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Experimental Study on RC Beams Using Stay-In-Place GFRP Forms

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ABSTRACT

Stay-In-place (SIP) formworks are considered as a novel construction technology. This paper presents an experimental study on conventional reinforced concrete (RC) beams strengthened by using SIP Glass Fiber Reinforced Polymer (GFRP) formwork. The experimental test program includes twelve specimens of RC beams without and with strengthening by SIP GFRP forms. Specimens were prepared and classified into four groups. The first group contains three RC solid beams without strengthening, and the second group contains three specimens of RC hollow beams without strengthening. The third group contains three specimens of RC hollow beams strengthened by using SIP GFRP forms. The fourth group contains three specimens of RC hollow beams strengthened by SIP GFRP forms as well as by additional three GFRP sheets at the tension side of the SIP form. The studied parameters include the ratio of main reinforcement, presence of hollow PVC tube, using SIP forms and the additional strengthening by using GFRP sheets. All specimens were loaded by four-point bending test until failure. For comparative study, the test results recorded the crack patterns, cracking and ultimate failure loads, mode of failure and load-deflection curves. The experimental results showed a significant improvement in the flexure behavior of RC beams using SIP GFRP forms compared with the corresponding reference beams without strengthening.

Keywords: RC beams, strengthening, GFRP, stay-in-place forms, flexure behavior.

INTRODUCTION

The Fiber Reinforced Polymer (FRP) is considered as Advanced Composite Material (ACM). FRP composites are characterized by outstanding physical and mechanical properties, including low self-weight, high tensile strength and very good resistance to corrosion. Recently, FRP composite materials have been used in the field of civil engineering constructions especially in corrosive environments [1,2]. They can be used as internal reinforcement for beams, slabs [3,4], or as external reinforcement for strengthening or rehabilitation different structures such as beams, slabs, and columns [5-8]. FRP composites have been used extensively in civil engineering applications in Egypt in recent years [9,10].

Stay-In-Place (SIP) formwork is a permanent system generally used in construction projects throughout the world that will become as basic part of the structural element [11]. SIP forms are considered as a innovative construction technology because of their advantages of rapid execution, saving in construction equipment and being more economic as regards the expenses of labor required for the construction in addition to make hollowing sections at the tension side that will make it lightweight and consequently less expenses. One of the most important applications is the concrete-filled steel or FRP tubes that are becoming an alternative for different structural members such as columns and piles [12-15]. SIP formwork are also used intensively for walls, beams and slabs [16-22]. Commercially available GFRP shapes as SIP open structural forms for concrete structures, including bridge decks and girders.

The main objectives of this study are to show the effect of using a GFRP SIP pultruded formwork as skin reinforcement and strengthening the SIP forms using additional GFRP woven wraps to increase the strength of RC beams. In this research, an experimental test program of RC beams without and with SIP GFRP formwork is achieved. The results indicate outstanding performance of the rectangular RC hollow beams with SIP GFRP forms in terms of load deflection behavior, ultimate failure load -to-weight ratio, and energy absorption compared to the conventional RC beams.

EXPERIMENTAL PROGRAM

An experimental test program is prepared and carried out to study the behavior and performance of half-scale RC beams using SIP GFRP forms in flexural. The details of the experimental test program which include, the dimensions and properties of SIP formwork, the dimensions and reinforcement of RC specimens, material properties, test set up, instrumentation and the test procedures are presented.

Specimens Details

Twelve specimens of RC solid and hollow beams of typical dimensions without and with SIP GFRP forms are classified in four groups and each group has three specimens having three different flexural steel reinforcement ratios.

Specimens of typical prismatic dimensions 160 × 280 × 2500 mm were prepared. They were tested in 4-point bending test. The effective clear span is 2300 and the distance between the two test loads is 600mm. Figure 1 shows the dimensions of the specimens. The tested specimens were classified in four groups, and each group contains three specimens as follows:

Group 1: contains three specimens RΦ10, RΦ12, RΦ16 of conventional RC solid beams with three different lower longitudinal reinforcement bars 2Φ10, 2Φ12 and 2Φ16 respectively. Figure 2 shows the reinforcement details of the tested beams. They are considered as reference specimens.

