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Structural Behavior of Hollow Beam Reinforced with Different Types of GFRP Stirrups

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Abstract: This study investigates the behavior of SCC hollow beams reinforced by GFRP bars, which have lighter weight, lower cost, and high corrosion resistance compared to conventional steel reinforcement. Eighteen SCC beams with dimensions of (1200×225×150) mm were divided into three groups. Each group had 5-beams according to the types of stirrups (steel, (full, 2L-, 4bar, and 4U) GFRP)) stirrups in all groups with three reference beams. The longitudinal reinforcement was 6Ø10mm steel bars, 6Ø10mm GFRP bars, and (3steel+ 3GFRP) bars for the first, second, and third groups respectively. All beams were SCC concrete with a longitudinal rectangular hollow (50×100) mm. The results showed that the ultimate load of a hollow beam was decreased by the ratio of (13%, 11%, and 8%) compared to the first, second, and third groups respectively. In the first group, the ultimate load of a hollow beam reinforced with (steel stirrups) increased by about (3%), (6%), (21%), and (11%) compared to the hollow beam reinforced with (full, 2L, 4bar, 4U-bar) GFRP stirrups respectively. In the second group, the ultimate load of a hollow beam reinforced with (steel stirrups) increased by about (4%), (9%), (49%), and (14%) compared to the hollow beam reinforced with (full, 2L, 4bar, 4U-bar) GFRP stirrups respectively. In the third group, the ultimate load of a hollow beam reinforced with (steel stirrups) increased by about (3%), (6%), (23%), and (14%) compared to the hollow beam reinforced with (full, 2L, 4bar, 4Ubar) GFRP stirrups respectively. The best case, according to the ultimate load among the stirrups, was steel stirrups, which gave the highest shear strength compared to the other stirrups because of the low elasticity of the GFRP stirrups. While compared to the other GFRP stirrups, GFRP full stirrups had the highest shear strength because there is one connection point compared to two or four connecting points for other types.

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السلوك الانشائي للعتبات المجوفة المسلحة بأنواع مختلفة من حلقات GFRP

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الخلاصة

تتضمن هذه الدراسة سلوك العتبات المجوفة للخرسانة ذاتية الرص والمسلحة بقضبان GFRP، والتي تتميز بوزن أخف وتكلفة أقل ومقاومة عالية للتآكل مقارنة مع حديد التسليح التقليدي. ثمانية عشر عتبة من الخرسانة ذاتية الرص بأبعاد (1200×225×150)ملم مقسمة إلى ثلاث مجموعات ولكل مجموعة خمس عتبات حسب أنواع الحلقات (steel, GFRP full, 2L- GFRP, 4bar-GFRP, and 4U- GFRP stirrups) مسلحة في جميع المجموعات مع ثلاث عتبات مرجعية. المجموعة الأولى كان التسليح الطولية حديد 6Ø10 ملم، المجموعة الثانية التسليح الطولي GFRP 6Ø10 ملم، والمجموعة الثالثة التسليح الطولي هجين (3steel +3GFRP). جميع العتبات ذات تجويف طولي مستطيل بأبعاد (100×50)ملم. أظهرت النتائج أن الحمل النهائي للعتبات المجوفة المسلحة ادى الى نقصان بنسبة (13%, %11, 8%) مقارنة بالعتبات المصمتة المسلحة بالحديد، العتبات المصمتة المسلحة بـ GFRP، والعتبات المصمتة ذات التسليح الهجين على التوالي. في المجموعة الأولى، زاد الحمل النهائي للعتبات المجوفة المسلحة بحلقات حديد بنسبة (3%, 6% ,21%, 11%) مقارنة مع العتبات المجوفة المسلحة بحلقات (GFRP full, 2L- GFRP, 4bar-GFRP, and 4U- GFRP stirrups) على التوالي. في المجموعة الثانية، زاد الحمل النهائي للعتبات المجوفة المسلحة بحلقات الحديد بنسبة (4%, 9% ,49%, 14%) مقارنة مع العتبات المجوفة المسلحة بحلقات (GFRP full, 2L- GFRP, 4bar-GFRP, and 4U- GFRP stirrups) على التوالي. في المجموعة الثالثة، زاد الحمل النهائي للعتبات المجوفة المسلحة بحلقات الحديد بنسبة (3%, 6% ,23%, 14%) مقارنة مع العتبات المجوفة المسلحة بحلقات (GFRP full, 2L- GFRP, 4bar-GFRP, and 4U- GFRP stirrups) على التوالي. أفضل حالة وفقاً للحمل النهائي هي حلقات الحديد اعطت أعلى مقاومة للقص مقارنة بالحلقات الأخرى بسبب معامل المرونة المنخفض في حلقات GFRP. بينما عند المقارنة بين حلقات GFRP, فان حلقات GFRP full اعطت أعلى مقاومة للقص مقارنة بحلقات GFRP الأخرى لأن الربط في حلقات GFRP full بها مفصل واحد بينما الحلقات الأخرى من GFRP تربط بمفصلين أو أكثر.

الكلمات الدالة: قضبان الالياف البوليمرية الزجاجية، حلقات الالياف البوليمرية الزجاجية، الاعتاب المجوفة، خرسانة ذاتية الرص.

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1.INTRODUCTION

Reinforced concrete structures have been the target of unsuccessful attempts to stop corrosion. However, a few decades ago, scientists discovered a brand-new material called Fiber Reinforced Polymer, which resembles conventional steel yet has a higher tensile strength (FRP). Fiber-reinforced polymers (FRP) are regarded as a desirable substitute for steel for the internal reinforcement of concrete buildings due to their sturdiness, high strength-to-weight ratio, and acceptable fatigue qualities [1,2]. Additionally, many steel-reinforced concrete structures exposed to maritime environments and deicing salts need pricey and time-consuming upkeep. Using fiber-reinforced polymer (FRP) as an alternative reinforcing material in reinforced concrete structures has recently come to light as a creative approach to the corrosion problem [3,4]. Shear reinforcement is usually applied in the form of closed stirrups; on the other hand, it is hard to make. When the resin has not been yet hardened or has already been hardened, the FRP reinforcement can be bent. Stirrups can be made by heating and bending a straight FRP bar into the desired shape [4,5]. In modern building practice, most curved/shaped steel bars are pre-bent and pre-cut to the off-site

