

Can Existing Design Codes Be Used to Design Flexural Reinforced Concrete Elements Strengthened with Externally Bonded Novel Materials?

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Abstract. The use of composite overlays to strengthen or rehabilitate existing structural elements has been investigated over the past few decades. The most common composites that were used are based on Glass or Carbon fibers impregnated in an organic polymeric matrix, known as GFRP or CFRP, respectively. Thus, many design codes throughout the world provide methodologies to calculate the flexural strength of reinforced concrete members strengthened with externally bonded Carbon or Glass fiber composites. It is essential to keep in mind that the experimental databases that were used in these codes were based on experiments conducted on these materials. However over the last years new materials have emerged, such as steel fibers (SRP/SRG) and basalt fibers (BFRP), as well as textile reinforced mortars (TRM). In this study the target was to investigate if the analytical models described in the codes can effectively be used to describe these novel materials as well. In order to do so, a statistical analysis was conducted to compare experimental results to results obtained using the methodologies described in the codes. It was found that most codes perform surprisingly well and in only few cases they do not provide acceptable results.

1. Introduction

Over the last decades due to aging infrastructure and an increase in design loads several researchers studied the possibility to rehabilitate or strengthen existing reinforced concrete structures. The answer was given by the use of “exotic” materials such as fiber-reinforced polymers (FRP) that up to that time were very expensive and were used mainly in the aerospace industry [1]. Since then their prices have dropped significantly, and thus their affordability and availability increased. In the first studies Glass, Aramid or Carbon fibers were utilized. The resins used were organic polymers, such as epoxy, polyester, vinylester resins etc. Based on these materials a significant number of experiments were conducted. Due to increasing interest in the aforementioned strengthening systems several organizations decided to develop design codes in order to provide guidance through design tools for civil engineers. These design codes were based on an experimental database containing the aforementioned materials. Some of the codes actually provide specific coefficients for Glass and Carbon fibers. However, during the last decade, new materials have been investigated. These materials include fibers such as basalt [2] and steel [3] and inorganic matrices such as Geopolymer [3] and cementitious mortars [4]. None of the existing codes discuss the use of steel or basalt fibers and even more the use of inorganic matrices.

The codes that were examined in this study include the American Concrete Institute ACI 440 [5], the international federation for structural concrete (fib) [6], the Canadian standard (ISiS) [7], the Japanese code (JSCE) [8], the Egyptian code [9], and the design recommendation presenter by the British



Concrete Society (TR55) [10]. In all these codes several modes of failure are taken in consideration. In normal reinforced concrete design there are mainly two failure modes, yielding of the steel reinforcement and crushing of concrete. When a structural element is strengthened with externally bonded composite materials some additional modes of failure can be identified, such as fracture of the fibers, debonding of the composite, shear failure of the concrete cover. In most codes the failure mode is dictated by the maximum strain that can be developed in the FRP. It was noticed that brittle failures that were based on the delamination of the FRP or the shear failure of the composites occur at much lower strains compared to the characteristic maximum strain of the composite material. Therefore the design methodologies suggest the use of reduction factors in order to drive the design in more ductile modes of failure. However, the new materials mentioned before differ in terms of either the matrix used or the fibers compared to the GFRPs and the CFRPs. The different material properties can very well affect the performance of the strengthened elements. Thus the question that this study tries to answer is if these older codes can be used to predict the flexural capacity of reinforced concrete structural elements strengthened with externally bonded novel composites.

2. Design models

In the following paragraphs a short description of the examined design models is presented.

2.1. American concrete institute (ACI 440.2R-08)

The American Concrete Institute Committee 440 design guidelines [5] are based on strain compatibility as well as force and moment equilibrium. ACI suggests that strain at the time of strengthening, at the concrete substrate, must be considered. FRP is not permitted to carry compressive stresses, according to ACI 440.2R-08. ACI introduces two safety factors ϕ and Ψ_f . The first depends upon the strain in the steel reinforcement at the time of failure, thus it depends upon the mode of failure. More specifically ϕ equals 0.9 for a tension-controlled failure (ductile) while a value of 0.65 is recommended for a compression-controlled failure (brittle without yielding). In the transition zone between the previous two extremes, ϕ can be determined from the linear interpolation. The second factor Ψ_f is a strength reduction factor for the FRP, which is multiplied by the flexural contribution of FRP reinforcement (M_{nf}), as shown in equation (1):

$$M_{nf} = \Psi_f A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2} \right) \quad (1)$$

where:

A_f is the FRP cross sectional area

f_{fe} is the FRP effective strength

d_f is effective depth of FRP shear reinforcement

β_1 is factor taken as 0.85 for concrete strength f_c' up to and including 28 MPa

c is the distance from extreme compression fiber to the neutral axis, in. (mm)

The, Ψ_f , factor is taken as 0.85 based on the reliability analysis of the experimentally calibrated statistical values to mainly account for the less predictable failure mode of delamination of FRP reinforcement [11].

