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Experimental and Analytical Study of the Behavior of Corrugated Sandwich Steel Beams with Different Corrugation Shapes

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ABSTRACT

High-performance steels are ideal for highway bridge due to their strength, corrosion resistance, toughness, and weld-ability. Innovative designs have been used, such as using corrugated webs to provide improved shear stability without needing transverse stiffeners. Experimental work identified triangle corrugated plates with three samples and compared with two corrugation shapes from previous studies. The study conducted FEA to analyze the effect of corrugation type and depth on sandwich corrugated beam behavior using four types (trapezoidal, rectangular, triangle, and octagonal) and three depths (20-30-40 mm). The tested beams showed optimal results when the plate's penal length equaled its height. The corrugation shape affects the beam shear strength, and the best type was the rectangular corrugation. A good agreement is found when comparing the FE results to the experimental findings. The best type, according to the FE results, was rectangular with a 20 mm depth. This study shows that corrugated beams can withstand higher ultimate loads than traditional steel girders due to improved web stability, demonstrating their superior strength against applied loads.

1. INTRODUCTION

Recently, corrugated steel webs were created to use thin plates without transverse stiffeners in structures like bridges. The corrugated beams combine flat steel plates as flanges and corrugated steel plates as webs. The flanges are considered to serve as the girder's flexural strength, and the corrugated web is supposed to give the girder its complete shear capacity. Thus, the corrugated web is in a pure shear stress state. Failure of a corrugated plate could result from the steel yielding of webs applied to pure shear stress. It may also happen as a result of web buckling caused by either local panel instability between two folds or general web instability spanning two or more panels. Another possibility of failure is an interactive failure mode between these several failure criteria. As a result, it is vital to investigate the shear behavior of corrugated webs, concentrating on the many failure modes that influence the web design. The corrugated webs used to make plate girders are frequently trapezoidal or other forms (see Figure 1). A kind of evenly distributed stiffening in the transverse direction of a girder is provided by the corrugated profile in webs. A girder with corrugated webs may employ thinner webs than a plate girder with stiffened flat webs, resulting in a higher load-carrying capacity for less money.

Oh et al. [1] developed composite members to enhance the serviceability and ductility of steel and reinforced concrete structures. They experimented with steel beams with typical wide web and corrugated webs, finding that corrugated web steel beams showed significantly higher efficiency in pre-stressing than typical web steel beams. Hajsadeghi et al. [2] conducted a study on beams with corrugated webs using nonlinear pushover and cyclic analyses, revealing that using corrugated webs offers a larger rotation capacity than conventional steel coupling beams. Cao et al. [3] conducted an experiment study combined with FEA to examine the stability of corrugated beams with an H-shape. Results indicated that the web shear capacity increases with corrugation arrangement, increasing the corrugated web thickness, and using full stiffeners; they also showed a good agreement between the results of the experimental and the FE for load-deflection behavior.

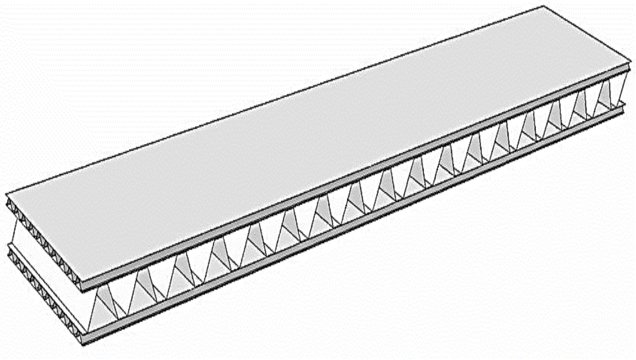


Figure 1. Sandwich corrugated section

Kotb's study on the shear strength of corrugated plate girders found that the interactive buckling mode is the controlling mode for moderate sub-panel widths. The experimental findings were compared to an interaction equation proposed by another researcher and with the FEA results, indicating that the experimental results align with the proposed interaction equation and with the FEA results [4]. Cammarata et al. studied road bridge design using welded sinusoidal corrugated steel web beams. They analyzed steel girders with plain, stiffened, and corrugated webs by using SAP 2000 and found a transversal stress distribution due to the shape of web corrugation. The results were validated by the Italian and European codes [5]. Wang et al. [6] conducted a study on the shear performance of steel I-girders with horizontal or/and vertical corrugation stiffeners. The study found that all beams collapsed due to shear buckling of the corrugated web. Horizontal stiffeners improved the corrugate's axial stiffness and resistance to bending moments, while vertical stiffeners had no impact.

Wang et al. [7] proposed using corrugated steel webs in suspension bridge towers to enhance seismic performance. They studied the structural behaviors of three corrugated steel webs with different shear-span ratios. Results showed that specimens with higher shear-span ratios displayed a hysteretic curve and stable ductile flexural failure, indicating strong energy dissipation. However, specimens with low shear-span ratios failed due to shear buckling, causing deplorable hysteretic behavior and pinching. Lee et al. [8] conducted a nonlinear FEA to determine the impact of corrugation shape and horizontal-tilted panel ratio. They also analyzed previous studies' equations, finding the Euro code equation more conservative than other recommended formulae. Dhakate and Balu conducted a study on the buckling strength of corrugated girders using ANSYS software. Results showed that corrugated web buckling strength is superior to conventional I-girders, and maximum strength is achieved with a 45° angle corrugation plate [9]. Chen et al. [10] conducted a study on the flexural behavior of composite corrugated box girders using experimental, numerical, and analytical methods. They tested two bridge models with hollow steel tubes and concrete-filled steel tubes (see Figure 2). Results showed that both girders had good ductility and failed ductility. The concrete poured into the steel tubes increases the yield load and decreases the deflection.

