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FINITE ELEMENT ANALYSIS OF COMPOSITE PLATE GIRDERS WITH A CORRUGATED WEB

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Abstract

Corrugated steel plates are widely used in pre-stressed box girder bridges due to its ability to achieve an adequate shear buckling resistant and reduce the dead weights. The present study aimed to determine the static behaviour of two and four panels composite plate girder with a corrugated web by using LUSAS software. The numerical models were validated according to the outcomes of a previous experimental test. The validation results indicated a good consistency in terms of load-deflection response, shear strength and failure mode. Intensive parametric studies were carried out to determine the effects of corrugation angle (α), corrugated web thickness (t_{web}), flange thickness (t_{flange}) and concrete strength on the behaviour of composite plate girder. The results indicated a positive increase in the shear strength and change in the failure mode of the both investigated girders with the increase of corrugation angle, web and flange thickness. On the other hand, a slight effect was noted for the concrete strength on the shear resistance and failure mode of the composite plate girders with corrugated webs, therefore, a considerable reduction in the construction cost might be achieved by utilizing a normal concrete strength in the design.

Keywords: Corrugation angle, Deflection, LUSAS, Plate girder, Web thickness.

1. Introduction

In the last decades, high-performance steel had broadly used in the highway bridge applications due to its high strength, excellent toughness, as well as good weld-ability and corrosion resistance. The main impediments to its effective use in conventional flat plate girders are the web instability, excessive deflections, and fatigue failure. The innovative design of webs with different corrugations types such as trapezoidal and sinusoidal had successfully overcome these limitations via provide enhanced shear stability and eliminate the needs for transverse stiffeners which significantly reduces the girder weight and cost [1].

Corrugated web girders can be constructed with two non-composite steel flanges, or composite with concrete at upper flange only or both flanges. Corrugated web system is widely used in pre-stressed box girder bridges. Several experimental tests were conducted to assess the behaviour of non-composite and composite plate girders with corrugated webs [2-10]. In case of composite plate girders with corrugated webs, Sayed-Ahmed [11] and Shanmugam and Baskar [12] stated that the corrugated web solely provides the shear strength of the cross-section, while the flanges solely provide the flexural strength of the girder with no contribution from the corrugated web. Three failure modes of the local buckling, global buckling, and an interaction were noted in the case of corrugated webs.

In the same context, Kadotani et al. [13] concluded that 65% of the shear acting on the girder was resisted by the corrugated steel web, with the proportion decreasing after the yielding of steel. Zhou et al. [14] indicated that a big part of bending moment is burdened by the top and bottom of concrete slab, while the shear force is mainly burdened by corrugated steel web and distributed uniformly along the direction of corrugated steel web height. Shitou et al. (2008) [15] found that the shear contribution of corrugated steel web increased with the propagation of cracking in the concrete flanges but decreased gradually after reaching the yielding state. Ding et al. [16] noted that the yielding torque and ultimate torque of composite box girder decreased when the thickness of corrugated steel web decreased under a pure torsion load.

In this field, the finite element method (FEM) had given a good alternative to evaluate the response of steel plate girders with corrugated webs [17-22]. Yi et al. [23] used ABAQUS software to study the shear buckling behaviour of non-composite trapezoidal corrugated steel webs. The results showed that the interactive shear buckling mode and strength was not influenced by material inelasticity or yielding, but rather by the geometry of the corrugated plate.

Basher et al. [24] determined the behaviour of composite plate girders with trapezoidal curved corrugated webs by using LUSAS software. The results indicated that the ultimate shear resistance is influenced significantly by the width and depth of the corrugation. Larger corrugation width and depth caused a drop in ultimate shear strength.

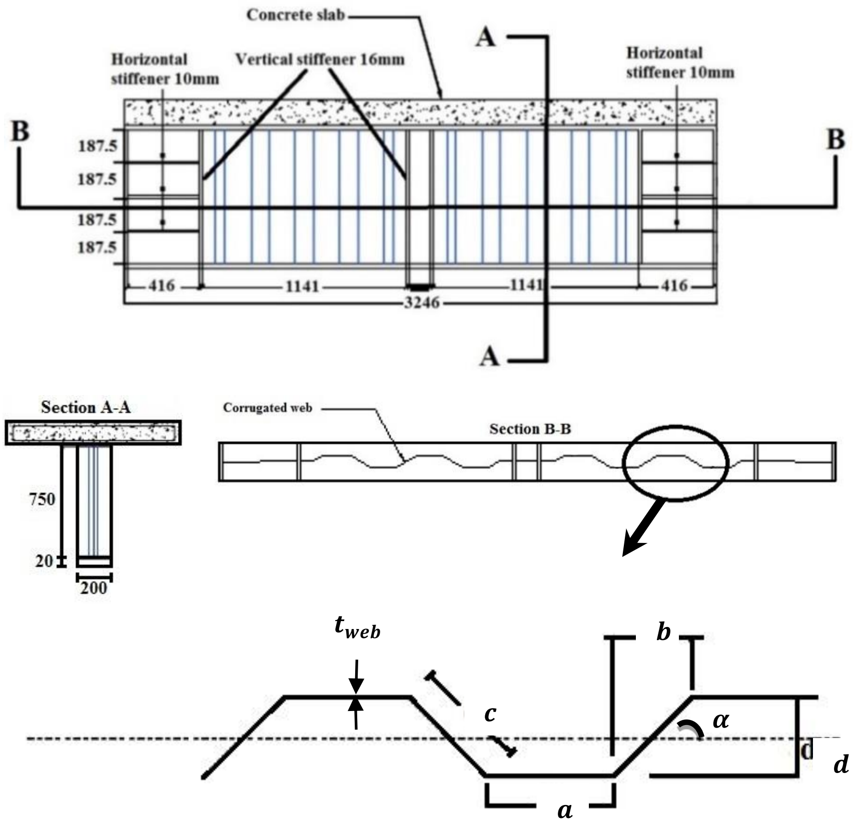
Eldib [25] studied the behaviour of non-composite curved corrugated steel webs of bridges by using ANSYS software. The results indicated that the corrugation angle has a considerable effect on the behaviour of curved corrugated webs, where higher corrugation angles produce a tremendous increase in the shear buckling strength of curved corrugated webs.

