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Understanding Impact Resistance of Hollow Core Slabs Using FRP Retrofitting. A Comparative Analysis of GFRP And CFRP

Mina Maxi [1*], Rana Essam[1], Mariam Ehab[1]
[1] Civil Engineering Department, The British University in Egypt

[*]E-mail: Mina Maxi, mina.maxi@bue.edu.eg

Abstract. Sudden Impact of structural events poses a significant threat to life safety and structural stability. In other words, the local failure(s) of structures can lead to the collapse of other members and eventually a partial or total collapse. Impact load is one of the extreme loads that are not usually taken into design consideration because of its high cost to be prevented unless the usage of the building dictates this extra care. Hollow core slabs, while offering advantages in terms of weight and construction efficiency, are particularly vulnerable to localized damage in comparison with other slab systems to localized damage, which could lead to progressive collapse. This research investigates the effectiveness of Fiber Reinforced Polymer (FRP)retrofitting techniques in enhancing the impact of resistance of hollow core slabs, aiming to mitigate progressive collapse risks and improve structure resilience. In this paper, the significance of FRP retrofitting techniques and properties for different types have been discussed and compared, focusing on Glass Fiber-Reinforced Polymer (GFRP) and carbon Fiber-Reinforced Polymer (CFRP). By evaluating various case studies, experimental analyses, and numerical simulations, the effectiveness, durability, and performance of FRP retrofitting strategies are examined as well to show the most suitable material for resisting impact load. The findings of this study will provide valuable guidance for engineers and designers in selecting the most suitable FRP material for retrofitting hollow core slabs, enhancing structural integrity and safety against impact loading. Furthermore, this research identifies research gaps and potential areas for further investigation, contributing to the development of a more effective and resilient research orientation for enhanced structure systems.

1. Introduction

Nowadays, the safety of constructions and their inhibitors is becoming a focus of research [1]. The construction industry tends to retrofit existing structures to sustain new types of loading such as seismic or other severe loads to make it safer for the residents. Retrofitting is strengthening existing structural elements to improve their performance under new load applications such as impact load using new construction technology, features, and components. Not only does retrofitting make the existing industry safer but it also increases sustainability levels in terms of carbon production, reduces carbon footprint, and preservation of cultural heritage.
Extreme loading situations are very common, such as impact loads (e.g. Rock falling), which happen at high velocity and transmit an enormous amount of energy into the structure, leading to

severe local deformations and structural damage. The impact condition may take place in combinations of tension, compression, torsion, bending, or any one of these. Slabs are the most fragile element to withstand point peak load in comparison to columns or beams because their axial stiffness is less than the aforementioned elements. Hollow core slabs (HCS) are light in weight which makes the dead weight of the construction lighter and the seismic response of the structure in general better because it will minimize the amplitude of the motion. Thus, serves better and is used in covering larger spans as well, however, the main contribution of (HCS) is the fast track in construction and the early finish in comparison with the regular slabs.
However, the response of the (HCS) is not very promising regarding impact. Its response is not the same as that of regular reinforced concrete or prestressed concrete. The structural damage in such systems is very hard to retrofit or mend, thus it is very important to reinforce it to be more resilient before the impact occurrence. It was shown that the vibration of the concrete topping and the void is an independent action. The weak spots of the (HCS) were defined as: thin flange, and thin web. Most research pointed out that enhancing the (HCS) will be very beneficial in terms of monetary value and structural rigidity since it will combine two major pros: the lightweight which will make it preferable for use in longer spans (especially bridges) and the resilience to withstand large loading occurrences.
The gap of this research lies in the little we know regarding the retrofitting of (HCS) and their response regarding extreme loads since its is very light in weight and are capable of withstanding gravity loads but weak in the response of peak point dynamic load, the practical gap plays an important role as the (HCS) are not very common to be used and even be used to resist such loads.

The main aim of this paper is to review the past literature to give the latest state-of-the-art brief on how to enhance (HCS) using GFRP and CFRP with strengthening forms (sheets, strips bars, etc.), type of testing (Simulation or Experimental) in a brief Table as in following sections to guide the next research to which application is best for a certain scenario..