For a FRP-strengthened reinforced concrete section, the following failure modes are likely to take place in flexure: (i) Ductile crushing of concrete: crushing of concrete in compression after yielding of tensile steel (desirable failure mode), (ii) Brittle crushing of concrete: crushing of concrete in compression before yielding of tensile steel (undesirable failure mode), (iii) Rupture of FRP: rupture of FRP reinforcement after yielding of tensile steel (desirable failure mode) and (iv) Debonding of FRP: The intermediate crack-induced debonding of FRP reinforcement.

It is important to note that a failure mode which was mentioned by several researchers [12], is not covered by ACI 440. This failure mode is a shear delamination of the concrete cover initiating at the FRP curtailment, and is typically mentioned as cover delamination.

ACI introduces an FRP strength reduction coefficient, C_E , which is related to the type of fibers and the environment that the FRP will be used. Values of this factor range from 0.5 to 0.95.

Finally ACI provides equation (2) in order to calculate the design strain of the FRP overlay:

$$\varepsilon_{fd} = 0.41 \sqrt{\frac{f'_c}{nE_f t_f}} \leq 0.9\varepsilon_{fu} \quad (2)$$

where:

ε_{fd} is the design FRP strain,

ε_{fu} is the ultimate FRP strain,

E_f is the FRP modulus of elasticity,

t_f is the FRP thickness,

f'_c is the concrete compressive strength

2.2. ISIS Canada (design manual)

The ISIS Canada Research Network provided a design manual for the design of strengthened reinforced concrete structural elements with fiber reinforced polymers. According to the manual the most commonly used fibers are Glass and Carbon, while the matrices are epoxy, vinyl ester or polyester resins. The internal force due to tension in the FRP reinforcement can be expressed using equation (1).

$$T_{frp} = \phi_{frp} A_{frp} E_{frp} \varepsilon_{frp} \mu \varepsilon \leq \varepsilon_{frpu} \quad (3)$$

where:

T_{frp} is the internal force due to tension in FRP reinforcement,

ϕ_{frp} is a safety factor related to the FRP material used,

A_{frp} is the cross sectional area of the FRP

The safety factor ϕ_{frp} depends upon the types of the fibers and the type of structure. ISIS makes a distinction between bridges and buildings. For buildings and Carbon fibers the suggested value is 0.75 while for Glass fibers 0.6.

2.3. TR 55

TR 55 [10] suggests that partial safety factors to be applied to the characteristic mechanical properties are a function of the type of fiber and the manufacturing/site application process. Thus:

$$\gamma_{mF} = \gamma_{mf} \times \gamma_{mm} \quad (4)$$

where γ_{mf} depends on the type of fiber and γ_{mm} depends on the manufacturing and/or site application process. Specific values are given in [10]. The accuracy with which the properties obtained from test samples reflect the overall properties of the material will depend on the method of manufacture, the level of quality control and application. It is essential that material properties used in design are replicated in the site application. It should be taken into consideration that the many products (fibers and matrices) offered in the market place possess different properties.

2.4. Fib bulletin 14

fib Bulletin 14 [6] proposes the use of FRP material safety factors in order to reduce the stresses in the FRP. The design guidelines recommend an even further reduction of the allowable FRP strain at ultimate when the design is governed by concrete crushing or bond failure.

In this situation the FRP design stress f_{fd} becomes:

$$f_{fd} = \frac{f_{fk}}{\gamma_f} \frac{\varepsilon_{fue}}{\varepsilon_{fum}} \quad (5)$$

where:

f_{fk} is the FRP characteristic strength,

γ_f is a safety factor which varies from 1.35 to 1.50 depending upon the type of fibers (1.35 for Carbon, 1.40 for Aramid and 1.50 for Glass), values are presented in Table 3.1 of [5],

ε_{fue} is the effective ultimate FRP strain expected to be reached in situ, and

ε_{fum} is the mean strain obtained through uniaxial tensile testing

Typically for flexural strengthening cases the ratio:

$$\frac{\varepsilon_{fue}}{\varepsilon_{fum}} = 1 \quad (6)$$

It should be mentioned that fib Bulletin 14 [5] points out that the γ_f factors are subject to further study, due to the limited numbers of experimental results.

