retrofitting Method

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Abstract

In this study, a novel retrofitting method are presented to enhance both the structural capacity and construction efficiency for reinforced concrete beams while reducing the use of heavy retrofitting materials and equipment, ultimately contributing to carbon emission reduction. The proposed retrofitting method involves the use of prefabricated components, quickly assembled on-site using bolts and chemical anchors. The structural tests were conducted on three concrete beams, comparing those non-retrofitted specimens. The proposed retrofitting method increased both the maximum load capacity and ductility of reinforced concrete beams. The maximum load capacity of the test specimens retrofitted with the proposed modularized steel plats was found to increased by up to four times compared to un-retrofitted beam. The flexural performance increased by about 1.17 times, depending on the presence of vertical grid. The ductility capacity increased by about 2.5 times.

Keywords: concrete beams, retrofitting method, carbon efficient, steel plate, module, bolt connection

1 Introduction

Structural retrofitting becomes necessary when design codes are revised or when there's a change in load requirements. The common methods employed for retrofitting include steel jacketing and fiber-reinforced polymer (FRP) jacketing. Steel jacketing involves attaching steel angles or plates through welding and filling the gaps with cement mortar or epoxy. Several studies have evaluated its effectiveness, with some showing an increase in load capacity and ductility. Tarabia and Albakry (2014) conducted axially loaded test on ten column specimens. Size of steel angles, strip spacing, and grout material were considered as parameters. They reported that most of the specimens were failed due to buckling of the steel angle by crushing of the columns. Alvarez et al. (2018) presented the nonlinear analysis procedures for concrete columns retrofitted with steel jackets. Backbone curves were constructed of circular and rectangular retrofitted columns to evaluate the response of jacketing columns. Chrysanidis and Tegos (2020) proposed new type of hybrid jackets composed of metal grid jacket and high strength mortar. It has been proven that the proposed systems can improve strength and ductility than conventional method.

In this paper, a modularized retrofitting method was proposed to overcome the limitation of traditional jacketing retrofitting method. Instead of using heavy steel tubes or jackets that typically require equipment for material movement and installation, the proposed approach utilizes modularized steel plates, including L and Z-shaped steel plates, which reduces the overall weight of retrofitting materials. This weight reduction allows for equipment-free material movement and installation, contributing to carbon emission reduction attributed to equipment use. Also, this method offers the potential for carbon emission reduction through the avoidance of additional production, corrections, and extensions in construction timelines caused by manufacturing errors in retrofitting materials. A total of three retrofitted concrete beams and one control beam specimen were fabricated and tested to evaluate that the proposed retrofitting details were capable of improving the load carrying capacity and ductility.

2 The Retrofitting Methods

The proposed retrofitting system is designed to significantly improve structural performance and streamline the assembly process through modularization. This approach introduces retrofitting components comprising Z-shaped side plates, L-shaped lower plates, and bottom plates, and base plates integrated with verticals grid as illustrated in Figure 1 (a). In the retrofitting process for concrete beams, two L-shaped lower plates are securely attached to the underside of the beam using chemical anchors, ensuring precise alignment for the subsequent installation of Z-shaped side plates.

with vertical grid as shown in Figure 1 (a). Two L-shaped lower plates are fixed to the bottom of the concrete beam using chemical anchors. L-shaped lower plates help easy and accurate installation of the Z-shaped side plates. The Z-shaped side plate is connected to the L-shaped lower plate using bolts and then bonded to the side of the concrete beam using the chemical anchors. The vertical grid is inserted into the Z-shaped side plate and combined using bolts. The space formed under the concrete beam is filled with mortar. The details of concrete beam retrofitted with modularized steel plates are shown in Figure 1 (b). By assembling L-shaped lower and Z-shaped side plates with bolts, the depth of the parts being extended can be adjusted, and it is easy to design and construct regardless of the size of the members. In addition, grid is installed vertically to resist tensile stress, so no subsequent process is required to install additional flexural reinforcement on the site.

