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Flexural Behavior of Hollow Concrete Beams Constructed using Stay-In-Place FRP Forms

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Abstract: The present work studies the flexural behavior of a new type of staying in place (SIP) forms which could be used for beams in future buildings. Six specimens were prepared with (SIP) and tested under four points bending loads. The first group contains two specimens; both of them are supplied with inverted FRP U shape strips to improve the bond between FRP form and concrete. The first specimen contains a PVC tube without reinforcing while the second specimen contains a PVC tube wrapped by three layers of GFRP sheets. The second group contains two specimens; both of them are prepared with upper FRP hooks to improve the bond between FRP form and concrete. Also, the first specimen of the second group contains a PVC tube without reinforcing while the second specimen contains a PVC tube wrapped by three layers of GFRP sheets. The third group contains two specimens; both of them are prepared with upper FRP hook and have three layers of CFRP in the bottom inner face of the form. Both specimens contain unreinforced PVC tube, and the second specimen is prepared with transversal FRP links to improve the bond between FRP form and concrete. The experimental results included ultimate load, load-deflection and load-strain relationships, also; the cracking behavior and failure mode were observed and recorded. The experimental results showed an improvement in the flexural strength of the tested specimens as FRP reinforcement is added to PVC tube or to the form. Also, using FRP hook was the best technique to improve the bond between FRP form and concrete. Moreover, the tested specimens were simulated numerically using ANSYS (version 15). The ultimate loads according to the numerical simulation were higher than the corresponding experimental results by 5% to 38%.

Keywords: Reinforced concrete beam; Flexure Failure, Stay-in-place form, Fiber Reinforced Polymer.

الملخص العربى:

يقدم هذا البحث دراسة عن سلوك الانحناء لانواع مُستحدثة من الفرم الباقيه فى المكان التى يمكن تطبيقها للكمرات الخرسانية. تم اعداد ست عينات باستخدام فرم من الألياف الزجاجية، وتم اختبارها فى الانحناء، بالتحميل في أربعة نقاط. وتحتوى المجموعة الاولى على عينتين كلاهما تم تدعيمه بشرائح مقلوبة من البوليمرات المسلحة بالالياف على شكل حرف U للحد من الانبعاج بمنطقة الضغط، في كلتا العينتين تم وضع ماسورة من الــ PVC بمنطقة الشد، وتم تسليح الماسورة خارجياً باحدى العينتين والاخري بدون تسليح. وتحتوى المجموعة الثانيه على عينتين يختلفا عن المجموعة الأولي فقط في عمل خطاف بكل شفة رأسية للفرمة كنظام بديل للحد من الانبعاج. اما بالنسبة للمجموعة الثالثة فتختلف عن الثانية بلصق شرائح من الالياف الكربونية على السطح السفلى للفرمة، واضيف لأحدى العينتين كانات عرضيه من الالياف الزجاجية لتحسين التماسك بين الخرسانة والفرمة، ولم يتم تسليح الماسورة لكلتا العينتين. تم تسجيل الحمل والترخيم والانفعال لجميع العينات المختبرة كما تم رصد انتشار الشروخ. ودلت النتائج المعملية أن تسليح الماسورة بمنطقة الشد أو أَضافة طبقات شرائح الالياف الكربونية أدى لتحسين السلوك الانحنائي للعينات،

كما أن عمل خطاف بكل شفة رأسية للفرمة كان الأفضل لتحسين التماسك. كما تم اعداد نموذج عددى ببرنامج (ANSYS)، وأعطت النتائج النظرية مقاومة تفوق العينات المعملية بحوالي 5 % الى 38 %.

1. Introduction

The use of new construction systems in future building has been an essential subject to cope with technological and scientific advance in all fields. Recently the evolvement of stay-in-place FRP forms has given a great hope to be the future structures owing to its ability to carry loads resulting from its capacity to resist stresses, so it can bear flexural moments and shearing forces instead of steel reinforcement. In addition, this type of beams has the advantage of rapid execution, saving in construction equipment and being more economic as regards the expenses of labor required for the construction in addition to hollowing section at the tension side which will make it light weight and consequently less foundation expenses. Viewing the previous researches in this aspect, It's obvious that studying the flexural behavior of concrete beams using stay in place FRP forms hasn't been effectively done in a manner that makes its application easy and overcome the disadvantages of use especially, buckling of the flanges. Mainly this can be done through three techniques based on FRP elements which are: 1) inverted U-shape, 2) hook and 3) transverse links. In addition to increasing the bearing ability by changing the type of fibers and its cross-section area.

Generally, few researches have been carried out in this field all over the world. Hart Noah Honickman (2008), provided a study of beams with unfamiliar shape which normally used in residential buildings, the tested beams failed prematurely due to debonding between concrete and flange. Olivier Remy (2012) studied a lightweight stay-in-place formwork as a concept for future building applications. Two types of cross sections were considered: (1) a rectangular cross section, and (2) a rounded shape. He found that the applicability of the proposed design methodology was verified by means of an experimental program and he added numerical model and found that there is a good agreement between the experimental and analytical results. Mark Stewart Nelson (2013), carried out experimental and analytical investigation of five full scale concrete bridge decks specimens with structural FRP stay in place forms. He found that the optimal concrete deck system, with GFRP SIP form and FRP rebars showed remarkable ultimate strength and ductility. The absence of the upper GFRP rebars in the GFRP SIP form deck eliminated the reserve strength about 17% beyond the punching shear failure. In addition, other researches dealed with the rest of construction elements e.g. columns, slabs and walls. This study has focused on the concrete beams manufactured using stay-in-place FRP forms, in order to investigate their structural behavior, specially the bond between concrete and FRP forms.

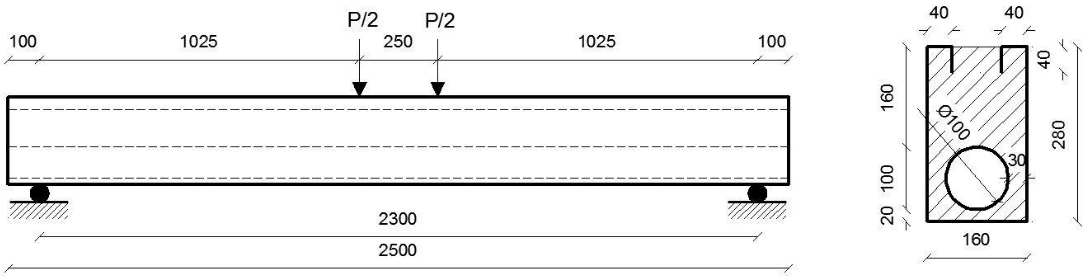
2. Experimental program

A test program was carried out to assess the potential of using stay-in-place FRP form in order to improve the flexural resistance of hollow concrete beams. The tested specimens were half-scale models. The dimensions of the tested specimens were chosen to produce flexural failure mode. All the tested specimens were simply supported beams.

