Numerical Study on Behavior of Hollow Core Slabs Strengthened by CFRP Plates subjected to Monotonic and Repeated Loads

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Abstract

This paper presents the findings of a numerical study of thick hollow core slabs. Near-surface mounted and external bounded techniques were used to strengthen the slabs under repeated loading and monotonic loading. Two series included 20 specimens; the first series had four validation experimental results slabs. The second series had sixteen strengthened slabs, where eleven slabs was modeled under monotonic loading and nine other slabs were modeled under repeated loading. The main parameters are the different effects (length, thickness, strength method) of CFRP used in tension reign and the effect of load type in the slabs. The numerical results showed that the external CFRP bounded effect's load values are less than the NSM-CFRP thickness effect. And the effect of length in slabs with external bounded of CFRP under monotonic load gave the best behavior in ultimate loads compared to slabs under repeated load. The thick slabs with hollow core that tested under repeated load had turned from flexural failure mode to shear-flexure failure mode

Keywords: hollow core, thick slabs, NSM-CFRP, EB-CFRP repeated load, monotonic load, CFRP plates
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1. Introduction

Reinforced concrete slabs are the most popular structural elements and have become one of the most significant construction elements employed in many different types of engineering structures. In any building panel, the slab element may offer lower support as in (floor) or upper construction as in (roof). Slabs are created in many ways, such as pre-cast or compounded with a wide range of structural systems such as solid, waffle voided, ribbed, and hollow. In concrete structures, hollow core prefabricated members are commonly used for the floors and roofs. These systems are inexpensive and simple to set up [**Stanton, J.F., 1992] [1]**. [**Bison 2007] [2]** The main advantages of the slabs with hollow cores system. It reduces the dead load of building, cost, time, and extremely long spans. [**Hoogenboom P.C.J. 2005][3], [Chung J.H. et. al 2010][4], and [Mahdi A.S. 2011] [5]** presented a numerical study in behavior of hollow core concrete slabs with different ways. **[Neale, K.W. et. al 2011] [6]** presented nonlinear finite element modeling of reinforced concrete elements that have been externally reinforced using fiber reinforced polymers (FRPs). This study also proved that reliable numerical models are incredibly useful tools for getting insight into processes that are very hard to assess experimentally. [**Daud, R. et. al 2015][7]** studied the nonlinear behavior of an adhesive layer connecting carbon fiber reinforced polymer (CFRP) to reinforced concrete one-way slabs. The FE model accounted for the nonlinearity of the concrete with cyclic loading by calculating the stiffness degradation in the concrete for both compression and tension effects. The proposed three-dimensional finite element model presents a more realistic model for capturing the interface slip profile of composite sheets with the concrete slab under various cyclic loading stages. [**Kankeri, P. et. al 2018] [8]** studied the behavior of hollow-core slabs reinforced by FRP. This study explored several strengthening techniques, CFRP thickness, and CFRP length. These investigations should help us better understand how numerically NSM FRP strengthening systems connect under repeated loading conditions and identify the overall behavior and failure modes.

2. Numerical Program of Slabs

2.1Details of slabs

All slabs are of (1200mm) length, (600mm) width and, (200mm) thickness.**Figures 1** and **2** show the actual dimensions with slab shape and loading information.

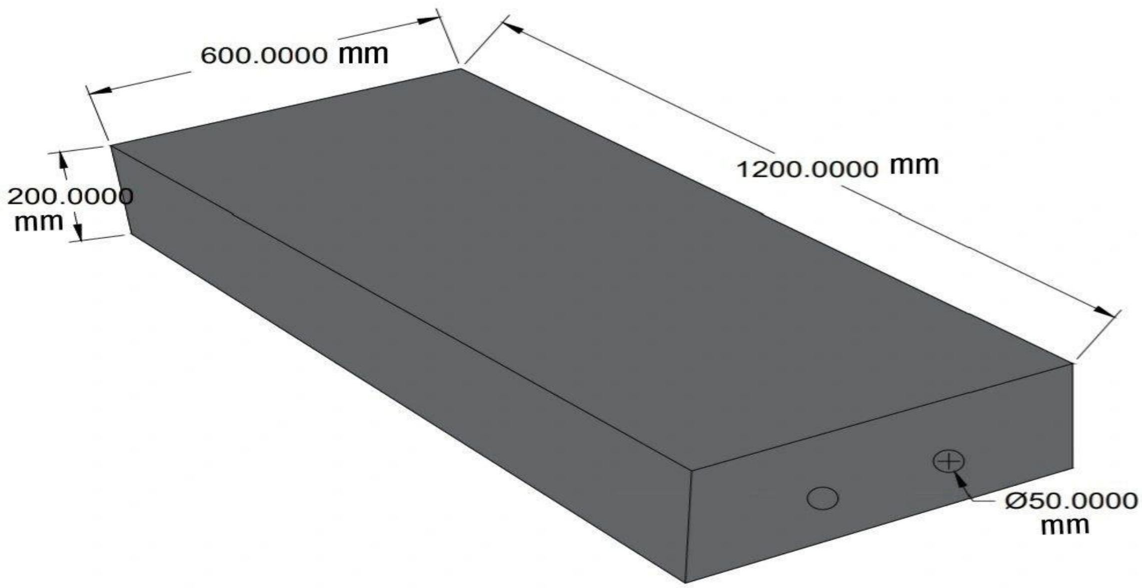
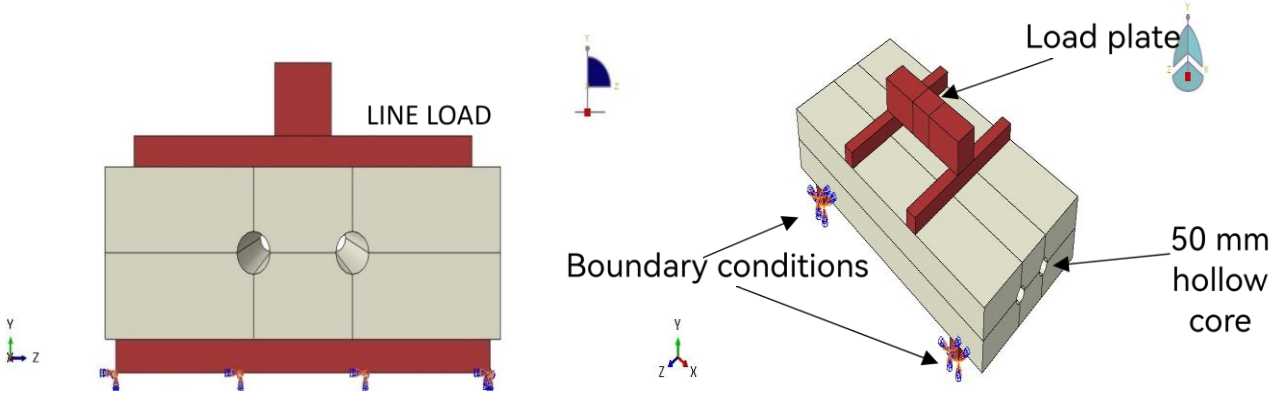


