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FLEXURAL BEHAVIOR OF COMPOSITE BEAMS WITH CORRUGATE WEB

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ABSTRACT

The experimental programs involve testing of five beams with the same length and shear connectors subjected to two concentrated loads. The main objective of this study to investigate the effect of using different types of materials (carbon and galvanized steel) for flat and corrugate web. The corrugate beams have varied the sub-panel fold of a single wave (100-150) mm. Practical results show that the galvanized steel webs have an ultimate flexural capacity lower than that for carbon steel by about (53% and 50%) respectively for flat and corrugate web. The increasing of the wave of sub-panel fold causes significant decreases in flexural capacity by about (5%). Practical results show also that the corrugate web with carbon or galvanized steel exhibited better results as compared with flat web beams in stuffiness ductility and energy absorption.

KEYWORDS

Composite Beam, Corrugated web, Flat web, Flexural Beams, Hybrid steel.

1. INTRODUCTION

Steel structures are becoming used in construction due to their ease of assembly and speed, as well as other benefits including durability and strength to weight ratio. On the other hand, compared to reduced loading, this kind of architecture has very large spans. There are instances where the typical steel section meets the strength requirement but falls short of the deflection condition for serviceability (Al-Thabhawee, H.W., 2017). For building reasons, rolled steel beams come in several of types. The web within these beams must be of minimum thickness in order to fully utilize the material's optimum strength. However, the procedure of decreasing thickness is not a simple task. To resolve this problem, corrugated web beams are manufactured (Manoj Kumar et al., 2018).Steel beams with trapezoidal web have gained significant popularity in recent years. Steel-concrete composite beams are widely utilized in structural engineering due to their ability to significantly enhance the flexural strength and

stiffness of steel beams. The utilization of trapezoid web has additionally been discovered to reduce the concentration of stress at the connection where the web and flange are welded together (Troge, Pethrick and Hayward, 2005). (Saleh, S.M. and AlMosawi,2018) Indicated the importance of shear connectors in achieving composite action and improved beam performance. (Kim et al., 2011) Prestressed composite beams with corrugated webs were tested for bending. The experiments used three full-scale composite beams with corrugated webs, both prestressed and non-prestressed. The authors compared beam flexural behavior before and after concrete composite. Also evaluated Composite member horizontal shear strengths. They discussed how the corrugated web composite beam improves prestressing efficiency and flexural rigidity. (Abdel Hafez et al., 2012) Investigated the performance of concrete-steel beams with corrugated webs that are supported at both ends when subjected to vertical loads. The study modeled composite beam bending and shear properties using ANSYS. Comparing the model's results to the authors' and other researchers' experiments proved its validity. Corrugation in the composite beam web increases stiffness and ductility, according to the study. The purpose is also to evaluate concrete slab and composite action on composite beam moment and shear. The beam's resistance to high loads and shear increases with corrugated web thickness. (Zhou et al., 2016) Investigated the assessment of bending in a non-prismatic beam with corrugated steel webs, specifically evaluating the bending and shear deformation in these beams. The study emphasised the need of considering shear deformation in the design of non-prismatic beams with corrugated steel webs. This is because these structures have thin-walled sections with low shear stiffness. (Wang et al., 2019) Studied an empirical investigation on the cyclic properties of Corrugated steel web composite beam. The study investigated the seismic performance of suspension bridge tower cross beams utilizing corrugated steel plates as web elements. Three scaled composite beam models with different shear-span ratios were quasi-statically tested. Test results showed that the high shear-span specimen had flexible bending failure and efficient energy dissipation. Also offered simplified equations for measuring composite beams' bending capacity and shear buckling resistance with corrugated steel webs. These equations produce results that match experimental results. (Nawar et al., 2023) Investigated in the flexural properties of exterior prestressed composite steel-concrete I-beams with single and double corrugated webs. Three prestressed beams with single and double corrugated webs (SCW and DCW) underwent testing using four-point loads. Externally prestressed beams employ linear tendons running parallel to their length. During the tests, it was observed that SCW beams demonstrated a higher shear buckling strength when compared to DCW beams with the same web thickness. The nonlinear behavior of the tested beams was simulated using ABAQUS and validated with experimental results. (Elamary et al., 2017) Examined the behavior of composite beams including corrugated webs when subjected to flexural loads. The study examined the impact of steel flange on the process of failure of a composite beam. Four complete composite beams were manufactured and subjected to testing. Two beams come with shear connectors, which are made out of concrete and steel flanges. The remaining beams possess flanges made mainly of concrete, which are provided with shear connectors and an additional layer of steel mesh. The top steel flange provides the main horizontal restriction for the web panel, effectively preventing local buckling in the corrugated web. The composite concrete-steel section with a top steel flange exhibits a 30% greater stiffness and a 12% higher ultimate load compared to the section without the top steel flange. (Kadhim and Ammash, 2021) Conducted a study of the concrete-filled corrugation to evaluate the shear strength of the steel I-girder. This study used triangular, trapezoidal, and rectangular corrugations. The wall corrugation shapes have a depth of 60mm. Two groups were subjected to testing: one group without concrete encasement and the other group with concrete encasing the steel web on both faces of the I-girder. The shear strength of the concrete-filled corrugated web girders was greater than that of the unfilled ones. The study additionally showed that the placement of corrugations has an impact on the shear resistance of concrete-encased steel girders. (Dhafer et al., 2021) Examined the strength and stability of thin webs in steel and composite girders. The researchers conducted experiments on steel plate beams and composite beams using a new corrugated weave pattern. Corrugated web girders demonstrated different characteristics and greater shear strength compared to flat web girders. The study highlighted the significance of the deck slab in enhancing the shear resistance of ultra-high-performance concrete composite girders. The authors' conclusion states that corrugated web reinforcement has the ability to substitute web reinforcement in composite girders. This approach enhances shear strength by 44% compared to flat web composite girders. The finite element analysis conducted using ABAQUS software produced results that were consistent with the experimental findings. (Górecki and Śledziewski, 2020) Discussed experimental evaluation how a concrete slab affects composite bridge girders with sinusoidal steel web. Bending behavior was evaluated on three near-real scale beams. The study indicated that composite and non-composite corrugated-web steel beams failed similarly. It has been shown that composite beams, which include corrugated webs, exhibit higher levels of sectional stiffness and strength when compared to non-composite beams containing corrugated webs. Also. The concrete slab enhances the shear strength capacity of the composite beams, as demonstrated in the study by (Vasdravellis, G. and Uy, B., 2014). Also, the shear strength of the composite beam is determined by the shear strength of both the concrete and the steel beam as noted listed below:

