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The Effect of Shear Span on the Behavior of Triangularly Corrugated Web Steel Girders

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Abstract

Built-up steel girders have many applications in structural engineering, both in bridges and buildings. Flat web steel girders, which are the traditional choice, involve several weaknesses. Girders with corrugated webs were found to be more effective in their load-carrying capacity and deflection than girders with flat webs. In light of this, an effort is made in this work to examine how the addition of triangular corrugated webs influences the load-bearing capacity and deflection of steel girders. This study aimed to determine whether or not the strength of built-up steel with corrugated webs could be improved. A concentrated midspan load was applied to six simply supported steel beams of varying span-to-depth ratios (1.0, 1.833, and 2.5) and web corrugation amplitudes (30 and 60 mm). An increase in ultimate strength of 15.7% to 35.1% was found for webs with triangular corrugations of 30 mm and from 2% to 29.1% for webs with corrugations of 60 mm. A reduction in deflection of up to 35.3% can be attained when using triangular corrugated webs. It was also found that using webs with 30 mm corrugations was more efficient than using webs with 60 mm corrugations. The effect of corrugation was found to fade when the span-to-depth ratio increased to 2.5. This led to the conclusion that using webs of 30 mm amplitude of triangular corrugation could improve the strength and serviceability of steel girders.

Keywords: Plate Girders; Corrugated Web; Built-Up Steel Girders; Shear Span; Triangular Corrugation.

1. Introduction

Most buildings and highway bridges rely heavily on built-up steel girders for their primary structural support. It has beneficial properties over reinforced and pre-stressed concrete and even rolled steel girders, coming from its comparatively lightweight and the ability to design section dimensions to satisfy the desired serviceability and strength requirements. However, they may be susceptible to local web buckling and shear failure, among other weaknesses. The capacity of such girders to carry loads can be enhanced by using web stiffeners, which increase the shear capacity of the girder and the web buckling load [1, 2]. Another way to improve the web buckling load is by using a corrugated web rather than a flat one, which reduces weight and welding labor by eliminating stiffeners and reducing web thickness [3]. Web thicknesses between 2 and 5 mm and aspect ratios of 150 to 260 were initially proposed for use in German plate girders with corrugated webs [4].

Many previous works focused on examining various modifications to enhance the capacity of built-up steel girders by overcoming their weaknesses. Elgaaly et al. [5] investigated the web buckling of steel beams with trapezoidal corrugated webs. Two fabricated steel beams with web panels were made, each with a stiffener attached at its beginning, end, and midpoint. Four experiments were conducted on the simply supported beams, each involving applying a load at midspan, observing the beams collapse due to the weaker web, and then repairing the beams with stiffeners and having

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the beams re-tested. In addition, a nonlinear finite element analysis was performed using the ABAQUS general-purpose code. The authors found that web buckling is local in large corrugations and global for finer corrugations. In addition, the authors proposed a formula to estimate the web's buckling load by modeling it as an orthotropic plate. Elgaaly et al. [6] explored the trapezoidal corrugated web's contribution to steel beams' bending strength. Six beam specimens were tested by four-point loading, and nonlinear analysis and parametric studies were performed in the ABAQUS code. The results showed that bending and shear stresses did not interact, and the beams failed due to buckling in the compression flange. The web also made a negligible contribution to the ultimate moment capacity of steel beams.

Sayed-Ahmed [4] described the use of corrugated webs in existing and proposed bridges. Critical failure mechanisms and design considerations for such structures were also covered. The author also developed an interaction equation that considers the buckling and yielding of the web in other work [7]. Sayed-Ahmed used finite element modeling and numerical linear analysis in a third paper [8] to investigate the web buckling modes and post-buckling strength of steel girders with a corrugated web of trapezoidal profile using FEM. An equation considering the various failure criteria was proposed and examined. The author found that using corrugated webs for steel girders increases the lateral torsional buckling strength by 12% to 37%. The contribution of corrugated steel web to the bending strength of steel girders and girders with concrete-filled tubular flanges has been investigated in several previous works [9–11]. The shear strength and buckling mode of steel girders with corrugated webs were also investigated in previous studies [12–19]. The implementation of corrugated metal webs in pre-stressed concrete girders can be found in the works of Machimdamrong et al. [20] and Jiang [21]. The strength of encased girders with corrugated webs was explored by He et al. [22] and Kadhim & Ammash [23]. Bridge girders of box sections having corrugated webs were explored in the works of Zhang et al. [24] and Zhang et al. [25].

