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Design for repair and strengthening of reinforced concrete beam structures using fiber reinforced polymer (FRP)

Nguyen Ngoc Thang [1 *], Pham Nguyen Hoang [1]

[1] Faculty of Engineering, Thuyloi University

KEYWORDS

Fiber reinforced polymer
Strengthening the structure
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ABSTRACT

Composite materials made from high molecular weight fibers and polymers, commonly known as Fiber Reinforced Polymers (FRPs), have emerged as a modern alternative to traditional materials in the repair and restoration of damaged structures. FRP materials are characterized by their lightweight nature, excellent corrosion resistance and extremely high tensile strength. They come in a variety of forms, from thin factory-made sheets to dry fiber fabrics that can be wrapped around the shape of structural members and then impregnated with a polymer-based binder. The relatively thin profile of cured FRP layers makes them particularly suitable for applications where aesthetic considerations are required in concrete structures. This paper presents a method for designing reinforced concrete beam structures in civil construction works using FRP panels. This method is applied and evaluated through a case study at a project of a Trade Center, Supermarket and Product Exhibition Complex in Hoang Mai District, Hanoi.

1. Reinforcement of reinforced concrete structures with fiber materials

FRP material - Fiber Reinforced Polymer is a type of composite material made from fiber materials, of which three commonly used fiber materials are carbon fiber CFRP, glass fiber GFRP and aramid fiber AFRP. The characteristics of these fibers are very high tensile strength, very large elastic modulus, low weight, high abrasion resistance, good insulation, heat resistance, and durability over time. FRP types used in construction are often in the form of: FRP in sheet form; FRP in bar form, FRP in cable form, FRP in fabric form, and roll form. In repairing and reinforcing construction works, FRP in sheet form and single-woven fabric, cross-woven fabric, unidirectional or multi-directional woven fabric are often used as shown in Fig. 1 [1].

Carbon Composite Fiber is a fiber containing at least 90 % carbon atoms that are strictly controlled during the pyrolysis of theoriginal raw material fibers. The material is compatible with base resins: Epoxy, Vinylester with density: 100 g/m^2 - 1200 g/m^2. The main advantages of this FRP material reinforcement method are shown in previous studies including: High tensile strength, 10-15 times higher than steel tensile strength; light and versatile, suitable for different structural shapes; Reinforcement of structures subject to bending, shearing and compression. In addition, the construction and installation process is quick, easy, does not affect the architecture of the building, the material is durable over time and in chemical environments, easy to calculate and re-check with the software provided by the manufacturer are also outstanding advantages mentioned. [2, 3]. The mechanical properties of CFRP carbon fiber and GFPR glass fiber are shown in tables 1 and 2 below [4].

The mechanical properties of some types of adhesives used for structural reinforcement are shown in Table 3 below [4].

Figure 1. FRP fiber material reinforcing reinforced concrete structures [1].

*Corresponding author: thangnn@tlu.edu.vn

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Table 1. Mechanical properties of CFRP carbon fiber [4].

Carbon Fiber Type	Density [g/cm^3]	Tensile modulus of elasticity [GPa]	Tensile strength [MPa]	Maximum elongation (%)
Standard	1.7	250	3700	1.2
High intensity	1.8	250	4800	1.4
High elastic modulus	1.9	500	3000	0.5
Ultra high elastic modulus	2.1	800	2400	0.2

Table 2. Mechanical properties of GFPR glass fibers [4].

Fiberglass Type	Density [g/cm^3]	Tensile modulus of elasticity [GPa]	Tensile strength [MPa]	Maximum elongation (%)
Type A	2.57	72.5	3400	2.5
Type E	2.46	73	2760	2.5
Type C	2.46	74	2350	2.5
Type S	2.47	88	4600	3

Table 3. Mechanical properties of reinforcing adhesives [4].

