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Corrugated web steel girders-A state of the art review

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ABSTRACT: *Plate girders are widely used in bridges as well as industrial buildings. As we know, plate girders have maximum moment carrying capacity than any other hot rolled sections used. To carry these moments economically, normally webs with larger depth to thickness ratio are used resulting in slender sections which are susceptible to web buckling. Hence to avoid web buckling and to gain maximum strength, corrugations are provided in the web region. The corrugated steel plate can be used in many fields of applications because of its favorable properties. This new achievement has helped engineers to design more optimal structures. In this paper, a review of the research carried out on corrugated web steel girders both experimentally and analytically is presented.*
KEYWORDS:*Corrugated web, different loading, geometric parameters*

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I. INTRODUCTION

Plate girders have been used for many years mainly in bridges and industrial buildings. The I - section or H - piles are commonly used section in steel plate girder. Ordinary shapes of these beams are constructed from two parallel flanges and a web where about 30-40% of the entire weight is contributed by the web part. As we know, I - beams are subjected flexural members and these are mainly designed for bending moments and shear forces. Economical design of beams 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 in the web. The main benefit of the corrugated web beam is to increase the stability of the beam against buckling. A corrugated web girder is shown in the figure 1 represents a new structural system that has excellent load carrying capacity.

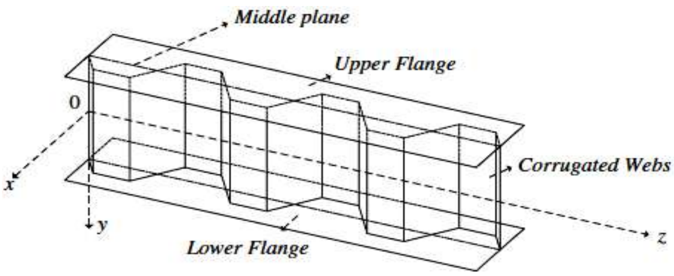

Figure 1. Trapezoidal corrugated web girder[8]

The purpose of using corrugated web is that it permits the use of thin plates without the need of intermediate stiffeners. Furthermore, the use of thinner webs results in lower material cost, with an estimated cost savings of 10-30% in comparison with the conventional fabricated sections and more than 30% compared with standard hot rolled sections.

II. CORRUGATION PROFILE AND ITS APPLICATIONS

2.1Types of Corrugation Profiles

In order to increase the shear capacity of the web portion, research has been carried out worldwide on plate girder with different corrugation profile in the web region viz trapezoidal, sinusoidal, triangular, square, rectangular etc. The sinusoidal profiling of the web generally avoids failure of the beam due to loss of stability before it reaches the plastic limit loading.

Also sinusoidal profiling eliminates the problem of the local buckling of the web. This aspect represents an advantage compared to the trapezoidal web beams, whose web may fail due to local buckling, as it is made up by a number of flat sections. Triangular web profiles as shown in figure 2 were also chosen as a corrugation in web region. Due to the introduction of slanting stiffeners, it shows a greater bending strength compared to trapezoidal corrugated web profile.

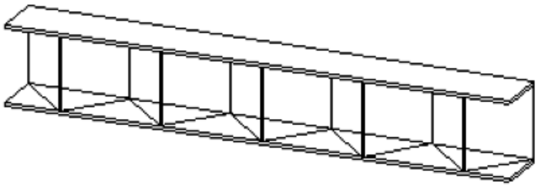

Figure 2. Triangular corrugated web profile[9]

The dimensioning of corrugated web beam is popularly based on EN-1993-1-5 Annexure D, which covers only web thickness up to 3mm. Also older German standards like DASt-Ri.015 for corrugated web beams, but this standard deals with beam with trapezoidal corrugated webs only. The EN 1993-1-5 gives rules for both trapezoidal and sinusoidal corrugations. The most commonly used corrugation profile for corrugated web plates is the trapezoidal web profile.

Figure 3 shows the corrugation configuration and geometric notations where w is the maximum fold width, b is the maximum flat panel width, c is the maximum inclined panel width, h_r is the depth of corrugation, α is the corrugation angle and t_w is the web thickness.

