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ARTICLE

Deflection analysis of welded steel I-girders with corrugated webs based on first yield

Sinusoidal corrugated profile webs have been popularly used in steel structural designs to replace the flat webs in conventional welded beams, while there are better performances in corrugated web beams (CWBs) regarding more stability and less material used to against beam failures caused by buckling. Previous studies have provided that CWBs enabled numerous favourable benefits to be recognised as alternatives to the traditional weld beams in designing structures. Furthermore, as CWBs are proposed as the major load-carrying elements, the maximum deflection in the elastic range is one of the important beam properties that should be precisely estimated and calculated. To find an appropriate method in computing the maximum deflection of CWBs based on the first yield for civil communities in Australia, proposed equations based on other standards will be employed to calculate the theoretical results for the comparisons with simulation-based results. While applying the linear analysis simulations provided by SAP 2000, ultimate limit state design theory has also been used with requirements stated by AS 4100. In this study, the results in theoretical calculations and numerical simulations have been compared to conclude that the highly defined equations by ASTM [37] and Sause et al. [38] could precisely estimate the maximum deflections of CWBs based on the first yield in conjunction with requirements and limitations in Australian standards, which could be adequate for the structural design calculations in Australian design fields.

Keywords deflection; steel; corrugated web beams; optimisation; SAP 2000; load-carrying capacity; ultimate limit state design; finite element analysis; steel structures; bending moments; beams and girders

1 Introduction and background

Corrugated web beams (CWBs) and girders have been widely utilised as the main load-carrying components in the existing and new-developing structures [1, 2]. Previous studies state that the nature of corrugated webs can thin the plates and stiffeners, avoid the out-plane buckling failures and provide stronger internal capacities [3–5]. The shapes of the corrugation, such as sinusoidal, trapezoidal and rectangular shapes, have been validated to have more favourite properties, including stronger stiffness, higher ductility ratio and more energy dissipation capacity than the normal beams [6–9]. As a result, structures assembly, including continuous girders and rigid frames from CWBs, has been utilised in many major composite structures [10–12]. Zevallos et al. [10] and Wang et al. [12] also mentioned that the first bridge built with corrugated web girders and concrete decks was located in Cognac Bridge in France.

Based on previous studies, CWBs are actively analysed and studied for different structural behaviour [13]. Kim et al. [14] pointed out that beams with corrugated webs had better ductility and serviceability compared to conventional beams. They provided a series of experimental results which showed the loading-resistance capacity of CWBs was significantly higher than the conventional steel beams. Lin et al. [15] stated that the stability against shear yielding buckling of the beams was improved by the corrugated nature after comparing the experimental and numerical results, where the profile of the corrugated webs could act as a kind of horizontal-direction stiffener, which can dramatically increase the total beam stiffness and stability. Moreover, because of the improved stability to the lateral torsional buckling, the CWBs can resist higher shear forces than the traditional beams [16]. According to Farzampour [4], this alternative option of beams was modelled in finite element (FE) simulation as the main lateral load resisting elements in a beam-column system to investigate the shear capacity, in which the author found that the experimental results were higher than the results of the flat web beams, which could be considered as a conservative option to replace the ordinary beams in the building design. According to Park et al. [17], the weight of CWBs could be reduced by 30 % to 40 % comparing with the traditional flat plate girders because the significant amount of reinforcing stiffeners was replaced by the corrugated webs. They also stated that the corrugated members could still provide high material efficiency and better shear resistance with less material used. Similarly, by using the concept of the beam optimisation to the CWBs to thin the web thickness and reduce the beam height, the CWBs could achieve the material saving up to 20 % while maintaining the same level of capacity in both the shear and flexural behaviours [18]. Lin et al. [18] mentioned that using the shorter section of CWBs to replace the selected ordinary beams in a proposed building design could satisfy the needs of the economic design because the lighter beam features could assist designers to save the raw material cost and the total saved beam height could be utilised to add more floors to that building proposal.