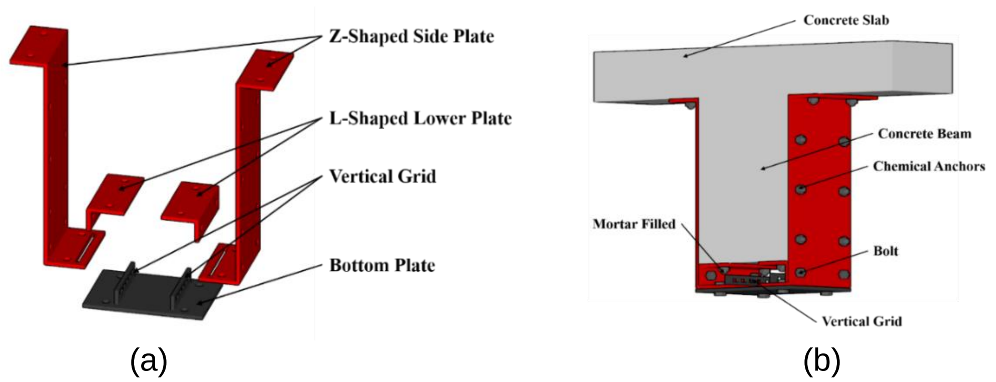
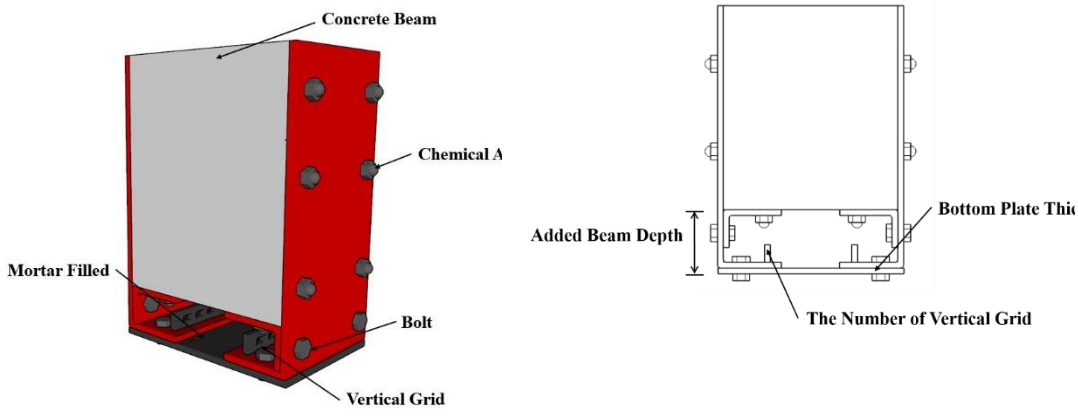


Figure 1: Proposed retrofitting system: (a) The components of proposed retrofitting system; (b) The retrofitted concrete beams.

3 Experimental Program

In this paper, the total of five specimens were manufactured, including one reinforced concrete beam and four reinforced concrete beams retrofitted with the modularized steel plates. The finite element analysis to optimize the dimensions of each component was performed assuming the real in-situ situations that beams are supporting the slabs. In this study, the slab (flange) parts in T-shaped section only provide the spaces to fix the steel plates by using chemical bolts. Therefore, flanges were not considered when the specimens were manufactured as shown Figure 2. Figure 3 shows the details of the specimens. The concrete beams of all specimens were designed to be 300 mm wide, 350 mm high and 4,500 mm long. The thickness of Z-shaped side plate was 2.5 mm, the thickness of the L-shaped lower plates was 5mm, and the spacing of chemical anchors and bolts was 300mm, using the same in zigzag format. The depth of the new beam was 100 mm, the thicknesses of the bottom plate was 10 mm. The number of vertical grids considered as experimental variables, which are expected to affect the flexural behavior and bonding effect. The number of vertical grids were 0, 2, and 4. For the specimen with two vertical grids, the spacing of each grid was 200 mm, and for the specimen with four vertical grids, each grid was installed at spacing of 65 mm. The specimen illustration is organized in Table 1, and the details of the specimen, according to each variable, are shown in Figure 2. The 28-day compressive strength of the concrete used in this experiment was 24 MPa. For the tensile and compressive reinforcement, deformed rebar was used with a diameter of 19mm and its yield strength is 400MPa. Steel plate was used with a yield strength of 275 MPa. The high-strength bolts which is F10T M16 bolts with a diameter of 16 mm was used to connect the concrete beams. The material properties are summarized in Table 2.