$$V_t = V_s + V_c$$

V_t= total shear. V_s= steel shear. V_c= concrete shear.

This study investigates the mechanical properties and performance of composite beams with a corrugated web under flexural loads, using different materials in web such as (carbon and galvanized steel). Many aspects are examined, including toughness, ductility, stiffness and ultimate strength.

2. EXPERMENTAL WORK

2.1. Specimens Design and Details

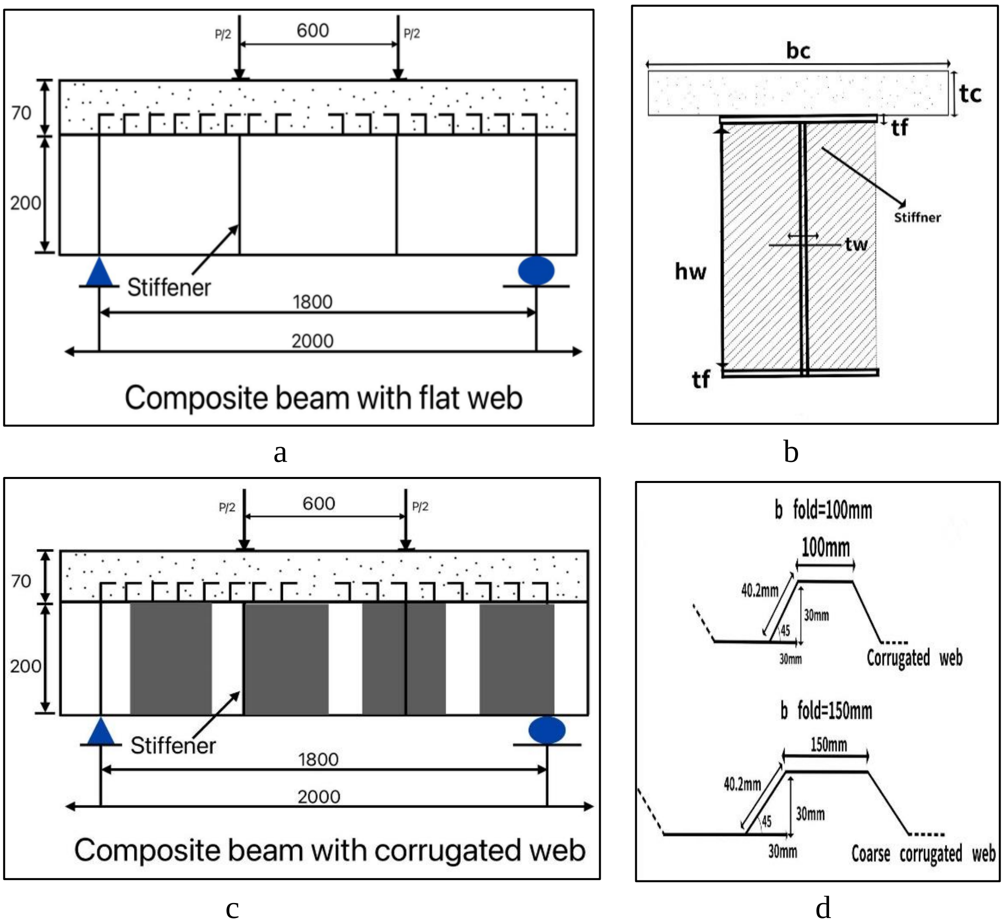
This study experimentally investigates the flexural strength of hybrid steel-concrete composite beams. Five composite concrete I-beams with steel webs (flat and corrugated) were constructed. The overall length of each one was 2000 mm, and they were supported on a length of 1800 mm. The composite beam with a corrugated web exhibits a trapezoidal shape in its corrugation. Two waves were chosen in the form of a trapezoid. Both waves were similar in corrugation formation and geometric notation, differing only in the length of the sub-panel fold either 100mm or 150mm for one wave in Table 1 more detail the five composite beams tested in the research.

