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EFFECT OF SHEAR SPAN-TO-DEPTH RATIO ON BEHAVIOR OF SANDWICH CORE STEEL GIRDER WITH CORRUGATED WEB

Key words: steel beam, shear span, corrugated web, sandwich core, experimental results

Introduction

Corrugated steel girders are typically comprised from upper and lower flanges connected by corrugated steel webs. Using the corrugated web in lieu of the flat web in girders modifies the behavior of the system, resulting in several desirable features. Extensive research has been conducted during the last 30 years to explore the response of members with corrugated webs (Hamilton, 1993; Elgaaly, Hamilton & Seshadri, 1996; Abbas, Sause & Driver, 2006; Driver, Abbas & Sause, 2006; Kadhim & Ammash, 2021). Many aspects were considered in these investigations, including the shear behavior, the flexural behavior, the torsional behavior, the fatigue behavior and so on. The results of these studies showed that girders with corrugated steel webs have several advantages such as significant shear stability, high strength-to-weight ratio, eliminate the need for transfer stiffeners, long fatigue life, high out of plane stiffness, and lower cost compared to conventional steel web girders.

To accelerate the production speed of girders with corrugated webs, and to overcome the low efficiency of manual welding, robots have been utilized in the production process as shown in Figure 1 (Pasternak & Kubieniec, 2010; Ibrahim, 2015; Hassanein, Elkawas, Bock, Shao & Elchalakani, 2021). Three-dimensional printing has been also recently introduced in production process (Abureden, Hasan & Ababneh, 2021). Due to its favorable properties, girder with corrugated web has been increasingly used in

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different type of structures such as, bridges, industrial buildings, airplane hangars, and hydraulic structures (He, Liu, Chen & Yoda, 2012; Aydın, Yuksel, Yardımcı & Gokce, 2016; Zhou, Liu, Wang & Fahmi Hassanein, 2020). During the last three decades, steel girders with corrugated webs have been widely exploited in several bridges constructed in different countries: Japan, France and China. Due to this widespread of exploiting the girders with corrugated web, the expectation that the conventional girders with flat web will vanish within the next few decades and will be taken over by girders with corrugated web (Hassanein & Kharoob, 2014; Ibrahim 2015). Figure 2 shows examples of structures constructed using corrugated steel web.

To further enhance the stiffness and strength of steel girders that constructed with corrugated webs, two plates (skins) may be added to the face and the back of the corrugated plate (web) to form a sandwich core. Experimental work conducted by Ammash and Al-Bader (2021) showed that girders with sandwich core web (corrugated web and skins) have higher load capacity than girders with corrugated web only.

Using steel girders with different shear span-to-depth ratios (*a*/*d*) and core thickness may have a significant impact on the ultimate load capacity and mode failure of such kind

FIGURE 1. Using robots in production process Pasternak and Kubieniec (2011)

FIGURE 2. Examples of structures constructed using corrugated steel web: a – Ilsun bridge (Jung, Yi & Kim, 2010); b – industrial building (Parys, 2017); c – column and girder in industrial building (adopted from Ibrahim, 2015); d – airplane hangar (adopted from Ibrahim, 2015)

of structures, since the responses the girders could be switched from shear control to flexural control. To the extent of our knowledge, there is no study has been conducted on effect of *a*/*d* and core thickness on the performance steel girders with sandwich core constructed with corrugated web. In this paper, the influences of *a*/*d* and core thickness on the performance of sandwich core steel girders with corrugated webs will be experimentally investigated and compared with conventional flat web girders.

Experimental work

A total of nine girder specimens with simple span were fabricated and tested under mid span concentrated force to investigate impacts of the shear span-to-depth ratio (*a*/*d*) and depth of the corrugation on the performance of core sandwich girders with corrugated web. The specimens are categories as follows:

- A – three specimens with flat web (FW),
- B – three specimens with sandwich core web that have 30 mm core depth (SCW30),
- C – three specimens with sandwich core web that have 60 mm core depth (SCW60).

