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EXPERIMENTAL VALIDATION OF OPTIMUM RESISTANCE MOMENT OF CONCRETE SLABS REINFORCED WITH CARBON FIBRE-REINFORCED PLASTIC

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ABSTRACT

Fibre-Reinforced Plastics (FRPs) have been suggested as suitable reinforcement for concrete structures among other solutions to combat corrosion problems in steel reinforced concrete. This paper presents the experimental validation of optimum resistance moment of concrete slabs reinforced with Carbon-Fibre Reinforced Plastic (CFRP). Eight specimens of two-way spanning slabs reinforced with CFRP bars were used in the experiment. They were designed to achieve two classical failure modes: rupture of the reinforcements (tension failure) and crushing of the concrete while the reinforcement remains elastic (compression failure). This was accomplished by using reinforcement ratios less, and more than the balanced reinforcement ratio, ρ_{frpb}, for the slabs, respectively. All the slabs failed as predicted. The results obtained show that the design formulations for predicting the minimum flexural resistance of an CFRP-reinforced concrete member provided by CSAS806-02(R07) have been underestimated. The design formulations were found to underestimate the resistance moment capacity of CFRP-reinforced concrete slabs by about 33%.

Keywords: *optimum resistance moment, concrete slabs, CFRP, design formulation.*

1. INTRODUCTION

One of the major concerns about steel as reinforcement for concrete structures is its susceptibility to corrosion in a wet and harsh environment. Aggressive environments are not concrete-friendly because in an aggressive environment concrete may be open to chemical attacks, which break down the alkaline barrier in the cement matrix. This exposes the steel reinforcement in the concrete structures to corrosion, resulting in a loss of strength for the steel and structural capacity of the reinforced member. For this and many other reasons, Fibre-Reinforced Polymer (FRP) bars are considered as an alternative to steel for concrete reinforcement. However, the apparent high cost of FRP in comparison with steel and other conventional materials, has been a disapproving restraint [1]. Aside the cost concerns, the most significant technical obstacle stopping the extended use of FRP materials is lack of long-term and durability performance information comparable to the information available for traditional construction materials [2].Most of the information available on composites is not related to civil engineering applications. Also, the absence of reliable design methods to determine the ultimate strength of structural elements reinforced with FRP has inhibited its use in the construction industry, despite its numerous advantages. Inspite of all these inhibitions, FRP-reinforcement in concrete structures are gaining wide acceptance as an effective substitute for steel reinforcement, especially for the cases in which aggressive environment produces high steel corrosion, or lightweight is an important design factor, or transportation cost increase substantially with the weight of the materials.

Pultrusion, braiding, and filament winding are three common processes of manufacturing FRP [3]. Pultrusion is one of the most popular and common methods for producing linear composite elements with the primary reinforcing fibres in the longitudinal direction. It is a continuous filament moulding process incorporating fibre reinforcement with thermosetting resin matrices [4]. Continuous strands of reinforcing material are drawn from spools of fibres, through a resin tank, where they are saturated with resin, and then through a number of wiper rings into the mouth of a heated die. This process simultaneously forms and heat-cures the FRP into reinforcing rods [3]. The speed of pulling through the die is predetermined by the curing time needed. To ensure

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good and strong bond with concrete, the surface of the bars is usually interwoven, spiral wound or sand-coated.

Lightly reinforced sections may fail immediately after cracking if the flexural strength or resistance moment of the reinforced element is less than the cracking moment for the member [5]. This type of failure occurs suddenly and without warning, and must be avoided. For this reason, [6] provides for minimum flexural resistance by requiring the resistance moment of an FRP-reinforced concrete member, M_r, to be at least 50% greater than the cracking moment, M_{cr}. However, [7] opined that this value could be stepped up to about 33% to get the optimum resistance moment. They stated that the resistance moment capacity of FRP-reinforced concrete slabs has been underestimated by about 33% in the design formulations by the code. This paper presents the experimental validation of the optimum resistance moment of concrete slabs reinforced with Carbon Fibre-Reinforced Plastic (CFRP) proposed by [7].