According to the previous studies, the numerical approach had succeeded to determine the behaviour of corrugated plate girders, nevertheless, the numerical study of the composite plate girders still need a further investigation. Therefore, the current study mainly focused on the numerical analysis of composite plate girder with the corrugated web by using LUSAS software. The effects of corrugation angle (α), concrete strength, and the thickness of web (t_{web}) and flange (t_{flange}) on the ultimate shear strength of composite plate girders had been evaluated.

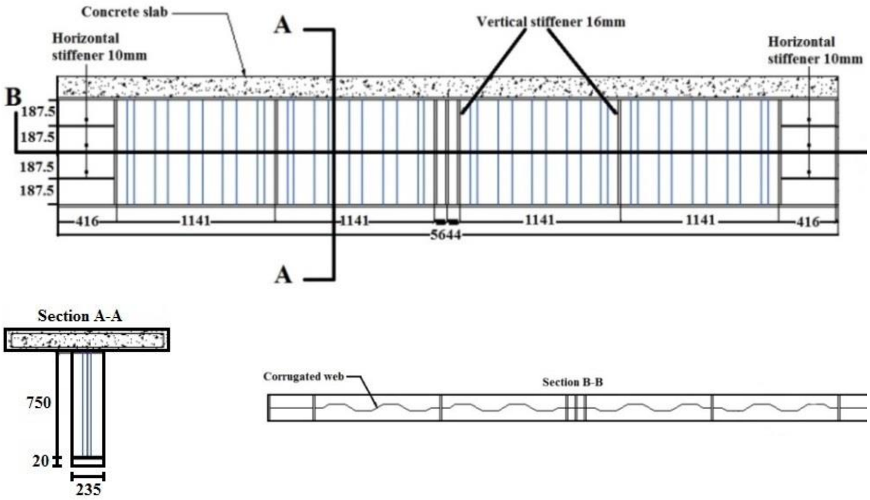
2. Numerical Model

2.1. Geometry and meshing

The geometrical details of the numerical models were defined according to the experimental test of composite plate girders with two (2-CPG) and four panels (4-CPG) carried out by Shanmugam et al. [12] as shown in Fig. 1. where a is the flat panel width, b is the horizontal projection of the inclined panel width, c is the inclined panel width, α is the corrugation angle, d is the corrugation depth, and t_{web} is the web thickness.



(a) 2-CPG.



(b) 4-CPG.

Fig. 1. Geometry details of numerical models.

The numerical models of composite plate girders were created by considering the corrugated steel web as a surface geometric and the upper concrete flange as a volume, while the reinforcement was defined as a line as shown in Fig. 2. The eight nodes thin shell element (QSL8) had utilized to model the web, stiffeners, and flanges due to its nodal freedom can provide an ability to model the intersecting shells. On the other hand, the concrete at upper flange was modelled by using twenty nodes solid hexahedral element (HX20) which considers as the most appropriate element that could be used with the thin shell element (QSL8) during analysis. The reinforcement was modelled by the bar element (BRS3) [26]. A convergence test was performed to determine the optimum mesh size by using four element sizes of 100×100 mm, 80×80 mm, 65×65 mm, and 50×50 mm. The results indicated that the element size of 80×80 mm is the most appropriate to estimate the shear load capacity of composite plate girder within a high accuracy and less computational time as compared with other element sizes.

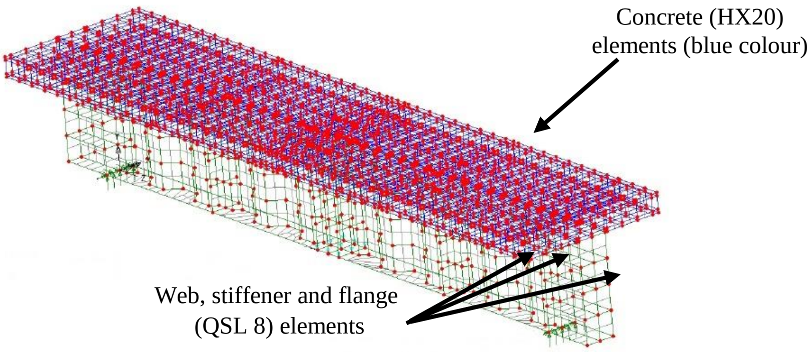


Fig. 2. Numerical model of 4-CPG.

2.2. Material model and properties

2.2.1. Steel plate girder and reinforcement

The steel plate girder and reinforcement were simulated as an elastic-perfectly plastic material in both tension and compression [22]. The material properties of flanges, web, stiffeners, and reinforcement were shown in Table 1, where E_s is the Young modulus of steel, υ is the Poisson ratio, and f_{sy} is the yield stress of steel. Figure 3 presents the typical stress-strain curve of steel.

Table 1. Properties of steel plate girder and reinforcement.