Three shear span-to-depth ratios (*a*/*d*): 1, 1.833 and 2.5, were considered for each category. Two core depths (Fig. 3) were also examined. The section dimensions for each category were selected so all the beams have the same weight. Dimensions of the specimens are presented in Figure 4 and Table 1. Same materials were used for all the specimens (properties of material are provided in Table 2). The specimens were loaded in 2,000 kN capacity testing machine, one concentrated load at mid span was applied and gradually increased until failure. The testing machine was stopped at different load level to read the mid span deflection of the tested beam. Linear variable displacement

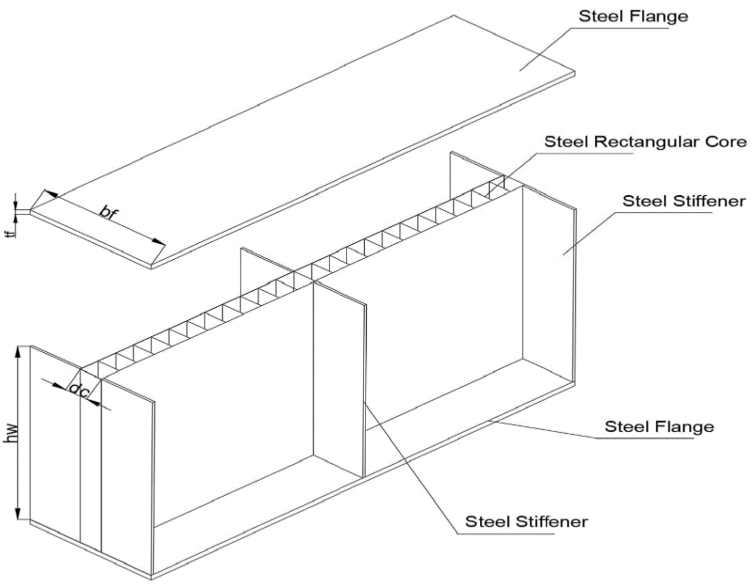

FIGURE 3. Details of the sandwich core web girder

TABLE 1. Dimensions of the tested beams

Group	Core thickness (d_c) [mm]	Span-to-depth ratio (a/d)	Flange width (b_f) [mm]	Flange thickness (t_f) [mm]	Web height (h_w) [mm]	Web thickness (t_w) [mm]	Corrugated thickness (t_c) [mm]	Skin thickness (t_s) [mm]	Span
A Flat web	–	1	200	6	300	3	–	–	600
		1.833	200	6	300	3	–	–	1 100
		2.5	200	6	300	3	–	–	1 500
B SCW30	30	1	200	6	300	–	1	1	600
		1.833	200	6	300	–	1	1	1 100
		2.5	200	6	300	–	1	1	1 500
C SCW60	60	1	200	6	300	–	1	1	600
		1.833	200	6	300	–	1	1	1 100
		2.5	200	6	300	–	1	1	1 500

TABLE 2. Material properties of the tested specimens

Element		Thickness (t) [mm]	Yield strength (F_y) [MPa]	Ultimate strength (F_u) [MPa]	Modulus of elasticity (E) [GPa]
Flange/stiffener		6	358	467	205
Flat web		3	402	455	203
Core sandwich web	corrugated web	1	410	206	206
	skin	1			

transducer (LVDT) deflection gauge was installed in mid span at the center of the bottom flange of each beam. To avoid bearing of the flanges, stiffeners with 300 mm width and 6 mm thickness were added to the both side of the web (one under the load and the other at each support). Photos for specimen's preparation and testing setup are shown in Figure 5. Samples of the tested beams during testing are provided in Figure 6.

