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A Review of Composite Steel Plate Girders with Corrugated Webs

Ghazwan Ghanim*, **Wael S. Baldawi**, **Ammar A. Ali**

Civil Engineering Department, University of Technology-Iraq, Alsina'a street, P.O Box 10066, Baghdad, Iraq.
*Corresponding author Email: 40210@uotechnology.edu.iq

HIGHLIGHTS

- A corrugated steel plate girder is a vastly used structural element in numerous fields of application due to its many favorable characteristics.
- The use of corrugated web girders has been increasing in recent years due to Optimizations in the automated manufacturing process of corrugated steel webs and a decrease in weight.
- This new achievement corrugated web girders is help engineers to design more optimized structures by greater depth to a thickness ratio.

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ABSTRACT

A corrugated steel plate girder is a vastly used structural element in numerous fields of application due to its many favorable characteristics. A corrugated web girder, the bending moments, and application forces are only transferred by means of flanges, that the maximum moment carrying capacity is more than any other hot-rolled sections used, while transverse shear forces are only transmitted through a corrugated steel web, webs at a greater depth to a thickness ratio are usually used resulting in slender sections that are susceptible to buckling on the Flat web. The use of corrugated web girders has been increasing in recent years due to optimizations in the automated manufacturing process of corrugated steel webs and a decrease in weight. Thus, to avoid buckling on the web and to obtain maximum strength, corrugations are provided in the area on the web. Corrugated steel plate girder's ability to be used in numerous fields of application due to its preferred properties. The main advantage of the corrugated web plate girders over the hot rolled girders is the flexibility in the dimensions of the girder. Improvement in the plate girders is essential to take full advantage of this asset. This new achievement has helped engineers to design more optimized structures. This paper provides a review of several studies on corrugated steel web plate girders and plate girders improvement.

1. Introduction

The steel plate girders are built-up members. A plate girder consists of steel plates that can be welded or bolted together to form a deep girder larger than that can be produced by rolling. As such, it can withstand greater loads over larger spans [1, 2] The typically welded girder consists of a flange plate welded to a deep corrugated web plate. The bolted formulation consists of flanges made of corners and cover plates anchored to the web plate. Steel Plate Girders may have vertical stiffeners attached to the steel web and flange plate. Corrugated steel web girders are girders constructed with a thin-walled corrugated steel web and wide flange plates. Defining a web profile generally avoids girder failure due to loss of stability before the plastic load limit for the web is reached. In general, trapezoidal, zigzag, and sinusoidal profiles are used. Thin corrugated steel web girders provide a significant reduction in weight compared with hot rolled profiles or I-sections welded [3]. Web failure buckling is prevented by corrugation steel web. Corrugated web buckling resistance is comparable to the thickness of smaller planar webs. By virtue of the improvements in the automatic manufacturing process, it became possible to use corrugated steel web up to 6 mm thick. So, the field of application of this type of plate girder has been greatly extended. Even short bridges spans are possible now. Economical design of girders normally requires thin webs. But if the web is extremely thin, the problem of plate buckling may arise. So, the possible ways to reduce this risk is by using thicker plates or web stiffeners. This could be improved in the best way by introducing corrugations on the web. The main benefit of the corrugated web beam is to increase the stability of the beam against buckling. A corrugated web girder represents a new structural system that has excellent load-carrying capacity [4].

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2. Corrugation Profile and Applications

2.1 Types of Corrugation Web

Due to increase shear strength of the web part, worldwide searches were carried out on the steel plate girders with different shapes of corrugation in the web area: trapezoid, sinusoid, triangle, square, rectangle, etc.

Figure 1: Plate girder with corrugated web and different web heights with no stiffeners [5, 6]

Web sinusoidal profiling generally avoids girders failure because of loss of stability before reaching the plastic loading limit. Also, sinusoidal profiling removes the problem of local web buckling. This aspect represents the advantage of comparing trapezoidal web girders, which may cause failure due to local web buckling, as it consists of several flat parts. The zigzag web shapes as shown in Figure (2) were also selected as the corrugation in the web region. Due to the introduction of inclination stiffeners, it exhibits greater bending strength than the trapezoidal corrugated web shape.

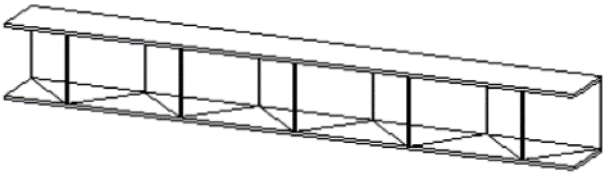

Figure 2: Zigzag corrugated web girder [5]

The dimension measurement of corrugated web girders is commonly based on EN-1993-1-5 Appendix D, which covers web thicknesses until 3mm. Also, older German standards such as DASt-Ri.015 for corrugated web girders, but this standard only deals with trapezoidal corrugated web girders. EN 1993-1-5 gives rules for both trapezoidal corrugations and sinusoidal. The most used corrugating profile for corrugated web panels is the trapezoidal web shape, as shown in Figure (3).