As the CWBs are replacing the normal flat web beams in the different design regions, there are a series of significant properties of CWBs which need to be analysed. The CWBs are the basic elements in the structural design which play critical roles to resist and transfer the loads to the foundation by the beam-column system [19–22]. Hence, the deflection of CWBs should be clearly investigated, which is essential for the deflection limit check. A functional method called active deflection control to analyse the deflection of the CWBs has been mainly focused on some studies [23]. Wang et al. [24] conducted investigations to study the displacement of beams with corrugated webs by using the stiffness factors. The deflection of the I-girder with corrugated webs can be determined by $\Delta = P/k_0$. k_0 is the initial stiffness in Eq. (3), k_s is the shear stiffness in Eq. (2), and k_b is the bending stiffness in Eq. (1), respectively.

$$k_b = \frac{48EI}{L^3} \tag{1}$$

$$k_s = \frac{4A_w G}{L}\eta \tag{2}$$

$$k_0 = \frac{k_b k_s}{k_b + k_s} \tag{3}$$

where E is the Young's modulus; I is the moment of inertia about the major axis; A_w represents the sectional area of the corrugated steel web; L represents the span length of the simply supported I-girder; G is the shear modulus; and η indicates the shape coefficient of CWBs. After comparing the theoretical results and simulation-based results, the significant differences in the comparison result indicated that these highly structured formulas had underestimated the deflection of CWBs [24].

Leblouba and Tabsh [25] examined the displacement analysis of CWBs by considering the reliability criterion stated in specifications in AISC-360-16 [26], which is the Specification for Structural Steel Buildings by the American Institute of Steel Construction and CSA-S16-14 [27] being the Design of Steel Structures by the Canada Standard Association. They used Eqs. (4) and (5) to compute the deflection appeared in the mid-span of the CWBs.

$$k_s = \frac{G t_w h_w}{a} \tag{4}$$

$$\delta_s = \frac{V_n}{k_s} \tag{5}$$

where G is the shear modulus of the steel material and a is the shear span of the beam; t_w is the web thickness and h_w indicates the web depth. They demonstrated 49 shear performance tests for four steel I-girders with corrugated webs, where there was not a good agreement between results from the shear tests and the theoretical results. The main reason of the overestimated deflection was that the author assumed the shear load to be uniformly distributed along the web.

Several studies [28–34] performed different types of FE simulations and deflection limit tests to validate the experimental data against the theoretical results. Due to the imprecise determination of the shape factor k_s and assumptions of pure bending or shear acting to the structures, the deformations of CWBs were accidently underestimated or overestimated with inaccurate coefficient estimations [35]. They also indicated that some researchers assumed varied live-to-dead load ratios in the functional settings, which would affect the calculation processes to gain precise results. Ultimately, the precise estimation to the deflection of CWBs is unable to be achieved by the above-mentioned researchers. The CWBs have been popularly used in some main structures of the civil engineering projects in Australia. However, there is no direct approach to analysis the beam deflection of CWBs, in which the deformation limit of CWBs is one of the main requirements of the safety design. As a result, a comprehensive approach to accurately calculate the deflection of CWBs is highly required in order to utilise CWBs in Australian engineering design fields, where the steel design standard AS 4100 [36] in Australia does not include a section listed any methods to calculate the beam deformations.

2 Theoretical background

In this study, a reasonable approach to estimate the deflection of CWBs will be developed, as the main objective, for Australian civil engineering communities, by considering the equations stated by the supplementary guidelines ASTM [37]. Based on the research performed by Sause et al. [38], the conservative method to calculate the deflection of CWBs with the trapezoidal shape will be selected as a component of the equations to calculate the deflection of sinusoidal shape web beams because the equations from Sause et al. [38] could acceptably estimate the deformation of CWBs [35]. Thus, this study will combine the approaches from ASTM [37] and Sause et al. [38] to establish the purposed equations to generate the theoretical results, where Eq. (8) introduced by ASTM [37] will be used as the formula to precisely represent the beam total stiffness. Eqs. (6) and (7) from Sause et al. [38] will be considered as the starting point to calculate the bending stiffness and the shear stiffness respectively of the CWBs.

$$k_b = \frac{3LEI}{a^2(L-a)^2} \tag{6}$$

$$k_s = \frac{L h_w t_w G}{a(L-a)} \cdot \left(\frac{\beta + \cos\alpha}{\beta + 1}\right) \tag{7}$$

$$k_0 = \frac{k_b k_s}{k_b + k_s} \tag{8}$$

where E is the Young's modulus, G is the shear modulus of elasticity equal to 80×10^3 MPa, L is the corrugation length, a is equal to a quarter of the corrugation length, I is the second moment of inertia about the major axis, α is the corrugation angle, β is the ratio of a and L, k_b is the bending stiffness, and k_s is the shear stiffness.