2.1. Details of test specimens

Six half-scale specimens were prepared. All the specimens have the same dimensions, as shown in Fig. 1, the plan dimensions are 160*2500 mm, and the depth is 280 mm. The tested specimens were designed to be simply supported with clear span 2300 mm. The specimens are divided into three groups, as shown in Table1. Basically; all the FRP forms were manufactured from three layers of E-glass fiber.

The first group includes two specimens; SIPU and SIPUR which were provided with upper FRP U-shape strips to avoid the lateral buckling of FRP forms at the compression side. The second group contains also two specimens named SIPH and SIPHR, in which FRP forms were extended making hooks to improve the concrete – FRP bond at compression flange. SIPUR and SIPHR have internal PVC tube reinforced by three layers of GFRP sheets. SIPU and SIPH were provided with unreinforced PVC tube. The third group includes tow specimens named SIPHC and SIPHI which their forms were strengthened by two layers of 100 mm width CFRP sheets fixed internally at the bottom side. Specimen SIPHC was provided by upper FRP hooks to improve the concrete – FRP bond, however transversal FRP links are used in addition to the hooks in specimen SIPHCI for better bond between concrete and FRP forms.



All dimensions in mm

Figure. 1. Dimensions and details of the specimen.

Table 1. Experimental test program.

Group	Specimen code	Specimens Description			
		SIP form component	Bottom reinforcement for the form	Flange shape	Reinforcement of inner PVC tube
No. 1	SIPU	3 layers of GFRP sheets	----------	Inverted U shape strips	unreinforced
	SIPUR				3 layer of GFRP sheets
No. 2	SIPH		----------	Hooks	unreinforced
	SIPHR				3 layer of GFRP sheets
No. 3	SIPHC		2 layers of 100 mm width CFRP sheets	Hooks	unreinforced
	SIPHCI			Hooks and transversal links	unreinforced

2.2 Preparation of tested specimens.

Stay-In-Place FRP Forms were produced in the Concrete Lab. of Faculty of Engineering in Benha. A special metallic form was used to compress the FRP forms, the form was made from aluminum chequered plate, as shown in Fig. 2. All FRP forms were produced using three layers of E-glass woven roving, sika wrap-hex 430 G from sika Egypt Company. The fiber was impregnated by unsaturated polyester with a copalite hardener. Using a smooth surface of melamine wood covered by gel-coat, the FRP forms were produced by the mentioned mold successively. The FRP forms were compressed then a hot light of metal halide lamb 400 watt is used for curing the polyester. Fig.3. shows different shapes for the stay-in-place forms. Three techniques were used to improve the bond between the form and the concrete in order to avoid the lateral buckling of the upper flange. The first technique based on adding inverted U shape strips made from GFRP (specimens SIPU and SIPUR). In the second technique the upper ends of the form was formed as hooks (specimens SIPH, SIPHR & SIPHC), while in the third technique, transversal GFRP links is used in addition to FRP hooks (specimen SIPHCI). Fig. 4 shows the different used techniques. In all specimens, a PVC tube of 100 mm diameter and 5 mm thickness was added. For specimens SIPUR and SIPHR, the PVC tube was wrapped by three layers of GFRP sheets of the same glass fibers, while in the rest of specimens, the PVC tube was unreinforced. The FRP forms were prepared to fulfill the required dimensions of the specimens. As shown in Table (1), the specimens of group (3) (SIPHC & SIPHCI) were strengthened by two layers of 100 mm width CFRP sheets which fixed internally at bottom side of FRP forms prior to concrete placing.

Concrete mix was placed to a depth of 20 mm then the PVC tube was added and the concrete placing was continued to fill all depth of the form. The concrete was vibrated mechanically and the concrete surface was finished. The specimens were left in the lab atmosphere until testing date.

Figure. 2. Aluminum chequered plate mold for manufacturing of FRP forms.

Figure. 3. FRP forms used for stay-in-place concrete beams.

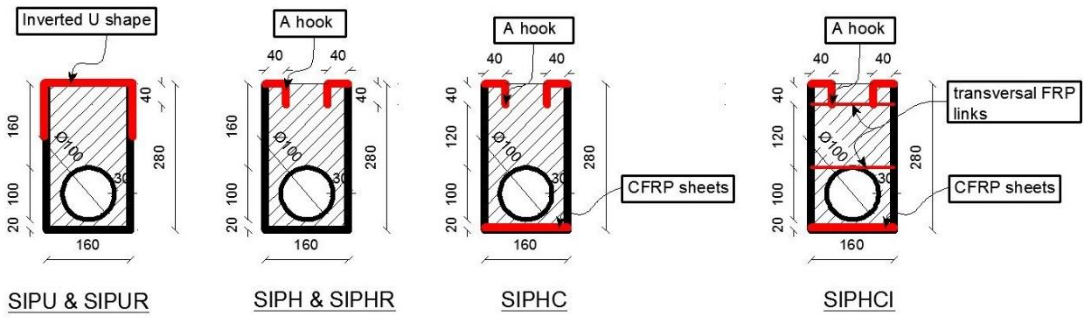


Figure. 4. Shapes of the stay-in-place forms.

2.3. Material properties

2.3.1 Concrete

A trial mixes were prepared and a suitable mix was selected to get target cubic compressive strength of 300 kg/cm2 after 28 days. The constituents of concrete mix and its proportions are presented in Table 2.

Table 2. Constituents of concrete mix and its proportions.

Compressive target strength (kg/cm^2)	Cement (Kg/m^3)	Crushed dolomite (Kg /m^3)	Sand (Kg/m^3)	Water (Liter/m^3)
300	350	1260	630	175

2.3.2 FRP

The E-glass fibers used to produce the stay-in-place forms were Sika wrap Hex-430G, which is a product of Sika Company, and the used polymer was unsaturated polyester. GFRP, also used to reinforce the PVC tube. High strength carbon fibers manufactured by Sika Company under trade name Sika Wrap Hex-230C and epoxy Sikadur-330 are used as a bottom reinforcement in the inner surface of the forms. The Mechanical properties of the used fibers are given according to the manufacturer in Table 3.

Table 3. Mechanical properties of FRP.

Property	GFRP	CFRP
Fabric design thickness	0.17 mm	0.13 mm
Weight / Area	0.43 kg/m^2	0.225 kg/m^2
Tensile strength	23000 kg/cm^2	43000 kg/cm^2
Modulus of elasticity	760000 kg/cm^2	2380000 kg/cm^2
Strain at failure	2.80%	1.8%

3. Test Procedure

The tests were carried out in the Reinforced Concrete Lab at the Faculty of Engineering in Benha. The loading system consisted of rigid system of reaction frame, 100 ton maximum capacity, and hydraulic jack of 100 ton maximum capacity, also connected to electrical pump which provides oil pressure. The specimens were prepared for testing as a simply supported under four point bending loads. The specimens were simply supported over a clear span of 2300 mm. A spreader beam was used to transfer the load to the tested specimen through two loading points of 250 mm spacing at the mid span of the beam. Vertical deflection, first cracking load and ultimate failure load, were recorded. Five linear variable differential transformers (LVDT) were used to record the deflection at 5 detected points, as shown in Fig. 5. Propagation of cracks was marked after each load increment up to failure. Fig.6. illustrates the test set-up.