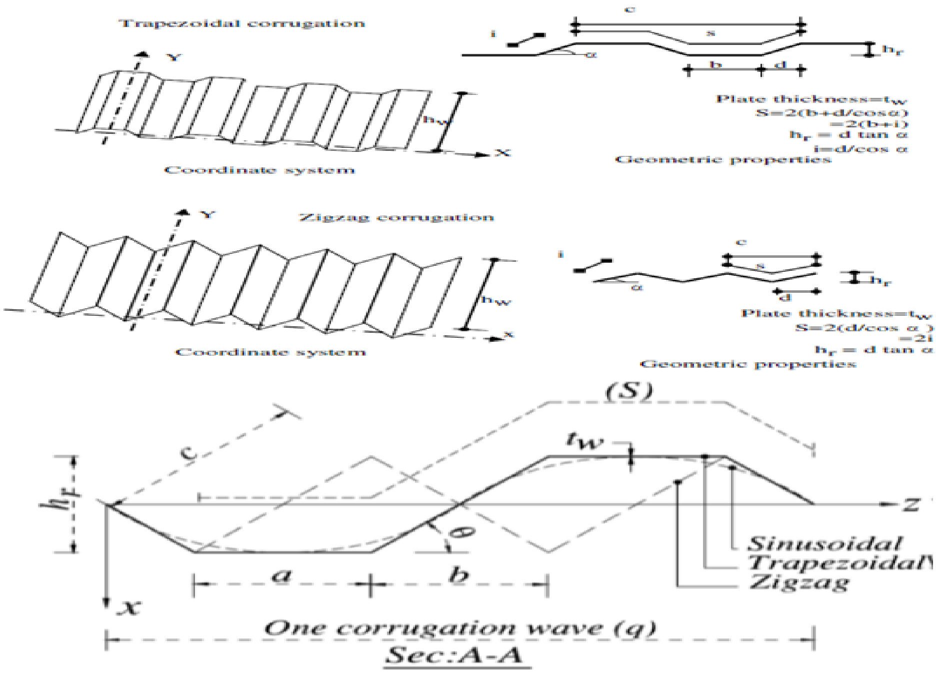

Figure 3: Corrugation configuration and geometric notation. [3]

2.2 Applications of Corrugated Web Girders

Corrugated steel web plates are also used in heavy industrial buildings in single or multi-span frames as shown in Figure (4). Different types of structural applications have been introduced to the market using corrugated steel metal as a web in a plate girder or in a shear wall. Still many applications are undergoing research and developments, especially for the case steel plate shear walls with corrugated webs. It can be used as a plate girder or mezzanine floor regular beams.

Portal frame Column and crane girder Curved airplane hangar

Figure 4: Corrugated web girder in industrial buildings

3. Behavior of Corrugated Web Girder Subjected to a Different Type of Loading

Civil engineering structures are subjected to different types of the load depending on the serviceability of the structures. In the case of steel structural, the girder may be corrugated web under one type of load that is purely shear loading, bending moment, and patch load. Or under load combination combined bending moment and shear load, combined loading and shear load or combined load patch, bending moment and shear loading. Each of these load types causes a different mode failure. Therefore, the design varies depending on which load the girder is exposed to.

4. Behavior of Corrugated Web Girder Under Shear Loading

Bergfelt, A. and Leiva-Aravena [7] studies the feasibility of using corrugated steel web girders to cover long spans, investigate different buckling of shear modes of corrugated webs, and the girders were specially manufactured to study the local and global buckling mode. The observed failure patterns were because of the interaction between local and global buckling mode. Russian Lou and Edmund [8]numerically investigated using the finite element software, ABAQUS, to simulate the experimental results conducted by Bergfelt, A. and Leiva-Aravena [7]. It was found that increasing the corrugation angle changed the mode of buckling from global buckling to local buckling. The relationship between the maximum shear capacity and both web height and thickness are confirmed. Legally et al. [9] argued that the shear deformation has to be taken into account when calculating the deflection of the girder using the corrugated web. At the same time, the moment of inertia of the cross-section can be considered a neglect of the web contribution. Saied-Ahmed [3] consider the design portion of I steel girder with a corrugated web by numerical modeling ANSYS as the FE program. The buckling conduct was studied and interaction formula was suggested. The post-buckling strength was largely dependent on the plate width of the corrugated steel web and varied between 3% and 53%. Also, the lateral buckling resistance of the corrugated girder was 12% to 37% larger than the flat web beam. Based on the FEA, it was inference that the flange-to-thickness ratio, which the Code of Practice currently utilizes as one of the criteria classifying the compression of the section, should be based on the large overhead of the flange of the corrugated web. Moon et al. [10] based on the results of the experimental tests, large trapezoidal corrugated webs were made to verify the suggested shear buckling strength. Also, the shear strengths offered is compared to those suggested by previous researchers. They concluded that the proposed shear strength provides a good calculation of the shear strength of the corrugated steel web. Souse and Braxton [11] focused on the shear strength of the trapezoidal corrugated steel web. Formerly developed equations for calculating the shear strength of trapezoidal steel corrugated webs are summarized. The different formulas for prophesying shear strength are then compared to the results of the selected test. A new formula has been developed that takes into account the interaction of different shear failure modes. More than 100 results of the previous researches are curated and estimated according to relevant test specimen's criteria. Also, the equation is assumed to give the best comparison with test results and shear test results by others. Pasternak and Kubieniec[12]examined the actual behavior at the intersection between the flange and the plate corrugated web of the girder using ABAQUS for the corrugated web with fixed (F) and simple (S) boundary conditions. The results suggested that when the flanges were sufficiently rigid (t_f / t_w<3.0), the girder exhibited a mechanism of shear failure. While if the plates of the corrugated web are relatively rigid (t_f / t_w<3), the girder strength is controlled by the deformation of the flanges. Tw, tf, HW and b are the thickness of the web, the thickness of the flange, the height of the web and the flat panel width of the corrugated web. Based on the numerical results, it was located that the trapezoidal corrugated steel web plates with fixed connections needed to satisfy the geometric condition of b / hw0.2. In addition, it has been found that to calculate the interactive buckling force, the coefficient of global buckling is 59.2 must be used because it fits better with the finite element results than another value of 68.4.Hassanein and Karoo [13]assessed the shear strength of corrugated web girders using a realistic initial deficiency amplitude using ABAQUS FEA. Based on analytical research, an equation has been proposed for the corrugated steel web of the girder to calculate the shear strength.Cao, Jiang, and Wang [14]carried out both FEA and experimental examination on the H-shaped corrugated web girder. Two various buckling modes combining local and global bending were observed in the experimental test. Parametric studies were performed by changing the thickness of the web and the stiffeners (full and half stiffeners). The parametric study results indicated that as the thickness of the web increased, the shear capacity of the corrugated web increased by 45% on average. The specimens, 3mm thickness of corrugated steel web showed a high shear carrying capacity with full stiffener. It was also concluded that, under the same web thickness and corrugation conditions, the shear strength of the full stiffener restraint was higher than those of the semi-stiffener restraint condition, by about 3%.

