

ENVIRONMENTAL AND ECONOMIC COMPARISON OF FRP REINFORCEMENTS AND STEEL REINFORCEMENTS IN CONCRETE BEAMS BASED ON DESIGN STRENGTH PARAMETER

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ABSTRACT. This paper compares steel rebars with three FRP's commonly used in construction namely, Carbon fibers Reinforced Polymer (CFRP) , Basalt fibers Reinforced Polymer (BFRP) and Glass fibers Reinforced Polymer (GFRP). This paper tries to analytically compare both the environmental and the economic viability of different FRP's rebars as an substitute to traditional steel rebars in RC beams. A Matlab code is developed for the same based on ACI 440-4R-06 to obtain the ultimate flexure design. The functional units are taken as Mu/m³ and Mu/kg to carry out the sustainability comparison among different types of reinforcements. The results shows that the CFRP rebars are most economical (approx. about 55% cheaper than steel rebars) despite being the costliest material (costs 4 times the steel rebar) due to material being of low density and higher ultimate tensile strength. The results for CO₂ emissions and Energy content shows that the BFRP rebars are most environment friendly (i.e. produces 93% less CO₂ emissions and consumes 68% less energy in production as compared to steel rebar). The future market is expected to be with the use of BFRP rebars in precast members as the mass production will result in reduction of the cost and make the material cost effective.

Keywords: Corrosion, CO₂ Emissions, FRP's, Functional Unit, RC beams.

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INTRODUCTION

The effect of corrosion of reinforcement on the durability and service life of the reinforced concrete (RC) structures is a matter of great concern for civil engineers. The annual repair and rehabilitation cost of such structures is a massive burden on the construction industry. The alternative developed in recent times in order to prevent this loss is the use of Fiber Reinforced Polymer Reinforcements. The salient features of the FRP reinforcements are non-corrosiveness, high tensile strength, extremely light in weight as compared to traditional steel reinforcements and are easy to use while casting members. These properties make them appealing alternative of steel reinforcement especially for structures exposed to severe environments.

The FRP material have been in use as a retrofitting material in construction industry from the last few decades [1]. They have been used in concrete girders of large span bridges, concrete beams [3], concrete slabs and masonry walls [4]. The FRP is presently used as substitute for traditional steel reinforcement bars in the construction market [1, 2]. Among all the FRP material, the glass fibres are the most widely and commonly used material in construction industry due to its easy availability and low cost of manufacturing [5, 6]. However, in recent times, carbon fibres is becoming more popular material[7] due to it being stiffer than glass fibres, and its elastic modules being in the same range to that of steel reinforcements [5]. Another variety of fibre which has been used in recent times is basalt fibre [6, 8-10]. Many manufacturers are motivated to use this fibre. It is due to its favorable properties such as high ecological compatibility during production process, low cost and better functional properties [8-11]. When compared to steel, the density of basalt (2600 kg/m³) is approximately one third of the density of steel (7680 kg/m³) making it lighter yet stronger material. The higher strength to weight ratio for BFRP as compared to steel may serve better when its environment performance is considered..

In the past, only few studies have discussed the environmental and cost implications of different FRP rebars in comparison with steel rebars. A thorough search of the relevant literature yielded no such study which has investigated the design strength of concrete beams reinforced with different FRPs and steel rebars in correlation with their material cost and environmental impact. Both these aspects of the FRPs are studied here in a holistic approach. This study compares steel rebars with three FRP's commonly used in construction namely, Basalt fibers Reinforced Polymer (BFRP), Carbon fibers Reinforced Polymer (CFRP) and Glass fibers Reinforced Polymer (GFRP). The material cost feasibility of each FRP's as an substitute to traditional steel rebars in RC beams is also covered. Finally, closing remarks and future scope of FRP rebars in construction industry are reported.

RESEARCH SIGNIFICANCE

This research is initiated to find the environmental economics of structures designed with different FRP rebars as against the traditional steel rebars. The main aim of the research is to analyze the different reinforcement materials on parameters like initial cost of material, CO₂ emissions and energy consumption during manufacturing of raw materials i.e. study is mainly focused on cradle to gate. Here, a reinforced simply supported concrete beam is designed as per ACI code. A Matlab code is developed for the same based on ACI 440-4R-06[12] to obtain the ultimate flexure design strength. The code provides us the ultimate moment carrying capacity for the different scenarios. The functional units are taken as Mu/m³ and Mu/kg to carry out the comparative analysis between different types of

reinforcements used in concrete beams. These results will lead to promote the use of more economical and eco- friendly material in construction industry resulting in saving both in terms of cost and reduction of CO₂ impact on environment.

