



FLEXURAL STRENGTHENING WITH FRP SYSTEMS EXPERIMENTAL RESULTS VS. EXPECTED RESULTS BASED ON ACTUAL DESIGN GUIDELINES

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ABSTRACT: This paper describes the design criteria for flexural strengthening of reinforced concrete structures with FRP systems presented in the design guidelines published by FIB [1] and ACI[2]. Two laboratory research programs were carried out, one at the Faculty of Engineering University of Oporto (FEUP) and the second at University of Minho (UM). An analysis is presented comparing experimental results of these programs and predicted results by the FIB and ACI proposals.

1. INTRODUCTION

The characteristics of fibre reinforced polymers (FRP), the particularities of elements reinforced by FRP systems and issues related to the bond technique, emphasize the urgent need to establish specific rules for the application of these strengthening systems in civil construction. Recently, some design guidelines have been published with the main objective of defining dimensioning criteria for structures strengthened with FRP in accordance with the current format of calculation of reinforced concrete structures and prestressed concrete structures. FIB bulletin 14 [1] and the publication of the ACI committee 440 [2] are the two documents taken into account in this paper.

The main objectives of this investigation are to evaluate the suggested design criteria in these manuals, for the application of this technique of structural strengthening by external bonding (EBR), as well as checking its adequacy to a more recent strengthening technique known NSMR or "near surface mounted reinforcement". This paper presents a comparative analysis between the results of two experimental programs and predicted ones, applying design criteria suggested by FIB and ACI. Special emphasis is given to the flexural strengthening design and to the definition of design criteria, main object of the master thesis in course by Azevedo [3].

2. FLEXURAL STRENGTHENING OF RC STRUCTURES BY FRP SYSTEMS

The following items summarize the dimensioning philosophy, pointing out principles of calculation and safety concepts in the two documents analysed, FIB [1] and ACI [2].

2.1 General Considerations

Calculation is based on analytical models and it is assumed that: i) the principle of Euler-Bernoulli is valid; ii) perfect compatibility of deformations between materials, imposing a diagram of linear extensions throughout all the strengthened section; iii) Force equilibrium is assured; iv) tension strength of concrete is neglected; v) the FRP presents a linear elastic behaviour until failure. Based on these principles and taking into account the initial strength and deformation state of the element, before the application of the reinforcement, as well as the constitutive laws of the materials, it is possible to predict the behaviour of a structure strengthened for bending with FRP in

ultimate limit state (ULS) and serviceability limit state (SLS). In this paper, only the ULS analysis is studied. The design strength moment (M_{Rd}) is obtained by the Equation 1 and Equation 2 for FIB and ACI respectively.

$$M_{Rd} = \begin{cases} A_s \cdot f_{syd} \cdot (d - \frac{\lambda}{2} \cdot x) + A_f \cdot E_f \cdot \varepsilon_f \cdot (h - \frac{\lambda}{2} \cdot x) & \text{with } \lambda = 0,80 - \text{FIB} \end{cases} \quad (1)$$

$$M_{Rd} = \begin{cases} A_s \cdot f_{syd} \cdot (d - \frac{\beta_1}{2} \cdot x) + \psi_f \cdot A_f \cdot E_f \cdot \varepsilon_f \cdot (h - \frac{\beta_1}{2} \cdot x) & \text{with } \beta_1 = 0,80 - \text{ACI} \end{cases} \quad (2)$$

The ACI publication introduces a parameter " ψ_f ", as a safety coefficient for the FRP flexural strength contribution, as it is a recent technique.

2.2 Failure Modes

The strength capacity of a structural section depends on the control of the failure modes. The collapse of a structure strengthened in bending with FRP can occur by: i) Concrete crushing before steel yielding; ii) Steel yielding followed by FRP fracture; iii) Steel yielding followed by concrete crushing; iv) Concrete crushing coincident with steel yielding and FRP fracture; v) Delamination of the concrete substrate due to shear/tension; vi) Debonding at the interfaces concrete-adhesive or adhesive-FRP. In cases i) to iv), it is assumed full composite action between materials until failure and in v) and vi) cases the failure is premature due to loss of composite action.