Cao et al. [26] conducted experimental and finite element investigation of the buckling and shear loads and mode of buckling failure of H shape steel girders of corrugated webs. Five specimens of welded fabricated steel girders with plain and corrugated webs of the trapezoidal profile with stiffeners arranged as pairs were tested and numerical analysis using ANSYS software was also performed. The authors found that local and global buckling failures were noticed and the shear strength of the corrugated web could increase by up to 45% compared to girders having plain webs. Erdal et al. [27] used a stochastic algorithm to determine the optimum design of corrugated composite beams. The design variables were the concrete slab thickness, the location of studs, the steel web, the flange height, and the web profile.

To examine the failure mechanism of steel girders with trapezoidal corrugated webs and non-welded inclined folds, Elamary et al. [28] conducted three-point loading test study on six full-scale hybrid steel girders using different grades of steel for flanges and webs. The authors observed buckling in the web and flange, followed by tearing in the web for samples in which the inclined folds of the corrugated web were not welded to the flanges. Górecki & Sledziewski [29] investigated the effect of web thickness, length, and amplitude of corrugation waves on the strength and deflection of steel girders. Shear and bending span effects on the strength and failure mode of steel girders with corrugated webs were investigated using an experimental and finite element analysis by Sharaky et al. [30]. The study depicted that the shear span is the main factor that affected the ultimate strength. The effect of the shear span of steel girders with corrugated sandwich webs was experimentally studied by Abdulla et al. [31]. It was discovered that the shear span/depth ratio had a negative effect on girder performance in terms of ultimate load and deflection. Abdullah & Muhaisin [32], who conducted an experimental study to examine the performance of built-up steel girders, also found that girders in which the web is composed of two skin plates and a trapezoidal corrugated core plate performed better than girders in which the web was made of a single skin plate. Three-point loading tests were conducted on nine girders with study parameters including span-to-depth ratio and corrugation profile dimensions. The mode shape and natural frequency of steel girders with flat and corrugated webs under free vibration were explored by Sayed et al. [33]. Various corrugation profiles were analyzed experimentally and using finite elements, then compared to one another. A comprehensive review of corrugated steel webs can be found in Prathebha & Helena [34] and Ghanim et al. [35].

The previous works show that using a corrugated web represents a promising approach that could enhance the strength and performance of built-up steel girders. Most of these works focused on trapezoidal and rectangular corrugations, while little attention was given to triangular one. In this work, built-up steel girders with webs of triangular corrugation were experimentally investigated to evaluate the impact of this shape of web profile and the shear span-to-depth ratio on their strength and deflection.

2. Materials and Methods

Six built-up steel girder test specimens featuring an I-section and webs with triangular corrugations are fabricated and prepared for evaluation. Each girder comprises top and bottom flanges (200 mm wide and 6 mm thick) and a triangularly corrugated web (300 mm in height and 2 mm in thickness). To prevent local web and flange buckling, vertical stiffeners made of steel plates measuring 300 mm in height, 6 mm in thickness, and 99 mm in width are welded on both sides of the webs at support and load application points. Similar beam dimensions and properties to those used by Kadhim & Ammash [23] are used in this work 6 and 3 mm steel plates conforming to ASTM A36/A36 M [36] requirements were used to manufacture the flanges, web, and stiffeners, and 7018 steel electrodes were used in the welding process. The tensile strength, yield point, and modulus of elasticity of the plates used to fabricate specimens with ASTM A36/A36M-01 are listed in Table 1. A typical beam with a corrugated web and stiffeners at the three locations is shown in Figure 1-a.