Group 2; contains three specimens ROΦ10, ROΦ12, ROΦ16 of RC beams of three different lower longitudinal reinforcement bars as in Group 1. Each specimen has a hollow PVC tube of diameter 100 mm, 2 mm thick and 2000 mm length. Figure 3 shows the reinforcement of the tested beams and the PVC tube dimensions. They are considered as reference specimens.

Group 3; contains three specimens FOΦ10, FOΦ12, FOΦ16 of RC beams with fabricated SIP GFRP forms. Each specimen has a hollow PVC tube as in Group 2. Figure 4 shows the reinforcement, dimensions of PVC tube and details of SIP forms.

Group 4; contains three specimens FOΦ10-3G, FOΦ12-3G, FOΦ16-3G of RC beams with SIP GFRP forms were fabricated. Each specimen has a hollow PVC tube as in Group 2. SIP forms were strengthened by additional 3 layers of GFRP. Figure 5 shows the reinforcement, dimensions of PVC tube, details of SIP forms and strengthening GFRP layers.

Table 1 summarizes the experimental test program for the different tested specimens in this research.

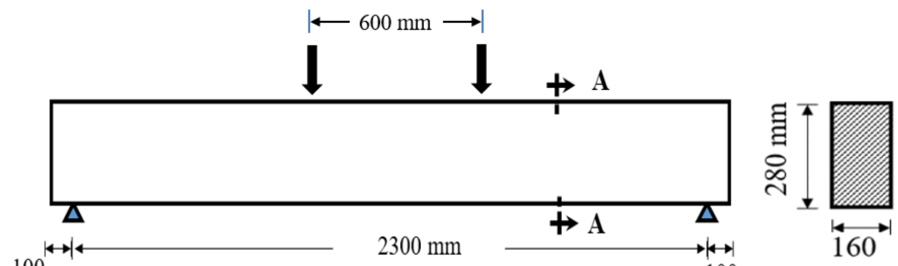
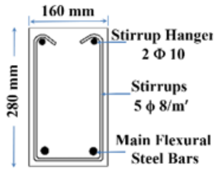
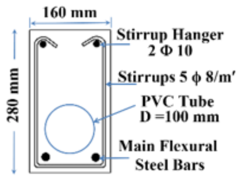
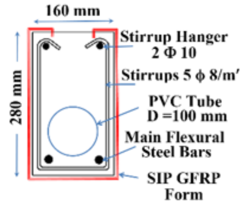
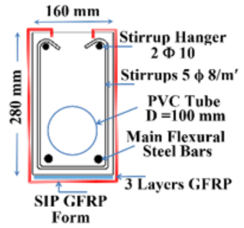


Table 1: Experimental test program

Group	Beam Code	SIP Form	Flexural Reinforce-ment.	Beam Cross-section	Details of Reinforcement	Description
1	**RΦ10**	-	2 Φ 10	Solid		Reference specimens of RC solid beams
	RΦ12	-	2 Φ 12	Solid		
	RΦ16	-	2 Φ 16	Solid		
2	**ROΦ10**	-	2 Φ 10	Hollow		Reference specimens of RC hollow beams
	ROΦ12	-	2 Φ 12	Hollow		
	ROΦ16	-	2 Φ 16	Hollow		
3	**FOΦ10**	3 GFRP layers	2 Φ 10	Hollow		RC hollow beams using SIP forms of 3 GFRP layers
	FOΦ12	3 GFRP layers	2 Φ 12	Hollow		
	FOΦ16	3 GFRP layers	2 Φ 16	Hollow		
4	**FOΦ10-3G**	3 GFRP layers	2 Φ 10 + 3 GFRP sheets	Hollow		RC hollow beams using SIP forms of 3 GFRP layers and strengthened by 3 GFRP layers
	FOΦ12-3G	3 GFRP layers	2 Φ 12 + 3 GFRP sheets	Hollow		
	FOΦ16-3G	3 GFRP layers	2 Φ 16 + 3 GFRP sheets	Hollow		

Test Set-up and Instrumentation

Figure 6 shows the loading rig. Loads were applied in increments using a hydraulic jack of 50-ton maximum capacity. The applied load was equally distributed on two concentrated points using spreader rigid steel beams. Specimens were tested in pure bending as simply supported. The clear span of tested beams was 2300 mm and the distance between the two upper loading points was 600 mm. Five dial gauges of 0.01 mm accuracy and total capacity of 20 mm were used for measuring deflections under the concentrated loads. Deflections under the concentrated loads, first cracking loads and ultimate failure loads were recorded. Propagation of cracks was marked after each load increment up to failure.

