Experimental Performance of RC Beams Strengthened with Aluminum Honeycomb Sandwich Composites and CFRP U-Jackets

M. Kantarci[1] · M.M. Maras[1] · Y. Ayaz[1]

Abstract

This study aims to investigate the flexural behavior of reinforced concrete (RC) beams strengthened using aluminum honeycomb sandwich panels (AHSPs) with three different thicknesses (6, 10, and 15 mm) and CFRP U-Jackets with different cross-section configurations (i.e. support and middle sections). The experimental performance of RC beams was evaluated utilizing AHSPs and CFRP composites under four-point bending tests. The strengthened RC beams (HCRC-2-HCRC-10) were compared with the control beam (HCRC-1) in terms of flexural load carrying capacity, ductility, failure modes, and cracks patterns. The results revealed that the HCRC-9 beam specimen strengthened using 15 mm thickness AHSP displayed higher flexural performance than its counterparts. The HCRC-9 beam exhibited more ductile behavior, which depends on the failure mode. Strengthening with AHSP decreased visible width shear cracks compared to the un-strengthened beam. It was also detected that increase in the thickness of AHSP improved the flexural behavior of RC beams.

Keywords AHSPs · Strengthening · Ductile · Bending test · Failure

Introduction

Fiber-reinforced polymer (FRP) composites have been used in retrofitting strengthened masonry and reinforced concrete (RC) structures [1–3], marine and coastal structures [4], highway bridge [5], repair and strengthening of piping and infrastructure facilities [6, 7] and protection of structures against explosion and impacts [8]. Recent applications have indicated that FRP composites may be economically and effectively [9] applied for both traditional [10, 11] and new construction [12] repairing and strengthening of existing structures. FRPs are the most widely used structural composite materials [13]. In recent years, composite materials have played a significant role in repairing and retrofitting damaged masonry [14, 15] and RC buildings [16, 17] due to their performing properties, such as high strength, corrosion resistance, low permeability and ease of application. For this reason, RC elements using fibers with innovative polymeric materials can be obtained both high ductility and strength at strengthening studies under the external effects

[17]. It has been stated that these innovative geosynthetic polymeric materials, which have been used in recent years, improve the RC structure elements under different loads in proper bonding to concrete [18, 19]. Moreover, new innovative materials on the structural retrofitting combined with the energy performance improvement of buildings have been proposed [20, 21].

Honeycomb composite materials were formed by placing a honeycomb core between two thin layers of high strength and bonding the components to each other with strong adhesives [22] that can transfer load transfer from one surface to another, and high rigidity is obtained with low weights [23]. The analyses of the aluminum honeycomb structure and components included [24] constituent materials and ply properties [25], face laminates, and core wall engineering properties [26]. The adhesive used between aluminum honeycomb core geometry and surface layers ensures that both elements act as a whole by strongly binding them [27].

As a result, a structure with high torsional rigidity [28] and bending stiffness [29] is obtained. The cell (core) part of the honeycomb composite plates was the hexagonal honeycomb [30] or the light density part, called the honeycomb. Sandwich composite boards were obtained as a result of covering the honeycomb cells with the upper and lower surface cover [31]. Honeycomb

✉ M.M. Maras
murat.maras@inonu.edu.tr

1 Department of Civil Engineering, Inonu University, Malatya, Turkey

composite panels require lightness [32] and are used where weight is a critical problem and at the same time high strength is required. The aim is to increase the stiffness by increasing the thickness [33] of the material with light structures. These materials are bonded to high-strength [34] lower and upper surfaces with strong adhesives [35] that can transfer load from one surface to another.

In the paper, the effect of three different coated honeycomb sandwich panels with core height on the mechanical properties of the RC beams was investigated under laboratory conditions. The novelty of this research aims to investigate the strength of RC beams with aluminum honeycomb sandwich panels (AHSPs) with three different thicknesses and different cross-section configurations (i.e. support and middle sections). In the study, the effect of three different coated honeycomb sandwich panels with core height on the mechanical properties of the RC beams was investigated under laboratory conditions. The paper presents the flexural behavior of RC beams strengthened using aluminum honeycomb sandwich panels with three different thicknesses and CFRP U-jackets with these configurations. CFRP material is used in different structural carrier systems and is a high-cost material in building reinforcements. However, in our studies, it is aimed to reduce the cross-sections by applying these elements in different parts. In addition, low-cost aluminum honeycomb sandwich composites have been used as an alternative to CFRP plates. Honeycomb composite materials exhibited rigidity in RC beams by transferring the load properly thanks to their high strength and core structure.

The structural behavior of strengthened RC beam specimens was tested using honeycomb sandwich panels and CFRP in four-point bending tests. The panels have displayed many advantages over conventional materials owing to their high ductility and low permeability, greater corrosion resistance, light material, and high tensile and compression strength. Many researchers have investigated the experimental behavior of RC elements strengthening with the FRPs. Nevertheless, it is very

scarce to use AHSPs in structural repair and strengthening works. The panels have distinct advantages, such as resistance to fatigue and high bending strength. Therefore, AHSPs and CFRP composite are considered to be a significant application area for retrofitting methods for masonry and RC structures.

Materials and Methods

Materials

Concrete

All specimens were cast cured in laboratory condition. The compressive strength test was performed by respectively using 150 mm × 150 mm × 150 mm cube samples. The average test results of the three samples were found as 23.2 MPa. Then, the slump funnel was filled in three equal stages; it was skewered with a standard bottle stick at each grade. The detailed properties of concrete using an RC beam are demonstrated in Fig. 1.

Steel bars

Three types of steel reinforcing bars were used to prepare the beam cage. The top and bottom steel bars of 10 mm /12 mm with an ultimate strength of 516 MPa and 510 MPa were utilized as longitudinal reinforcement. The steel bars of 8 mm / were also utilized as a stirrup. The steel bars used in RC beams are shown in Fig. 2.

Details of Specimens

The tension and compression bars were two 12 mm and two 10 mm diameter bars, respectively (Fig. 3). The transversal steel bars also formed 8 mm-diameter steel stirrups at a distance of 100 mm along the two shear spans of the

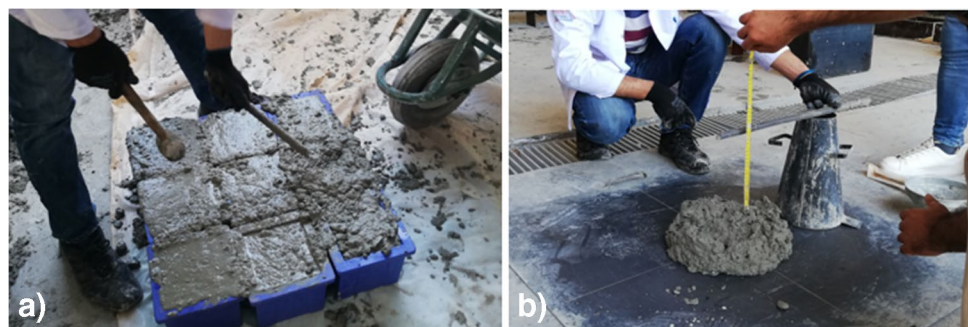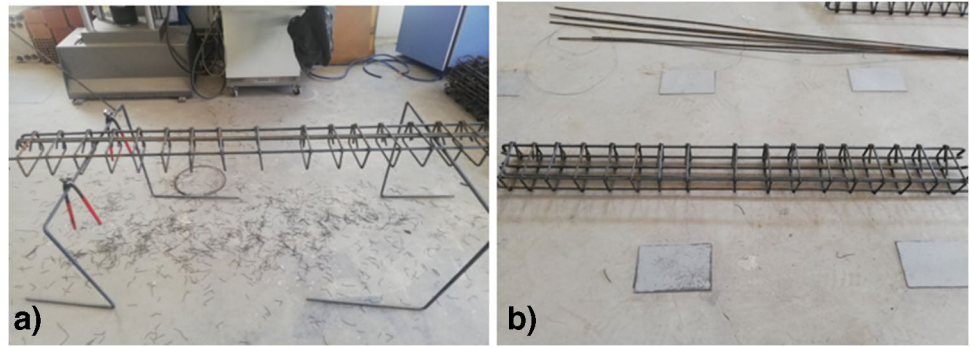**Fig. 1** Concrete samples (**a**) Cube samples (**b**) Slump test

Fig. 2 Steel bars used in RC beams

RC beam specimens. RC beams were in rectangular cross-Sects. 100 mm wide, 150 mm high and 2000 mm in length.

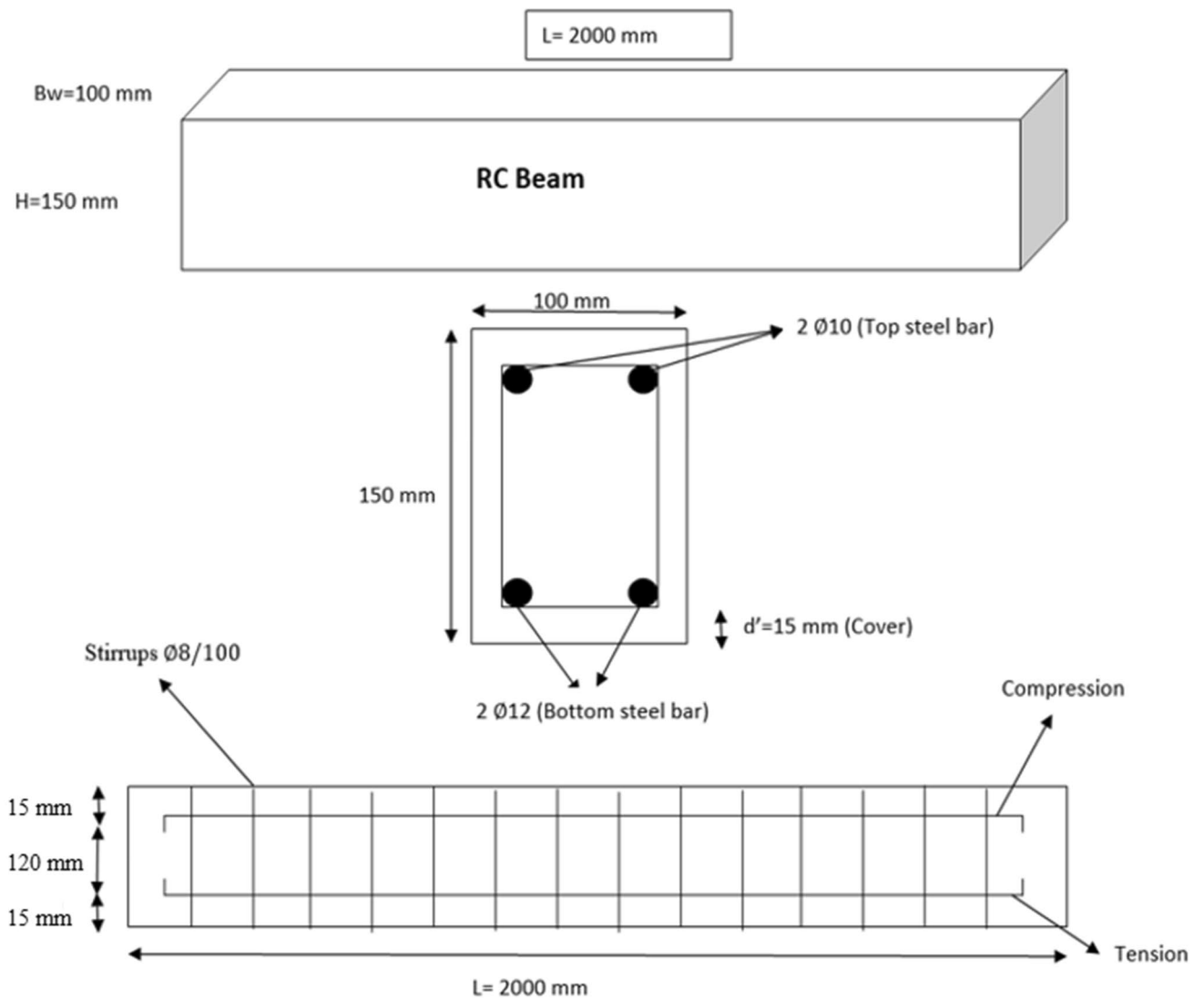The detailed reinforcement size of the beam is demonstrated in Fig. 3.