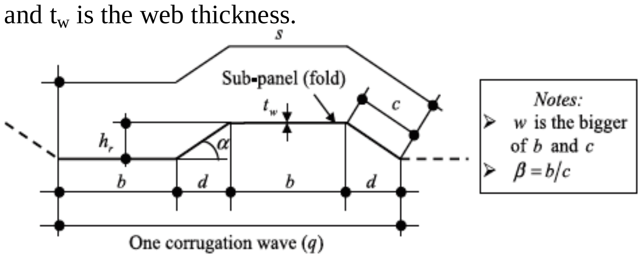

Figure 3. Corrugation configuration and geometric notation[10]

2.2 Applications of Corrugated web girders

Corrugated web profiles are also used in heavy industrial buildings in single or multi span frames shown in figure 4. In Innsbruck stadium, Austria, 16m long sinusoidal beams are used as purlins. By applying corrugated webs to extradosed bridges and cable stayed bridges, it is possible to increase the span further. Figure 5 represents the usage of corrugated web girder in bridge construction.

Figure 4. Corrugated web girder in industrial buildings

Figure 5. Corrugated web girder in Bridge construction

III. BEHAVIOUR OF CORRUGATED WEB GIRDER SUBJECTED TO DIFFERENT TYPES OF LOADING

Civil engineering structures are exposed to different types of loading depending upon the serviceability of the structures. In the case of steel bridges, the corrugated web girder might be under one type of loading that is pure shear loading, bending moment, patch loading or under a combination of loading that is combined shear loading and bending moment, combined patch loading and shear loading or combined patch loading, shear loading and bending moment. Each of these type of loading causes different failure mode. Therefore, the design varies depending on which applied load the girder is subjected to. Numerous studies have been presented and summarized in table 1.

Table 1. Corrugated web girders subjected to various load cases

S.I. No.	Author(s)	Year	Shape of corrugated web profile	Type of loading	Analytical (A), Experimental (E) and Numerical (N)	Parameters studied	Remarks
1.	Luo et al	1994	Trapezoidal	Combined shear and compressive loading	A and N	Overall geometric parameter, various loading forms and different boundary conditions.	Interactive curves were suggested for practical design.
2.	Luo et al	1996	Trapezoidal	Patch	A and N	Overall geometric parameters	Empirical formulae were suggested.
3.	Luo et al	1996	Trapezoidal	Shear	A and N	Overall geometric parameters	Ultimate shear capacity was suggested.
4.	Abbas et al	2003	Trapezoidal and Sinusoidal	Shear and Bending	N, A and E	Overall geometric parameters	New shear strength and flexural strength theory were recommended to AASHTO bridge design specifications.
5.	Ezzeldin	2007	Trapezoidal	Pure Shear	N and A	Different panel width to web height ratio and various spans.	An interaction equation defining the interactive failure mode of the corrugated web plate was proposed.
6.	Pasternak et al	2010	Sinusoidal	Shear	A and E	-	Focused on welding simulations and residual stress arising from welding process.
7.	Kovesdi et al	2011	Trapezoidal	Patch	A and E	Different loading length, various loading positions, change thickness of flange and change in span.	Failure mode, load carrying capacity and post ultimate behavior were analyzed.
8.	Moon et al	2012	Trapezoidal	Bending	A and N	Different corrugation angle and various spans.	Equation for moment gradient correction factor was suggested.
9.	Denam et al	2012	Triangular	Concentrated loading	A	Different span and corrugation angles.	Presented the analysis in terms of flexural stiffness.
10.	Hassanein et al	2013	Trapezoidal	Shear	A and N	Overall geometric parameters.	New interactive shear buckling formula was proposed.
11.	Hassanein et al	2013	Trapezoidal	Shear	A and N	Overall geometric properties	Proposed a formula for the shear strength calculations of corrugated web girder.
12.	Sedky et al	2013	Trapezoidal	Concentrated loading	A	Overall geometric parameters- web slenderness, corrugation angle and aspect ratio of web.	Presented the analysis in terms of load vs deflection.
13.	Ibrahim et al	2014	Trapezoidal	Bending	A and N	Different corrugation angle and flange width.	A new warping constant was derived.
14.	Jager et al	2015	Trapezoidal	Combined bending, shear and	A and N	Overall geometric parameters	Developed a design interaction equation for the

				patch			combined M-V-F loading
15.	Qi Cao et al	2015	Trapezoidal	Shear	A and E	Various web thickness and varied the stiffeners as full and half stiffeners.	Three failure modes were observed and presented the analysis in terms of load vs deflection curves.
16.	Kovesdi et al	2017	Trapezoidal	Bending and Shear	A and N	Overall geometric parameters	Determined the transverse bending moment and its effect on load carrying capacity.

