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NUMERICAL INVESTIGATION OF RETROFITTING WAFFLE SLABS WITH CARBON FIBRE REINFORCED POLYMER PLATES

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Abstract

As a result of shopping centres closing and being converted into either accommodation or factories, engineers have been needing to come up with new and innovative solutions to help increase the strength and decrease the deflection of already built concrete structures. If the structure's purpose was to change, then the building would need to be redesigned to ensure its structural integrity. The objective of this study is to investigate the effects that retrofitted Carbon Fibre Reinforced Polymer (CRFP) plates have on the strength of healthy and corroded waffle slabs. 3D state-of-the-art finite element modeling software will be used to create accurate models that can be used to perform nonlinear analyses. Within these models, factors such as deteriorated concrete and corroded steel will also be modelled to investigate the effects of using CFRP plates as a strengthening approach to deteriorated Reinforced Concrete (RC) structures, and in this case with waffle slabs.

Keywords: Carbon Fibre Polymer, Waffle Slabs, Corrosion, Retrofit, Reinforced Concrete, Finite Element Method

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1 INTRODUCTION

The majority of shopping malls in South Africa and around the world make use of the waffle slab system, since it allows one to cover large spans by optimising the use of the RC material. Over time, all RC structures will eventually develop cracks and deteriorate due to environmental hazards that affect the building's material, thus waffle slabs are also affected by this phenomenon. To strengthen existing waffle slabs, CFRP plates can be installed on the tension side of the slab's section. Other advantages such as ductility and shear resistance can also be achieved through this solution. According to Kim et al. [1], CFRPs can increase the stiffness of a beam against impact loading and increase the shear resistance. Soudki et al. [2] concluded in their research that retrofitting a slab with CFRPs increases the punching capacity by 29% as well as the stiffness while lowering deflections. These attributes make CFRP plates a favourable solution when retrofitting RC structures.

This research work's objective is to have an in-depth view into a waffle slab's mechanical response to the retrofitting and the efficiency of implementing CFRP plates as a strengthening method. To make the simulations more realistic, material deterioration is also considered and incorporated within the numerical models.

2 METHODOLOGY

The research will be performed through the use of 3D detailed analysis using Finite Element Analysis (FEA) software. It has been shown through numerous numerical investigations by Nicolaides & Markou [3] that Reconan FEA [4] has the ability to capture the realistic behaviour of bare and retrofitted RC structures under monotonic and cyclic limit state loading conditions. A similar approach will be used, and adjustments will be made where needed to model the RC waffle slabs that are bare or retrofitted with CFRP plates. It is important to note here that Reconan FEA was validated through the use of experimental results as presented in [5-8].

The slabs will be modelled and analysed considering different loads as well as different parameters that relate to the material properties and the geometry of the intervention applied herein for the needs of this research work. Parameters such as thickness of plates will be varied to understand the effects of the strengthening approach on the slab's overall mechanical response and ultimate capacity. A RC waffle slab with no CFRP plates will be modelled to form a base line that will be used to compute the overall effect of the retrofitting. Finally, parameters such as corroded rebar and deteriorated concrete will be used to further investigate the effects of CFRP plates when implemented on a structure that has suffered deterioration due to environmental hazards.

2.1 Modelling of Waffle Slabs with No Deterioration.

The waffle slab (see Figure 1) that was modelled was discretized using 8-noded hexahedral elements that had an average size of 100x100x100mm. All the reinforcement was discretized and modelled as embedded rod elements except for the longitudinal rebar in the four columns, which were modelled as Natural Beam-Column Force-Based (NBCFB) Elements [9]. A total of 30 916 elements were used to discretize the waffle slab, including the four RC columns. In addition to that, 1 764 hexahedral elements were used to model the slab's CFRP plates for the case of the retrofitted models.

The thicknesses for the CFRP plates on the slab were 1.2, 1.4, 2.4 and 2.8 mm. These thicknesses were acquired from the Sika CarboDur Plates data sheet [10], a product that is used by VSL Construction Solutions (Pty) Ltd, who are specialists in the retrofitting of CFRP plates in South Africa. According to the information found within this sheet [10] the costing was calculated to assess the cost vs strength benefit for each retrofitting scenario. A total of 196 m of CFRP plates are needed to implement the retrofitting as shown in Figure 1. It is important to note that the most common CFRP plates come in 1.2 mm or 1.4 mm thick strips and cannot be layered in more than 2 layers according to VSL Construction Solutions. Therefore, the 2.4 mm and the 2.8 mm plates were achieved by using a 2-layer implementation of the 1.2 mm and 1.4 mm, respectively.