Figure 1: Slab Geometry



(a) Front view of hollow core slab **(b) Details of hollow core slab**

Figure 2: Details of Two Lines Loading

2.2 Loads

The two lines loading was applied as an equal pressure on the top surface of a load plate across a concrete contact width. A modified load technique specified by **FEMA461 [9]** was used to model the cyclic load. In the repeated loading protocol, the first stage of the low fatigue cycle used ten cycles of 10% of deformation amplitude in the monotonic load. This would be followed by three more amplitude cycles until complete failure. In the monotonic loading is applied as pressure on the top surface of a concrete. General static technique was used to represent the applied repeated loading

2.3 Model of numerical simulation

The model was presented using the general numerical program package ABAQUS. The isoperimetric eight-node brick element (C3D8R) was used to model concrete. Every node may move in three dimensions in the x, y, and z axes. While the three-dimensional two-node bar element with three-dimensional motions, truss element (T3D2) was chosen to represent reinforced steel rebars, the three-dimensional four-node with lower integration and hourglass control (S4R5) was chosen to represent CFRP plates. For each slab, a two-line load was applied as uniform pressure at the top of the slab in the same area and position of the experimental test.Displacement boundary conditions were employed to model the model's end supports in order to accurately simulate an analytical model that has been similar to the tested slabs. These boundary conditions had to be applied at the locations where the experiment's test specimens were supported. The specimens were simply supported along the two shorter edges, so all of the nodes along one of the supporting lines were fixed in the y and z directions, and all of the nodes along the other supported line were fixed in the x, y, and z directions as shown in **Figure 3**.

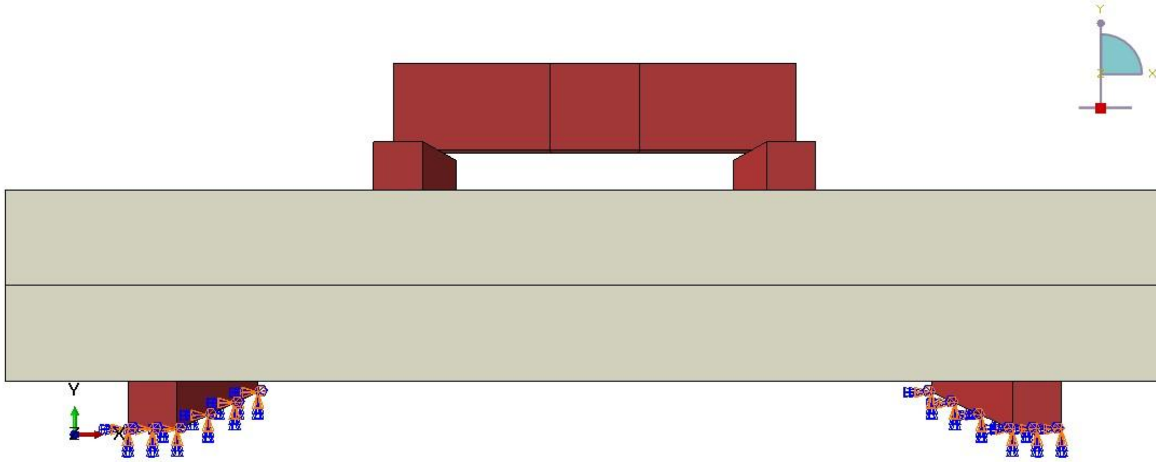


Figure 3: Shows An Isometric View of Applied Loads and Supports' Boundary Conditions.

3. Modeling Validation Experimental Results

3.1Monotonic loading section

The validation of the present numerical modeling program has been completed by concrete slab as a control slab reinforced with steel bars from author experimental studies **[10]**. The numerical data values of ultimate load and displacement are compared to the experimental results for the control slab under monotonic loading. The numerical results are close to the experimental results.**Figure 4** presents a comparison of load-deflection curves produced from numerical simulation results and the experimental analysis, showing high agreement between both sets of data over the entire loading range.At a deflection of 12.16 mm, the ultimate experimental load was 363 kN. However, a deflection of 12 mm, the ultimate numerical load was 362.2 kN. This indicates that the failure load in the numerical simulation is 0.2 percent more than the experimental load.