2.5. Japanese society of civil engineers

Japanese Society of Civil Engineers provides recommendations for the design of reinforced concrete structures with externally bonded FRPs [8]. The design guidelines also recommend an even further reduction of the allowable FRP strain at ultimate to account for the case of premature delamination. More specifically the allowable FRP strain is reduced by 30%. There is no distinction between the different FRP types.

2.6. Egyptian code of practice (ECP)

The Egyptian Code of Practice (ECP) provides recommendations for the design of reinforced concrete structures with externally bonded FRPs [9]. The design guidelines also recommend an even further reduction of the allowable FRP strain at ultimate to account for the case of premature delamination. Initially the allowable FRP strain is divided by 1.50. Furthermore, the allowable FRP strain is multiplied by a safety factor that varies from 0.75 for Glass fibers to 0.95 for carbon fibers. The design code does not offer alternatives for other types of fibers or externally bonded overlay systems such as the TRM.

3. Experimental data

A series of experimental data were collected from different experiments [4, 13-32] conducted on reinforced concrete beams strengthened for flexure with different externally bonded FRP systems. The systems that were examined were based on Glass, Carbon, Aramid and Basalt fibers. Additionally TRM systems were examined. An experimental database was created that included all relevant information regarding the tested beams, such as beam dimensions, reinforcement, properties of materials used, thickness and width of FRP system, maximum load capacity, type of failure. A total of 290 beams are included out of which 159 are strengthened with CFRP, 20 with GFRP, 8 with BFRP, 37 with SRP and 66 with TRM. The experimental data were used to run an analysis using the aforementioned six design codes.

4. Analysis and discussion

A statistical analysis was conducted to compare analytical flexural beam strengths to experimental strengths. More specifically correlation analysis was performed (Pearson and Spearman's correlation coefficient) for each design code. Pearson correlation coefficient indicates a measure of strength of a linear association between the two variables (in our case experimental beam strength vs. analytical beam strength) while Spearman's rank correlation coefficient is a nonparametric measure of rank correlation. Figure 1 shows experimental vs. theoretical values that were plotted using the design methodology described previously. In these graphs all available experimental data were used regardless of FRP type. In each graph one main diagonal line was plotted which indicates the exact linear relationship between the experimental and the theoretical flexural strength. A point above the diagonal line means that an analytical value is higher than the corresponding experimental, and therefore one can conclude that the model overestimates the beam's flexural strength. On the contrary points below the diagonal indicate that the model underestimates the beam's strength, and thus provides safe predictions. The percentages of beams that failed at bending moments lower than that estimated by the codes are: 90% for JSCE, 84% for ISIS, 81% for TR55, 80% for ECP, 79% for ACI, and 65% for fib. It is evident that if we exclude the fib design recommendations the remaining codes perform very well. It should be noted though, that the fib design recommendations were drafted using much smaller experimental databases than the one used in this article, since at the time the available experimental data were significantly fewer than today.

As can be seen in Table 1. the design code that exhibits the highest Spearman correlation coefficient is JSCE followed by ISIS and ACI, while JSCE exhibits also the highest Pearson correlation coefficient, followed again by ACI. Based on these results it can be concluded that the JSCE design recommendation provides both safety and great correlation between experimental and analytical values. However in cases where the flexural strength was high (more than 200kNm) it provided significantly lower values than the experimental.