Fig. 3 Details of test beams

Table 1 Mechanical properties of FRP composites

FRP type	Mechanical Properties				
	Thickness (mm)	Specific Gravity (g/m^2)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (%)
CFRP	0.70	600	4137	242	1.5

Strengthening Materials

Adhesive

Teknobond 300 TIX adhesive was used as a bonding composite material between the concrete substrate and the aluminum honeycomb sandwich panels. The adhesive components were produced at a mix ratio of 3:1 to accomplish a uniform grey color. The values of tensile, flexural, bond and

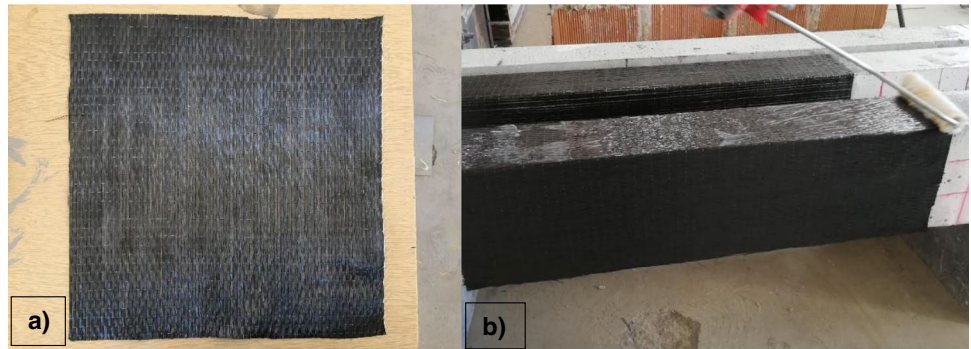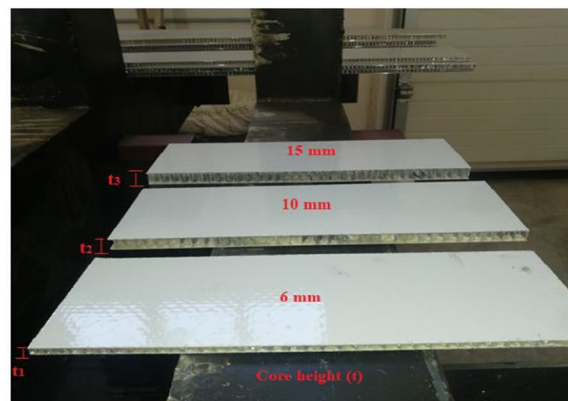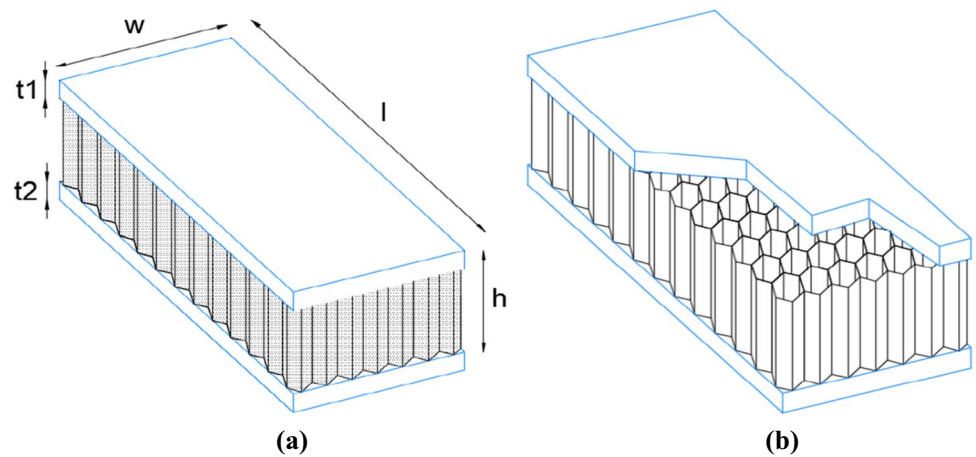**Fig. 4** Textile used in this study: (**a**) CFRP textile; (**b**) Epoxy application

Fig. 5 Aluminum honeycomb sandwich panels (AHSPs). (**a**) Honeycomb composite panel dimensions. (**b**) General view of composite panel. (**c**) Three different GRP-coated honeycomb sandwich panels

(a)   **(b)**

(c)

Table 2 Properties of honeycomb sandwich panels

Panel type						
	Height (h)	Width (w)	Length (l)	CTP		Thickness
				Top	Bottom	
Group A	6	100	1800	1		1
Group B	10	100	1800	1		1
Group C	15	100	1800	1		1
(all dimensions in mm)						

compressive strength of the epoxy adhesive as provided by the manufacturer are 30 MPa, 40 MPa, 4 MPa, and 80 MPa, respectively.

CFRP types

CFRP was preferred due to its high strength and rigidity. The fiber composite displays unique performance with excellent mechanical and bonding properties. CFRP composite with a thickness of 0.70 mm, a width of 500 mm, and 2500 mm in length was used for repair and retrofitting the RC beam samples. The values of the tensile strength, elastic modulus, and elongation of the CFRP as given by the manufacturer are 4137 MPa, 242 GPa, and 1.5%, respectively. The mechanical characterization of fiber textile was provided by Art Construction project engineering company in Turkey (Table 1 and Fig. 4).

Honeycomb sandwich panels

Honeycomb Sandwich Panels (GRP coated honeycomb sandwich panel) made of aluminum core and glass reinforced polyester surface coating were investigated as reinforcement material. In this study, three different GRP-coated honeycomb sandwich panels with 6 mm, 10 mm, and 15 mm core height were used. The honeycomb sandwich panels were also used on the lower surface of the RC beams in a rectangular cross-section with 100 mm × 1800 mm (width x length) dimensions. Dimensions and general views of the honeycomb composite panels are given in Fig. 5.

Aluminum honeycomb sandwich panels have high tensile strength and ductility. Also, the presence of a honeycomb structure between the plates is predicted to increase the bending strength of the structure. The properties of the AHSPs are demonstrated in Table 2.

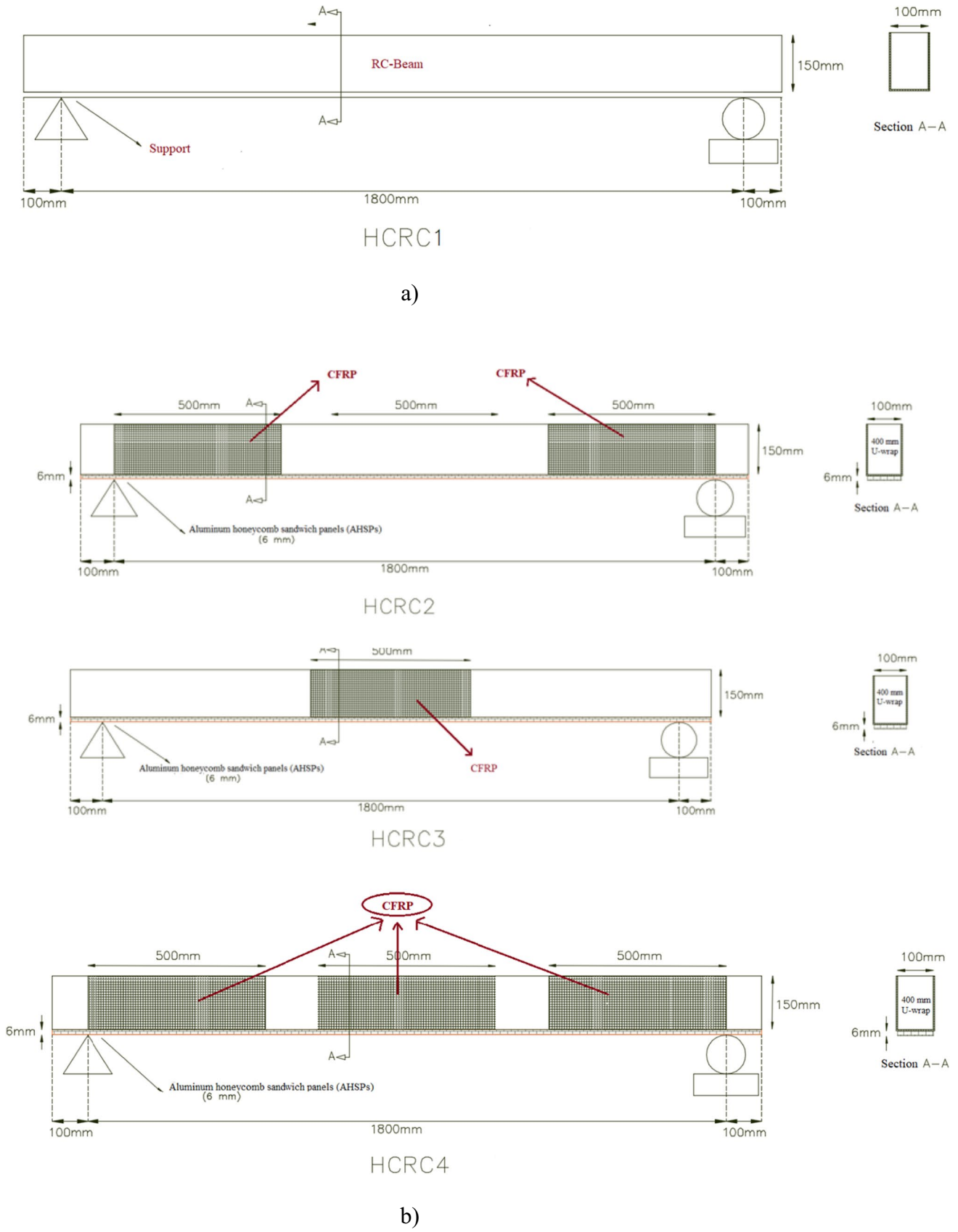**Fig. 6** Strengthening process of RC beams; (**a**) AHSPs (**b**) Epoxy application **c**) Strengthened RC beams

