



A Comparative Study of the Flexural Beam Design with Externally Bonded FRP Material Using ACI 440 2R-08, ISIS Canada And FIB-14 Bulletin

Mr. Aditya N. Contractor¹, Dr. S.A. Vasanwala².

¹Student (Ph.D.), ²Professor,

Department of Applied Mechanics,
S.V.N.I.T., Surat- 395 007, Gujarat, India.

Abstract: To enhance the quantitative load carrying capacity of structural elements, externally bonded fibre reinforced polymer (FRP) composite materials have successfully been applied to reinforced concrete beam elements. The guidelines for the proposed designing methods such as ACI 440 2R-08, ISIS CANADA and FIB-14 for an externally bonded FRP material are beam elements. These methods are based on approximately the same philosophy. Taking only shear crack effect into consideration, fib Bulletin 14 was the first to publish guidelines for externally bonded FRP reinforcement for RC structures. Shear cracks in concrete elements are inclined and may result in debonding. In ISIS code, the design strain is not limited up to debonding failure and existing substrate strain is not deducted for effective strain of fiber. The strength reduction factors are also different than ACI method to find out the compressive strength of beam elements. Therefore, an effort has been made in hand work to compare the design steps and resisting moment of FRP materials on beam elements by all the three methods. The flexural capacity in guidelines comes from three parts: concrete, steel and FRP. However, detail of each code is different from one another.

Keywords: FRP composite material, Flexural, Substrate Strain, ACI 440 2R-08, ISIS, FIB -14, debonding failure, shear cracks

I. Introduction

Concrete is one of the most common building materials and is used for Reinforced Concrete (RC) structures. Typically, concrete structures are very durable, but need to be strengthened with time. The reasons may be cracking due to environmental effects, new building codes or damage resulting from earthquakes.

Though concrete can withstand compressive loads very well, it is sensitive to tensile forces. Therefore, concrete structures are typically reinforced by casting steel bars in areas where tension can arise. This cannot be done afterwards, and one strengthening method, is therefore to glue reinforcement on the exterior of the structure in the areas exposed to tension, increasing both the strength and stiffness of the beam elements.

Fibre composite can be used in reinforcing concrete structures externally. Fibre composite materials have several advantages like low density, formability, ease of fabrication and bonding, corrosion resistance, light weight. They can be easily installed and are easy to cut to length on site. Therefore, fibre composite as external reinforcement for concrete structures has become very attractive and popular around the world in the field of retrofitting design. To assure good bond between FRP composite material and concrete surface, it must be cleaned or sandblasted down to aggregate. Then composite materials can be made from a variety of resins/glue and fibres depending upon desired physical, mechanical properties and economic consideration. (Malek and Saadatmanesh 1996).

If FRP is loaded in fibre direction, then FRP will generally behave linearly elastically to failure. If one study the behaviour of RC beams strengthened with FRP laminations then different modes of failure have been reported by (Saadatmanesh & Ehsani in 1991). Rupture of the plate or compression of concrete controls the strength of the beam. At the end of the beam if the beam fails locally then it may lead to premature failure of the strengthened beam. The main reasons for the failure are the flexural cracks and shear and normal stress concentration at the cut-off point. There are different types of design steps claimed by different countries to find out the flexural strength having same philosophy. To compare and to find the final output different to that method some guidelines are not mentioned or avoided. This document mentions the steps & the methods to compare the flexural elements i.e. ACI 440 2R-08, ISIS and FIB-14.

II. ACI Method

A. Environment Reduction Factor (CE)

Environmental conditions affect the fibers and resins of various types of FRP system. Environmental factors namely alkalinity, salt water, high humidity and freeze-thaw cycle are responsible for degrading FRP system. Tensile strength, ultimate tensile strength & Elastic modulus are the mechanical properties.

Table 1: Environment Reduction Factor For Various FRP System And Exposure Condition.