After gathering the results of the beam stiffness k_0 for each CWB, the deflection δ will be calculated from $\frac{P}{k_0}$, where P is the maximum load that each CWB can safely resist. As a result, the above-mentioned highly structured equations will be used to estimate the maximum deflection of CWBs, which will be utilised to compare with the results from FE simulations via strictly implementing the requirements and properties of steel beams stated in Australian Standards. Hot Rolled and Structural Steel Products property tables [39] will be used to set the necessary beam properties and features in SAP 2000 in order to accurately perform the FE simulations. This software has been used by several researchers [40–44] to investigate mechanical behaviour of structures. Moreover, all other essential information including factors of load combination, factors for buckling checks, and modification factors of required loads will be extracted from AS/NZS 1170.1 [45].

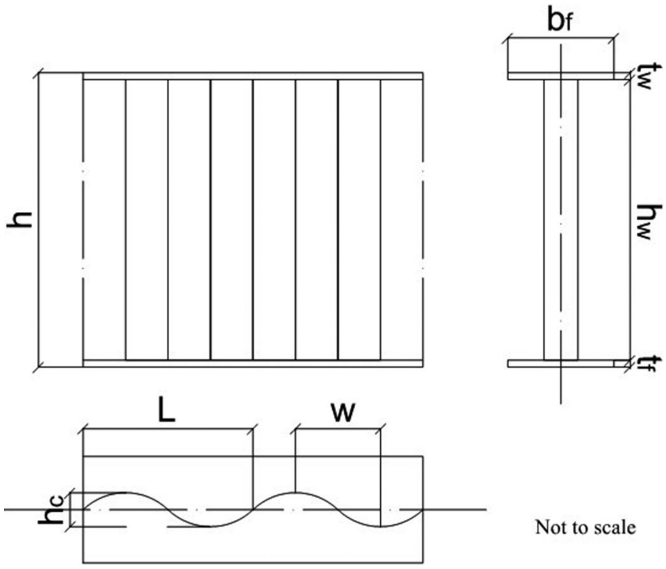

Fig. 1 Typical illustration of a CWB

3 Methodology

Lin et al. [18] stated that the CWBs with a corrugated length of 400 mm and the corrugated angle of 30° performed favourable mechanical capacities comparing with other corrugated sizes, and this selected size will be used to replace the flat web in the conventional beams. A CWB numerical model sample has been illustrated in Fig. 1, where it presents the geometry dimensions of the simulated model in this study. In addition, the cross-sectional geometry for the fundamental dimensions is selected as the same values cited from the Hot Rolled and Structural Steel Products property tables [39].

Based on Fig. 1, the factor of h_w indicating the web depths of the CWBs and the factor of t_w indicating the web thickness will be used to estimate the deflection in Eq. (7). Due to the remodelling of the web geometries, the elastic buckling investigation should be performed to avoid buckling failure on the new webs. Moreover, as required by AS/NZS 1170.1 [45], all buckling factors should be greater than 1.0 while applying design load combinations to the analysis, in which the buckling factors being less than 1.0 will result in web buckling, including lateral torsional buckling, flexural torsional buckling, global buckling and local buckling [46]. SAP 2000 FE analysis software [46] has been used to comprehensively investigate the maximum deflections for CWBs based on the first yield with favourable functions for analysis, where the deflection capacities gained from numerical investigations will be compared with the results obtained from the theoretical results by Eqs. (6), (7) and (8). Lastly, the viability of the highly structured equations could be tested while strictly applying requirements stated by the Australian standards, where Australian civil engineering communities could apply the investigated equations to estimate the deflections of CWBs in the practices.