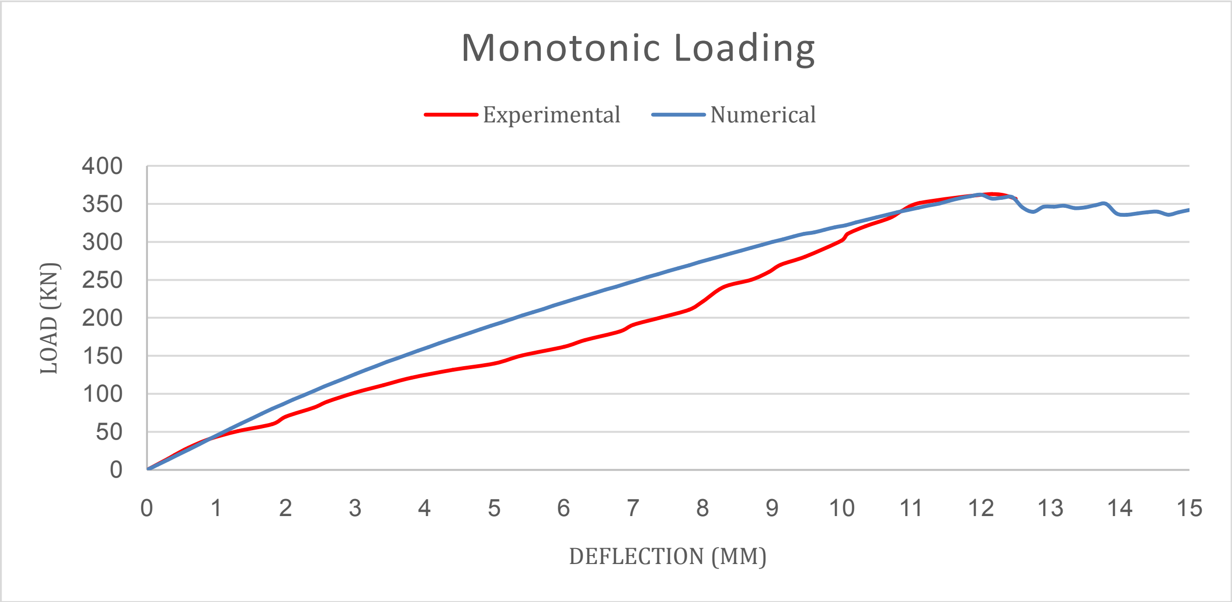
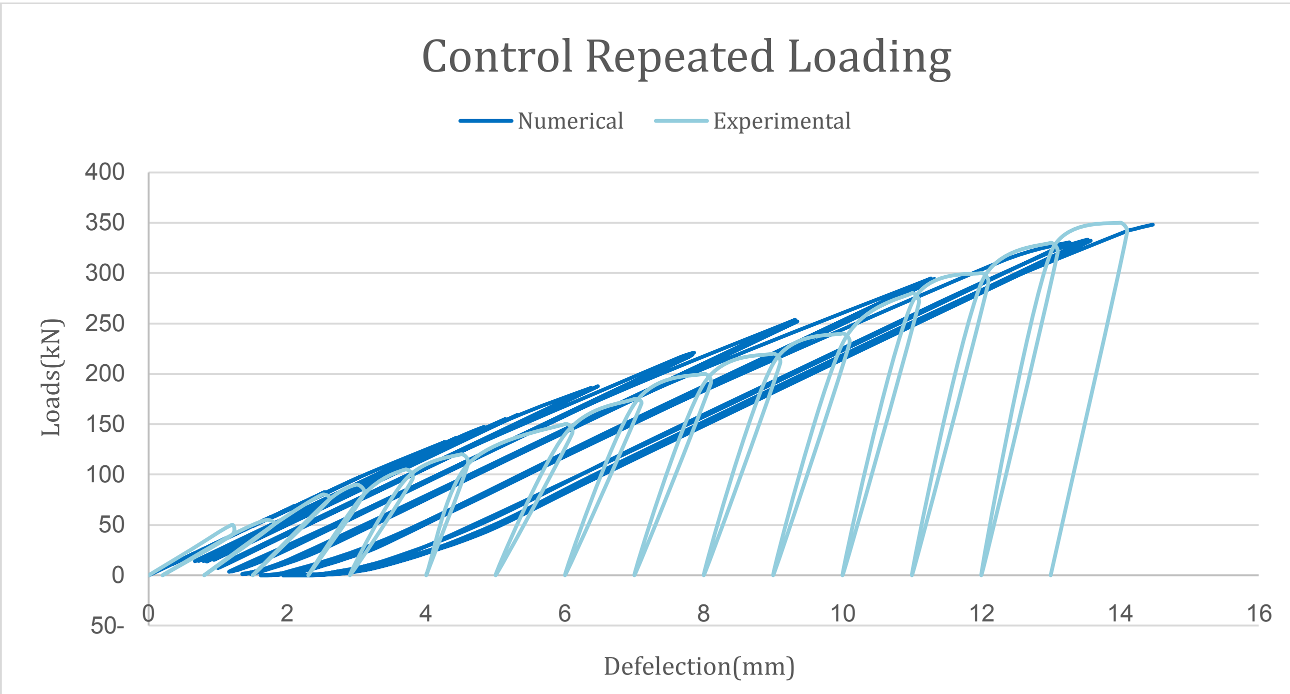