Fig.1 explain the detail of composite beams with flat and corrugated web and the shape of corrugation. All the beams were made of a hybrid section of steel; they have the same flange with a thickness of 4 mm and are made of high-resistance steel. The web has a thickness of 2 mm and can be either flat or corrugated. It is made of either carbon steel (symbolized by A) or galvanized steel (symbolized by B). In order to construct a composite section, the upper flange of the steel section was joined to the concrete slab (70*350 mm) by means of shear connections. A steel bar with a specific diameter of 10 mm was used. In the form of an angle with dimension of (45*35) mm as a shear connector, which can be expressed as (10 mm–L45mm–H35mm) as shown in Fig. 2.

Table 1. The Dimensions of Specimens.

Groups	Symbol	Slab Thickness (mm)	Dimension of steel section (mm)				
			tf	bf	hw	tw	b* fold
Group A4*	A4FW	70	4	120	200	2	-----
	A4CW	70	4	120	200	2	100
	A4CCW	70	4	120	200	2	150
Group B4*	B4FW	70	4	120	200	2	-----
	B4CW	70	4	120	200	2	100

4*=flange thickness, b* the length of sub-panel fold for corrugated web



a b c d

Fig. 1. Specimens' details: a-Composite beam with flat web, b- side view of section, c-Composite beam with corrugated web, d-Corrugated shapes

2.2. Manufacturing of Specimens

The steel beams were made with flanges (4*120) mm, and the web of the beam (2* 200) mm. Steel plate Specimens were brought from several sources according to the section of steel to be designed for the test Specimens from steel. Using a steel cutting tool, the steel plates were meticulously cut to the necessary dimensions. The flanges were connected to the web by welding and from two-sided for the section. followed Straight stiffeners (4*200 mm) were placed at the supports and beneath the load points using a welding machine and argon gas. After that, the shear connectors were welded at equidistant points along the center of the upper edge. After that, solid wood molds were made, with dimensions of 2000 x 350 mm and a thickness of 70mm. The molds were reinforced with reinforcement bars, and the molds were also wiped with oil. Next, the steel beams were placed in the middle over the wooden formwork, aligned longitudinally. Subsequently, the molds were cast. The specimens were divided into two groups according to the type of steel making up the web: A for the web made of carbon steel and consists of three composite beams with a web (flat, corrugated, coarse corrugated) and B for the web made of galvanized steel and consists of two composite beams with a web (flat, corrugated). Table 2 provides a detailed description of the specimens.

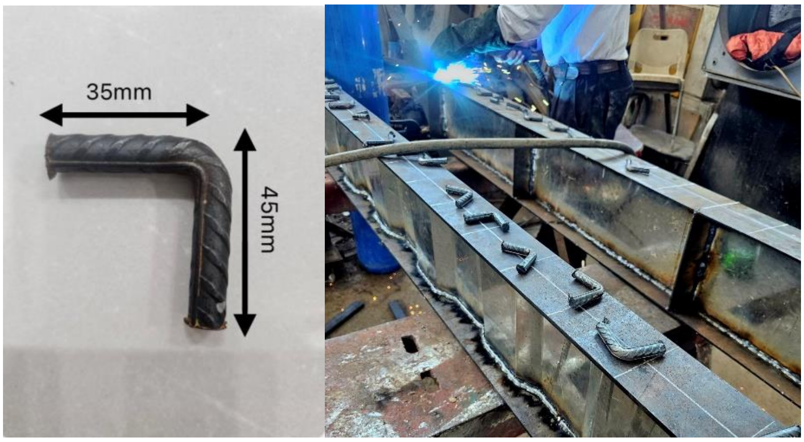


Fig. 2. Connection Design and Process of Welding

Table 2. The description of Specimens.