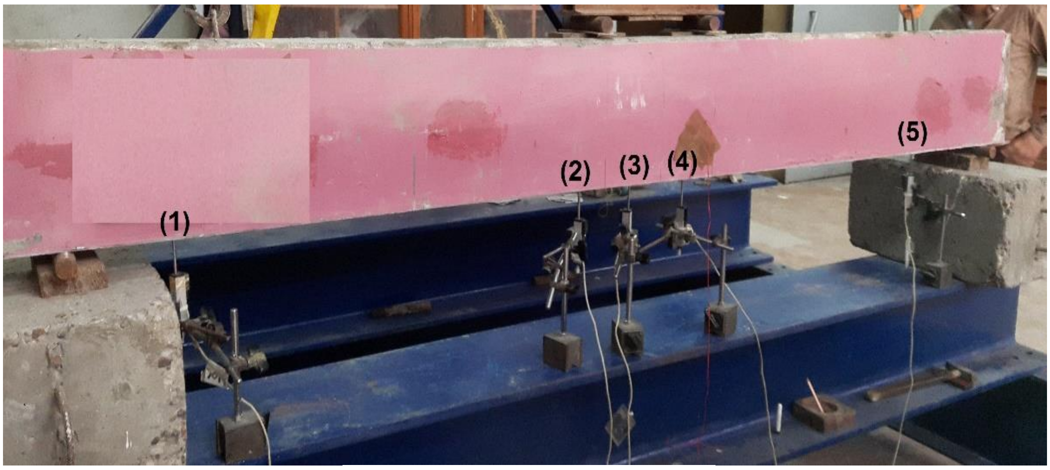


Figure. 5. LVDT locations.

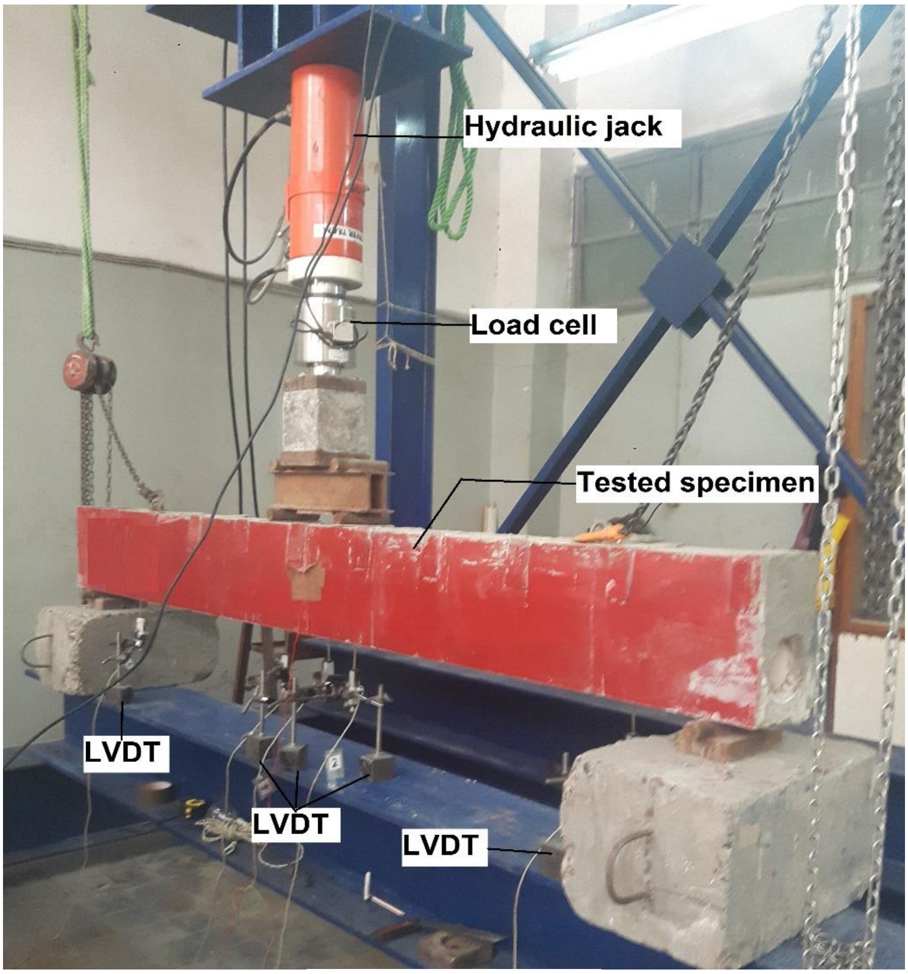


Figure. 6. Test set up.

4. Results and Discussions

For all the tested specimens, the load deflection curve was plotted and the crack propagation was monitored and recorded. Comparisons between the results of different specimens were carried out to reveal the effect of the parameters considered in this study.

4.1. Load-deflection relationships

The vertical deflections were measured at specified locations, as shown in Fig. 5. Vertical deflections were recorded against each load increment up-till slab failure. For each tested specimen the relationship between the central deflection at point (3) versus the applied load was plotted. In this sub-section the load deflection relationships were compared to reveal the effect of the study parameters. Figs. 7 & 8. show the effect of reinforcing the PVC tube. Figs. 9, 10 & 11. show the effect of using the different techniques (inverted U shape strips, FRP hook& transversal links) to improve the bond between concrete and the FRP and, also, to avoid the lateral buckling of the form. Fig. 12. shows the effect of adding CFRP sheets on the flexural behavior of the tested specimens.

4.1.1. Effect of reinforcing of PVC tube

The effect of this parameter could be observed by studying the behavior of specimens SIPU & SIPUR and specimens SIPH & SIPHR. The specimens with PVC tube reinforced using three layers of GFRP sheets had the highest ultimate load and the lowest deflection at all loading stages compared to other specimen due to reinforcing the PVC tube, see Figs (7 & 8). The ultimate load of specimen SIPUR was higher by 49% compared to specimen SIPU. Also, the deflection was reduced by 52% at ultimate recorded load of SIPU specimen.

However, the specimens provided with extended FRP hooks (SIPH & SIPHR) were affected slightly due to the reinforcing of PVC tube. The high efficiency of FRP form due to its good bond with concrete may minimized. The effect of the tube reinforcing is shown in Fig. 8.