forms and lengths. Contrary to the FRP reinforcements, the steel bars have an elastoplastic quality that makes it simple to cold bend them into the desired shape [6]. Recently, hollow cross-sections have been commonly used in building and bridge structures. A longitudinal opening is used to manufacture hollow beams cast on site, precast, and prestressed concrete members to save weight and cost and pass electrical and mechanical services or other utilities as a side benefit [7]. Hollow sections are often utilized for the aesthetics of their shape and architectural requirements or in circumstances where their engineering qualities dictate. The hollow structural sections were used in various fields, such as buildings, bridges, marine structures, halls, and towers [8]. The ultimate bearing capacity of GFRP RC beams is higher than steel RC beams [9-11]. The GFRP RC beams showed more considerable deflections than steel RC beams [12,13], [10]. The number of cracks in the GFRP reinforced beam was higher than in the conventional beam, and when compared to the control beam, the average crack spacing of the GFRP reinforced concrete beam was greater [3,14]. The GFRP reinforcing bars have a relatively low modulus of elasticity, low

ductility, and low stiffness compared to conventional steel. These qualifications reduced stiffness results in deflections more considerable than conventional steel-reinforced members at any load stage. Because of these large deflections, structural designs may be governed by deflection limitations [14-16]. The concrete beams reinforced with GFRP bars have lower shear strength than beams reinforced with steel bars [16]. To investigate the structural behavior of tests of a new type of composite bar used as shear reinforcement for concrete beams, shear-reinforced beams with GFRP stirrups and GFRP-headed bars were tested up to failure. Therefore, a new type of shear reinforcement can be performed by directly comparing the shear behavior of beams reinforced with normal GFRP stirrups vs. GFRP-headed bars. The GFRP-headed bars are better than the GFRP stirrups as shear reinforcement in concrete beams. These bars, unlike GFRP stirrups, enable stress redistribution in diagonally cracked bars [17]. To study the shear behavior of continuous concrete beams reinforced with GFRP Bars, continuous concrete beams were constructed and tested. The main variables were the concrete strength, longitudinal reinforcing type and ratio, and effective depth. The experiments' findings showed that in the normal-strength concrete (NSC) and high-strength concrete (HSC) models, the shear strength of GFRP-RC continuous beams increased with the longitudinal reinforcement ratio in beams with and without shear reinforcement [18]. Compared to the steel stirrups, the GFRP stirrups increased the ultimate torsional strength and toughness. However, the GFRP stirrups unaffected the cracking torque or vertical deflection, which agreed with previous findings. Thus, the bonded GFRP stirrups are considered a good alternative steel stirrup to conventional or bent GFRP stirrups [19].

2. SUMMARY OF PREVIOUS STUDIES

Many investigations studied hollow beams reinforced with steel reinforcement, yet little research has studied hollow beams reinforced with GFRP or hybrid reinforcement (GFRP + steel) as longitudinal reinforcement. Many works have studied the GFRP reinforcement beam, yet a few researchers have studied using hybrid reinforcement with (GFRP + steel). Finally, five different types of stirrups were studied in the present research. Four of them were GFRP, and one of them was steel. Most studies used one type of stirrup, i.e., a closed stirrup.

3. OBJECTIVE OF THE STUDY

In general, using hollow beams in concrete structures is one of the solutions to reduce the structure's weight and construction cost, which are part of the objectives of the present research, as the main goal is to use GFRP stirrups to reinforce the beam and compare them with the steel stirrups. The present study aims to know the effect of hollow core on the strength of beams and the effect of using different types of GFRP bar stirrups instead of steel stirrups.

4. EXPERIMENTAL PROGRAM

4.1. Materials

The weight of the components required to make one cubic meter of concrete is shown in Table 1.

Table 1 Details of the Successful Trial Mix for SCC.

Cement (Kg/m³)	Sand (Kg/m³)	Gravel (Kg/m³)	S.P. (lit/m³)	L.P (Kg/m³)	Water	W/C %
395	769	767	7.5	172	188	0.47

4.1.1. Reinforcing Bars

The reinforcing steel bars utilized in this investigation had diameters of 10, 8, and 6 mm.; while the GFRP bar used in this investigation had diameters of 6mm and 10mm. At the bottom of the section, steel bars with a diameter of 10 mm were used to resist tensile stresses caused by bending, and steel bars with a diameter of 6 mm were used as stirrups to resist shearing stress. Three samples of each bar diameter were tested to determine the characteristics of the steel bars. The test results are shown in Table 2, which conformed to the ASTM A615 requirements [20]. The GFRP bars tests were carried out by the American standard ACI 440.3R-04 [21]. The GFRP bar's properties as shown in Table 3.

Table 2 Test Results of the Steel Bar Reinforcement.

Bar diameter (mm)	Yield stress (MPa)	Ultimate stress (MPa)	Modulus of Elasticity (GPa)
6	540	570	200
8	500	550	200
10	580	670	200

Table 3 Properties of the GFRP Manufacturer/Test.

| Bar diameter (mm)	Ultimate stress (MPa)	Modulus of elasticity (GPa)
6	1200/920.7	30/26.3
10	990/980	50/40.04

4.1.2. Thermoformed GFRP stirrups

Four different types of GFRP stirrups were used. GFRP reinforcement is limited due to the unavailability of the reinforced curved or commercial form available due to the difference in durability and deterioration of GFRP. The cold-bending steel stirrups are easily formed due to the steel reinforcement's high elasticity, unlike the GFRP bars, which cannot be cold-bent except by applying heat. Three types of GFRP bars were bent by heating to make different stirrups, as shown in Fig. (1-3). Using these types of stirrups aims to determine the best type of stirrups that can be used to resist shear forces and compare them with steel stirrups.