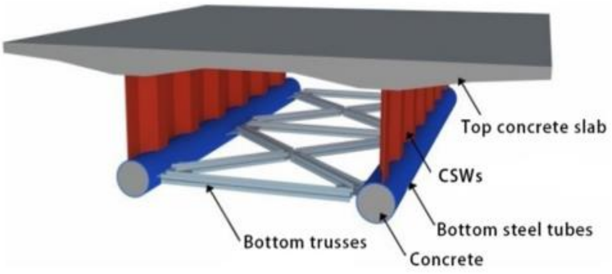


Figure 2. Composite corrugated box girder

Yossef devised a new approach for determining the shear strength of curved corrugated webs that takes global as well as local buckling into account. The formula included elastic and inelastic regions. The finite element model examined the impact of curvature, web thickness, and corrugation angle on I-girder behavior, finding that curvature had minimal effect [11]. Li et al. [12] examined the flexural behavior of corrugated beams under flexural load. They developed and analyzed FE models with various variables, revealing that changes in steel yield strength and span-to-depth ratio significantly affect the maximum load-carrying capacity of beams. The numerical and theoretical results have been shown to be in good agreement [12]. Ammash and Al-Bader's [13] study examined the shear, flexure, and ultimate failure of corrugated steel I-girders under one-point load. They used ten specimens, including a flat web and triangular, rectangular, and trapezoidal corrugation shapes. The results showed different failure modes and a 28% increase in trapezoidal corrugation beam strength [13]. Kadhim and Ammash investigated the shear strength of corrugated steel I-girders filled with concrete, using three shapes. They found that corrugated girders with concrete had greater shear strength than those without concrete encasing. The corrugation shape also impacted the shear strength of concrete-filled steel girder [14].

Many tests on corrugate plates with various corrugation orientations, shapes and stiffeners showed that the studied parameters were affected on the properties of the corrugated plates [15-17] also, Manoj Kumaar et al. [18] utilized ABAQUS software to examine the flexural behavior of beams with flat and corrugated webs. Dang et al. [19] investigated the mechanical properties of multilayered corrugated sandwich panels. They discovered that increasing the number of corrugation layers considerably enhances panel performance.

Albdiry and Ammash [20] attempted to determine the optimal core geometries and placements that could provide a greater stiffness without reducing weight. They found that edgewise triangle corrugated sandwich panels had the maximum flexural strength, whereas edgewise square core sandwich panels had the greatest compression strength.

Without additional transverse or longitudinal stiffeners, the corrugated steel exhibits better stiffness and shear strength when compared to a conventional steel plate, making the corrugated web girder an economical construction system. This research aims to understand the behavior of corrugated steel plates by testing twelve corrugated sandwich beams divided into four groups with various corrugation shapes, each with three samples. Also, a numerical study based on the FEA is performed to investigate the shear capacity of corrugated beams with different shapes and depths of the corrugation.

2. EXPERIMENTAL PROGRAM

2.1 Test specimens

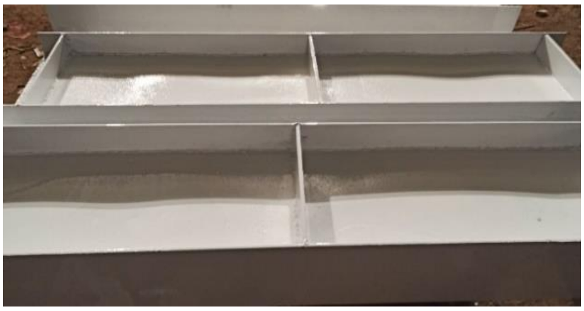
To investigate the behavior of the corrugated steel webs under concentrated load at the beam midspan, three I-girder specimens with triangle shape of corrugations were designed and compared with other type of corrugation that studied previously and then simulated by using ANSYS program. The specimens are categorized into four groups: A, B [21], C [22], and D, each consisting of three samples with flat web, rectangular, trapezoidal and triangle corrugation, respectively. The studied specimens have the same dimensions as previous, height of (300) mm, (6, 200) mm thickness and width (bf) of flange, respectively, thickness of web plates (tw) of 3 mm, and corrugated thickness (Tc) of 1 mm. Total lengths of specimens are 600, 1100, and 1500 mm. So, the specimens' shear to span ratio (a/d) was 1, 1.833, and 2.5 and the effective height of 30 mm. The web was continuously welded to the flange.

Transverse stiffeners were welded at the point of loading and the supports with a thickness (ts) of 1 mm to avoid web local failure resulting from concentrated load. as shown in Figure 3. Table 1 summarizes the dimensions of the tested girders; Figure 4 shows the different types of corrugation.

Table 1. Dimension details of the specimens

No.	Group	dc (mm)	(a/d)	Dimensions (mm) b_f	t_f	h_w	t_w	T_c	T_s	α	Total Span Length
Flat-1	A Flat web		1	200	6	300	3		1.5	----	600
Flat-1.667			1.833	200	6	300	3		1.5	----	1100
Flat-2.5			2.5	200	6	300	3		1.5	----	1500
Rect-1	B Rectangular	30	1	200	6	300	3	1	1.5	90	600
Rect-1.833			1.833	200	6	300	3	1	1.5	90	1100
Rect-2.5			2.5	200	6	300	3	1	1.5	90	1500
Trap-1	C Trapezoidal	30	1	200	6	300	3	1	1.5	45	600
Trap-1.833			1.833	200	6	300	3	1	1.5	45	1100
Trap-2.5			2.5	200	6	300	3	1	1.5	45	1500
Tria-1	D Triangle	30	1	200	6	300	3	1	1.5	45	600
Tria-1.833			1.833	200	6	300	3	1	1.5	45	1100
Tria-2.5			2.5	200	6	300	3	1	1.5	45	1500