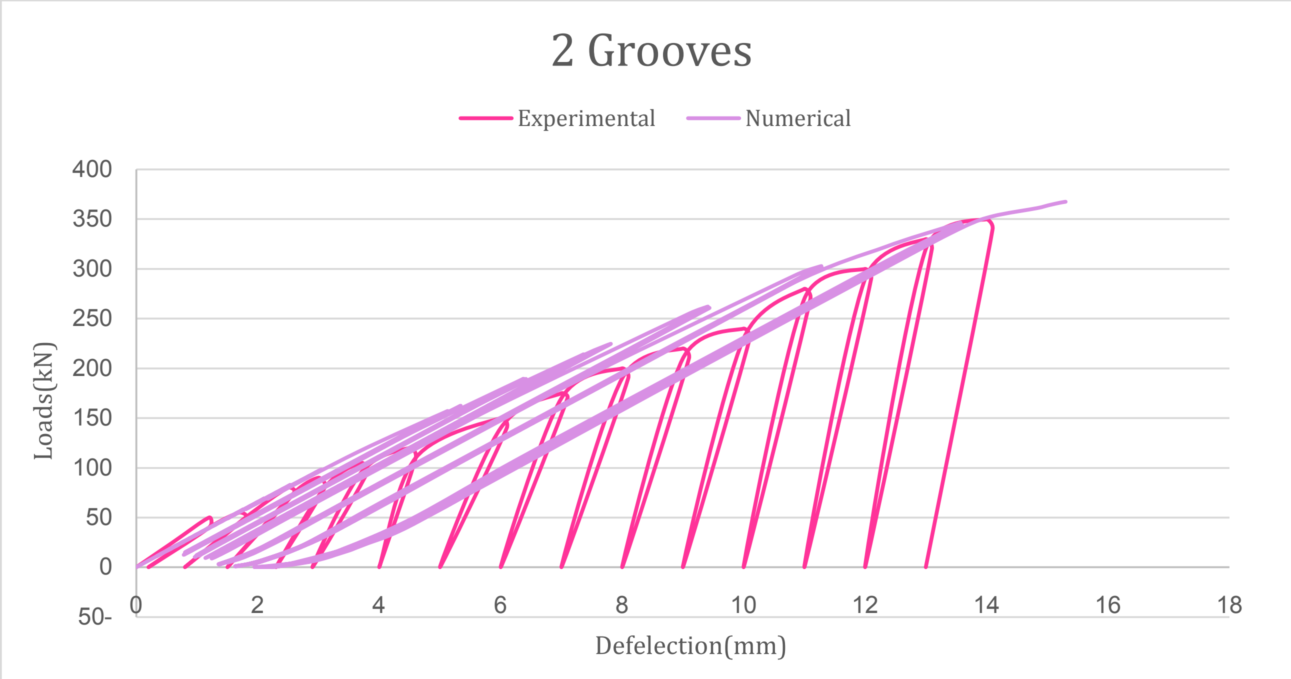
Figure 4:**Comparison of Experimental Load-Deflection Curves and Numerical for RC One-Way Hollow Core Slab under Monotonic Loading**

3.2 Repeated loading section

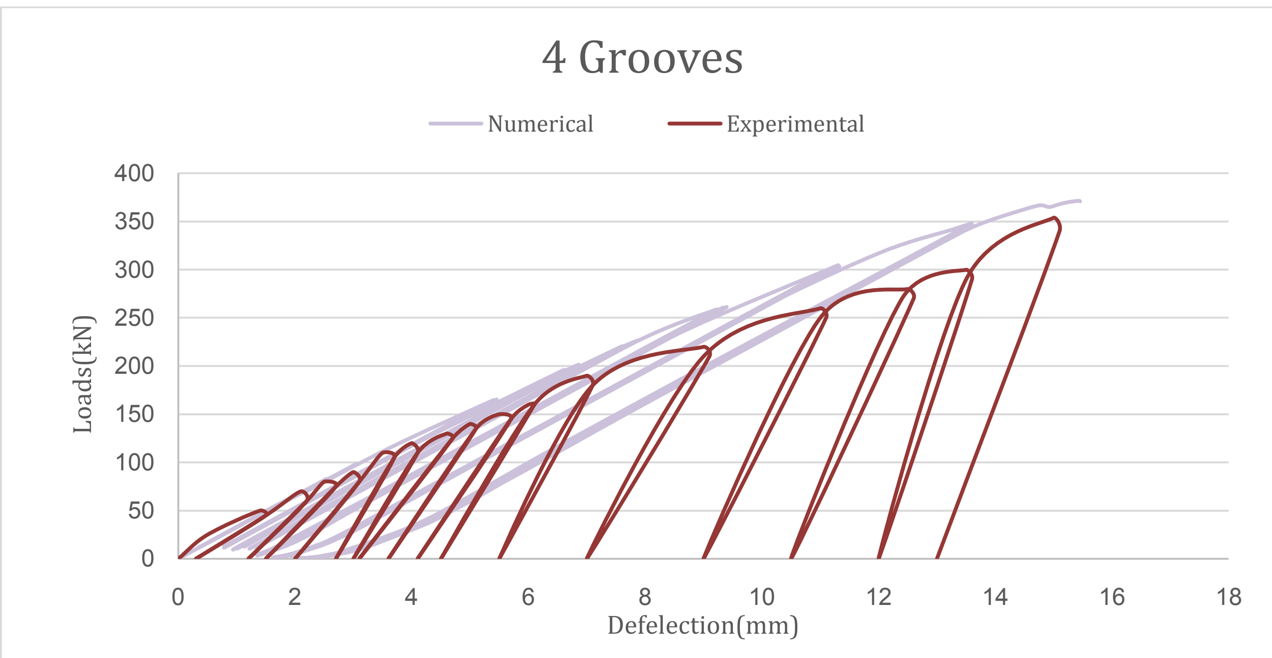
The load deflection behaviors of the RC slab subjected to cyclic loads are for both experimental and numerical outcome significantly similar as shown in **Figure 5**. As can be seen, the results of numerical model show slightly higher load than the experimental load which is acceptable, since the numerical analysis is considered as energy lower bound theorem. This reduces the magnitude of calculated strain and as result yields higher stress values. Furthermore, there is no visible degradation in the numerical load deflection curve. This is due to the fact that the interfacial bond stress and fracture energy for the cyclic case are limiting for the specific load protocol chosen.