Imposing one of the first four failure modes and limiting the extension on the conditioning material, it is possible to determine, by force equilibrium, the neutral axis position and calculate the effective extension in the FRP, the extensions and the stresses in the internal steel reinforcement. However, in the design it is necessary to consider the hypothesis of occurrence of the characteristic premature failures in structures strengthened for bending by EBFPR. Due to difficulty in detecting them, the current information on the safety criteria is small. One hypothesis consists in limitation of the FRP deformation.

2.3 FRP Deformation Level

This item describes the method proposed by each publication to analyse the premature failure modes by debonding of FRP in ULS. In a general way, the proposals advise the control of the FRP deformation level at the critical section, as well as other safety verifications such as at the anchorage zone, stresses at interface and crack spacing.

The ACI imposes a calculation criterion for the maximum FRP extension value to avoid premature failures. A " k_m " parameter that depends on its thickness (t_f), its modulus of elasticity (E_f) is suggested as presented in Equation 4. The design extension value (ε_{fd}) is obtained through Equation 3:

$$\varepsilon_{fd} = k_m \cdot \varepsilon_{fk} \quad (3)$$

$$k_m = \begin{cases} \frac{1}{60 \cdot \varepsilon_{fk}} \cdot \left(1 - \frac{n \cdot E_f \cdot t_f}{360000} \right) \leq 0,90 & \text{if } n \cdot E_f \cdot t_f \leq 180000 \\ \frac{1}{60 \cdot \varepsilon_{fk}} \cdot \left(\frac{90000}{n \cdot E_f \cdot t_f} \right) \leq 0,90 & \text{if } n \cdot E_f \cdot t_f > 180000 \end{cases} \quad (4)$$

The FIB document does not impose a specific restriction for the FRP deformation to control premature failures, although it admits that the FRP must obey, in the critical section, to the condition (5):

$$\varepsilon_{f \min} \leq \varepsilon_f \leq \varepsilon_{fd} \quad (5)$$

$$\varepsilon_{f \min} = f(\text{ductility criteria}) [1] \quad (6)$$

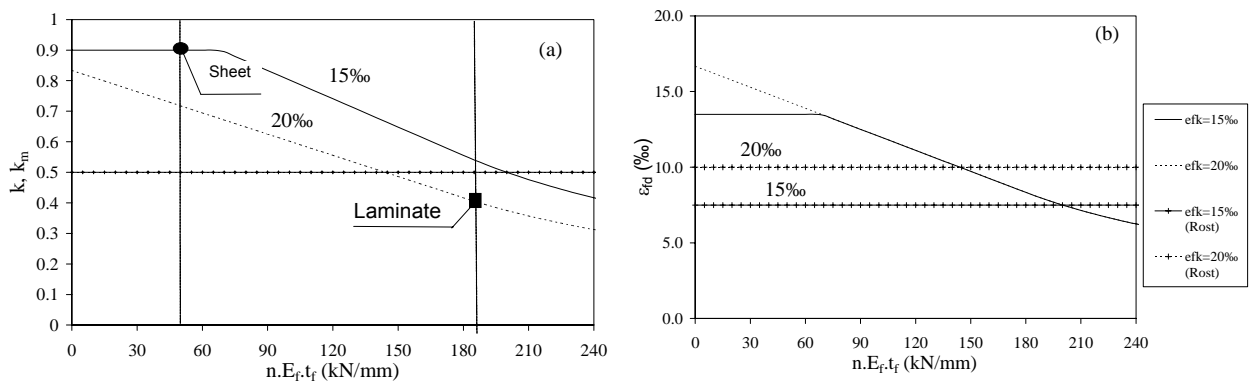
Rostasy and Neubauer [4] studies should be mentioned, where recommendations are suggested in terms of the limitation of the maximum value of the FRP extension to the smaller value of the conditions (7) and (6). To simplify, in this paper, this criterion will be mentioned as the “Rostasy criterion”.

$$\varepsilon_{fd} \leq 5 \cdot \varepsilon_{sy} \quad (7)$$

$$\varepsilon_{fd} \leq 0,50 \cdot \varepsilon_{fk} = k \cdot \varepsilon_{fk} \quad (8)$$

According to FIB, the analysis of the premature failure mechanisms can be carried out through a series of specific verifications that will not be analysed in this paper.