Sr. No.	Exposure Conditions	Fiber Type	Environmental reduction factor CE
1.	Interior exposure	Carbon	0.95
		Glass	0.75
		Aramid	0.85
2.	Exterior exposure (Bridges, piers and unenclosed parking garages)	Carbon	0.85
		Glass	0.85
		Aramid	0.65
3.	Aggressive environment (chemical plants and wastewater treatment plant)	Carbon	0.85
		Glass	0.50
		Aramid	0.70

B. Strength Reduction Factor

To reduce the ductility of original member, externally bonded FRP reinforcement to strength the flexural is used. Loss of ductility can be avoided in some cases. But the sections experiencing significant loss of ductility should not be overlooked. The level of strain in steel which is at ultimate limit state should be checked in order to maintain a significant degree of ductility. To achieve an appropriate ductility for reinforced concrete members having non-prestressed steel reinforcements, the strain in the steel at the point of concrete crushing of failure of the FRP should include delamination or debonding values of at least 0.005.

$$\Phi = \begin{cases} 0.9 & \text{for } \epsilon_t \geq 0.005 \\ 0.65 + \frac{0.25(\epsilon_t - \epsilon_{sy})}{0.005 - \epsilon_{sy}} & \text{for } \epsilon_{sy} < \epsilon_t < 0.005 \\ 0.65 & \text{for } \epsilon_t \leq \epsilon_{sy} \end{cases}$$

Where in above equation ϵ_t is the net tensile strain in extreme tension steel at nominal strength. So, $\phi = 0.9$ for ductile & $\phi = 0.65$ for brittle section, where the steel does not yield.

An additional strength reduction factor for FRP " ψ_f " is applied to the flexural strength contribution of the FRP reinforcement. The recommended value of $\psi_f = 0.85$.

C. Failure Modes

The potential flexural failure modes for externally strengthened reinforced concrete flexural members are as follows:-

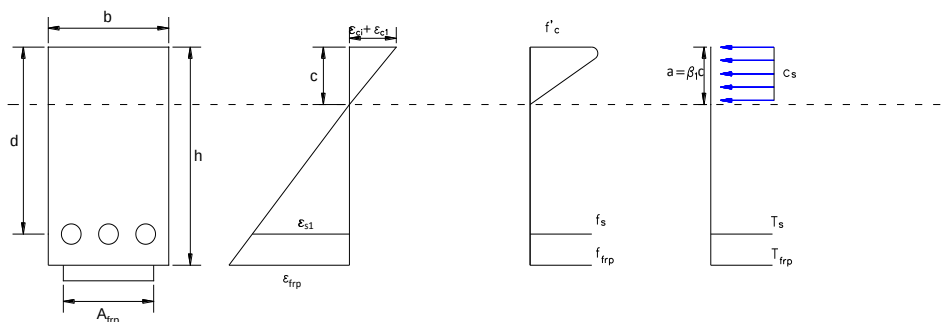
1. Concrete crushing before yielding of the reinforcing steel
2. Steel yielding followed by concrete crushing.
3. Steel yielding followed by FRP rupture.
4. Debonding of the FRP reinforcement at the FRP/concrete interface.

D. Design Effective Strain

Cover delamination of FRP debonding can occur if the forces in the FRP cannot be sustained by the Substrate; such behaviour is known as debonding. A failure controlled by FRP debonding may govern if it is away from the section where externally bonded FRP laminates. To avoid an intermediate crack-induced debonding failure mode,

the effective strain in FRP reinforcement should be limited to ϵ_{fd} , as per SIunits is $\epsilon_{fd} = 0.41 \sqrt{\frac{f'_c}{n t_f E_f}} \leq 0.9 \epsilon_{fu}$

Fig. 1. Internal stress and strain distribution of member under flexure by ultimate limit state as per ACI method



E. Existing Substrate Strain

It is applied at the tension side of the beam at the time of laminating. There is some strain existing due to self weight and any pre-stressing forces and other load dead load, the substrate to which the FRP is applied will be strained. These strains should be taken into account as initial strains and should be removed from the strain in the FRP. The initial strain level on the bonded substrate; ϵ_{bi} , can be examined from an elastic analysis. The elastic analysis of the existing member should be based on cracked section properties.