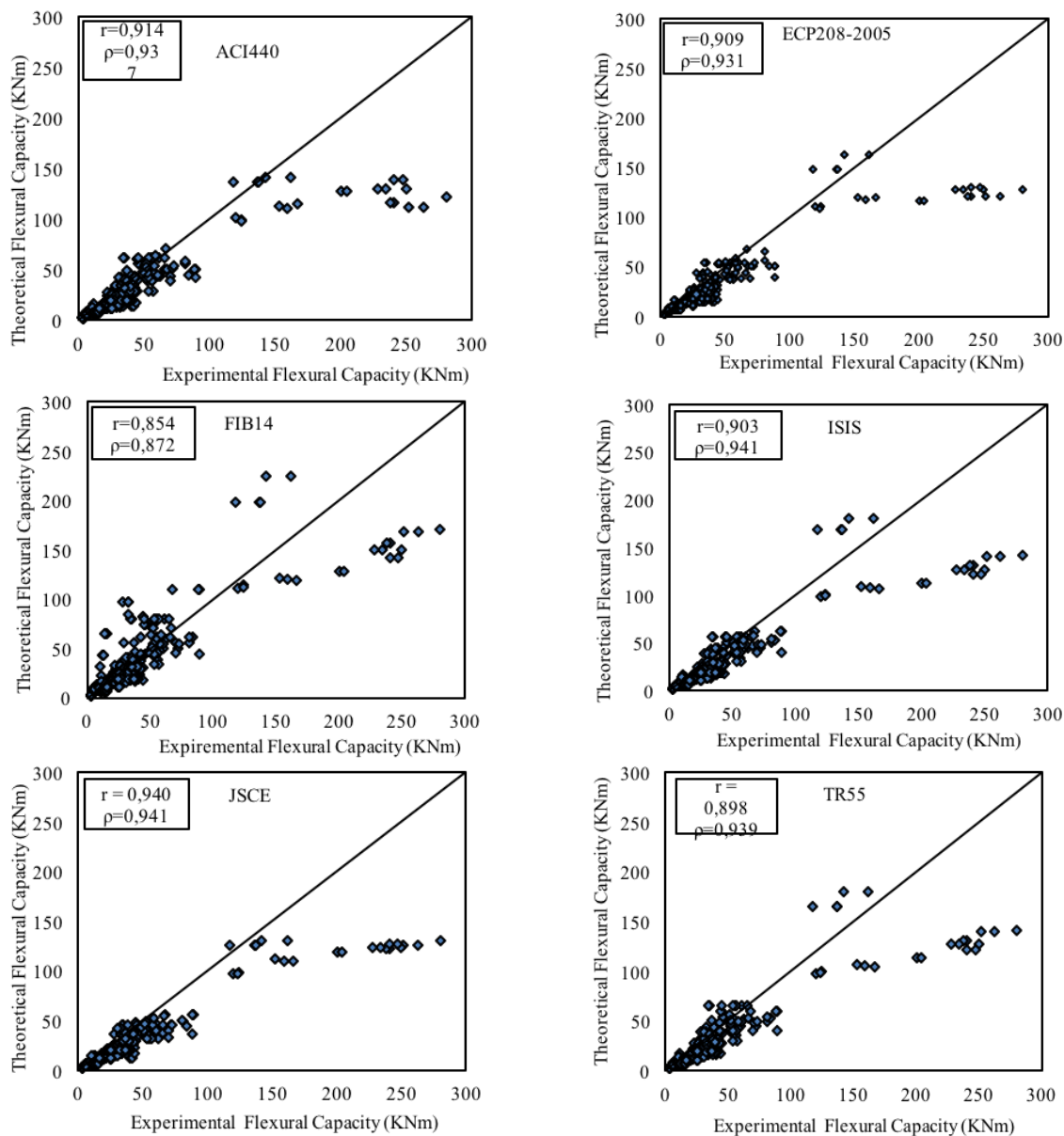


Figure 1. Experimental vs theoretical moment capacity values for the six examined codes.

Figure 2. shows similar graphs but for reinforced concrete beams strengthened with Textile Reinforced Mortars that are not covered by any design code. In order to obtain the analytical results, the same equations recommended for CFRP/GFRP were used. Even though some assumptions were made, it can be noticed that all codes perform very well in terms of safety. JSCE underestimated all beam strengths, while ACI and fib, which were the most unsafe, proved to be unsafe only in 15% of the cases. Strong Spearman coefficients (shown in the graphs) display that there is a very good correlation between experimental and analytical values. However, Pearson correlation coefficients in this case were relatively low, ranging from 0.68 to 0.70 (while in the previous case the coefficients were higher than 0.85). Similar graphs were obtained for other types of composite materials as well such as SRP/SRG and BFRP. The difference was that the Pearson correlation coefficient was higher than 0.95 when SRP/SRG was used for all codes. A fact that indicates, that existing codes can be very efficient to describe the SRP/SRG strengthening technique.

Table 1. Pearson correlation coefficients for examined design manuals.

Code	Spearman Correlation Coefficient (ρ)	Pearson Correlation Coefficient (r)
ECP208-2005 [9]	0,931	0,909
FIB14 [6]	0,872	0,854
ISIS [7]	0,941	0,903
TR55 [10]	0,939	0,898
JSCE [8]	0,941	0,940
ACI440 [5]	0,937	0,914