Fig. 7 AHSPs and CFRP strengthening schemes. (**a**) Control RC beam (**b**) Group A (6 mm thickness AHSP) **c**) Group B (10 mm thickness AHSP) **d**) Group C (15 mm thickness AHSP)
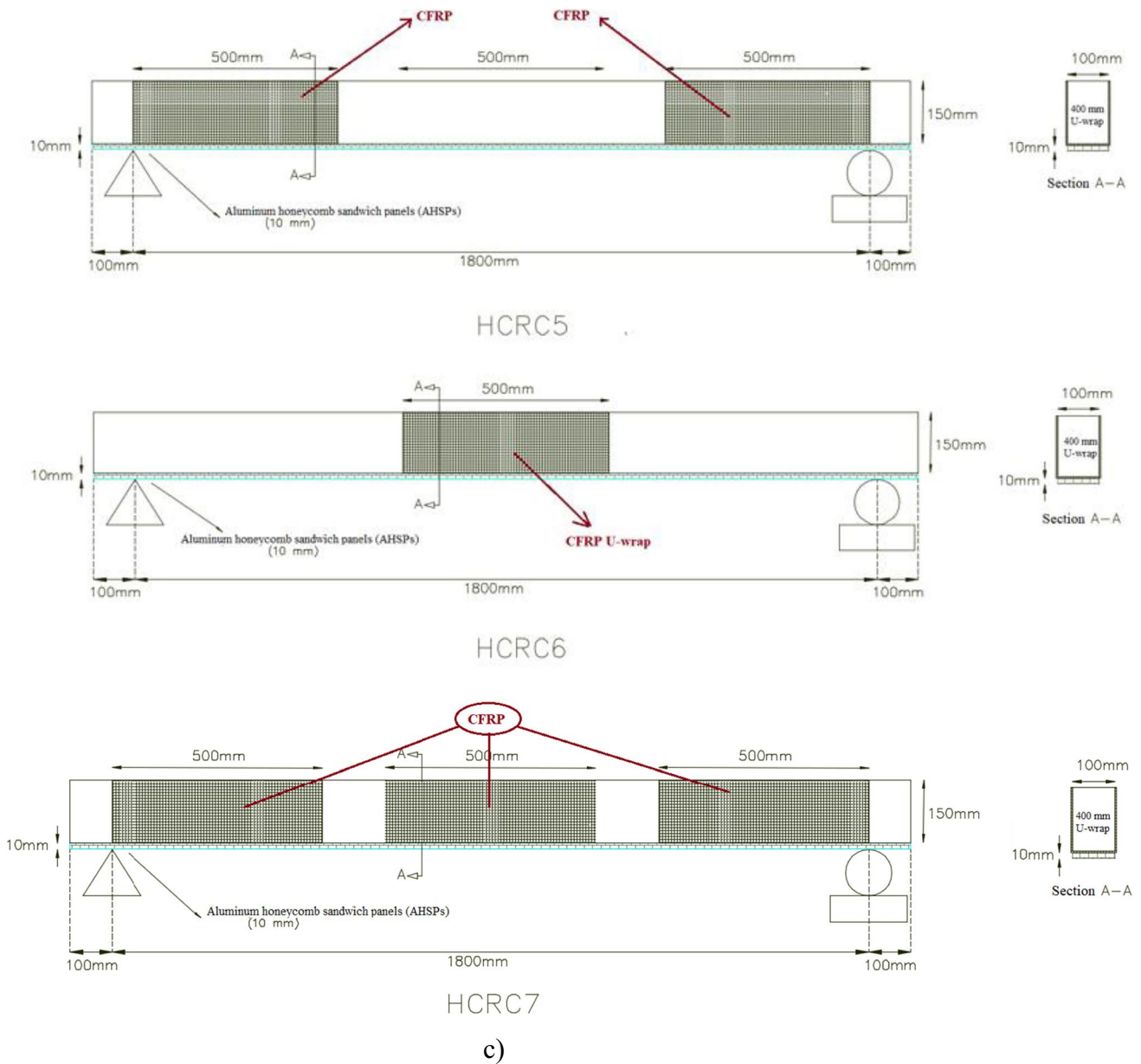
Fig. 7 (continued)

Strengthening Procedure

In this study, the strengthening of RC beams, which was one of the carrier elements, with different composite materials was investigated honeycomb composite panels, one of the leading materials in recent years, have been used for reinforcement work. To strengthen the beams against bending force, aluminum was chosen as the surface core material. Control RC beam and strengthened RC beams in nine different configurations were used as test elements. Honeycomb composite panels of 6 mm, 10 mm, and 15 mm thickness were also used as the

reinforcement material of three of the RC beams (Fig. 6(a)). In addition, strengthening CFRP material was externally bonded to the surface of the RC beam specimens with U-wrapped shape at the configuration of the different cross-sections (i.e. support and middle sections) in Fig. 6(b) and (c).

The strengthening material (AHSPs) was externally bonded to the bottom of the beams over a length of 1800 mm (see Fig. 7(a), (b), and (c)) and CFRP U-shaped wraps were applied immediately before the application of the honeycomb composite panels. Nine out of ten RC beams were strengthened with FRPs U-shaped wraps. Out of nine
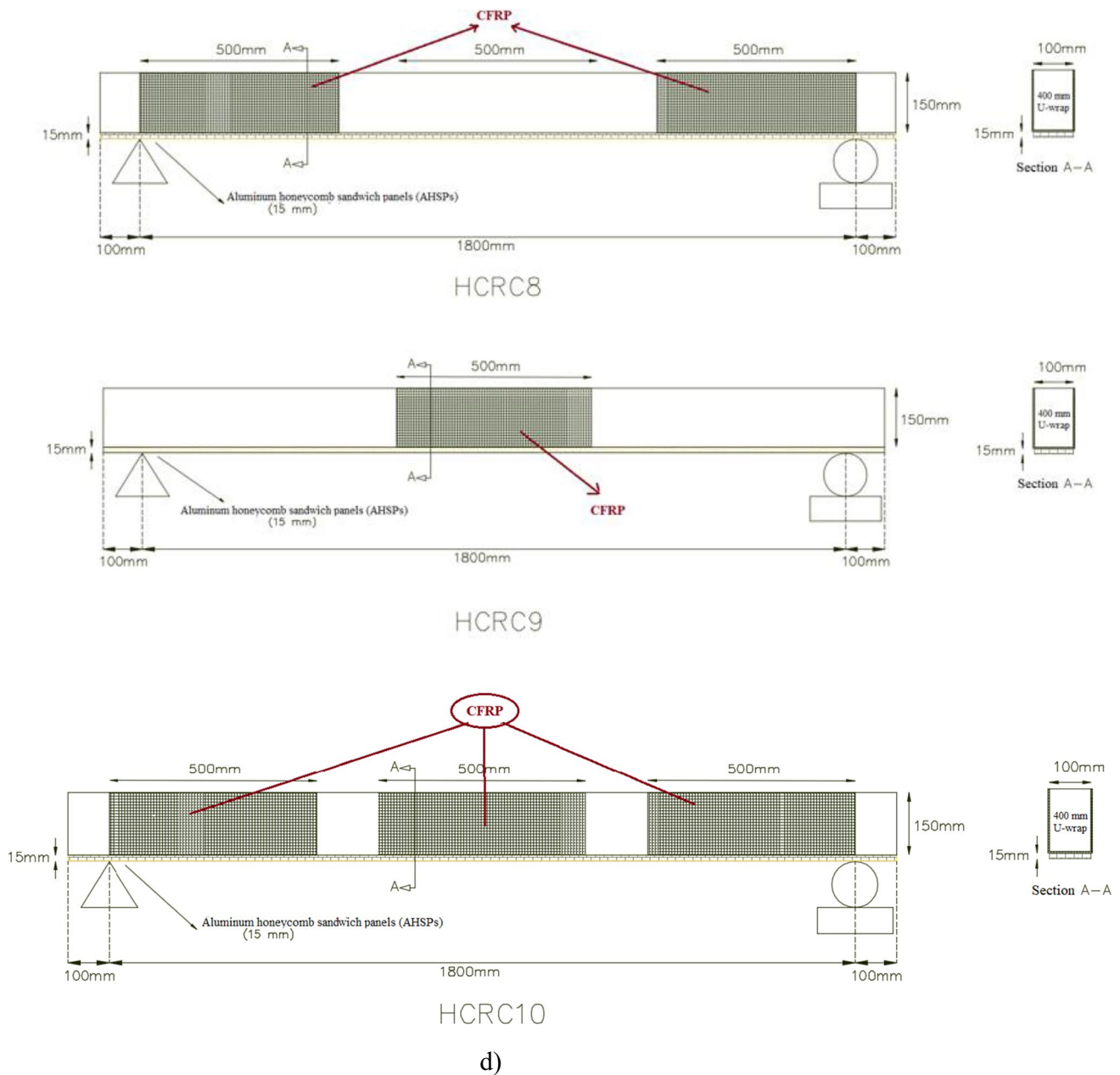
Fig. 7 (continued)

strengthened RC members, three RC beam specimens were strengthened with 6 mm thickness honeycomb composite panels, the other three beam specimens were strengthened with 10 mm thickness honeycomb composite panels, and the remaining three RC beam specimens were also strengthened with 15 mm thickness honeycomb composite panel.