2. Methodology

The methodology used in this research is a combination of quantitative and qualitative analysis. Where the previous research was carefully gathered, filtered, and sorted out to be categorized into main aspects to show the relevance between Hollow core slabs, GFRP, or any other FRP-based materials. The research approach used was deductive where previous theories were gathered and reorganized and were compared with each other to confirm the similar outputs to be used as guidelines for future projects or designers to aid them in their relevant project. Scopus-indexed papers and conferences were only the main source of our literature with a mixture of journal papers and case studies. A comparative analysis was conducted between the outputs of these papers to show the effect of different FRP materials usage on (HCS) under impact loading specifically and extreme loads in general such as seismic loads, blasts, etc. The flow of our methodology is shown in Figure 1.

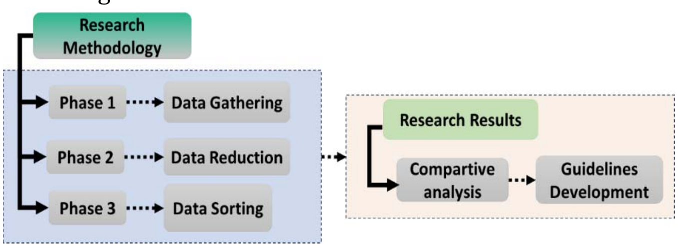

Figure 1 Research methodology flow chart

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3. Literature Review

Different techniques of enhancing (HCS) against extreme activity is shown in Figure 2. A summarization of the previous literature conducted in our research is shown in the following Figure 3. Where three main attributes were our focus (Hollow Core Slabs, FRP & and Extreme Loading events). By focusing on the ratification of CFRP, & GFRP on the (HCS) under impact loading. Summarized guidelines were developed as shown in the following section on the preferred material and dimensions to be used to reinforce (HCS) to sustain extreme loads in general and impact loads in specific

3.1 Hollow Core Slabs (HSC)

Hollow core slabs have numerous benefits. Their low weight makes handling and installation easier and substantially lessens the overall strain on the structure. Because of their remarkable spanning ability and lightweight, they can cover large spans without the need for extra support beams, which simplifies the construction process and allows for more design options.

According to Mahboob et.al. [2] because of their hollow cores, which maximize load-carrying capacity while using less concrete, their design makes economical use of material. Because of its strength and lightweight, this is an affordable and environmentally friendly choice. These slabs also perform exceptionally well in terms of fire resistance