4.2. Beam Details

The experimental procedure included pouring eighteen concrete beams divided into three groups, each group including five beams, and three reference beams. The tests continued up to fail. The hollowness ratio was equal in all beams at 15% and located in the middle of the section in the longitudinal direction with dimensions of (50×100) mm. All beams were self-compacting concrete, and the flexural reinforcement ratios (ρ) were equal in all beams (ρ=1.61%). The section dimensions were 225mm×150mm, with a total length of 1200mm, and a clear span of 1100mm. 6Ø10mm steel and GFRP bars were used in the longitudinal direction at the bottom of the section to resist the tensile stresses resulting from bending. In contrast, 6mm diameter steel and GFRP bars, used as stirrups, at 130mm center to the center, were used for shear reinforcement. 2Ø8mm steel bars were used in the upper longitudinal direction to assist in forming the required steel cage. The shear-to-depth ratio was constant(a/d = 2.06). The main variables in this research were the longitudinal reinforcement and stirrups types. Table 4 shows the details of the beams used. Three control beam samples were used. The first group included longitudinal reinforcing steel bars 6Ø10mm, the second group included longitudinal reinforcing GFRP bars 6Ø10mm, and the third group included longitudinal reinforcing with hybrid (3steel+ 3GFRP) bars 6Ø10mm with five different types of stirrups in each group, as shown in Figs. (1, 2).
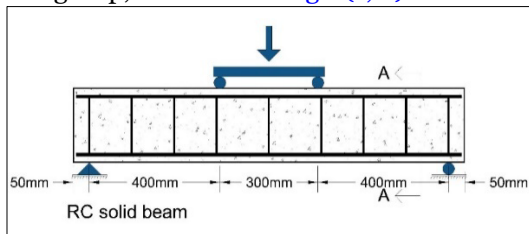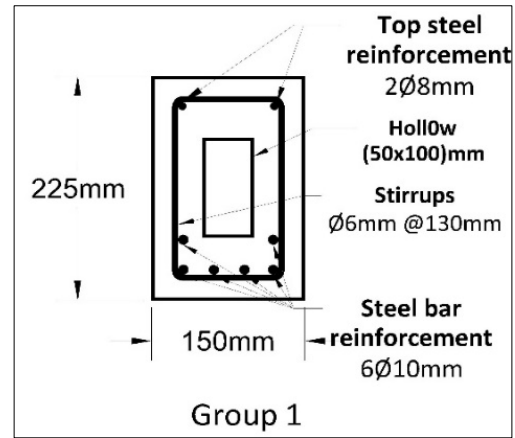
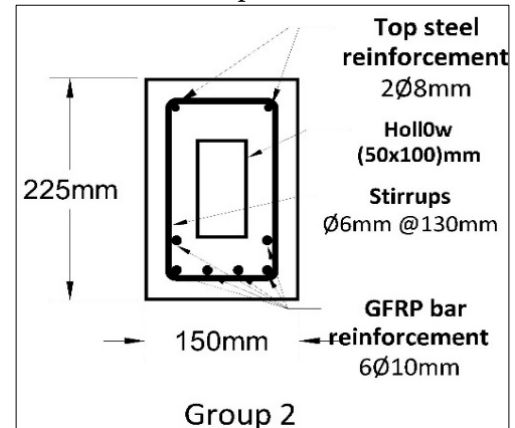

a- Dimensions Reinforced Solid Beam.
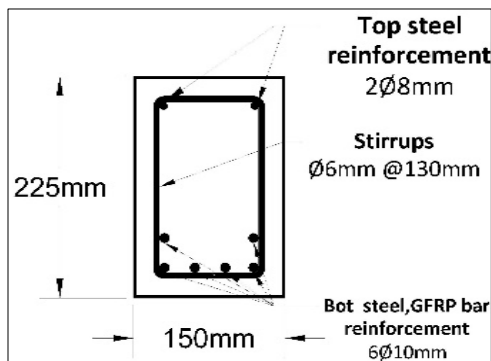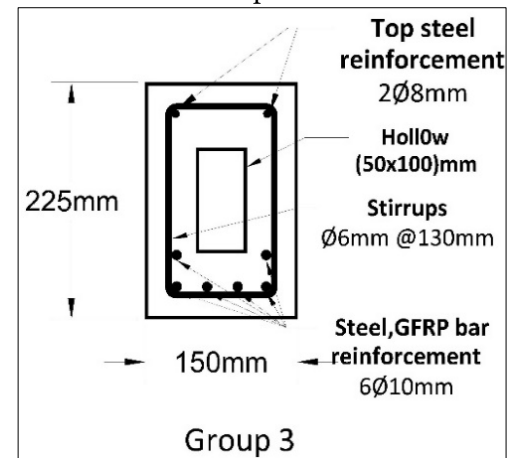

b- Details of Cross Section.

Fig. 1 Dimensions and Reinforcement Details of Reinforced Solid Beam.

a-First Group Reinforcement

b-Second Group Reinforcement

c-Third Group Reinforcement

Fig. 2 Dimensions and Reinforcement Details of Reinforced Hollow Beams.

4.2.1. Types of formed stirrups used

Five different types of stirrups in each group, as shown in Fig. 3 (a, b, c, d, and e), were used:
- **a-** Steel Stirrups (SS).
- **b-** GFRP full stirrups Heat-Bending (GFSHB).
- **c-** 2L- Shaped GFRP Stirrups Heat-Bending (2L-GSHB).
- **d-** 4Bar-Shaped GFRP Bar Stirrups (4B-GBS).
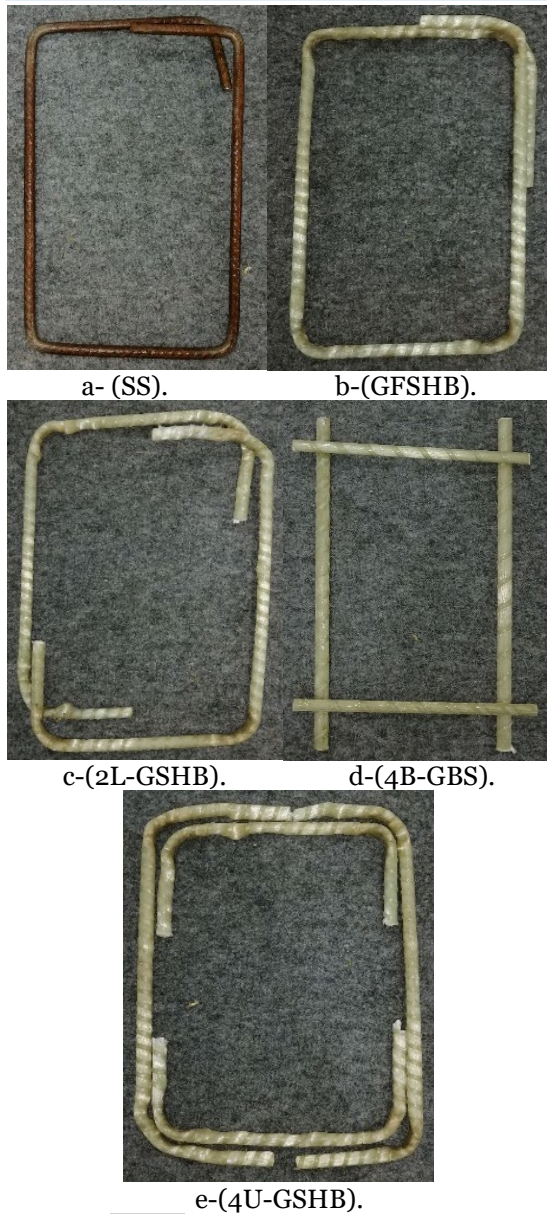- **e-** 4U- Shaped GFRP stirrups Heat-Bending (4U-GSHB).

a- (SS). b-(GFSHB).

c-(2L-GSHB). d-(4B-GBS).

e-(4U-GSHB).
Fig. 3 Stirrup Types Details.