2. MINIMUM FLEXURAL RESISTANCE OF FRP-REINFORCED RECTANGULAR CONCRETE SECTIONS

The moment of resistance of a beam or slab section is the moment of the couple which is set up at the section by the longitudinal forces created in the beam or slab by its deflection. The minimum resistance moment of FRP-reinforced concrete sections is given by [6] as:

$$M_r \geq 1.5 M_{cr} \qquad (1)$$

The cracking moment (M_{cr}) is determined from the modulus of rupture of the concrete, f_r the moment of inertia of the transformed uncracked section, I_ra and the distance from the centroidal axis of the transformed uncracked section to the extreme tension fibre, y_r, using [5]:

$$M_{cr} = \frac{f_r I_r}{y_t} \qquad (2)$$

In (2), $f_r = 0.6\sqrt{f_c'}$ is the modulus of rupture of concrete, $M_{cr}$is the cracking moment, I_t is the Moment of inertia of transformed uncracked section and y_t is the Distance from the centroidal axis of transformed uncracked section to the extreme tension fibre.

However, [6] and [8] permit the use of the gross moment of inertia, I_g instead of I_t to computeM_{cr}

The general ultimate moment for a singly FRP reinforced concrete section is given by [6]as Equation (1) above, which is equivalent to:

$$M_r = 0.25 f_r b d^2 \qquad (3)$$

This equation is proposed by [5] to be represented as:

$$M_r = 0.25 \beta_0 f_r b d^2 \;\; = \;\; k b d^2 \qquad (4)$$

where, β_0 is an underestimation factor observed in the cracking moment of concrete, and

$$k = 0.25 \beta_0 f_r \qquad (5)$$

Therefore, $\beta_0 = \frac{k}{0.25 f_r}$

From [5], k is given as:

$$k = \frac{1}{\left(C_{opt}^m\right)^2} \qquad (6)$$

where:

$$C_{opt}^m = \frac{\left(1.8656 f_{frp} - f_c\right)}{\sqrt{\left[f_{frp} f_c\right]\left(0.6996 f_{frp} - 0.75 f_c\right)}} \qquad (7)$$

C_{opt}^m is the maximum optimum design variable, k is a function of C_{opt}^m *and* K_{opt}^m is the maximum optimum value of k. Equation (7) implies that the value of C_{opt}^m can be determined at every choice of concrete and CFRP strength in a reinforced concrete slab section. For instance, if $f_c = 25N/mm^2$*and* $f_{frp} = 1431N/mm^2$ $C_{opt}^m = 0.44075$.*and*$K_{opt}^m = 5.00354$. Consequently, (5) becomes:

$$0.25 \beta_0 f_r = 5.00354 \qquad (8)$$

Therefore, $\beta_0 = 6.67139$. It was observed that this same value is not obtained for other CFRP-singly reinforced sections with various combinations of CFRP and concrete strengths. The value of modulus of rupture, f_r, of concrete seems very conservative compared to steel reinforced concrete. For a higher value of modulus of rupture of concrete, f_r which is $0.8\sqrt{f_c}$, β_0 becomes 5.00354.

Taking ratio of β_0 for $0.6\sqrt{f_c}$ toβ_0 for$0.8\sqrt{f_c}$, gives a value of 1.3333333333 for various combinations of CFRP and concrete strengths [9]. This is shown in Table 1.

3. MATERIALS AND METHODS

3.1 Materials

Two sizes of CFRP reinforcement bars, 8mm and 3mm diameters, produced by Mitsubishi Chemical Company, Japan, were used in the test programme. The diameters of the bars were measured as 7.98mm and 2.87mm for the 8 and 3mm diameters respectively. The measured diameters and the manufacturers' guaranteed tensile strengths of $1970N/mm^2$*and* $1431N/mm^2$ for 8mm and 3mm bars respectively, were used in the design calculations. Normal concrete of $25N/mm^2$compressive strength was used. This was ascertained by laboratory tests.