Test setup and Testing Procedures

All RC beam specimens were subjected to flexural bending tests demonstrated in Fig. 8(a)–(b). The net span was 1800 mm, and the strengthening configuration resulted in a 650 mm-long shear span and a 500 mm-long constant moment zone. The uniaxial load was applied using a servo control hydraulic actuator (60-ton capacity) which was vertically fixed on a stiff reaction frame (Fig. 8(a)). The load was applied monotonically under the flexural test at a rate of 1 mm/min. For all beams strengthened with AHSPs plates and CFRP strips, the vertical loads were recorded with a data logger using a load cell.
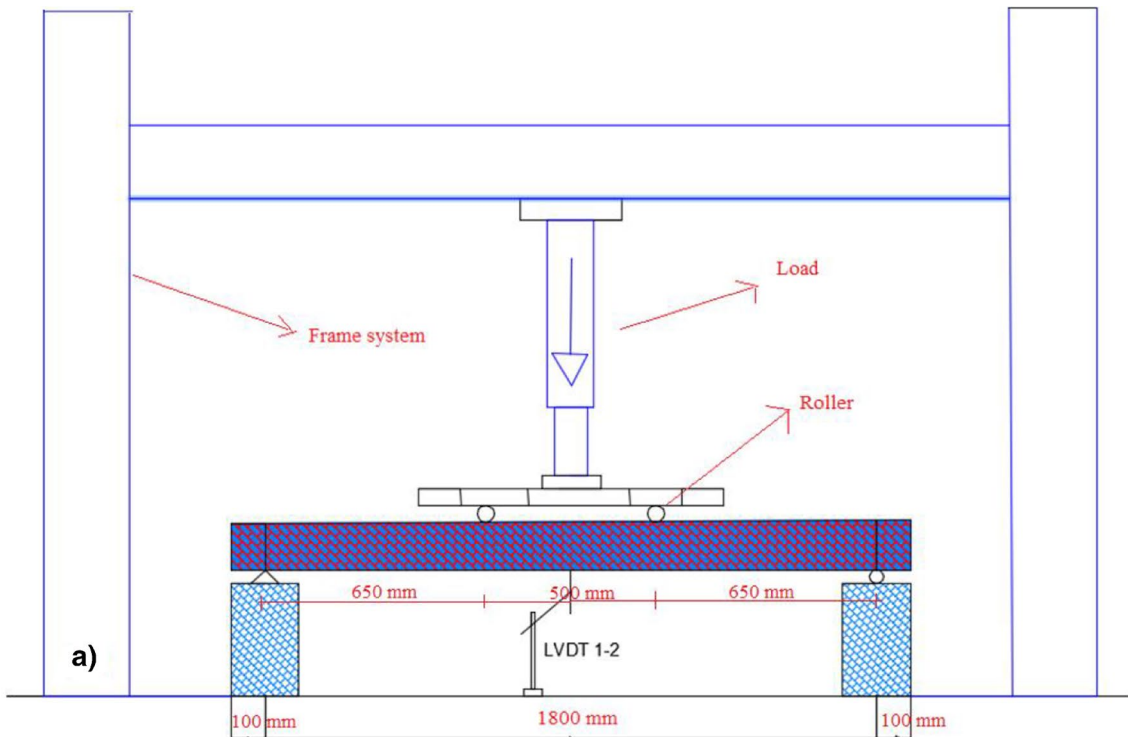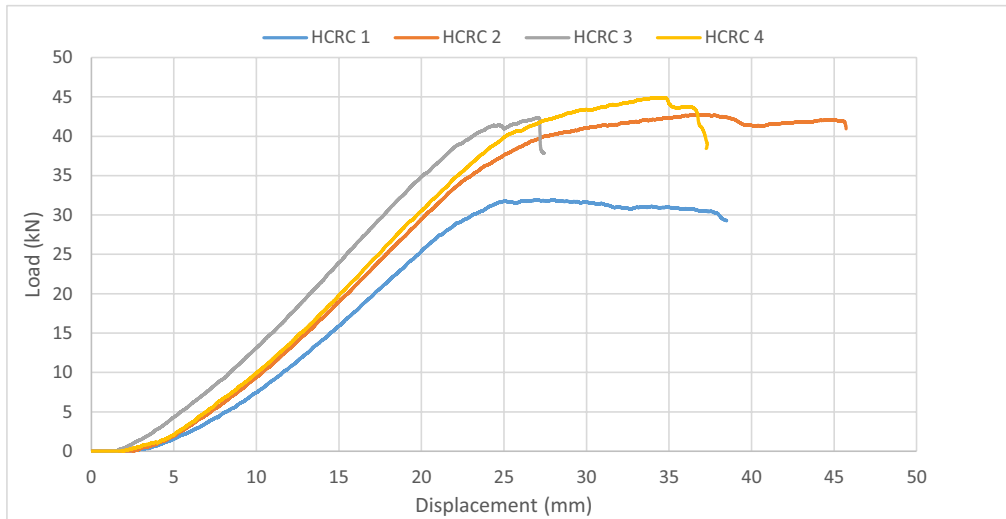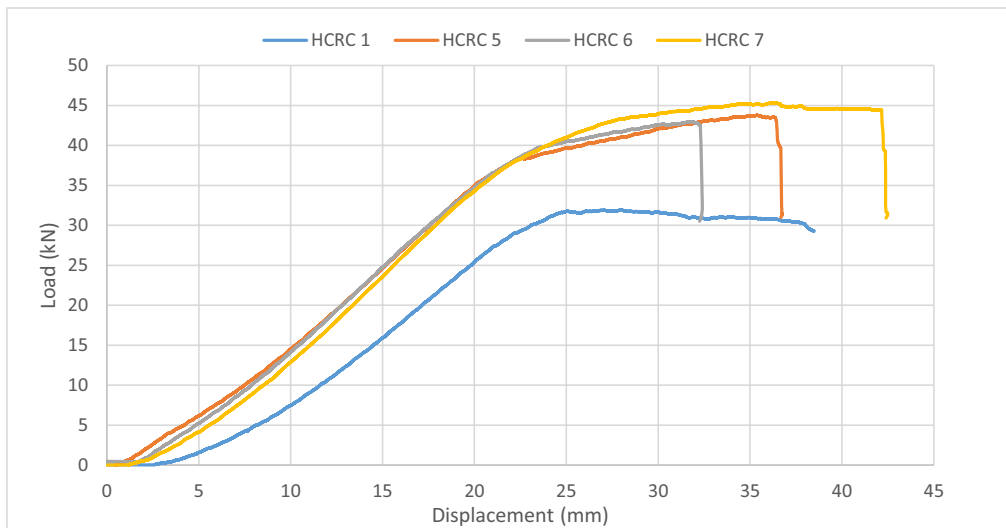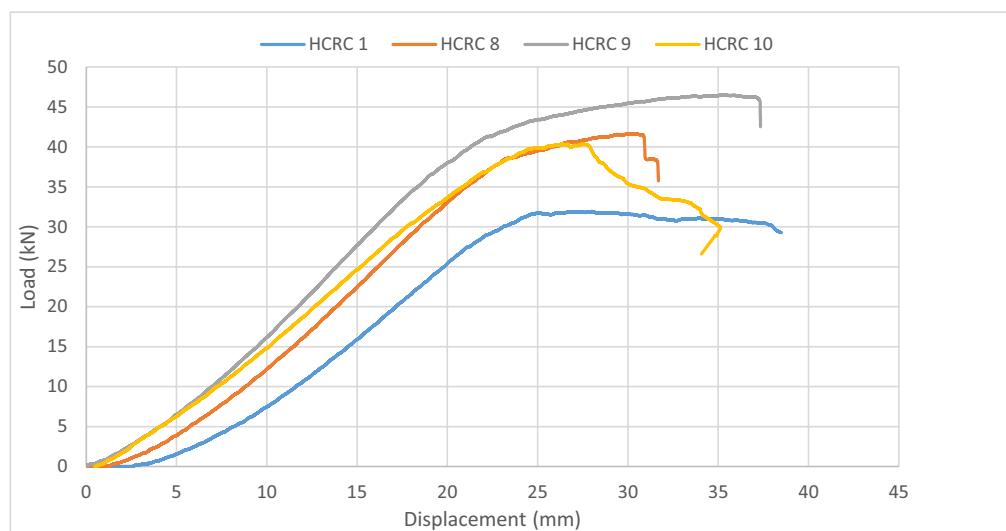
Fig. 8 (**a**) Front view (frame system), (**b**) Testing procedures (four-point bending)

a)

b)

c)

◄**Fig. 9** Load–displacement curves of the RC beams. (**a**) 6 mm thickness AHSPs strengthened and control beams (**b**) 10 mm thickness AHSPs-strengthened and control beams **c**) 15 mm thickness AHSPs-strengthened and control beams