4.3. Test Setup and Devices

A universal test machine (SANS) was used to test the beams. The device capacity is 2000 kN with a load rate of 1.5 kN/s. The Vertical deflection was measured at the mid-span of the beam specimens by linear variable differential transformers (LVDTs). The gauge was placed under the bottom face of the tested beam. The beam dimensions were 1200 mm effective length, 150 mm width, and 225 mm depth. The beams were placed inside the machine on the designated cushions and applied to the four-point load from the top two loading points to the sample. In addition, a 300 mm steel plate was used to transfer the center load generated by the hydraulic system to two equal loading points on the top surface of the beaming, Fig. 4. The crack patterns were monitored with every loading phase. The positions and development of cracks were indicated on the side surfaces of the shear beams [22][23]

Fig. 4 The Beam under the Test Device.

Table 4 General Details of the Tested Beams.

Beam Group	Beam Symbol	Longitudinal Reinforcement	Stirrups Types
Reference 1	Solid	steel bar 6 Ø10 mm	(SS)
Reference 2	Solid	GFRP bar 6 Ø10 mm	(SS)
Reference 3	Solid	(steel + GFRP) bar 6 Ø10 mm	(SS)
The first group	H.B.S.1	steel bar 6 Ø10 mm	(SS)
	H.B.S.2	steel bar 6 Ø10 mm	(GFSHB)
	H.B.S.3	steel bar 6 Ø10 mm	(2L-GSHB)
	H.B.S.4	steel bar 6 Ø10 mm	(4B-GBS)
	H.B.S.5	steel bar 6 Ø10 mm	(4U-GSHB)
The second group	H.B.G.1	GFRP bar 6 Ø10 mm	(SS)
	H.B.G.2	GFRP bar 6 Ø10 mm	(GFSHB)
	H.B.G.3	GFRP bar 6 Ø10 mm	(2L-GSHB)
	H.B.G.4	GFRP bar 6 Ø10 mm	(4B-GBS)
	H.B.G.5	GFRP bar 6 Ø10 mm	(4U-GSHB)
The third group	H.B.S.G.1	(Steel + GFRP) bar 6 Ø10 mm	(SS)
	H.B.S.G.2	(Steel + GFRP) bar 6 Ø10 mm	(GFSHB)
	H.B.S.G.3	(Steel + GFRP) bar 6 Ø10 mm	(2L-GSHB)
	H.B.S.G.4	(Steel + GFRP) bar 6 Ø10 mm	(4B-GBS)
	H.B.S.G.5	(Steel + GFRP) bar 6 Ø10 mm	(4U-GSHB)

5. RESULTS AND DISCUSSIONS
5.1. The Test Results

At the early stages of loading, all tested beams were in an elastic state where the defects in their structure and the cracks disappeared at any place, and the deflections at the mid-span were small and proportional to the applied load. The effect of the hollow on the strength of the beam was apparent. For the control beam (solid beam), initial flexural cracks were observed, and cracks in the vertical direction were observed first between two-point loads at the beam's bottom at the maximum moment region. When the load was increased, one failure mode appeared, which can be classified as a shear failure. While in most other beams of the hollow section, as the load increased, the first diagonal crack (shear crack) appeared at the mid-height of the diagonal region bounded by load and support positions in both shear spans at the same load level or little different and then extended upwards toward the load point. Then these inclined cracks multiplied and became wider in shear spans. One or more cracks propagated faster than the others and reached the top. The beam details, cracking loads, ultimate loading, cracking deflection, and maximum deflection of the tested beams are presented in Table 5.

5.2. Mechanical Properties
5.2.1. First cracking load (Pcr)
5.2.1.1. Effect of hollow on the first cracking load of the beam

The results showed that the first cracking load of a hollow beam reinforced with steel reinforcement (H.B.S.1) was less than a solid beam reinforced with steel by 16%. A hollow beam reinforced with GFRP reinforcement (H.B.G.1) was less than a solid beam reinforced with GFRP by 12%, and a hollow beam hybrid reinforced with (Steel+ GFRP) reinforcement (H.B.S.G.1) was less than a solid beam reinforced with (Steel+ GFRP) by 14%, as shown in Fig. 5. The results indicated that the hollow reinforced concrete beams had lower first cracking load than solid beams due to the existence of the hollow core. These voids reduced the beam section's moment of inertia, reducing the flexural rigidity that decreased the first cracking load.

Table 5 Test Results of Specimen Beams.

Beam Group	Beam Symbol	Longitudinal Reinforcement	Stirrups Types	Load (KN) (Pcr)	(Pu)	Deflection(mm) (Δy)	(Δu)	Failure Mode
Reference 1	Solid	Steel bar 6 Ø10 mm	(SS)	80	207.8	5.2	7.94	Shear
Reference 2	Solid	GFRP bar 6 Ø10 mm	(SS)	66	185.5	7.2	10.42	Shear-compression
Reference 3	Solid	(Steel + GFRP) bar 6 Ø10 mm	(SS)	74	192	5.8	8.45	Shear
The First Group	H.B.S.1	Steel bar 6 Ø10 mm	(SS)	67	180.2	6	8.20	Shear
	H.B.S.2	Steel bar 6 Ø10 mm	(GFSHB)	63	175.6	5.5	8.86	Shear
	H.B.S.3	Steel bar 6 Ø10 mm	(2L-GSHB)	44	169.4	5.5	8.52	Shear
	H.B.S.4	Steel bar 6 Ø10 mm	(4B-GS)	36	142.9	4.2	8.99	Shear
	H.B.S.5	Steel bar 6 Ø10 mm	(4U-GSHB)	41	161	5.4	8.91	Shear
The Second Group	H.B.G.1	GFRP bar 6 Ø10 mm	(SS)	58	165.3	9.2	11.88	Shear-compression
	H.B.G.2	GFRP bar 6 Ø10 mm	(GFSHB)	51	158.3	9.3	13.92	Shear-compression
	H.B.G.3	GFRP bar 6 Ø10 mm	(2L-GSHB)	34	151.2	8.3	11.20	Shear-compression
	H.B.G.4	GFRP bar 6 Ø10 mm	(4B-GS)	26	84.6	5.5	10.50	Shear-compression
	H.B.G.5	GFRP bar 6 Ø10 mm	(4U-GSHB)	30	142.2	8.8	12.21	Shear-compression
The Third Group	H.B.S.G.1	(Steel + GFRP) bar 6 Ø10 mm	(SS)	64	176	7.1	8.91	Shear
	H.B.S.G.2	(Steel + GFRP) bar 6 Ø10 mm	(GFSHB)	59	171.5	6.2	9.33	Shear
	H.B.S.G.3	(Steel + GFRP) bar 6 Ø10 mm	(2L-GSHB)	41	165.3	6.8	9.21	Shear
	H.B.S.G.4	(Steel + GFRP) bar 6 Ø10 mm	(4B-GS)	35	134.9	6.3	9.30	Shear-compression
	H.B.S.G.5	(Steel + GFRP) bar 6 Ø10 mm	(4U-GSHB)	37	150.8	6.3	9.22	Shear-compression