4.1 Behavior of Corrugated Web Girder Under Concentrated Loading

De'nan and Hashim [5] investigated the influence of a zigzag web profile on bending performance. It is found that the zigzag corrugated web plate has a higher bending strength in the main and secondary axis when the corrugation angle is 45 ° or 75 °. Also, the deflection of the zigzag corrugated web plate was lesser than the flat web and trapezoidal corrugated web. Today et al. [15]carry out an FEA using ANSYS on 96 specimens and the results were shown in the form of load versus displacement curves. It can be noted that the corrugated steel web girder has a higher loading capacity and lower deflection compared to the flat web. With a 30 ° corrugated angle, the girder demonstrated higher load capacity than other corrugation angles. Also, for small initial defects, the total deviation from the level is reasonably small at early load ages.

4.2 Behavior of Corrugated Web Girder Under Patch Loading

R. Lou and Edmund [16]investigated the capacity of the corrugated web girder under patch-loading using the Romberg-Osgood model of web strain hardening; It was found that the ultimate capacity of the corrugated web girder was 8-12% higher than the load obtained with the perfect elastic-plastic mode. Also, the ultimate capacity of the plate girder increased with the increase in the corrugation angle. The ultimate strength of α = 75 ° and 90 ° were conformable. Moreover, the maximum loading strength has increased almost in ratio to the corrugated web thickness and flange thickness. Kövesdi and Duane [17] specified the patch-loading strength of the corrugated web girder using ANSYS as a non-linear FEA and the variable geometry arrangement tested 12 samples. Four imperfection shapes were analyzed. The first critical buckling mode and sinusoidal corrugated web girder were investigated and a modified sinusoidal corrugated web girder was developed to predict the position of the buckling mode. Numerical calculations showed that the applied scaling factor was the fold length divided by 200 if the first torsion mode or modified sinusoidal forms were equivalent to geometric deficiency.

4.3 Behavior of Corrugated Web Girder Under Combined Loading

Lou and Edmund [18]also researched the behavior of the buckling trapezoidal corrugated web plates under in-plane loading, which the FEA analyzed. Several engineering variables have been studied and an experimental equation proposed. Under compressive longitudinal loading, when α (angle of corrugation) = 15 ° - 30 °, the global buckling controls when $\alpha \geq 45$ °, local buckling is controlled. Based on these buckling modes, a simplified formula was calculated for calculating local buckling stress using the average buckling modulus and local buckling stresses using the width of the corrugated plate. Abbas and Wrasse[19] recommended the shape of the demonstrated web's corrugated web girder and strength parameters. Furthermore, a new buckling theory was developed by looking at the effect of transverse bending of a flange. Also, the corrugated web girder with a higher depth of webs has more potential to be economical. Jaeger et al. [20]suggested a combined moment interaction curve, shear, and patch loading. 400 FE simulations were performed to study the shear (V) - patch (F) interaction behavior. 160 FE simulations were carried out to study the behavior of the bending (M) - shear (V) reaction. Bending failure was observed to occur in a compression flange in the middle of a parallel web fold where the protruding flange is larger. 400 FE simulations were performed to study the bending reaction (M) - loading patch (F). Based on the FEA to study, the result presented that only a slight decrease of resistance is placed in the M-V interaction curve, so the girder can be neglected in the corrugated web. From the interaction curve, M-V-F suggested a new formula which showed a good approximation of the bottom surface of the interaction bound to the results of numerical simulations, if the bending, shear buckling, and resistance correction were calculated by FEM simulations. The proposed formula was also applicable to the bending and shears buckling resistance of the EN 1995-1-5.Kövesdi et al. [21] studied girders' bending and shear interaction conduct with trapezoidal corrugated steel webs. Based on the investigation, the additional normal stress and the normal stress produced by the bending influence inside the plane were compared. The numerical estimate showed that the variation between the maximum values of normal edge stress could be significant by considering or neglecting the influence of the transverse bending moment. But this effect can be significant to elastic design. Based on FEA, it was also observed that the M-V interaction conduct of corrugated web beams did not depend on the corrugation plate. However, the ultimate value of the transverse bending moment relays on it. No relationship was noted between the value of the transverse bending moment and the reduction in bending resistance if the plastic design was applied. It can also result in that both the support type (longitudinal and lateral) can significantly reduce the maximum value of the additional normal stress within the region of the support sites.

5. Behavior of Composite Corrugated

Mo et al[22] tested with four composite corrugated web girders under cyclic flexural loading. Test beams were 5.04 m long and 0.395 m deep. The girder cross-section of 1/6 scale is constructed for Shania Bridge in Japan. The tests aimed to verify the conduct of this structural system under cyclic-loading and the predictability of the load-deflection curve. FEA has been developed to simulate the experimental tests. The results presented a good agreement between the FEA and experimental results. The results also cleared the high levels of ductility provided by these structural systems under periodic loading. El-Metwally [23] examined five simply supported composite girders at a length of 5.5 meters, under two-point loads, as in Figure (4). Beams are manufactured with reinforced concrete top flange, pre-stressed concrete bottom flange, and custom-made zigzag corrugated steel web. The pre-stressing strength has been chosen so that the lower flange fibers do not suffer from any cracks reaching 70% of the girder's maximum bending capacity. The only parameter in the test series was the width of the corrugated web sub-plate. The intent was to investigate the tendency of the corrugate web to be governed by local or global buckling mode, ass seen in Figure (5).