(i) Slab 2



(i) Slab 3



(ii) Slab 4

Figure 5:The Load Deflection Behaviors of RC Slab between Experimental and Numerical

3.3 Crack patterns

Figure 6 shows the cracks and failure mode along the hollow-core slabs with a constant core diameter (50 mm) for slab1 for numerical and experimental purposes. The ABAQUS computer application shows different colors in model where concrete elements are crushing or cracking. The failure mode was flexural failure for experimental and numerical simulations which are the same failure under monotonic load.

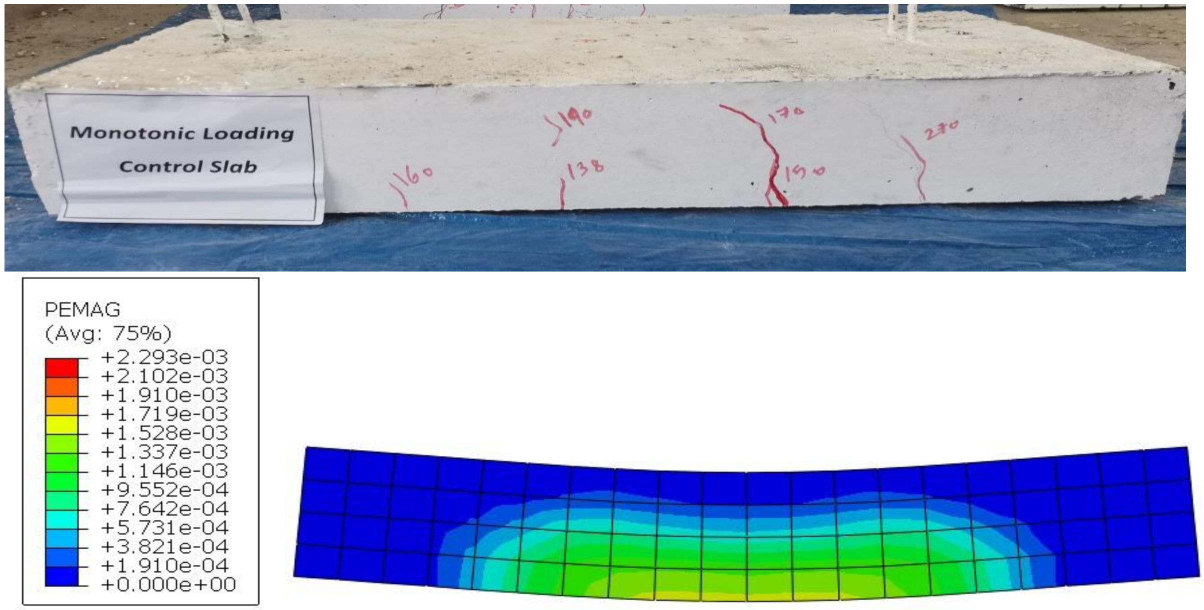


Figure 6: Experimental andNumerical Cracking Pattern of Slab1

The failure mode was a shear-flexure failure for specimens subjected to repeated load with NSM CFRP plates strengthened and without NSM CFRP plates (control) in both the experimental and numerical simulations. **Figure 7** represents the experimental crack pattern and numerical for Slabs 2 under repeated load with small different in failure load. For extra loading, cracks continued to expand, and significant interfacial cracks began to form near to the loaded region. When compared to the slab under monotonic loading with slabs under repeated loading, the ultimate load in slab 1 monotonic response is much larger than the ultimate load in the fatigue response (i.e. Slab 2 & Slab 3). This is because the influence of repeated load cycles on the stiffness of the slabs is smaller than the effect of increased CFRP.