The variations of k_m , k and of ε_{fd} with the product $n \cdot E_f \cdot t_f$ (axial rigidity of the reinforcement per unit of FRP width) are presented in Fig. 1 (a) and (b), for two values of ε_{fk} (15‰ and 20‰, usual in commercial systems). The increase of rigidity and of the ultimate extension of the FRP leads to a reduction of k_m , or either, a reduction of the effective design extension of the FRP. Analysing Fig. 1, according to ACI, for a commercial FRP laminate ($\varepsilon_{fk} \sim 20‰$) with $n \cdot E_f \cdot t_f = 192000 \text{ N/mm}$, a maximum exploitation of $0,39 \cdot \varepsilon_{fk}$ can be admitted in the calculation. For a two layer sheet of ($\varepsilon_{fk} \sim 15‰$) and $n \cdot E_f \cdot t_f = 51060 \text{ N/mm}$ (26,6% of the laminate rigidity) the maximum exploitation is $0,90 \cdot \varepsilon_{fk}$. The Rostasy criterion proposes the same maximum value of exploitation for the two types of FRP ($0,50 \cdot \varepsilon_{fk}$).



(a) FRP deformation limitation criteria.

(b) Maximum FRP extension criteria

Figure 1

3. EXPERIMENTAL PROGRAM

To evaluate the design principles suggested in the FIB and ACI publications, two experimental programs are presented on the flexural strengthening of RC structures with FRP through the externally bonding reinforcement technique (EBR) [5] and through the near surface mounted reinforcement technique (NSMR)[6].

3.1 EBR Strengthening Technique

An experimental program of strengthening was carried out by Juvandes and Dias, at FEUP [5]. This program was based on a campaign of bending tests on four series of reinforced concrete slabs. The series were named as: series N (reinforced concrete models with $6\phi 6$), series M (reinforced concrete models strengthened with FRP sheet cast "in situ") and series L (reinforced concrete models strengthened with FRP laminates). In each one of series M and L, two models with pre-cracked concrete had been strengthened.

Table 1 refers to, main results in terms of maximum extension observed in the FRP (ϵ_{fmax}), the maximum bending moment (M_{max}) as well as the failure mode, for the selected models.

Table 1 – Experimental Results for Slab Models [5].

Slabs			ϵ_{fmax}	M_{max}	Failure Mode
Series	Model	FRP system	(‰)	(kN.m)	
M	LC3R	Replark 20	10,92	11,08	FRP rupture [FR]
M fend.*	LA3R		11,14	10,32	
L	LC2S	CarboDur S512	11,83	7,67	FRP debonding [FD]
L fend.*	LB2S		9,18	7,78	
L	LD4BL	MBrace Laminate LM	10,42	6,88	
L	LE4I	INEGI Laminate	10,24	6,60	

* - pre-cracked models before strengthening.

3.2 NSMR Strengthening Technique

An experimental program carried out at UM by Fortes [6] is presented. The program consisted the strengthening of four series of RC beams by the NSMR technique through which small laminates are inserted in the concrete cover layer. Eight beams with rectangular cross-section were distributed by 4 series of 2 beams, having each series a different longitudinal steel reinforcement ratio. In each one of the series, only one beam was strengthened. The FRP reinforcement was dimensioned in order to achieve, in the strengthened beams, a double strength capacity compared to the unstrengthened beams, resulting in 3 strengthening systems consisting of 1, 2 and 3 laminates, depending on the steel reinforcement ratio, ρ_s , of each series.

Table 2 refers to the main results in terms of maximum extension observed in the FRP (ϵ_{fmax}), maximum bending moment (M_{max}) as well as the failure mode just for the strengthened models.

Table 2 – Experimental results for beam models [6].