Where, M_{DL} = moment due to dead load on the beam.

I_{cr} = cracked moment of inertia.

E_c = Modulus of elasticity of concrete.

F. Serviceability

The stress in the steel reinforcement under service load should be limited to 80% of the yield strength,

$$f_{s,s} \leq 0.8 f_y$$

And the stress in concrete should be $f_{c,s} \leq 0.8 f'_c$

III. ISIS Method

A. Environment Reduction Factor

The strength reduction factors are high compared to ACI method and so it is mostly compensated.

Table 2: Strength Reduction Factor

Material reduction factor	For building	For bridges
ϕ_c	0.6	0.75
Φ_s	0.85	0.9
ϕ_{frp} carbon	0.7	0.78
ϕ_{frp} glass	0.6	0.76

Generally the ϕ_{frp} carbon = 0.75 and ϕ_{frp} glass= 0.5 is considered for the calculation.

B. Failure Modes

Failure modes are same as given in ACI method.

An assumption is to be made and the failure mode should be checked as it is not clear regarding which type of failure it will be. If the assumption results incorrect then a different failure mode is assumed and the analysis is repeated. In this method it is assumed that the fourth failure mode FRP debonding will not occur and can be ignored (in practice this assumption is assured through the use of specialized anchorage technique).

C. Design of Flexural Beam

By using the familiar concept of strain compatibility, design of flexural element can be carried out, the strain and stress distribution over the cross section at failure can be described as shown in figure below.

Now the equilibrium of internal forces required are the three stress resultants (concrete in compression, steel in tension T_s , and FRP in tension T_{frp}) sum to zero.

$$C_c = T_s + T_{frp}$$

The stress resultant can be determined as

$$C_c = \Phi_c \alpha_1 f'_c \beta_1 b c$$

Fig.2. ISIS assumed stress block

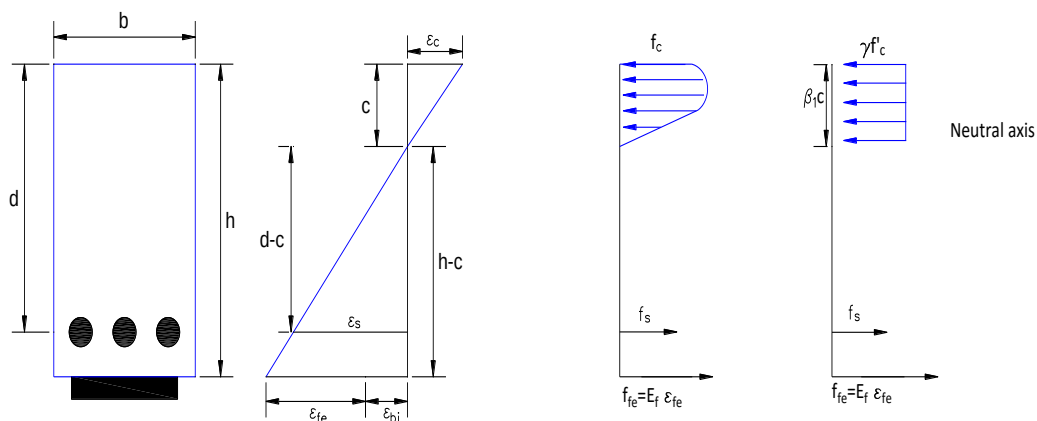
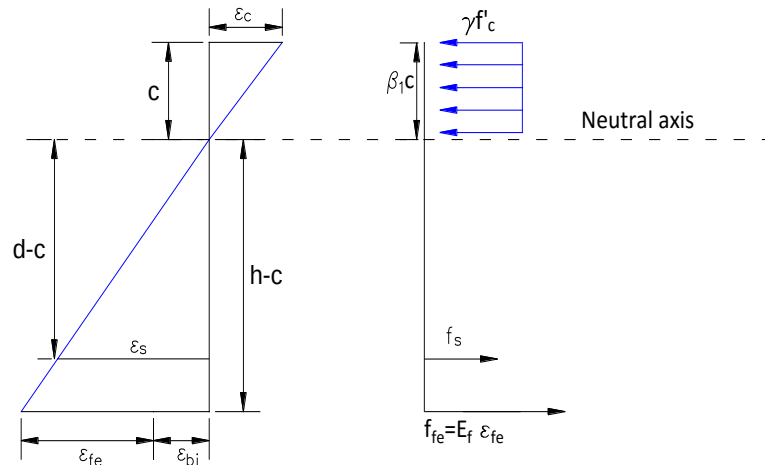