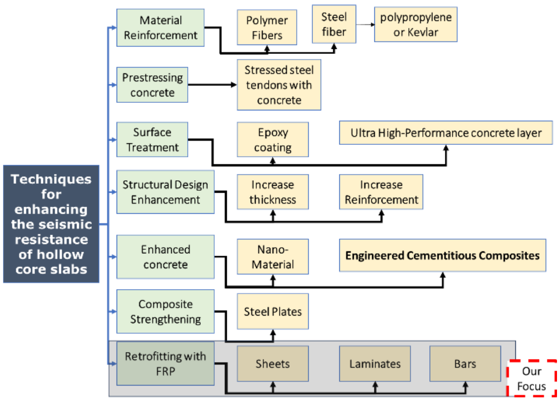

Figure 2 Techniques to enhance (HCS) against Seismic activity

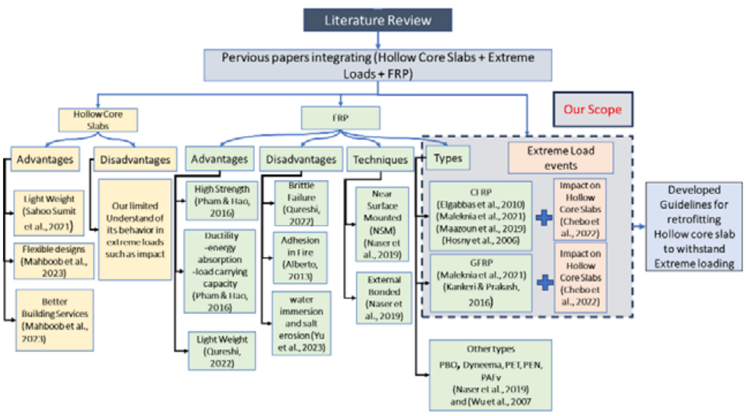

Figure 3 Literature Review Map

(HCS) are prefabricated off-site, which greatly shortens construction timeframes. In addition to guaranteeing accuracy and consistency in production, this reduces disturbance on-site. In addition to their inherent advantages, HCS) provides exceptional flexibility in design. The hollow cores enable smooth integration of necessary Building services, such as plumbing and electricity, enabling customization and flexibility to meet various requirements.
Their precast nature and adaptable design help to facilitate quicker, more efficient, and ultimately more environmentally friendly building methods. However, it was not studied carefully under extreme loading conditions such as seismic loading, impact or blast loading, etc.

3.2 Hollow Core Slabs Under Impact Load without enhancmenet

Chebo et al. [3] experimentally studied (HCS) with consecutive impact loading at three distinct locations (center of the slab, edge, and corner). To investigate the behavior of a single-span (HCS)

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under impact, impact loading is represented as a 0.6 ton iron ball dropped from a height of 1400 cm. The behavior of a single-span (HCS) under sequential impact loads at multiple locations was examined in this study. The results showed that the hollow core units had irreversible damage, and the narrow web, thin flanges, and voids were the points of weakness. It was observed that following flange fracture, there was no strand participation in load resistance. The study underlined the significance of code restrictions for flange and web thickness, suggested solutions such as shear connectors, and stressed the effect that location has on the slab system's capacity. Using filler materials, such as foam, to absorb energy and lessen brittle fractures in thin flanges was one of the recommendations as well as using FRP enhancements.

3.3 Fiber Reinforced Polymer (FRP)
In general, FRP materials are made of continuous, high-strength fibers embedded (the reinforcing component) in a polymer matrix, such as resin. The polymer matrix serves as a binder to protect the fibers and make it easier to transfer loads to and between them. Naser et.al. [4] narrowed down the types of FRP that are traditional (FRP): carbon fiber (CFRP), glass fiber (GFRP), aramid fiber (AFRP), basalt fiber (BFRP), and certain recently created composites polyethylene naphthalate (PEN) and polyethylene terephthalate (PET). Each type has its characteristics, usage, and weakness points. The most known CFRP and GFRP will be discussed in detail in the latter sections

3.3.1 Advantages of (FRP)
FRP has great material option for the construction-enhancing sector since it requires less maintenance and its useful material characteristics. It possesses a low ratio between volume and weight and an increasing strength relative to its weight as well. Moreover, the impact resistance of reinforced concrete buildings, such as slabs, can be increased by using FRP materials. They lead to improved ductility, energy absorption, and load-carrying capacity. Many references pointed out that the main advantages of FRPs are their resistance to corrosion, lightweight, high strength, and predicted lifetime durability. However, the main advantage is their ability to enhance shear, axial load-bearing capacity, extremely enhanced flexural and torsion capacity, seismic withstand, and durability.

3.3.2 Disadvantages of (FRP)
Querashi et.al. [5] stated that FRPs are characterized by a brittle failure mode, which occurs suddenly without enough warning cracks. Because of the different stress nature of FRPs, the principles of stress distribution and plasticity are disregarded. Correia et.al. [6] stated there are concerns with the behavior of FRP adhesion in hot temperatures and when exposed to fire. Yu et.al. [7] stated that the two primary factors that affect the behavior of the FRP-to-concrete bond to deteriorate are water immersion and salt erosion. Pham and Hao [8]stated that there is an uncertainty existing regarding its rupture strain under impact loads and FRP debonding mechanism.