3.1 Numerical simulation assumptions

There will be several assumptions to properly complete the FE model simulations in SAP 2000, and a typical model with meshed elements of CWBs shown in Fig. 2, in which the uniformly distributed load (UDL) will be applied on the top flanges of CWBs. Accordingly, the distribution load labelled in each meshed area is displayed as green colour by the SAP 2000 software to present the area load shown in Fig. 2. The 3, 5 and 7 m of the beam length will be selected, which were popularly adopted in main beam structures in the Australia buildings, and the supported conditions were selected as pin and roller supports. Loads applying on the compression flanges will be precisely represented by the constant pressures, while the top flange was fully retrained to resist lateral torsional buckling for each CWB. There were two 10-mm-thick stiffener plates applied on both sides of the beam to prevent the twisting along the beam. The pin and roller supports were simulated with node applying along the middle depth of the stiffener. However, modelling the same stiffener nodes restricted at only one end in the longitudinal direction can eliminate rigid body deformation along the beam axis. EF simulation standard shell elements supported by SAP 2000 can mesh all elements of the beam.

3.2 Design and analysis parameters

Some researchers [4, 7, 15] have mentioned that the corrugated feature can improve the bending and shear strength of the CWBs with less deflection. To start with the load determination, firstly, the UDL ω^* is set to be the

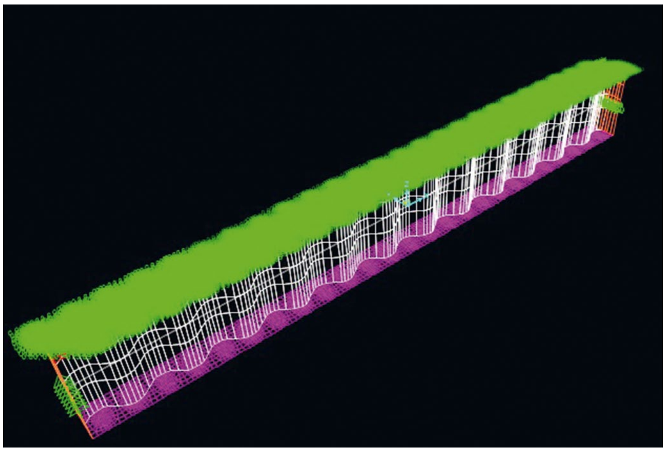

Fig. 2 Design of a 3D beam model with end stiffeners subjected to a UDL

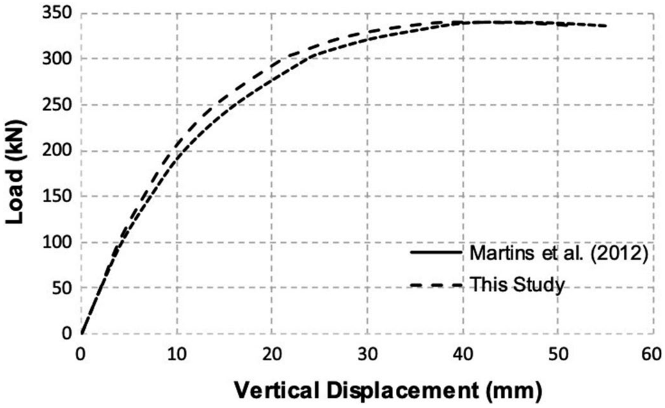

Fig. 3 Load-deflection curves estimated by the numerical model developed in this study with the experimental data reported by Martins et al. [48]

highest load that could be safely resisted by each CWB while reaching the maximum allowable stress on the first yield. According to AS 4100 [36], the maximum allowable shear stress is 0.6 f_y and that for bending stress is 0.9 f_y. A trial-and-error process will be conducted to determine the maximum UDL ω*, where each trial-and-error process will be paused if the flexural or shear stress limitation is approached. After that, the maximum UDL and the maximum deformation will be recorded.

Based on AS/NZS 1170.1 [45], the primarily designed load input to the FE simulation in SAP 2000 is calculated by load combination of 1.2DL + 1.5LL, where the LL is live load and DL is the dead load applying on the beams. According to suggestions practised by the Australian civil engineering communities, the equation DL = 3LL could be used to properly represented the relationship between the live load and the dead load. Hence, the load relationships of DL = ω*/1.7 and LL = ω*/5.1 can be utilised as the inputs to SAP 2000. To clearly present the conducted methodology in this research, a flow chart is demonstrated in Fig. 3. In this research, two different structural steel grades of 300PLUS-300 and 300PLUS-280 are selected to model the CWBs, which have the same mass density of 7849 kg/m^3.