Fig. 3. Stress-strain block at ultimate failure by concrete crushing



$$T_s = \phi_s A_s f_s \text{ with } f_s \leq f_y$$

$$T_{frp} = \phi_{frp} A_{frp} E_{frp} \epsilon_{frp} \text{ with } \epsilon_{frp} \leq \epsilon_{frpu}$$

And the final flexure moment is calculated by

$$M_r = T_s (d - (\beta_1 c)/2) + T_{frp} (h - (\beta_1 c)/2)$$

IV. FIB method

A. Failure modes

In this method failure modes can be divided into two sections :- 1) unless the concrete reaches crushing in compression or FRP fails in tension, the full composite action of concrete and FRP will be maintained. 2) Composite action will be lost before sections

Fig.4.FIB Stress Block

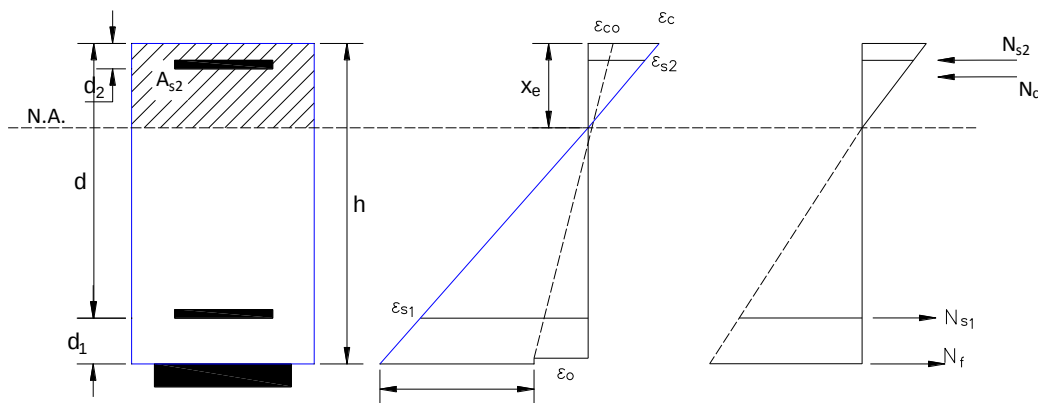


Table 3: Comparison of Flexural Design for Beam

Step No.	ACI method	ISIS method	FIB-14 Method
Step 1	f_{fu}^* = ultimate tensile strength ϵ_{fu}^* = ultimate breaking or rupture strain E_f = Modulus of elasticity of FRP	f_{fu}^* = ultimate tensile strength ϵ_{fu}^* = ultimate breaking or rupture strain E_f = Modulus of elasticity of FRP	E_f = Modulus of elasticity of FRP
Step 2	Design material properties (take $c_e = 0.95$ for interior exposure) $f_{fu} = c_e f_{fu}^*$ $\epsilon_{fu}^* = c_e \epsilon_{fu}^*$ Multiply above terms with environmental reduction factor.	Environment reduction factor not included in ISIS method.	Environment reduction factor not included in FIB method.
Step 3	Preliminary calculations such as area of steel reinforcement and area of fibre laminate. $A_f = n t_f w_f$ $E_c = 5700 \sqrt{f_c'}$	Preliminary calculation Stress block factor $\beta_1 = 0.97 - 0.0025 f_c' \geq 0.67$ $\alpha_1 = 0.85 - 0.0015 f_c' \geq 0.67$	Preliminary calculation $A_f = n t_f b_f$