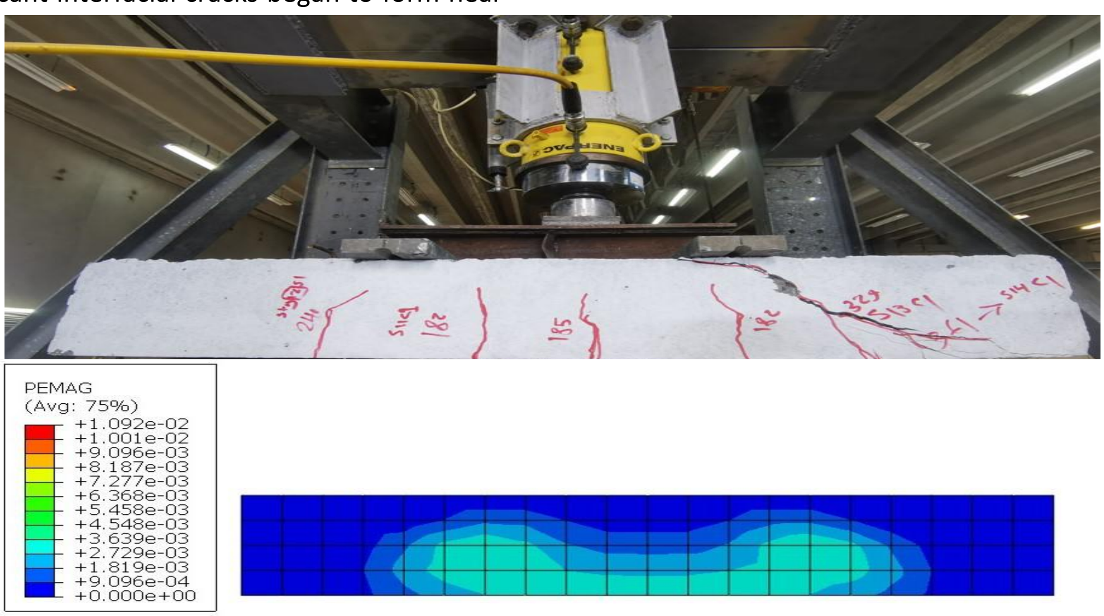


Figure 7: Experimental andNumerical Cracking Pattern for Slabs 2

4. Parametric study

The following studies have investigated the parameters the behavior of hollow-core reinforced concrete slabs:

4.1 Monotonic loading section

4.1.1 CFRP length effect

This section aimed to provide light on the effect of CFRP length by four slabs includes two slabs with 2 grooves of NSM-CFRP (length =800 mm and length=600 mm), and two slabs with 4 grooves of NSM-CFRP (length =750 mm and length =500 mm). When comparing CFRP plates for 2 grooves with a length of 600mm (load= 349.9 kN) and length of 800mm (load= 369.3 kN). The best behavior is whenever the length increases, the ultimate load increases. Also, CFRP plates for 4 grooves with a length of 500mm (load= 352.4 kN) and length of 750mm (load= 366.9 kN) had the same behavior with 2 grooves CFRP. **Figure 8** shows the load-length curves of CFRP length effect. **Table 1** shows the load and length for slabs were tested under monotonic loading.

Table 1: load and length for slabs under monotonic load

Slab type	Grooves	CFRP length(mm)\thickness\external	Load (kN)	Deflection (mm)
CFRP length effect	2 grooves	600	349.9	11.8
		800	369.3	11.7
	4 grooves	500	352.4	11.7
		750	366.9	11.2

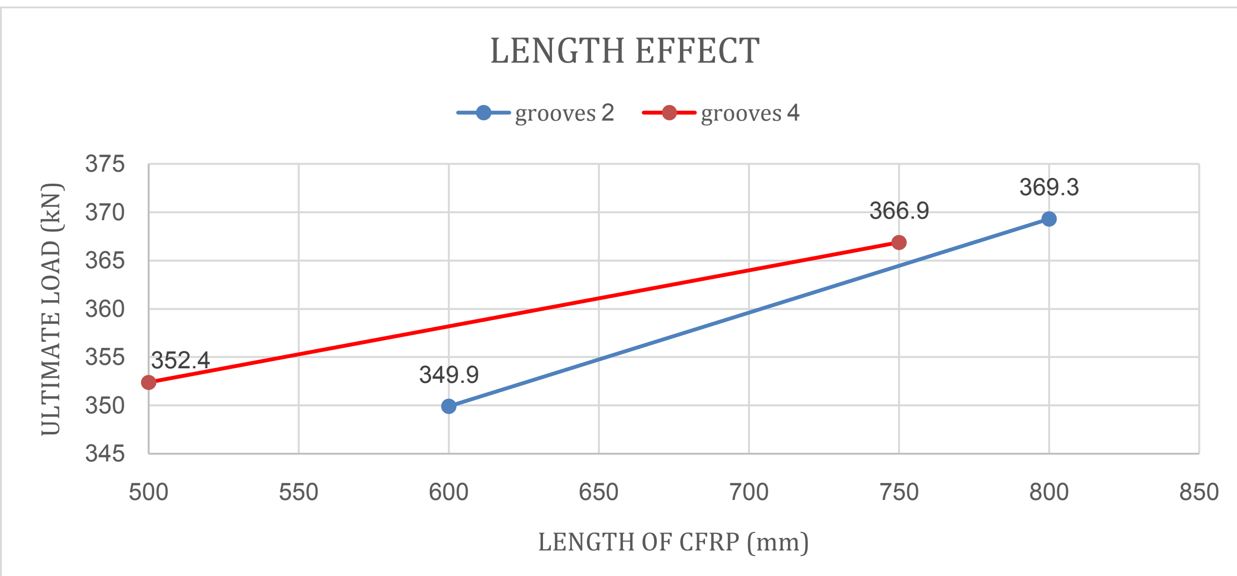


Figure 8: Load- length curves of CFRP

4.1.2 CFRP thickness effect

This section aimed to provide light on the effect of CFRP thickness by four slabs includes two slabs with 2 grooves of NSM-CFRP (thickness =2.4 mm and thickness =3.6 mm) and two slabs with 4 grooves of NSM-CFRP (same thickness of 2 grooves) with constant length is 1000mm. When comparing CFRP plates for 2 grooves with a thickness of 2.4 mm (load= 380.8 kN) and thickness of 3.6 mm (load= 391.6 kN). The best behavior is whenever the thickness increases, the ultimate load increases. Also, CFRP plates for 4 grooves with a thickness of 2.4 mm (load= 422.5 kN) and thickness of 3.6 mm (load= 366.9 kN) had the same behavior with 2 grooves CFRP. But when comparing 2 grooves with 4 grooves we can see significant improvements for 4 grooves. See **Figure 9** shows the load-thickness curves of CFRP thickness effect.**Table 2** shows the load and thickness for slabs were tested under monotonic loading.