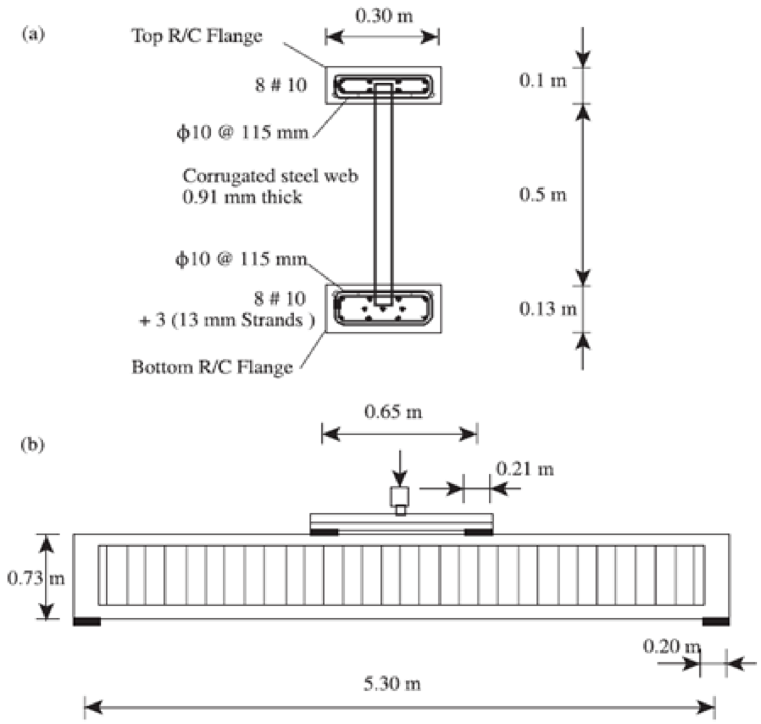

Figure 5: Composite specimen tested by El-Mentally [23]

The experimental results demonstrated that individual diagonal buckles started in the branch panels in both shear spans. Then, the diagonal buckles began to cross the fold lines and extend to the adjacent sub-panels. Then, the diagonal buckles began to cross the fold lines and extend to the adjacent sub-panels. The load-vertical deflection curves of all tested samples showed elastic behavior and the discharge portion of the curves showed a recovered deflection of approximately 50.El-Mentally et al. [24]suggested a formula to show the interaction between the three failure modes: local buckling, global buckling, and shear yield. Kim et al. [25] conducted a preliminary design study composite and non-composite bending strength of concrete concrete-filled tube flange girders using high-performance steel, as shown in Figure (6). The researchers performed a parametric study on design of bending strength, considering LTB and submission to building and service conditions. The system has an optimized LTB strength. They also conducted experimental research and investigated it with finite element analysis. The experiments showed that the horizontal (lateral) displacements of the beams were influenced by the initial deflects.

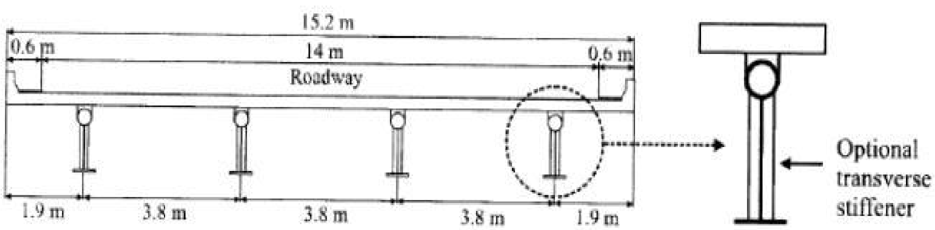

Figure 6: Prototype bridge tested by Kim et al. 2005[25]

Kim et al. [26] girders and two pre-stressed composite girders were manufactured with a full-scale corrugated web and experimental results were conducted to study the bending behavior, as shown in Figure (7). The bending behavior of girders, reflecting the corrugated web effect, was verified. The tests resulted in the following conclusions;