Results and Discussions

Load–Displacement Curves

Figure 9 demonstrates the load–displacement curves for the group of tested RC beam specimens having different AHSPs (6, 10, and 15 mm thickness) and CFRP cross-section configurations (i.e. support and middle sections). The flexural response of the control RC beam specimen and strengthened RC beam specimens are also demonstrated for comparison. From Fig. 9, for RC beam specimens, it was concluded that AHSPs and CFRP composites retrofitting with different configurations resulted in higher load capacity and displacements at ultimate load values compared to control RC beam samples. The application of these composites was increased rapidly in the strengthening works due to their fast and easy application [36], energy absorption [37], and their high tensile strength [38–40] compared to traditional techniques. The amounts of gain in ultimate load values were 34.3%, 32.1%, and 40.5% over the reference beam specimen for the strengthening of HCRC-2, HCRC-3, and HCRC-4 beam samples using 6 mm thickness honeycomb sandwich panel and CFRP U-wraps strengthened, respectively. The surface material of the honeycomb sandwich panels carried the bending load [41, 42] and protected the structure against abrasion [43] while providing the lightweight intermediate layer material of the panels carried the flexural strength [37, 44, 45] caused by external loads. Also, CFRP U-wraps or U-jackets [46–48] on the behavior of RC beams provided high load capacities and ductility, while the amounts of gain in displacements values at ultimate loads were 45.6%, 32.3%, and 50% over the control beam specimen for HCRC-5, HCRC-6, and HCRC-7, respectively. It was evident that honeycomb sandwich panels strengthening delayed diagonal cracks [19, 37, 49] and so helped in increasing load capacities [18, 44, 50, 51] and this was proportional with thickness [52, 53] of honeycomb sandwich panels. The maximum load recorded for RC beam specimens using 15 mm thickness honeycomb sandwich panels HCRC-8, HCRC-9 and HCRC-10 were 42 1, 47.3, and 40.2 kN, respectively, which yields 31.2%, 46.7%, and 25.5% increase in the load capacity. Many researchers have stated that, as the cell density of honeycomb sandwich composite panels increased, the cell shear rigidity and flexural strength of the panels also increased [20, 41, 54, 55]. It was confirmed that the moment of inertia increased [56, 57] with increasing core thickness in these composites, which is the main reason for the increase in the slope [37, 58, 59] in the linear part of the graph. Consequently, all specimens strengthened with AHSPs and CFRP-retrofitted RC beam samples displayed flexural strength significantly higher compared to the reference RC beam sample. As the thickness increased in these honeycomb composites, good adhesion between the concrete and the plate was achieved, and, thus, the RC beams exhibited ductile behavior.
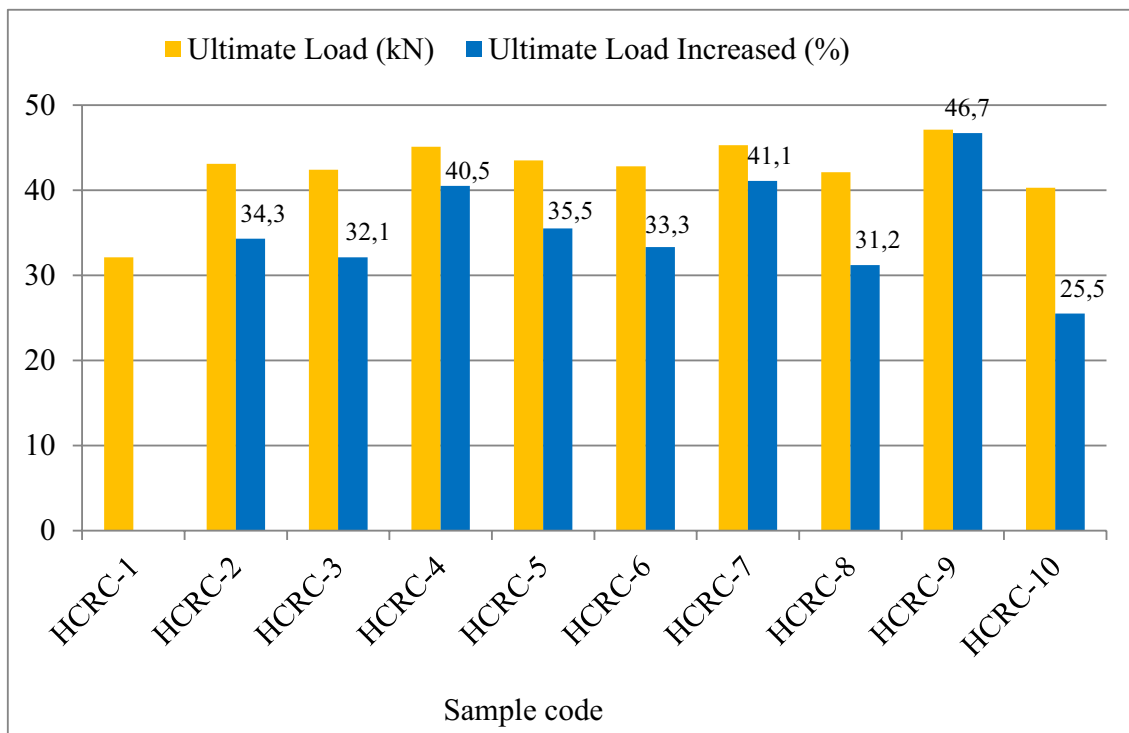
Flexural Load Carrying Capacity

The effects of different thickness honeycomb sandwich panels and CFRP U-wraps strengthened are presented in this study. The variation between the initial and final cracking load of the RC beam specimens is given in detail in Fig. 10. The first cracking load was determined to specify the location of the first crack point and then the loading process continued until the ultimate failure of the RC sample in Fig. 10. The reference beam HCRC-1 specimen failed at a load of 32.1 kN by concrete surface crushing after yielding steel reinforcement. The initial flexural cracks were observed at the mid-span at a total load of roughly 10.2 kN. The crack's width increased with increasing the load up along the complete length of the RC beam specimen failure. The comparison of the first cracking between HCRC-2, HCRC-3, and HCRC-4 using 6 mm thickness honeycomb sandwich panel strengthened samples demonstrates higher enhancement from 31.4%, 38.2%, 34.3% according to the control sample (HCRC-1), respectively, as shown in Fig. 10(a). Many researchers have reported that sandwich panels were highly efficient composite elements by supporting the bending strength [18, 41, 60, 61] of surface materials under bending load, tolerating lateral forces, and stabilizing the structure against buckling [20, 62–64]. In addition, the strengthening of the HCRC-8, HCRC-9, HCRC-10 beam samples using 15 mm thickness honeycomb sandwich panel increased the first cracking loads up to 42.2%, 26.5%, and 48.1%, respectively, compared to the un-strengthened RC beam sample (Fig. 10(a)). It was observed that sandwich composite with lower thickness posed more stress under the same load. For this reason, the 6 mm thick sandwich plates had a lower buckling load than the thicker plates. Similarly, it was stated that, as the core thickness increased [52, 56, 65, 66], the maximum load amount the RC beams could carry [67–69] compared to the control RC beam specimen also increased.

The performance of RC beam specimens in increasing the ultimate load capacity of the beams is compared to the control RC beam specimen in Fig. 10(b). The strengthening of HCRC-2, HCRC-3 and HCRC-4 beam samples using
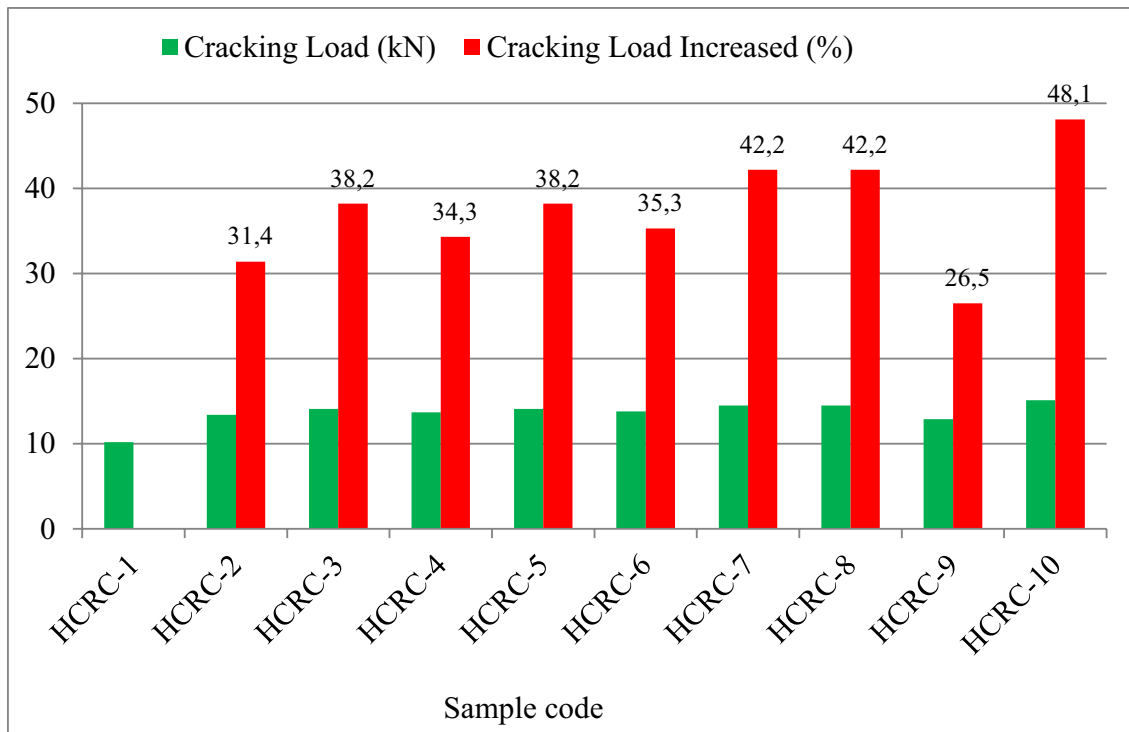
a)

b)

Fig. 10 The flexural load-carrying capacity of RC beams. (**a**) Initial cracking load and increase in the cracking load compared to reference sample (**b**) Ultimate load capacity and increase in ultimate load capacity compared to reference sample

6 mm thickness honeycomb sandwich panel strengthened increased the ultimate loads up to 34.3%, 32.1%, and 40.5%, respectively, compared to beam sample in Fig. 10(b). Also, the strengthening of the HCRC-5, HCRC-6, HCRC-7 beam samples using 10 mm thickness honeycomb sandwich composite panel as a strengthening reinforcement increased its load capacity up to 35.5%, 33.3%, and 41.1%, respectively, compared with the un-strengthened RC beam sample. The cells in the composite used in the honeycomb structure assumed the function of the body of the RC beam [70]. Honeycomb cells resisted shear force [41, 71, 72] and increased the strength [73, 74] of the structure. At the same time, the cells provided regular and reinforced support on the surface [75, 76]. Finally, the strengthening of the HCRC-8, HCRC-9, HCRC-10 beam samples using a 15 mm thickness honeycomb sandwich composite panel as a strengthening reinforcement increased its load capacity up to 31.2%, 46.7%, and 25.5%, respectively, compared with the un-strengthened RC beam sample. The RC beams strengthened at the middle section displayed more ductile and energy absorption capacity, which depends on the failure mode. As a result, the load–displacement curves, strengthened RC beams exhibited higher load capacity than control RC beams.

The ultimate load of HCRC-3 is smaller than that of HCRC-2 and HCRC-4, and the ultimate load of HCRC-6 is smaller than that of HCRC-5 and HCRC-7. In this study, the reinforcements made in the middle regions of the specimens reinforced with CFRP and low-thickness composites (6 mm, 10 mm) showed better results in increasing the load. However, the ultimate load of HCRC-9 is larger than that of HCRC-8 and HCRC-10. AHSP composites with high thickness exhibited a more rigid behavior than CFRP composite

materials. Therefore, RC beam specimens with high plate thickness (15 mm) exhibited more load increase than CFRP materials.

Displacement Ductility

Figure 11 demonstrates the relation of the ductility indexes for all tested RC beams. All the AHSPs and CFRP-strengthened RC beam samples display a ductility index higher than control samples.

The ductility index of the RC beam specimens is defined as the ratio of the mid-span deflection at yield load with the mid-span deflection at ultimate load. It is explained in detail in the equation below.

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \tag{1}$$

where (Δ_u) is the displacement of a structural element and (Δy) is the displacement at yield limit.