Figure 3. Location of transverse stiffeners

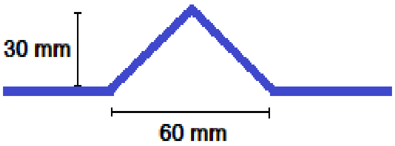


Conventional plate girder

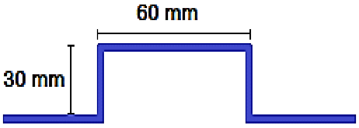
Trapezoidal corrugated beam

Tringle corrugated beam [21]

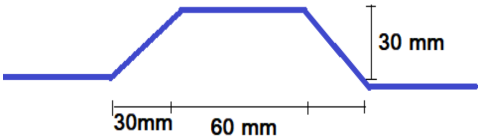
Rectangular corrugated beam [22]



Triangular corrugation



Rectangular corrugation [22]



Trapezoidal corrugation [21]

Figure 4. The shape of the corrugation

Table 2. Material properties of the steel plates

Element	Modulus of Elasticity (GPa)	Ultimate Strength (MPa)	Yield Strength (MPa)
Corrugated Plate/Skin	206	410	305
Flange/Stiffener	205	467	358
Flat web	203	455	402

It was crucial to determine the steel's mechanical properties to analyze the results, so the tensile tests were appropriately implemented. The measured Young's modulus (Es), tensile yielding stress (fy), and ultimate stress (fu) are presented in Table 2.

2.2 Test setup and loading program

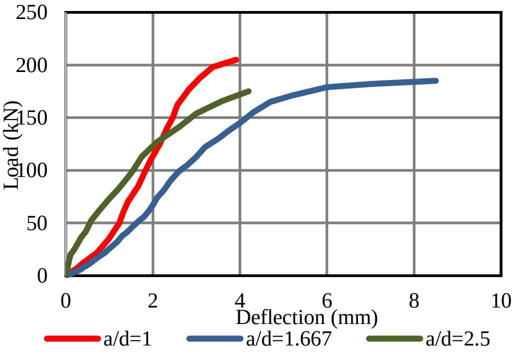
The structure laboratory at the University of Basrah was used to conduct static testing on corrugated steel plates. Figure 5 depicts the hydraulic universal testing equipment with a load capability of 2000 kN. One point load at the mid-span was applied to the simply supported beams so that the web is under constant shear stress. To maintain the applied load's stability and avoid slide and failure in the top flange, a steel plate is inserted between the girder flange and the load cell, while the beam beneath the test specimen is employed to assure the level's stability throughout the testing. The vertical displacements are measured with a dial gauge installed below the mid of the bottom flange. The Lab VIEW program was used to record the load values.

Figure 5. The testing machine

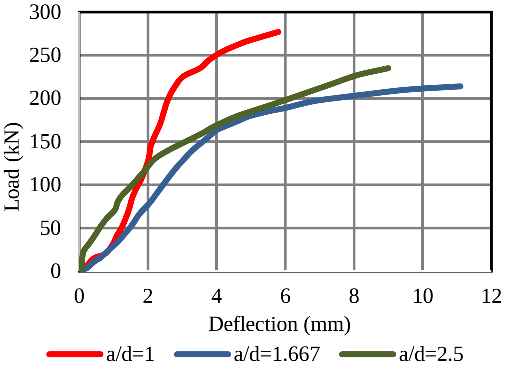
3. RESULTS AND DISCUSSION

The load-deflection relation of test beams is described in Figure 6. The highest load capacity can be obtained when the panel length to depth ratio (a/d) is equal to 1; that is, the panel is a square. It equals 277 kN from the results of previous study, the load carrying capacity was 205, 288 and 296 kN for plate, Trapezoidal and rectangular plates [21, 22]. The best type to use is the corrugated beam with a rectangle section (see Figure 7).

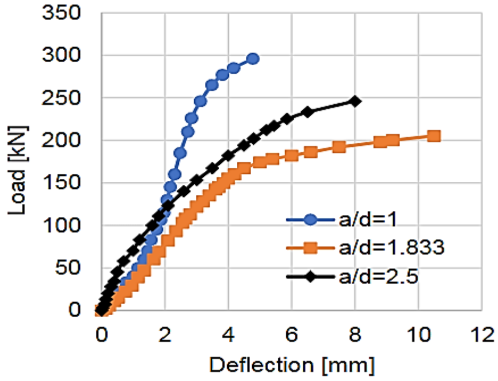
Table 3 shows the amount of increasement in load- carrying capacity and deflection when using a corrugated sandwich beam in comparison with the conventional plate in group A, where the highest growth in load carrying capacity is 35.122% for triangle corrugated steel beam with 1 a/d.



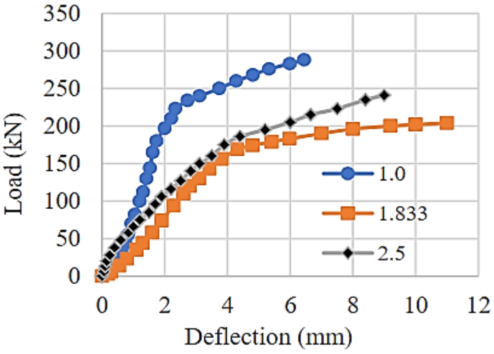
Flat steel web girder



Triangle corrugated beam



Trapizoidall corrugated beam [21]



Rectangular corrugated beam [22]