Type of glue	Density [g/cm^3]	Tensile modulus of elasticity [GPa]	Tensile strength [MPa]	Maximum elongation (%)
Polyester	1.2	4.0	65	2.5
Epoxy	1.2	3.0	90	8
Vinylester	1.12	3.5	82	6
Phenolic	1.24	2.5	40	1.8

Figure 2. Construction steps for FRP fiber bonding to reinforce reinforced concrete structures [6, 7].

Recent studies have proposed a method for repairing and reinforcing structures using FRP panels based on the principle of repairing and reinforcing reinforced concrete structures using FRP panels, which is to place the FRP panels in the position where the load-bearing capacity needs to be increased with the fiber direction consistent with the load-bearing direction to take advantage of the tensile strength and durability of the FRP fibers, while ensuring that the FRP panels do not delaminate or separate from the concrete surface [5]. In [6, 7], the main steps for constructing FRP panels are listed as follows: first, prepare to repair the concrete surface; second, apply primer to increase adhesion, smooth the surface, apply glue or adhesive; step 3, place the panels on the adhesive layer, wait for the adhesive layer to dry for the specified time, then apply the next layers, and the final step is to wait for the structure to dry completely, then apply protective and aesthetic coatings.

Currently, the two most popular construction methods for FRP panels and fabrics are dry lay-up and wet lay-up [8, 9]. With dry lay-up construction, the process of dry lay-up of FRP panels can be divided into six steps as follows: *1) Concrete surface preparation:* The concrete surface must be carefully treated to ensure that the bond between the FRP panels and the concrete is stable throughout the subsequent working process. Cracks, chipped debris and rusted reinforcement must be removed and patched with suitable repair mortars. In the technical requirements of this preparation step, all cracks with a width greater than 0.025mm must be pumped with epoxy for repair. *2) Structural primer:* The reinforced position must be primed using a short or medium roller. *3) Applying putty to level the surface:* Putty is used to level the surface and fill defects; complete coverage is not necessary but must be handled carefully with a hand trowel, can be applied to a wet primed surface without waiting for the paint to dry. *4) Applying the first layer of glue:* The glue is brushed onto the primed surface and leveled with a roller, the glue layer is about 15mm to 20mm thick depending on the type of glue, note that in this step the amount of glue used also depends on the type of FRP. *5) Gluing the FRP panels*: The FRP panels are measured and cut before being placed on the surface to be reinforced. The process of gluing the FRP panels is to place them on the concrete surface and press gently on the glue layer. Before peeling off the backing paper, use a rubber roller to roll in the direction of the fibers so that the glue penetrates into the individual fibers. The roller should never be rolled perpendicular to the fiber direction to avoid possible damage to the fibers. *6) Apply the second layer of glue*: The second layer of glue can be applied 30 minutes after the previous bonding and rolling of the FRP sheet. At this point, the first layer of glue has completely absorbed into the FRP sheet, the second layer of glue is applied to the FRP sheet with a medium-sized roller with a thickness of about 15 to 20 mm.

With wet lay-up FRP sheet bonding: The wet lay-up method of FRP sheet bonding is basically the same as the dry lay-up method, however, the wet method differs in the step of applying glue to the FRP sheet. In this method, when bonding FRP sheets using the wet method, we only use a dry FRP cloth that has not been impregnated with resin. The dry FRP sheet will be soaked with resin until saturated and bonded to the thoroughly treated concrete surface.

Figure 3. Construction of FRP fiber bonding to reinforce reinforced concrete structures [8, 9].

The advantage of the wet bonding method is that it can be used for large-sized structures, and the connection between FRP panels is more secure. However, when using the wet bonding method, the amount of glue is very large, so the waiting time is longer. The process of applying resin to FRP panels can use a resin impregnation machine for large-width FRP panels or can be done manually by hand for small-width FRP panels.