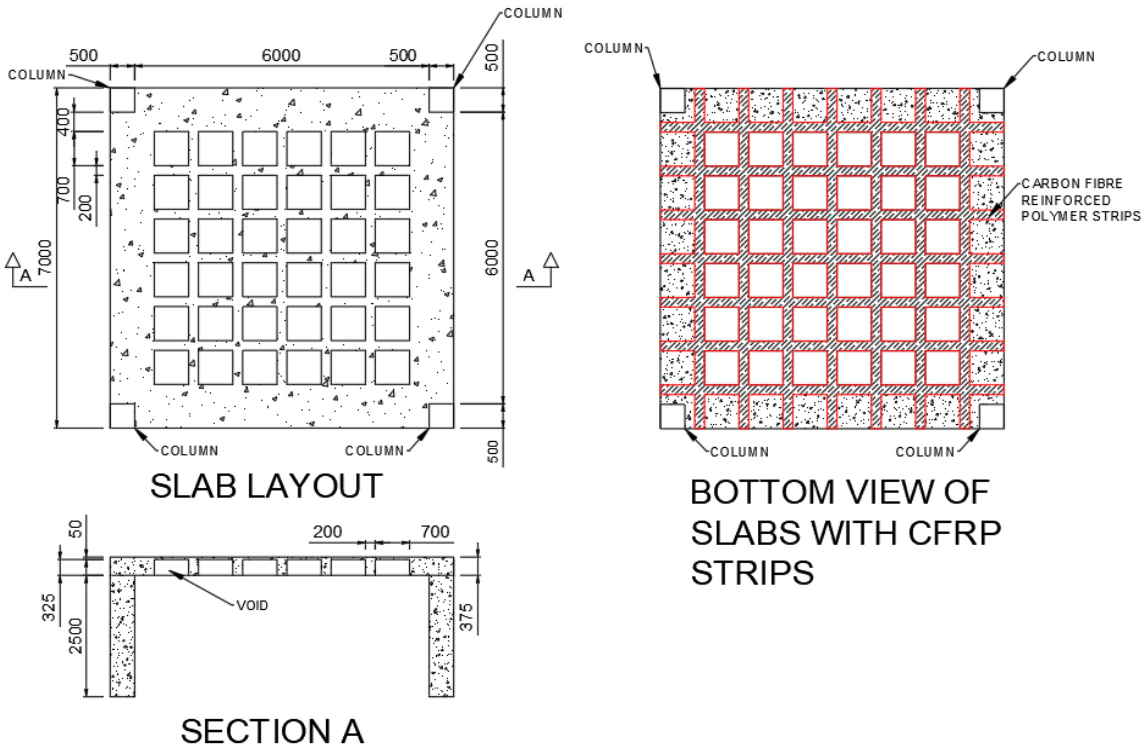

Figure 1: Layout and dimensions of the waffle slab.

As it can be seen in Figure 1, the under-study RC waffle slab was 7x7 m, with four 2.5 m in height columns. The full thickness of the slab, web and width of the rib was 375 mm, 50 mm, and 200 mm, respectively. In Figure 1, one can see the layout and dimensions of the RC slab that was used to perform the investigation in this research work.

At the base of the columns, a steel plate was modelled to ensure no local failure occurred which would lead to premature analysis instabilities. The reinforcement in the columns consisted of eight ∅20 longitudinal rebars with ∅12 stirrups spaced at 100 mm. In the slab, two ∅12 longitudinal rebar were used in the top and bottom for each rib with ∅8 stirrups spaced at 200 mm. On the outer edges of the slab until the start of the waffle's voids, ∅12 longitudinal rebars spaced at 102.5 mm were used in both directions. In the web of the waffle slab (in between ribs), ∅8 longitudinal steel rebars were used at the top and bottom for in both directions. The concrete cover throughout the slab was assumed to be equal to 50 mm.