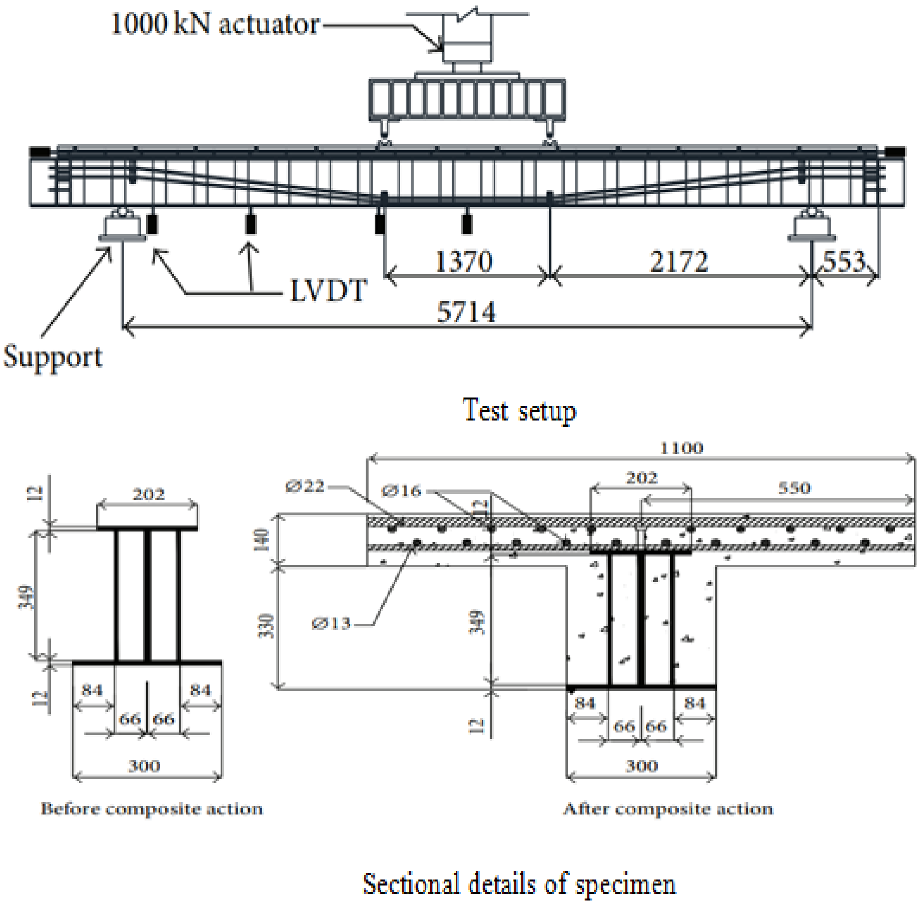

Figure 7: Details of pre-stressed composite CWG by(Kim et al. 2011) [26]

1) The corrugated steel web girder was very effective in introducing greater pre-stressing at the upper and lower flanges, than the typical I-shaped steel girder because of the corrugated web effect.
2) Using the inertial efferent moment and effective web zone factor, suggested in their research, made the corrugate effect easier to consider and introduced a very accurate calculate close to the test results.
3) As Compared with the non-pre-stressed sample FNC, the flexural stiffness and capacity of the pre-stressed sample FPCE1 and FPCE2 increased by about 20 and 25 %, respectively, which verifies the best structural performance, in the view point of span length and story height, from the pre-stressed composite girder with corrugated steel web, suggested in the previous paper.

Oh et al. [27] Both theoretical and experimental studies were carried out to find out the effect of corrugated steel webs to girders upon the transfer of pre-stressing as shown in Figure (8). Through the FEA and the classical structural mechanics path, two analysis models were proposed for the quantitative evaluation of the effect of corrugated web, which were also verified by the examine results. Based on the experiments and analyzes conducted in this study, the following conclusions were acquired;

1) Based on the FEA, it was confirmed that the corrugated effect induced in the steel girders with corrugated webs onto pre-stressed transfer was largely dominated by the geometric properties of the corrugated web.
2) The magnitude of the pre-stress's instantaneous rapid loss was stressed because of the elastic shortening and the anchorage-seating loss was sensible.
3) It was experimentally verified that the pre-stressing was introduced into the upper and lower flanges of the steel girder with corrugated web, which are the main bending strength elements, which were greatly increased, as compared with the typical I-section steel girder due to the corrugated web effect. Also, very few strains were induced on the corrugated web, in contrast to a typical wide flange girder.

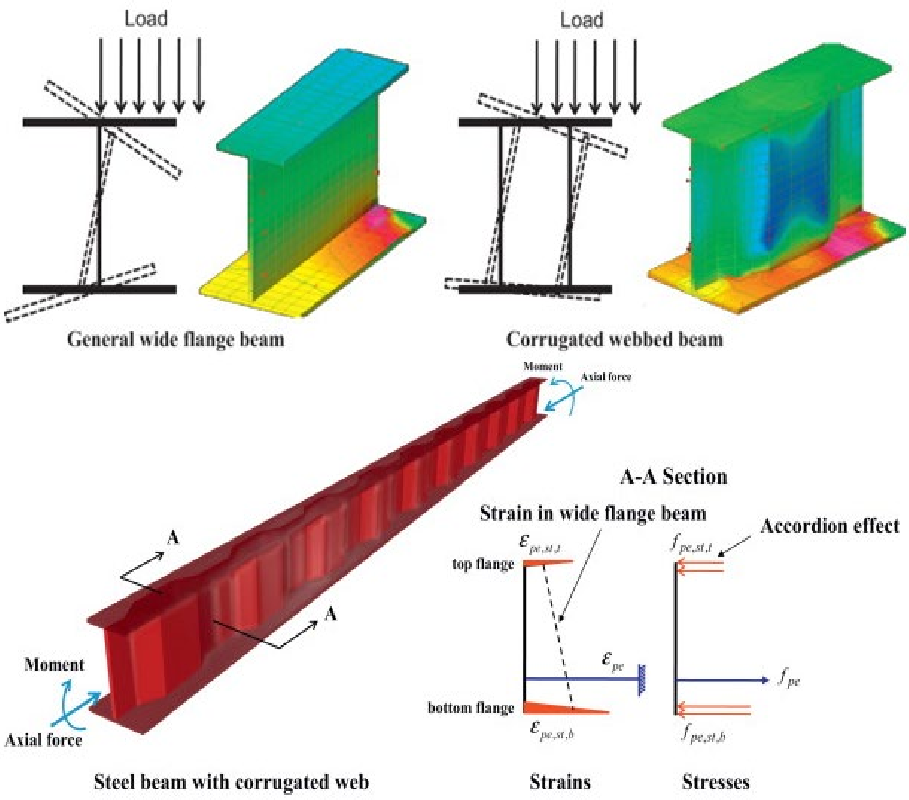

Figure 8: Accordion effect in CWG by (Oh et al. 2012)[27]

He et al. [28] The mechanical action of the corrugated web composite box girder and slab of steel tube has been experimentally examined by testing a full scale model as shown in Figure (9). A FEA model and a simplified analytical method for assessing the load bearing capacity have been proposed depending on the experimental tests. The following conclusions have been drawn from the research;