4 Validation of the developed numerical model

Previous studies [47, 48] provided the numerical and experimental models to verify different performances for CWBs. To confirm the credibility of the FE simulation models performed by SAP 2000 in this study, the experimental results collected from this model had been contrasted to the practical results conducted by Martins et al. [48]. They comprehensively demonstrated parametric experiments on three full-scale composite connections for CWBs, including the PSS 600 × 150 × 12.5 × 2.0 for specimens 1 and 2 and PSS 600 × 150 × 8/12.5 × 2.0 for specimen 3. Since the similar features performing on the beam to investigate the corrugated beam models, the experimental results for specimen 1 were chosen to verify the functional numerical results in this study. Then, the same FE simulation approach with shell elements utilised in this study was selected to carry out the investigations on the required beam to obtain the essential data for the comparison in the next step. Finally, the results generated from the same FE simulation technique utilised in the CWB models in this research have been validated against the load-deflection curve published by Martins et al. [48] in Fig. 3. Fig. 3 has clearly illustrated that the curve of the load–deformation gained from parametric experiments of FE models in SAP 2000 consistently fits with the practical results demonstrated by Martins et al. [48]. Lastly, the numerical model developed in this research can be utilised as an adequate model to illustrate the mechanical and physical properties of steel I-girder for corrugated webs. The credibility of the developed FE model in SAP 2000 has been verified throughout the consistent agreement between numerical analysed results and the practical results tested by Martins et al. [48]. As a result, the FE model provides a high degree of accuracy for predicting different behaviours of CWBs.

5 Results

5.1 Results for 5 m CWBs

In this research, based on Hot Rolled and Structural Steel Products property table [39], five different welded beams from each category are selected to estimate the deformation based on the first yield, in which the traditional flat webs of selected beams will be reformed with corrugated webs to form new-designated CWBs. Table 1 summarises the applied values of beam features for new CWBs, directly related to the deflection calculations. After practical simulations with SAP 2000, the inputs to SAP 2000 and the corresponding results are shown in Tab. 2. Then, the values of second moment of inertia I_{xx} are calculated utilising the relationship between I and Δ_{Max} (Tab. 2). For the theoretical analyses, the deflection estimation starts from Eqs. (6) and (7) to calculate the bending stiffness k_b and shear stiffness k_s. The bending stiffness factor k_b is quotient by the multiplication of corrugated length L, Young's modulus E, and secondary moment area I over

Tab. 1 Properties of corrugated web beams (5 m)

Designation	t_w (mm)	h_w (mm)
700CWB115	7	660
	8	660
	9	660
	10	660
	11	660
800CWB122	7	760
	8	760
	9	760
	10	760
	11	760
900CWB175	9	860
	10	860
	11	860
	12	860
	13	860
1000CWB215	13	960
	14	960
	15	960
	16	960
	17	960
1200CWB249	13	1120
	14	1120
	15	1120
	16	1120
	17	1120

the special relationship between total corrugated length L and quarter of the length a. The stiffness k_s is computed with the individual beam features, including corrugated length L, the height of beam h_w, the thickness of beam t_w, the shear module of elasticity G, and a quarter of corrugated length a. When these two factors are derived, the initial stiffness k_0 would be computed to estimate the beam's deflection. Besides, P is the applied unit force calculated by distribution load ω. Lastly, the deflection would be generated throughout by the initial stiffness using the equation $\Delta = P/k_0$ illustrating in Tab. 3.

5.2 Effects of length variation

To further explore the applicability of the above-mentioned equations [37, 38] to calculate the maximum deflection based on the first yield, the analyses to other popular beam lengths including 3 m and 7 m are performed. Similar to the investigations to 5 m CWBs, the buckling analysis should be performed to investigate the web conditions against the buckling. Tab. 4 clearly shows that the smallest buckling factors for 3 m CWB are much higher than the minimum value of 1. Therefore, the conclusion could be made that the replacements in the webs could safely resist different types of web buckling. The inputs to SAP 2000 and the corresponding results are shown in Tab. 5 by practical simulation. In this length series analysis, the applied UDL of 3 m length would re-

Tab. 2 Formal simulation results (5 m)