Table 1 shows the properties of the materials defined within the numerical models. The 1.2 mm and 1.4 mm CFRP plates had different properties and these different properties were also considered within the models. The CFRP plates were modelled over the ribs and extended to and from the edges of the slab. The CFRP properties were extracted from the Sika CarboDur Plates data sheet [10]. The RC waffle slabs were loaded with a distributed load over the top surface. It is noteworthy to state that the models ran for approximately 12 hours and 10min on a 3.7 GHz PC that had 64 Gb RAM.

Modelled properties for the corroded and deteriorated materials			
Concrete		**Steel**	
Undeteriorated compressive strength	30 MPa	**Uncorroded compressive strength**	450 MPa
Percentage decrease from calculations above	15%	Percentage decrease from calculations above	20%
Deteriorated compressive strength	25.5 MPa	**Corroded compressive strength**	360 MPa

Table 2: Properties of the materials used in the numerical model.

Modelled Properties of the Material					
Concrete		**Steel**		**1.2 mm CFRP Plates (CarboDur S)**	
Young's Modulus	30 GPa	**Young's Modulus**	200 GPa	**Young's Modulus**	165 GPa
Compressive Strength	30 MPa	**Compressive Strength**	450 MPa	**Tensile Strength**	3100 MPa
Tensile Strength	1.5 MPa	**Poisson Ratio**	0.3	**Poisson Ratio**	0.3
Poison Ratio	0.2				
				1.4 mm CFRP Plates (CarboDur M)	
				Young's Modulus	210 GPa
				Tensile Strength	3200 MPa
				Poisson Ratio	0.3

Table 1: Modified material properties

2.2 Modelling of the Waffle Slabs with Deterioration of the Concrete or Rebar

For this model, the strength of the rebar and the concrete was decreased to mimic the effects deteriorated concrete and corroded rebar. Franceschini et al. [11], calcualted for certain exposure classes what the strength decrease of the concrete strength and area reduction of the rebar would be at various exposure durations. Based on their assumptions and taking into account the environment of South Africa, it was assumed herein that the lowest exposure class would be applicable. Therefore exposure class XS1 was used, which is described as being exposed to airborne salt, but does not have direct contact with salts. An exposure time of 80 years was implemented and based on Franceschini et al. [11], the calculated percentage decrease of the material strengths was derived and implemented for the needs of this research work.

In regards to steel, the cross-sectional area loss was 18.88% for a 19 mm rebar after 80 years in XS1 exposure class. According to Franceschini et al. [11], it was found that the area loss increased as the original rebar size decreased. It was therefore assumed that a 20% cross-sectional area reduction would be realistic for the RC waffle slab models, considering the rebars used in this research work were 12 mm in diameter. The percentage was applied directly to the strength of the rebar thus the yielding and ultimate stress of the rebars were decreased by 20%. The new corroded rebar strength can be seen in Table 2.

In relation to the concrete material, the compressive strength loss was calculated and was found to be approximately equal to 15% for a 50 MPa concrete after 80 years in XS1 exposure class. In Table 2, one can see the new material properties of concrete, while it is important to note that it was assumed that this deterioration was uniform throughout the concrete domain. Additionally, the Young modulus for both materials were not modified due to deterioration.

Figures 2 to 6 show the RC waffle slab model that was developed through the use of the pre-processing software FEMAP. These figures show the hexahedral and embedded rebar meshes as they were developed for the needs of this parametric investigation.

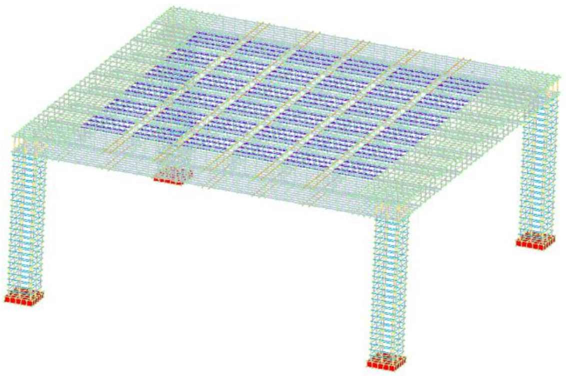

Figure 2: Embedded rebar mesh of the waffle slab.