Figure 6. Load deflection curve at different a/d

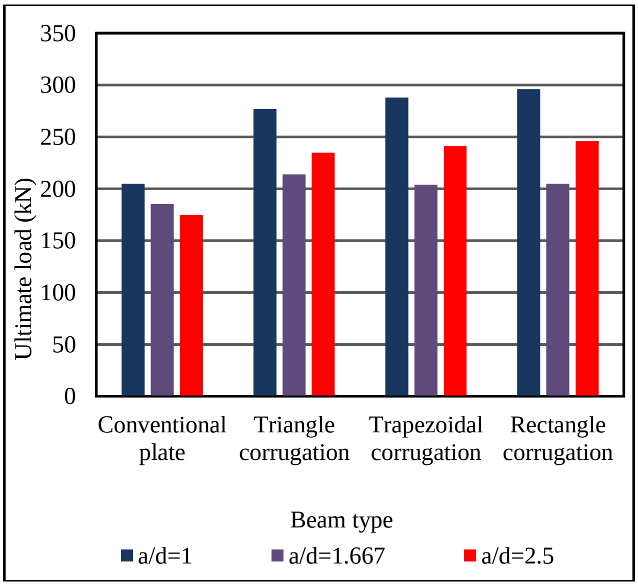


Figure 7. Ultimate load for different types of beams at a/d=1

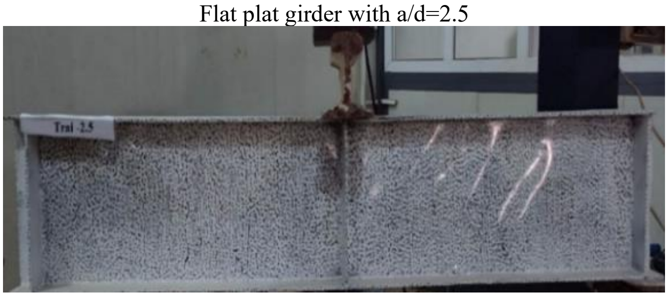
Table 3. Test results for all specimens

No.	(a/d)	Ultimate Load	Increase in Ultimate Load Compared with Plates of Group A	Maximum Deflection	Increase in Maximum Deflection Compared with Plates of Group A
Flat-1	1	205	-	3.915	-
Rect-1	1	296	44.390	4.78	22.095
Tria-1	1	277	35.122	5.8	48.148
Trap-1	1	288	40.488	6.45	64.751
Flat-1.833	1.833	185	-	8.5	-
Rect-1.833	1.833	205	10.811	10.5	23.529
Tria-1.833	1.833	214	15.676	11.1	30.588
Trap-1.833	1.833	204	10.270	11	29.412
Flat-2.5	2.5	175	-	4.2	-
Rect-2.5	2.5	246	40.571	8	90.476
Tria-2.5	2.5	235	34.286	9	114.286
Trap-2.5	2.5	241	37.714	9	114.286

Flat plat girder with a/d=1

Triangle corrugated girder with a/d=1

Flat plat girder with a/d=2.5



Triangle corrugated girder with a/d=2.5

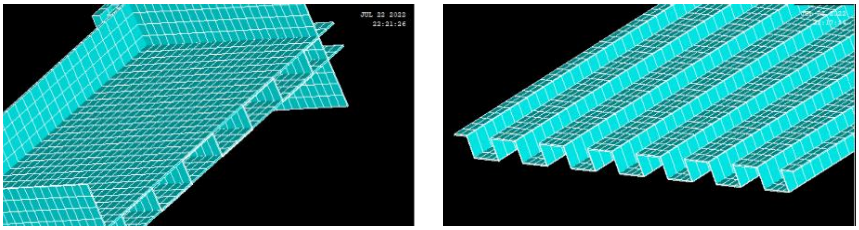
Figure 8. Mode failure of specimens

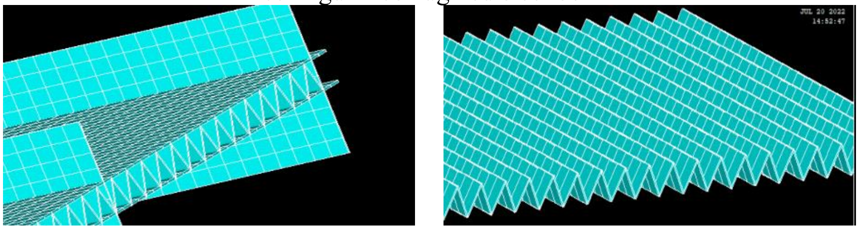
The progression of web buckling was closely noticed till the specimen reached at its maximum load to observe the shear behavior of corrugated webs. Figure 8 displays specimens' failure mode. There was no obvious distortion at the start of the loading stage; nevertheless, as the load was raised, a gradual increase in out-of-plane deformation was seen, resulting in specimen failure. Furthermore, after the maximum load, the girders' loading capacity is rapidly lowered.

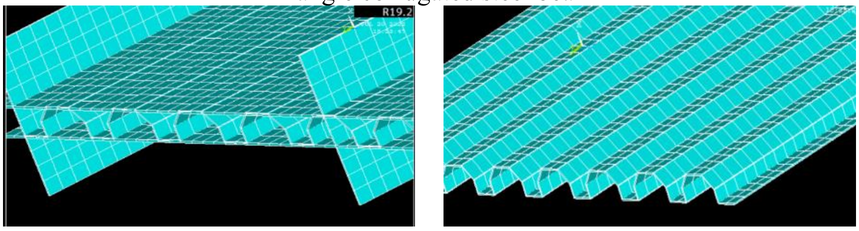
The experimental models conclude that the penal length-to-width ratio and the corrugation shape should be used as criteria for classifying the section's compactness. In comparison to the control beam, corrugated web beams have higher strength while being less expensive.