Girder Parts	E_s (GPa)	υ	f_{sy} (MPa)
Top flange	200	0.3	272
Bottom flange	200	0.3	273
Web	200	0.3	286
Vertical stiffener	200	0.3	286
Horizontal stiffener	200	0.3	286
Reinforcement	179	0.3	350

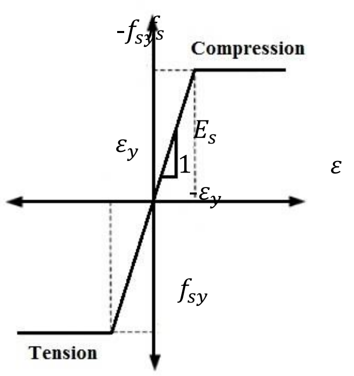


Fig. 3. Stress - strain of steel plate girder.

2.2.2. Concrete

The material properties and typical stress-strain of the concrete that utilized in the current study are shown in Table 2 and Fig. 4, respectively, where E_c is the Young modulus of concrete, $f_c^`$ is the compressive strength of concrete, and f_t is the tensile strength of concrete. A smeared crack model was used to simulate the concrete in the sense that it does not track any individual macro-cracks. Whereas, cracking is assumed to happen when the stress reaches to crack detection surface failure and its orientation can be stored for subsequent calculations.

Table 2. Properties of concrete for each girder.

Girder Type	E_c (GPa)	υ	f_c`(MPa)	f_t (MPa)
2-CPG	28	0.2	40	3
4-CPG	25	0.2	25	1.996

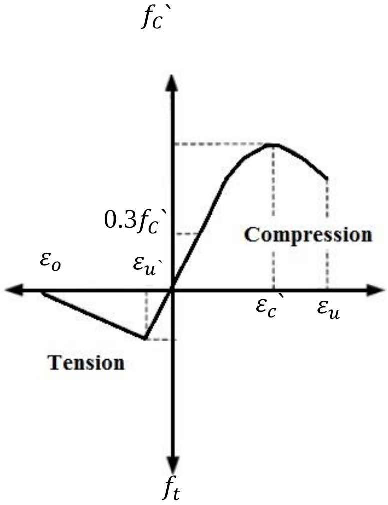


Fig. 4. Stress-strain curve of concrete.

2.3. **Boundary conditions and contact**

A simply supported boundary condition was assigned at the bottom of the girder at a distance 416 mm from the edge and the lateral displacement at the top flange was fixed. A concentrated load was applied at the mid-span of the girder as shown in Fig. 5. The full interaction was assumed between the reinforced concrete and the top flange of steel plate girder.

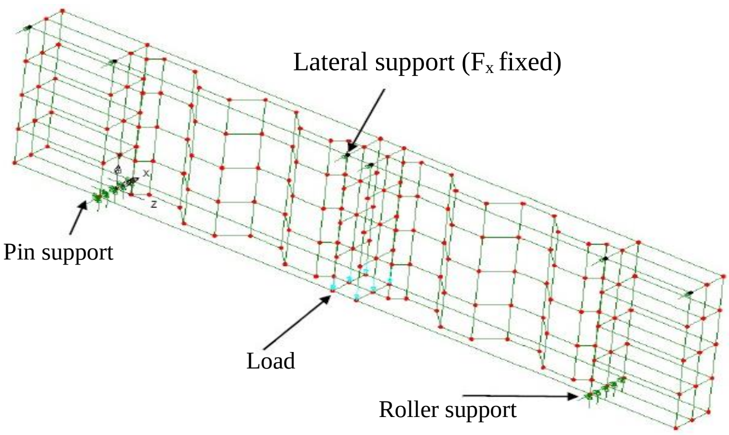
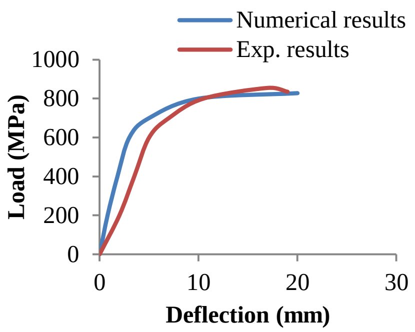


Fig. 5. The boundary condition of 2-CPG.

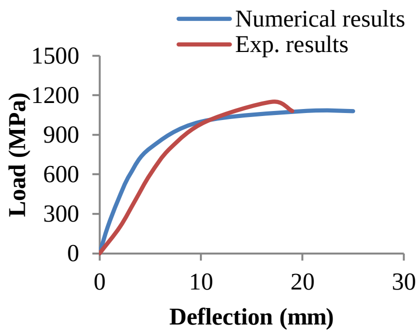
3. Results and Discussion

3.1. Validation results

To ensure the accuracy of the numerical models, a comparison was carried out with the experimental outcomes of Shanmugam et al.[12]. The comparison of the results appeared a good consistency in terms of the load-deflection response behaviour and ultimate shear strength within differences range of 3.26% and 6.48% for 2-CPG and 4-CPG, respectively, as shown in Fig. 6.



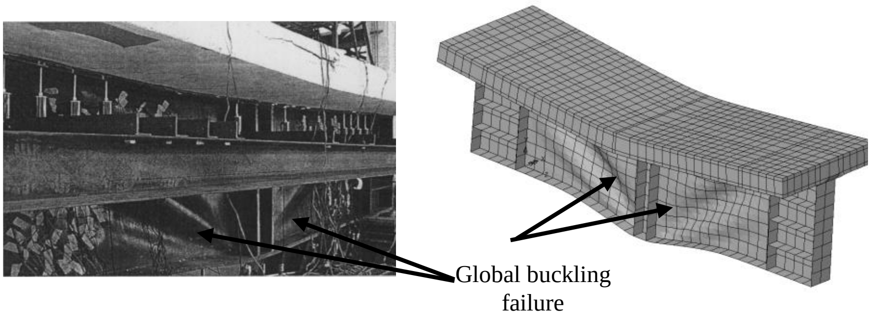
(a) 2-CPG.



