Experimental and Numerical Investigation of Composite Girders with Thin Corrugated Webs

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Abstract. The capacity of composite girders may depend on their web stability; thus, webs could be reinforced with stiffeners or corrugated shapes adopted to increase such stability. Developing on two previous techniques, a corrugated shape was used in a new pattern, similar to a transverse stiffener, to increase the flexural rigidity of the plate, causing the shear stability of the webs to increase. Three composite girders were manufactured using the new pattern of corrugated web and tested under static loading. The results showed that the girders with corrugated shapes had different behaviours to girders with flat webs. The examination of a composite girder with a deck slab of UHPC also revealed that the deck slab worked with the web to resist the shear stress, suggesting that the corrugated technique could be used as an alternative to reinforcing the web, especially in composite girders. This technique increased the shear strength capacity by about 44% over that of flat web composite girders. All composites failed due to the web buckling, without crushing or cracking of the UHPC deck, where the normalised shear reached 0.7 of the yield shear stress for the corrugated web. Finite element analysis using ABAQUS software was performed, which showed reasonable agreement between results and enabled the study of additional parameters without combination factors.

Keywords. corrugated web, elastic buckling, post-buckling, ultra-high-performance concrete.

1. Introduction

As traffic volume grows, additional modern structures are required to support traffic volume; in particular, many intersections have become overpass bridges, and bridges for highways or expressways always have long spans. In other buildings, for various architectural purposes, long spans have also become a favoured feature. Such structural constriction should be lightweight, high strength, and ductile, and these essential properties must be examined under static loading.

The composite profile can be used in bridges and in building construction to support bridge decks, building floors, or roofs. The composite section is particularly widely adopted for bridgework and is practically universal for plate girder or beam bridges with reinforced concrete decks. Plate-girder props are added to the concrete deck during construction and continuously for live service, to reduce deflection [1].

Plate girder, however, induces local instability, as it is deeper and has a thin web. Conventionally, intermediate stiffeners are used to develop a tension field action, which increases the capability of the member to resist shear load. Additional stiffeners may also be used at points of concentrated load or bearings points to prevent compressive force being applied on the web directly or to reduce the effects of web crippling [2].
The aspect ratio, depth to length, for a plate girder is about 1/6 to 1/15, which means that a plate girder has a high depth. A high depth of web, according to its thickness, is thus required, and such a web has a week stability against shear strength [2]. The weakness of the web can be compensated for by using intermediate stiffeners. In this study, a plate girder web was reinforced with corrugated plate to enhance stability, a technique that has been used for three decades. The corrugated plate properties match the features of the orthotropic plate, also known as anisotropic plate, with materials with different elastic properties in two orthotropic directions [3]. The possible variations in these properties mean that the corrugated plate is just one of the applications of the orthotropic plate, with greater flexural rigidity along one direction than the other. Corrugated plate instead of a flat plate is thus often used in civil applications such as composite slab and girder webs.

To avoid web buckling, the web is generally reinforced with intermediate stiffeners, increasing the critical shear buckling stress [4]. Unstiffened webs may be used due to being less expensive than stiffened webs, or when stiffeners are aesthetically unacceptable [5].

Corrugated web may be used as an alternative to transverse stiffeners on a web, which increases the shear strength capacity of the web [6]. There are many types of corrugation possible, with trapezoidal and sinusoidal options [7] commonly used in highway bridges and building structures.

Corrugated webs fail due to instability, with shear buckling failure modes that can be classified into three types: Local buckling occurs in a single fold; global buckling extends in multiple folds, with buckles extending over the whole depth of the web; and interactive buckling occurs due to interactions between local and global buckling [6]. Global buckling appears to be predominant for fine corrugation, while local buckling appears more commonly in course corrugation [7]. The shear strength of corrugated web girders depends on numerous factors, including web depth, thickness, corrugation geometry, and materials.

The main advantages of corrugated web girders is that they are 30 to 60% lighter than equivalent flat web girders with the same capacity of shear strength. Thus, larger spans can be created with less weight. Moreover, in the corrugated web, the critical shear buckling stresses are increased, and the out-of-plane stiffness of the web is increased, eliminating the need for vertical stiffeners, and improving the aesthetics of the structure [7].

In flexural failure, the corrugated web reduces flange vertical buckling significantly. However, corrugated web is weak to direct stress due to bending moment. The bending stress is resisted only by the flange only, removing the need for an interaction diagram when calculating shear strength. Inelastic buckling occurs when local or global elastic buckling exceeds 80% of yield stress, \( r_e \); Elgaaly [8] thus proposed a reduction factor equal to 0.8 for calculating inelastic buckling.