5.2.1.2 Effect of GFRP stirrups types

Different types of GFRP stirrups in the beams' reinforcement affected the first cracking load of the beams compared to the reinforcement of the steel stirrups. Five types of stirrups were used in each group. In the first group, the first cracking load of a hollow beam reinforced with (steel stirrups) increased by about 6%, 34%, 46%, and 38% compared to the hollow beam reinforced with (full, 2L, 4bar, 4U) GFRP stirrups, as shown in Fig. 6. In the second group, the first cracking load of a hollow beam reinforced with (steel stirrups) increased by about 12%, 41%, 55%, and 48% compared to the hollow beam reinforced with (full, 2L, 4bar, 4U) GFRP stirrups, as shown in Fig. 7. In the third group (reinforced longitudinal by (Steel+ GFRP)), the first cracking load of a hollow beam reinforced with (steel stirrups) increased by about 8%, 35%, 45%, and 42% compared to the hollow beam reinforced with (full, 2L, 4bar, 4U) GFRP stirrups, as shown in Fig. 8. The steel stirrups were the best first cracking load among other stirrups, as shown in Table 6 for all groups because of high modulus of elasticity of the steel stirrups. Compared with other cases, the GFRP full stirrups had the best first cracking load compared to the other of the GFRP stirrups because the GFRP full stirrups tied had one joint, while the other of the GFRP stirrups tied in two or four joints and the effect of heating during the bending process.

5.2.2. Ultimate Load (Pu)
5.2.2.1. Effect of hollow core

The results showed that the ultimate load of a hollow beam reinforced with steel reinforcement (H.B.S.1) was less than a solid beam reinforced with steel by 13%, a hollow beam reinforced with GFRP reinforcement (H.B.G.1) was less than a solid beam reinforced with GFRP by 11%, and a hollow beam hybrid reinforced with (Steel+ GFRP) reinforcement (H.B.S.G.1) was less than a solid beam reinforced with (Steel+ GFRP) by 8%, as shown in Fig. 9. The results indicated that the hollow reinforced concrete beams had a lower ultimate load than the solid beams' due to the existence of the hollow core. These voids reduced the beam section's moment of inertia and reduced the flexural rigidity which decreased the ultimate load.
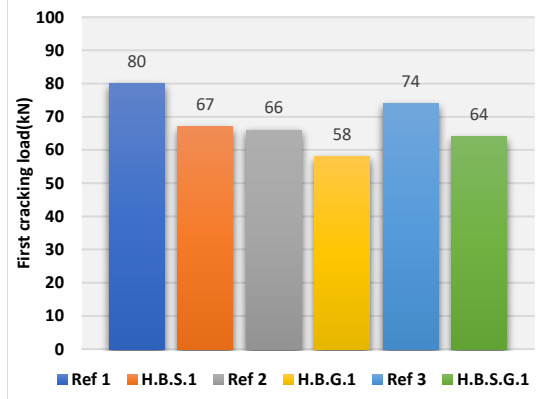

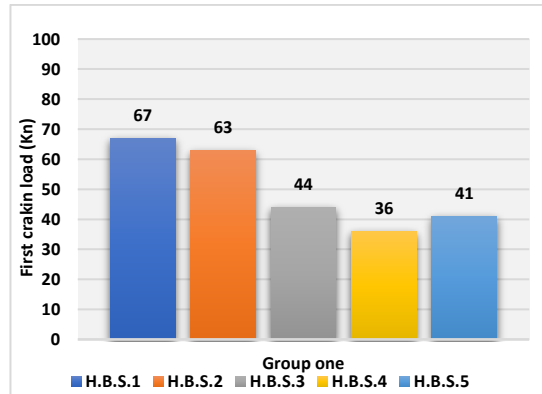**Fig. 5** First Cracking Load for Control and Hollow Beams.

Fig. 6 First Cracking Load of Different Types of GFRP Stirrups Instead for Group One.
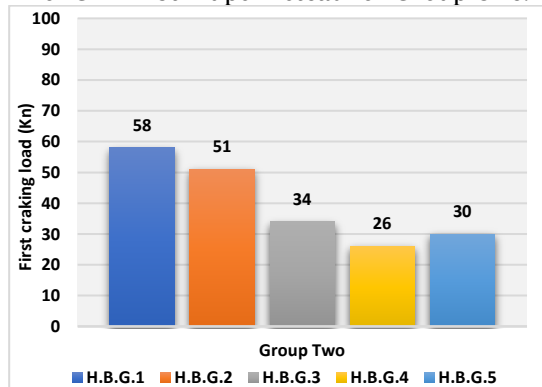

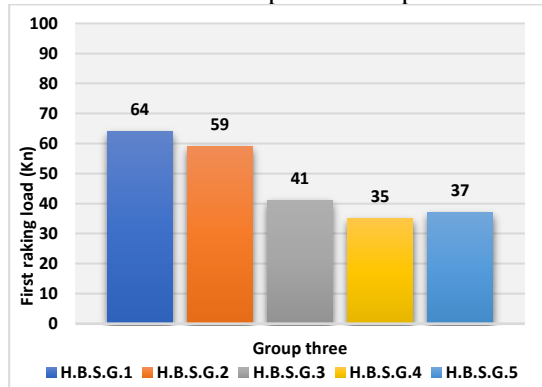**Fig. 7** First Cracking Load of different Types of GFRP Stirrups for Group Two.

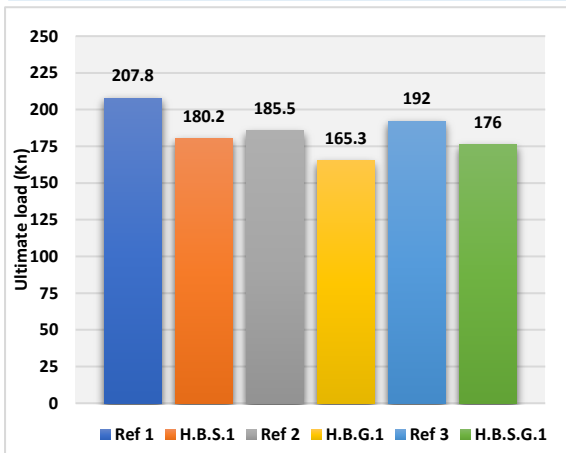**Fig. 8** First Cracking Load of Different Types of GFRP Stirrups for Group Three.