(a) (b)

Figure 2: The test parameters: (a) The fabrication of proposed retrofitting system in the experiment; (b) test parameters.

Table 1: The test specimen parameters.

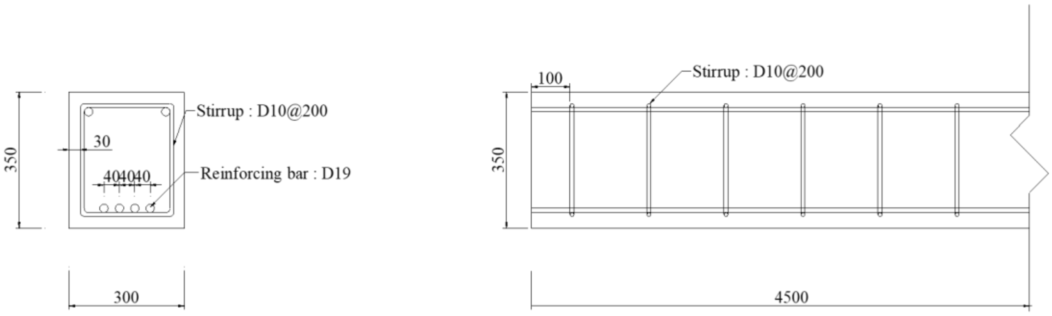
No.	Name	Added beam depth (mm)	Bottom plate thickness (mm)	Vertical grid (EA)
1	RC	-	-	-
2	D100-2	100	10	2
3	D100-4	100	10	4
4	D100-0	100	10	-

[1] D: additional depth

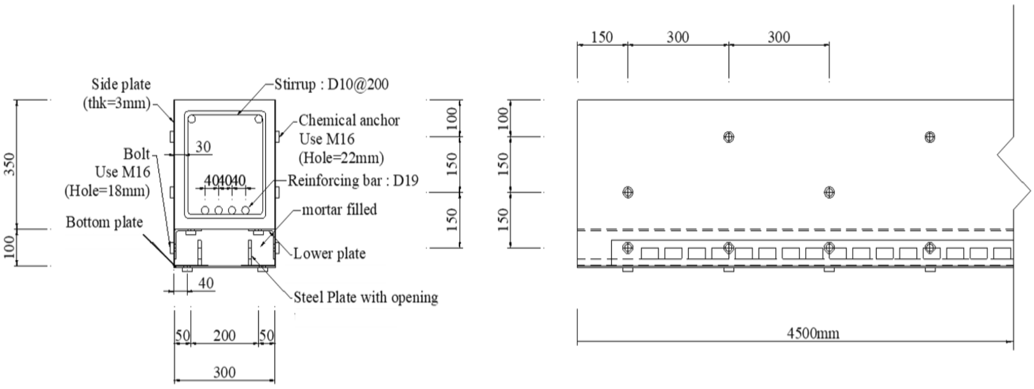
[2]2 : The number of vertical grid (2 : 2EA, 4 : 4EA, 0 : 0EA).

Table 2: Material properties.