1) The girder test results demonstrate that the structure is in an elastic state under the design load, the normal stress of the steel pipe, and the shear stress of the corrugated steel web is much lower than the permissible values in the state for service. Furthermore, the steel yield load is about 5.5 and 2 times for the design load and the service load, while the splitting when the yield of steel is about 13 and 3 times the design condition and serviceability respectively. It was assured that the composite girder test has sufficient loading capacity and ductility.
2) A FE three-dimensional model was created that considers nonlinear materials to investigate static behavior under a partially distributed load. The curves of the load-displacement and stress distribution prophesy by the finite element model match well with those obtained from the experiment results, showing the accuracy of the suggested finite element model.
3) Experimental and numerical strains on the corrugated steel web were very small even next yielding of the lower slab while the corrugated web shear stress increased linearly with applied loading and uniformly distributed along with the height of the corrugated web. It was found that the flexural strength was withstood from the top and bottom slabs without considering the contribution of the corrugated steel web because of the effect-corrugated. Still the shear strength was nearly resisted on the corrugated web.
4) A simplified analytical style has been suggested to predict the loading strength of composite girders with corrugated webs according to the stress-strain relationship, the stress distribution of cross-section and equilibrium conditions. The simplified analytical load strength is a little lower than that tested and FE, indicating that it can be used to prognosticate the loading strength of this composite girder with corrugated steel webs at the margin of safety.

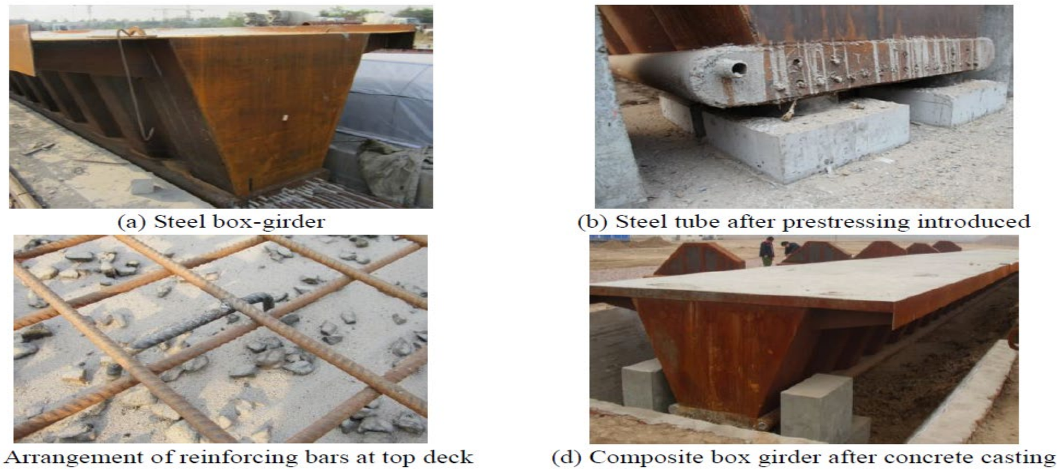

Figure 9: Fabrication process of test specimen by He et al. 2014 [28]

Oh et al. [29] The corrugated webbed pre-stressed composite member was developed to improve the efficiency of the pre-stress introduced into the steel beam. Additionally, a unified analysis model that can estimate the nonlinear flexural behavior of the composite member and the accordion effect of the corrugated webbed steel beams at the pre-stressing stage was proposed. This innovative composite member can reduce the amount of steel materials used. Flexural tests were carried out to investigate their structural performances, and their behaviors were analyzed in detail by a nonlinear finite element analysis, as shown in Figure (10). The following conclusions were drawn:

1) The nonlinear finite element analysis approach presented in this study was able to properly evaluate the structural behaviors of the discontinuous-webbed pre-stressed composite members, including the flexural strengths and the stiffness as well as the local behaviors.
2) From the results of both the tests and the finite element analyses, it was confirmed that the introduction efficiency of pre-stress to the top and bottom flanges, which are the main flexural resistance elements, was greatly improved by using the accordion effect of the steel beam fabricated with the discontinuous webs.
3) With the reduced cross-section of the steel web due to the openings, the shear stresses in the web steel plate are likely to be partially increased. Its effect was; however, marginal, and sufficient safety can be achieved by considering the reduced cross-section in the calculation of the shear strength of the discontinuous-webbed pre-stressed composite member according to the design specification.

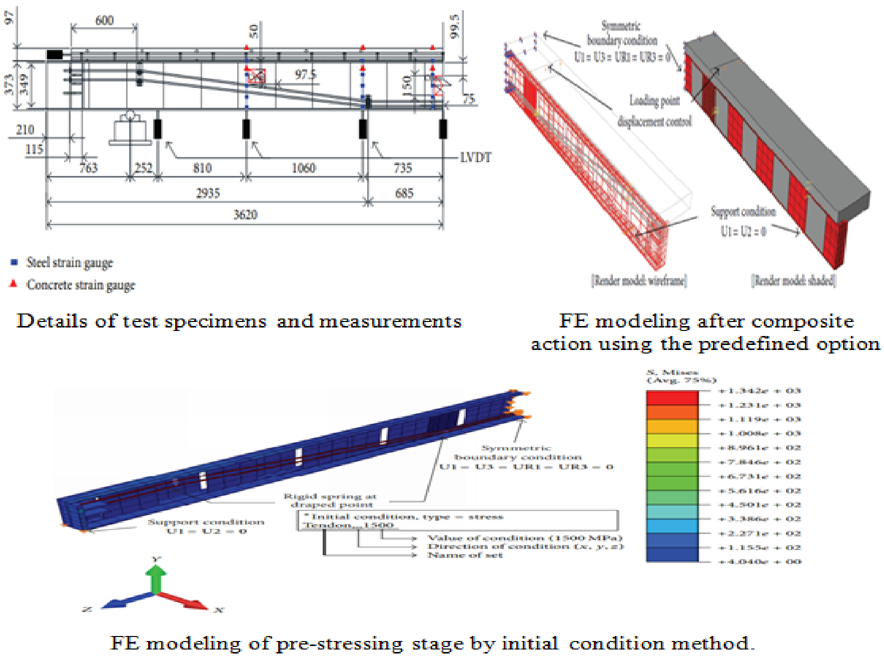

Figure 10: Figure 10: Test setup and location of measurements devices by Oh et al. [29]