METHODOLOGY

The methodology adopted in this paper can be divided into two parts. The primary section documents the analytical design approach used to determine the design strength of the concrete beams using different FRP and steel rebars, whilst the latter outlines the sustainability aspects of the methodology which is used to analyze the sustainability of different reinforcements based on the energy consumption and CO₂ emissions produced up to the material manufacturing stage. Along with the sustainability study, the cost of materials consumed in the production of beams is also compared with certain assumptions.

Scope

In this study, a MATLAB code is developed based on ACI 440-1R-06[12] to obtain the ultimate flexure design for beams reinforced with FRP's. The present study is mainly focused on analysis of compression-controlled sections for FRP rebars and tension controlled for steel rebars. The strain compatibility approach is used in order to obtain neutral axis and ultimate moment. The MATLAB code is developed in order to analyze the beam. The design methodology is based on ACI 440.1R-06. Later, the sustainability analysis for the different systems of rebars is carried out. The cost ratio for concrete is taken as "1" as it is assumed that the nature of concrete is used in all the beams is same and the cost ratio for rebars is taken from various literatures [14] and industry data [15][16]. To study the CO₂ emission and energy consumption, the data is taken from literature[17][18][19]]and computed with functional units as defined above to obtain the desired results.

Design Approach

The FRP reinforced concrete beams are designed on the philosophy of balanced ratio. The balanced ratio as per ACI code is defined as the reinforcement ratio at which the rupture of the tendons and crushing of the concrete takes place simultaneously. The failure of concrete is considered to occur when the strain at the extreme fibre reaches the value of $\epsilon_{cu} = 0.003$. The effect of confinement of concrete due to presence of stirrups is not considered in evaluation of this value of strain limit. The Whitney's stress block diagram is being used here to study and model the behavior of concrete. The failure in the tendon occurs when the strain in the tendon reaches the value of ultimate tensile strain capacity ϵ_{pu} . The balanced reinforcement ratio, ρ_b is given as:

$$\rho_b = 0.85 \beta_1 \frac{f_c'}{f_{fu}} \frac{E_f \epsilon_{cu}}{E_f \epsilon_{cu} + f_{fu}} \quad (1)$$

where, β_1 is the stress-block factor for concrete; f_c' is the specified compressive strength of concrete, MPa; f_{fu} is the design ultimate tensile strength of FRP tendon and anchorage system, MPa; ϵ_{cu} is the ultimate strain in concrete in compression. Figure 1 shows the stress strain diagram along with the cross section for a balanced section condition.

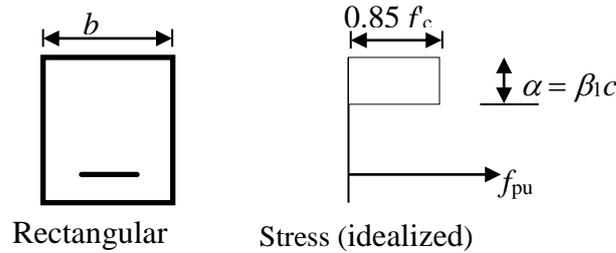


Figure. 1 Stress and strain conditions (ACI 440-4R, 2004[13]).

The beam section can be designed as a tension controlled section or as a compression controlled section. The section is said to be compression controlled if the reinforcement ratio ρ is greater than ρ_b , and the crushing of concrete occurs before the failure of tendons. In case when ρ is less than ρ_b , the tendons rupture before the failure of concrete and this condition is termed as tension controlled section condition. In such cases, value of strain in concrete will be less than 0.003 at failure of the beam. The strain compatibility approach is used in order to obtain neutral axis and ultimate moment. The ultimate moment for over reinforced section is equal to:

$$M_u = f_f * \rho_f * \left(1 - 0.59 * \frac{\rho_f * f_f}{f_c'} \right) * b * d^2 \quad (2)$$

where f_f is the stress in rebar at the time of failure in compression zone. Using the above equations 11 the ultimate moments are calculated. The code uses above equations to obtain the ultimate design moment at failure of the concrete beams so designed. The flow of the MATLAB code is summarized in a flow chart shown in Figure 2.

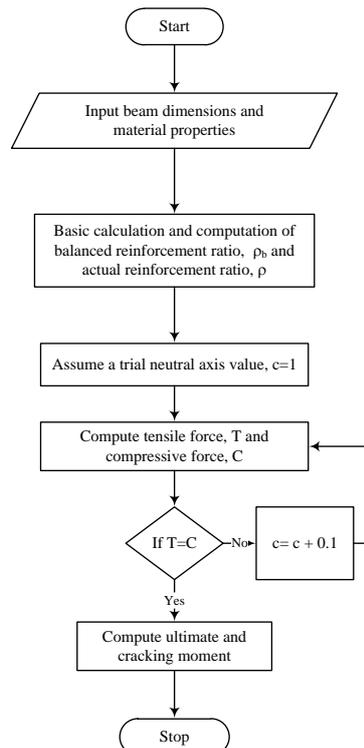


Figure. 2 Flowchart of the MATLAB code.