4. FINITE ELEMENT MODELING

Figure 9 shows four groups of girders with different types of corrugated webs that were modeled to validate the experimental results and study corrugate depth's effect. These girders were modeled using ANSYS software (V-19.2) [23]. The models were created using a two-dimensional ANSYS 4-node shell element with six degrees of freedom, translation, and rotation in the nodes' x, y, and z directions. The modeled beams were simply supported with hinge and roller supports at the ends and applied to a point load at the beam midspan, which is represented as a force distributed over a small area, which is almost identical to the area of the plate that was used to shed the load in the experimented models, as depicted in Figure 10. The flange thickness and width were 100 mm and 10 mm, respectively. The span was taken equal to 600 mm for girders with corrugated webs. The corrugation depth of girders was chosen to be equal to 20, 30, and 40 mm; the dimensions of modeled girders were listed in Table 4.


Rectangular corrugated steel beam


Triangle corrugated steel beam



Octagon corrugated steel beam

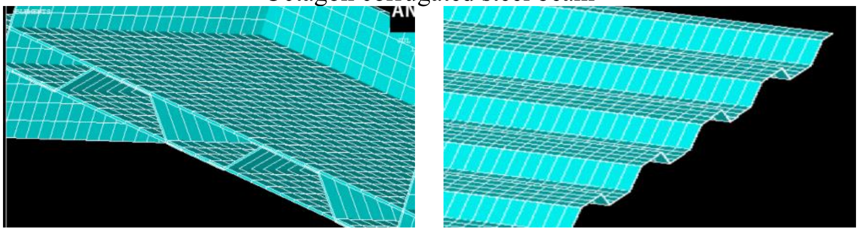

Trapezoidal corrugated steel beam

Figure 9. FE models with different corrugation types

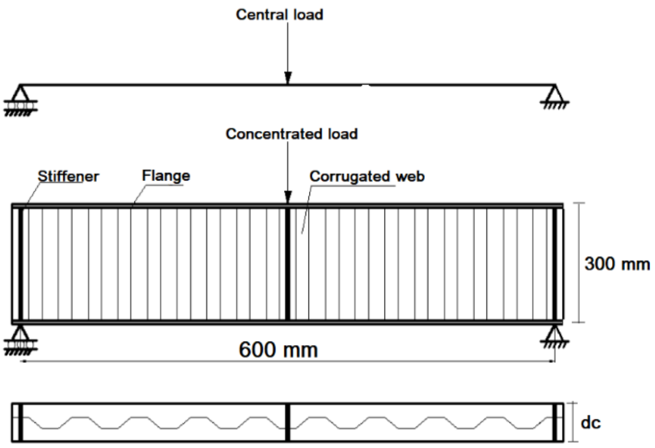


Figure 10. Geometry and load application of the modeled girders

Table 4. Dimensions of the FE models

Name	Group	dc (mm)	(a/d)	Dimensions (mm)						α	Total Span Length
				b_f	t_f	h_w	t_w	T_c	T_s		
Trap-20		20	1	200	6	300	3	1	1.5	45	600
Trap-30	Trapezoidal	30	1	200	6	300	3	1	1.5	45	600
Trap-40		40	1	200	6	300	3	1	1.5	45	600
Rect-20		20	1	200	6	300	3	1	`1.5	90	600
Rect-30	Rectangular	30	1	200	6	300	3	1	1.5	90	600
Rect-40		40	1	200	6	300	3	1	1.5	90	600
Trai-20		20	1	200	6	300	3	1	1.5	45	600
Trai-30	Triangle	30	1	200	6	300	3	1	1.5	45	600
Trai-40		40	1	200	6	300	3	1	1.5	45	600
Octa-20		20	1	200	6	300	3	1	1.5	45	600
Octa-30	Octagon	30	1	200	6	300	3	1	1.5	45	600
Octa-40		40	1	100	10	300	3	1	1.5	45	600

5. FINITE ELEMENT RESULTS

Table 5 contains the results of the modeled specimens produced during the experimental work. Figure 11 depicts a bar chart that compares the outcomes of the experiment and the FEA. The comparison of these two results shows a good agreement. Due to the good connection between the beam sections in the FE models, the estimated deflection from the FEA findings was smaller than that from the experimental work.

In this part, a comparison was made between the different heights of different corrugation types. It was noted in Figure 12 that by decreasing the height (increasing the number of corrugations), the ultimate load of the specimens would increase for beams with all corrugation types.

Also, comparing the four different corrugated types with a fixed height equal to 20 mm showed that the rectangle corrugation could withstand a more significant load than the other types. The beam with triangular corrugation had the less deflection when the same load was applied, as shown in Figure 13.

Table 5. Finite element results

Type	Ultimate Load (kN) (FEM)	Ultimate Load (kN) (EXP.)	Ultimate Def. (mm) (FEM)	Ultimate Def. (mm) (EXP.)	Ultimate Shear Strain
Trap-20	280.5	-	2.285	-	0.00258
Trap-30	265.5	288	2.172	6.45	0.00262
Trap-40	250.0	-	1.442	-	0.00262
Rect-20	313.3	-	2.885	-	0.00259
Rect-30	287.9	296	2.095	4..78	0.00261
Rect-40	270.0	-	1.498	-	0.00261
Trai-20	275.0	-	1.892	-	0.00262
Trai-30	263.2	277	1.373	5.8	0.00259
Trai-40	250.0	-	2.102	-	0.00258
Octa-20	280.5	-	2.184	-	0.00260
Octa-30	269.4	-	1.966	-	0.00261
Octa-40	258.5	-	1.365	-	0.00256