Step 4	Existing substrate strain The existing state of strain is calculated assuming the beam is cracked and only loads acting on the beam at the time of the FRP installation are dead loads $k=0.334$ $\epsilon_{bi} = \frac{M_{DL}(h-kd)}{I_{cr} E_c}$	Existing substrate strain this is assumed as zero in ISIS method because the variation due to existing substrate strain is very less	Initial strains at extreme fibres Compression $\epsilon_{co} = M_o x_o / E_c I_{co}$ Tension $\epsilon_o = \epsilon_{co} h - x_o / x_o$ $\epsilon_{s2} = \epsilon_{cu} ((X-d_2)/X)$ M_o = moment during strengthening I_{co} = moment of inertia of the cracked section
Step 5	Determine the design strain This design strain is calculated to prevent against debonding failure $\epsilon_{fd} = 0.41 \sqrt{\frac{f_{cr}}{n t_f E_f}} \leq 0.9 \epsilon_{fu}$ This should be less than rupture strain to control the debonding failure	Determine the design strain In ISIS method debonding failure mode is not accounted because by using special anchorage system it can be prevented.	Determination of failure model $0.85 \Psi f_{cd} b x + A_{s2} E_s \epsilon_{s2} \geq A_{s1} f_{yd} + A_f E_f \epsilon_f$ If this condition satisfy then follow step 6, If this condition not satisfy than go to step no 7
Step 6	Effective strain in FRP $\epsilon_{fe} = 0.003 \left(\frac{h-c}{c} \right) - \epsilon_{fi} \leq \epsilon_{fd} \leq 0.9 \epsilon_{fu}$	Find neutral axis depth As per force equilibrium $C_c = T_s + T_{frp}$ the stress resultant can be determined as $C_c = \phi_c \alpha_1 f'_c \beta_1 b c$ $T_s = \phi_s A_s f_y \text{ With } f_s \leq f_y$ $T_{frp} = \phi_{frp} A_{frp} E_{frp} \epsilon_{frp}$ With $\epsilon_{frp} \leq \epsilon_{frpu}$ Effective strain in FRP This means that strain in the compression fibre of the cross-section is the assumed failure strain for concrete in compression. Once neutral axis depth is known from strain compatibility strain is check out $\epsilon_{cu} = 0.0035$ should be less than rupture strain ϵ_{frpu} If above condition satisfy than go to step 7 If above condition not satisfy than go to step 8	Failure FRP rupture $\epsilon_f = \epsilon_{fd}, \epsilon_c, \epsilon_{s2}, \epsilon_{s1}$ Stress block coefficients $\Psi = \Psi(\epsilon_c), \delta = (\delta_c)$ $\varphi = \begin{cases} 1000 \epsilon_c \left(0.5 - \frac{1000}{12} \epsilon_c \right) & \text{for } \epsilon_c \leq 0.002 \\ 1 - \frac{3000 \epsilon_c}{8 - 1000 \epsilon_c} & \text{for } 0.002 \leq \epsilon_c \leq 0.0035 \\ \frac{1000 \epsilon_c (3000 \epsilon_c - 4) + 2}{2000 \epsilon_c (3000 \epsilon_c - 2)} & \text{for } 0.002 \leq \epsilon_c \leq 0.0035 \end{cases}$
Step 7	Calculate the stress level in the reinforcing steel and FRP $\epsilon_s = (\epsilon_{fe} + \epsilon_{bi}) \left(\frac{d-c}{h-c} \right)$	Factored moment of resistance can be obtained by $\epsilon_{frp} = \epsilon_{cu} \left(\frac{h-c}{d - \frac{\beta_1 c}{2}} \right) > \epsilon_{frpu}$ $M_r = \phi_s A_s f_y \left(d - \frac{\beta_1 c}{2} \right) + \phi_{frp} A_{frp} E_{frp} \left(h - \frac{\beta_1 c}{2} \right)$ To avoid sudden and brittle failure of the externally strengthened member, we ensure that the internal steel has yielded $\epsilon_s > \epsilon_y \text{ to secure ductil}$ $\epsilon_s = \epsilon_{cu} \left(\frac{d-c}{h-c} \right) > \epsilon_y$ And if this not satisfy than reduce the amount of FRP laminate and regulate until steel yielded in final design	Failure - concrete crushing $\epsilon_c = \epsilon_{cu}, \epsilon_f, \epsilon_{s2}, \epsilon_{s1}$ Stress block coefficient $\Psi = 0.8, \delta_c = 0.4$
Step 8	Calculate steel level in reinforcing & FRP $f_s = E_s \epsilon_s \leq f_y$ $f_{fe} = E_f \epsilon_{fe}$	Again assume that the failure occurs by tensile failure of FRP, $\epsilon_{frp} = \epsilon_{frpu}$ this means that and the strain in concrete in compression is less than $\epsilon_{cu} = 0.0035$ Where, $C_c = T_s + T_{frp}$ $T_s = \phi_s A_s f_y$ $C_c = \phi_c \alpha_1 f'_c \beta_1 b$ $T_{frp} = \phi_{frp} A_{frp} E_{frp} \epsilon_{frp}$ Verify that the strain in extreme compression fibre is than $\epsilon_c = \epsilon_{frpu} \frac{c}{h-c} < \epsilon_{cu}$	The neutral axis depth $0.85 \Psi b x f_{cd} + A_{s2} \sigma_{s2} \leq A_{s1} f_{yd} - A_f \sigma_f = 0$
Step 9	Calculate the internal force resultant and check equilibrium $\alpha_1 = \frac{3 \epsilon'_c \epsilon_c - \epsilon_c^2}{3 \beta_1 \epsilon_c'^2 - 4 \epsilon_c - \epsilon_c}$ $\beta_1 = \frac{6 \epsilon_c' - 2 \epsilon_c}{6 \epsilon_c' - 2 \epsilon_c}$	Calculate factored moment of resistance of section using $\epsilon_{frp} = \epsilon_{frpu}$ $M_r = \phi_s f_y A_s \left(d - \frac{\beta_1 c}{2} \right) + \phi_{frp} E_{frp} A_{frp} \epsilon_{frp} \left(h - \frac{\beta_1 c}{2} \right)$	Flexural capacity after strengthening $M_{Rd} = A_{s1} f_{yd} (d - \delta G_X) + A_f E_f \epsilon_f (h - \delta G_X) + A_{s2} E_s \epsilon_{s2} (\delta G_X - d_2)$