Beams			ϵ_{fmax}	M_{max}	Failure Mode
Series	Model	FRP system	(‰)	(kN.m)	
2	V2R2	Laminate	12,8	19,73	FRP Delamination [FDel]
3	V3R2	(No Commercial	12,8	20,59	
4	V4R3	reference)	10,6	23,84	

4. RESULT ANALYSIS

Maximum bending moments and deformation values in the experimentally observed FRP are compared with the predicted values according to FIB [1] and ACI [2] documents.

Using a MathCAD spreadsheet developed by Azevedo [3], two distinct calculations were defined. In the first one, named "crit.1", the average properties of the materials are considered, but the value of the safety factor ψ_f suggested in ACI is 0,85 and, the indications of Rostasy [4] are taken into account in the calculation in accordance with FIB philosophy. In the second one, named

"crit.2", the average properties of the materials are also considered, the philosophies of the two documents are respected (allowing the FRP to reach maximum possible extension) and a unitary value for the safety factor ψ_f suggested in ACI is imposed.

4.1 EBR Strengthening Technique

Table 3 refers to the necessary data for the estimation of the strength capacity of each experimental model according to each of the philosophies referred.

Table 3 – Slab cross-sections data and FRP mechanical properties [3]

Series	Model	b	h	d	As	ρ_s	f_{cm}	f_{sym}	E_{sm}	E_f^*	ϵ_{fk}^*	A_f	ρ_f
		(cm)	(cm)	(cm)	(cm ²)	(%)	(MPa)	(MPa)	(GPa)	(GPa)	(‰)	(cm ²)	(%)
M	LC3R	44,0	8,1	6,8	0,85	0,28	63,3	635,6	225,3	230	15,0	0,31	0,09
M fend	LA3R	44,0	7,6	6,3	0,85	0,31	63,3	635,6	225,3	230	15,0	0,31	0,09
L	LC2S	44,0	8,4	7,1	0,85	0,27	63,3	635,6	225,3	160	20,0	0,38	0,10
L fend	LB2S	44,0	8,5	7,2	0,85	0,27	63,3	635,6	225,3	160	20,0	0,38	0,10
L	LD4BL	44,0	8,1	6,8	0,85	0,28	49,7	555,0	225,3	150	14,0	0,45	0,13
L	LE4I	44,0	7,8	6,5	0,85	0,30	49,7	555,0	225,3	160	15,0	0,45	0,13

* - values supplied by the manufacturers

Table 4 and Fig. 2 (a) and (b) concern the FRP extension at failure (ϵ_{fu}), the moment at failure (M_u) and the failure mode, the experimental results observed and the predicted results adopting the design criteria of FIB and ACI.

Table 4 – Experimental results vs. Predicted results by FIB e ACI.

Series	Model	Experimental			FIB				ACI				
		ϵ_{fu}	M_u	Failure Mode	Crit.1		Crit.2		Failure Mode	ϵ_f	Crit.1		Failure Mode
					ϵ_f	M_u	ϵ_f	M_u			M_u	M_u	
M	LC3R	10,92	10,75	FR	7,50	7,61	15	11,81	FR	13,5	9,80	10,92	FR
M fend	LA3R	11,14	8,74	FR	7,50	7,09	15	11,02	FR	13,5	9,13	10,18	FR
L	LC2S	11,83	10,37	FD	10,0	8,60	20	13,54	FR	7,81	6,91	7,49	FR
L fend	LB2S	9,18	9,20	FD	10,0	8,71	20	13,72	FR	7,81	7,00	7,59	FR
L	LD4BL	10,42	8,86	FD	7,00	6,63	14	10,30	FR	7,14	6,17	6,62	FR
L	LE4I	10,24	8,79	FD	7,50	6,86	15	10,85	FR	6,70	5,90	6,44	FR