Table 1. Material properties

Element	Plate thickness (mm)	Tensile strength (MPa)			Yield point (MPa)		Modulus of Elasticity (GPa)
		Test result	ASTM A36/A36M-01 Min	ASTM A36/A36M-01 Max	Test result	ASTM A36/A36M-01 Min	
Flange and Stiffener	6	450	400	550	292	250	205
Web	2	442			283		203

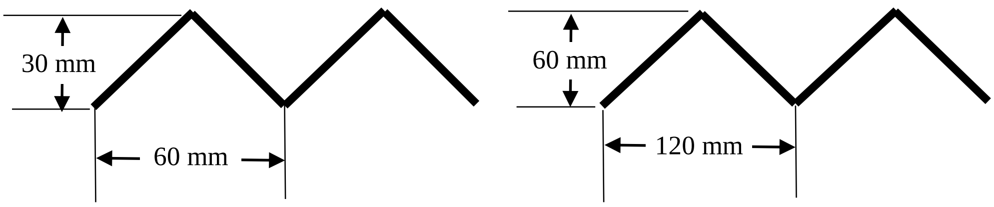
(a) Typical girder specimen (b) Shape of corrugated web

Figure 1. Typical girder with stiffeners and corrugated web and corrugated web

The main purpose of the present work is to explore the impact of the shear span to depth (a/d) ratio and the effect of corrugation amplitude on the deflection, ultimate load, and failure mode. So, the beam specimens were categorized into two groups. Each one consisted of three specimens of shear span to depth ratio of 1.0, 1.833, and 2.5. The difference between the two groups was in the amplitude of corrugation; the first one was 30 mm, and the second was 60 mm. The values of previous parameters are similar to those adopted in the work of Abdulla et al. [31] for sandwich steel corrugated girders. Triangular zigzags are obtained by the hydraulic pressing of a flat steel plate to make the required corrugation size, as shown in Figure 1-b. A description of the dimensions of specimens is listed in Table 2. The geometry and dimensions of the two types of corrugations are shown in Figure 2.

Table 2. Dimensions of Specimens

Group	Identification	Flange Width (mm)	Flange Thickness (mm)	Web Depth of Corrugation (mm)	Web Height (mm)	Web Thickness (mm)
I	TW1.0/30	200	6	30	300	2
	TW1.833/30					
	TW2.5/30					
II	TW1.0/60			60		
	TW1.833/60					
	TW2.5/60					



(a) 30 mm corrugations (b) 60 mm corrugations

Figure 2. Geometry and dimensions of 30 mm and 60 mm corrugations

3. Testing Procedures

The test specimens were supported only at their ends and subjected to a vertically concentrated load at their midpoint. The tests were set up by applying the loads gradually to enable the measurement and recording of deflection at midspan for each load step, monitoring the web and/or flange buckling, and recording the ultimate load. A sample of the specimen in a testing machine and typical web buckling failure are shown in Figure 3.

(a) Testing of a typical specimen (b) Buckling of corrugated web

Figure 3. Testing of typical girder and typical mode of failure of corrugated web

All test specimens were subjected to a concentrated point load at the midspan that was increased over the test. Each of the six samples had its midspan deflection measured at a series of loading rates, and the load at which the flange or web buckled was noted and recorded. Finally, the ultimate capacity was determined to be the load at which deflection and/or buckling significantly increased without an equivalent increase in the load. A description for procedure of work is shown in Figure 4.