Symbol	Description
A4*FW	Hybrid steel-concrete composite beam with flat web Web (carbon steel)
A4 CW	Hybrid steel-concrete composite beam with corrugated web Web (carbon steel)
A4 CCW	Hybrid steel-concrete composite beam with coarse corrugated web Web (carbon steel)
B4 FW	Hybrid steel-concrete composite beam with flat web Web (galvanized steel)
B4 CW	Hybrid steel-concrete composite beam with corrugated web Web (galvanized steel)

4*=flange thickness

3. TEST SETUP

3.1. Instrumentation

The work was done in the laboratories of the Babel tower com. for Studies and Scientific research and the instruments utilized comprises an electronic electrical pressure device as shown in Fig. 3 that was fitted with a very precise sensor to monitor vertical displacement throughout the testing procedure. Additionally, the device was outfitted with a hydraulic crane that could exert pressure levels of up to 600 MPa. The control device is linked to a computer and is used to measure load, displacement, and stress values. The output includes data in Excel format as well as graphical representations illustrating the relationship between load, displacement, and time. These graphs include information on the maximum load (measured in MPa), maximum stress (measured in MPa), and deformation (measured in mm).

Fig. 3. Mechanical Testing Machine

3.2. Load Condition

Performed the tests on five specimens. The beams that were utilized were simply supported and had an 1800 mm clear span. the side supports were installed under the beam to maintain the balance of the level during the test. In order to apply a load to the beam, two loads were placed in a symmetrical manner between the supports. The beam's span was marked by four significant spots, namely, two end supports and two loading points. the space between the loads was 600mm.The space between the loads is equal to the space between the load and the support. There is homogeneous bending moment in four-point bending, and shear force between the loading points is zero. As a result, it results in pure bending loading.

3.3. limiting standard

The limiting standard refers to a standardized scale or value that is utilized to compare the outcomes of different sections in order to evaluate their efficiency on a common scale.

Deflection is used as a standardized metric to check the sections of this article's load bearing capacities. In the BS 5950-5:1998 "Code of practice for design of cold formed narrow-gauge sections," the deflection limit is described as the span's ratio /300."

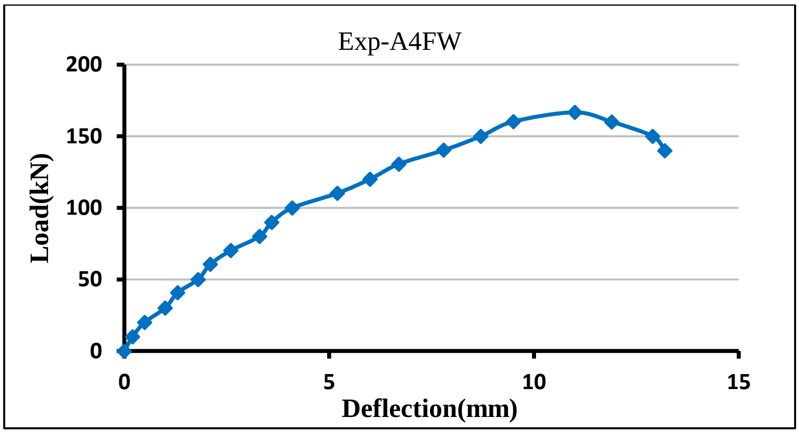
4. RESULTS

Five different types of specimens were used for the testing of flexural beams, and universal testing apparatus with a 600kN capacity and configurable supports suitable for the necessary span was used. The amount of deflection at the middle point of the beam was recorded for each load pulse. The failure load was identified for the test specimens by using the load-vertical and lateral deflection curve.

4.1. A4FW Composite Beam with Flat Web (Group One)

Composite concrete I-beam consists of a hybrid steel section; the flanges are high-resistance steel. And the web was carbon steel with a flat shape, connected to the concrete slab (70*350) mm. The length of the span was 2000 mm. The A4 FW section has a maximum load capacity of 166.7kN., and the beam exhibited a deflection of 11mm at the midpoint of its span.

a



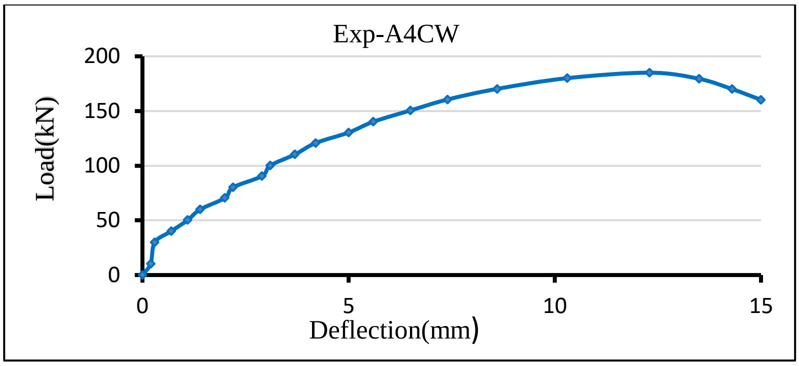
b

Fig. 4. a-Failure Mode A4FW, b-Load-Deflection Curve of A4FW

4.2. A4CW Composite Beam with Corrugated Web (Group One)

Composite concrete I-beam consists of a hybrid steel section; the flanges are high-resistance steel. And the web was carbon steel with Corrugated shape, connected to the concrete slab (70*350) mm. The length of the span was 2000 mm. The A4CW section has a maximum load capacity of 185 kN., and the beam exhibited a deflection of 10.3mm at the midpoint of its span.