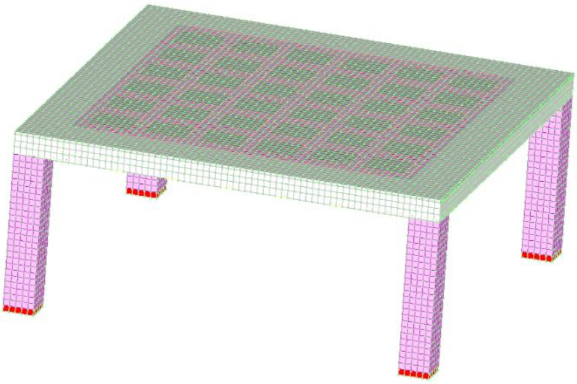

Figure 3: Hexahedral mesh of the waffle slab.

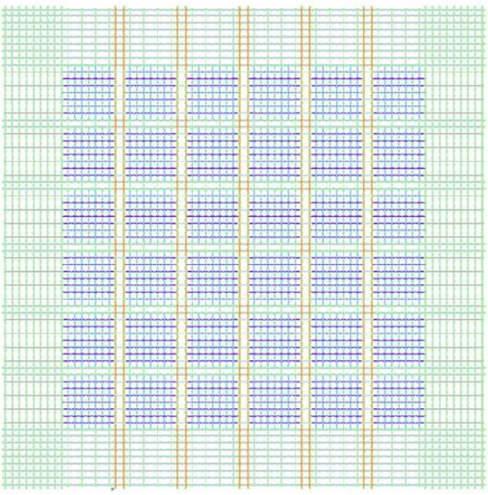

Figure 4: Top view of the embedded rebar mesh of the waffle slab.

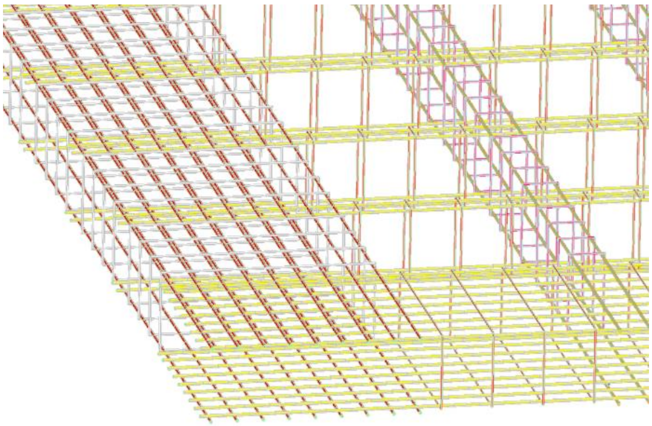

Figure 5: Close up of the embedded rebar mesh of the waffle slab.

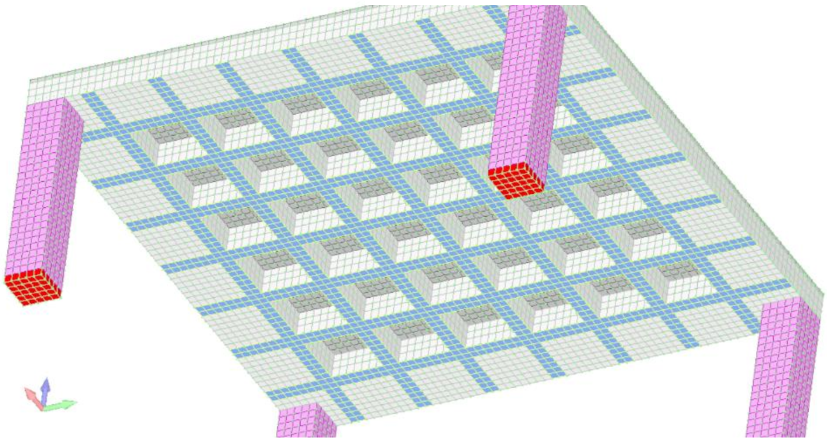

Figure 6: Bottom view of the hexahedral mesh including the CFRP plates on the waffle slab.

3 RESULTS AND DISCUSSION FROM THE ANALYSIS WITH NO DETERIORATION.

In Figure 7, one can see the load vs deflection curves of a waffle slab retrofitted with 1.2 mm, 1.4 mm, 2.4 mm, and 2.8 mm thicknesses of CFRP plates. The waffle slab without CFRP plates was also added in this graph for comparative reasons. It is easy to observe that the load vs deflection curves numerically obtained from the models indicate that the stiffness, yielding point and overall structural capacity increases as the CFRP plate thickness increases. These results were expected since the addition of thicker CFRP plates made the vertical resistance of the RC waffle slabs higher introducing additional stiffness and strength. In Figure 8 and 9, the deformed shape and the solid von Mises strain contour can be seen prior to failure for different load levels as they resulted from the nonlinear analysis.