3.3.3 Techniques and forms of (FRP) placement
Abdel-Kader and Fouda [9] stated that there are several methods to attach fiber-reinforced polymer (FRP) to structural elements, including wrapping, external bonding, and near-surface mounting. Also, it was stated that for flexural strength, FRP plates or sheets can be attached to the tension side of a structural member [6], [9]. For shear strength, they can be attached to the web sides of a beam or around a beam. Additionally, FRP sheets can be wrapped around a column to provide confinement and enhance strength and ductility. According to Pham and Hao [8] FRP

materials such circumstances could be laminates, sheets, plates, or reinforcing bars as used in the near-surface-mounted method. as shown in Figure 4. FRP plates are applied in the flexural strengthening of beams

3.3.3.1 *Near Surface Mounted.* In near-surface mounting, a concrete member is cut into a longitudinal groove, then an adhesive in the groove, and an FRP strip or bar is inserted. Hawileh and Nasser [4], [10] both stated that NSM has been demonstrated to more effectively use bonded FRP materials than the other strengthening techniques. Siddika et.al. [11] stated that NSM is more practical than externally bonded due to its prevention of debonding failure and protection of fiber polymer from harsh environments

3.3.3.2 *Externally bonded.* FRP products, such as plates and sheets, are used on concrete surfaces (externally bonded) [4]. The external bonded strengthening technique advantage is simple and quick to conduct. Yu etal. [7] stated that the adhesion behaviour between fiber – reinforced polymer (FRP) and concrete is a critical factor in the strengthening efficiency of external bonding repair methods. Moreover, debonding failure is the most common failure mode for the externally bonded technique. The expected externally bonded modes of failure are shown in Figure 5.

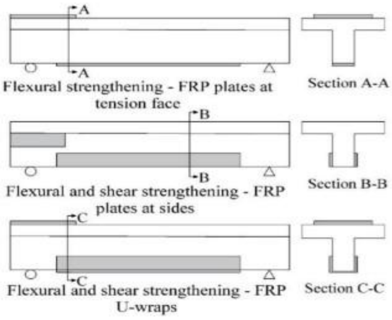

Figure 4 Strengthening by externally bonded FRP laminates, and U-wraps placing. [12]

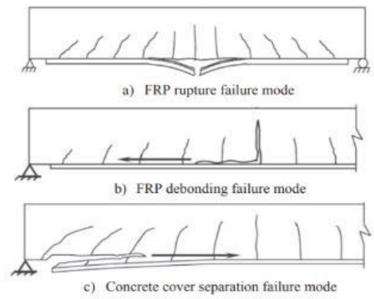

Figure 5 FRP laminates externally bonded strengthened plates reinforced concrete members failure modes. [4]

3.4 CFRP Hollow Core Slab under Monotonic Load.

The optimization of CFRP flexural strengthening in prestressed hollow core concrete slabs (HCS) is the subject of numerous studies. The most recent study, Elgabbas et al. [13], examined six full-scale precast prestressed (HCS) specimens analytically and experimentally. Six pre-tensioned strands with a diameter of 6 mm each have been used to reinforce the six specimens. Additionally, it was externally bonded and strengthened in positive bending using CFRP-NSM. The external bond was tested for failure under a monotonic load, which was increased gradually by 10 kN increments. Simply supported slabs are tested in four points of bending under a monotonic load till failure under successive 10 kN.

According to El gabbas [13] the highest strengthening performance was achieved using the NSM approach. Given that the externally bonded laminate's total activation and 50% rupture were changed by doubling its CFRP area, it is more suited for situations where serviceability is strictly controlled. Flexural strengthening restrictions became a key concern due to the greater bond of the NSM technique. Nevertheless, as the shear-tension failure happened at a high degree of flexural damage, no additional detrimental effects on deformity were noticed. The anchor that was externally bonded increased capacity by 70%, nearly reaching NSM, although deflection dropped by 50%. The method of external bonding without anchoring and the consequent debonding failure of CFRP resulted in the least effective strengthening of all the structural characteristics. This includes a capacity increase of 15% at much lower deformation and failure strains and the least uniform distribution of cracks. The 24% activation of the laminates at failure demonstrated the technique's drawbacks.

3.5 CFRP Hollow Core Slab Under Negative Load.

Nine (HCS) with varying setups of CFRP stripes were strengthened against negative moments and were examined experimentally by Hosny et.al. [14]. CFRP stripes have been bonded to the negative moment zone. The experiment's goal was to investigate the increased strength of (HCS) made possible by applying different CFRP techniques. They found that upper moment and the cracking moment resistance of the CFRP-bonded to (HCS) had increased significantly when compared to control specimens. Furthermore, in the study's slabs, crossed CFRP strips were bonded on top of the principal longitudinal strips, avoiding the formation of debonding cracks and postponing early failure.