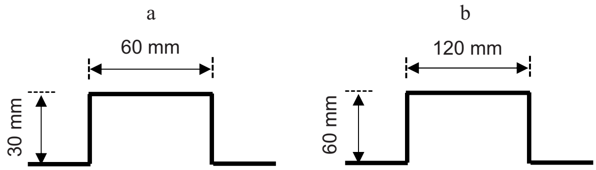

FIGURE 4. Rectangular web corrugation used in this study: a – SCW30; b – SCW60

FIGURE 5. Preparation of the specimens and test setup

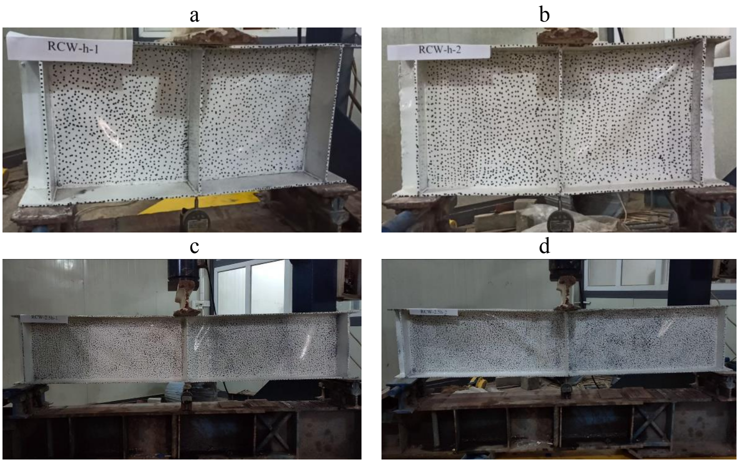

FIGURE 6. Girders with sandwich core during testing: a – SCW30 with $a/d = 1.0$; b – SCW60 with $a/d = 1.0$; c – SCW30 with $a/d = 2.5$; d – SCW60 with $a/d = 2.5$

Results and discussion

Figures 7–9 show the load–mid span deflection curves for girders with flat web, sandwich core web with 30 mm thick (SCW30), and sandwich core web with 60 mm thick (SCW60), respectively, at different *a*/*d* ratios. The relationship between ultimate load and *a*/*d* ratio for the three cases considered (flat web, SCW30 and SCW60) are shown in Figure 10. Figures 11–13 represent the load–mid span deflection curves for all the three types of webs considered at *a*/*d* equals to 1.0, 1.833 and 2.5 respectively. The ultimate load capacities for all the tested specimens are presented in Table 3.

Based on the results obtained from this study, the following notes can be observed.

- For the same *a*/*d* ratio, girders with sandwich core webs have higher ultimate load capacity than girders with flat web. At *a*/*d* = 1.0, the difference was about 44 and 20% for girders with web thickness of 30 and 60 mm respectively. This difference can be attributed to effect of corrugation in preventing the web local buckling.