a



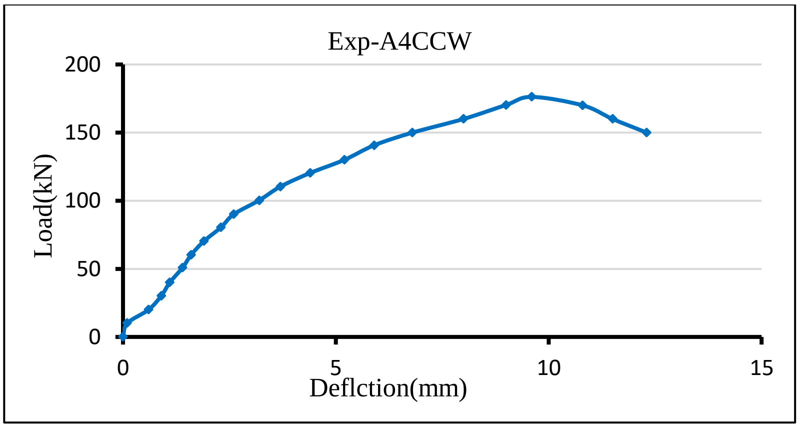
b

Fig. 5. a-Failure Mode A4CW, b-Load-Deflection Curve of A4CW

4.3. A4CCW Composite Beam with Coarse Corrugated Web (Group One)

Composite concrete I-beam consists of a hybrid steel section; the flanges are high-resistance steel. And the web was carbon steel with a Coarse Corrugated shape, connected to the concrete slab (70*350) mm. The length of the span was 2000 mm. The A4CCW section has a maximum load capacity of 176.2 kN., and the beam exhibited a deflection of 11mm at the midpoint of its span.

a



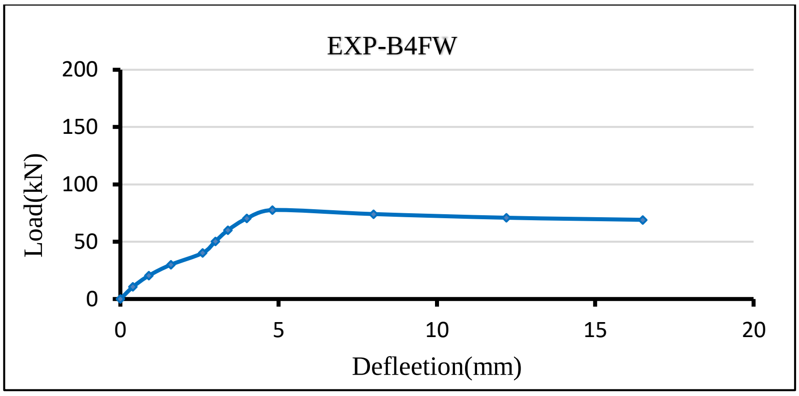
b

Fig. 6. a-Failure Mode A4CCW, b-Load-Deflection Curve of A4CCW

4.4. B4FW Composite Beam with Flat Web (Group Two)

Composite concrete I-beam consists of a hybrid steel section; the flanges are high-resistance steel. And the web was galvanized steel with a flat shape, connected to the concrete slab (70*350) mm. The length of the span was 2000 mm. The B4FW section has a maximum load capacity of 77.76kN., and the beam exhibited a deflection of 6.5mm at the midpoint of its span.

a



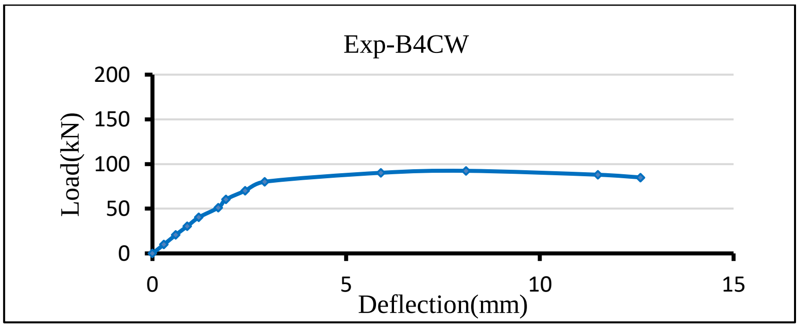
b

Fig. 7. a-Failure Mode B4FW, b-Load-Deflection Curve of B4FW

4.5. B4CW Composite Beam with Corrugated Web (Group Two)

Composite concrete I-beam consists of a hybrid steel section; the flanges are high-resistance steel. And the web was galvanized steel with Corrugated shape, connected to the concrete slab (70*350) mm. The length of the span was 2000 mm. The B4FW section has a maximum load capacity of 92.4kN., and the beam exhibited a deflection of 7.5mm at the midpoint of its span.