Table 2: load and thickness for slabs under monotonic load

Slab type	Grooves	CFRP length\thickness(mm)\external	Load (kN)	Deflection (mm)
CFRP thickness effect	2 grooves	2.4	380.8	13.8
		3.6	391.6	13.9
	4 grooves	2.4	405.6	14.2
		3.6	422.5	14.1

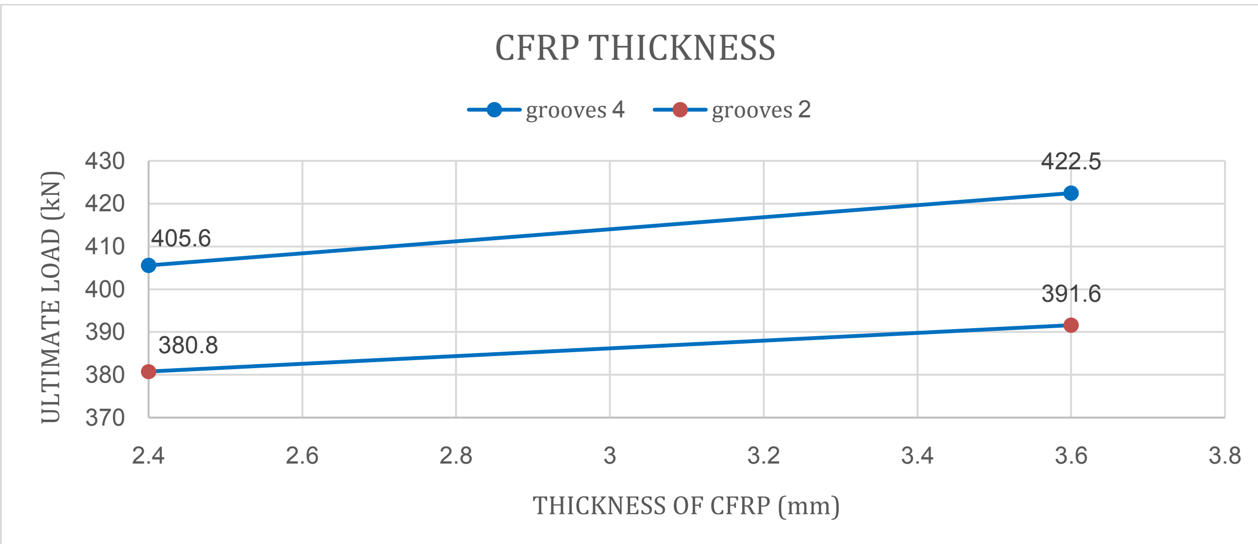


Figure 9: Load- thickness curves of CFRP

4.1.3 CFRP external bounded effect

This section aimed to find the best behavior of externally bounded technique (EB) with the same type of plates in NSM-CFRP plates. The dimension of CFRP used is length =1000 mm, width =400 mm, and thickness = 1.2 mm. The 2 CFRP plates had been used instead of 2 grooves and 4 CFRP plates had been used instead of 4 grooves. **Table 3** shows the EB-CFRP result on slabs with a hollow core. As a result, the ultimate load of 2 plates is 380 kN with 12.6 mm deflection, while the ultimate load of 4 plates is 406.4 kNwith 12.4 mm deflection. That indicates whenever the area of CFRP plats increases, the ultimate load increases.

Table 3: load and external effect for slabs under monotonic load

Slab type	Grooves	CFRP length\thickness\external	Load (kN)	Deflection (mm)
CFRP external bounded effect	-	2 EB-CFRP plates	372.7	15.4
	-	4 EB-CFRP plates	385	15.6

4.2 Repeated loading section

4.2.1 CFRP thickness effect

The effect of CFRP thickness by four slabs includes two slabs with 2 grooves of NSM-CFRP and two slabs with 4 grooves of NSM-CFRP with the same thickness of monotonic loading. The results presented that the thickness of CFRP plates has a positive effect on the ultimate load in slabs. The slab with 2 grooves gave 376 kN and 389 kN for 2.4 mm and 3.6 mm, respectively. At the same time, the 4 grooves gave 395 kN and 411 kN for 2.4 and 3.6, respectively. Both slabs tested under repeated load (fatigue load). **Figure 10** shows the details of load thickness. The slabs were tested under repeated loading, shown in **Table 4**.

Table 4: load and thickness effect for slabs under repeated load

Slab type	Grooves	CFRP thickness\external	Load (kN)	Deflection (mm)
CFRP thickness effect	2 grooves	2.4	376	16.7
		3.6	389	17.3
	4 grooves	2.4	395	17.1
		3.6	404.5	17.4