(b) 4-CPG.

Fig. 6. Comparison between numerical and experimental results.

Also, the global buckling failure mode at the intermediate supports was dominant in both cases of composite plate girders due to the high tension stresses and showed a good agreement with the experimental test as shown in Fig. 7. According to the above results, the numerical solution could be considered as a successful method to predict the ultimate shear strength and failure mode of the composite plate girders within a short time and less computational cost as compared with the experimental test.



(a) Experimental. **(b) FEM.**

Fig. 7. Failure modes of 2-CPG.

3.2. Parametric studies

Intensive parametric studies had carried out to investigate the effect of corrugated web geometry on the behaviour of composite plate girders particularly the corrugation angle (α), and web thickness (t_{web}). In addition, the effect of flange thickness (t_{flange}) and concrete strength on the ultimate shear strength of the composite plate girders with two and four panels had been evaluated as described in Table 3.

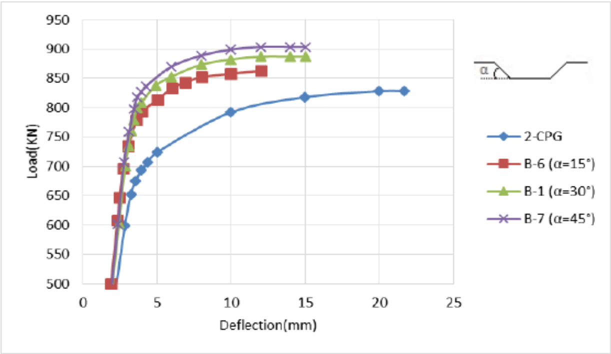
Table 3. Details of parametric studies.

Panels	Model Title	α	t_{web} (mm)	t_{flange} (mm)	f_c` (MPa)
Two	B-1	30	3	20	40
	B-2	30	5	20	40
	B-3	30	6.25	20	40
	B-4	30	3	15	40
	B-5	30	3	25	40
	B-6	15	3	20	40
	B-7	45	3	20	40
	B-8	30	3	20	25
	B-9	30	3	20	60
Four	B-10	30	3	20	25
	B-11	30	5	20	25
	B-12	30	6.25	20	25
	B-13	30	5	15	25
	B-14	30	5	25	25
	B-15	15	5	20	25
	B-16	45	5	20	25
	B-17	30	5	20	40
	B-18	30	5	20	60

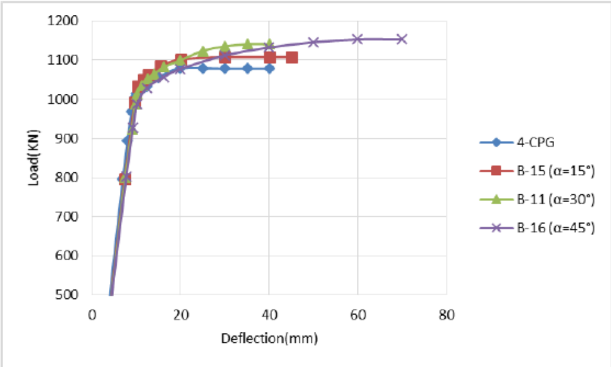
3.2.1. Effect of corrugation angle (α)

The effect of three corrugation web angles (15°, 30°and 45°) on the behaviour of composite plate girders with two and four panels had evaluated at the same web thickness. The results revealed that the high values of corrugation angle could considerably affect ohe load-deflection response and increase the ultimate shear strength of composite plate girders with two or four panels as described in Fig. 8. The maximum increase in shear strength occurred in cases of two panels composite plate girders which increased by 4.1, 6.88, and 7.85%, respectively, as compared with the experimental results of 2-CPG. Similar remarks were stated by other researchers [25, 27].

Moreover, Fig. 9 indicated that the failure modes of corrugated web composite plate girders with two and four panels significantly varied with the increase of corrugation angle value. The global buckling failure mode was dominant at the lower values of α, however, with the increase of α to 45 ° the failure mode was changed at both cases of composite plate girders to local buckling particularly observed at the intermediate supports of the girder.

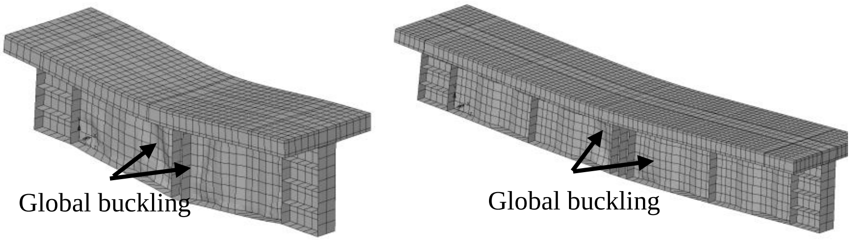


(a) Two panels.

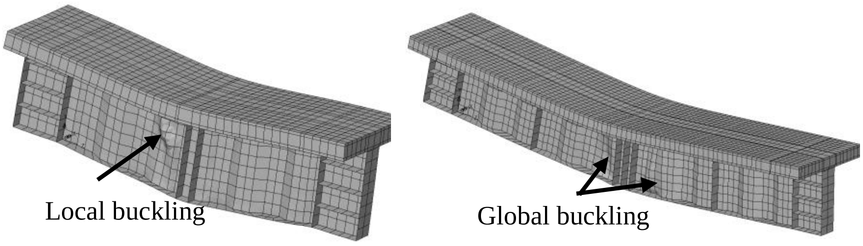


(b) Four panels.