2. Design of reinforced concrete structures using fiber materials

2.1. Reinforcement design principles

The authors in [10, 11] provide the basis for calculating the reinforcement of reinforced concrete structures using carbon fibers and indicate the calculation of reinforcement according to the calculation principle of reinforced concrete structures, specifically including: 1) Hypothesis of the correlation of steel deformation in concrete structures and FRP fibers; 2) Hypothesis of no slippage between FRP fibers/sheets and concrete surface and 3) Ignoring the tensile strength of the adhesive layer and of the concrete.

These calculations are based on several failure mechanisms of FRP reinforced beams as shown in Figure 4 below.

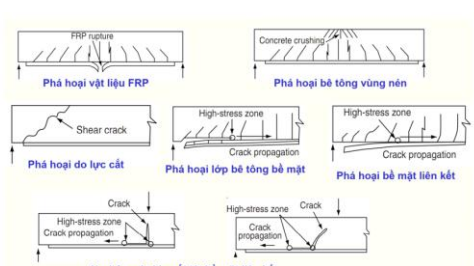

Figure 4. Failure mechanism of beam structure reinforced with FRP fiber material [10, 11].

2.2. Calculation of reinforced concrete beam reinforcement according to ACI 318 – 85 [12]

2.2.1. Preliminary calculation to select the number of FRP layers required

Flexural capacity of old reinforced concrete beams:

$$\varphi.M_n = \varphi.A_s.f_y.\left(d-\frac{a}{2}\right) \qquad (1)$$

with:

$$a = \frac{A_s f_y}{0{,}85 f_c^{'} b} \text{ and } \varphi = 0.9 \qquad (2)$$

If $\varphi.M_n \geq M_u$ no reinforcement is needed, if $\varphi.M_n < M_u$ then reinforcement is needed.

Area of FRP sheet required for reinforcement:

$$A_f = \frac{T}{\varphi 0{,}85 f_{fu}} \qquad (3)$$

with:

$$T = \frac{M_u - \varphi M_n}{0{,}9d} \qquad (4)$$

Number of FRP layers required is selected according to (n_f is an integer):

$$n_f = \frac{A_f}{w_f t_f} \qquad (5)$$

with FRP sheet size is $W_f\ t_f$

2.2.2. Calculate the initial deformation at the bottom of the beam at the time of FRP sheet gluing construction

State of concrete at the time of FRP sheet bonding , case $M_{cr} < M_{ip}$ cracked state ; if $M_{cr} \geq M_{ip}$ uncracked state

Cracking moment of concrete beam is determined by:

$$M_{cr} = f_r.S_m \qquad (6)$$

With:

$$f_r = 7{,}5.\sqrt{f_c^{'}} \text{ and } S_m = \frac{I_g}{h/2} \qquad (7)$$

Initial deformation of concrete at the bottom surface of the beam in cracked state:

$$\varepsilon_{bi} = \frac{M_{ip}(h-h_d)}{I_{cr}E_c} \qquad (8)$$

With:

$$k_d = \frac{\sqrt{((E\ \ /E_c)A\ \ )^2 + 2b(E_s/E_c)A_s d - (E_s/E_c)A_s}}{b} \qquad (9)$$

and:

$$I_{cr} = b.\frac{(k_d)^2}{12} + b.k_d\left(\frac{k_d}{2}\right)^3 + \frac{E_s}{E_c}.A_s.(d-k_d)^2 \qquad (10)$$

Initial deformation of concrete beam in uncracked state:

$$E_{bi} = \frac{M_{ip}C_b}{I_g E_c} - \frac{P_e}{A_c E_c}\left(1+\frac{ec_b}{r_g^2}\right) \qquad (11)$$

2.2.3. Bearing capacity of beam after reinforcement with FRP plate:

$$M_n = A_s.f_s\left(d-\frac{\beta_1 c}{2}\right) + 0{,}85.A_s.f_s\left(h-\frac{\beta_1 c}{2}\right) \qquad (12)$$

With:

$$\beta_1 = 1{,}05 - 0{,}05\frac{f_c^{'}}{1000} \text{ and } c \approx 0{,}02.d \qquad (13)$$