MATERIALS PROPERTIES

Specimens were cast using a normal density concrete. Testes were carried out according to ECP-203-18 [23] in Faculty of Engineering, Menoufiya Laboratory (Mounir H. Soliman Lab). The materials used in preparing the RC specimens were cement, clean sand, crushed dolomite, water, steel reinforcement, glass fiber reinforced polymer (GFRP) and polyester. Table 2 defines concrete mix proportions, slump test results and compressive strength after 7 and 28 days. Table 3 shows the mechanical properties of steel reinforcement.

Table 2: Concrete mix proportions and compressive strength

Mix No.	Mix proportions (kg/m^3)				Unit Weight	C. A/ F.A.	W/C%	Slump (mm)	Compressive Strength (kg/cm^2)	
	C	W	F.A	C.A					7 days	28 days
1	350	175	630	1260	2430	2	50	35	235	302

Where: C= Portland cement from Suez Company
W = Water
F. A. = Fine aggregate
C. A. = Coarse aggregate (crushed dolomite with a nominal max. size of 25mm)

Table 3: Mechanical properties of steel reinforcement

Nominal diameter mm	Grade	Actual area (cm^2)	Unit weight (kg/m)	Yield strength (kg/cm^2)	Ultimate strength (kg/cm^2)	Elongation %
Φ 8	24/35	0.470	0.372	3100	4800	26
Φ12	36/52	1.091	0.902	3860	5697	16
Φ16	36/52	1.971	1.572	4200	5950	14

E-Glass fiber reinforced plastics (GFRP)

GFRP based on impregnating resin [24] were used in this study to produce the stay in place form. It is used also as a strengthening layers for the formwork. Material is field laminated using polyester to form a glass fiber reinforced polymer (GFRP) used to strengthen structural elements. GFRP is a bidirectional woven glass fiber fabric for the dry application process. This glass fiber fabric is available in a package of one roll in a cardboard box with length of 80 m. Design thickness of the glass fiber was 0.17 mm and available in width of 500 mm, The characteristic properties of GFRP woven wraps are given in Table 4.

Table 4. Mechanical properties of Sika Wrap Hex-430G [24]

Property	Value
Fabric length/Roll	≥ 80 m
Fabric width	500 mm
Fabric design thickness	0.17 mm
Weight / Area	0.43 kg/m^2
Tensile strength	23000 kg/cm^2
Modulus of elasticity	760000 kg/cm^2
Strain at failure	2.80%

Polyester

Polyester is a solvent free of a low viscosity, which consists of two components unsaturated polyester and peroxide. It has the ability to be in flow state even at low temperatures, and in the presence of moisture. The properties of used polyester (according to the manufacturer) are given Table 5.

Table5. Mechanical properties of polyester material [24]

Property	Value
Flexural strength	750 kg/cm^2
Tensile strength	50 kg/cm^2
Elongation	4%
Modulus of elasticity	24000 kg/cm^2
Bond strength to concrete at 23oC for dry concrete	82 kg/cm^2
Bond strength to steel at 20oC	200 kg/cm^2
Water absorption	24 hr. cold 30 : 100^o 34mg 44mg

EXPERIMENTAL RESULTS

Cracking and modes of failure

All tested beams were failed due to pure bending. Debonding and rapture in GFRP forms were observed in beams at mid-span due to tensile stress at ultimate failure load. After the debonding and rapture of GFRP forms, the flexural resistance of the tested specimens dropped suddenly, however, the specimens did not suddenly completely collapse whereas the steel reinforcement in yield state maintained slowly the acting load till the complete failure of the specimens.

The behavior of the tested beams was investigated through recording deflections under the concentrated loads, cracking and ultimate loads, crack propagation at different stages of loading and failure modes. The results were compared to evaluate the used technique. During the tests, cracks occurred at different loading stages were marked. First cracks were initiated at the center of specimens from the lower tension surface and directed upward. More cracks were observed in in both sides of specimens in symmetrical forms. Figures 7-10 show the crack patterns for all tested beams in the different groups.