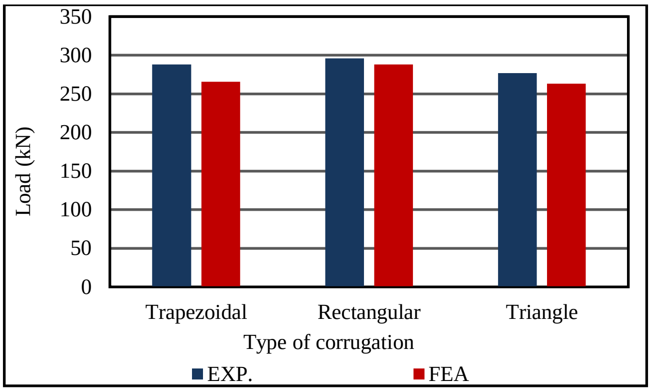
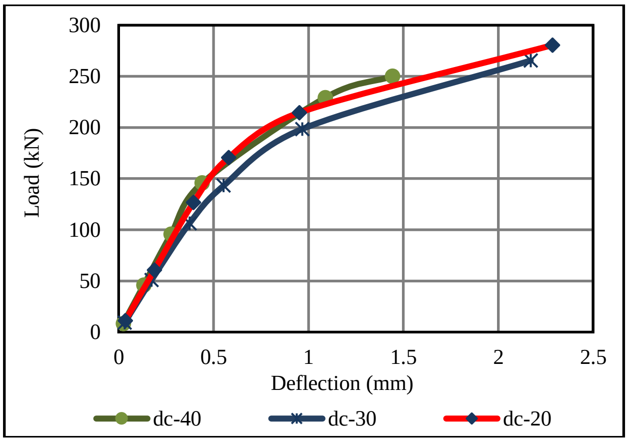
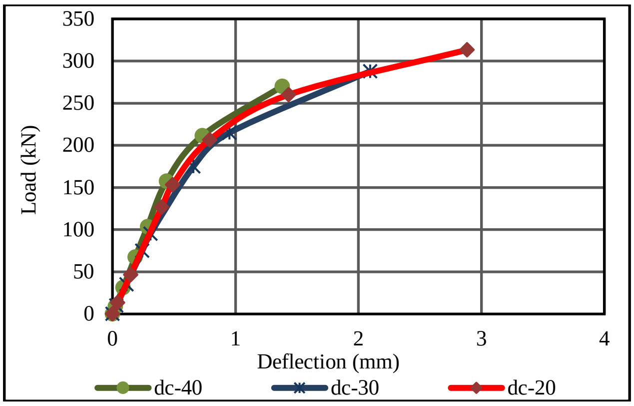


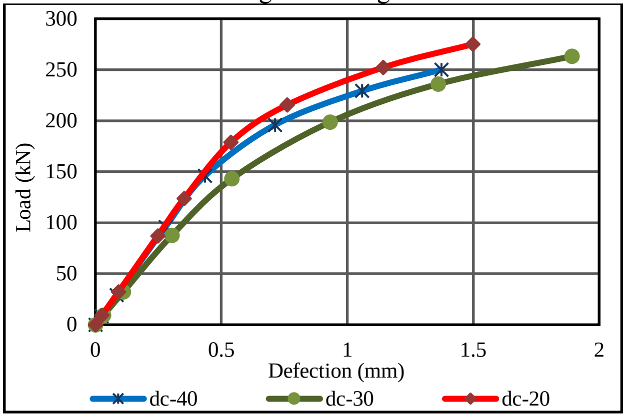
Figure 11. Comparison between experimental and FEA results



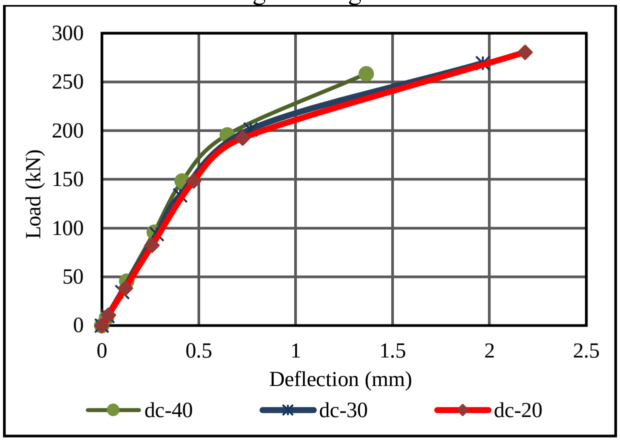
Trapezoidal corrugation



Rectangular corrugation



Tringle corrugation



Octagon corrugation

Figure 12. Load-deflection relationship of different corrugated depths

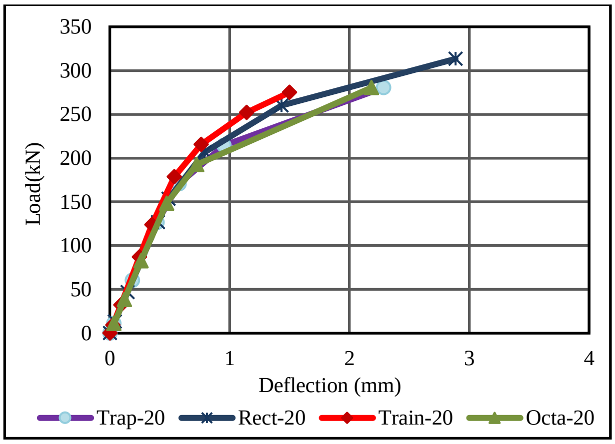
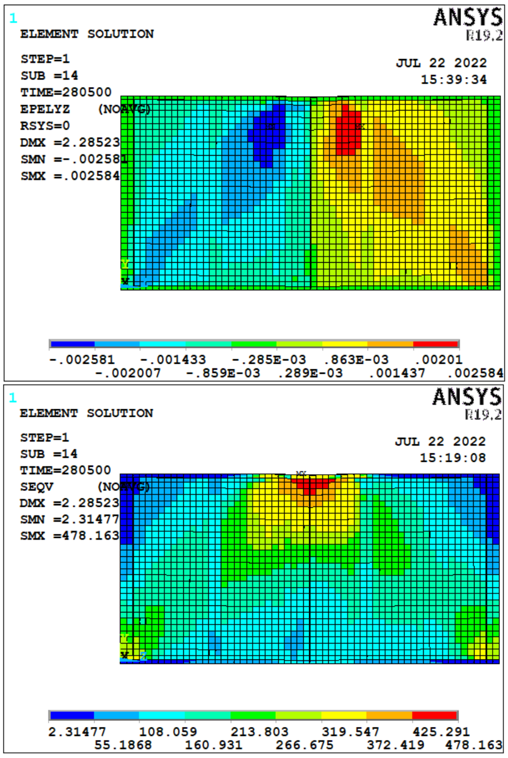