3.2 Specimens

Eight specimens of two-way spanning slabs reinforced with CFRP bars were used in the experiment. They were designed to achieve two classical failure modes: rupture of the reinforcements (tension failure) and crushing of the concrete while the reinforcement remains elastic (compression failure). This was accomplished by using reinforcement ratios less, and more than the balanced reinforcement ratio,ρ_{frpb}, for the slabs, respectively. Table 2 gives the details of test specimens.

Table 1: Underestimation for various CFRP-singly reinforced concrete sections

S/N	Strength of CFRP N/mm²	Strength of Conc N/mm²	C_{opt}^{m}	K_{opt}^{m}	β_0 for $0.6\sqrt{f_c}$ (1)	β_0 for $0.8\sqrt{f_c}$ (2)	Ratio $\frac{1}{2}$	% Under estimation	Objective Function Y
1	1431	20	0.49981	4.00299	5.96749	4.47548	1.333	33.33	0.5941
		25	0.44705	5.00354	6.67139	5.00354	1.333	33.33	0.5312
		30	0.40811	6.00396	7.30779	5.48084	1.333	33.33	0.4849
		35	0.37785	7.00423	7.89288	5.91966	1.333	33.33	0.4488
		40	0.35345	8.00434	8.43731	6.32798	1.333	33.33	0.4198
		50	0.31014	10.3961	9.80159	7.35119	1.333	33.33	0.3682
		60	0.28312	12.4749	10.7367	8.05257	1.333	33.33	0.3360
2	1970	20	0.49875	4.02008	1.49819	1.12365	1.333	33.33	0.5920
		25	0.44610	5.02499	1.67499	1.25625	1.333	33.33	0.5393
		30	0.40724	6.02975	1.83479	1.37610	1.333	33.33	0.4924
		35	0.37703	7.03474	1.98181	1.48636	1.333	33.33	0.4861
		40	0.35269	8.03922	2.11852	1.58889	1.333	33.33	0.4261
		50	0.31546	10.0487	2.36850	1.77638	1.333	33.33	0.3787
		60	0.28799	12.0572	2.59430	1.94572	1.333	33.33	0.3478
6	2255	20	0.49857	4.02006	5.99275	4.49456	1.333	33.33	0.59401
		25	0.44609	5.02501	6.70001	5.02501	1.333	33.33	0.53130
		30	0.40723	6.02992	7.33938	5.50539	1.333	33.33	0.48202
		35	0.37702	7.03477	7.92729	5.94547	1.333	33.33	0.44849
		40	0.35268	8.03956	8.47444	6.35583	1.333	33.33	0.41953
		50	0.31545	10.0489	9.47422	7.10566	1.333	33.33	0.37505
		60	0.28798	12.0579	10.3778	7.78336	1.333	33.33	0.33190

3.3 Experimental Procedure

Figure 1 shows a schematic diagram of the test setup. The slab is a two-way spanning square slab supported along four sides on a wooden frame. The slabs were supported on four sides on a wooden frame mounted on steel supports. A steel plate was placed on the slab to ensure that applied load is uniformly distributed over the slab surface. The slabs were loaded by manually operated hydraulic machine and readings taken as indicated by the dial gauge at failure of the slabs. Four of the slabs were designed to fail by rupture of reinforcement, which is tension failure. The other four slabs were designed to fail by crushing of concrete, which is compression failure.