Compared with the control sample (HCRC-1), the ductility index of sample HCRC-2, HCRC-3, and HCRC-4 increased 22.6%, 12.9%, and 25.8%, respectively. The ductility index HCRC-6 and HCRC-7 beam sample also increased 19.4% and 29.1%, respectively, compared to that of the control RC beam sample. The honeycomb of specific energy absorption rate was highly influenced by the structural parameters of the structure [77, 78]. Reinforcements made with the core material increased the specific energy absorption rate [79]. Moreover, the ductility index HCRC-8 and HCRC-10 beam strengthened with 15 mm thickness honeycomb sandwich panel increased by 24.3% and 28.3%

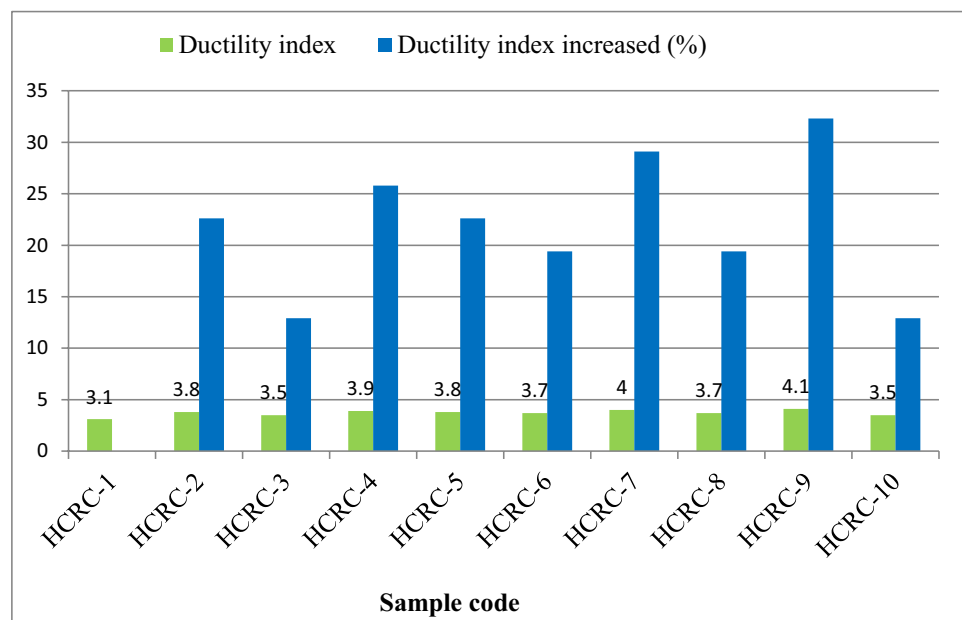**Fig. 11** Ductility indices based on deformability

Fig. 12 The crack pattern for RC beam specimens: (**a**) Close up of RC beams; (**b**) Complete look of RC beams

a)   b)

in comparison to un-strengthened HCRC1 beam specimen, respectively. Honeycomb cores were used especially in areas with a high need to absorb the energy [60, 80, 81] generated by the impact. Among all the RC beam samples, HCRC-9 showed the largest ductility, while the un-strengthened beam specimen UHRC-1 displayed the smallest ductility. High ductility index showed that the structural element could cause high deformation [41, 82, 83] under loads without a significant reduction in its flexural strength. As a result, all strengthened beams demonstrated higher ductility index than the corresponding reference beam specimen. Especially in the samples reinforced with 6 mm thick plates, crushing occurred in areas close to the support. In the specimens reinforced with AHSPs composites, the deflection, especially in the beams, was reduced. In addition, thanks to these composites, a slight increase in strength has been achieved.

Fig. 13 Crack patterns of reference and externally reinforced beams. (**a**) Group A (Control HCRC-1 beams) (**b**) Group B (6 mm thickness honeycomb sandwich panel strengthened RC beams) (**c**) Group C (10 mm thickness honeycomb sandwich panel strengthened RC beams) (**d**) Group D (15 mm thickness honeycomb sandwich panel strengthened RC beams)
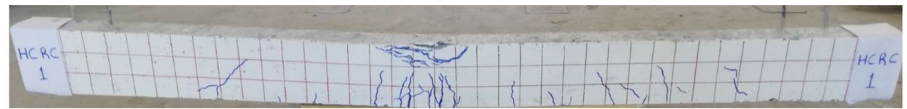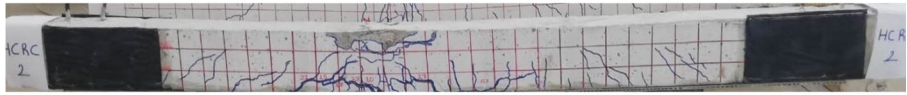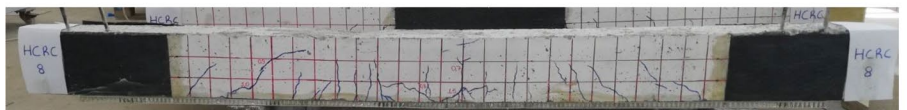
Table 3 Representative load increase due to strengthening methods for RC beam

Specimen	Retrofitted method	Main parameter	Loading system		
			Ultimate Load (kN)	Load Increased (%)	Failure mode
Experimental results	HCRC-1	–	Reference	32.1	–	Crushing
	HCRC-3	Middle	CFRP+AHPS	42.4	+34.3	Debonding
	HCRC-5	Support	CFRP+AHPS	43.5	+35.5	Flexural
	HCRC-7	Support+Middle	CFRP+AHPS	45.3	+41.1	FRP rupture
	HCRC-8	Middle	CFRP+AHPS	42.1	+31.2	Shear crack
	HCRC-10	Support+Middle	CFRP+AHPS	40.3	+25.5	Interface
References	RC-Beam [1]	Middle	FRP-jacket	189	+18.1	Small cracks
	RC-Beam [36]	U-wrapped	CFRP	173.1	–	FRP rupture
	Wood-Beam [50]	Bottom	CFRP+AHPS	98.0	+212.1	Shear failure
	Sandwich panel [66]	–	Composite	47.1	44.2	Flexural
	RC-Beam [82]	Laminate	CFRP	133.0	+52.9	Rupture
	RC-Beam [84]	–	PVA-ECC	60.3	+14.8	Flexural

In the samples reinforced with CFRP, on the other hand, it showed high energy absorption by showing high deformation feature rather than strength effect.

Failure modes of the Specimens

The formation of the crack patterns of RC beams is demonstrated in Fig. 12. All strengthened RC beam specimens demonstrated similar behavior as observed for the reference beam specimen up to cracking. After the cracking, the load-displacements relationship of the HCRC-4 beam specimen was strengthened using a 6 mm thickness honeycomb sandwich panel and CFRP strips were nearly similar to that for the HCRC-10 beam specimen strengthened using 10 mm thickness honeycomb sandwich panel and CFRP U-jackets. For the beam, the HCRC-2 specimen was strengthened with 6 mm thickness AHSPs and CFRP strips, initially; flexural cracks were formed at the mid-span. Strengthening beam HCRC-4 with CFRP strips controlled the crack width in comparison with the HCRC-1 beam specimen. The failure of HCRC-3 was observed at a total applied load of 42.4 kN by debonding of the honeycomb sandwich panel at the strip–epoxy interface. The failure modes of HCRC-8 also formed thin diagonal shear cracks at the middle section. Similarly, the type of failure, could also be described as shear cracks [84–87]. Thanks to the aluminum plates in the HCRC 9 and HCRC 10 samples, the carrying capacity has increased. However, in the HCRC 10 sample, poor adherence was observed between the concrete and the CFRP used in the middle region. In HCRC 10 sample, with the accumulation of the load in the region between the middle and the support, the shear cracks intensified and thus exhibited less ductile behavior.

The novelty of this research aims to investigate the strength of RC beams with aluminum honeycomb sandwich panels (AHSPs) with three different thicknesses and cross-section configurations (i.e. support and middle sections). In previous studies, reinforcement studies were carried out by using high-cost CFRP materials in all beam regions. In the study, the most suitable strengthening method was determined by both reducing the CFRP material and using more cost-effective aluminum plates. It is not known how CFRP and AHPS composites behave under load in RC beams. Therefore, the effect of this strengthening combination was determined by the experimental study. As a result, the most suitable strengthening method was obtained by reducing the shear cracks in the RC beam sample reinforced with CFRP by using a 15 mm thick plate in the middle region.

The representative failure modes for all RC beam samples tested are demonstrated in Fig. 13. The failure pattern of the reference beam specimen (HCRC-1) is a typical flexural failure mode in Fig. 13(a). For the beam HCRC-1 control sample, firstly flexural cracks were started from mid-span,

and then the failure of the reference beam sample was occurred through concrete spalling at the top of the compression region, as shown in Fig. 13(a). In the case of the beam, HCRC-2 strengthened using a 6 mm thickness honeycomb sandwich panel, the propagation, and formation of diagonal cracks was similar to those of beam HCRC-3 in Fig. 13(b). Eventually, the honeycomb sandwich panel debonded from the RC beam specimen's (Group B) soffit with parts of the concrete surface attached. This type of failure mode is quite common and brittle for the composite plates RC beam specimens [34, 88, 89]. It may be observed that the failure modes of HCRC-5 and HCRC-6 were occurred with wide shear cracks at the interface between the concrete surface and epoxy adhesive, as demonstrated in Fig. 13(c). The beams strengthened using a 10 mm thickness honeycomb sandwich panel failed due to CFRP rupture at the constant moment region of the RC beam specimens (Group C). All samples strengthened with honeycomb sandwich panels failed in bending tests after exhibiting ultimate load higher compared to the reference sample. In the case of beam HCRC-8 and HCRC-9 strengthened with 15 mm thick aluminum honeycomb sandwich panel (AHSP), the ultimate total applied load at failure was 42.1 kN and 47.1, which is 31.2% and 46.7% higher than that of the reference beam specimen (HCRC-1), respectively. For the RC beam samples strengthened with the honeycomb sandwich panel, the apparent width of shear cracks were reduced [90, 91]. As a result of using 15 mm, thickness AHSP and CFRP, an important increase in the flexural load carrying capacity was observed owing to the high ductility of the bond strength of the composites. Therefore, HCRC-8 and HCRC-9 beam specimens using high thickness plates and CFRP strips are more effective than the control beam specimen under the bending tests. The results demonstrated that the first crack load could be increased greatly by increasing the thickness of the honeycomb sandwich panels. The highest ultimate load increase was obtained in the HCRC-9 sample. As the thickness increased in these honeycomb composites, good adhesion between the concrete and the plate was achieved, and, thus, the RC beams exhibited ductile behavior. The experimental results are compared with recent studies in Table 3.

Conclusion

In this study, the effect of using three different thickness honeycomb sandwich panels on the RC beam strengthening techniques was investigated. The strengthened RC beam using AHSPs and CFRP was evaluated.

i- All specimens strengthened with AHSPs and CFRP-retrofitted RC beam samples displayed flexural strength significantly higher compared to the reference RC beam sample.

ii- The RC beams strengthened at the middle section displayed greater ductility and energy absorbing behavior, which depends on the failure mode.

iii- Among all the RC beam samples, HCRC-9 showed the largest ductility, while the un-strengthened beam specimen UHRC-1 displayed the smallest ductility.

iv- Strengthening beam HCRC-4 with CFRP strips controlled the crack's width in comparison with the HCRC-1 beam specimen.

v- As the core thickness increased, the maximum load that the RC beams could carry increased compared to the reference RC beam sample.

vi- CFRP material is used in different structural carrier systems and is a high-cost material in building reinforcements. However, in our studies, it is aimed to reduce the cross-sections by applying these elements in different parts. In addition, low-cost aluminum honeycomb sandwich composites have been used as an alternative to CFRP plates. Honeycomb composite materials exhibited rigidity in RC beams by transferring the load properly thanks to its high strength and core structure.