Fig. 9 Ultimate Load for Control and Hollow Beams.

5.2.2.2. Effect of different types of GFRP stirrups

Five types of GFRP stirrups were used in each group of the reinforced concrete beam. In the first group (reinforced longitudinally by steel), the ultimate load of a hollow beam reinforced with (steel stirrups) has a higher value of ultimate load by about 3%, 6%, 21%, and 11% compared to the hollow beam reinforced with (full, 2L, 4bar, 4U) GFRP stirrups, as shown in Fig. 10. In the second group (reinforced longitudinally by GFRP), the ultimate load of a hollow beam reinforced with (steel stirrups) better GFRP stirrups by about 4%, 9%, 49%, and 14% compared to the hollow beam reinforced with (full, 2L, 4bar, 4U) GFRP stirrups , as shown in Fig. 11. In the third group (reinforced longitudinally by (Steel+ GFRP)), the ultimate load of a hollow beam reinforced with (steel stirrups) better than the GFRP stirrups by about 3%, 6%, 23%, and 14% compared to the hollow beam reinforced with (full, 2L, 4bar, 4U) stirrups, as shown in Fig. 12. The best case, according to the ultimate load among the stirrups in the reinforced beams, was steel stirrups with the highest shear strength compared to the other because of the low modulus of elasticity in GFRP stirrups. Compared to the other GFRP stirrups, the GFRP full stirrups showed the highest shear strength because they tied in one joint, while the other GFRP stirrups tied in two or four joints and because of the heating effect during the bent process.

5.3. Load-Deflection Relationships

The deflection at mid-span was measured for the concrete beams to be checked using linear variable differential transformers (LVDTs). When the final loads were applied to the beams until failure, following the first crack commencement, each curve changed to a nonlinear shape by changing the slope from its initial linear form (the beam was in an elastic

condition). The third stage began as the applied load gradually climbed to the maximum load at failure while the deflection rapidly increased. The results are shown in Table 6 and Figs. (13-15) show the effect of the presence of hollow on load-mid-span deflection response. It can be seen that the deflection of the hollow beam reinforced with steel reinforcement (H.B.S.1) increased by about 3% compared to the solid beam reinforced with steel. The deflection of a hollow beam reinforced with GFRP reinforcement (H.B.G.1) increased by about 12% compared to the solid beam reinforced with steel. The deflection of a hollow beam hybrid reinforced with (Steel+ GFRP) reinforcement (H.B.S.G.1) increased by about 5% compared to the solid beam reinforced with (Steel+ GFRP). From the obtained results, it can be noted that the solid beam had lower deflection values than the hollow beams' due to the existence of the hollow core. These voids reduced the beam section's moment of inertia, which reduced the flexural rigidity resulting in a deflection decrease, as shown in Figs. (13- 15).
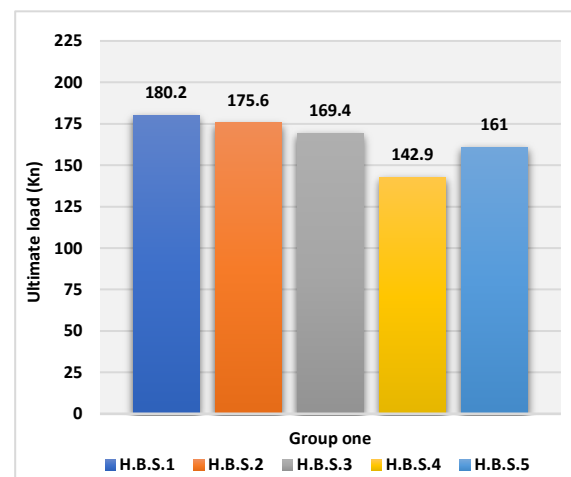

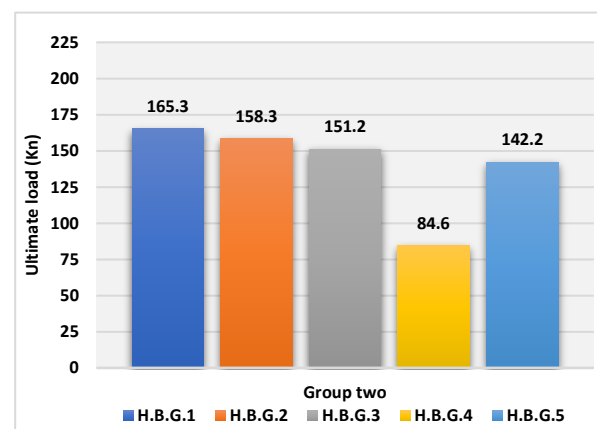**Fig. 10** Ultimate Load of Different Types of GFRP Stirrups for Group One.

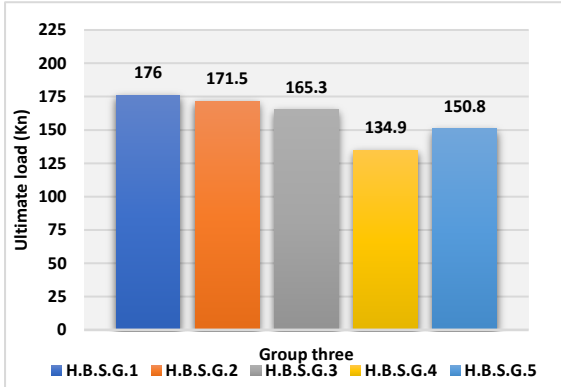**Fig. 11** Ultimate Load of Different types GFRP Stirrups for Group Two.

Fig. 12 Ultimate Load of Different Types of GFRP Stirrups for Group Three.
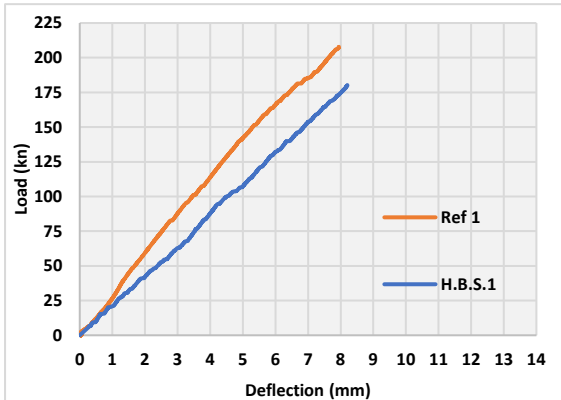

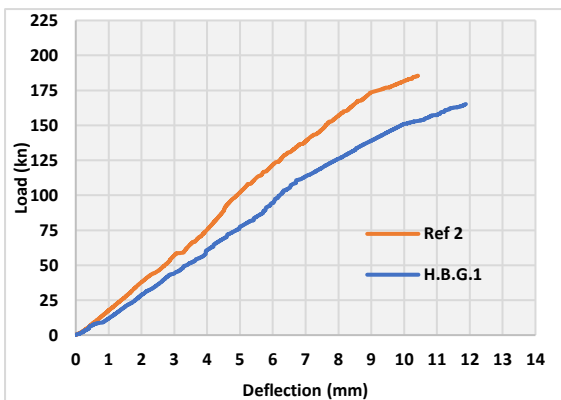**Fig. 13** Load-Mid Span Deflection Curve for Reference 1 and (H.B.S.1).