Figure 13. Load-deflection relationship of different corrugated shapes



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RSYS=0
DMX =2.28523
SMN =-.002581
SMX =.002584

JUL 22 2022
15:39:34

-.002581    -.001433    -.285E-03   .863E-03    .00201
     -.002007    -.859E-03   .289E-03    .001437    .002584
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ELEMENT SOLUTION

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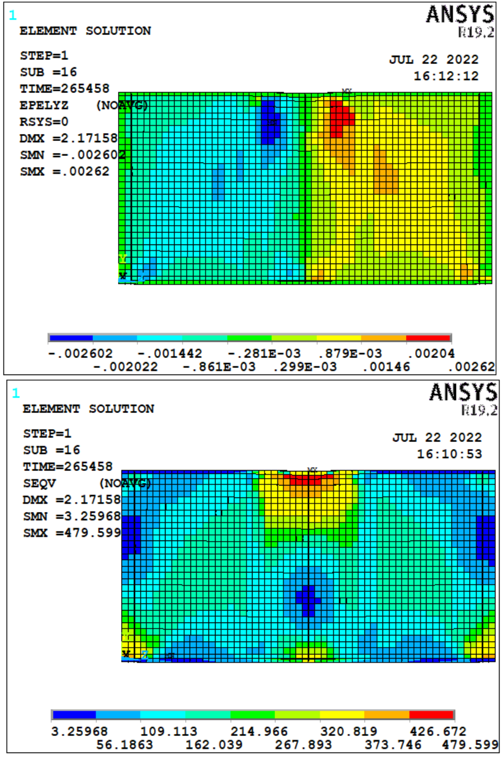
SEQV      (NOAVG)
DMX =2.28523
SMN =2.31477
SMX =478.163

JUL 22 2022
15:19:08

2.31477     108.059     213.803     319.547     425.291
     55.1868     160.931     266.675     372.419    478.163
```

Trapezoidal corrugated steel beam with a/h=1, dc=20



```
ELEMENT SOLUTION

STEP=1
SUB =16
TIME=265458
EPELYZ    (NOAVG)
RSYS=0
DMX =2.17158
SMN =-.002602
SMX =.00262

JUL 22 2022
16:12:12

-.002602    -.001442    -.281E-03   .879E-03    .00204
     -.002022    -.861E-03   .299E-03    .00146     .00262
```

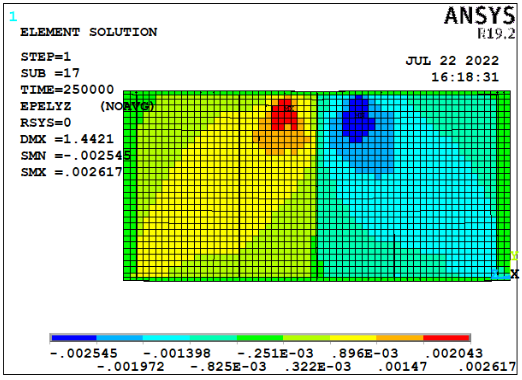
```
ELEMENT SOLUTION

STEP=1
SUB =16
TIME=265458
SEQV      (NOAVG)
DMX =2.17158
SMN =3.25968
SMX =479.599

JUL 22 2022
16:10:53

3.25968     109.113     214.966     320.819     426.672
     56.1863     162.039     267.893     373.746    479.599
```

Trapezoidal corrugated steel beam with a/h=1, dc=30

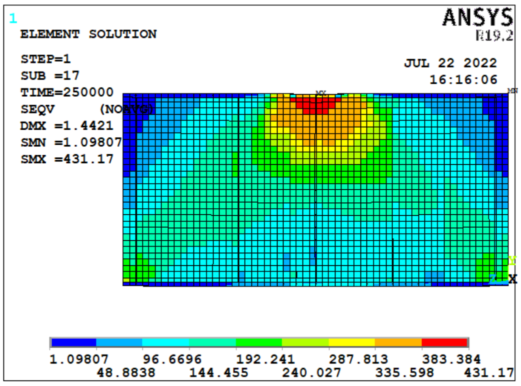


```
ELEMENT SOLUTION

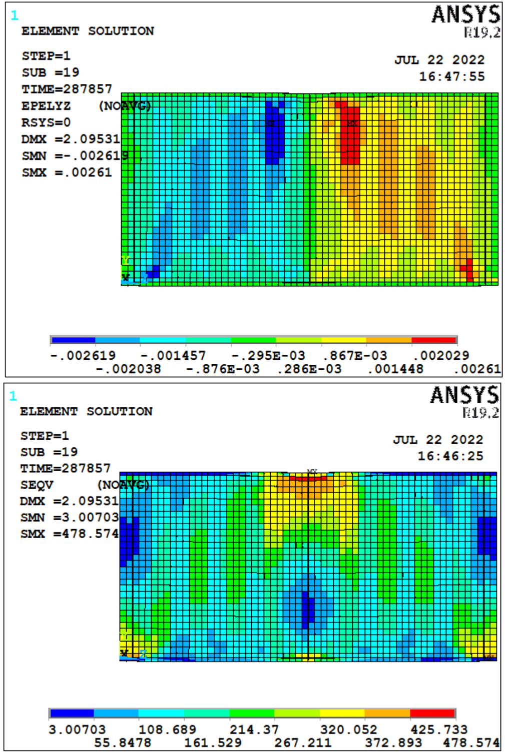
STEP=1
SUB =17
TIME=250000
EPELYZ    (NOAVG)
RSYS=0
DMX =1.4421
SMN =-.002545
SMX =.002617