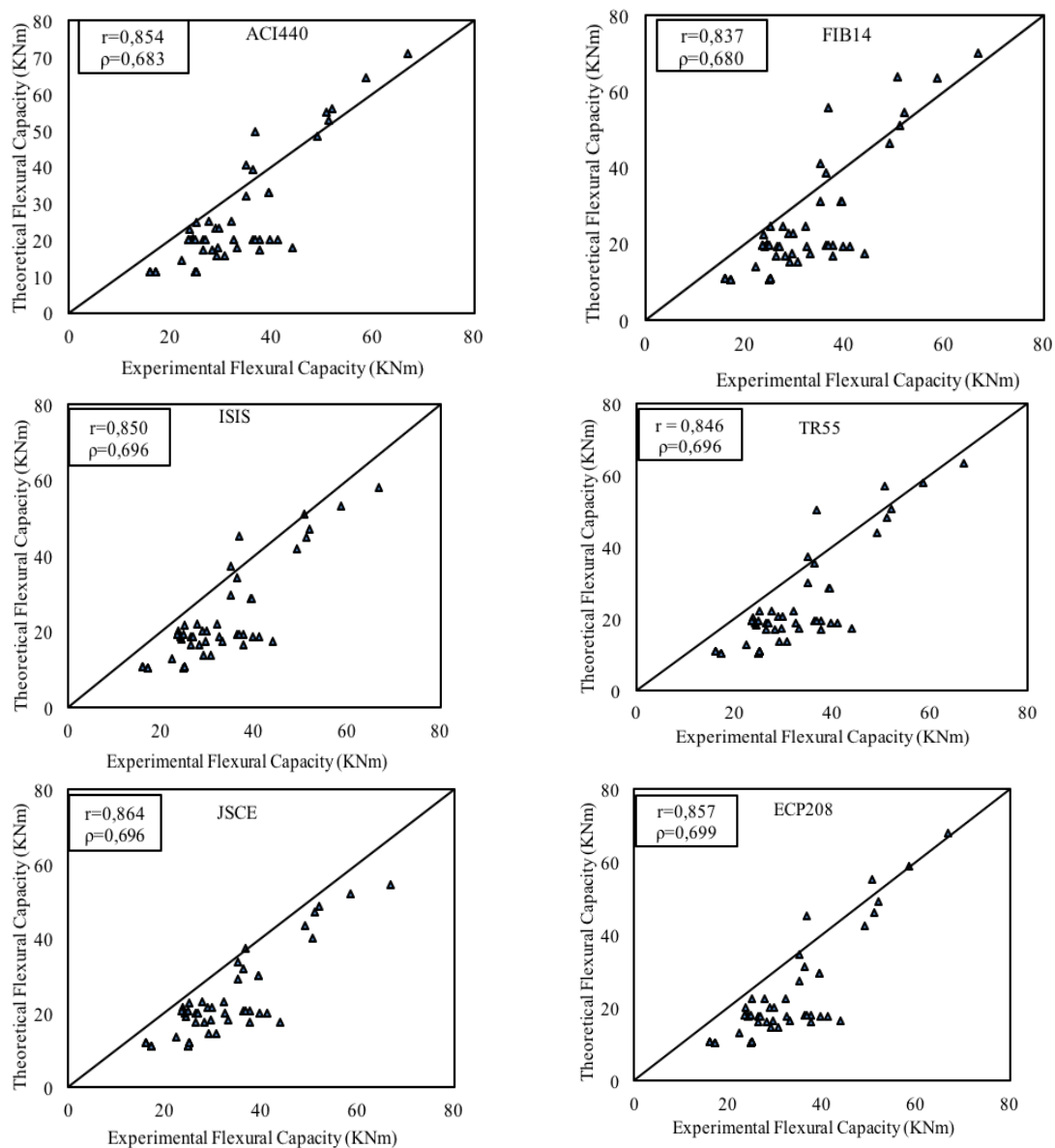
**Figure 2.** Experimental vs. theoretical moment capacity of RC beams strengthened with TRM.

Table 2. Performance of JSCE and ACI for five different types of composite overlays.

		CFRP	GFRP	SRP/SRG	BFRP	TRM
JSCE	Safety Ratio	83%	91%	94%	100%	98%
	Pearson Coef.	0.949	0.938	0.946	0.98	0.864
ACI	Safety Ratio	69%	86%	94%	100%	85%
	Pearson Coef.	0.916	0.947	0.981	0.947	0.854

The performance of two best performing overall codes is provided in Table 2. More specifically, both safety ratio (% of beams failed at load over the design load), and Pearson's correlation coefficient are presented for JSCE and ACI for all five different types of composite overlays. It is clear that both codes can be used regardless of the composite material.

5. Conclusions

Based on the performed statistical analysis it can be concluded that almost all codes (other than fib) can be successfully used to describe the flexural strength of reinforced concrete beams strengthened with externally bonded materials regardless of their specific type. However in some cases the available experimental database is quite small and definitely more experiments are necessary in order to tweak and verify the equations proposed by the codes. All codes should take in consideration the different types of composite materials, available in the market place, that can be used as externally bonded strengthening systems. Finally the design methodology that performed the best in terms of both safety and correlation is the one described by JSCE. The authors believe that some changes in the JSCE code may provide even better results.

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