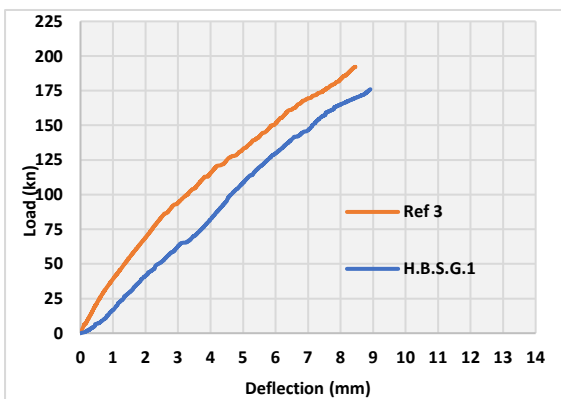**Fig. 14** Load-Mid Span Deflection Curve for Reference 2 and (H.B.G.1).

Fig. 15 Load-Mid Span Deflection Curve for Reference 3 and (H.B.S.G.1).

Different types of GFRP stirrups in the beams' reinforcement had a clear Load-mid Span Deflection of the beams compared to the reinforcement of the steel stirrups; five types of stirrups were used in each group, as shown in Fig. 3. In the first group (reinforced longitudinal by steel), the Load-mid Span Deflection of a hollow beam reinforced with (steel stirrups) decreased by about (7%), (4%), (9%), and (8%) compared to the hollow beam reinforced with (GFRP full, 2L- GFRP, 4bar-GFRP, 4U- GFRP) stirrups reinforced, as shown in Fig. 16. In the second group (reinforced longitudinal by GFRP), the Load-mid Span Deflection of a hollow beam reinforced with (steel stirrups) decreased by about (15%) and (3%) compared to the hollow beam reinforced with (GFRP full, 4U- GFRP) stirrups reinforced, a hollow beam reinforced with (steel stirrups) increased by about (6%), and (12%) compared to the hollow beam reinforced with (2L- GFRP, 4bar-GFRP) stirrups reinforced, as shown in Fig. 17. In the third group (reinforced longitudinal by (Steel+ GFRP)), the Load-mid Span Deflection of a hollow beam reinforced with (steel stirrups) decreased by about (5%), (3%), (4%), and (3%) compared to the hollow beam reinforced with (GFRP full, 2L- GFRP, 4bar-GFRP, 4U- GFRP) stirrups reinforced, as shown in Fig. 18.
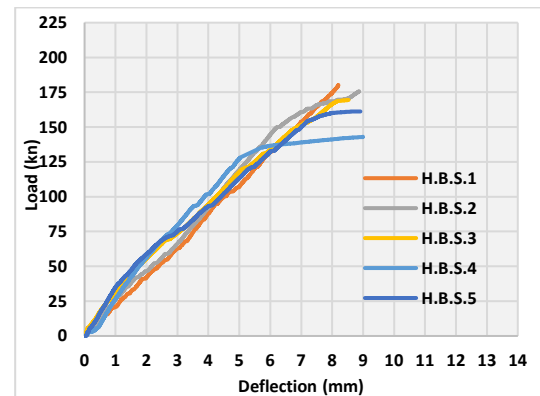
Fig. 16 Load-Mid Span Deflection Curve of Different Types of GFRP Stirrups for Group One.
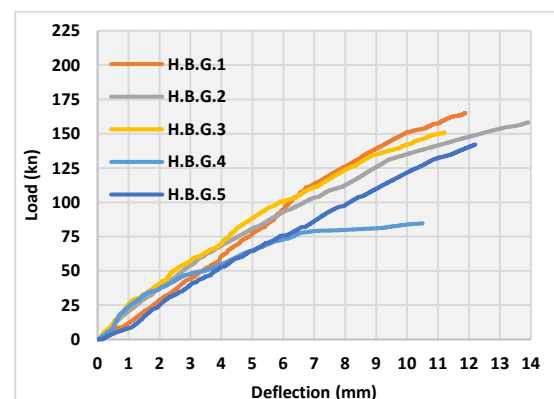

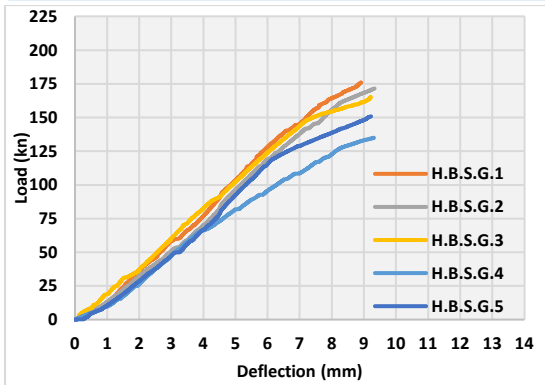**Fig. 17** Load-Mid Span Deflection Curve of Different Types of GFRP Stirrups for Group Two.

Fig. 18 Load-Mid Span Deflection Curve of Different Types of GFRP Stirrups for Group Three.
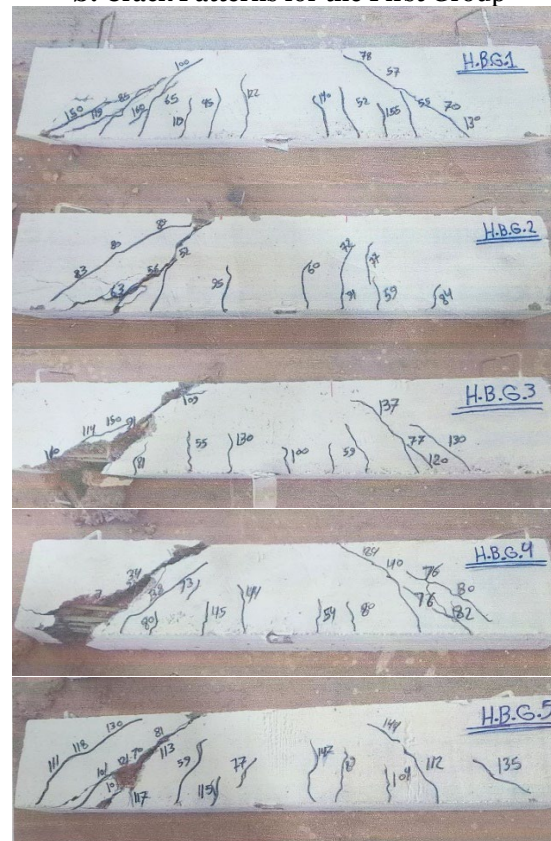
5.4. Crack Pattern