JUL 22 2022
16:18:31

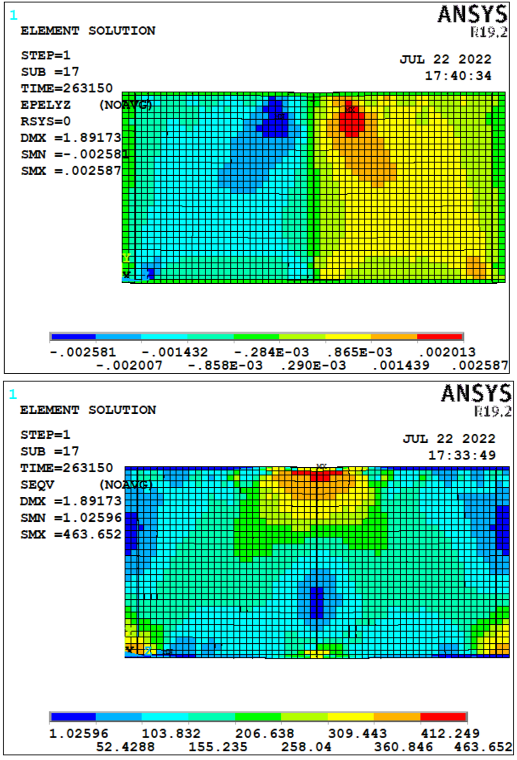
-.002545    -.001398    -.251E-03   .896E-03    .002043
     -.001972    -.825E-03   .322E-03    .00147     .002617
```



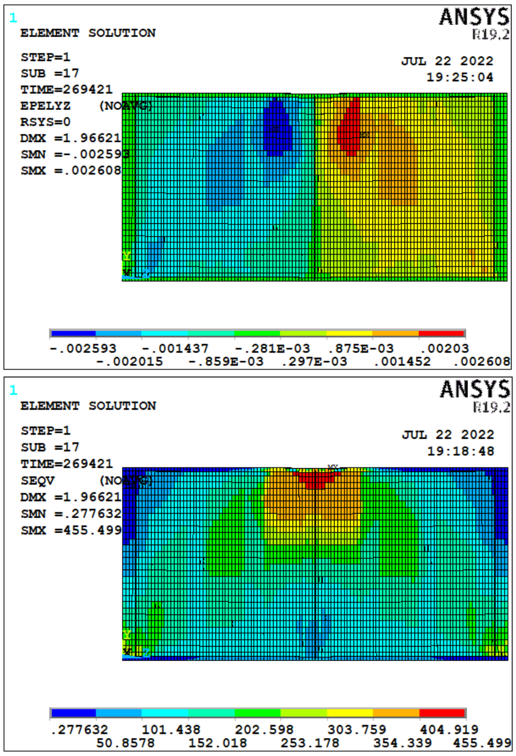
Trapezoidal corrugated steel beam with a/h=1, dc=40



Rectangular corrugated steel beam with a/h=1, dc=30



Triangle corrugated steel beam with a/h=1, dc=30



Octagon corrugated steel beam with a/h=1, dc=30

Figure 14. Strain and Von-Mises stresses for several specimens

Figure 14 displays the Von-Mises stresses and longitudinal shear strain values along the web face at the ultimate load for several specimens. Compression causes the stresses and strains at the blue-colored region to be negative, while tension causes them to be positive at the red-colored zone. The strain appeared to be almost linear and stable at the start of the loading procedure. The tension and compression zones became increasingly clear as the loading process advanced. When the model reached the maximum load, the model failed.

Depending on the FE results obtained from the ANSYS program and their closeness to the experimental results, the FE analysis can be used to represent thresholds with other sizes, designs, and shapes without the need for practical experiments that are expensive, tiring, and require a lot of time. However, the slight difference from the test results remains a small problem that requires solutions and further studies.

6. CONCLUSION

According to this study, plate girder webs could be made out of corrugated steel plates in an inventive way. Static tests were performed on three conventional plate girders and three sandwich corrugated steel beams of the same weight and depth but different shear-span ratios (a/d). Also, the ANSYS program's finite element modeling analyzed the impact of two parameters. (corrugation shape and depth). The following conclusions were obtained:

- The beams' ultimate load capacity and ductility are improved by switching to corrugated steel girders from a flat plate.
- The span-to-depth ratio affects the behavior of studied girders, with load-carrying capacity increasing as the shear-span ratio decreases.

- The experimental results demonstrated that corrugated steel girders with rectangular cross-sections that previously studied could withstand higher loads than the triangle and other steel girders.
- Triangle Girders and the other in groups A, B, and C can sustain a substantially higher ultimate load than traditional steel girders in group A by roughly 44.39%, 35.12%, and 40.49%, respectively, showing that the rise is due to an improvement in the web's stability to resist the applied loads. The results obtained from the finite element modeling were significantly closer to that obtained from experimental work.

In the end, we find that this study was useful in knowing the importance of corrugated plates and how changes in their shape and size affect their strength. Also, in the future, there is a possibility to study other shapes or study the corrugated plates in the presence of concrete in a broader way, as some of the research that was mentioned previously was also conducted on it.

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