Table 3 shows that the implementation of 1.2 mm CFRP plates increased the strength by 123%. On the other hand, by adding a 2.8 mm plate of CFRPs, a 262% increase in strength was observed.

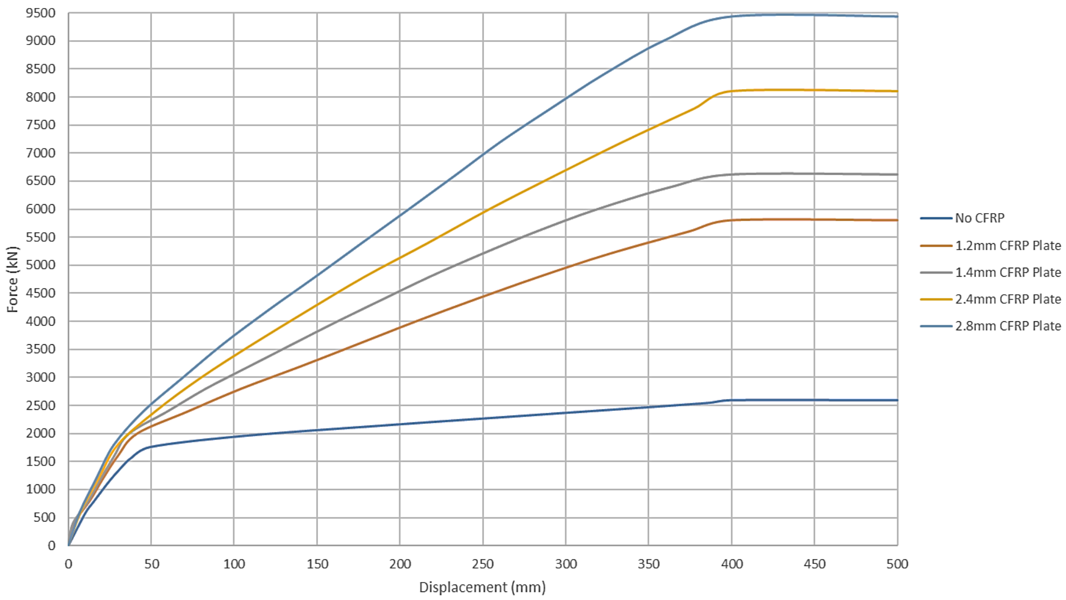

Figure 7: Force vs Displacement for various thicknesses of CFRP plates.

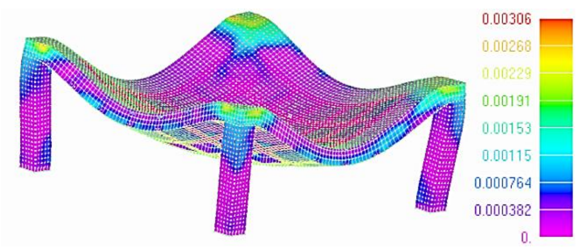

Figure 8: Solid von Mises Strain contour and deformed shape of the waffle slab with 2.4 mm CFRP Plates before the first crack occurred.

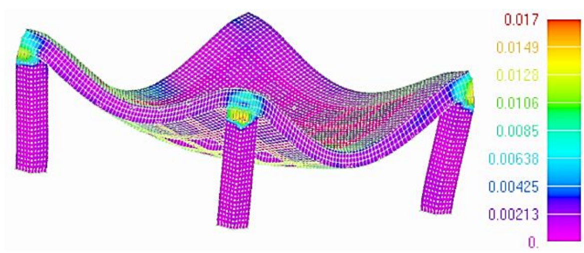

Figure 9: Solid von Mises Strain contour and deformed shape of the waffle slab with 2.4 mm CFRP plates after the first crack occurred.