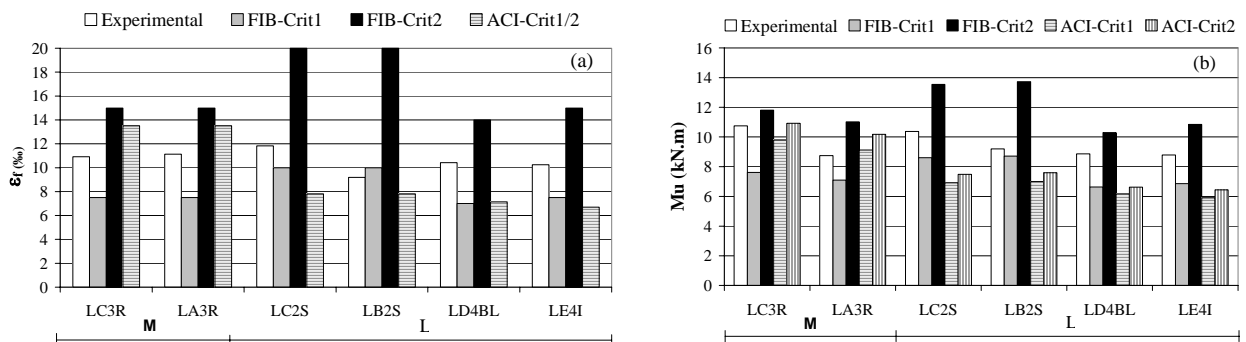


Figure 2: Experimental vs. analytical predictions by FIB and ACI: ϵ_f (a) and M_u (b).

In terms of maximum FRP deformations (Fig. 2 (a)), it can be observed that: i) The introduction of limitation criteria for the maximum value of FRP extension in the calculation tends to the

experimental behaviour; ii) Comparing with experimental behaviour at failure, the maximum effective FRP extension suggested in ACI (crit.1/crit.2) is lower for models strengthened with laminates and higher for models strengthened with sheets.

In terms of strength capacity (Fig. 2 (b)), it can be observed that: i) The FIB philosophy (crit.2) predicts values above the experimental ones for all the studied models, except if, in the calculation, the Rostasy criterion (FIB-crit.1) is introduced; ii) Failure in the experimental models occurred before the predicted by the models strengthened with sheets (except in the calculation using the Rostasy criterion (FIB-crit.1)) and much later than predicted by the models strengthened with laminates, these results being more conservative in respect to the ACI philosophy (crit.1/crit.2); iii) the pre-cracked models behave in a similar way to the rest, independently of the applied FRP system. This is not contemplated in the ACI and FIB philosophies.

4.2 NSMR Strengthening Technique

Table 5 refers to the necessary data for estimation of the strength capacity of each experimental model according to each of the philosophies referred.

Table 5 – Beam cross-sections data and FRP mechanical properties [3]

Model	b (cm)	h (cm)	d (cm)	As (cm ²)	ρ_s (%)	f_{cm} (MPa)	f_{sym} (MPa)	E_{sm} (GPa)	f'_{sym} (MPa)	E'_{sm} (GPa)	E_f^* (GPa)	ϵ_{fk}^* (%)	A_f (cm ²)	ρ_f (%)
V2R2	10,0	17,7	15,30	0,848	0,56	46,1	750	200	500	200	158	17,0	0,2781	0,16
V3R2	10,0	17,5	15,06	1,068	0,71	46,1	500	200	500	200	158	17,0	0,2781	0,16
V4R3	10,0	18,0	15,50	1,508	0,97	46,1	500	200	500	200	158	17,0	0,4172	0,23

* Values obtained by test

Table 6 and Fig. 3 (a) and (b) concern the FRP extension at failure (ϵ_{fu}), the moment at failure (M_u) and the failure mode, the experimental results observed and the predicted results adopting design criteria of FIB and ACI.

Table 6 – Experimental results vs. Predicted results by FIB e ACI.