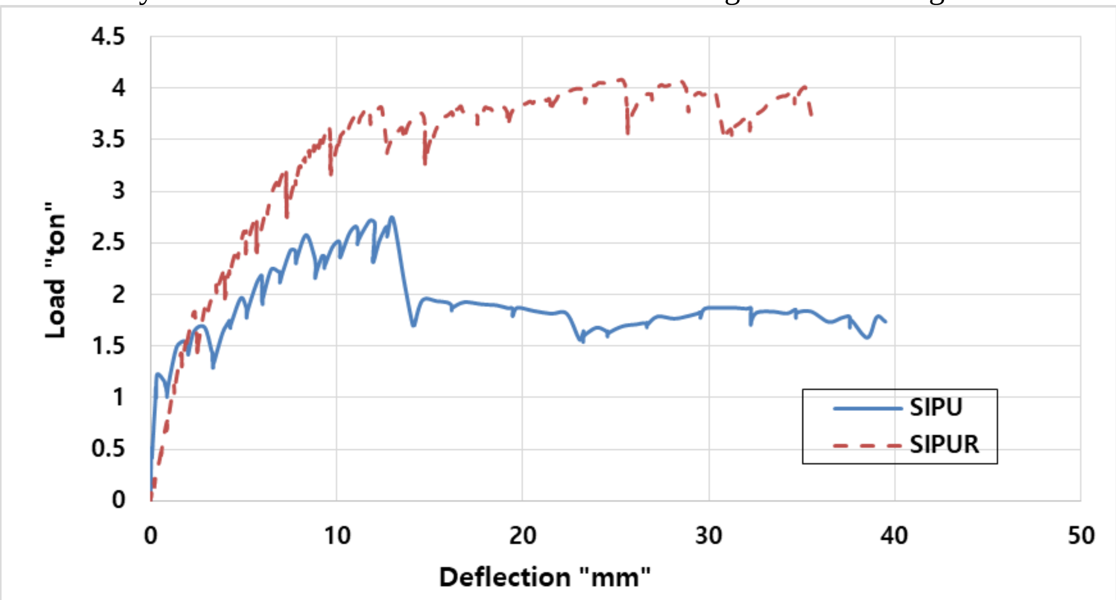


Figure. 7. Comparison between Load-Central deflection relationships of the specimens (SIPU and SIPUR).

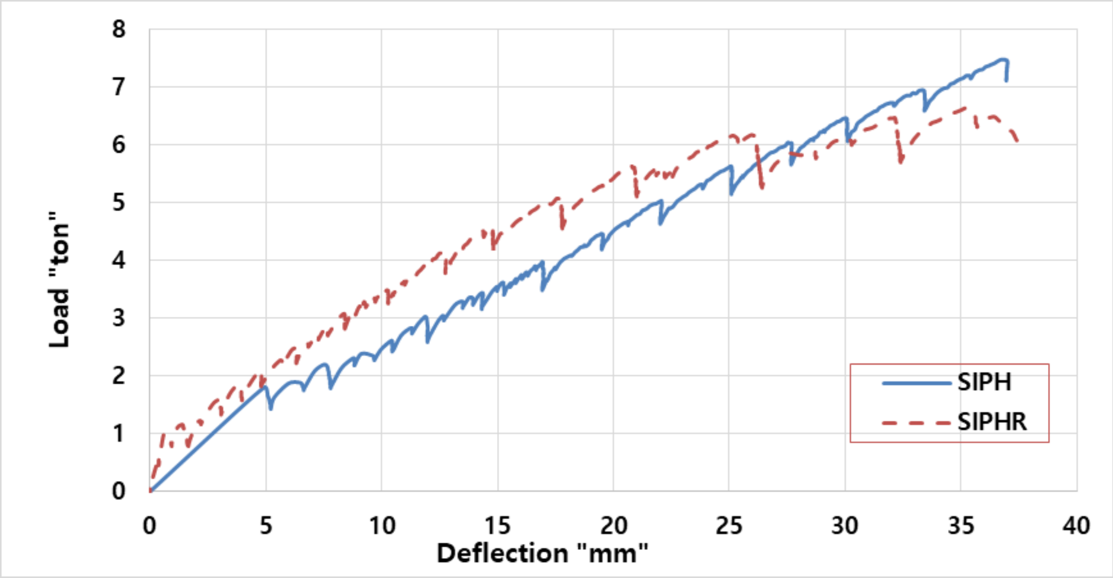


Figure. 8. Comparison between Load-Central deflection relationships of the specimens (SIPH and SIPHR).

4.1.2. Effect of improving the bond between FRP and concrete

The effect of this parameter could be observed by studying the behavior of specimens SIPU & SIPH, specimens SIPUR & SIPHR and specimens SIPHC & SIPHCI, which correspond to three techniques to improve the bond between FRP forms and concrete and, also, to avoid lateral buckling of FRP forms as previously mentioned. The specimens with extended FRP hooks had the highest ultimate load and the lowest deflection at all loading stages. In comparison with the specimen with inverted U strips (SIPU), using extended FRP hooks (SIPH) led to increase the ultimate load by 169%, and to reduce the deflection by 15% at ultimate recorded load of specimen SIPU.

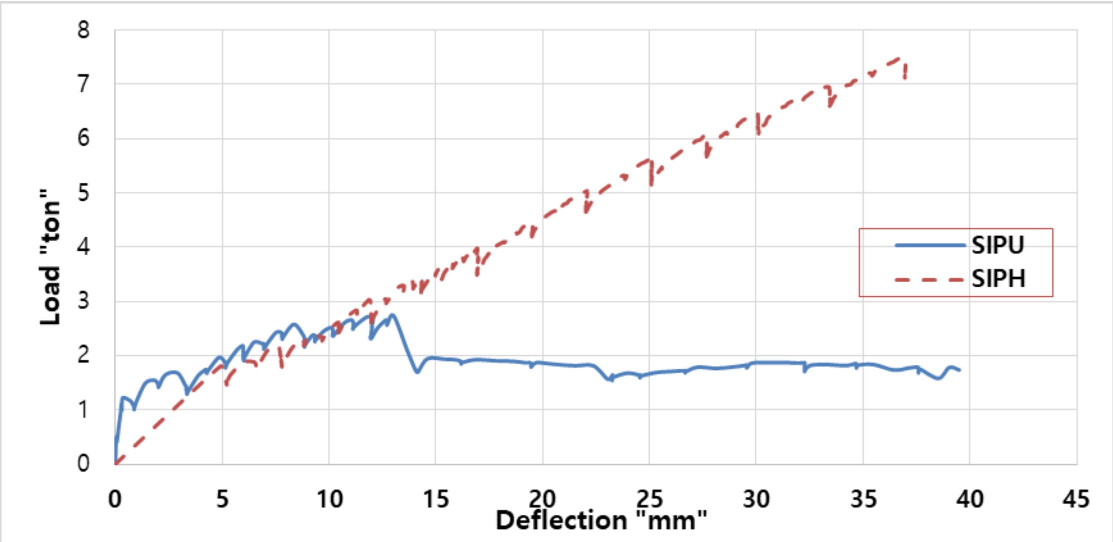


Figure. 9. Comparison between Load-Central deflection relationships of the specimens (SIPU and SIPH).