From Table 3, we can also see the cost of the preparation, supply and installation of each plate thickness used when strengthening the structure. One can see that the installation of the 1.4 mm thick plate is substantially more expensive than the 1.2 mm thick plate. One can see that retrofitting by using two 1.2 mm plates (2.4 mm plate) is more cost effective and provides more strength than when retrofitting with one 1.4 mm plate. In terms of cost vs strength achieved from the different CFRP plates, the installation of two 1.2 mm thick plates to achieve the thickness of 2.4 mm, would be more economical than the 2.8 mm thick plate (two 1.4mm thick plates), and only provides an extra 50% additional strength. If the price was a large factor in solving the problem, and usually it is in the construction industry, then the 2.4 mm thick plate would be the best option to ensure a substantial increase in strength and be the most cost-effective solution for the problem. In addition to that, Table 3 shows the cost of increasing the strength of the structure by 1%, where once more the most cost-effective strengthening scenario is when the 2.4 mm CFRP plates are used.

CFRP Plates Thickness	**F_{ND} (kN)**	**Strength Increase due to CFRP**	**Retrofitting Cost**	**Cost per 1% of strength increase (R/%)**
No. CFRP	600	-	-	
1.2 mm	800	123%	=196m x R1015/m =R198 940.00	1617
1.4 mm	620	155%	=196m x R1827/m =R358 092.00	2310
2.4 mm	110	212%	=196m x R1450/m =R284 200.00	1340
2.8 mm	430	262%	=196m x R2610/m =R511 560.00	1952

Table 3: Summary of the ultimate force for the cases of no deterioration

As it was stated above, an additional advantage that derives when implementing the CFRP pates is that the slabs' deflection for the same load level decreases as the CFRP plate thickness increases. This can be seen as an advantage since it could be significantly beneficiary in case an owner chose to repurpose an existing structure thus introduce additional loads at the slabs of the building, where the waffle slabs would face a problem in relation to the maximum allowed deflection for the serviceability load combinations.

4 RESULTS FROM THE ANALYSIS WITH DETERIORATION.

Figure 10 shows the comparative graph as it derived from the nonlinear numerical analysis by using the assumption that the RC waffle slabs are deteriorated due to the XS1 exposure for 80 years. The results from the deteriorated slab look similar to the curves shown in Figure 7 and therefore it was decided to develop individual graphs for each CFRP plate thickness to further investigate the differences between the deteriorated slabs and the slabs without deterioration. The differences between the two scenarios can be seen in Figures 11, 12, 13, 14 and 15.

Table 4 shows a comparison between the ultimate force obtained from the analysis for the slabs with and without deterioration. As it can be depicted a large difference is depicted in the case of the 2 slabs that were not retrofitted. It is evident that a slab without retrofitting will experience large strength losses when deterioration develops due to environmental hazard exposure. On the other hand, it was found that the thicker the plate for retrofitting, the less the deterioration influenced the numerically derived strength. For the case of the 2.4 and 2.8 mm thick plates, the difference between the deteriorated and healthy the slabs were negligible. This phenomenon is attributed to the level of deterioration that was 20% and not larger than 30% that would have significantly affected the overall strength of the structural system.