3.6 CFRP Hollow Core Slab Under Blast Load

Maazoun et.al.[15] studied experimentally and numerically the effectiveness of externally bonded with different CFRP strips orientation under blast load. A close-range explosion was conducted on three retrofitted slabs: control, 2 strips CFRP, and 4 strips CFRP specimen, using a 0.5 m standoff distance. The explosive was 1500 gram of C-4 at mid-span beneath the slab measuring deflection. The numerical test involved using LS-DYNA software to compensate the experimental results of the blast load, predicting deflection and crack distribution. The results obtained from the numerical analyses closely match the experimental tests. It was found that externally bonded reinforcement using CFRP strips significantly improved the flexural strength and stiffness of reinforced concrete (HCS) under blast loading. Also, in slabs with 2 strips and 4 strips, there is a decrease in the deflection at the midspan of the strengthened (HCS) of 16% and 30%, respectively.

3.7 Optimal Sheet Length for CFRP and GFRP Strengthening

Maleknia et.al.[16] studied numerically the effectiveness of sheet length of CFRP and GFRP in enhancing loading capacity and displacement. The numerical test conducted on ANSYS software examined versus length of sheets. The study determined the ideal length to insert a CFRP sheet from the face of the support was roughly one-fifth. The ideal length for GFRP sheets was approximately one-third. Moreover, the study demonstrated that the capacity of the slabs wasn't affected by the installation of FRP sheets at longer lengths than the ideal length.

3.8 The Behavior of GFRP on (HCS)

Kankeri et.al.[17] studied experimentally the behavior of precast prestressed (HCS). Specifically, with the effectiveness of bonded overlay, NSM GFRP bar, and hybrid techniques. The hybrid technique combines the bonded overlay and NSM GFRP bars technique or combines of bonded overlay and NSM GFRP bars technique with an additional shear key. The results indicated that hollow core slabs' strength and stiffness significantly improved through the bonded overlay technique. The slabs' strength is similarly improved by the NSM strengthening technique, however, their ductility is reduced. It was shown that the hybrid strengthening technique was the most successful in raising the slabs' final strength and ductility. Displacement was enhanced as well in the NSM technique and bonded overlay with shear key and NSM technique

4 Research output and guidelines

A comparative analysis was conducted by comparing all the tested specimens across 5 references. A total of 37 specimens were gathered considering (GFRP and CFRP) on (HCS). Strengthening techniques were gathered such as Externally bonded (EB), Near Surface Mounted (NSM), and Bonded overlay. Different forms of enhancements were highlighted as well such as (Strips, meshes, and bars). The detailing of each enhancement was pointed out as well, the results were compared with each other in comparison with deflection, Ultimate moment, and Ultimate load capacity as shown in Table 1, Table 2, and Table 3 respectively. Where the difference between deflection with enhancement and with control is calculated and ranked. For the CFRP the best deflection reduction occurred upon using an EB sheet of 200 cm from the face of each support with a length of 9m, for ultimate moment capacity EB strips with the difference between them of 1.5m gave the optimum capacity, and for the ultimate point load capacity was using anchored EB strips. For the GFRP, EB sheets 9m long and 60 cm from each support was the optimum deflection reduction, for the ultimate point load was using NSM bars 5Ø12. for an ultimate moment, not enough research was funded to cover this point.

5 Conclusion

The usage of (HCS) has numerous benefits. It allows a variety of designs since it is prefabricated and light in weight, thus can cover larger spaces with minimal support in relevance with regular slabs (solid, Flat, etc.). However, the problem lies in the little we know about the behavior of (HCS) under extreme loads (such as impact or blast waves). A comprehensive background study was conducted to understand the current solutions by comparing the data from previous research that is most close and relevant. The paper outputs were as follows:1) A comparative analysis was conducted of 37 specimens across 5 references. 2)They were ranked per paper and with each other (global ranking). 3) For seismic activity the best enhancement was CFRP EB-sheets with 9m long reduced maximum deflection (200cm from support). 4) For GFRP EB-sheets with 9m long reduced the maximum deflection (60cm from support). 5)For moment control (three longitudinal CFRP strips bonded of 1.5 m) shall be used. 6) For highest point load enhancement (NSM 5Ø12 GFRP bars) shall be used. These techniques could be used later on for further research using experimental or Applied Element Methods (AEM) for 3D full or less-scale experiments. This could enhance (HCS) to withstand severe loads, which could be revolutionary for the construction industry.