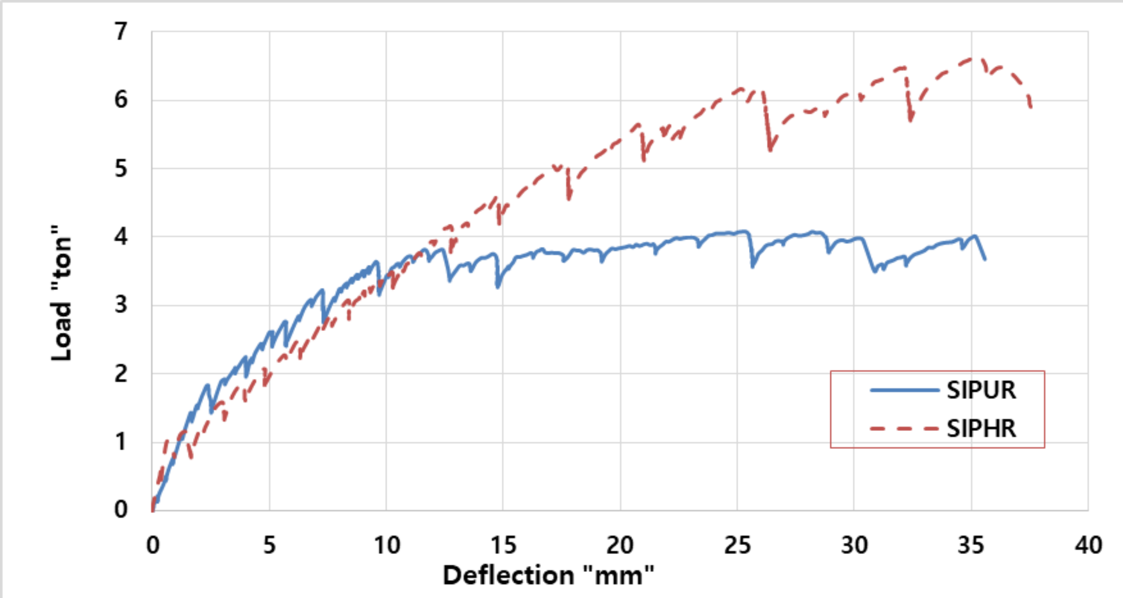


Figure. 10. Comparison between Load-Central deflection relationships of the specimens (SIPUR and SIPHR).

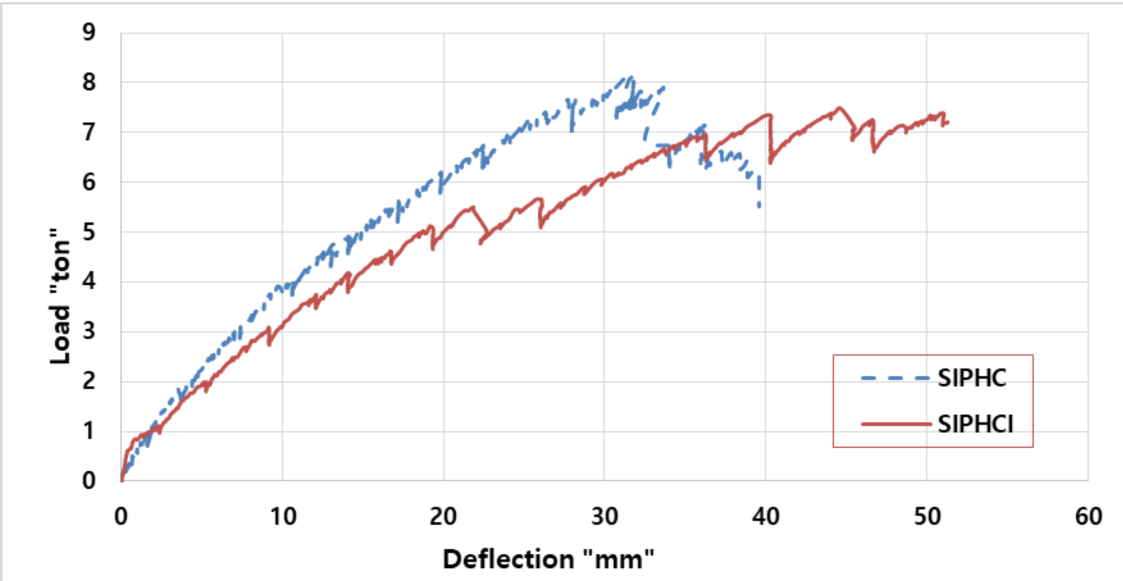


Figure. 11. Comparison between Load-Central deflection relationships of the specimens (SIPHC and SIPHCI).

4.1.3. Effect of strengthening the stay in place form using CFRP

The effect of this parameter could be observed by studying the behavior of specimens SIPH & SIPHC. The specimen (SIPHC) which had the highest ultimate load and the lowest deflection at all loading stages due to strengthening the stay in place form by two layers of 100 mm width CFRP sheets. The ultimate load was higher by 8%, and the deflection was reduced by 26% at ultimate recorded load of SIPH specimen.

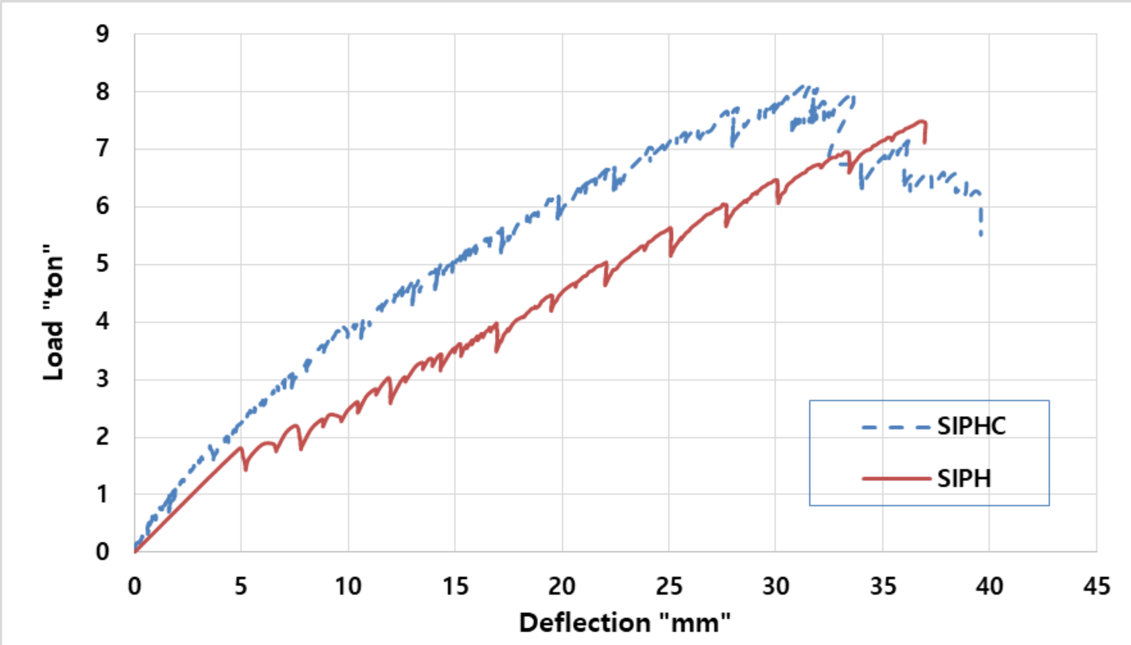


Figure. 12. Comparison between Load-Central deflection relationships of the specimens (SIPHC and SIPH).