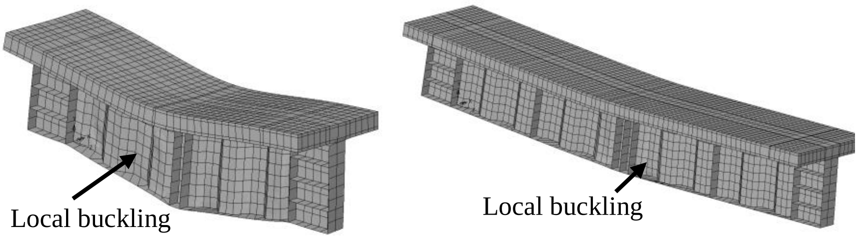
Fig. 8. Effect of corrugation angle (α) on the load-deflection behaviour of composite plate girder.



(a) $\alpha = 15°$.



(b) $\alpha = 30°$.

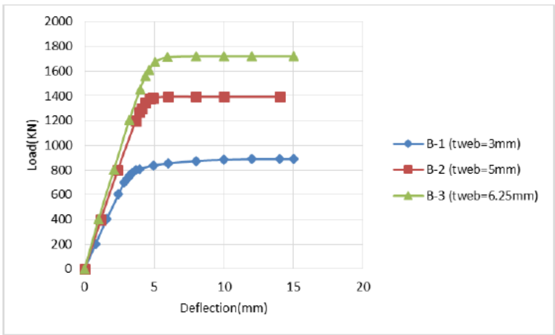


(c) $\alpha = 45°$.

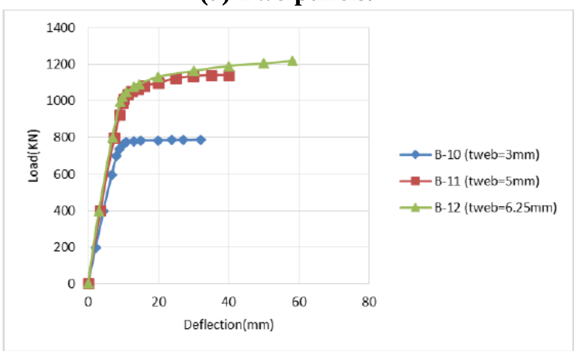
Fig. 9. Failure modes of composite plate girder with two and four panels at different corrugation angles.

3.2.2. Effect of web thickness

Figure 10 shows the effect of three corrugated web thicknesses of 3, 5 and 6.25 mm on the load-deflection behaviour of composite plate girders with two and four panels at the same corrugation angle of 30°. The results indicated that the ultimate shear resistant of composite plate girders with two and four panels significantly increased with the increase of corrugated web thickness and the maximum increase in shear strength observed in case of two panels composite plate girders (B-3) by 107.6% as compared with B-1. Identical behaviour was observed by Sause and Braxtan [28] for trapezoidal corrugated steel plate under shear load.



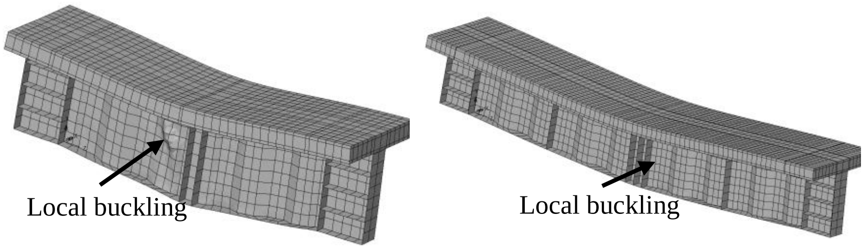
(a) Two panels.



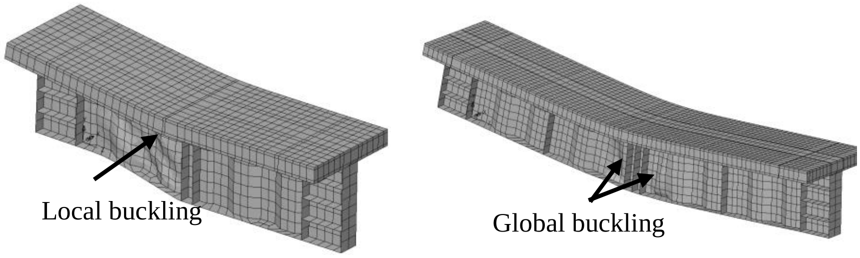
(b) Four panels.

Fig. 10. Effect of web thickness on the load-deflection behaviour of composite plate girders.

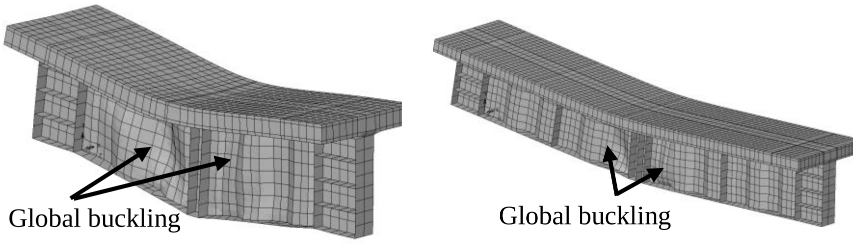
Moreover, the effect of corrugated web thickness on the failure mode of composite plate girders with two and four panels was observed as shown in Fig. 11. It can be noted that the web thickness has an effective role in the failure behaviour of both investigated girders. Whereas, the thinner corrugated webs with a thickness of 3 mm appeared a local buckling failure nearby the intermediate supports, while the thicker webs appeared a global failure on both sides of the intermediate supports especially at web thickness of 6.25 mm.