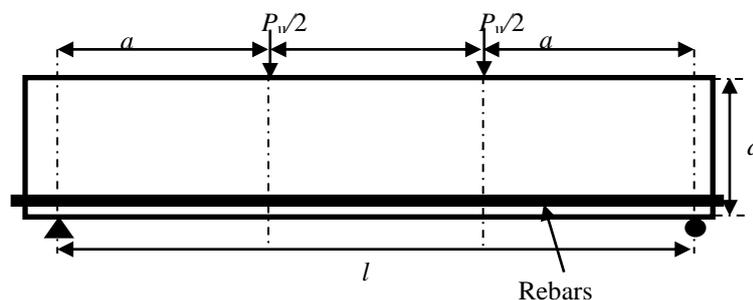
Functional Unit

The Functional Unit (FU) as defined by ISO 14040- 1997 [14] states that it is a measure of the performance of the functional outputs of the product system. The functional units defined in this study are in accordance with the guidelines stated in EN 15804-2012 [15] and ISO 14040,1997. The different functional units based on volume of concrete and its characteristic strength have been used earlier to compare the different types of concrete[16] . Here in this study the ultimate moment carrying capacity (M_u) of the reinforced concrete beams is used a standard parameter for comparison of concrete beams designed using different reinforcing materials. There are two functional units defined here namely, FU1 (M_u/m^3) and FU2 (M_u/kg). The first is used to study the impact of concrete and latter is used to study the impact of reinforcements in the RC beams

Sustainability Study

The most preferred material to be used in place of steel would be produced at a lower temperature which will minimize the energy requirement and should yield less CO_2 gas to limit Green House Gas emissions . In this regard, GFRP proves to be the most preferred material on paper [17]. However, this may not result it being most sustainable material compared to other FRPs due to its substantially lower tensile strength. So, these stand alone values of CO_2 emissions and energy consumption does not give one a clear picture that which alternative is more suitable and environment friendly when used in construction industry.

In order to answer the above problem, an approach based on the comparison of different FRPs with steel based on their design carrying capacity in RC beams is proposed. For the analysis, a trail rectangular beam cross section is studied. This research study only focuses on the flexural behavior of the beam; hence, the assumed cross section should be such that it fails only in flexure. To ensure this, results of Kani (1979)[18] are referred for the selection of dimensions of the trail section as shown in Figure 3. As per the experimental results, the shear arm ratio $a/d \geq 2.7$ should be satisfied for the complete flexure failure of beam (Kani, 1979).



Beam Specification:

$b=200$;	Beam width (mm)
$D=300$;	Beam depth (mm)
$l=2.75$;	Length of beam (m)
$cc=40$;	Clear cover for the beam (mm)
$f_{ck}=40$;	Grade of Concrete (MPa)
$ff_u=1200$,	Ultimate Design strength of BFRP bars (MPa), CRFP bars (MPa) and GFRP
2000 and 750;	rebars (MPa) respectively
$y_{cb}=24$;	Unit weight of concrete (in kN/m^3)
$a=916$	Loading position (mm)
$a/d=3.52$	Shear arm ratio

Figure 3 Trail section assumed as per Kani's diagram.

Using these results, the quantity of concrete and rebars in each beam is calculated. Further using these data, the defined functional units are calculated. The calculation of the same is illustrated in the table 1.

Table 1 Beam design calculations and functional unit computation

S.N O.	REBAR TYPE	BEAM DIMENSIONS			CONCRETE QTY (CU. M)	REBAR IN KG	MU AT FAILURE (MATL AB CODE)	FUNCTIONAL UNIT (MU/M3)	FUNCTIONAL UNIT (MU/KG)
		Width, b	Depth, D	Length, l					
1	CFRP Rebar	200	300	2750	0.165	1.02	89.39	541.76	87.38
2	BFRP Rebar	200	300	2750	0.165	1.72	76.27	462.24	44.45
3	GFRP Rebar	200	300	2750	0.165	2.91	84.54	512.36	29.08
4	Steel Rods (HYS D)	200	300	2750	0.165	6.16	57.7	349.70	9.36

Further, the calculated values of the two FUs are compared with the data of CO₂ emissions and energy consumption of the materials taken from various literature and industries. Using these data, kg-CO₂/Mu and energy consumed (MJ)/ Mu is evaluated. This analysis is carried out for the cradle to gate phase of the materials only. The table 2 shows this evaluation of data. Further, the cost of the FRP reinforcements are compared with that of steel reinforcements in form of cost ratios as considering cost of steel as 1. The assumption made is that the concrete is uniform and the its cost is same for all the types of beams designed here. Using these values, Cost/Mu is evaluated and results are compared.