4.2. Cracking and ultimate loads

Table.4 presents the deflection and load values at first cracking and at failure, and also the ductility indices, for all the tested specimens. The specimen SIPHC had the highest ultimate load. Generally, the specimens with hooks had the highest ultimate load in comparison with the specimens with inverted FRP U shape strips. Using hooks, as an extension of FRP forms seems to be the best technique to improve the bond between the concrete and FRP form and, also, to immune the lateral bucking of FRP forms at compression zone.

Table 4. Main results of the tested specimens.

Group	Specimen code	1st Cracking		Ultimate		Ductility	Mode of failure
		Load (ton)	Δcr (mm)	Load (ton)	Δul (mm)	Δul / Δcr	
No. 1	SIPU	1.75	4.4	2.75	13.0	2.95	First mode
	SIPUR	2.6	5.3	4.1	35.2	6.64	First mode
No. 2	SIPH	5.1	23.1	7.4	37.0	1.6	Second mode
	SIPHR	4.7	16.3	6.5	36.0	2.21	First mode
No. 3	SIPHC	5.5	17.7	8.0	33.0	1.86	Second mode
	SIPHCI	5.7	28	7.35	50.6	1.81	Second mode

4.3. Ductility

Ductility means the ability of a member to undergo inelastic deformations beyond the yield deformation without any considerable loss of load bearing capacity. The ductility of the specimens was considered as the ratio of the deflection at ultimate load to the deflection at first crack load as shown in Table. 4. Generally, first group specimens which provided with upper FRP U-shape strips revealed higher ductility compared to other specimens due to the lower values of deflections corresponding to the cracking loads of this group.

Figure.13. Failure mode of specimen (SIPUR), (SIPU) and (SIPHR), the first modes.

Figure.14. Failure mode of specimen (SIPH), (SIPHC) and (SIPHCI), the second mode.

5. Finite element analysis

The un-cracked stiffness Ki and the ultimate stiffness Ku were obtained from the load-deflection values of the tested specimens, as presented in Table. 5. It shows that the un-cracked stiffness (Ki) is almost, increased for the majority of the tested specimens. Adding lower concrete layer reinforced by reinforcement steel, CFRP& GFRP bars mesh led to increase Ki while adding lower concrete layer reinforced by externally bonded GFRP sheets led to decrease Ki.

In this part, the tested specimens were simulated using the FEA program ANSYS (version 15). The numerical results of the simulated beams were compared with the experimental results.

All the simulated models are simply-supported beams subjected to two point load. The concrete and resin are modeled with a higher order 3-D element named SOLID65. SOLID185 is used to define FRP sheets and form. A fully bonded interface between FRP forms and concrete was assumed.

Four materials were used in modeling the specimens such as concrete, CFRP sheets, GFRP sheets and epoxy resin Sikadur® 330. The compressive stress-strain relationship of concrete is considered to be linear from zero to one-half the ultimate compressive strength, and the strain at the ultimate compressive strength ranges from 0.002 to 0.003. CFRP and GFRP strips were modeled by linear orthotropic material while epoxy sikadur® 330 were modeled as linear isotropic material. Table. 6 presents the properties of the used material.

Table 6. Properties of the used materials.

Material	Compressive strength (MPa)	Tensile strength (MPa)	Poisson`s ratio	Modulas of elasticity (GPa)
Concrete	25	2.8	0.2	20
CFRP strips	--	4300	0.3	230
GFRP strips	--	2250	0.3	70

The experimental results obtained from testing of the tested specimens are compared with those obtained from the finite element modeling. The experimental and numerical results of load versus mid-span deflection are compared for each specimen, as shown in Figs. (15 to 20). The typical deformed shape of the finite element models obtained by ANSYS (version 15) is as shown in Fig. 21. Table. 7 presents a comparison between the numerical and experimental ultimate loads. It can be noticed that the ratio of the numerical ultimate load to experimental one ranged from 1.05 to 1.38. It can be observed that ANSYS almost predicts a higher ultimate load compared to the load observed during experiments.

Table 7. Comparison between experimental and numerical results.

Specimen code	Pu, exp.	Pu, num.	$\frac{\text{Pu, num.}}{\text{Pu, exp.}}$
SIPU	2.75	3.00	1.09
SIPUR	4.10	4.35	1.06
SIPH	7.40	8.20	1.11
SIPHR	6.50	9.00	1.38
SIPHC	8.00	8.42	1.05
SIPHCI	7.35	9.05	1.23

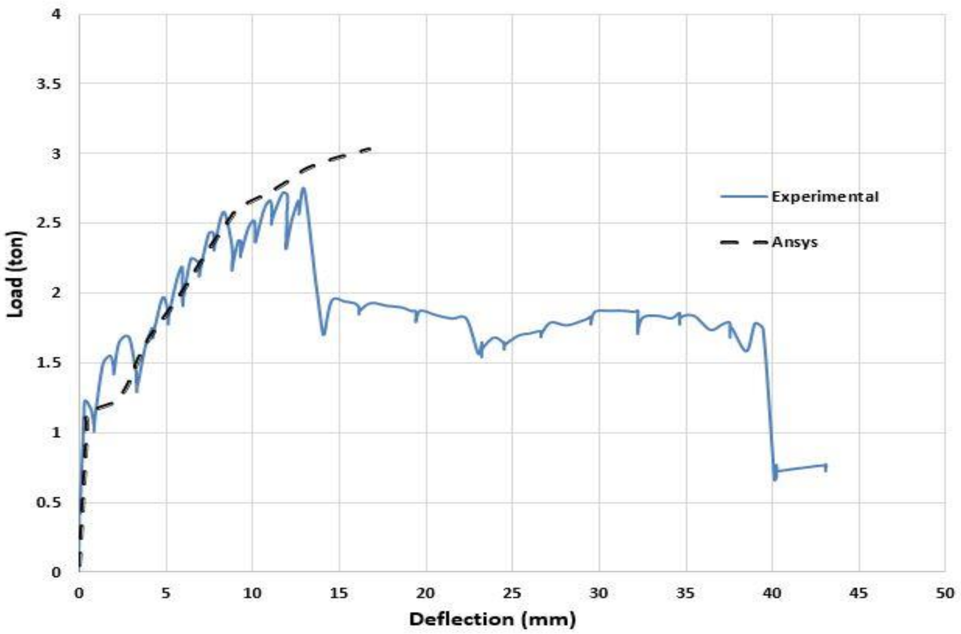


Figure. 15. Comparison between experimental & numerical load-deflection curves of tested specimen (SIPU).