Web stability can be increased in several ways, including using transverse or longitudinal stiffeners, as mentioned by Chen et al. [4] and Bergfelt et al. [9]. Likewise, using a corrugated technique to increase the stability of the web was discussed by Abass et al.[10]. Such corrugation of webs is affected by several factors, such as welded length as noted by Sharman and Fisher [11]; fold configuration, as investigated by Dahlen and Krona [12]; web slenderness, as studied by Elgaaly, and Hamilton [8]; and the height of the corrugations, as examined by Gil et al. [13]. These researchers have thus revealed that the corrugations may be used to increase the stability of the web, and that a trapezoidal corrugation technique may be preferable to using transverse stiffeners, as adopted in the present study, which sought to develop a unique new pattern of corrugation simulating the additional positive effects of transverse stiffeners.
Generally, composite girders have greater capacity than plate girders\[14\]. Alongside investigation of the new corrugation pattern, this study thus sought to make a comparison between corrugated web composite girders and corresponding flat web composite girders, as well as examining the length to depth ratio effects. Previous research has shown that composite girders are affected by the slenderness of the web [15] and that the shear connector is an important factor affecting the behaviour of the composite girders [16] and [17]. The thickness of the slab also influences the shear strength capacity of composite girders, as noted by Yoo and Choo [18].

This study utilised the corrugation technique to reinforce webs and increase web stability in composite girders, with the corrugated pattern proposed as an alternative to intermediate stiffeners. The webs were thus folded in trapezoidal shapes, and these folds were distributed longitudinally at constant intervals. The trapezoidal folds were thus formed in sequential directions for each side.

2. Experimental Program

2.1. General

This study investigated the behaviours and shear stability of composite girders with corrugated webs. The shape of the corrugation was implemented as a trapezoid, a new mode of corrugation as shown in Error! Reference source not found.. This corrugation technique has been suggested for use as an alternative to transverse stiffeners by Dhafer [19]. The shape of the corrugation consists of four trapezoidal folds for each panel of the web, with every two folds forming one side while the two others form the opposite side and are distributed at a constant distance of 260 mm. This pattern of corrugation simulates using one set of intermediate transverse stiffeners in sequential mode. The proposed corrugation remains part of the web panel, as a flat web between two adjacent folds or sub-panel, with a width of 185.5 mm.

2.2. Composite girders

Three composite girders comprised of corrugated web and UHPC formed the deck. The designation of the composite girders with corrugated web was C.CWxx, where, the first part, “C.” refers to the composite section, while the second part “CW” refers to the corrugated web, and the third part “xx” refers to the sequence number of the girders. Broadly, the parameter studied here was the effect of the length to depth ratio L/D, as explained in Error! Reference source not found.. However, the study also investigated the influence of the using deck slabs as compared with plate girders without composite action, as previously investigated by Haitham and Dhafer [20].

![Figure 1. Corrugation Shape.](image1)

![Figure 2. Details of composite corrugated web.](image2)
2.3. Concrete Deck-Slab

The deck slab was manufactured from UHPC without main reinforcement steel, as proposed by Haitham and Dhafer [21]. The concrete ingredients were Portland cement, fine aggregate passed through a sieve size of 600-micrometres, and micro-silica fume. The ingredients were mixed with superplasticiser and water and steel fibre was added to 4.5% volume content. The deck was cast in the workshop, and, after setting, the concrete was cured by immersion in hot water at 60 °C. The deck slab was used to represent precast concrete, so it was first prepared and then connected to the steel plate girders.

The thickness of the slab was set to 35mm, though the mid-width concrete depth enlarged the thickness from 35 mm to 50 mm to create a haunch with a height of 15 mm and width of 150 mm, as shown in Figure 3. The haunch provided a more suitable height for studs to be embedded inside the concrete, increasing the contact shear area of the connectors. The deck width was 400mm, which is, however, lower that the effective width according to the ACI [22].

2.4. Shear Connectors

The connector studs used had head diameters of 12 mm and lengths of 75 mm. These studs were distributed along the flange as pairs (two studs for each row). The studs were placed in holes prepared inside the concrete, as shown in Figure 4 and then tightened using a micrometre adjustable torque wrench. All nets were tightened until the torsion moment equalled 140 kN.m. The pairs of studs were distributed with spacing of 175 mm along the span, in a longitudinal direction, as shown in Figure 5, giving twelve pairs of studs in each composite beam. The distance between studs in the same row in the transverse direction was equal to 70 mm. The stud properties and distribution distances were obtained from the push-out tests conducted by Dhafer [19].