Table 2. Comparative results for reinforced concrete beams

S.NO.	REBAR TYPE	Mu AT FAILURE (AS PER ACI CODE) [12]	TOTAL COST RATIO/Mu [19][20][21]	%TOTAL COST RATIO/Mu	KG- CO ₂ /Mu [22][23]	% KG- CO ₂ /Mu	MJ/Mu [22][24]	% MJ/Mu
1	CFRP Rebar	89.39	0.049	54.83%	1.49	39.46%	6.89	31.70%
2	BFRP Rebar	76.27	0.092	15.95%	1.48	39.72%	5.04	49.97%
3	GFRP Rebar	84.54	0.070	35.50%	1.39	43.36%	5.37	46.77%
4	Steel Rods (HYS D)	57.7	0.109	-	2.46	-	10.08	-

VALIDATION

The results of the developed code were validated from the experimental and analytical results obtained from the literature. The code is validated for different reinforcing materials including steel and FRPs. The results are compiled and shown in Table 3.

Table 3. Comparison of results from literature and MATLAB code

S.No	Rebar Type	Beam Dimensions			Concrete Qty (Cu. M)	% rebar	Mu at Failure (Literature data) [25]	Mu at Failure (Matlab Code)
		Width, b	Depth, D	Length, l				
1	CFRP Rebar	200	300	2750	0.165	0.80%	80.89	78.8
3	GFRP Rebar	200	300	2750	0.165	1.60%	77.47	72.4
4	Steel Rods (HYSR)	200	300	2750	0.165	1.30%	55.1	57.7

RESULTS AND DISCUSSION

The result shows that the with CFRP rebars as reinforcement in beams, it resulted in being the most economical (approx. about 55% cheaper than steel reinforced beams) despite being the costliest material (approx. CFRP rebars costs 4 times the steel rebar) due to material being of low density and higher ultimate tensile strength. Also, due to high ultimate carrying capacity, the requirement of concrete is reduced resulting in further cost reduction of beams. The results for CO₂ emissions and Energy content shows that the GFRP reinforced beams are most environment friendly in terms of CO₂ emissions being 43% less CO₂ emissions with respect to steel reinforced beams and BFRP reinforced are more environment friendly in terms of energy consumptions being 50% less energy consumption with steel reinforced beams as depicted in Figure 4.

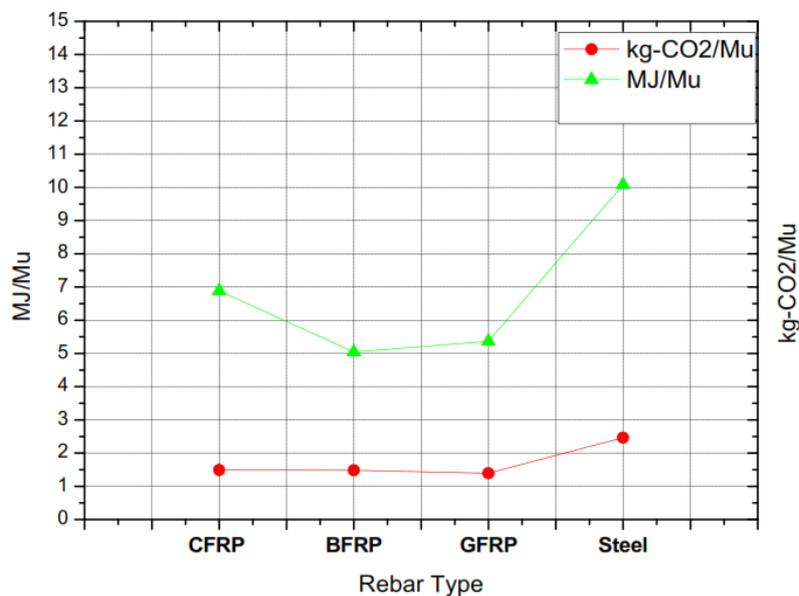


Figure. 4 Parametric study results plot

In the future, the market for BFRP rebars is expected to grow for its use in precast concrete members as the mass production of the rebars will result in reduction of the cost and will make the material cost effective.

CONCLUDING REMARKS

On the basis of the derived results of this study, the following conclusions are being drawn:

- i. The CFRP rebars proves to be most economical among all the alternatives despite being the costliest material.
- ii. The GFRP rebar is estimated to cause the least CO₂ emission (kg-CO₂/Mu) making it the most best alternative in order to reduce the green house gasses effect.
- iii. The BFRP rebar consumes the least energy in production (MJ/Mu) making them the most eco-friendly alternative to steel rebars.
- iv. In future with the advancement of technology and mass production of the BFRP rebars, the cost of production is expected to reduce drastically which will make it the most cost effective and eco-friendly alternative to steel rebars especially in pre-stressed concrete beams.
- v. The further development of proper design and construction codes for RC beams using FRP will promote the use of these in construction industry.

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