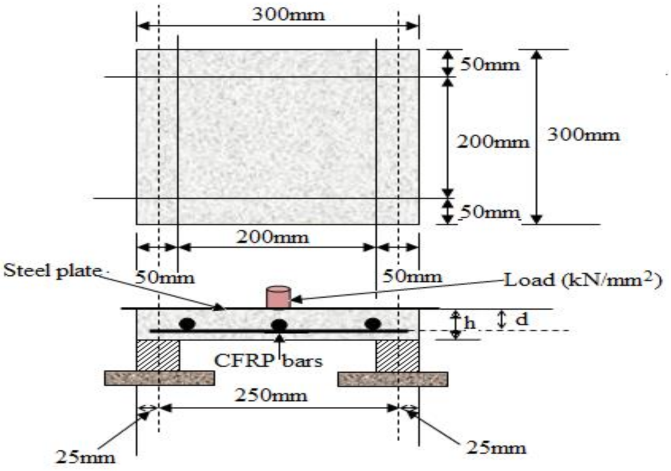

Figure 1: Schematic diagram of the test setup

3.4 Design of Experimental Slabs

Table 2 shows the details of test specimens, while the properties of the materials used in the experiment are shown in Table 3.

3.3 Validation Procedure

SLAB 1: (h = 150mm) for 8mm diameter CFRP bar (Actual diameter = 7.98mm)

Spacing of rods, S = 150mm centres

Concrete cover, c $= 2.5d_b = 2.5 \times 8 = 20mm$

$$\text{Effective depth}, d = 150 - \left(20 + \frac{7.98}{2} \times 2\right) = 122.02mm$$

$$\text{Area of reinforcement}, A_{frp} = A_b \times \frac{1000}{S}$$

$$= 333.427mm^2/m$$

$$\text{Reinforcement ratio}, \rho_{frp} = \frac{A_{frp}}{bd} == 0.00273$$

Balanced reinforcement ratio, ρ_{frpb}

Balanced reinforcement ratio ρ_{frpb}

$$= \alpha_1 \beta_1 \frac{\phi_c f_c}{\phi_f f_{frpu}} \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frpu}}\right),.$$

where,

$$\beta_1 = 0.97 - 0.0025 f_c' = 0.97 - 0.0025 \times 25 = 0.9075 \geq 0.67, \text{Ok.}$$

$$\alpha_1 = 0.85 - 0.0015 f_c' = 0.85 - 0.0015 \times 25 = 0.8125 \geq 0.67, \text{Ok,}$$

$\phi_c = 0.6 =$ material resistance reduction factor for concrete [6]

$\phi_f = 0.75 =$ material resistance factor for CFRP [6]

$$\rho_{frpb} = 0.8125 \times 0.9075\left(\frac{0.60}{0.75}\right)\left(\frac{25}{1970}\right)\left(\frac{0.0035}{0.0035+0.013}\right) = 0.00159 < 0.00273$$

$\rho_{frp} > \rho_{frpb}$; Therefore failure will be by concrete crushing (Compression failure).

Stress in CFRP at ultimate limit state (ULS)

$$f_{frp} = 0.5E_{frp}\varepsilon_{cu}\left[\left[1+\frac{4\alpha_1\beta_1 f_c'}{\rho_{frp}\phi_{frp}E_{frp}E_{cu}}\right]^{1/2} - 1\right] = 1936/mm^2$$

Moment of Resistance

$$M_r = \phi_{frp}f_{frp}A_{frp}\left(d-\frac{a}{2}\right)$$

Neutral axis =

$$a = \frac{\phi_{frp}E_{frp}\varepsilon_{frp}A_{frp}}{\phi_c(\alpha_1 f_c'\ )b} = 40.42mm$$

$$M_{rcode} = \phi_{frp}f_{frp}A_{frp}\left(d-\frac{a}{2}\right) = 49.29kNm/m$$

$$M_{crack} = 0.25 f_r bd^2 = 11.167kNm/m$$

$$M_{crackropt} = 0.3325 f_r bd^2 = 14.852kNm/m$$

$$M_{rexp} = \alpha_{sx}nl_x^2 = 57.00kNm/m$$

where, M_{rcode} is the moment of resistance given by the code, M_{crack} is the cracking moment of concrete, $M_{crackropt}$ is the optimized cracking moment of concrete and M_{rexp} is the moment of resistance due to experiment.