Declarations

Conflict of Interest All authors declare no conficts of interest.

References

1. Mohammed AA, Manalo AC, Maranan GB, Muttashar M, Zhuge Y, Vijay P, Pettigrewg J (2019) Effectiveness of a novel composite jacket in repairing damaged reinforced concrete structures subject to flexural loads. Comp Str 233:111634. https://doi.org/10.1016/j.compstruct.2019.111634

2. Babamohammadi S, Fantuzzi N, Lonardi G (2019) Mechanical assessment of hollow-circular FRP beams. Comp Str 227:111313. https://doi.org/10.1016/j.compstruct.2019.111313

3. Carozzi FG, Bellini A, D'Antino T, Felice G, Focacci F, Hojdys L et al (2017) Experimental investigation of tensile and bond properties of Carbon-FRCM composites for strengthening masonry elements. Comp Part B: Eng 128:100–119. https://doi.org/10.1016/j.compositesb.2017.06.018

4. Li J, Xie J, Liu F, Lu Z (2019) A critical review and assessment for FRP-concrete bond systems with epoxy resin exposed to chloride environments. Comp Str 229:111372. https://doi.org/10.1016/j.compstruct.2019.111372

5. Demers CE (1998) Fatigue strength degradation of E-glass FRP composites and carbon FRP composites. Const Build Mat 12:311–318. https://doi.org/10.1016/S0950-0618(98)00012-9

6. Hota G, Liang RF, (2011) Advanced fiber reinforced polymer composites for sustainable civil infrastructures, International symposium on innovation & sustainability of structures in civil engineering, Xiamen University, China

7. Hollaway LC, Head PR (2001) Advanced Polymer Composites and Polymers in the Civil Infrastructure. Elsevier, Oxford

8. Pham TM, Hao H (2016) Review of concrete structures strengthened with FRP against impact loading. Str 7:59–70. https://doi.org/10.1016/j.istruc.2016.05.003

9. Maras MM, (2021) Mechanical properties of confined damaged concrete strengthened with fiber reinforced polymer wraps. El-Cez J S Eng 8(2):706–717. https://doi.org/10.31202/ecjse.866687

10. Frigione M, Lettieri M (2018) Durability issues and challenges for material advancements in FRP employed in the construction industry. Poly 10(3):247. https://doi.org/10.3390/polym10030247

11. Maras MM, Kantarcı F (2021) structural performance of reinforced concrete (RC) moment frame connections strengthened using FRP composite jackets. Arab J Sci Eng 46:10975–10992. https://doi.org/10.1007/s13369-021-06120-6

12. Nanni A (2003) North American design guidelines for concrete reinforcement and strengthening using FRP: Principles, applications and unresolved issues. Constr Build Mater 17:439–446. https://doi.org/10.1016/S0950-0618(03)00042-4

13. Turco V, Secondin S, Morbin A, Valluzzi MR, Modena C (2006) Flexural and shear strengthening of un-reinforced masonry with FRP bars. Compos Sci Technol 66(2):289–296. https://doi.org/10.1016/j.compscitech.2005.04.042

14. Triantafillou TC (1998) Strengthening of masonry structures using epoxy-bonded FRP laminates. J Compos Constr 2(2):96–104. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:2(96)

15. Grande E, Imbimbo M, Sacco E (2011) Bond behavior of CFRP laminates glued on clay bricks: experimental and numerical study. Comp Part B 42(2):330–340. https://doi.org/10.1016/j.compositesb.2010.09.020

16. Realfonzo R, Napoli A, Pinilla JGR (2014) Cyclic behavior of RC beam–column joints strengthened with FRP systems. Constr Build Mater 54:282–297. https://doi.org/10.1016/j.conbuildmat.2013.12.043

17. Majumder S, Saha S (2021) Quasi-static cyclic performance of RC exterior beam-column joint assemblages strengthened with geosynthetic materials. Structures 29:1210–1228. https://doi.org/10.1016/j.istruc.2020.12.010

18. Majumder S, Saha S (2021) Shear behaviour of RC beams strengthened using geosynthetic materials by external and internal confinement. Structures 32:1665–1678. https://doi.org/10.1016/j.istruc.2021.03.107

19. Majumder S, Saha S (2020) Behaviour of reinforced concrete beam strengthened in shear with geosynthetic. Adv Struct Eng 23(9):1851–1864. https://doi.org/10.1177/1369433220901820

20. Khan HA, Nanda RP (2020) Out-of-plane bending of masonry wallette strengthened with geosynthetic. Constr Build Mater 231:117198. https://doi.org/10.1016/j.conbuildmat.2019.117198

21. Maras MM, Kose MM (2021) Structural behavior of masonry panels strengthened using geopolymer composites in compression tests. Iran J Sci Technol Trans Civ Eng 45:767–777. https://doi.org/10.1007/s40996-020-00433-6

22. Heimbs S (2009) Virtual testing of sandwich core structures using dynamic finite element simulations. Comput Mater Sci 45:205–216

23. He M, Hu W (2008) A study on composite honeycomb sandwich panel structure. Mater Des 29(3):709–713. https://doi.org/10.1016/j.commatsci.2008.09.017

24. Bai Y, Yu K, Zhao J, Zhao R (2018) Experimental and simulation investigation of temperature effects on modal characteristics of composite honeycomb structure. Compos Struct 201:816–827. https://doi.org/10.1016/j.compstruct.2018.06.106

25. Davalos JF, Qiao P, Xu XF, Robinson J, Barth KE (2001) Modeling and characterization of fiber-reinforced plastic honeycomb sandwich panels for highway bridge applications. Compos Struct 52:441–452. https://doi.org/10.1016/S0263-8223(01)00034-4

26. Renji K, Nair PS, Narayanan S (1996) Modal density of composite honeycomb sandwich panels. J Sound Vib 195(5):687–699. https://doi.org/10.1006/jsvi.1996.0456

27. Paik JK, Thayamballi AK, Kim GS (1999) The strength characteristics of aluminum honeycomb sandwich panels. Thin-Walled Struct 35(3):205–231. https://doi.org/10.1016/S0263-8231(99)00026-9

28. Dharmasena KP et al (2008) Mechanical response of metallic honeycomb sandwich panel structures to high-intensity dynamic loading. Int J Impact Eng 35(9):1063–1074. https://doi.org/10.1016/j.ijimpeng.2007.06.008

29. Huang WC, Ng CF (1998) Sound insulation improvement using honeycomb sandwich panels. Appl Acoust 53(1):163–177. https://doi.org/10.1016/S0003-682X(97)00033-9

30. Zhao Y, Sun Y, Li R, Sun Q, Feng J (2017) Response of aramid honeycomb sandwich panels subjected to Intense impulse loading by Mylar Flyer. Int J Impact Eng 104:75–84. https://doi.org/10.1016/j.ijimpeng.2017.02.008

31. Zhou G, Hill MD (2009) Impact damage and energy absorbing characteristics and residual in-plane compressive strength of Honeycomb sandwich panels. J Sandwich Struct Mater 11:329–356. https://doi.org/10.1177/1099636209105704

32. Beukers A (1999) Lightness, the inevitable renaissance of minimum energy structures. In: Van Hinte (ed). Rotterdam: 010 Publishers

33. Zhong J, Zhou Y, Bao Q, Wang E, Li Q (2017) Strengthening mechanism of channel steel plate for notched concrete beams against fracture: test and numerical study. Eng Fracture Mech 180:132–147. https://doi.org/10.1016/j.engfracmech.2017.05.027

34. Yang C, Xu P, Yao S et al (2018) Optimization of honeycomb strength assignment for a composite energy-absorbing structure. Thin Wall Struct 127:741–755. https://doi.org/10.1016/j.tws.2018.03.014

35. Farooq U, Ahmad MS, Rakha SA et al (2017) Interfacial mechanical performance of composite honeycomb sandwich panels for aerospace applications. Arab J Sci Eng 42:1775–1782. https://doi.org/10.1007/s13369-016-2307-z

36. Zaki MA, Rasheed HA, Alkhrdaji T (2019) Performance of CFRP-strengthened concrete beams fastened with distributed CFRP dowel and fiber anchors. Compos B Eng 176:107117. https://doi.org/10.1016/j.compositesb.2019.107117

37. Kim Y, Ghannoum WM, Jirsa JO (2015) Shear behavior of full-scale reinforced concrete T-beams strengthened with CFRP strips and anchors. Constr Build Mater 94:1–9. https://doi.org/10.1016/j.conbuildmat.2015.06.005

38. Lestari W, Qiao PZ (2005) Damage detection of fiber-reinforced polymer honeycomb sandwich beams. Compos Struc 67(3):365–373. https://doi.org/10.1016/j.compstruct.2004.01.023

39. Gartner A, Douglas E, Dolan C, Hamilton H (2011) Small beam bond test method for CFRP composites applied to concrete. J Compos Constr 10(6):52–61. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000151

40. Tatar J, Hamilton HR (2015) Bond durability factor for externally bonded CFRP systems in concrete structures. J Compos Constr. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000587

41. Bezazi A et al (2007) Fatigue life prediction of sandwich composite materials under flexural tests using Bayesian trained artificial, neural network. Int J Fat 29:738–747. https://doi.org/10.1016/j.ijfatigue.2006.06.013

42. Giglio M, Manes A, Gilioli A (2012) Investigations on sandwich core properties through an experimental–numerical approach. Compos Part B-Eng 43:361–374. https://doi.org/10.1016/j.compositesb.2011.08.016

43. Toradmal K, Waghmare P, Sollapur S (2017) Three-point bending analysis of honeycomb sandwich panels experimental approach. Int J Eng Tech 3(5):189–193

44. Belingardi G et al (2007) Fatigue analysis of honeycomb-composite sandwich beams. Comp Part A 38:1183–1191. https://doi.org/10.1016/j.compositesa.2006.06.007

45. Wahl L, Maas S, Waldmann D, Zürbes A, Frères P (2012) Shear stresses in honeycomb sandwich plates: analytical solution, finite element method and experimental verification. J Sandwich Struct Mater 14(4):449–468. https://doi.org/10.1177/1099636212444655

46. Al-Tersawy SH (2013) Effect of fiber parameters and concrete strength on shear behavior of strengthened RC beams. Constr Build Mater 44:15–24. https://doi.org/10.1016/j.conbuildmat.2013.03.007