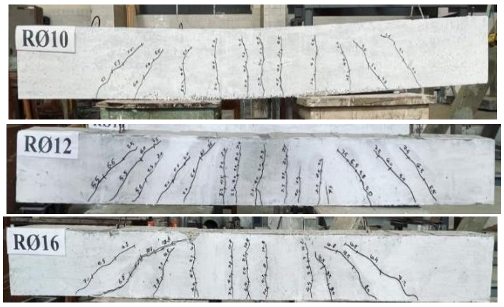


Fig. 7: Crack pattern of specimens in Group 1 at failure

Fig. 8: Crack pattern of specimens in Group 2 at failure

Fig. 9: Crack pattern of specimens in Group 3 at failure

Fig. 10: Crack pattern of specimens in Group 4 at failure

First cracking and ultimate loads

Using different flexural reinforcement ratios 0.35%, 0.5% & 0.9% increased the ultimate capacity. Ultimate failure loads for specimen RΦ12 and RΦ16 increased by about 40% and 93% with respect to RΦ10 respectively. The first cracking loads were decreased for hollow RC beams ROΦ10, ROΦ12 and ROΦ16 in Group 2 due to the cavity of the PVC tubes, by about 13%, 8% and 8% with respect to the reference specimens RΦ10, RΦ12 and RΦ16 in Group 1, while the ultimate loads decrease by about 11%, 7.5% and 7% respectively.

The recorded first cracking loads were increased for RC beams having SIP GFRP forms in Group 3, FOΦ10, FOΦ12 and FOΦ16, by about 233%, 263% and 275% with respect to the reference specimens ROΦ10, ROΦ12 and ROΦ16 in Group 2, while the ultimate failure loads increased by about 120%, 82% and 50 % respectively. It is notice that using SIP GFRP forms increases the ultimate capacity and these effects is decreased with increasing the percent of reinforcement.

The first cracking loads were increased for RC beams having strengthened SIP GFRP forms in Group 4, FOΦ10-3G, FOΦ12-3G and FOΦ16-3G, by about 280%, 286% and 275% respectively with respect to the reference specimens ROΦ10, ROΦ12 and ROΦ16 in Group 2 while the ultimate loads increased by about 160%, 102% and 70 % respectively. For specimens in Group 4, the ultimate capacity due to GFRP strengthening layers for SIP forms were increased by about 18%, 14% and 13% with respect to specimens in Group 3 respectively. Figure 11 compares cracking and ultimate loads for specimens in different Groups. Figure 12 compares the ultimate load to beam weight factor to consider the effects of the presence of hollow part in RC beams using SIP forms. This factor increases the effects of using hollow RC beams in Groups 2, 3 and 4 with respect to solid RC beams in Group 1.