SLAB 2: (h = 100mm) for 8mm diameter CFRP bar (Actual diameter = 7.98mm)

Spacing of rods, S = 150mm centres

Concrete cover, c = 20mm

$$\text{Effective depth} \quad d = 100 - 20 - \frac{7.98}{2}\times 2 = 72.02mm$$

$$\text{Area of reinforcement}, A_{frp} = A_b \times \frac{1000}{S} = 333.427mm^2/m$$

$$\text{Reinforcement ratio}, \rho_{frp} = \frac{A_{frp}}{bd} = 0.00463$$

Balanced reinforcement ratio, ρ_{frpb}

$$\text{Balanced reinforcement ratio}, \rho_{frpb} = \alpha_1\beta_1\frac{\phi_c f_c'}{\phi_f f_{frpu}}\left(\frac{\varepsilon_{cu}}{\varepsilon_{cu}+\varepsilon_{frpu}}\right),$$

$\rho_{frpb} = 0.00159 < 0.00465$; $\rho_{frp} > \rho_{frpb}$;

$\rho_{frp} > \rho_{frpb}$; Therefore failure will be by concrete crushing (Compression failure).

Stress in CFRP at ultimate limit state (ULS)

$$f_{frp} = 0.5E_{frp}\varepsilon_{cu}\left[\left[1+\frac{4\alpha_1\beta_1 f_c'}{\rho_{frp}\phi_{frp}E_{frp}E_{cu}}\right]^{1/2} - 1\right] = 1434N/mm^2$$

Moment of Resistance: $M_r = \phi_{frp}f_{frp}A_{frp}\left(d-\frac{a}{2}\right)$

Neutral axis

$$a = \frac{\phi_{frp}E_{frp}\varepsilon_{frp}A_{frp}}{\phi_c(\alpha_1 f_c'\ )b} = 40.42mm$$

$$M_{rcode} = \phi_{frp}f_{frp}A_{frp}\left(d-\frac{a}{2}\right) = 18.58kNm/m$$

$$M_{crack} = 0.25 f_r bd^2 = 3.890kNm/m$$

$$M_{crackropt} = 0.3325 f_r bd^2 = 5.174kNm/m$$

$$M_{rexp} = \alpha_{sx}nl_x^2 = 34.20kNm/m$$

Table 2: Details of test specimens

Slab Thickness (h)	Bar Diameter	Slab mark	Area of bar (mm^2)	ρ_{frp}	ρ_{frpb}	Predicted mode of failure
						Compression failure
150mm	7.98mm	SH150-D8	333.427	0.00273	0.00159	Crushing of concrete
150mm	7.98mm	SH150-D8	333.427	0.00273	0.00159	Crushing of concrete
						Tension failure
150mm	2.87mm	SH150-D3	43.133	0.00034	0.00215	Rupture of rebars
150mm	2.87mm	SH150-D3	43.133	0.00034	0.00215	Rupture of rebars
						Compression failure
100mm	7.98mm	SH100-D8	333.427	0.00463	0.00159	Crushing of concrete
100mm	7.98mm	SH100-D8	333.472	0.00463	0.00159	Crushing of concrete
						Tension failure
100mm	2.87mm	SH100-D3	43.133	0.00056	0.00213	Rupture of rebars
100mm	2.87mm	SH100-D3	43.133	0.00056	0.00213	Rupture of rebars

Table 3: Properties of Materials Used

Diameter of CFRP bar (mm)	Area of CFRP bar (mm^2)	Tensile strength of CFRP bar (N/mm^2)	Ultimate of CFRP bar strain	Elastic modulus CFRP of bar (N/mm^2)	Compressive strength of concrete (N/mm^2)
8 (7.98)	50.014	1970	0.0130	151538	25
3 (2.87)	6.47	1431	0.0119	120000	25