a



b

Fig. 8. a-Failure Mode B4CW, b-Load-Deflection Curve of B4CW

5. INTERPRETATION AND DISCUSSION

This section deals with an experimental result of the research and is divided into seven parts as following. The outcomes of the five suggested categories are displayed in Table 3.

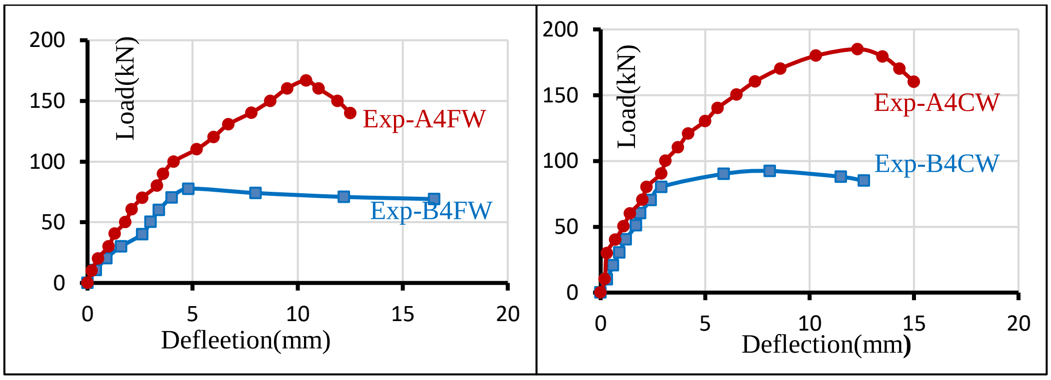
Table 3. The Outcomes of the Specimens

Symbol	Ultimate Load (kN)	Total Weight (kg)	Ultimate Deflection (mm)	Efficiency%	Ductility	Stiffness ratio kN/mm	Modulus of toughness
A4FW	166.7	143.78	11	1.16	3.5	15.12	1953.418
A4CW	185	144.33	10.3	1.3	5.4	17.96	2064.417
A4CCW	176.2	144.13	11	1.22	6.17	16.02	1630.507
B4FW	77.6	143.86	5.5	0.54	1.9	11.94	1198.664
B4CW	92.4	144.45	7.3	0.64	2.2	12.66	984.753

5.1. The impact of web material type

When comparing a composite beam with a carbon steel web to a composite beam with a galvanized steel web, there is a 53% drop in the load bearing capacity of the specimen at the limiting deflection for a flat web (A4FW to B4FW), and a 50% decrease for a corrugated web (A4CW to B4CW). This is because carbon steel and galvanized steel both consist of iron and carbon. However, carbon steel has an alloy concentration of less than 2%, whereas galvanized steel has an alloy content ranging from 10-30%.

As the carbon ratio increases in the alloy, the steel becomes increasingly resistant to bending, whereas a lower carbon ratio makes the steel more pliable and easier to shape. (USI), (MRS Steel)

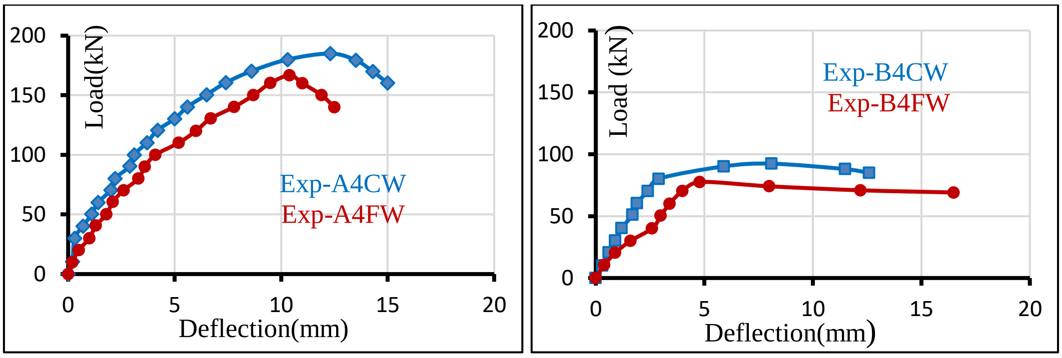


a b

Fig.9. A comparative of the Load-Deflection curve with respect to variations in the web material, a. composite beam with flat web, b. composite beam with corrugated web.