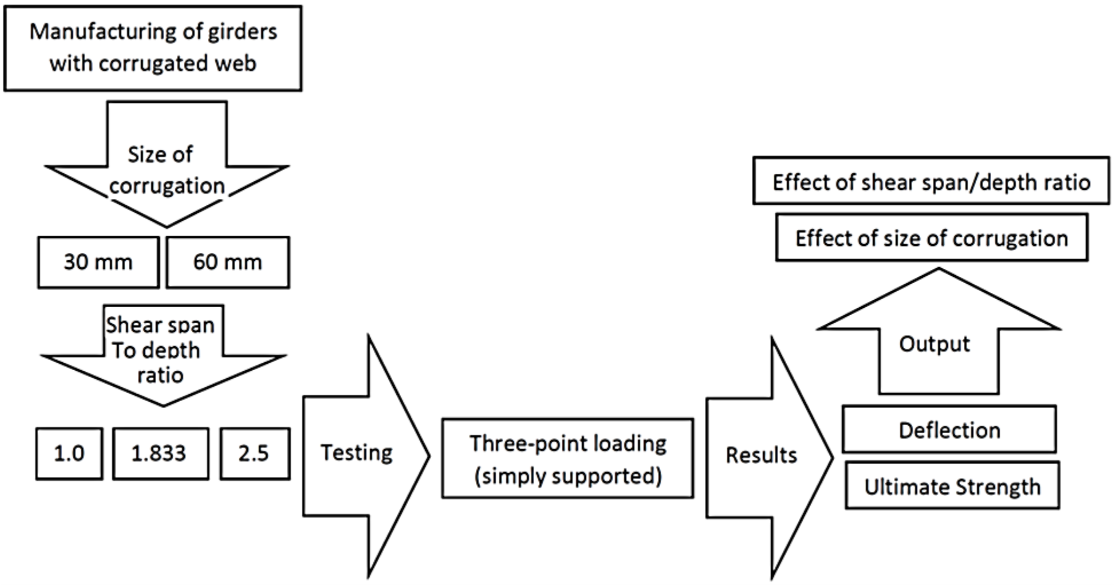


Figure 4. Flow chart of the work methodology

4. Results and Discussion

4.1. Effect of Shear Span/Depth Ratio

Figures 5 and 6 display the varying deflection with the applied load at different stages for beams with 30 and 60 mm corrugations and three values of the shear span/depth (a/h) ratio. Figure 6 shows that as a/h increases, rigidity decreases for beams with a 60 mm corrugation. The fact that the deflection increases with increasing a/h indicates this, given that the applied load remains constant. This is not the case for the beams shown in figure 4, which have a corrugation of 30 mm. For these beams, the deflection values for the mid-value of a/h are greater than the deflection for the other two values. However, a general trend can be noticed that the deflection increases as the shear span/depth ratio increases. This is evident when comparing the curves for the case of a/h = 1.0 with those of the other two ratios, both in the 30 mm and 60 mm corrugation cases. This finding agrees with the conclusion found by Abdullah et al. [31].