The bearing capacity of the beam must $\varphi.M_n$ be greater than the calculated bending moment M_u (with coefficient). The value $\varphi$is now determined as follows:

$$\varphi = \begin{cases} 0,90 Khi\varepsilon_s \geq 2\varepsilon_{sy} \\ 0,50 + 0,20\dfrac{\varepsilon_s}{\varepsilon_{sy}} Khi\varepsilon_{sy} < \varepsilon_s < 2\varepsilon_{sy} \\ 0,70 Khi\varepsilon \quad \leq \varepsilon \quad y \end{cases} \qquad (14)$$

3. Reinforcement of reinforced concrete beams at Hanoi Trade Center Project

3.1. Reinforcement design calculation

CDA Tam Trinh commercial center, supermarket and product display project, Hoang Mai, Hanoi, invested by Thanh Cong Group. During the process of putting into operation, the investor changed the usage function, leading to a significant increase in the load of the project on the floor. After checking and calculating, with the load corresponding to the new function, the current beam and floor structure at some locations did not ensure the load-bearing capacity. The proposed solution was to design and reinforce the beam and floor with FRP material by covering them on the outside.

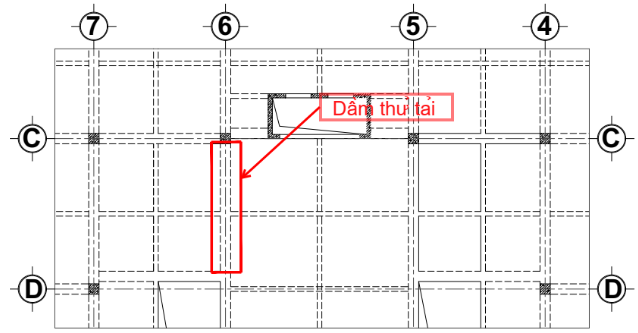

Figure 5. Beam location for design calculation, reinforcement and load testing.

The test calculation results are listed in Table 5, the beam and floor reinforcement plan using FRP material with material parameters has been selected and listed in Table 6 below.

Table 4. Parameters and data of reinforced concrete beam reinforcement problem.

Type	Numerical order	Data parameters	Symbol	Value
Concrete	1	Density of concrete	g_c	2500 kg/m^3
	2	Specific gravity of concrete	γ_c	24.53 kN/m^3
	3	Strength of concrete	f'c	18 MPa
	4	Elastic modulus of concrete	E_c	19900 MPa
	5	Modulus of failure of concrete	f_r	2.67 MPa
	6	Steel - concrete conversion factor	$n = E_s/E_c$	10.0
Steel	1	Density of steel	g_s	7850 kg/m^3
	2	Specific gravity of steel	γ_s	77.01 kN/m^3
	3	Yield strength	f_y	400 MPa
	4	Modulus of elasticity of steel	E_s	200000 MPa
Cross section size	1	Beam Width	b	550 mm
	2	Beam height	h	600 mm
Reinforcement arrangement	1	Number of tensile reinforcement	n_t	5
	2	Number of compression reinforcement	n_c	4
	3	Diameter of tensile steel bar	Φ_t	22mm
	4	Compression steel diameter	Φ_c	25mm
	5	Tensile steel area	A_t	1901 mm^2
	6	Compressive steel area	A_c	1963 mm^2
	7	Distance from center of tensile reinforcement to compression edge	d	558 mm
	8	Distance from center of compression steel to compression edge	d'	42 mm

Table 5. Calculation results to test the bending capacity of the beam.