Lamar et al. [30] the experimental investigation investigated contributes effect of a top steel flange of composite concrete steel beams with the corrugated web as an important factor for both overall behavior and flexural capacity well as on the failure mechanism of the concrete slab. From this experience, the following conclusions were drawn:

1) The web plate upper horizontal restraint, which prevents local buckling in the corrugated web, is provided by the upper steel flange.
2) The concrete slab horizontal sliding is preventing by a complete shear connection between the concrete and top steel flange.
3) The main part of the concrete-steel composite beam, responsible for the strut-and-tie failure mechanism, is the upper steel flange.
4) The first cracks formed by the support and connection mechanism depend on the width of the contact surface between the concrete slab and the upper steel flange.
5) The concrete and steel composite section with steel flange shows 30% higher stiffness and 12% rise in final load over that obtained in the section without the upper steel flange, as evidenced by the conduct of the composite section with the upper steel flange. As seen in Figure (11).

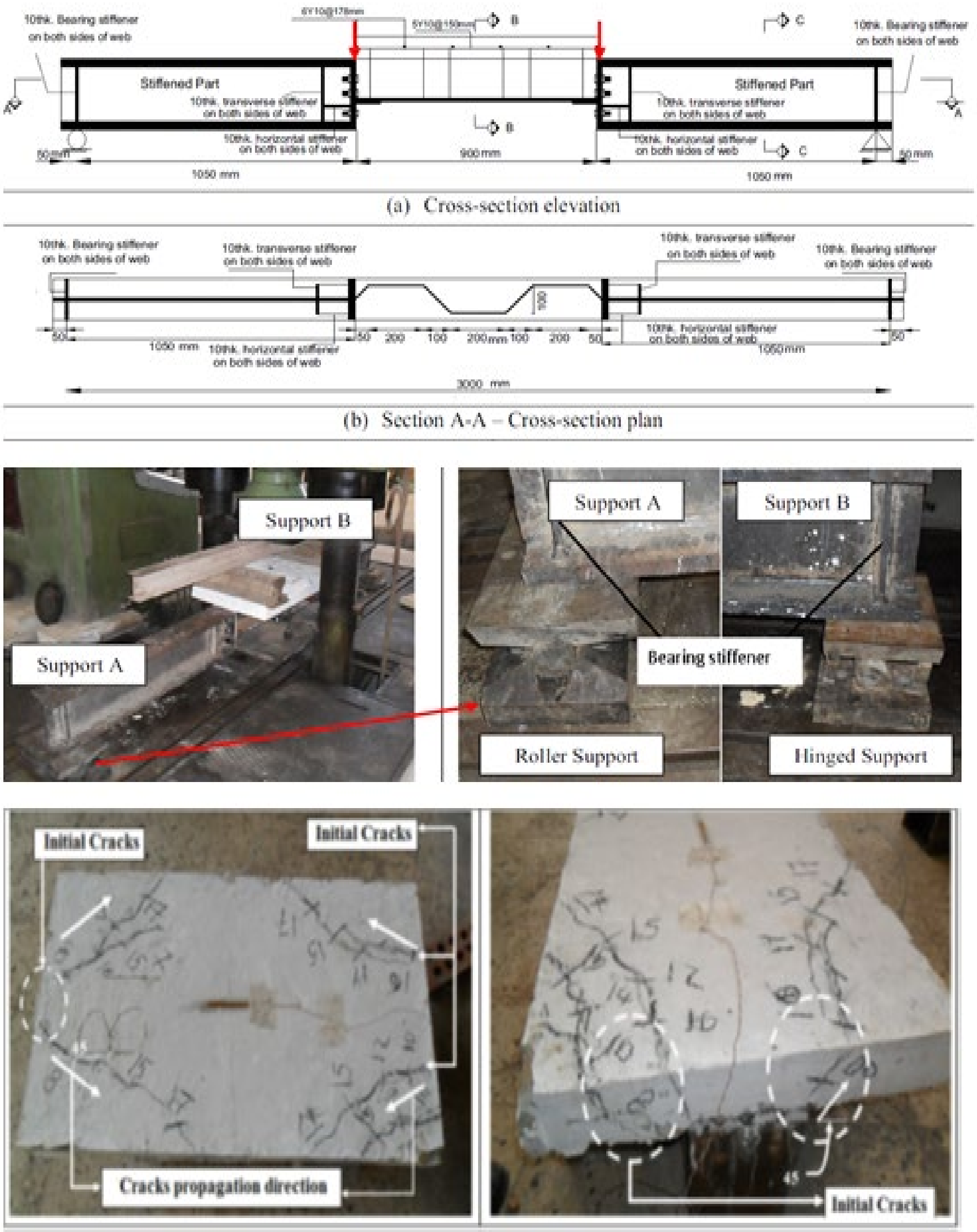

Figure 11: Test setup and location of measurements devices by Lamar et al. 2017) [30]

Gerick and Śledziewski [31]analyze the girder behavior of I-shaped steel-concrete composite girders with sinusoidal web geometry when subjected to a four-point load test. So it was that composite girders with corrugated steel web could transmit large loads without using web stiffeners. The absence of ribs in the corrugated web girders, especially under load points, did not cause buckling on the local web. The only effects were the raised strain values, as measured by strain gauges installed near the loading zones.as shown in Figure (12).