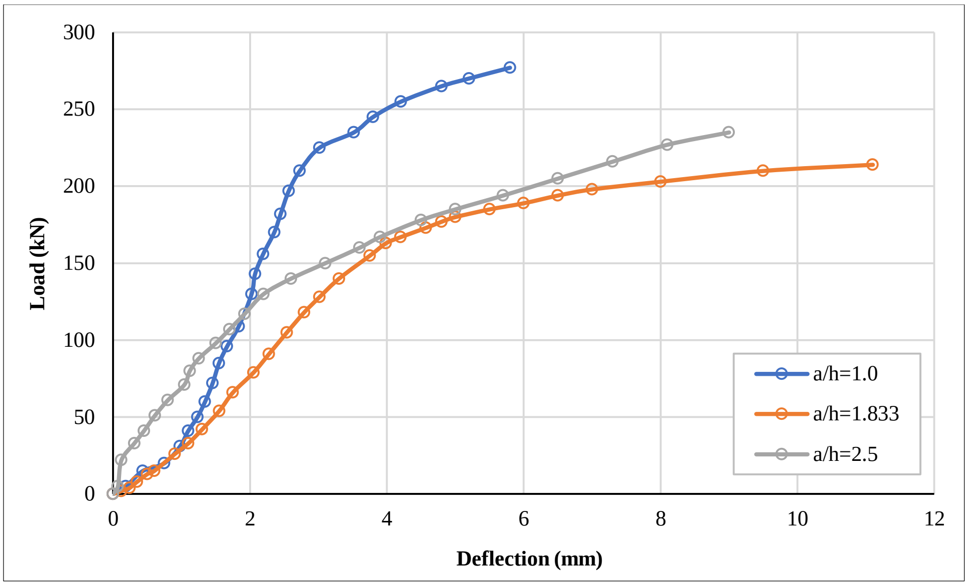


Figure 5. Variation of deflection with the applied load for 30 mm corrugation

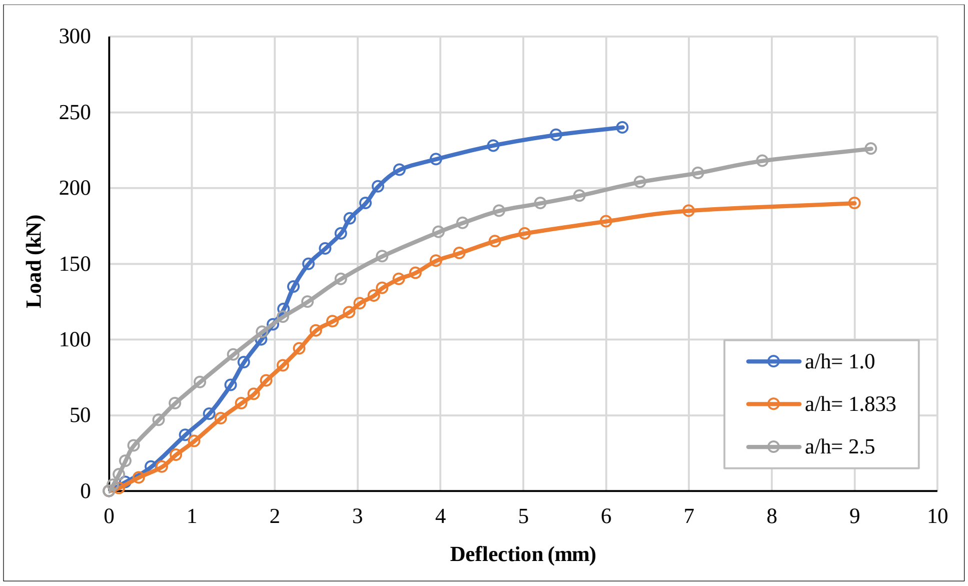


Figure 6. Variation of deflection with the applied load for 60 mm corrugation

4.2. Effect of Size of Corrugation on Ultimate Strength

Figure 7 depicts the relationship between the ultimate load and the shear span-to-depth ratio for the two groups of 30 and 60 mm corrugations, compared to the ultimate load values for a steel girder with the same dimensions but having a flat web tested in Abdullah et al. [31]. From these relations, it can be concluded that the corrugations' presence increases the girder's ultimate load capacity for all values of the a/h ratio. For beams with 30 mm corrugations, the increments in the ultimate strength compared to beams with flat webs were 35, 15.7, and 34.3% for span-to-depth ratios of 1.0, 1.833, and 2.5, respectively. The corresponding increments for beams with 60 mm corrugations were 17.1, 2.7, and 29.1%. Since a corrugated web is stiffer than a flat one, it can minimize buckling, which is why corrugated webs are more commonly used. Comparing the performance of girders with corrugated webs indicates that those with 30 mm corrugations perform better than those with 60 mm corrugations. This can be justified by the increasing ability of occurrence of local buckling in the corrugations as their length increases. These findings also agree with Abdullah et al. [31].

4.3. Effect of Size of Corrugation and Shear Span/Depth Ratio on Deflection

Variation of midspan deflection with the applied load for girders with 30 and 60 mm corrugated webs are compared to those of girders with a flat web, as reported by Abdullah et al. [31]. Figures 8 to 10 display these variations for three shear span-to-depth ratios.