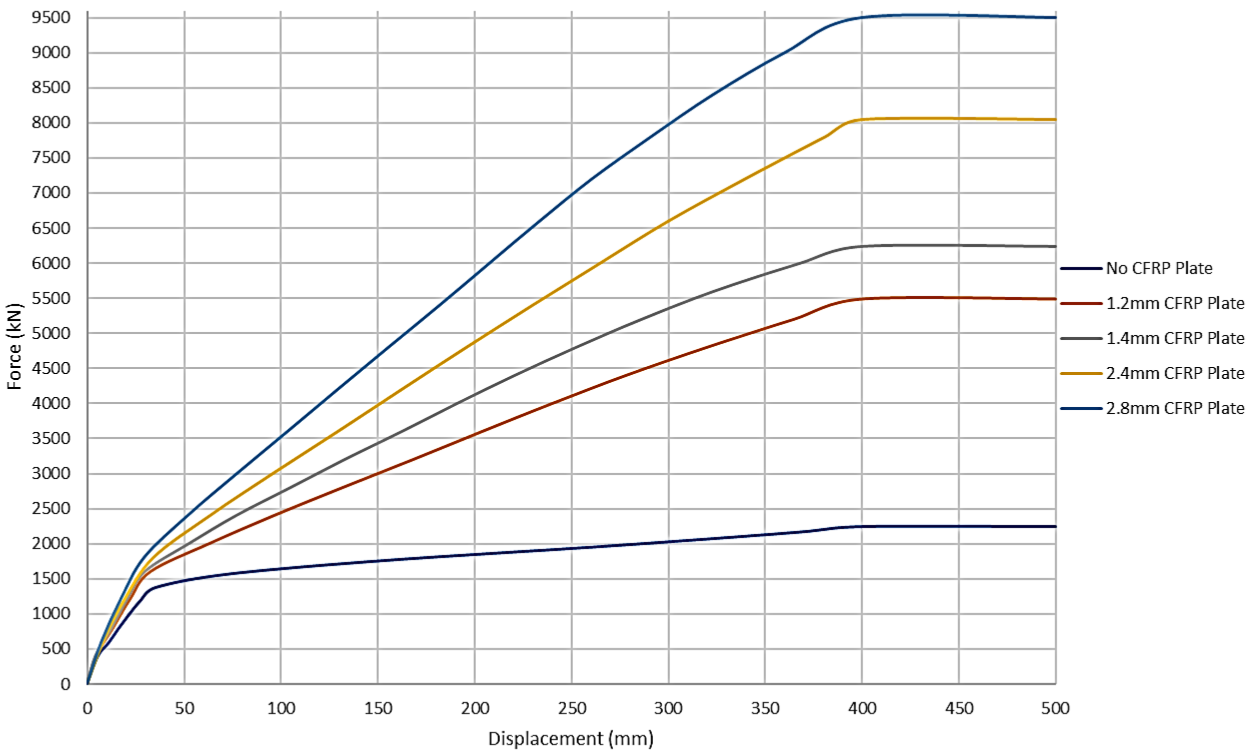

Figure 10: Force vs displacement curves of the deteriorated RC waffle slabs with various thicknesses of CFRP plates.

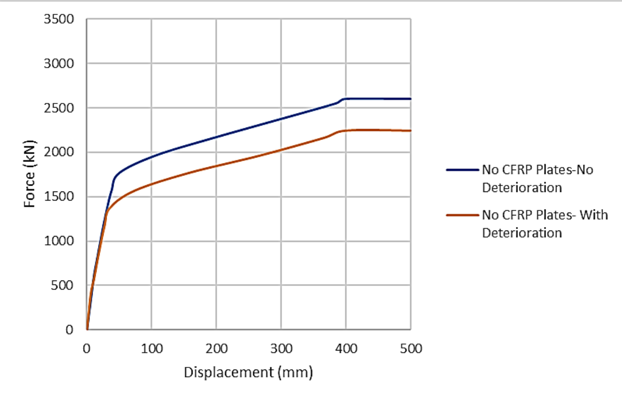

Figure 11: Force vs displacement curve of the deteriorated and undeteriorated waffle slab with no CFRP plates retro fitted.

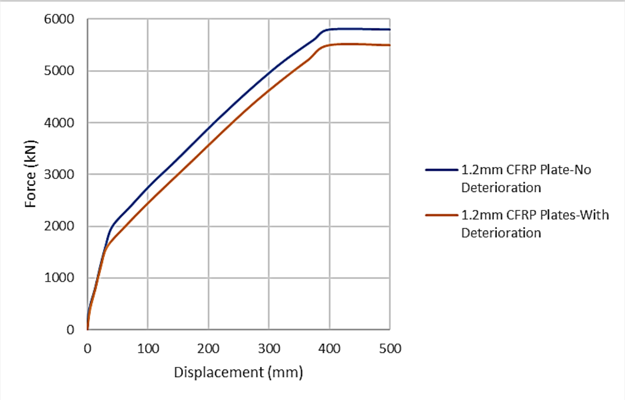

Figure 12: Force vs displacement curve of the deteriorated and undeteriorated waffle slab with 1.2 mm thick CFRP plates retro fitted.