Designation	t_w (mm)	M (kN m)	ω^* (kN/m)	LL (kN/m^2)	DL (kN/m^2)	Simulation deflection (mm)	I_{xx} (10^6 mm^4)
700CWB115	7	850	272	213.33	640.00	7.4	1650.4
	8	900	288	225.88	677.65	7.5	1724.1
	9	950	304	238.43	715.29	7.6	1796.0
	10	1000	320	250.98	752.94	7.8	1842.0
	11	1050	336	263.53	790.59	7.9	1909.6
800CWB122	7	1050	336	263.53	790.59	8.2	1839.8
	8	1100	352	276.08	828.24	8.1	1951.2
	9	1150	368	288.63	865.88	8.1	2039.9
	10	1200	384	301.18	903.53	8.1	2128.6
	11	1250	400	313.73	941.18	8.2	2190.2
900CWB175	9	1830	586	459.29	1377.88	9.1	2655.9
	10	1880	602	471.84	1415.53	9.0	2784.7
	11	1930	618	484.39	1453.18	8.9	2918.9
	12	1980	634	496.94	1490.82	8.8	3059.0
	13	2030	650	509.49	1528.47	8.8	3136.2
1000CWB215	13	2350	752	589.80	1769.41	9.1	3710.4
	14	2400	768	602.35	1807.06	9.0	3831.4
	15	2450	784	614.90	1844.71	9.0	3911.2
	16	2500	800	627.45	1882.35	8.9	4035.9
	17	2550	816	640.00	1920.00	8.8	4163.4
1200CWB249	13	2850	912	715.29	2145.88	7.5	5459.8
	14	2900	928	727.84	2183.53	7.3	5707.8
	15	2950	944	740.39	2221.18	7.2	5886.8
	16	3000	960	752.94	2258.82	7.1	6070.9
	17	3050	976	765.49	2296.47	7.0	6260.3

Tab. 3 Deflection calculation of CWBs (5 m)

Designation	t (mm)	k_b (N/mm²)	k_s (N/mm²)	k_0 (N/mm²)	P (N/m)	Theoretical deflection (mm)
700CWB115	7	3,094,420	38,000	37539.0	272,000	7.2
	8	3,232,759	40,000	39511.1	288,000	7.3
	9	3,367,457	41,000	40506.8	304,000	7.5
	10	3,453,802	42,000	41495.4	320,000	7.7
	11	3,580,587	44,000	43465.9	336,000	7.7
800CWB122	7	3,449,590	42,000	41494.8	336,000	8.1
	8	3,658,472	44,000	43477.1	352,000	8.1
	9	3,824,766	47,000	46429.5	368,000	7.9
	10	3,991,060	48,000	47429.6	384,000	8.1
	11	4,106,655	50,000	49398.6	400,000	8.1
900CWB175	9	5,417,535	67,000	66181.5	585,600	8.8
	10	5,627,395	69,000	68164.2	601,600	8.8
	11	5,841,970	71,000	70147.5	617,600	8.8
	12	6,061,422	74,000	73107.5	633,600	8.7
	13	6,214,489	77,500	76545.4	649,600	8.5
1000CWB215	13	6,956,944	85,000	83974.0	752,000	9.0
	14	7,183,908	88,000	86935.1	768,000	8.8
	15	7,333,573	91,000	89884.6	784,000	8.7
	16	7,567,319	93,000	91870.9	800,000	8.7
	17	7,806,377	95,000	93857.8	816,000	8.7
1200CWB249	13	10,237,069	127,000	125443.8	91,2000	7.3
	14	10,702,055	132,000	130391.7	92,8000	7.1
	15	11,037,775	134,000	132392.7	94,4000	7.1
	16	11,382,953	139,000	137323.1	960,000	7.0
	17	11,737,993	145,000	143230.7	976,000	6.8

Tab. 4 Minimum buckling factor check for CWBs (7 m)

Designation	t (mm)	Buckling factor
700CWB115	7	3.147637
	8	4.600533
	9	2.572192
	10	2.670888
	11	2.138182
800CWB122	7	2.239817
	8	1.860693
	9	1.777307
	10	1.618256
	11	2.818360
900CWB175	9	3.672910
	10	2.757117
	11	3.307604
	12	3.147637
	13	2.767033
1000CWB215	13	2.507113
	14	2.436615
	15	2.364708
	16	2.322246
	17	2.277852
1200CWB249	13	1.058991
	14	1.711201
	15	2.304573
	16	2.817262
	17	3.269376

main the same with the loads in 5 m CWBs. Then, the values of second moment of inertia I_{xx} are calculated utilising the relationship between I_{xx} and Δ_{Max} as shown in Tab. 6.