(a) t_{web} **= 3 mm.**



(b) t_{web} **= 5 mm.**

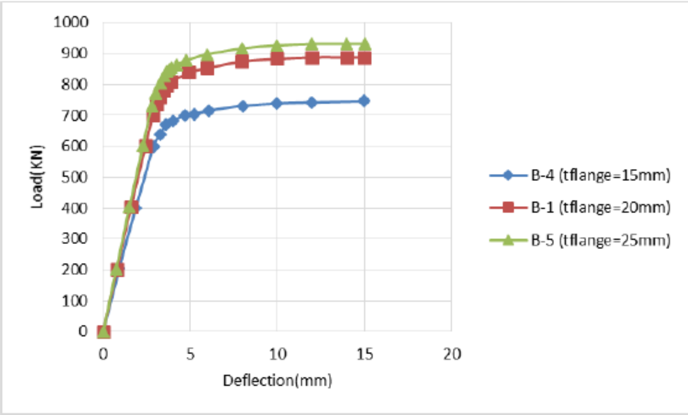


(c) t_{web} **= 6.25 mm.**

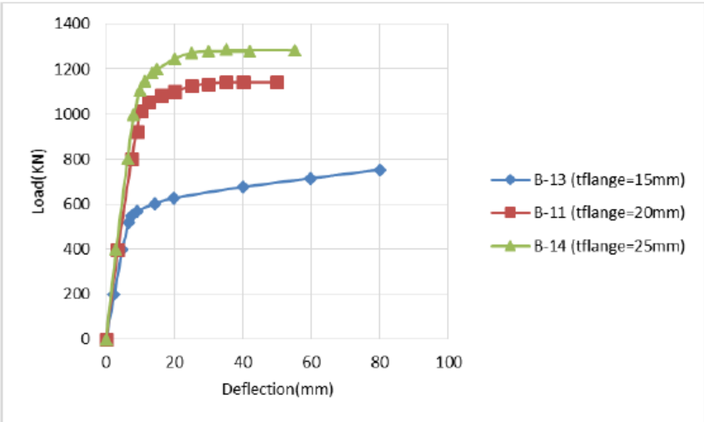
Fig. 11. Failure modes of composite plate girders with two and four panels at different corrugation web thicknesses.

3.2.3. Effect of flange thickness

The load-deflection behaviour of composite plate girders with two and four panels affected by three flange thicknesses of 15, 20 and 25 mm had examined at the same web thickness and corrugation angle as shown in Fig. 12. The increment of flange thickness values showed a significant influence on the shear strength resistant of the composite plate girders with two or four panels and the highest effect of flange thickness was observed in case of four panels plate girders (B-14) which increased by 18.61% as compared with B-13.



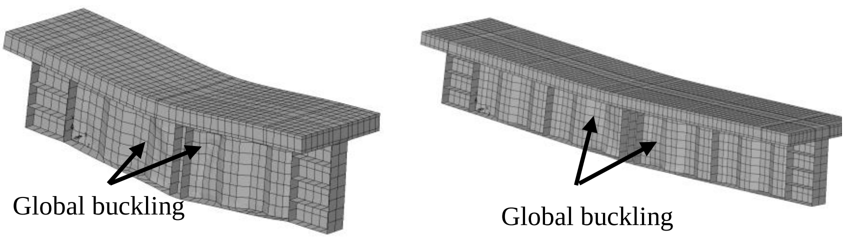
(a) Two panels.



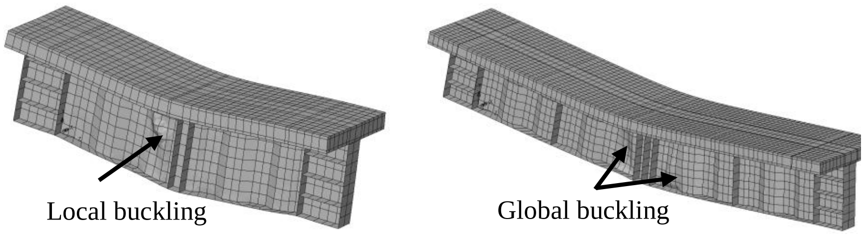
(b) Four panels

Fig. 12. Effect of flange thickness on the load-deflection behaviour of composite plate girder.

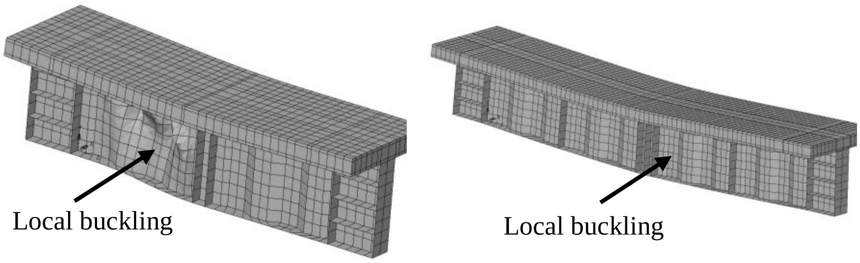
Furthermore, the influence of flange thickness (t_{flange}) on the failure mode of composite plate girders with two and four panels was evaluated as shown in Fig. 13. The increase of flange thickness caused a significant variation in the failure mode of the plate girder, whereas, the thicker flanges of 25 mm appeared a local buckling failure as compared with the thinner flanges of 15 mm, which showed a global failure in both, investigated cases of composite plate girders.



(a) t_{flange} = 15 mm.



(b)) t_{flange} = 20 mm.