SLAB 3: (h = 150mm) for 3mm diameter CFRP bar (Actual diameter = 2.87mm)
Spacing of rods, S = 150mm centres
Concrete cover, c = 20mm

$$\text{Effective depth} \quad d = 150 - 20 - \left(\frac{2.87}{2} \times 2\right) = 127.13mm$$

$$\text{Area of reinforcement}, A_{frp} = A_b \times \frac{1000}{S} = 43.133mm^2/m$$

$$\text{Reinforcement ratio}, \rho_{frp} = \frac{A_{frp}}{bd} = 0.000339$$

Balanced reinforcement ratio, ρ_{frpb}

$$\text{Balanced reinforcement ratio}, \rho_{frpb} = \alpha_1\beta_1 \frac{\phi_c f_c'}{\phi_f f_{frpu}}\left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frpu}}\right)$$

$$\rho_{frpb} = 0.00234 > 0.000339$$

$\rho_{frp} > \rho_{frpb}$; Therefore failure will be by CFRP rupture (Tension failure).

Stress in CFRP at ultimate limit state (ULS)

$$f_{frp} = 0.5E_{frp}\varepsilon_{cu}\left[\left[1 + \frac{4\alpha_1\beta_1 f_c'}{\rho_{frp}\phi_{frp}E_{frp}E_{cu}}\right]^{1/2} - 1\right] = 5312N/mm^2$$

Neutral axis

$$f_{frp} = \frac{f_{frp}}{E_{frp}} = 0.0443$$

$$c = \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frp}} \times d = 9.309mm$$

$$M_{rcode} = A_{frp}\phi_{frp}f_{frp}\left(d - \frac{\beta_c}{2}\right) = 21.120kNm/m$$

$$M_{crack} = 0.25f_r bd^2 = 12.122kNm/m$$

$$M_{crackropt} = 0.3325f_r bd^2 = 16.122kNm/m$$

$$M_{rexp} = \alpha_{sx}nl_x^2 = 53.20kNm/m$$

SLAB 4: (h = 100mm) for 3mm diameter CFRP bar (Actual diameter =2.87mm)
Spacing of rods, S = 150mm centres
Concrete cover, c = 20mm

$$\text{Effective depth}, \quad d = 100 - 20 - \left(\frac{2.87}{2} \times 2\right) = 77.13mm$$

$$\text{Area of reinforcement}, A_{frp} = A_b \times \frac{1000}{S} = 43.133mm^2/m$$

$$\text{Reinforcement ratio}, \rho_{frp} = \frac{A_{frp}}{bd} = \frac{43.133}{1000 \times 77.13} = 0.000559$$

Balanced reinforcement ratio, ρ_{frpb}

$$\text{Balanced reinforcement ratio}, \rho_{frpb} = \alpha_1\beta_1 \frac{\phi_c f_c'}{\phi_f f_{frpu}}\left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frpu}}\right)$$

$$\rho_{frpb}0.00234 > 0.000559$$

$\rho_{frp} > \rho_{frpb}$; Therefore failure will be by CFRP rupture (Tension failure).

Stress in CFRP at ultimate limit state (ULS)

$$f_{frp} = 0.5E_{frp}\varepsilon_{cu}\left[\left[1 + \frac{4\alpha_1\beta_1 f_c'}{\rho_{frp}\phi_{frp}E_{frp}E_{cu}}\right]^{1/2} - 1\right] = \frac{4092.403N}{mm^2}$$

Neutral axis

$$f_{frp} = \frac{f_{frp}}{E_{frp}} = 0.0341$$

$$c = \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{frp}} \times d = 7.18mm$$

$$M_{rcode} = A_{frp}\phi_{frp}f_{frp}\left(d - \frac{\beta_c}{2}\right) = 9.78kNm/m$$

$$M_{crack} = 0.25f_r bd^2 = 4.462kNm/m$$

$$M_{crackropt} = 0.3325f_r bd^2 = 5.934kNm/m$$

$$M_{rexp} = \alpha_{sx}nl_x^2 = 34.2kNm/m$$

4. RESULTS AND DISCUSSION

The results of the failure modes are shown in Table 3. From the Table, it is evident that four of the slabs failed by crushing of concrete while the reinforcement remained elastic, and four failed by rupture of the reinforcement before concrete crushed. All the slabs failed as predicted.