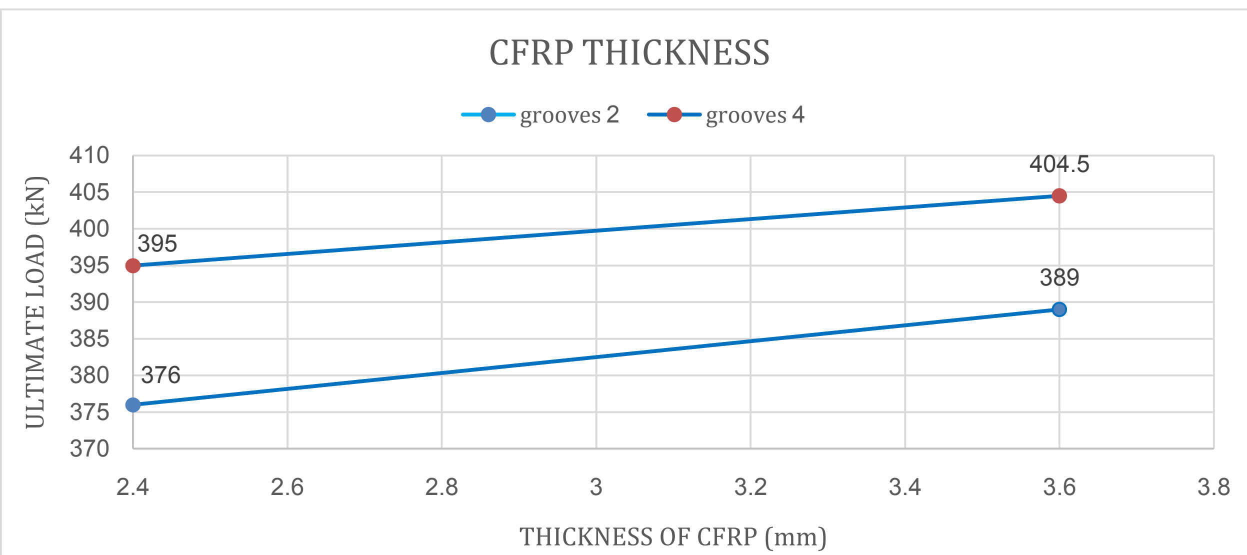


Figure 10: Load- thickness curves of CFRP

4.2.2 CFRP external bounded effect

The employed CFRP plate area is (1000, 40, and 1.2) mm for both slabs instead of 2 and 4 grooves. The purpose is to investigate the best behavior of EB-CFRP under repeated loading. See **Table 5;** the result showed the EB-CFRP with 4 plates (380 kN) gave the best behavior. If we compare slabs strengthen with EB-CFRP plats under monotonic load and repeated load, the monotonic gave a higher ultimate load than repeated because of loading and unloading system in repeated load protocol weakens the slabs. But slabs under repeated take more time in comparison with the monotonic load. The slabs were tested under repeated loading and monotonic load with comparison of CFRP external bounded effect (2 plates and 4 plates), shown in **Figure 11**.

Table 5: load and external effect for slabs under repeated load

Slab type	Grooves	CFRP length\thickness\external	Load (kN)	Deflection (mm)
CFRP external bounded effect	-	2 EB-CFRP plates	366	14.8
	-	4 EB-CFRP plates	380	14.8

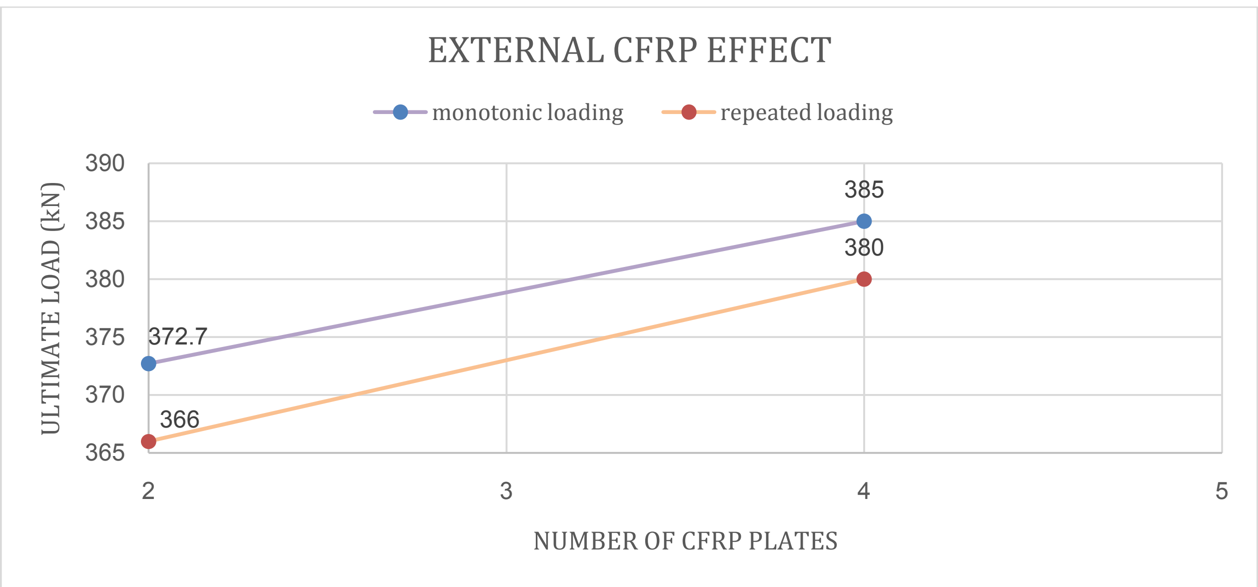


Figure 11: Load- Number of CFRP plates curves

Conclusion

- Comparison of load-deflection curves produced from numerical simulation results and the experimental analysis, showing high agreement between both sets of data over the entire loading range.
- In the validation of control monotonic slab and control repeated slab, the failure load in the numerical simulation is 0.2 and 0.01 percent respectively more than the experimental load. The failure modes for experimental and numerical simulation are the same.
- In the validation of strengthen monotonic slab and strengthen repeated slab, the failure load in the numerical simulation is 0.02 and 0.03 percent respectively more than the experimental load. The failure modes for experimental and numerical simulation are the same.
- The external CFRP bounded effect's load values are less compared to NSM-CFRP thickness effect.
- As can be seen, the effect of CFRP thickness for slabs under monotonic loading gave the best behavior of ultimate load than slabs under repeated loading.
- Comparison of external bounded of CFRP under monotonic loading with external bounded of CFRP under repeated loading, the slabs under monotonic gave a higher ultimate load than repeated.

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