![Figure 3. Deck-slab Details.](image3.png)

![Figure 4. Connection Details.](image4.png)

Four linear variation distance transducers (LVDT) were used. Two of these measured the vertical deflection at the mid-span at a distance of 1/8 of the effective length from the mid-span. The two remaining LVDT sensors were used to measure the lateral displacement, being perpendicular to the longitudinal axis at the top and bottom, as shown in Figure 5. The fourth LVDT also measured the relative slip value between concrete and steel based on the testing of the composite section.
Eight strain gauges were mounted on each composite girder to measure the strain at the section 262.5 mm from the centre section. Two uniaxial strain gauges were fixed on the bottom and top steel flanges, with three strain gauges mounted at the calculated neutral axis to measure shear strain. Finally, three strain gauges were mounted on the deck slab at the top and bottom, as illustrated in Figure 6.

![Figure 5. LVDT sensors set-up.](image1)

![Figure 6. Strain Gauge Arrangement.](image2)

### 3. Experimental Work

All girders were tested under static load to failure using a compression machine of 100-ton capacity. All girders were supported laterally at the ends to prevent torsional buckling.

#### 3.1. Composite Girder Results

The normalize shear and normalize deflection were plotted in Figure 7. Shear-relative deflection of composite CW.7 for the composite girders with the corrugated web. These girders are C.CW8, C.CW10, and C.CW9 which have L/D ratios of 10.5, 7.0, and 4.7, respectively. Girder C.FW9 failed earlier than girder C.FW10, while girder C.FW8 failed later. The normalize shear stress was 0.72, 0.65, and 0.56 for girders C.CW8, C.CW10, and C.CW9, respectively. These results revealed that the corrugated web increases the shear strength capacity of the composite girders especially when L/d ratio increased because of the web slenderness decreases.

Out-of-plane deformation appeared on the web for all composite girders without any crushing or cracking of the concrete, as observed in Error! Reference source not found.8. Interaction elastic buckling appeared between the folds of the corrugation and then extended to the folds themselves, suggesting that the failure occurred as elastic local buckling at the sub-panels (the panels between folds) and that the behaviour of the web transformed from beam analysis to truss analysis. The sub-panels thus behaved like tension members and the folds became prone to compressive stress.
3.2. Comparison between Flat Web And Corrugated Web

A comparison of the load-deflection curves of corrugated web girders and flat web girders, based on previous research by Muteb and Dhafer [20], was plotted in Figure 9. These curves show that the new corrugation technique increases the elastic buckling load. The incremental percentages of the elastic buckling load (E.B.L.) are 44%, 22%, and 20% between C.CW8 and C.FW8, C.CW10 and C.FW10, and C.CW9 and C.FW9, respectively. The new pattern of corrugation in conjunction with UHPC deck slab, as proposed in the present study, is thus an active technique that increases the stability of composite girders.
3.3. Comparison between Composite and Plate Girders

A comparison of shear capacity between composite girders and plate-girders, as achieved by Dhafer [19] with corrugated webs, showed that using UHPC as a deck slab produces a good increase. The percentages of the increments of the elastic buckling load were 20%, 50%, and 42% for corrugated web girders, as shown in Figure 10, suggesting that the increment in elastic buckling load capacity comes from the contribution of the deck slab of UHPC to resisting shear forces. The deck slab thus increases the shear strength capacity for the composite girders, as in Vasdravellis and Uy [23]. However, the shear strength of the composite girder depends on the shear strength of the concrete and shear strength of the steel girder [16], allowing the total vertical shear to be calculated by summation of the steel shear resistance and concrete shear resistance, as follows:

\[ V_t = V_c + V_s \]  

(1)

where \( V_t \) is the vertical total shear, \( V_c \) is the concrete shear resistance, and \( V_s \) is the web shear resistance of the plate girder.
4. Finite Element Modelling

This study adopted 3D finite element analysis using ABAQUS software. A solid element was used for the concrete deck slab, while a shell element was used for the flanges, stiffeners, and web. Analysis was performed initially with regard to linear buckling and then by the Riks method. A comparison between the test results and experimental results showed good convergence for the linear stage that, however, vanished when shear buckling occurred in FE, as the loading action continued after failure in the experimental test and thus the deflection varied. However, the mode of failure coincided with the experimental tests, as explained in Figure 11.
Figure 11. Testing and numerical mode of failure of the plate and composite girders.

A comparison between the results of experimental works and numerical analysis showed good convergence in linear elastic buckling, as shown in Figure 12. The incremental percentages of elastic buckling in numerical analysis were 6%, 5.8%, and 6.7% for corrugated web girders of types C. CW8, C. CW9, and C. CW10, respectively, as listed in Table 1.