3.1 Behavior of corrugated wed girder under shear loading

Luo et al [2] numerically investigated the shear capacity of the plate girder with trapezoidally corrugated web using non linear finite element analysis, ABAQUS. It was found to be that both the ultimate and post buckling shear capacity increases as the web thickness increases but they are not proportional to the cube of web thickness. Ezzeldin [5] studied the design aspects of steel I girder with corrugated web by numerical modeling using ANSYS as finite element software. The buckling behavior was investigated and interaction equation was proposed. The post buckling strength was found to be highly dependent on the panel width of corrugated webs and it varied between 3% and 53%. Also, the resistance of lateral torsional buckling of corrugated web girder was 12% to 37% higher than that of flat web girder. Based on the numerical model it was concluded that the flange outstand-to-thickness ratio, which is currently used by codes of practice as one of the criteria classifying the section compactness, should be based on the large outstand of the corrugated web girder's flange.

Pasternak et al [6] discussed the overall design process and the welding simulations between the flange and web. The residual stresses resulting from the welding process were studied using non linear analysis. Strain gauge measurements showed highly nonlinear normal stress distribution across the cross-section of flange especially in area of welding zone. This nonlinearity was much more visible in tension flange than in compression one, and can be an evidence of existing residual stresses resulting from welding process which are superimposed with those from bending. Hassanein et al [10] studied the actual behavior at the juncture between flange and corrugated web of the bridge girder using ABAQUS for corrugated web with simple (S) and fixed (F) boundary conditions. The results indicated that when flanges were rigid enough ($t_f/t_w \geq 3.0$), the girder exhibited shear failure mechanism. Whereas if the corrugated web plates were relatively rigid ($t_f/t_w < 3$), the strength of the girder is controlled by the deformation of flanges. t_f, t_w, b and h_w are thickness of flange, thickness of web, flat panel width of the corrugated web and height of the web. Based on the numerical results, it was found that the trapezoidally corrugated steel web plate segments with fixed junctures needed to satisfy the geometric condition of $b/h_w \leq 0.2$. In addition, it was found that to calculate the interactive buckling strength, the global buckling coefficient of 59.2 should be used because it fits better with the FE results than the other value of 68.4 according to [17]. Hassanein et al [11] evaluated the shear strength of bridge girders with corrugated web using the realistic initial imperfection amplitudes by using ABAQUS, finite element analysis. Based on analytical study, a formula for the shear strength calculation bridge girder corrugated web was proposed.

Qi cao et al [15] performed both finite element analysis and experimental investigation on corrugated web H shape girder. Two different buckling modes consisting of local and global buckling were observed in the experimental test. The parametric studies were carried out by varying web thickness and stiffener positions (full stiffener and half stiffener). The parametric study results indicated that as web thickness increases, shear capacity of corrugated web increased by 45% on average. Among all the specimens, 3mm thickness of corrugated web with full stiffener showed a higher shear carrying capacity. It was also inferred that, under the same web thickness and corrugation conditions, shear capacities of full stiffener restraint were higher than that of half stiffener restraint condition, by about 3%.

3.2 Behavior of corrugated wed girder under bending

Moon et al [8] investigated the flexural-torsional buckling of I-girder with corrugated web under linear moment gradient using ABAQUS. The moment gradient correction factor (C_b) for the I-girder with corrugated steel webs under linear moment gradient was proposed. Finally, the inelastic flexural–torsional buckling strength considering the effects of material inelasticity, initial imperfection, and residual stress were investigated. It was found that the inelastic buckling strength varied depending on the numbers of periods of the corrugations and direction of initial imperfection. From the series of finite element analysis, it was found that the flange of the girder deformed in the out of plane direction with a single curvature when corrugated web has an even number of half corrugations. Thus an odd number of half corrugations were effective to reduce transverse deformation of the flange prior to buckling.

Ibrahim et al [13] investigated the lateral torsional buckling strength of unsymmetrical plate girder with corrugated web by finite element analysis. The effects of different geometric parameters such as corrugation depth, horizontal fold length, web height, and un-symmetry parameter on the critical buckling moment were discussed. $M_{cr,cw}$ and M_p are critical moment of corrugated web and plastic moment. With the increase of h_w/t_w ratio from 100 to 250, the ratio of $M_{cr,cw}/M_P$ decreased by 14%. The location of centre of the shear centre was determined and a closed form of the warping constant was derived. It was found that the depth of corrugation has a major influence on critical lateral torsional buckling. Also, the unsymmetrical corrugated web girder has an elastic lateral torsional buckling capacity of up to 11% more than the plate girder with flat web.