5.2. The impact of the corrugated form of the web

The A4CW composite beam, with a corrugated web, exhibited an 11% higher ultimate load capacity compared to the A4 FW composite beam composed of carbon steel with a flat web. The load capacity of the composite beam with a corrugated web (B4CW), made from galvanized steel, exhibited a 19% increase in comparison to the composite beam with a flat web (B4FW). The corrugated webs enhance the Fy and Fu values of the composite beam compared with flat webs, which led to an increase the area under the curve. Therefore, corrugations improve the stability of the web prior to the beams reaching their maximum load-bearing capability. Integrating corrugated profiles into the webs of a beam results in consistent and evenly spread reinforcement in the perpendicular direction.



a b

Fig.10. A comparative of the Load-Deflection curve with respect to the impact of corrugation on a composite beam, a- group one using carbon steel for the web, b-group two using galvanized steel for the web.

5.3. The impact of increasing the wave's sub-panel length

Increasing the sub-panel of one wave from 100mm to 150mm resulted in a 5% reduction in the ultimate capacity of the composite beam A4CW to A4CCW. Increasing the length of the sub-panel for the wave, without altering the depth and slop angle of the corrugation, leads to a decreased maximum loading capacity and an increased similarity to a flat web.

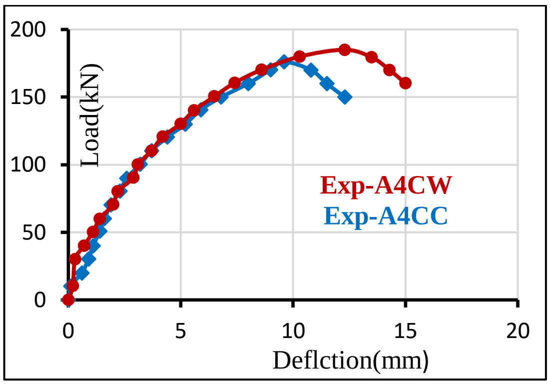


Fig.11. A comparative of the Load-Deflection curve with respect to the impact of increasing the wave's subpanel length

5.4. Efficiency

The efficiency of the section was calculated using the load-to-weight ratio. The ratio denotes the quantity of self-weight necessary for sustained each additional increment in the load-ultimate capacity of the sections. Consequently, a larger ratio indicates superior performance of the elements.

5.5. Ductility

The ductility of the section is the capacity of a material to undergo substantial plastic deformation prior to breaking. Plastic deformation refers to the lasting alteration of a material when subjected to external force, in contrast to elastic deformation, which can be reversed by removing the force. The corrugated beams have higher ductility ratios than the flat beams. The web of corrugated beams made of carbon steel had a ductility percentage of 50%, while that of galvanized steel was 16%. Carbon steel beams were 46% and 59% more ductile than galvanized steel beams for the flat web and corrugated web, respectively. Corrugated and carbon steel webs have a higher ratio of ultimate deformations to yield deformation. As a result of the characteristics of the corrugated shape and the properties of the web steel -forming material.

5.6. Stiffness

The stiffness of a beam defines its ability to withstand flexural deformation, with higher values indicating higher rigidity and less bending under a flexural load. Figure 9 displays the stiffness values for all the examined beam specimens.