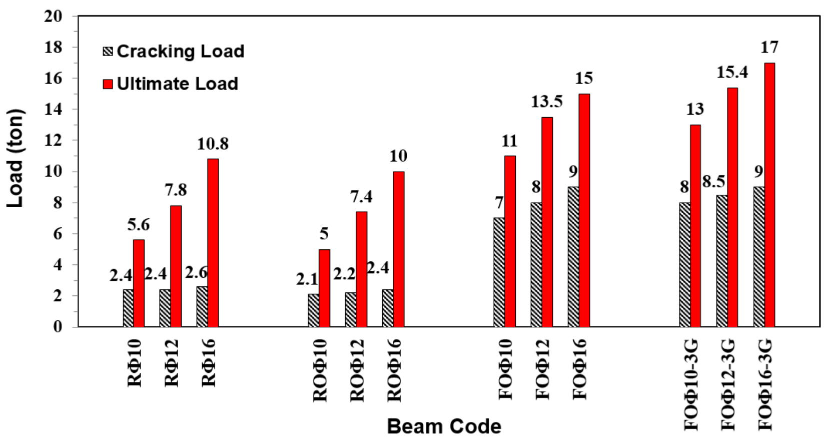


Fig. 11: Crack and ultimate failure loads

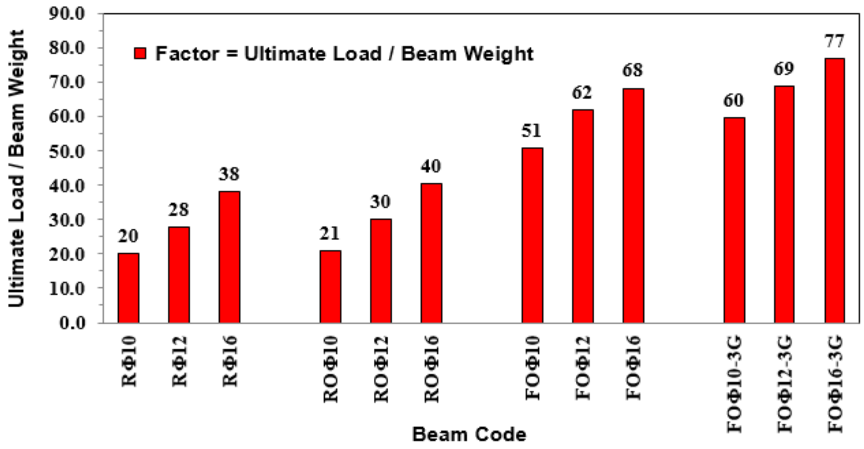


Fig. 12: Factor of ultimate failure load / beam weight

Deflection

Figure 13 shows a comparison between load-deflection curves for reference RC solid beams in Group 1 and reference hollow RC beams in Group 2. It is shown that specimens in Group 2 have higher deflection values compared to the corresponding solid specimens in Group 1 due to the reduction of the stiffness. Figure 14 compares load-deflection curves of RC beams using SIP GFRP forms in Group 3 with respect to the corresponding reference hollow RC beams in Group 2. It shows that the Group 3 has lower deflection values compared to Group 2 as the stiffness of beams increased due to using GFRP stay-in-place forms. The figure shows also that the ultimate capacity for Group 3 increased due to the presence of SIP forms. Figure 15 compares load-deflection curves of specimens having strengthened SIP GFRP forms in Group 4 with respect to the corresponding reference hollow RC beams in Group 2. It is shown that Group 4 had lower deflection values compared to Group 3. The figure shows also that the ultimate capacity for specimens in Group 4 increased due to strengthening more than specimens in Group 2 and 3. The least deflection is observed from beam FOΦ16-3G.