47. Li W, Leung CKY (2017) Effect of shear span-depth ratio on mechanical performance of RC beams strengthened in shear with U-wrapping FRP strips. Compos Struct 177:141–157. https://doi.org/10.1016/j.compstruct.2017.06.059

48. Fu B, Teng JG, Chen JF, Chen GM, Guo YC (2017) Concrete cover separation in FRP plated RC beams: mitigation using FRP U-Jackets. J Compos Constr 21:204016077. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000721

49. Juliyana M, Krishnan RS (2018) Experimental and simulation of split semi-torus key in PVC foam core to improve the debonding resistance of composite sandwich panel. Mater Res Expr 5:025307

50. Mosallam AS (2016) Structural evaluation and design procedure for wood beams repaired and retrofitted with FRP laminates and honeycomb sandwich panels. Compos Part B Eng 87:196e213. https://doi.org/10.1016/j.compositesb.2015.09.053

51. Sun Z, Shi S, Guo X, Hu X, Chen H (2016) On compressive properties of composite sandwich structures with grid reinforced honeycomb core. Comp Part B: Eng 94:245–252. https://doi.org/10.1016/j.compositesb.2016.03.054

52. Wang D (2009) Impact behavior and energy absorption of paper honeycomb sandwich panels. Int J Impact Eng 36:110–114. https://doi.org/10.1016/j.ijimpeng.2008.03.002

53. Sun G, Chen D, Huo X, Zheng G, Li Q (2018) Experimental and numerical studies on indentation and perforation characteristics of honeycomb sandwich panels. Compos Struct 184:110–124. https://doi.org/10.1016/j.compstruct.2017.09.025

54. Yi-Ming J et al (2017) Two-stage cumulative bending fatigue behavior for the adhesively bonded aluminum honeycomb sandwich panels. Mater Desig 54:805–813. https://doi.org/10.1016/j.matdes.2013.09.010

55. Abbadi A et al (2015) Experimental study on the fatigue behaviour of honeycomb sandwich panels with artificial defects. Compos Struct 120:397–405. https://doi.org/10.1016/j.compstruct.2014.10.020

56. Arbaoui J, Schmitt Y, Pierrot JL, Royer FX (2014) Effect of core thickness and intermediate layers on mechanical properties of polypropylene honeycomb multi-layer sandwich structures. Arch Metal Mater 59:11–16. https://doi.org/10.2478/amm-2014-0002

57. Arbaoui J, Moustabchir H, Pruncu CI, Schmitt Y (2016) Modeling and experimental analysis of polypropylene honeycomb multi-layer sandwich composites under four-point bending. J Sand Struct Mater 00:1–19. https://doi.org/10.1177/1099636216659779

58. Li D, Zhao C, Jiang L, Jiang N (2014) Experimental study on the bending properties and failure mechanism of 3D integrated woven spacer composites at room and cryogenic temperature. Compos Struct 111:56–65. https://doi.org/10.1016/j.compstruct.2013.12.026

59. Nirupama G, Reddy VD, Krishnaiah G (2014) Design and fabrication of spot welded corrugated panel under three point bending by FEM. Proc Eng 97:1282–1292. https://doi.org/10.1016/j.proeng.2014.12.408

60. Crupi V, Epasto G, Guglielmino E (2012) Collapse modes in aluminium honeycomb sandwich panels under bending and impact loading. Int J Imp Eng 43:6–15. https://doi.org/10.1016/j.ijimpeng.2011.12.002

61. Murthy O, Munirudrappa N, Srikanth L, Rao RMVGK (2006) Strength and Stiffness Optimization Studies on Honeycomb Core Sandwich Panels. J Reinf Plast Comp 25(6):663. https://doi.org/10.1177/0731684406058288

62. Daniel IM, Gdoutos EE, Rajapakse YDS (2009) Major accomplishments in composite materials and sandwich structures. Springer, Netherlands, p 818

63. Jeyakrishnan PR, Chockalingam KKSK, Narayanasamy R (2013) Studies on buckling behavior of honeycomb sandwich panel. Int J Adv Manuf Technol 65:803–815. https://doi.org/10.1007/s00170-012-4218-9

64. Shahverdi H, Barati MR, Hakimelahi B (2019) Post-buckling analysis of honeycomb core sandwich panels with geometrical imperfection and graphene reinforced nano-composite face sheets. Mater Res Express 6(9):095017

65. Gutierrez AJ, Webber JPH (1980) Flexural wrinkling of honeycomb sandwich beams with laminated faces. Int J Solids Struct 16(7):645–665. https://doi.org/10.1016/0020-7683(80)90023-2

66. Amran YHM, Rashid RSM, Hejazi F, Safiee NA, Ali AAA (2016) Response of precast foamed concrete sandwich panels to flexural loading. J Build Eng 7:143–158. https://doi.org/10.1016/j.jobe.2016.06.006

67. Farkas J, Jármai K (1982) Structural synthesis of sandwich beams with outer layers of box-section. J Sound Vib 84(1):47–56. https://doi.org/10.1016/0022-460X(82)90431-X

68. Potzta G, Kollár LP (2003) Analysis of building structures by replacement sandwich beams. Int J Solids Struct 40(3):535–553. https://doi.org/10.1016/S0020-7683(02)00622-4

69. Sayyad AS, Ghugal YM (2017) Bending, buckling and free vibration of laminated composite and sandwich beams: a critical review of literature. Compos Struc 171:486–504. https://doi.org/10.1016/j.compstruct.2017.03.053

70. Mullen SJ (1986) I-Beam Honeycomb Material, U.S. Patent No. 4,632,862

71. Imbalzano G, Linforth S, Ngo TD, Lee PVS, Tran P (2018) Blast resistance of auxetic and honeycomb sandwich panels: Comparisons and parametric designs. Compos Struct 183:242–261. https://doi.org/10.1016/j.compstruct.2017.03.018

72. Mousanezhad D, Ghosh R, Ajdari A, Hamouda A, Nayeb-Hashemi H, Vaziri A (2014) Impact resistance and energy absorption of regular and functionally graded hexagonal honeycombs with cell wall material strain hardening. Int J Mech Sci 89:413–422. https://doi.org/10.1016/j.ijmecsci.2014.10.012

73. Silva MJ, Gibson LJ (1997) The effects of non-periodic microstructure and defects on the compressive strength of two-dimensional cellular solids. Int J Mech Sci 39:549–563. https://doi.org/10.1016/S0020-7403(96)00065-3

74. Li JR, Cheng HF, Yu JL, Han FS (2003) Effect of dual-size cell mix on the stiffness and strength of open-cell aluminum foams. Mater Sci Eng A 362:240–248. https://doi.org/10.1016/S0921-5093(03)00570-7

75. Spadoni A, Ruzzene M, Scarpa F (2005) Global and local linear buckling behaviour of chiral cellular structure. Phys Status Solid B 242(3):695–709. https://doi.org/10.1002/pssb.200460387

76. Scarpa F, Burriesci G, Smith FC, Chambers B (2003) Mechanical and electromagnetic behaviour of auxetic honeycomb structures. Aeronaut J 2774:175–183. https://doi.org/10.1017/S00019240000013269

77. . Carruthers J, Kettle A, Robinson A (1998) Energy absorption capability and crash worthiness of composite material structures: a review. Appl Mech Rev 51635-51649.https://doi.org/10.1115/1.3100758

78. Bates SRG, Farrow IR, Trask RS (2016) 3D printed polyurethane honeycombs for repeated tailored energy absorption. Mater Des 112:172–183. https://doi.org/10.1016/j.matdes.2016.08.062

79. Al Antali A, Umer R, Zhou J, Cantwell WJ (2017) The energy-absorbing properties of composite tube-reinforced aluminum honeycomb. Compos Struct 176:630–639. https://doi.org/10.1016/j.compstruct.2017.05.063

80. Liu Y, Zhou Q, Wei X, Xia Y (2020) Testing and modeling tearing and air effect of aluminum honeycomb under out-of-plane impact loading. Int J Impact Eng 135:103402. https://doi.org/10.1016/j.ijimpeng.2019.103402

81. Xie S, Zhou H (2015) Analysis and optimisation of parameters influencing the out-of-plane energy absorption of an aluminium honeycomb. Thin-Walled Struct 89:169–177. https://doi.org/10.1016/j.tws.2014.12.024

82. Gao P, Gu X, Mosallam AS (2016) Flexural behavior of preloaded reinforced concrete beams strengthened by prestressed CFRP laminates. Compos Struct 157:33–50. https://doi.org/10.1016/j.compstruct.2016.08.013

83. Ismail MK, Hassan AAA (2017) Ductility and cracking behavior of reinforced self consolidating rubberized concrete beams. J Mater Civil Eng 29:1. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001699

84. Meng D, Lee CK, Zhang YX (2017) Flexural and shear behaviours of plain and reinforced polyvinyl alcohol-engineered cementitious composite beams. Eng Struct 151:261–272. https://doi.org/10.1016/j.engstruct.2017.08.036

85. Xu S, Hou L, Zhang X (2012) Flexural and shear behaviors of reinforced ultra high toughness cementitious composite beams without web reinforcement under concentrated load. Eng Struct 39:176–186. https://doi.org/10.1016/j.engstruct.2012.01.011

86. Hou L, Xu S, Zhang X et al (2013) Shear behaviors of reinforced ultra high toughness cementitious composite slender beams with stirrups. J Mater Civ Eng 26(3):466–475. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000833

87. Yuan F, Pan J, Wu Y (2014) Numerical study on flexural behaviors of steel reinforced engineered cementitious composite (ECC) and ECC/concrete composite beams. Sci China Technol Sci 57:637–645. https://doi.org/10.1007/s11431-014-5478-4

88. Thomsen H, Spacone E, Limkatanyu S, Camata G (2004) Failure mode analyses of reinforced concrete beams strengthened in flexure with externally bonded fiber-reinforced polymers. J Compos Const 8(2):123–131. https://doi.org/10.1061/(ASCE)1090-0268(2004)8:2(123)

89. Buyle-Bodin F, David E, Ragneau E (2002) Finite element modeling of flexural behaviour of externally bonded CFRP reinforced concrete structures. Eng Struct 24:1423–1429. https://doi.org/10.1016/S0141-0296(02)00085-8

90. Lu C, Zhao M, Jie L, Wang J, Gao Y, Cui X, Chen P (2015) Stress Distribution on Composite Honeycomb Sandwich Structure Suffered from Bending Load. Proce Eng 99:405–412. https://doi.org/10.1016/j.proeng.2014.12.554

91. Othman A, Barton D (2008) Failure initiation and propagation characteristics of honeycomb sandwich composites. Compos Struct 85(2):126–138. https://doi.org/10.1016/j.compstruct.2007.10.034