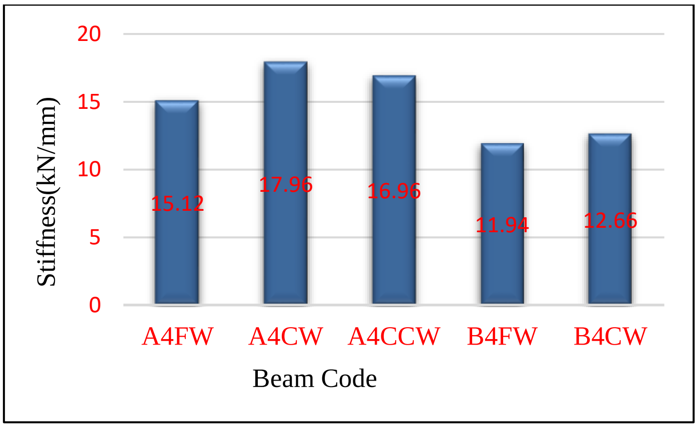


Fig. 12. Stiffness Values for Tested Beams

5.7. Toughness

Toughness is an important mechanical property that indicates the specimen’s capacity to withstand rupture. The energy absorbed by the beams depicted in Fig.10 provides an explanation of the material's flexural toughness. By partitioning it into three discrete regions, specifically Area I, Area II, and Area III, we may gain a more comprehensive comprehension of the material's behavior throughout various loading phases. These areas correspond to the flexural toughness of a material at different stages: the elastic stage (Area I), the elastic-plastic stage reaching ultimate flexural strength (Area II), and the post-plastic stage (Area III). Area I. The first group observed a 25% rise when moving from a flat web to a corrugated web, whereas the second group recorded a 10% increase. The reason for this is that the corrugated webs enhance the Fy and Fu values of the composite beam comparing with flat webs. Therefore, corrugations improve the stability of the web prior to the beams reaching their maximum load-bearing capability. The addition of corrugated profiles in the webs of a beam leads to a uniform and equally distributed reinforcement in the perpendicular direction. Regarding the replacement of carbon with galvanized material in the online content. The reduction in (Area I) is 17% for flat web and 26% for corrugated web. Area II, which relates to the highest bending strength, The substitution of carbon with galvanized web between the first and second groups resulted in a reduction of 73% for the flat web and 67% for the corrugated web. The galvanized steel and carbon steel have different compositions, which may explain why the galvanized steel fails more quickly. This is because the characteristics of the material that makes up the beam cause buckling to occur within its web in the shear zone, which in turn causes cracks to appear in the concrete slab under concentrated loads. As a result, the beam eventually reaches the ultimate load and enters the yielding stage. After achieving its maximum flexural strength, Area III showed similarities in both Group 1 and Group 2 when the web material was switched from carbon steel to galvanized steel. When corrugated web was used in place of flat web in the first and second groups, the reduction was 52% for the second group using galvanized web and 48% for the first group using carbon steel web.

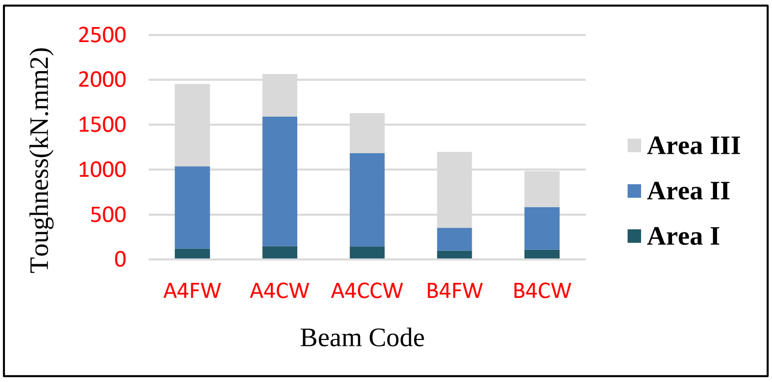


Fig. 13. Toughness Values for Tested Beams

6. CONCLUSION

A study was done on the flexural behavior of composite beams in this paper. Specifically, the study will focus on hybrid steel I-sections with a corrugated web and different combinations of materials. The aim to explain the effects of lengthening the single wave's sub-panel on the composite beam, as well as the influence of using galvanized steel in the web instead of carbon steel on the composite beam's ultimate capacity. The experiment involved building beams and testing five specimens. The following conclusions were reached:

1. When constructing composite beams using steel I-sections, it is essential to take into account web buckling in addition to factors such as thickness, depth, and web aspect ratio.
2. It was found that when galvanized steel was used instead of carbon steel as the web material for composite beams, the specimen's load-bearing capacity decreased about (53% and 50%) respectively at the limiting deflection for both flat and corrugated webs (A4FW to B4FW and A4CW to B4CW).
3. The A4CW composite beam constructed from carbon steel, which has a corrugated web, exhibited higher ultimate load capacity about (11%) than the A4 FW composite beam, which has a flat web. Also, the load-carrying capacity of the composite beam constructed from galvanized steel with a corrugated web (B4CW) exhibited a higher value about (19%) in comparison to the composite beam with a flat web (B4FW). This suggests that the corrugated fabric has improved its capacity to withstand greater loads.
4. Increasing the width of a single wave in the sub-panel from 100mm to 150mm resulted in a 5% reduction in the maximum load-bearing capacity of the composite beam A4CW to A4CCW.
5. The research found composite beams featuring a carbon steel web exhibited higher efficiency and more stiffness in comparison to those incorporating a galvanized steel web.
6. After assessing the toughness index of the composite beams, it was concluded that the composite beams with a carbon steel web beat those with a galvanized steel web, exhibiting greater elastic-plastic capabilities. Furthermore, the corrugated web of the beams demonstrated superior durability in comparison to their flat web**.**

7- Based on the ductility values, it was determined that beams with a web made of carbon steel exhibit greater structural flexibility compared to beams with a web made of galvanized steel (46% and 59%) respectively for flat and corrugated web. This difference can be attributed to the inherent properties of the respective materials.

8- To designing more efficient composite beams based on material characteristics, it is necessary to increase the thickness of the weakened material (galvanized). When it comes to web geometry, it is suggested to decrease the area of the wave, specifically the width of the sub-panel.

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