STT	Test calculation parameters	Symbol	Value	Conclude
1	Maximum compressive concrete deformation	ε_u	0.003	
2	Tensile steel content	$\rho = A_s/(bd)$	0.0062	
3	Compressive steel content	$\rho' = A'_s/(bd)$	0.0064	
4	Neutral axis height	c	59mm	
5	Height of compressive concrete stress block	a	50mm	
6	Deformation in compression reinforcement	$\varepsilon_{'s}$	0.0009	
7	Stress in compression steel	$f_{'s}$	172 MPa	
8	Nominal bending moment	M_n	399.4 kNm	
9	Resistance coefficient		0.9	
10	Calculated bending moment	M_r	359.5 kNm	
11	Calculated bending moment	M_u	438 kNm	
12	Static load bending moment	M_{DL}	284.7 kNm	Not satisfied
13	Steel content test	CD	0.11 < 0.42	
14	Minimum tensile steel content	min	0.00135	Satisfied

Table 6. TYFO SCH-41 Reinforcement Material Type.

STT	Parameter	Symbol	Value
1	Modulus of elasticity	E_f	82000 MPa
2	Thickness of each layer	t_f	1.00 mm
3	Tensile strength	f_{fu}^*	834 MPa
4	Allowable deformation	ε_{fu}^*	0.0085mm/mm
5	Number of layers of beam bottom reinforcement	n_f	1
6	Width of each layer	w_f	500 mm
7	Effective height of FRP layer for bending	d_f	601 mm

With the plan to strengthen reinforced concrete beams with FRP material, after calculating and checking, the results are shown in the tables below.

Table 7. Calculation of properties of FRP materials.

STT	Parameter	Value
1	Conditions of exposure	Contact in
2	Environmental discount factor (CE)	0.95
3	Calculated tensile strength (f_{fu})	792 MPa
4	Allowable deformation for calculation (ε_{fu})	0.00808mm/mm

Table 8. Concrete properties according to ACI318.

STT	Parameter	Symbol	Value
1	System number	β	0.85
2	Tissue heat piano return belong to calf tone	E_c	19940.4 MPa
3	Tensile steel area	A	1901 mm ^{2}
4	Compressive steel area	A'	19 63 mm ^{2}
5	FRP cross-sectional area	A_f	500 mm ^{2}a

Table 10. Calculation to check the bending condition of the structure after reinforcement.

STT	Moment component	Symbol	Value
1	Due to main steel	M_{ns}	393 kNm
2	Due to FRP fiber	M_{nf}	139 kNm
3	Total bending moment	M_r	461 kNm
4	Required bending moment (design)	M_u	438 kNm
5	Safety factor	n	1.05
		Conclude	Ensure

Table 9. Deformation and stress parameters.

STT	Parameter	Value	Comparison/Relationship
1	Initial deformation at the bottom of the beam (ε_{bi})	0.0016	
2	FRP design strain (ε_{fd})	0.00607	$< 0.9 \times \varepsilon_{fu} = 0.00727$
3	FRP effective strain (ε_{fe})	0.00607	$= \varepsilon_{fd}$
4	Compression zone concrete strain (ε_c)	0.00173	
5	Reinforcement deformation (ε_s)	0.00703	
6	Stress in steel (f_s)	400 MPa	$f_s = E_s * \varepsilon_s = fy$
7	Stress in FRP material	498 MPa	$f_{fe} = E_f * \varepsilon_{fe}$

3.2. Load test to check calculation results

Testing and evaluation process: TCVN 9344:2012 Reinforced concrete structures - Evaluation of the strength of structural members subjected to bending on the construction by static loading test method. The purpose of the pre- and post-reinforcement load test with FRP fibers for the beam items of the construction is to: 1) Compare the quantities reflecting the behavior of the beam structure before and after reinforcement; 2) Preliminary assessment of the bearing capacity of the reinforced beam structure. Based on the collected data, analysis and processing, to evaluate the effectiveness of the moment reinforcement of reinforced concrete structures with FRP fiber materials.

Compare the calculated data based on theory and the actual experimental results and then evaluate the calculation to ensure the construction of FRP fiber materials according to the stated requirements. The beam selected for testing is beam 1C22 at basement B1 reinforced by 01 layer of SCH41 fiber, glued along the length of 7.8m, glued width of 0.5m. PRF technical parameters at the load testing location are recorded in table 11 below.