Material	Compressive strength (MPa)		
Concrete	24		
Material	**Diameter (mm)**	**Yield strength (MPa)**	**Modulus of elasticity (MPa)**
Rebar	19	400	200,000
Stirrup	10	400	200,000
Material	**Yield strength (MPa)**	**Tensile strength (MPa)**	**Modulus of elasticity (MPa)**
Steel plate	275	410-550	205,000



(a)



(b)

Figure 3: Specimen details: (a) RC; (b) D100-2.

(a) D100-0

(b) D100-2

(c) D100-4

Figure 4: Crack propagation

4 Test Results and Discussion

1.1 Cracking Behavior and Modes of Failure

Figure 4 shows the crack pattern at maximum load for each specimen tested. As the number of vertical grids increased, the crushing and spalling of compression zone was more localized. The loading was terminated when the load was reduced 80% after the maximum load was reached. All the specimens showed flexural behavior as shown in Figure 4, cracks started appearing in the compression zone. As the load increased, the cracks of compression zone became wider, some spalling was observed on the mortar grouted on the bottom plate. The spalling of the mortar was observed differently according to the vertical grid. More spalling occurred in the D100-0 specimen without the vertical grid. Finally, as the concrete crushing and spalling increased, the load gradually decreased. Local buckling of the Z-shape side plates and bolt fracture were not observed in all retrofitted specimens. It is concluded that sliding was not observed at the end of the beam because the steel plates and concrete were perfectly bonded.

4.2 Load-Deflection Relationship

The Load-displacement curve is shown in Figure 5. Specimens retrofitted with modularized steel plates showed greater stiffness and maximum load than RC specimen. Retrofitted specimens showed similar initial stiffness. Remarkable differences were not observed in terms with the number of vertical grid between D100-2 and D100-4. The maximum load for D100-2 was 602 kN and that for D100-4 was 598 kN, but the maximum load for D100-0 was 514 kN, which was increased by approximately 1.17 times depending on the presence of vertical grid. This is to achieve the restraining effect of reinforcing parts on the mortar injected into reinforcing areas, and the flexural strength due to reinforcement is improved depending on whether or not it is installed.

The test results are summarized in Table 3. The nominal flexural strength P_n is calculated from plastic stress distribution method suggested by AISC 360-10 (2010). The yield load P_y defines a point as the yield load where a line parallel to the line connecting the origin to the maximum load meets the load-displacement curve as shown in Figure 5. The proposed retrofitting method have shown a increase in the strength. The experimental resulted in an average increase of 3.2 times the maximum load and an average increase of 1.3 times the maximum displacement.

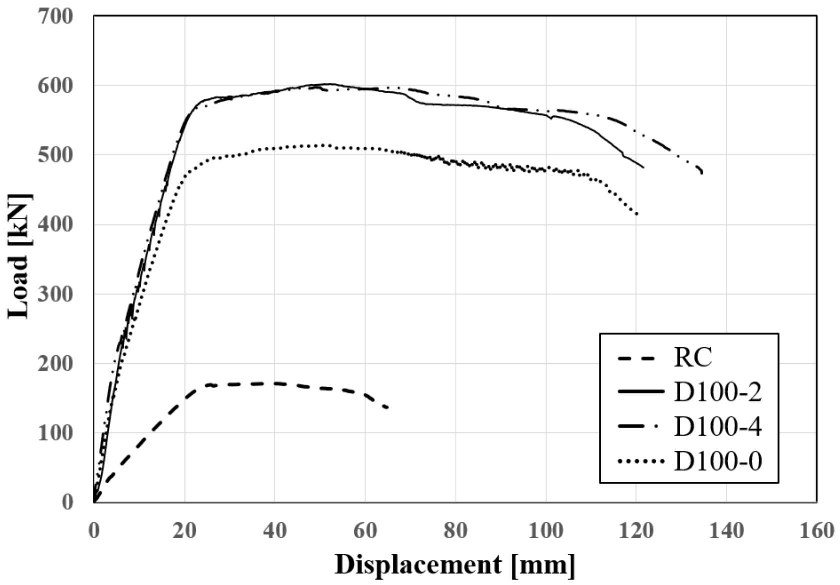


Figure 5: The load-deflection curve test results.