Model	Experimental			FIB						ACI				
				Crit.1		Crit.2		Crit.1		Crit.2				
	ϵ_{fu} (%)	M_u (kN.m)	Failure Mode	ϵ_f (%)	M_u (kN.m)	Failure Mode	ϵ_f (%)	M_u (kN.m)	Failure Mode	ϵ_f (%)	M_u (kN.m)	Failure Mode	M_u (kN.m)	Failure Mode
V2R2	12,8	19,73	FDel	8,5	14,88	FR	15,62	19,64	CC	6,55	12,76	FR	13,44	FR
V3R2	12,8	20,59	FDel	8,5	13,33	FR	16,23	18,47	CC	6,55	11,23	FR	11,91	FR
V4R3	10,6	23,84	FDel	8,5	19,52	FR	13,04	24,03	CC	6,55	16,34	FR	17,38	FR

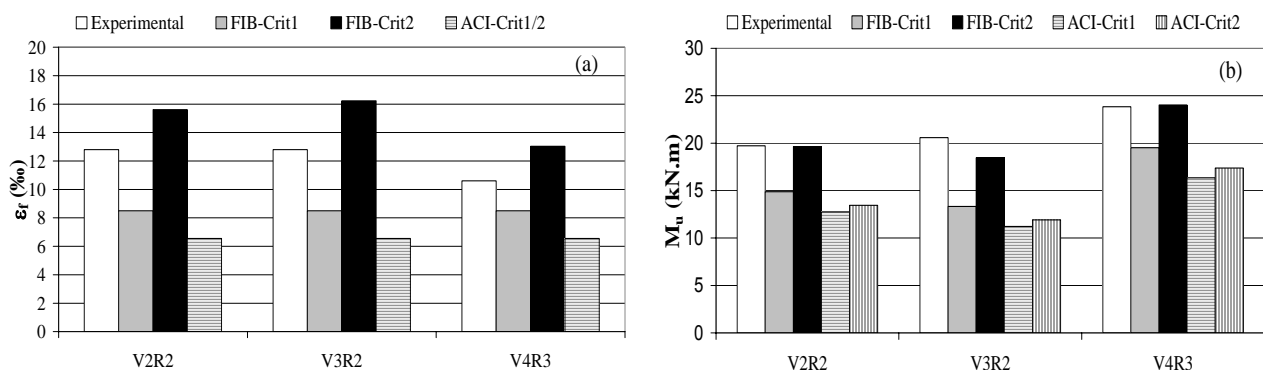


Figure 3: Experimental vs. analytical predictions by FIB and ACI: ϵ_f (a) and M_u (b).

In terms of maximum FRP deformations (Fig. 3 (a)), it can be observed that: i) The FRP deformation levels at failure obtained by FIB (crit.2) without imposing extension limitation, are higher than the experimentally obtained, but closer than in the models strengthened by EBR; ii) The limitation criteria for deformation adopted, following the ACI guidelines – crit.1/crit.2 (k_m and ψ_f) and the philosophy of the FIB-crit.1 through the application of Rostasy criterion (k), revealed to be inadequate.

Analysing Fig. 3 (b) it can be observed that prediction of the strength capacity obtained by FIB (crit.2) leads to values very close to the experimental ones, contrasting with the ones obtained imposing limitations to the FRP extension, which are conservative.

5. CONCLUSIONS

The comparative analysis of experimental results and predicted ones using FIB and ACI documents was carried out with reduced scale models, causing a possible scale effect not taken into account in this work. In this analysis assuming FRP systems mechanical properties values supplied by the manufacturers, can be important therefore not representing accurately the real characteristics of the materials applied in the strengthening.

Using the EBR technique, in the slab models strengthened with laminates it was observed that, in terms of extensions in the FRP, the ACI proposal and the FIB proposal applying the Rostasy criterion lead to similar values and close to the experimental ones. However predicting strength capacity is highly conservative according to these philosophies. Applying the FIB philosophy without any limitation of FRP deformation criterion, the obtained results for either FRP deformations or strength capacity are very far from the observed experimentally. In the slab models strengthened with sheets it was observed that only the FIB proposal associated with the Rostasy criterion still conservative either in terms of FRP deformations or in terms of strength capacity. Applying the ACI philosophy the ψ_f factor, the strength capacity values obtained were very close to the experimental ones demonstrating the utility of this safety coefficient. In these models, the FIB criterion without any limitation to the FRP deformation leads to non-conservative values.

6. REFERENCES

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