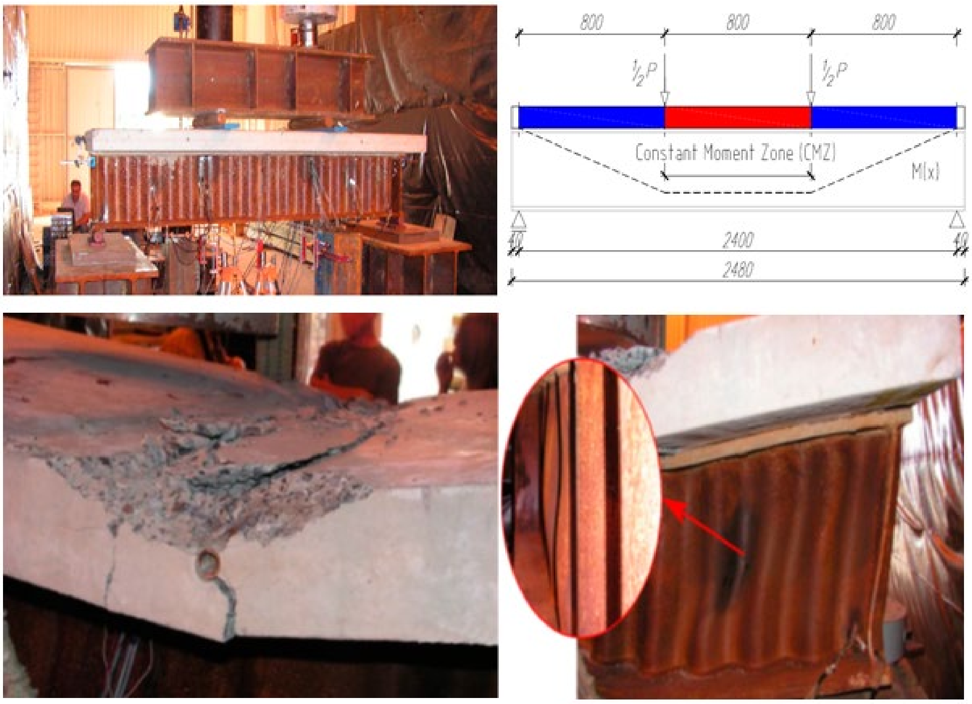

Figure 12: Test setup and location of measurements devices by Gerick and Śledziewski 2020[31]

Greuze and Babinski [32] strengthened corrugated web girders because their attachment to the concrete slab exhibits higher shear resistance than their non-strengthened counterparts. However, the effectiveness of the strengthening decreases slightly as the girder height or web thickness increases. To a decreased extent, resistance improvement is created, by taking a part of the shear force by slab, and to a greater extent, by optimizing the boundary conditions of the web. The results were an improvement from a significant raise in the torsional stiffness of the flange resulting in web-edge stiffening. The application of concrete slab causes an increase in global strength and expands the linear elastic range of the load - deflection relationship. In addition, the increase in plastic deformation can be slowed down. Obtained of the results can be utilized as a basis for evaluating the validation of strengthening potential structural. Concrete slab connected to a steel girder can be considered a substitution method to enhance shear strength in composite girders with the corrugated web.

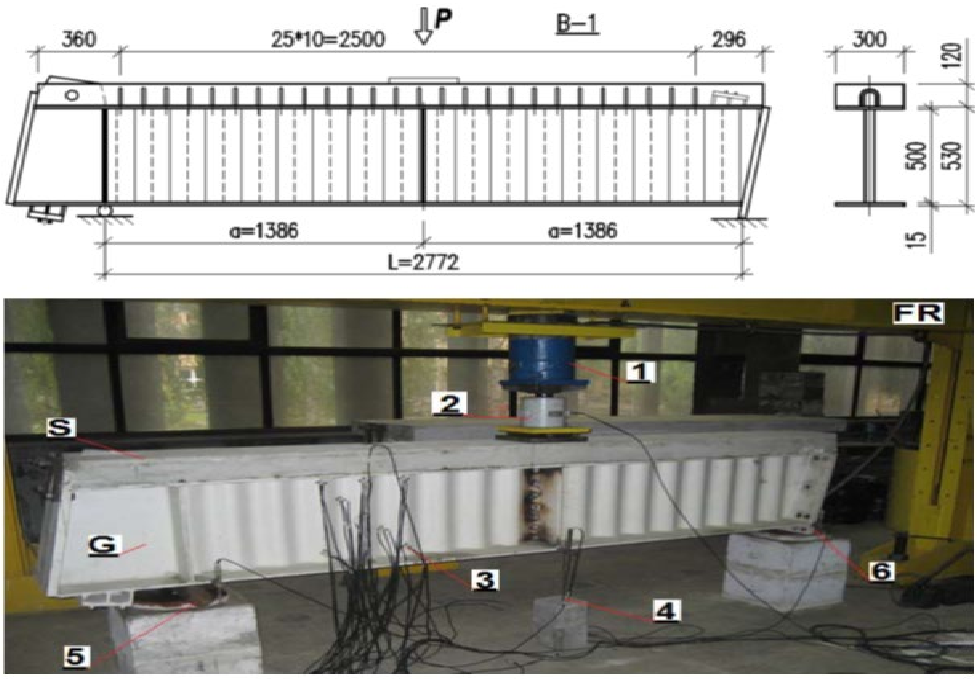

Figure 13: Composite girder B-1 WTA500 with a concrete slab – dimensions and static diagram [32]

6. Conclusions

Corrugated web girders are a promising case in the structural engineering of the world in general and bridges in particular. More recently, it has the lion's share in small and medium span bridges, and in the past few years, it has been implemented to remain cable bridges. In this paper, the differences in literature review studies of composite and non-composite corrugated steel girders under different types of loads are reported in detail. FE of corrugated steel beams was developed utilizing various FE software such as ABAQUS, ANSYS, and LUSAS to different research variants. Much remains to be done in studies for this type of structure. My prediction for the future is that within a period of 30 to 50 years, the traditional flat web solid welded plate girders will disappear and be replaced by corrugated web girders.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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