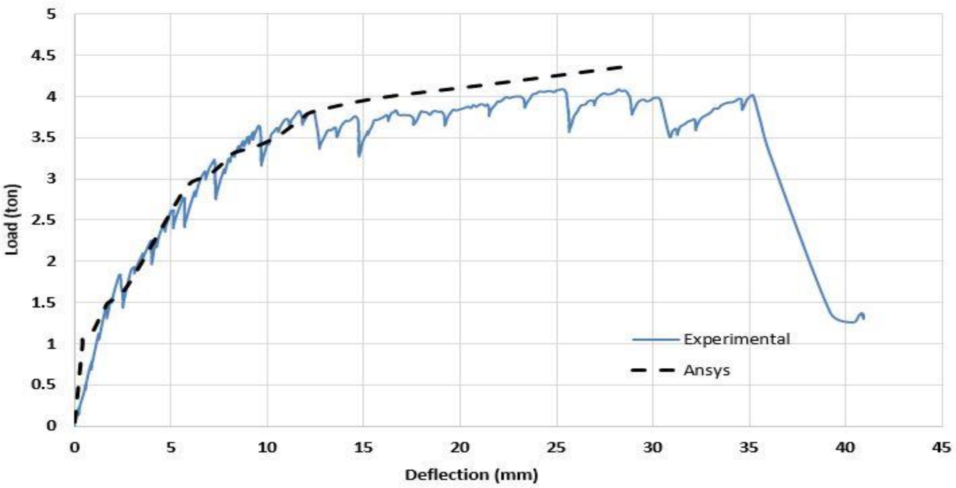


Figure. 16. Comparison between experimental & numerical load-deflection curves of tested specimen (SIPUR).

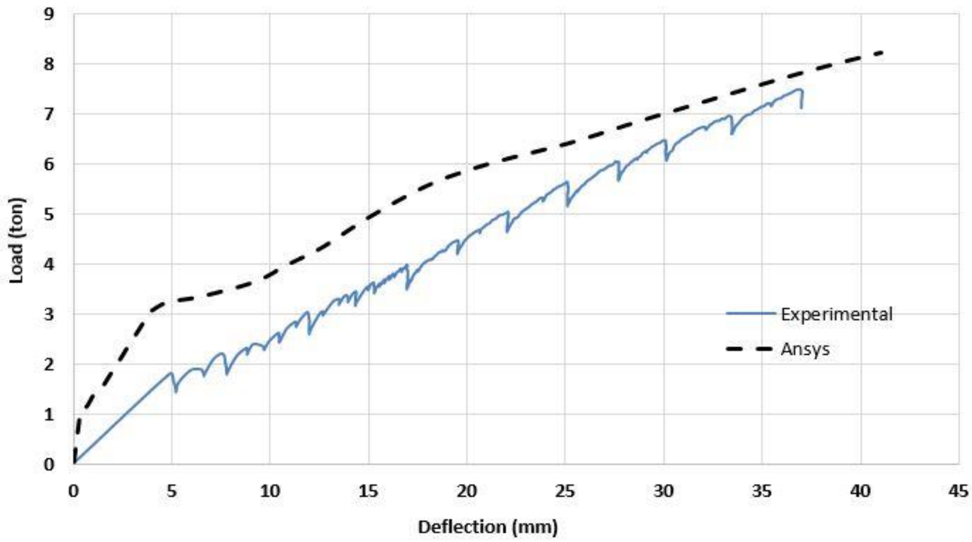


Figure. 17. Comparison between experimental & numerical load-deflection curves of tested specimen (SIPH).

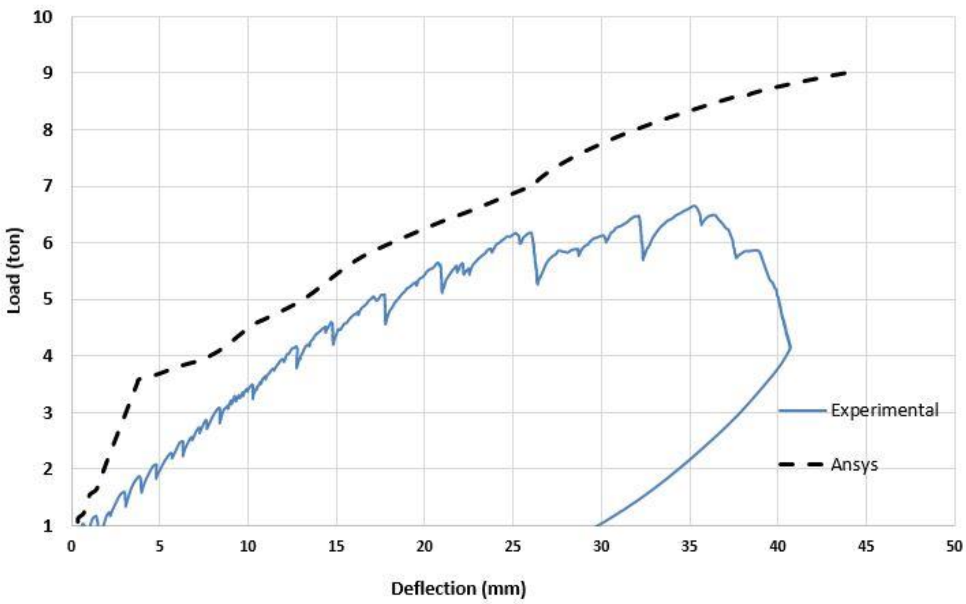


Figure. 18. Comparison between experimental & numerical load-deflection curves of tested specimen (SIPHR).

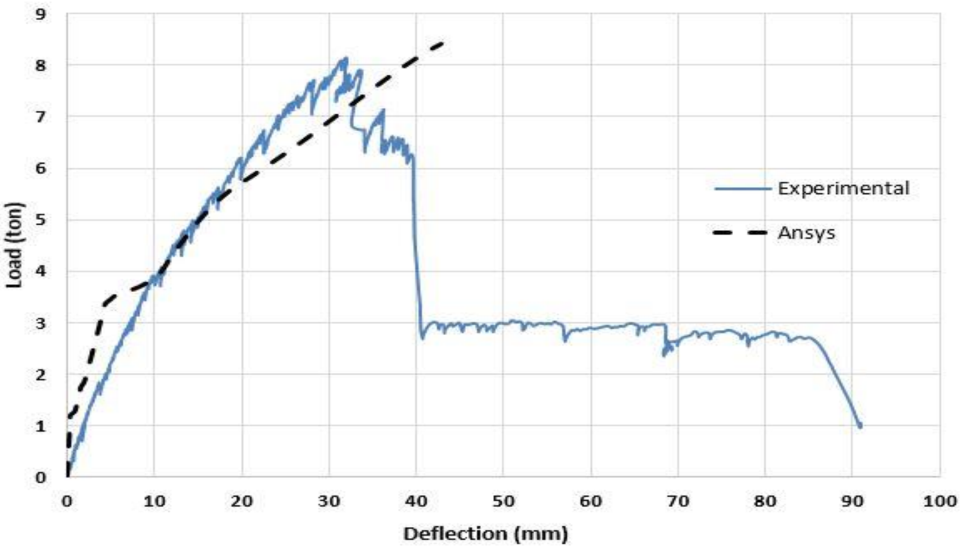


Figure. 19. Comparison between experimental & numerical load-deflection curves of tested specimen (SIPHC).