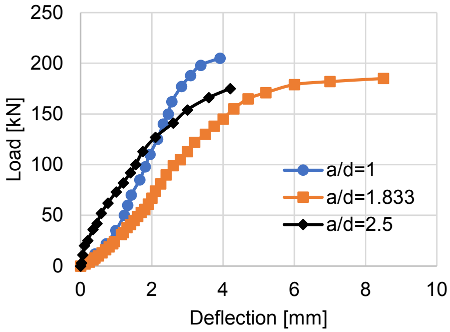

FIGURE 7. Load–mid span displacement curve for flat web with different *a*/*d*

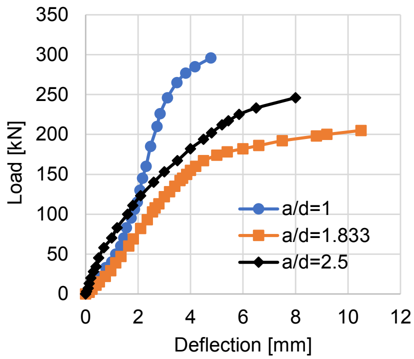

FIGURE 8. Load–mid span displacement curve for SCW30 with different *a*/*d*

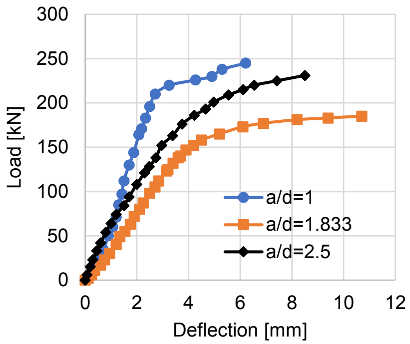

FIGURE 9. Load–mid span displacement curve for SCW60 with different *a*/*d*

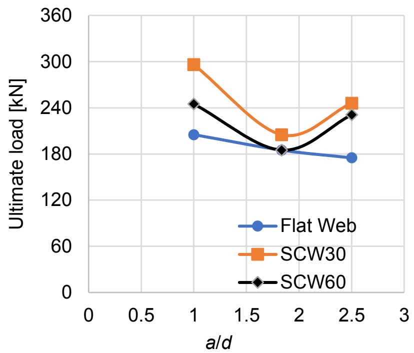

FIGURE 10. Ultimate load versus *a*/*d* ratio for flat web, SCW30 and SCW60

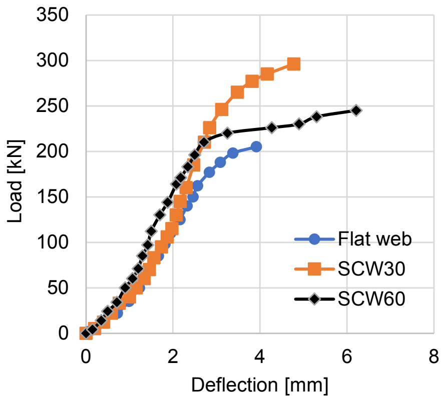

FIGURE 11. Load deflection curve for girders with flat web, SCW30 and SCW60 at *a*/*d* = 1.0

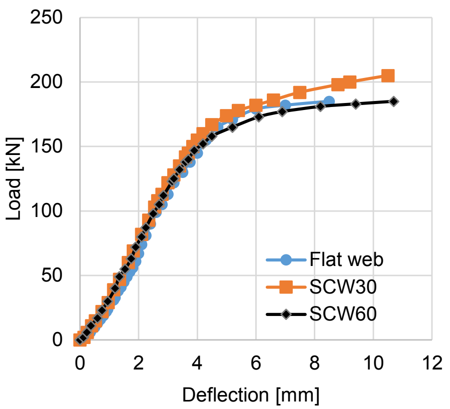

FIGURE 12. Load deflection curve for girders with flat web, SCW30 and SCW60 at *a*/*d* = 1.833

– Girders with sandwich core with web thickness of 30 mm (SCW30) have higher ultimate load capacity than girders with core thickness of 60 mm (SCW60), the

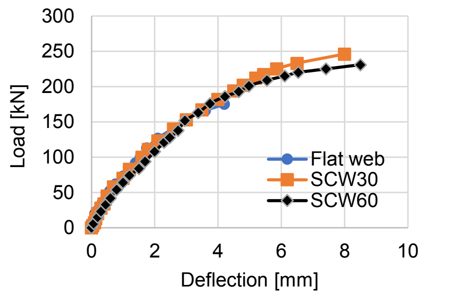

FIGURE 13. Load deflection curve for girders with flat web, SCW30 and SCW60 at *a*/*d* = 2.5

difference was about 20, 10 and 6% at *a*/*d* equals to 1.0, 1.833 and 2.5 respectively. This can be interpreted that the unsupported length of SCW60 is two times the unsupported length of SCW30 (as shown in Fig. 3), thus SCW60 is more suspected to local buckling than SCW30.

– For girders with flat web, the ultimate strength of specimens with *a*/*d* equals to 1.0 was about 8 and 17% higher than the corresponding strength for specimens with *a*/*d* equals to 1.833 and 2.5 respectively.

– The ultimate strength for girders with SCW30 at *a*/*d* equals to 1.0 was higher than the corresponding strength at *a*/*d* equals to 1.833 and 2.5 by about 44 and 20% respectively, while the ultimate strength for girders with SCW60 at *a*/*d* equals to 1.0 was higher by about 32 and 6%. The inconstancy of the results especially at *a*/*d* equals to 1.833 may be attributed to the effect of interaction between shear and flexure.

TABLE 3. Ultimate load capacities for the tested specimens

Span-to-depth ratio (*a*/*d*)	Ultimate load [kN]		
	flat web	sandwich core web	
		SCW30	SCW60
1.0	205	296	245
1.833	185	205	185
2.5	175	246	231

Conclusions

The impact of shear span-to-depth ratio and core thickness on the performance of sandwich core steel girders with corrugated web was investigated experimentally in this study. From the results of this work, the following observations were drawn.

- Sandwich core steel girders with corrugated web perform better than steel girders with flat web in term of both loading capacity and maximum displacement.
- The performance of the tested beams was noticeably affected by *a*/*d* ratio for all the categories considered in this study.
- For all the three categories (flat web, sandwich core with 30 mm thick, and sandwich core with 60 mm thick), girders with *a*/*d* equals to 1.0 perform better than girders with *a*/*d* equals to 1.833 and 2.5.
- Girders with sandwich core thickness of 30 mm demonstrate higher ultimate load capacity than girders with sandwich core of 60 mm, the maximum difference in the ultimate load capacity can be seen at *a*/*d* equals to 1.0.