	Where, $\epsilon'_c = \frac{1.5 f'_c}{E_c}$ Force equilibrium is verified by checking the initial estimate of c with $c = \frac{A_s f_s + A_f f_{fe}}{A_s f_s + A_f f_{fe} + A_c f_c}$		
Step10	Calculate moment of resistance $\phi_{MN} = \phi \left[\begin{array}{l} A_s f_s \left(d_f - \frac{\beta_1 c}{2} \right) \\ + \phi_f A_f f_{fc} \left(d_f - \frac{\beta_1 c}{2} \right) \end{array} \right]$ where, $\phi_f = 0.85$		

V. Design Data

The reinforced concrete beam as shown in Figure no.4 is singly reinforced and is strengthened in flexure with externally bonded carbon FRP on its tension face or bottom of a beam. Beam dimension and material properties are given below. Calculate the factored moment capacity of the beam.

Concrete strength, $f'_c = 30$ MPa

Internal steel reinforcement = 4 x 12 mm bars

Area of steel, $A_s = 453$ mm²

Yield strength of steel, $f_y = 415$ MPa

Modulus of Elasticity of steel, $E_s = 200$ GPa

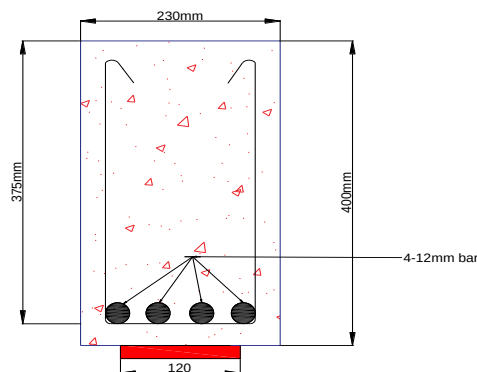
Carbon FRP properties

$A_{frp} = A_f = 120$ mm², $\epsilon_{fu} = 1.55\% = 186$ GPa

Length of beam = 5 m

Working dead load = 16 kN/m.