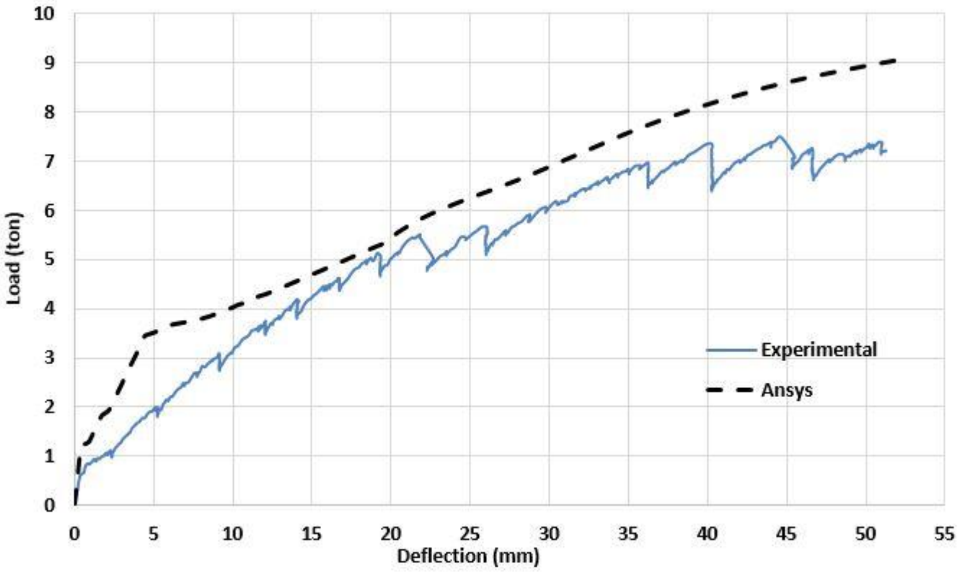


Figure. 20. Comparison between experimental & numerical load-deflection curves of tested specimen (SIPHCI).

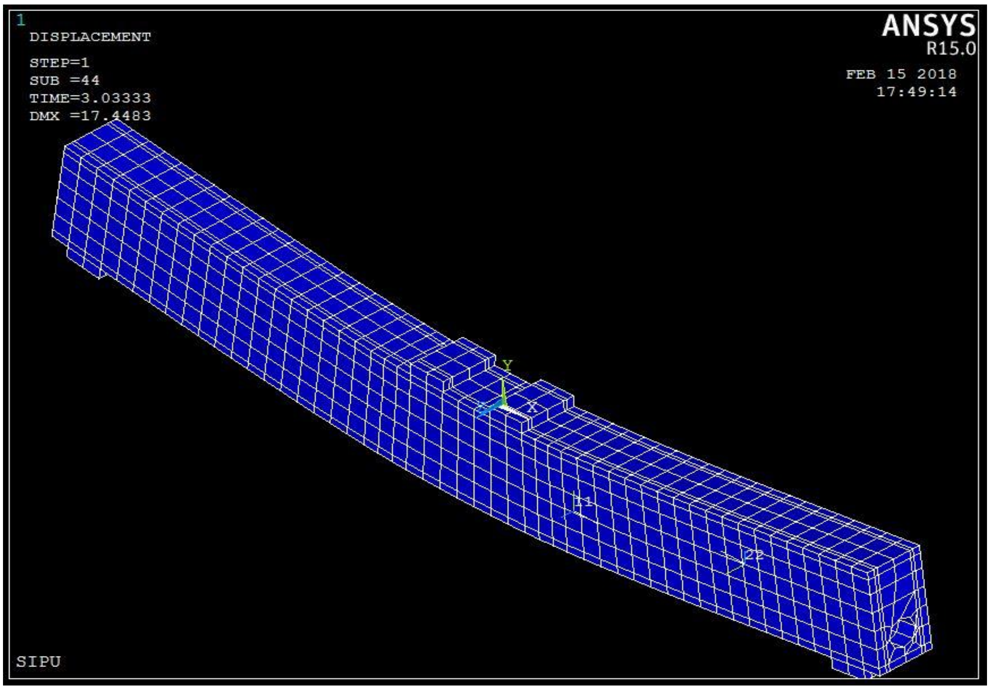


Figure. 21. Typical deformed shape of finite element model.

6. Conclusions

The main goal of the current research is examining the effect of using stay-in-place FRP form to improve the flexural resistance of hollow concrete beams. From the experimental results, the following conclusions could be drawn as follows:

- According to the experimental results obtained in this research, using stay-in-place FRP form showed accepted structural performance of hollow concrete beams in terms of flexural rigidity, initial cracking load and the ultimate carrying capacity.
- For specimens with inverted FRP U shape strips, reinforcing the internal PVC tube with GFRP sheets had a significant effect in increasing the cracking load and ultimate load by 33% and 49%, respectively. However, the reinforcement of PVC tube had not significant effect on the specimens with upper FRP hooks.
- Using extended FRP upper hooks (specimen SIPH) to improve the bond between FRP forms and concrete was an effective technique compared to using inverted FRP U shape strips (specimens SIPU). Each of cracking load and ultimate load were higher for specimen SIPH by 233% and 169% respectively, in comparison with the corresponding values of specimen SIPU. Also, the increasing in cracking load and ultimate load in case of reinforced PVC tube (SIPHR & SIPUR) were 161% and 49%, respectively. However, using transversal FRP links, in addition to the extended upper hooks, to improve the bond, had not showed any significant effect on the strength of the tested specimens, though higher ductility was observed in this case.
- As expected, adding inner CFRP reinforcement to the bottom side of FRP forms had a clear contribution in increasing the strength of the tested beams. Also, ductility index was increased slightly when CFRP was added.
- Two modes of failure were observed, the first one was a premature failure where a significant debonding between FRP form and concrete took place due to lateral buckling of

FRP at compression zone, in the second mode of failure a rapture in FRP form was observed in mid span due to tensile stress, the latter mode took place due to good bond between FRP form and concrete in case of extended upper hooks.

- According to the finite element models developed by ANSYS (version 15) to simulate the tested specimens, the ultimate loads were higher than the corresponding experimental results by 5 to 38%.

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