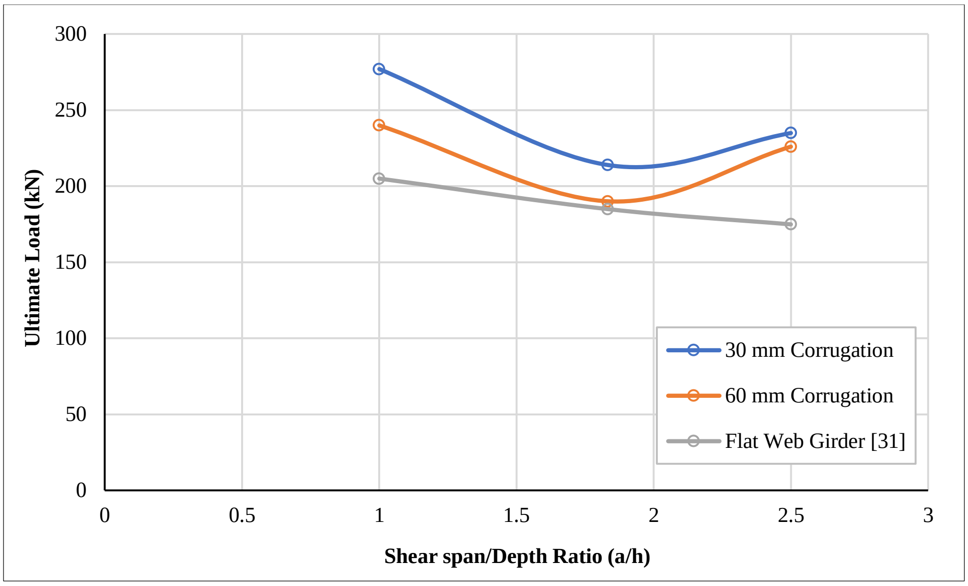


Figure 7. Variation of ultimate load with shear span/depth ratio

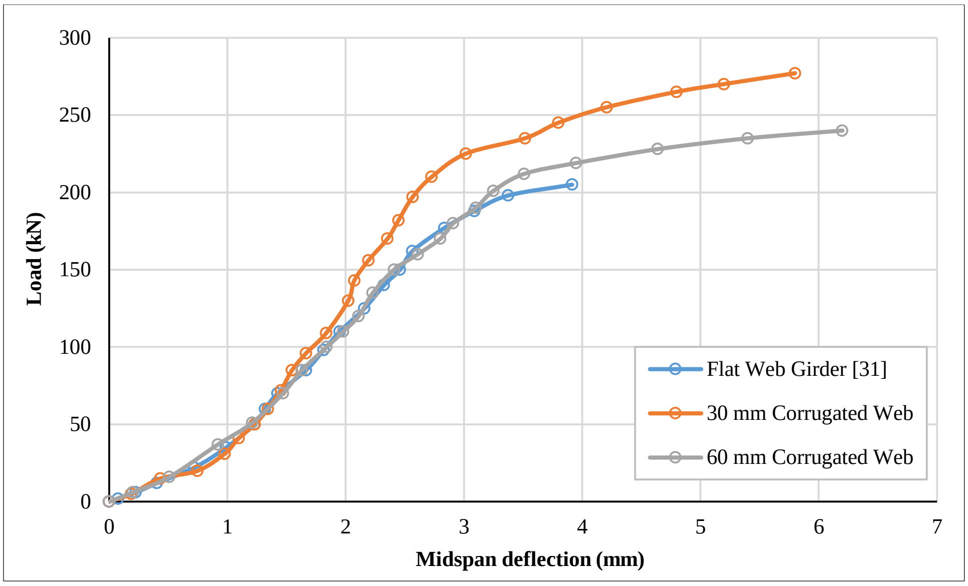


Figure 8. Deflection at midspan for a/h= 1.0

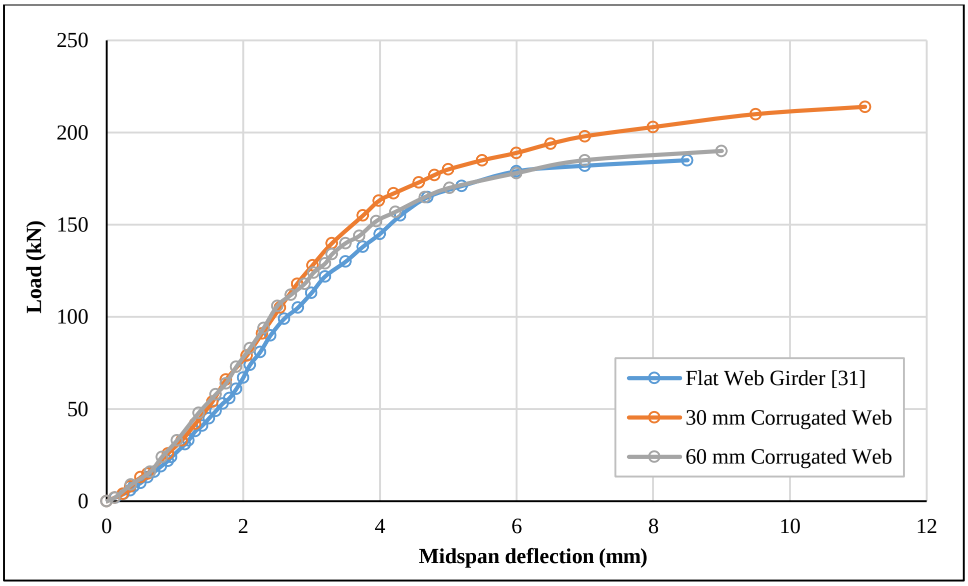


Figure 9. Deflection at midspan for a/h= 1.833

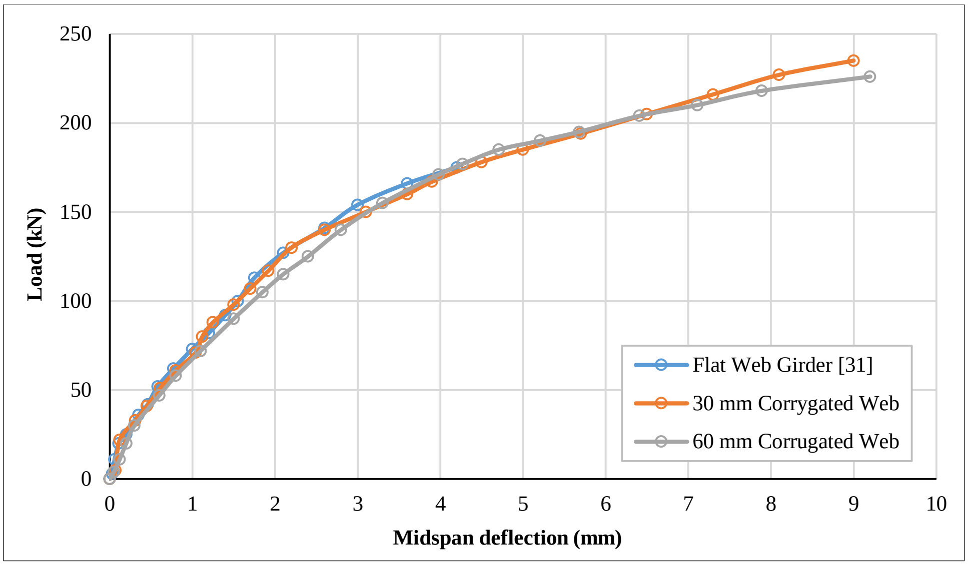


Figure 10. Deflection at midspan for a/h= 2.5

For shear span/depth ratios of 1.0 and 1.833, the deflection of girders with 30 mm corrugated webs was less than that of flat and 60 mm corrugated web girders. This led to the conclusion that moderate corrugations enhance the stiffness of the webs more efficiently than large corrugations. As the a/d ratio increased, it was found that the impact of corrugation on deflection decreased. This can be noted in Figure 10, which indicates that the deflection values for two cases of corrugated and flat webs are almost identical. The midspan deflection at ultimate load for a flat web girder with a/d = 1.0 was found to be 3.915 mm; this value at the same load was reduced by 31.9% and 14.6% for 30 and 60 mm corrugated web girders, respectively. For a/d= 1.833, the corresponding reductions were 35.3% and 17.6%, respectively.

5. Conclusions

Built-up steel girders were proven to be efficient at carrying loads over long spans, both in industrial buildings and bridges. This efficiency comes from their lightweight and the flexibility in selecting the desired shape and dimensions in order to meet the requirements of serviceability and