Figure 4: Beam Bounded With FRP Laminates



VI. Results

For different grade of concrete (f'_c) and remaining data are same consider for comparison of flexural strength of using FRP laminate.

Table-5

Sr. No.	Variation In Flexural Moment In kN-m.			
	Concrete strength (in N/mm ² .)	ACI method (Neglecting existing substrate strain) (Moment of resistance)	ISIS method (Moment of resistance)	FIB method (Flexural capacity after strengthening)
1.	20	137	154.4	194.5
2.	25	138.9	160.1	196.8
3.	30	140	163.8	198.3
4.	35	141	166.5	199.4
5.	40	141.6	168.5	200.2
6.	45	142.1	170.1	200.9
7.	50	142.5	171.4	201.4

VII. Conclusion

From the above result it is concluded that FIB method gives higher strength from amongst the given methods. However, the FIB does not take into significant consideration, the strength reduction factors. The ACI method is

addition to strength reduction factor, as also applicable to ISIS Canadian method also takes in to account the environmental reduction factors. The failure modes are clearly defined in ACI method, however in other methods the trial and error is resorted to get the failure modes. In ISIS Canadian Method debonding failure modes are not accounted. With the increase in the grade of concrete the moment of resistance do not increase significantly.

References

- [1]. Täljsten, B. (2002): .Strengthening of existing concrete structures with externally bonded Fibre Reinforced Polymers. Design and execution. Technical report. Luleå University of Technology, Division of structural engineering.
- [2]. L.A.Bisby,(2004): "An Introduction to FRP Strengthening of concrete structures" ISIS Education
- [3]. Module-4, CANADA, Department of Civil Engineering, Queen's University.
- [4]. ACI 440 2R-(2008)"Guide for the design and construction of externally bonded FRP system for strengthening concrete structures" ACI committee, Farmington Hills, U.S.A.
- [5]. Neale KW. And Labossière P., (1997), .State-of-the-art report on retrofitting and strengthening by continuous fibre in Canada., Non-Metallic (FRP) Reinforcement for Concrete Structures, Japan Concrete Institute, 1997.
- [6]. Technical Report on the Design and Use of Externally Bonded FRP Reinforcement for Reinforced Concrete Structures, fib Bulletin 14, TG 9.3, 2001.
- [7]. ISIS CANADA - Design Manual No. 4, September2001, "Strengthening Reinforced Concrete Structureswith Externally-Bonded Fibre Reinforced Polymers".
- [8]. Bhunga, Murad M. and Arora, N.K. (2012). "Comparative Studyof ER-FRP Laminated Beam Design with ACI 440.2R-08 and ISISCANADA method." International Journal of AdvancedEngineering Research and Studies.
- [9]. Hussain, M., Sharif, A., Basunbul, I. A., Baluch, M. H., and AlSulaimani,G. J. (1995), "Flexural Behavior of PrecrackedReinforced Concrete Beams Strengthened Externally by SteelPlates," ACI Structural Journal, vol. 92, No. 1, pp. 14-22.
- [10]. Saadatmanesh and Ehsani, 1991, "RC beams strengthened with GFRP plates - Part - I and Part-II," ASCE Journal of Structural Engineering, 117 (11) (1991), pp. 3417-3455.
- [11]. Malek, A.M., and Saadatmanesh, H. (1996). "Physical and mechanical properties of typical fibers and resins." Proc. 1st Conf. on Compos. In Infrastructure, Tucson Ariz., 68-79.