5.1 Research limitations

The research combining retrofitting hollow core slabs (HCS) with FRP on impact loading is not enough. No research was found that addresses this problem on 3D bases only localized specimens or simulations. Experimental data was not found regarding the enhancements of (HCS) against impact. The developed guidelines need to be verified by an applied case study. The key performance index (KPIs) to be checked is the deflection of the slab, its moment capacity, and its serviceability limits.

5.2 Future Recommendations

- To apply experimental testing of 3D scale structures to be accurate.
- The Applied Element Method (AEM) could be an answer to the experimental difficulties.

To check for FRP energy-absorbing material which will give maximum deflection without failure thus eliminating its brittle behavior under impact loading.

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Table 1 Enhancing technique effective ranking by Deflection.

Literature Comparative Analysis (Deflection)								
FRP Type	**Strengthening Technique**	**Strengthening Form**	**Strengthening Details**	**Deflection (mm)**	**Deflection Control (mm)**	**Ranked Per Paper**	**Ref.**	**Overall Ranking**
CFRP	EB	strips	EB CFRP area120 mm²	53.5	132	5		31
CFRP	Anchored EB	strips	Anchored EB CFRP area120 mm2	65	132	4		30
CFRP	NSM	strips	NSM CFRP area 60 mm²	122	132	3	[14]	26
CFRP	NSM	strips	NSM CFRP area 64 mm²	140	132	2		15
CFRP	NSM	strips	NSM/ CFRP area120 mm²	144	132	1		13
CFRP	EB	strips	EB three longitudinal CFRP strips bonded along the cantilever part.	14	2.45	4		14
CFRP	EB	strips	EB three longitudinal CFRP strips bonded a long cantilever and broken bond between the strands with a length of 1.5 m	24.6	2.4	3		12
CFRP	EB	strips	EB three longitudinal CFRP strips bonded a long cantilever additional 2 transverse and broken bonds between the strands with a length of 1.5 m	24.7	2.35	2	[15]	11
CFRP	EB	strips	EB three longitudinal CFRP strips bonded a long cantilever and an additional 1 transverse and broken bond between the strands with a length of 1.5 m	25.6	2.3	1		10
CFRP	EB	strips	EB 4 strips CFRP 250 reinforcement ratio (mm²/m)	46	65	5	[16]	29
CFRP	EB	strips	EB 4 strips CFRP 250 reinforcement ratio (mm²/m)	49	67.5	4		28
CFRP	EB	strips	EB 2 strips CFRP 200 reinforcement ratio (mm²/m)	55	65	3		26
CFRP	EB	strips	EB 2 strips CFRP 200 reinforcement ratio (mm²/m)	58	67.5	2		25
GFRP	EB	Sheets	50 cm from the face of support for the slab with a length of 1.5 m	15.5	12.00	1		23
CFRP	EB	Sheets	5 cm from the face of support for the slab with a length of 1.5 m	17.5	12	5		17
CFRP	EB	Sheets	15 cm from the face of support for the slab with a length of 1.5 m	17.5	12	5	[17]	17
CFRP	EB	Sheets	30 cm from the face of support for the slab with a length of 1.5 m	17.5	12	5		17
CFRP	EB	Sheets	50 cm from the face of support for the slab with a length of 1.5 m	17.5	12	5		17
CFRP	EB	Sheets	60 cm from the face of support for the slab with a length of 9 m	65	12	4		9
CFRP	EB	Sheets	120 cm from the face of support for the slab with a length of 9 m	115	12	2		7
CFRP	EB	Sheets	200 cm from the face of support for the slab with a length of 9 m	120	12	1		1
CFRP	EB	Sheets	300 cm from the face of support for the slab with a length of 9 m	90	12	3		8
GFRP	EB	Sheets	5 cm from the face of support for the slab with a length of 1.5 m	16	12	8		22
GFRP	EB	Sheets	15 cm from the face of support for the slab with a length of 1.5 m	18	12	6		16
GFRP	EB	Sheets	30 cm from the face of support for the slab with a length of 1.5 m	17	12	7		21
GFRP	EB	Sheets	50 cm from the face of support for the slab with a length of 1.5 m	15.5	12	9		23
GFRP	EB	Sheets	60 cm from the face of support for the slab with a length of 9 m	120	12	1		1
GFRP	EB	Sheets	120 cm from the face of support for the slab with a length of 9 m	120	12	1		1
GFRP	EB	Sheets	200 cm from the face of support for the slab with a length of 9 m	120	12	1		1
GFRP	EB	Sheets	300 cm from the face of support for the slab with a length of 9 m	120	12	1		1
GFRP	EB	Sheets	400 cm from the face of support for the slab with a length of 9 m	120	12	1		1
GFRP	Bonded Overlay	bars	Bonded overlay – no shear key	13.4	51	6		35
GFRP	NSM	bars	Hybrid–bonded overlay with shear key and NSM (5Ø12 GFRP bars)5Ø12	38	51	5		32
GFRP	NSM	bars	NSM Bars (specimen 1) (5Ø12 GFRP bars)	46.9	51	4	[18]	28
GFRP	NSM	bars	NSM Bars (specimen 2) (5Ø12 GFRP bars)	49.5	51	3		27
GFRP	-	bars	Bonded overlay with shear key	56.7	51	2		18
GFRP	NSM	bars	Hybrid–bonded overlay with no shear key and NSM (5Ø12 GFRP bars)	58.4	51	1		16