strength. However, there still some weaknesses through the possibility of occurring buckling in the webs and flanges. One of the methods adopted to eliminate or even reduce this possibility is the use of corrugated webs rather than flat ones. So that, in this work the use of steel built-up beams with triangularly corrugated webs was experimentally investigated to evaluate the improvement in their performance upon girders with flat webs.

- Six steel girders with 30 and 60 mm corrugation amplitudes were constructed and tested with span-to-depth ratios of 1.0, 1.833, and 2.5.
- The study's results imply that presenting webs with triangular corrugations increases the ultimate strength by 15.7 to 35% for webs with 30 mm corrugations and 2 to 29.1% for webs with 60 mm corrugations compared to flat webs.
- The increase in ultimate strength and the decrease in deflection were discovered to vary depending on the span-to-depth ratio.
- Regarding ultimate strength and deflection, 30 mm corrugated webs outperformed 60 mm corrugated webs. When triangular corrugated webs were used, the deflection could be reduced by up to 35.3%. This benefit disappeared for a/d = 2.5.

6. Declarations

6.1. Author Contributions

Conceptualization, M.D.A. and A.A.A.; methodology, M.D.A. and A.A.A.; investigation, M.D.A.; writing—original draft preparation, M.D.A. and A.A.A.; writing—review and editing, M.D.A. and A.A.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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