Table 11. Technical specifications of FRP materials.

Type fiber	Afternoon thick class Saturated fiber (mm)	Tissue heat elastic (GPA)	Strong Tensile strength (MPa)	Variable form destructive
SCH41	1.0	82	834	0.85 %
SEH25A	0.635	20.9	417	1.76 %

Test load:

Using water as the load, water tanks are installed and pumped in to create an effect corresponding to the design load to cause on the structure to be measured as follows: with $M_{test} \geq 90\ \%{*}M_{HTTT}$, in which M_{test}: Moment at the measured cross-section caused by the test load, M_{HTTT}: Moment at the measured cross-section caused by the live load calculated according to the design value.

According to the design documents, the calculated live load: 1.2*450 kg/m ^{2} = 540 kg/m ^{2}, on this basis, the testing unit chooses the test load as 700 kg/m ^{2}, equivalent to the water level height when reaching 100 % of the test load is 700mm. Table 12 divides the test load levels.

Table 12. Test load level division.

STT	Grant load	Water level height soy sauce application (cm)	Time space Hold Load (Minutes)
0	0 % P_{TN}	0	0
1	20 % P_{TN}	13.5	15
2	40 % P_{TN}	27.0	15
3	60 % P_{TN}	40.5	15
4	80 % P_{TN}	54.0	15
5	100 % P_{TN}	67.5	15
6	100 % P_{TN}	67.5	24 language
7	80 % P_{TN}	54.0	15
8	60 % P_{TN}	40.5	15
9	40 % P_{TN}	27.0	15
10	20 % P_{TN}	13.5	15
11	0 % P_{TN}	0	15

Load test method, measuring equipment arrangement:

On the cross section of the beam, before reinforcement, the device is mounted at the bottom of the beam. After the measurement, the deflection gauge is removed, but the strain sensors are left, and the FRP reinforcement layer is glued on top. At the post-reinforcement measurement, the deflection gauge is mounted in the same position as the previous measurement, and the sensor from the pre-reinforcement measurement attached to the concrete continues to monitor the data. The strain sensor is mounted in addition to the FRP reinforcement layer. Figure 6 details the location of the measuring device.

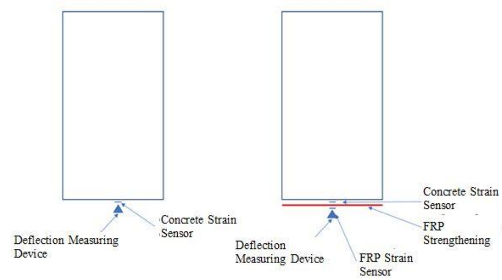

Figure 6. Arrangement of deflection and measuring equipment on the main beam.

Beam deflection measurement results:

Table 13 below shows the results of beam deflection measurements before and after reinforcement, Figure 7 shows the relationship between deflection and load level.

Table 13. Data table of beam structural deflection measurement before and after reinforcement.

STT	Load level	Before reinforcement (mm)	After reinforcement (mm)	Ratio (%)
1	0	0	0	
2	0.2	0.45	0.44	97.8
3	0.4	1.03	0.99	95.6
4	0.6	1.54	1.49	97.1
5	0.8	2.11	2	94.8
6	1	2.65	2.26	85.4

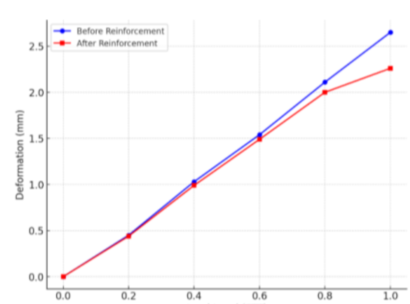

Figure 7. Relationship between deflection and load level before and after reinforcement.