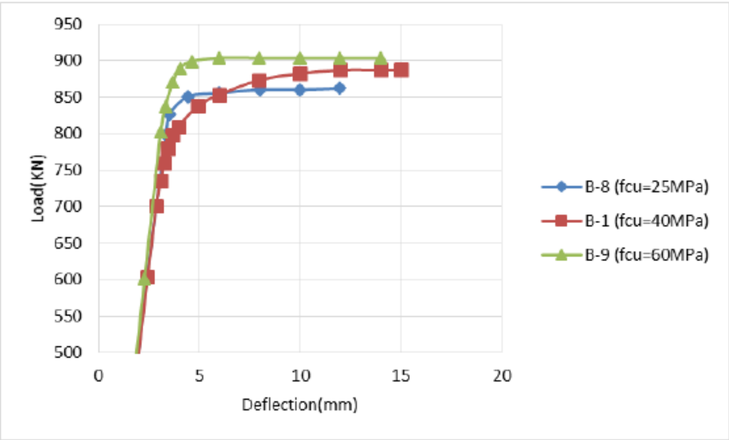


(c) t_{flange} = 25 mm.

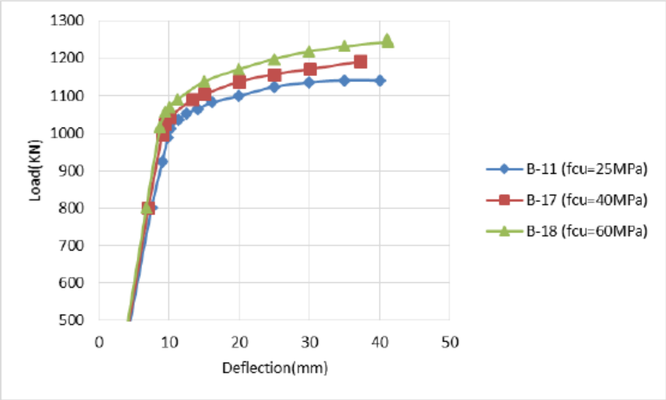
Fig. 13. Failure modes of composite plate girders with two and four panels at different flange thicknesses.

3.2.4. Effect of concrete strength

Furthermore, the effect of concrete strength on the behaviour of composite plate girders with two and four panels had studied. Three concrete strengths of 25, 40 and 60 MPa had evaluated as presented in Fig. 14. There is no a significant variation in the failure mode of the both investigated cases with the increase of concrete strength. The local buckling failure mode was dominant in case of two panels composite girders, while the global failure was observed in the case of four panels girders with corrugated webs.



(a) Two panels.



(b) Four panels.
Fig. 14. Effect of concrete strength on the load-deflection behaviour of composite plate girder.

Table 4 shows a slight increase in the shear strength of the composite plate girders with two and four panels with the increase of concrete strength. Hence, the normal concrete strength could significantly use in the design of corrugated web composite plate girders to reduce the construction cost.

Table 4. Effect of concrete strength on the shear strength capacity of composite plate girder with two and four panels.

Panels	Model Title	Shear Strength (kN)
Two	B-8	860
	B-1	885
	B-9	907
Four	B-11	1138
	B-17	1193
	B-18	1253

4. Conclusions

The results of this study can be summarized as follows:

- Validation results of the numerical models revealed a good consistency with the experimental results of composite plate girders with two and four panels regarding failure mode, load-deflection response behaviour, and ultimate shear strength with differences less than 1%.
- The increase of corrugation angle value indicated an obvious increment in the ultimate shear resistant of both composite plate girders and the maximum influence of corrugation angle was observed in case of two panels plate girders.
- The increase of corrugated web and flange thickness led to a significant increase in the shear strength capacity of both composite plate girders.
- The concrete strength showed a slight effect on the shear strength of both investigated cases. Hence, a normal concrete strength could efficiently use in the design of composite plate girders with the corrugated web to minimize the construction cost.

Acknowledgements

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Nomenclatures

a	The flat panel width, mm
b	The horizontal projection of the inclined panel width, mm
c	The inclined panel width, mm
d	The corrugation depth, mm
E_s	Young modulus of steel, GPa
E_c	Young modulus of concrete, GPa
f_{sy}	Yield stress of steel, MPa
$f_c^`$	Compressive strength of concrete, MPa
f_t	Tensile strength of concrete, MPa
t_{flange}	Flange thickness, mm
t_{web}	Web thickness, mm

Greek Symbols

α	Corrugation angle, deg.
ε	Strain
ε_o	Initial strain
ε_u	Ultimate strain
ε_y	Yield strain
υ	Poisson ratio

Abbreviations

2-CPG	Corrugated Plate Girder with Two Panels
4-CPG	Corrugated Plate Girder with Four Panels

References

1. Johnson, R.P.; Cafolla, J.; and Bernard, C. (1997). Corrugated webs in plate girders for bridges. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, 122(2), 157-164.
2. Driver, R.G.; Abbas, H.H.; and Sause, R. (2006). Shear behavior of corrugated web bridge girders. *Journal of Structural Engineering*, 132(2), 195-203.
3. Moon, J.; Yi, J.-W.; Choi, B.H.; and Lee, H.-E. (2009). Lateral-torsional buckling of I-girder with corrugated webs under uniform bending. *Thin-Walled Structures*, 47(1), 21-30.
4. Hassanein, M.F.; and Kharoob, O.F. (2013). Behavior of bridge girders with corrugated webs:(II) Shear strength and design. *Engineering Structures*, 57, 544-553.
5. Jiang, R.J.; Kwong Au, F.T.; and Xiao, Y.F. (2014). Prestressed concrete girder bridges with corrugated steel webs. *Journal of Structural Engineering*, 141(2), 04014108.