3.3 Behavior of corrugated wed girder under concentrated loading

Denam et al [9] studied the effect of triangular web profile on bending performance. It was found that the triangular corrugated web profile has a higher resistance to bending in minor and major axis when the corrugation angle is 45° or 75°. Also the deflection of triangular corrugated web profile was lesser than flat web and trapezoidally corrugated web. Sedky et al [12] has performed a finite element analysis using ANSYS on 96 models and the results were represented in the form of load vs displacement curves. It can be seen that, the corrugated web girder has higher load carrying capacity and lesser deflection compared with flat web. With an angle of corrugation 30°, the girder showed higher load carrying capacity compared with other corrugation angles. Also for small levels of initial imperfections, the total out of plane deflection is reasonably small in early ages of loading.

3.4 Behavior of corrugated web girder under patch loading

Luo et al [3] studied the strength of the corrugated web girder under patch loading with a Ramberg-Osgood strain hardening mode for webs; it was found that the ultimate strength of the girder was 8-12% higher than the obtained load with an elastic-perfect plastic mode. Also the ultimate strength of girder increased as the corrugation angle increases. The ultimate load for α=75° and 90°were identical. Furthermore, the ultimate load capacity increased almost proportionally to the web thickness and flange thickness.

Kovesdi et al [7] determined the patch loading resistance of corrugated web girder using ANSYS as non linear finite element analysis and experimentally 12 specimens were tested by varying geometrical arrangement. Four imperfection shapes were analyzed. The first critical buckling mode and the sine wave imperfection form were investigated and a modified sine wave imperfection was also developed to predict the first buckling mode. Numerical calculations showed that the applicable scaling factor was the fold length divided by 200, if the first buckling mode or the modified sine wave shapes are used as equivalent geometric imperfection.

3.5 Behaviour of corrugated wed girder under combined loading

Luo et al [1] also studied the buckling behavior of trapezoidally corrugated web panels under in-plane loading, analyzed by spline finite element method. Various geometric parameters have been investigated and empirical formula was suggested. Under longitudinal compressive loading, when α (corrugation angle)=15°-30°, global buckling governs when $\alpha \geq 45°$, local buckling governs. Based on these buckling modes, a simplified formula for calculating local buckling stress using average buckling coefficient and local buckling stresses using corrugated panel width were computed. Abbas et al [4] has recommended corrugated web girder shape and strength criteria for the demonstrated web. A new flexural theory has been developed by considering the effect of flange transverse bending. Also the corrugated girder with deeper webs has greater potential to be economical.

Jager et al [14] proposed an interaction curve for combined moment, shear and patch loading. 400 numerical simulations were executed to investigate the shear (F) – patch (V) interaction behavior. 160 numerical simulations were performed to investigate the bending (M) – shear (V) interaction behavior. It was observed that the bending failure occurs in the compression flange at the middle of the parallel web fold where the outstanding flange is greater. 400 numerical simulations were performed to investigate the bending (M) – patch loading (F) interaction. Based on the numerical investigation, the result showed that only slight resistance reduction were developed in M – V interaction curve, so it can be neglected in corrugated web girder. From M-V-F interaction curve a new equation was proposed which showed a good approximation of the lower bound interaction surface to the numerical simulations results, if the bending, shear buckling and patch resistances were determined by FEM simulations. The proposed equation was also applicable to the bending and shear buckling resistances of the EN 1995-1-5.

Kovesdi et al [16] investigated the bending and shear interaction behavior of girders with trapezoidally corrugated web. Based on the investigation, additional normal stress and the normal stress resulting from the in - plane bending effect were compared. The numerical calculations showed that the difference between the maximum values of flange normal stress can be significant by considering or neglecting the effect of transverse bending moment. But this effect can be significant for elastic design. Based on the numerical calculations it was also observed that the M-V interaction behavior of corrugated web girders does not depend on the corrugation profile. However the maximum value of the transverse bending moment depends on it. No relationship was observed between the magnitude of the transverse bending moment and the bending resistance reduction, if plastic design is applied. Also it can be concluded that both the type of support (longitudinal and lateral) can significantly reduce the maximum value of additional normal stress within a region of support locations.

IV. CONCLUSION

In this paper, various literature studies related to corrugated web steel girder under different types of loadings has been reported elaborately. Different parametric studies under different types of loading for various corrugation profiles are studied in depth. From table 1 the behavior of corrugated web girder is well understood under different types of loadings. The numerical modeling of corrugated web steel girders were developed using different finite element software such as ABAQUS, ANSYS, LUSAS in order to study the different parameters.

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