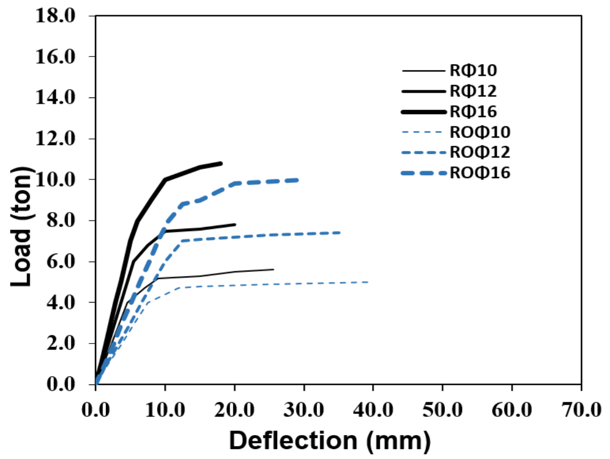


Fig. 13: Comparison between
Load-deflection Curves for Groups 1, 2

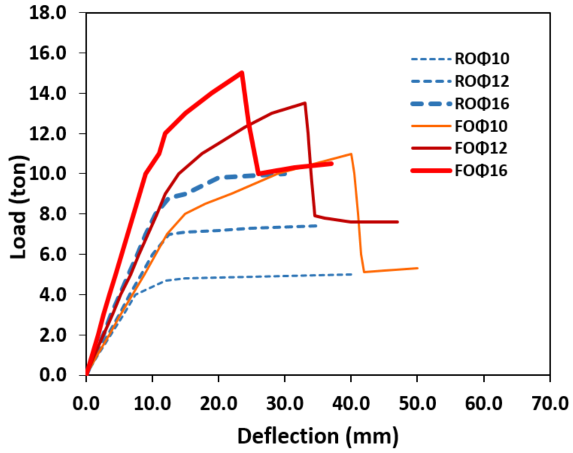


Fig. 14: Comparison between Load-deflection Curves for Groups 2, 3

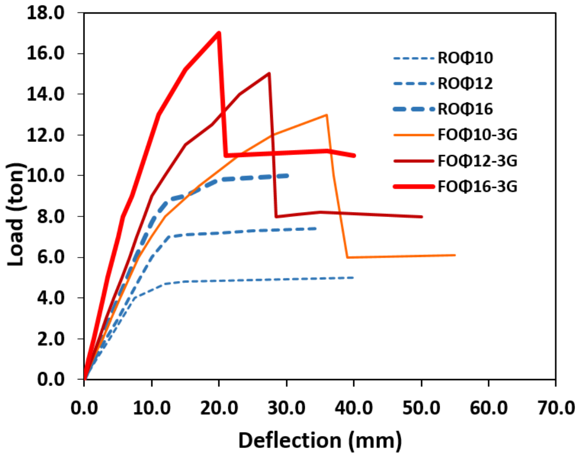


Fig. 15: Comparison between Load-deflection Curves for Groups 2, 4

Ductility and Energy absorption

The issue of ductility and energy absorption is very essential for inelastic behavior. In this study, the ductility and the energy absorption of the tested specimens are calculated and compared for different specimens. Ductility describes the extent to which a structure can sustain large deformations without failing. Ductility of a structure can be defined as the ratio between the maximum deflection due to the ultimate failure load and the maximum deflection at the first cracking load.

Figure 16 shows and compares the ductility for different specimens. Ductility is increased for the presence of the hollow part in RC beams in Group 2 with respect to the corresponding specimens in Group 1. It is noticed that ductility is decreased for Groups 3, 4 with respect to Group 2. Reductions were about 68%, 68%, 71% for specimens having SIP forms FOΦ10, FOΦ12 and FOΦ16 with respect to the reference specimens ROΦ10, ROΦ12 and ROΦ16 respectively. The noticeable decrease for ductility in Group 3, 4 may be attributed to the difficulty of recording the exact first cracking loads of concrete because of the presence of SIP forms.

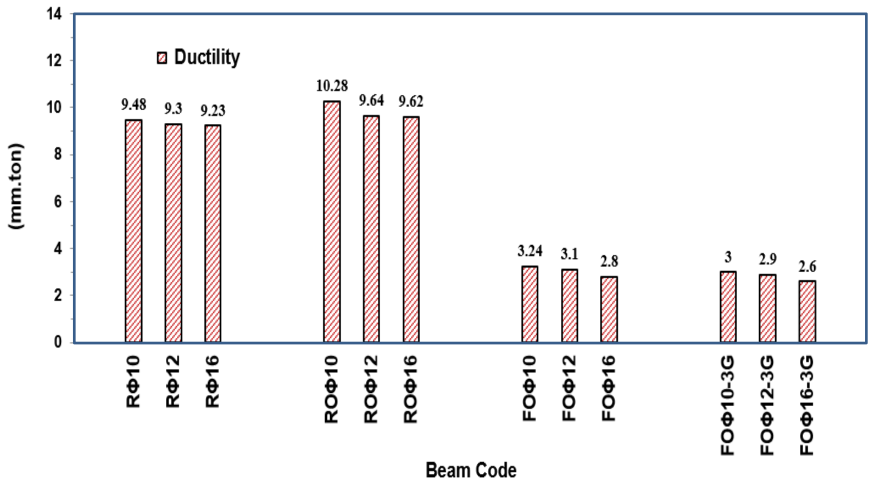


Fig. 16: Ductility for the tested different specimens

Energy dissipation or absorption can be specified by investigating non-linear and inelastic behavior of structure. It is defined as the area under the load-deflection curve at failure.

Figure 17 gives and compare the test results for the energy absorption for different specimens.

As shown from the figure, energy absorption is increased for the presence of the hollow part in RC beams in Group 2 with respect to the corresponding specimens in Group 1.

It is shown that noticeable energy absorption increases for Groups 3, 4 with respect to Group 2. The increases were about 125%, 109%, 80% for hollow RC beams having SIP forms FOΦ10, FOΦ12 and FOΦ16 with respect to the reference specimens ROΦ10, ROΦ12 and ROΦ16 respectively.