References

Abbas, H. H., Sause, R. & Driver, R. G. (2006). Behavior of corrugated web I-girders under in-plane loads. *Journal of Engineering Mechanics*, *132* (8), 806–814.

Abureden, G. A., Hasan, W. M. & Ababneh, A. N. (2021). Exploring potential benefits of additive manufacturing in creating corrugated web steel beams. *Journal of Constructional Steel Research*, *187*, 106975. https://doi.org/10.1016/j.jcsr.2021.106975

Ammash, H. K. & Al-Bader, M. A. (2021). Shear behaviour of steel girder with web-corrugated core sandwich panels. *IOP Conference Series: Materials Science and Engineering*, *1090* (1), 012017. https://doi.org/10.1088/1757-899X/1090/1/012017

Aydın, R., Yuksel, E., Yardımcı, N. & Gokce, T. (2016). Cyclic behaviour of diagonally-stiffened beam-to-column connections of corrugated-web I sections. *Engineering Structures*, *121*, 120–135.

Driver, R. G., Abbas, H. H. & Sause, R. (2006). Shear behavior of corrugated web bridge girders. *Journal of Structural Engineering*, *132* (2), 195–203.

Elgaaly, M., Hamilton, R. W. & Seshadri, A. (1996). Shear strength of beams with corrugated webs. *Journal of Structural Engineering*, *122* (4), 390–398.

Hamilton, R. W. (1993). *Behavior of welded girders with corrugated webs* (PhD thesis). University of Maine, Orono, ME.

Hassanein, M. F., Elkawas, A. A., Bock, M., Shao, Y. B. & Elchalakani, M. (2021). Effect of using slender flanges on EN 1993-1-5 design model of mono-symmetric S460 corrugated web bridge girders. *Structures*, *33*, 330–342.

Hassanein, M. F. & Kharoob, O. F. (2014). Shear buckling behavior of tapered bridge girders with steel corrugated webs. *Engineering Structures*, *74*, 157–169.

He, J., Liu, Y., Chen, A. & 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.

Ibrahim, B. S. A. (2015). *Steel plate girders with corrugated webs. Past present and future*. Kair: Ain Shams University.

Jung, K. H., Yi, J. W. & Kim, J. H. J. (2010). Structural safety and serviceability evaluations of prestressed concrete hybrid bridge girders with corrugated or steel truss web members. *Engineering Structures*, *32* (12), 3866–3878.

Kadhim, A. W. & Ammash, H. K. (2021). Experimental study of encased composite corrugated steel webs under shear loading. *Journal of Physics: Conference Series*, *1895* (1), 012062. https://doi.org/10.1088/1742-6596/1895/1/012062

Parys, A. (2017). *Primary structure, corrugated web beam*. Retrieved from: https://primarystructure.net/corrugated-web-beam

Pasternak, H. & Kubieniec, G. (2010). Plate girders with corrugated webs. *Journal of Civil Engineering and Management*, *16* (2), 166–171.

Zhou, M., Liu, Y., Wang, K. & Fahmi Hassanein, M. (2020). New asynchronous-pouring rapid-construction method for long-span prestressed concrete box girder bridges with corrugated steel webs. *Journal of Construction Engineering and Management*, *146* (2), 05019021. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001770

Summary

Effect of shear span-to-depth ratio on behavior of sandwich core steel girder with corrugated web. Girders with corrugated steel web are preferred and widely used in recently constructed bridges and industrial buildings. Sandwich core girders with corrugated web are constructed by adding two plates (skins) to the corrugated web. This study aims to investigate the shear span-to-depth ratio impact on the performance of sandwich core steel girders with corrugated web. Three span-to--depth ratios (*a*/*d*): 1.0, 1.833 and 2.5, were examined. The test includes three girders with sandwich web thickness of 30 mm, three girders with 60 mm sandwich web thickness, and three girders with conventional flat webs. A total of nine simply supported steel girders subjected to a concentrated load were fabricated and tested up to failure. The responses of the examined girders are presented in term of the load deflection curves, the ultimate load, and the maximum displacement. Among the conclusions drawn in this study that girders with sandwich core thickness of 30 mm demonstrate higher ultimate load capacity than girders with sandwich core of 60 mm, the maximum difference in the ultimate load capacity was about 20% and can be seen at *a*/*d* equals to 1.0. The results also pointed out that the behavior of the beams was noticeably impacted by the shear span-to-depth ratio.