Figure 12. Load Deflection curve of Exp. and FE.
Table 1. Comparative increments of FA analysis.

| Girders  | Exp. Elastic buckling load kN | FE Elastic Buckling Load kN | Increment percentage of FE than Exp. |
|----------|-------------------------------|-----------------------------|-------------------------------------|
| C.CW8    | 34                            | 39                          | 6%                                  |
| C.CW9    | 60                            | 63.5                        | 5.8%                                |
| C.CW10   | 45                            | 48                          | 6.7%                                |

4.1. Parametric Study

As all parameters in the experimental work of the present study were interlocked, a numerical investigation was also conducted to investigate these factors individually. The main factor investigated was the length to depth ratio, examined by reducing the depth of girders from 450 mm to 300 mm and then to 200 mm. This variation of the depth was associated with variations in web slenderness and the dimension aspect ratio of the sub-panels between folds of corrugation. Three further groups were also developed to study variables individually without considering the contributions of interactions between those variables.

The first group consisted of three girders, which were similar to girder C.CW9 with a variation in web thickness. The L/D ratio was kept equal to 4.7 and the D/W ratio was equal to 2.4. The web thickness was thus changed from 1.2 mm to 1.8 mm and then to 2.7 mm, which changed the slenderness ratios to 375, 250, and 167, respectively. Analysis of the results showed that the reduction in slenderness increased the shear strength capacity significantly, as shown in Figure 13. The displacement deformation at failure is illustrated in Figure 14.

![Figure 13. Load vs. deflection of girders with different slenderness’s.](image)

![Figure 14. Deformation shapes of girders with different slenderness’s.](image)
The second group also consisted of three girders, which had variation of the L/D ratio with constant web slenderness (equal to 375, a web thickness of 1.2mm) and a constant D/W ratio (2.4). The variation of the L/D ratio was created by increasing the length from 2.1 m to 3.15m and then to 4.725m. These variables changed the L/D ratio as 4.7, 7.0, and 10.5, respectively. The results of this group showed that the strength capacity of the girders with the new technique of corrugated decreases when the length to depth ratio increased, as explained in Figure 15. While the deformation shape is illustrated in Figure 16.

![Figure 15. Load Vs. Deflection of the Girders with Different L/D.](image)

4.2. Discussion

The third group were performed by three girders with a different distribution distance between the folds that were used as a new web reinforced technique as shown in Figure 17. The folds distributed at 185.5mm clear distance between folds (i.e., the sub-panel width which equals 185.5mm). Then that the distance increases to 281.25mm for the second girder, while the third girder had an interval distance between folds of corrugated equal to 417mm. Thereby, the aspect dimension ratio of the sub-panel between folds D/W became 2.4, 1.6, and 1.08, respectively. All previous girders had constant web slenderness’s of 375 and constant L/D ratios of 7.0. The increment ratio of the D/W, which is associated with increased distance between folds, thus reduced the shear strength capacity, as shown in Figure 18.

Generally, the new technique of corrugation could be used to increase the stability of the web. This action will be increased the shear strength of the girders when the web slenderness decreases. While when the length of the girders and distance between folds were reduced the shear strength capacity will be increased for the composite girders with the corrugated web. Generally, the mode of failure of a new corrugated technique was due to the Shear elastic buckling of the web between folds when this girder used as composite girders.
5. Conclusion and Discussion

The results of the tests and comparisons suggest that the post-buckling behaviours depend on length to depth ratio, L/D. When L/D was increased from 4.7 to 7.0, and then to 10.5 for corrugated web girders, the post-buckling behaviours were increased. The rates of shear elastic buckling, which corresponded to yield shear stress (normalised shear), were 0.72, 0.65, and 0.6 for girders C.CW8, C.CW10, and C.CW9, respectively. These rates, which are related to the L/D ratio, reduced when the L/D ratio decreased.

The corrugated technique increased the incremental percentage of the corrugated web by 44% over that of the flat web, while between girders C.FW10 and C.CW10, which gave a web slenderness equal to 250, the difference was 22%, and between girders C.FW9 and C.CW9, which had web slenderness equal to 375, by 20%. The UHPC deck slab enhanced the girder failure behaviours, which were more ductile when UHPC was used. The corrugated web girders were not prone to post-buckling behaviours, while the composite girders with corrugated web were prone to slight post-buckling behaviours, where elastic buckling occurred in one sub-panel then extended to others until failure occurred at all sub-panels.

The additional parameters examined by numerical analysis revealed three conclusions. The first is that the web slenderness affects the shear strength capacity of the new pattern of corrugation significantly. The second is that increases in the length to depth ratio decrease the shear strength capacity. The final conclusion is that when the distance interval between folds increases, the shear strength capacity decreases slightly.
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