The above results show that the reinforcement of concrete structures: beams and floors affects the stiffness of the structure but not significantly, depending on each load level, the deflection of the beam structure varies and decreases from 2.2-15.6 %, the structure is still working in the elastic stage. The reinforcement effect is obvious, shown at all load levels, the curve showing the deflection after reinforcement is always lower than before reinforcement, the difference is larger at high loads, specifically the difference in deflection between the two states increases gradually with the load, especially clear at load level 1.0 (reduced from 2.65 mm to 2.26 mm). On the other hand, the deflection reduction rate is high, the reduction efficiency ranges from ~85 % to ~98 %, showing that the construction quality and FRP materials play a very important role.

Beam stress strain measurement results:

Table 14 below shows the results of stress and strain measurements of the beam before and after reinforcement, Figure 8 shows the relationship between deflection and load level.

Table 14. Data table of stress and strain measurements of beams before and after reinforcement.

Load level %	Pre-reinforced concrete BD	Reinforced concrete BD	FRP material BD – SCH41 10-6	Comparison of BD of concrete before and after GC (%)
0	6.35	5.21	2.1	82
20	13.73	12.5	14.38	91.1
40	22.97	21.3	22.59	92.7
60	30.42	26.16	27.12	86
80	36.29	33.21	33.56	91.5
100	40.5	37.23	38.5	91.9

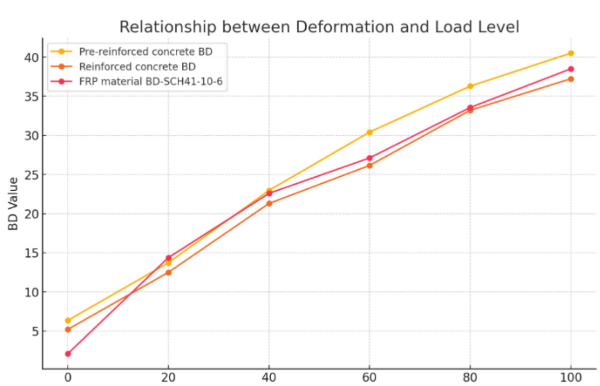

Figure 8. Relationship between deflection and load level before and after reinforcement.

The above results show that: The stress and deformation values of concrete and fiber materials are all within the allowable values. After reinforcement, the FRP material has shown the reinforcement efficiency, corresponding to each load level, the deformation is reduced by 8-14 % (ignored for values when the load is still small). The deformation of the fiber sheet and the deformation of the concrete are similar, they work together, participating in the load-bearing process of the structure, the adhesion between the fiber sheet and the concrete is guaranteed. The deformation of the concrete decreases when reinforced at all load levels, the deformation of the concrete after reinforcement is lower than before, showing that the load transfer to FRP has worked effectively. FRP's deformation increases gradually with the load, specifically the FRP curve is almost parallel to the concrete, showing that FRP has participated in the load-bearing process at the same time, contributing to reducing stress for the concrete. The comparative ratio of concrete deformation (before/after reinforcement) is quite high (ranging from 82 % to 92 %), which proves that FRP panels not only support at high load levels but also improve performance even at lower load levels.

4. Conclude

The FRP reinforcement method significantly improves the bearing capacity of beam structures under conditions of increased load, especially suitable for projects requiring renovation and upgrading of functions. FRP materials with outstanding advantages such as high tensile strength, light weight, corrosion resistance, easy construction and no change in the original shape of the structure have met the technical and aesthetic requirements in the repair and reinforcement process. Test calculations show that the reinforced structure ensures safe and sustainable operation and complies with current design standards. Through research and practical application in the project of a Trade Center, supermarket and product display in Hoang Mai district, Hanoi, it can be affirmed that the use of FRP synthetic fiber materials to reinforce reinforced concrete structures is an effective and feasible solution. This opens up the potential for widespread application of FRP technology in the field of repair and upgrading of civil and industrial works in Vietnam.

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