Table 3: Flexural test results.

No.	Name	P_n [1] (kN)	$P_{y,test}$ [2] (kN)	$P_{u,test}$ [3] (kN)	P_u $/P_n$	P_u $/P_y$	δ_y [4] (mm)	δ_u [5] (mm)
1	RC	138.06	137.55	171.65	1.24	1.08	18.09	38.72
2	D100-2	583.23	466.03	602.62	1.03	1.08	16.27	52.21
3	D100-4	585.03	423.40	597.55	1.02	1.07	13.90	49.25
4	D100-0	556.73	382.13	514.00	0.92	1.10	14.61	50.86

[1]P_n: The nominal force calculated by the nominal flexural strength applied to the beam.
[2]$P_{y,test}$: The yield load of each specimen.
[3]$P_{u,test}$: The maximum load of each specimen.
[4]δ_y: The displacement when the yield load applied.
[5]δ_u: The displacement when the maximum load applied.

4.3 Ductility Capacity

The ductility of flexural members, such as beams, can be calculated by the ratio of the maximum displacement and yield displacement after the maximum load is generated, without a sudden reduction of the load when the load is reduced to 70–80%. In this study, the ductility was calculated by dividing the displacement $\delta_{0.8Pu}$ when the maximum load was reduced to 80% of the maximum load after the maximum load was applied by the displacement δ_y when the yield load was applied. The ductility capacities of each specimen are summarized, as shown in Table 4. The ductility capacity of specimens retrofitted steel plates was shown to be at least 7.47 and up to 10.01, averaging 8.85. Compared to the RC specimen, the ductility capacity is about 2.5 times higher. The comparison of specimens according to the number of vertical grids resulted in improved ductility as the number of vertical grids increased to 7.47 for D100-4, 9.67 for D100-2, and 8.26 for the D100-B0 specimen. However, due to the thickness of the bottom plate and the presence or absence of vertical grid, excessive reinforcement on the tensile zone is considered to be possible due to the crushing of concrete. The ductility capability can be improved by the application of modularized steel plates.

Table 4. Analysis of the ductility capacity for each specimen.

No.	Name	$\delta_{0.8Pu}$ [1]	δ_y [2]	$\delta_{0.8Pu}/\delta_y$ [3]
1	RC	64.78	18.09	3.58
2	D100-0	134.88	13.48	10.01
3	D100-2	121.52	16.27	7.47
4	D100-4	134.43	13.90	9.67

[1]$\delta_{0.8Pu}$: The displacement when the maximum load reduced to 80%.
[2]δ_y: The displacement when the yield load applied
[3]$\delta_{0.8Pu}/\delta_y$: The ductility capacity of each specimen.

5 Conclusion

The purpose of this study is to propose and examine a modularized steel plate retrofitting method resulting in improved structural performance and constructability. The flexural test was conducted to evaluate the structural performance of concrete beams retrofitted with the proposed method. The main conclusions obtained from the study are as follows:

The maximum load capacity of the test specimens retrofitted with the proposed modularized steel plates was found to increase by up to four times compared to un-retrofitted beam. The number of vertical grid did not significantly affect stiffness, the increase in that number improved the ductility. In addition, the flexural performance increased by about 1.17 times, depending on the presence of vertical grid. The vertical grid attached to the bottom plate increased the confinement effect of the mortar and reduced spalling by acting as a flexural reinforcement.

The ductility was compared and analyzed. Compared to non-retrofitted reinforced concrete beams, the ductility capacity increased by about 2.5 times. This confirms that the application of the proposed retrofitting method can improve the structural performance of existing concrete members.

The experiment in this paper focused on the evaluation of flexural capacity of retrofitted concrete beams. Further experimental research is needed on shear behavior of concrete beam retrofitted with modularized steel plates. Also, a finite element model that can predict structural capacity is required for design stage.

Acknowledgements

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