Following the procedures mentioned in Section 5.1, the values of bending stiffness k_b, shear stiffness k_s, and bending stiffness factor k_b are computed, where the maximum elastic deflections for 3 m CWBs would be generated throughout by the initial stiffness using the equation $\Delta = P/k_0$ illustrating in Tab. 7. By using the same process as the above-mentioned sections, Tab. 4 depicts the smallest buckling factor of 7 m CWBs, which are also much higher than the minimum factor of 1. Thus, the 7 m CWBs could be safely used because the webs remain in safe conditions to resist against the web bucking failures. Similarly, bending stiffness k_b, shear stiffness k_s, and bending stiffness factor k_b and the corresponding deflections are summarised in Tab. 7.

Many researchers [15, 24, 49] have reported that there were many benefits in using the CWBs, including its material efficiency, better strengths, stronger stability, and less deformation mentioned, where these favourable features could attract more engineering designers specialising in various design regions. In this study, the highly consistent results in the comparisons indicate that the numerical methods by ASTM [37] and Sause et al. [38] could appropriately estimate the maximum deflections in

Tab. 5 Formal simulation results (7 m)

Designation	t_w (mm)	I_{xx} (mm^4)	Simulation deflection (mm)
700CWB115	7	1656.6	25.4
	8	1730.3	26.0
	9	1802.2	26.7
	10	1848.2	27.8
	11	1915.8	28.2
800CWB122	7	1846.0	24.6
	8	1957.4	24.8
	9	2046.1	25.1
	10	2134.8	27.8
	11	2196.4	25.9
900CWB175	9	2895.6	29.1
	10	3007.5	28.8
	11	3121.9	28.7
	12	3239.0	28.6
	13	3320.6	28.4
1000CWB215	13	3716.6	27.3
	14	3837.6	27.4
	15	3917.4	27.4
	16	4042.1	27.5
	17	4169.6	27.6
1200CWB249	13	5466.0	21.4
	14	5714.0	21.3
	15	5893.0	21.1
	16	6077.1	21.0
	17	6266.5	20.9

Tab. 6 Formal simulation results (3 m)

Designation	t_w (mm)	I_{xx}	Simulation deflection (mm)
700CWB115	7	1642.2	1.6
	8	1715.9	1.7
	9	1787.8	1.8
	10	1833.8	1.8
	11	1901.5	1.9
800CWB122	7	1831.6	1.9
	8	1943.0	1.9
	9	2031.7	1.8
	10	2120.4	1.8
	11	2182.0	1.8
900CWB175	9	2881.2	2.4
	10	2993.1	2.3
	11	3107.5	2.3
	12	3224.6	2.2
	13	3306.2	2.1
1000CWB215	13	3702.2	2.3
	14	3823.2	2.2
	15	3903.0	2.2
	16	4027.7	2.1
	17	4155.2	2.0
1200CWB249	13	5451.6	2.0
	14	5699.6	1.9
	15	5878.6	1.9
	16	6062.7	1.8
	17	6252.1	1.7

Tab. 7 Deflection calculation of CWBs (7 m)

Designation	t_w (mm)	k_b (N/mm^2)	k_s (N/mm^2)	k_0 (N/mm^2)	P (N/m)	Theoretical deflection (mm)
700CWB115	7	4,332,188	11,000	10972.1	272,000	24.8
	8	4,525,862	11,500	11470.9	288,000	25.1
	9	4,714,440	11,550	11521.8	304,000	26.4
	10	4,835,323	11,600	11572.2	320,000	27.7
	11	5,012,822	12,000	11971.3	336,000	28.1
800CWB122	7	4,829,426	14,000	13959.5	336,000	24.1
	8	5,121,860	14,400	14359.6	352,000	24.5
	9	5,354,672	14,750	14709.5	368,000	25.0
	10	5,587,484	15,200	15158.8	384,000	25.3
	11	574,9317	15,800	15756.7	400,000	25.4
900CWB175	9	7,584,549	20,400	20345.3	585,600	28.8
	10	7,878,352	21,400	21342.0	601,600	28.2
	11	8,178,758	22,550	22488.0	617,600	27.5
	12	8,485,991	23,000	22937.8	633,600	27.6
	13	8,700,284	23,600	23536.2	649,600	27.6
1000CWB215	13	9,739,721	27,800	27720.9	752,000	27.1
	14	1,005,7471	28,800	28717.8	768,000	26.7
	15	10,267,002	28,850	28769.2	784,000	27.3
	16	10,594,246	29,300	29219.2	800,000	27.4
	17	10,928,928	29,900	29818.4	816,000	27.4
1200CWB249	13	14,331,897	43,300	43169.6	912,000	21.1
	14	14,982,877	44,300	44169.4	928,000	21.0
	15	15,452,886	45,350	45217.3	944,000	20.9
	16	15,936,134	46,200	46066.5	960,000	20.8
	17	16,433,190	47,400	47263.7	976,000	20.7