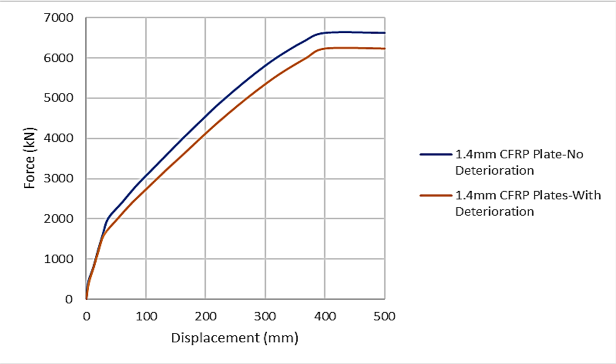

Figure 13: Force vs displacement curve of the deteriorated and undeteriorated waffle slab with 1.4 mm thick CFRP plates retro fitted.

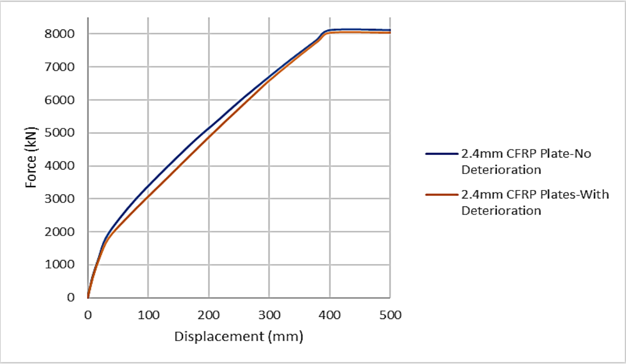

Figure 14: Force vs displacement curve of the deteriorated and undeteriorated waffle slab with 2.4 mm thick CFRP plates retro fitted.

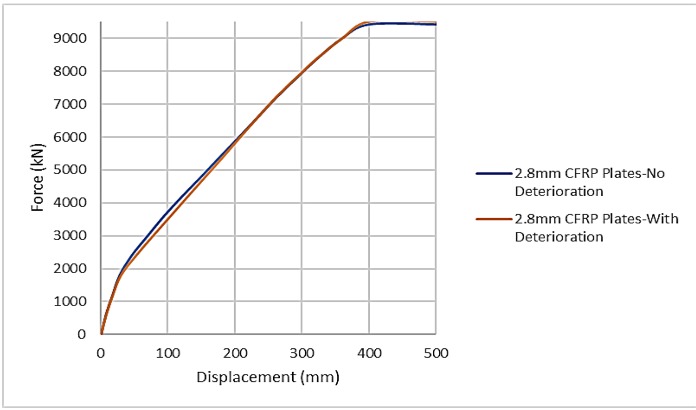

Figure 15: Force vs displacement curve of the deteriorated and undeteriorated waffle slab with 2.8 mm thick CFRP plates retro fitted.

CFRP Plates Thickness	F_{ND} (kN) No Deterioration	F_D (kN) With Deterioration	Difference $(F_{ND} - F_D) / F_{ND}$	Strength Increase due to CFRP
No CFRP	2600	2240	-13.8%	-
1.2 mm	5800	5490	-5.4%	145.1%
1.4 mm	6620	6240	-5.7%	178.6%
2.4 mm	8110	8050	-0.7%	259.4%
2.8 mm	9430	9500	0.1%	324.1%

Table 4: Table showing the difference between the forces at a deflection of 400 mm between the waffle slab with and without deterioration.

5 CONCLUSION AND FUTURE WORK

Within this paper, the effects of CFRP plates on the strength of existing RC waffle slabs was investigated. From the numerically obtained results, it was concluded that CFRP plates can significantly improve the strength of the existing waffle slabs by over 260% and can decrease the deflection of the slab accordingly. According to the cost of the CFRP plates, resulted the 2.4 mm thick plate to be the most economical solution in achieving a high increase in strength vs cost. The CFRP plates also increased the strength of existing RC waffle slabs with deteriorated concrete and corroded rebar, which was a problem that was also investigated herein. According to the parametric investigation, and similar to the previous conclusion, it was again found that the most cost-effective retrofitting solution is the one that foresees the use of the 2.4 mm CFRP thick plate. This is attributed to the optimum thickness of this CFRP plate, and the price offered by the manufacturer compared to the rest of the available CFRP plate thicknesses.

In future research, it would be beneficial to model the deterioration as an effect that is not uniformly distributed within the numerical model, which was an assumption made herein for simplicity purposes. In addition to this, the development of numerous models should be performed to investigate the ability of developing a formula that would allow professional Civil Engineers to decide the optimum approach and strategy when strengthening or retrofitting RC waffle slabs [12].

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