The results of the experimental data showed that hollow beams significantly affected the cracking pattern. The hollow beams were cracked at low loads compared to the solid beams. Generally, the number of cracks in the hollow beams was greater than that in the solid beams, as shown in Fig. 19 for the crack pattern for all tested beams. Different GFRP stirrups affected the cracking pattern compared to steel stirrups in the reinforced beam. Fig. 19 shows that the reinforced GFRP stirrups showed greater stress value for the transverse reinforcements, which led to more cracks and a wider crack width than the beams with steel stirrups.
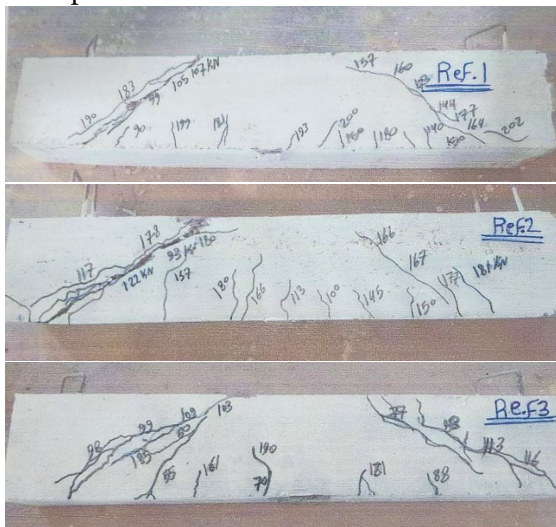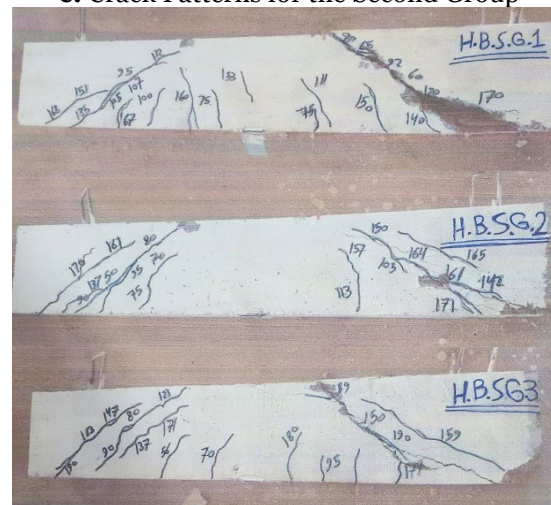

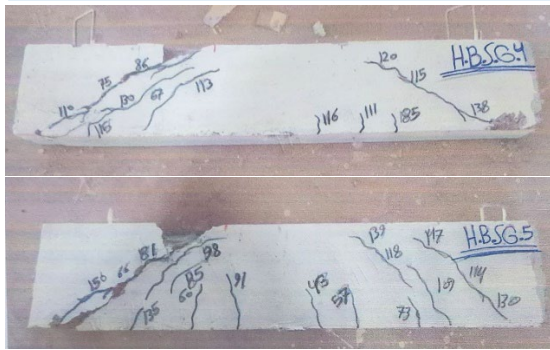**a.** Crack Patterns for the Control Beam
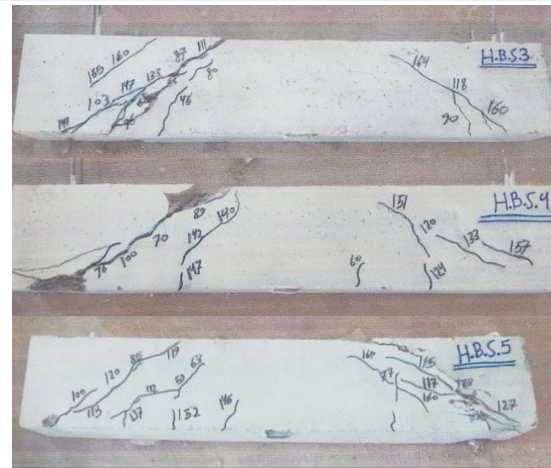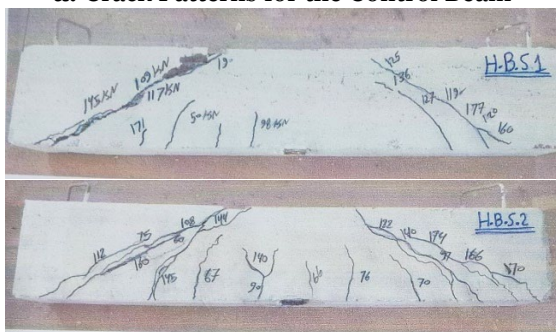
b. Crack Patterns for the First Group

c. Crack Patterns for the Second Group

d. Crack Patterns for the Third Group
Fig. 19 Crack Patterns for the Tested Beams.

6. CONCLUSIONS

Based on the results obtained from the experimental work, the following conclusions can be drawn:

1. In general, all hollow beams reduced the first cracking load and ultimate loading and increased the number of cracks compared to the reference beam.

2. The solid beam had lower deflection values than hollow beams because its moment of inertia was greater than the hollow beam's.

3. The deflection of a hollow beam reinforced by GFRP was less by (3%, 12%, and 5%) than the solid beam reinforced with steel, the solid beam reinforced with GFRP, and the hybrid solid beam reinforced with (3Steel+3GFRP), respectively, due to the low energy absorption and low modulus of elasticity of the GFRP bars.

4. The best case according to the ultimate load among the stirrups was the beam reinforced in shear by steel stirrups, which had the highest shear strength compared to the other types of stirrups due to the low GFRP stirrups modulus of elasticity. Compared to the GFRP stirrups, the GFRP full stirrups had the highest shear strength compared to the other GFRP stirrups because the GFRP full stirrups tied in one joint, while the other GFRP stirrups tied in two or four joints and because of the effect of heating during the bent process.

5. The GFRP stirrups reinforced beams displayed high deflections compared to steel stirrups reinforced beams due to the low energy absorption and low modulus of elasticity of the GFRP.

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