Tab. 8 Deflection calculation of CWBs (3 m)

Designation	t_w (mm)	k_b (N/mm^2)	k_s (N/mm^2)	k_0 (N/mm^2)	P (N/m)	Theoretical deflection (mm)
700CWB115	7	1,856,652	200,000	180550.9	272,000	1.5
	8	1,939,655	210,000	189485.1	288,000	1.5
	9	2,020,474	215,000	194322.1	304,000	1.6
	10	2,072,281	219,000	198068.0	320,000	1.6
	11	2,148,352	220,000	199563.9	336,000	1.7
800CWB122	7	2,069,754	209,000	189831.2	336,000	1.8
	8	2,195,083	219,000	199132.8	352,000	1.8
	9	2,294,860	233,000	211523.7	368,000	1.7
	10	2,394,636	245,000	222260.1	384,000	1.7
	11	2,463,993	252,000	228618.5	400,000	1.7
900CWB175	9	3,250,521	291,000	267089.1	585,600	2.2
	10	3,376,437	297,000	272987.3	601,600	2.2
	11	3,505,182	311,000	285655.0	617,600	2.2
	12	3,636,853	323,000	296653.3	633,600	2.1
	13	3,728,693	330,000	303168.7	649,600	2.1
1000CWB215	13	4,174,166	419,000	380777.8	752,000	2.0
	14	4,310,345	425,000	386856.0	768000	2.0
	15	4,400,144	439,000	399174.6	784,000	2.0
	16	4,540,391	451,000	410249.6	800,000	2.0
	17	4,683,826	458,000	417204.4	816,000	2.0
1200CWB249	13	6,142,241	547,000	502270.1	912,000	1.8
	14	6,421,233	553,000	509151.6	928,000	1.8
	15	6,622,665	567,000	522284.6	944,000	1.8
	16	6,829,772	579,000	533750.8	960,000	1.8
	17	7,042,796	586,000	540986.9	976,000	1.8

the elastic range for the sinusoidal CWBs, and this numerical approach could also be properly combined with requirement and limitations to comply with Australian standard, in which the highly structured equations are beneficial to calculate the deflection limitations during the structural designs for Australian engineers with its high credibility and applicability (Tab. 8).

6 Conclusion

In this parametric study, FE analysis has been conducted generate results in order to compare them with the theoretical calculations from the relevant equations so as to find proper equations in estimating the maximum deflection based on the first yielding for steel I-girders and beams with corrugated webs. Ultimate limit state design theory has been utilised to cover these studies containing numerical analysis with conjunction of AS 4100 [36] and the FE simulation with material and geometric linearity in SAP 2000. The trial-and-error process in finding the maximum UDL will be stopped when the flexural or shear stress approaches the corresponding stress limits, which is 0.9* f_y for the flexural stress check and 0.6* f_y for shear stress check. Comparing these results through these two methods, the differences are found between 1 % and 3.5 %, in which this range is considered as reasonable and acceptable results in the requirements of the conservative safety design. By reviewing the result comparisons between formula-based approach and results in FE simulations, the high degree of consistency suggests that it is conservatively safe to conclude that the high-structured equations from ASTM [37] and Sause et al. [38], which has been suggested by He et al. [35] to calculate the deflections of CWBs based on Chinese standards, could properly predict the maximum deflection within an acceptable accuracy based on the first yield for CWBs. Overall, the proposed numerical method combined with ASTM [37] and Sause et al. [38] can be easily adopted with high level of accuracy.

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