The details of the failure moment of the tested CFRP reinforced concrete slabs are presented in Table 4. It is clear from the results that the resistance moment is affected by the depth of the section, aside reinforcement ratio, which determines failure mode.

Table 4: Failure Moments of Specimens

Slab Specimen	M_{rcode} (kNm/m)	M_{rcrack} (kNm/m)	$M_{rcrackopt}$ (kNm/m)	$M_{experiment}$ (kNm/m)	Failure Mode
SH150-D8	49.29	11.167	14.852	57.000	Compression failure (Crushing)
SH150-D8	49.29	11.167	14.852	57.000	Compression failure (Crushing)
SH150-D3	21.12	12.122	16.122	53.200	Tension failure (Rupture)
SH150-D3	21.12	12.122	16.122	53.200	Tension failure (Rupture)
SH100-D8	18.58	3.890	5.174	34.200	Compression failure (Crushing)
SH100-D8	18.58	3.890	5.174	34.200	Compression failure (Crushing)
SH100-D3	9.78	4.462	5.934	34.200	Tension failure (Rupture)
SH100-D3	9.78	4.462	5.934	34.200	Tension failure (Rupture)

This is seen in the difference between the $M_{r,code}$ and $M_{r,exp}$ in the tension failure modes. This is expected since the reinforcement ruptures before the concrete crushes, proving that concrete has not reached its ultimate strain.

It is interesting to note that the ratios of $M_{r,crackopt}$ to $M_{r,code}$ in the compression failure modes are 0.3013 for 150mm thick slab, and 0.2785 for 100mm thick slab, respectively; whereas the ratios of $M_{r,crack}$ to $M_{r,code}$ for the same slabs are 0.2266 and 0.2094 respectively. Taking the average of the two values, 0.3013 and 0.2785, we have 0.2899, which is approximately 0.29. It is seen also that the ratio of $M_{r,crackpot}$ to $M_{r,crack}$is 1.33 in both slabs of thickness 150mm and 100mm. This means that the value of resistance moment of the concrete could be raised by about 33%. This value agrees with the value earlier obtained by [7]. Thus, the moment of resistance of a singly CFRP reinforced rectangular solid slab section may be expressed as:

$$M_r = 0.3325 f_r b d^2 \tag{9}$$

5. CONCLUSION

This work has critically looked at the varying complexities connected with the structural behaviour of CFRP singly-reinforced concrete slab sections, generally in their design formulations. As in the design of steel-reinforced concrete elements, the design requirements for FRP-reinforced concrete elements are strength requirements at the ultimate limit state and serviceability requirements for cracking and deflection. While the design of steel-reinforced elements is normally governed by the strength or ultimate limit state, FRP-reinforced concrete members are controlled by serviceability requirements, such as crack widths and deflections.

The design formulations for predicting the minimum flexural resistance of an FRP-reinforced concrete member provided by [6], has been optimized deterministically. The design formulations were found to underestimate the resistance moment capacity of FRP-reinforced concrete slabs by about 33% when considering the wholly rectangular stress block. This is the percentage underestimation of the cracking moment of concrete and validated in the laboratory by experiment. The findings herein lead to the following suggested equation to evaluate the resistance moment of FRP-reinforced rectangular concrete slabs:

$$M_u = 0.3325 f_r b d^2 \tag{10}$$

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