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Table 2 Enhancing technique effective ranking by Ultimate Moment

FRP Type	Testing type	Strengthening Technique	Strengthening Form	Strengthening details	Ult Moment (KN.m)	Ult. Moment Control (KN.m)	Ranking	Ref
CFRP	experimental	EB	strips	EB three longitudinal CFRP strips bonded a long cantilever additional 2 transverse and broken bonds between the strands with a length of 1.5 m	94.3	15.45	1	[15]
		EB	strips	EB three longitudinal CFRP strips bonded a long cantilever and broken bond between the strands with a length of 1.5 m	78.1		2	
		EB	strips	EB three longitudinal CFRP strips bonded a long cantilever and an additional 1 transverse and broken bond between the strands with a length of 1.5 m	76.9		3	
		EB	strips	EB three longitudinal CFRP strips bonded along the cantilever part.	41.4		4	

Table 3 Enhancing technique effective ranking by Ultimate point Load

Testing Type	FRP Type	Strengthening Type	Strengthening Form	Strengthening Details	Ultimate Load (kN) Specimen	Ultimate Load (kN) Control Specimen	Global Ranking	Failure Modes	Ref
Experimental	GFRP	NSM	bars	Hybrid–bonded overlay with no shear key and NSM 5Ø12	144.7	42.8	1	flexure shear	[18]
		NSM	bars	Hybrid–bonded overlay with shear key and NSM 5Ø12	131.8	42.8	2	flexure shear	
		-	bars	Bonded overlay with shear key	80.9	42.8	6	flexure failure	
		NSM	bars	NSM Bars (specimen 2) 5Ø12	88.8	42.8	3	flexure shear	
		-	bars	Bonded overlay – no shear key	59.2	42.8	9	Interfacial shear failure	
		NSM	bars	NSM Bars (specimen 1) 5Ø12	86.7	42.8	4	flexure shear	
	CFRP	EB	strips	EB CFRP area120 mm²	57.5	50	10	Debonding	[15]
		Anchored EB	strips	Anchored EB CFRP area120 mm²	90	50	5	Debonding	
		NSM	strips	NSM CFRP area 64 mm²	70	50	8	shear-tension	
		NSM	strips	NSM CFRP area 60 mm²	75	50	7	CFRP Rapture	
		NSM	strips	NSM/ CFRP area120 mm²	57.5	50	10	shear-tension	

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