6. Lee, D.H.; Oh, J.Y.; Kang, H.; Kim; K.S.; Kim, H.J.; and Kim, H.Y. (2015). Structural performance of prestressed composite girders with corrugated steel plate webs. *Journal of Constructional Steel Research*, 104, 9-21.
7. He, J.; Liu, Y.; Chen, A.; and Yoda, T. (2012). Mechanical behavior and analysis of composite bridges with corrugated steel webs: State-of-the-art. *International Journal of Steel Structures*, 12(3), 321-338.
8. Kang, H.; Lee, D.H.; Hwang, J.-H.; Oh, J.-Y.; Kim, K.S.; Kim, H.-Y. (2016). Structural performance of prestressed composite members with corrugated webs exposed to fire. *Fire Technology*, 52(6), 1957-1981.
9. Chen, X.-C.; Li, Z.-H.; Au, F.T.K.; and Jiang, R.-J. (2017). Flexural vibration of prestressed concrete bridges with corrugated steel webs. *International Journal of Structural Stability and Dynamics*, 17(02), 1750023.
10. Kövesdi, B.; Jáger, B.; and Dunai, L. (2016). Bending and shear interaction behavior of girders with trapezoidally corrugated webs. *Journal of Constructional Steel Research*, 121, 383-397.
11. Sayed-Ahmed, E.Y. (2001). Behaviour of steel and (or) composite girders with corrugated steel webs. *Canadian Journal of Civil Engineering*, 28(4), 656-672.
12. Shanmugam, N.E.; and Baskar, K. (2003). Steel-concrete composite plate girders subject to shear loading. *Journal of Structural Engineering*, 129(9), 1230-1242.
13. Kadotani, T.; Aoki, K.; Ashizuka, K.; Mori, T.; Tomimoto, M.; and Kano, M. (2002). Shear buckling behavior of prestressed concrete girders with corrugated steel webs. *Proceedings of* 1*st* *Fib Congress on Concrete Structure ine the* 21*st* *Century*, Osaka, Japan, Page 5-269-5-276.
14. Zhou, X.-h.; Kong, X.-f.; Hou, J.; Cheng, D.-l.; and DI, J. (2007). Shear mechanical property of composite box girder with corrugated steel webs. *Zhongguo Gonglu Xuebao* (*China Journal of Highway and Transport*), 20(2), 77-82.
15. Shitou, K.; Nakazono, A.; Suzuki, N.; and Asai, H. (2008). Experimental research on shear behavior of corrugated steel web bridge. *Doboku Gakkai Ronbunshuu A* (*Journal of Japan Society of Civil Engineers A)*, 64(2), 223-234.
16. Ding, Y.; Jiang, K.; Shao, F.; and Deng, A. (2013). Experimental study on ultimate torsional strength of PC composite box-girder with corrugated steel webs under pure torsion. *Structural Engineering and Mechanics*, 46(4), 519-531.
17. Ibrahim, S.A.; El-Dakhakhni, W.W.; and Elgaaly, M. (2006). Fatigue of corrugated-web plate girders: analytical study. *Journal of Structural Engineering*, 132(9), 1381-1392.
18. Abbu, M.; Özakça, M.; and Ekmekyapar, T. (2013). 3D FE modelling of composite box girder bridge. *Proceedings of the 2nd International Balkans Conference on Challenges of Civil Engineering, BCCCE*, Tirana, Albania.
19. Ding, Y.; Jiang, K.; and Liu, Y. (2012). Nonlinear analysis for PC box-girder with corrugated steel webs under pure torsion. *Thin-Walled Structures*, 51**,** 167-173.
20. Kövesdi, B.; Jáger, B.; and Dunai, L. (2012). Stress distribution in the flanges of girders with corrugated webs. *Journal of Constructional Steel Research*, 79, 204-215.

21. Naikwadi, S.P.; Kandekar, S.B.; and Talikoti, R.S. (2015). Numerical analysis of buckling strength of welded plate girder with corrugated web plate girder. *International Journal for Scientific Research & Development*, 3(1), 728-731.
22. Ren, H.-w.; Liu, B.-d.; and Chen, H.-b. (2008). Analysis of torsional vibration of concrete box-girder with corrugated steel webs. *China Journal of Highway and Transport*, 21(6), 64-68.
23. Yi, J.-W.; Gil, H.-G.; Youm, K.-G.; and Lee, H.-E. (2008). Interactive shear buckling behavior of trapezoidally corrugated steel webs. *Engineering Structures*, 30(6), 1659-1666.
24. Basher, M.; Shanmugam, N.E.; and Khalim, A.R. (2011). Horizontally curved composite plate girders with trapezoidally corrugated webs. *Journal of Constructional Steel Research*, 67(6), 947-956.
25. Eldib, M.E.A.-H. (2009). Shear buckling strength and design of curved corrugated steel webs for bridges. *Journal of Constructional Steel Research*, 65(12), 2129-2139.
26. FEA Ltd.(2005). *LUSAS. User Manual, Version* 13.7, in *Surrey, UK.*
27. Gil, H.-B.; Lee, S.-R.; Lee, H.-E.; and Yoon, T.-Y. (2005). Shear buckling strength of trapezoidally corrugated steel webs for bridges. J*ournal of Architectural Institute of Korea*, 24 (1A), 197-202 .
28. Sause, R.; and Braxtan, T.N. (2011). Shear strength of trapezoidal corrugated steel webs. *Journal of Constructional Steel Research*, 67(2), 223-236.