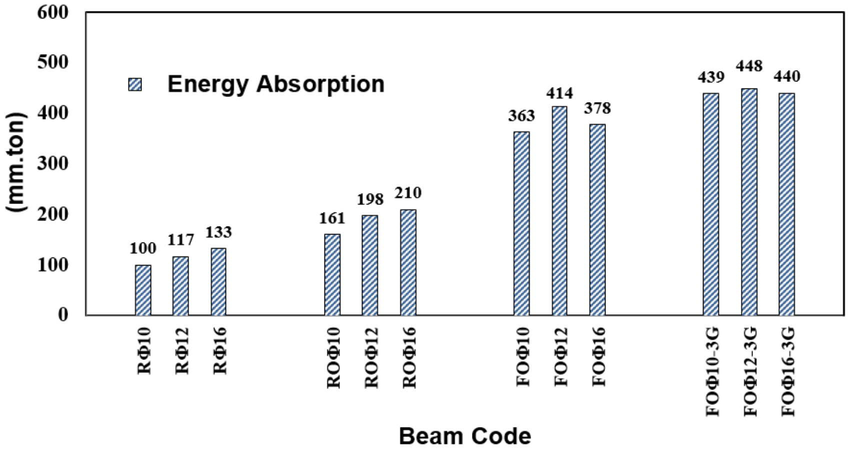


Fig. 17: Energy absorption for the tested specimens

While using SIP forms decreases the ductility, it increases the stiffness and energy absorption. Stiffness is a measure of force value that is required to displace a structure by a certain amount. Increasing the stiffness of the structure can be useful with respect to earthquake damage because it can limit the deformation demands on the structure. The ability of a structure to dissipate energy during deformations is very important, as it will keep deforming without reaching ultimate failure or collapse.

CONCLUSIONS:

Based on the research work, the following conclusions can be drawn:

1. All tested beams were failed due to bending. Using stay-in-place GFRP forms improved flexural resistance of tested beams.
2. Using different flexural reinforcement ratios 0.35%, 0.5% & 0.9% increased the ultimate capacity, the ultimate failure loads for specimens RΦ12 and RΦ16 increased by about 40% and 93% with respect to RΦ10 respectively.
3. Reducing the stiffness of RC beam by using hollow PVC tube, reduces both the weight of the beam and the ultimate failure load, but it increases the load to weight factor, ductility and energy absorption.
4. Using SIP GFRP formwork for hollow RC beams increased the ultimate capacity of beams. The ultimate failure loads increased by about 120%, 82% and 50% for specimens FOΦ10, FOΦ12 and FOΦ16 with respect to the reference specimens ROΦ10, ROΦ12 and ROΦ16 respectively.
5. Hollow RC beams having SIP GFRP formwork improved the ultimate failure loads more than the corresponding conventional solid RC beam by about 25%, 73% and 50% for specimens FOΦ10, FOΦ12 and FOΦ16.
6. Strengthening SIP GFRP formwork by additional GFRP layers for hollow RC beams increased the ultimate capacity. The ultimate failure loads were increased by about 18%, 14% and 13% for specimens FOΦ10-3G, FOΦ12-3G and FOΦ16-3G with respect to specimens FOΦ10, FOΦ12 and FOΦ16 respectively.

7. Measured ductility for specimens having SIP GFRP forms with respect to reference RC beams were decreased. The noticeable decrease may be attributed to the difficulty of recording the exact first cracking load due to existing SIP forms.
8. Energy absorptions of specimens having SIP GFRP forms increased more than the reference RC beams. The increases were about 125%, 109%, 80% for hollow RC beams having SIP forms FOΦ10, FOΦ12 and FOΦ16 with respect to the reference specimens ROΦ10, ROΦ12 and ROΦ16 respectively.
9. Extended GFRP upper hooks and transversal GFRP links in SIP formwork improved the bond between GFRP forms and concrete as well as preventing beam lateral buckling.
10. Debonding and rapture in GFRP forms were observed in beams at mid-span due to tensile stress at ultimate failure load. After the debonding and rapture of GFRP forms, the flexural resistance of the tested specimens dropped suddenly, however, the specimens did not completely collapse whereas the steel reinforcement in yield state maintained slowly the acting load till the complete failure of the specimens.

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