Research Article

Numerical Analysis of Hybrid Steel Beams with Trapezoidal Corrugated Web Nonwelded Inclined Folds

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Hybrid beams provide the opportunity to implement characterized steel sections by recruiting materials based on yield strength and the type of applied stress. Previous studies demonstrated that steel beams with a trapezoidal corrugated web (SBCWs) were affected by both fatigue cracks initiated along the inclined fold (IF) and the maximal additional stress located in the middle of the IFs. This paper presents a numerical study of hybrid SBCWs and nonwelded IFs. Numerical simulation is presented using the finite element (FE) method with the aid of the ANSYS software package. Three-dimensional FE models were developed considering the nonlinear properties of materials and geometric imperfection and validated using five hybrid specimens that were fabricated and tested experimentally by the authors. The load-deflection behavior and failure mechanism of the numerical results were in good agreement with the experimental results. The comparison of the FE models and the experimental results shows the good capability of the FE model to be used as a base for the parametric study. The parametric study focused on the effect of web thickness, flange thickness, web height, and flange and web steel grades. Furthermore, parametric studies are conducted to investigate the effects of the number and depth of the stiffeners on the behavior of hybrid SBCWs. We concluded that the flange thickness, web thickness, web height, and steel grades of flanges significantly affect the capacity and failure mode of hybrid SBCWs. We also concluded that the flange stiffeners have a significant effect on the overall behavior, toughness, and load capacity of SBCWs. Finally, a new equation is proposed to anticipate the shear capacity of SBCW nonwelded IFs based on the length of the welded horizontal fold.

1. Introduction

Steel beams with corrugated webs (SBCWs) have been widely used in the last four decades in bridges and in common steel structures. The SBCW can be used as the main girder or as a secondary beam. The main SBCWs can be loaded by one (mid-span load) or more concentrated loads transferred from secondary beams. This study is concerned with the SBCW carrying a secondary beam at its midspan (three-point bending). The main advantage of the trapezoidal corrugated web is the supporting condition provided by both longitudinal and inclined folds to each other. This property increases the out-of-plane stiffness of the SBCWs. However, the geometric characteristics of CWSBs have three weaknesses: first, the outstanding length of the compression flange; second, web eccentricity due to corrugation depth; and third, the flexural strength resisted only by the contribution of the flanges.

SBCWs have two different failure modes: the first failure mode is controlled by the web shear stress (web buckling), whereas the second is controlled by the flange yield stress (flange buckling). In 2005, Anami and Sause [1] analytically evaluated the fatigue strength of corrugated web-flange welds. The results revealed that the beam capacity significantly was affected by fatigue cracks initiated along the inclined folds (IFs) and then spread perpendicular to the principal stress direction. Thus, this study analytically presents the effect of nonwelded IFs. A few previous experimental or analytical studies reported hybrid SBCWs or the case of nonwelded IFs. Therefore, a general background
regarding the previous investigation on the behavior of SBCWs under shear and bending is presented in this section. The shear response of corrugated web beams has been subjected to numerous experimental and theoretical investigations on the shear buckling and shear strength of SBCWs [2–23]. This investigation was started in 1965 by Shimada [2]. Bergfelt and Leiva in 1984, Luo and Edlund in 1996, and Abbas in 2003 reported that the shear strength of SBCWs is governed by the shear yielding and buckling of the web [2–5]. Based on the analytical method conducted by Luo and Edlund [4], an empirical formula was proposed for predicting the shear capacity of SBCWs. Analytical and experimental studies on SBCWs loaded mainly with shear force were conducted by Elgaaly et al. [6] and others [7–18]. These studies were concerned with the local and global elastic buckling and the interaction between them, along with the corresponding theory. The focus of the studies was to predict the three types of shear buckling by developing formulae. Lindner [18] proposed using 70% of the shear buckling stress in the design calculation of the nominal shear strength of SBCWs. All these studies revealed that shear stress is uniformly distributed throughout the web height and gradually increases until buckling. Furthermore, local and global web buckling were observed to be most common in coarse and dense corrugations, respectively.

Regarding bending moment investigations, few previous investigations have focused on the determination of the bending resistance of steel or composite SBCWs [19, 24, 25]. Abbas et al. [19] reported that SBCWs under an in-plane shear and bending moment had two types of displacement: vertical displacement (in-plane deflection) and out-of-plane displacement (twisting), simultaneously. These displacements produce flange transverse bending, which means flange stresses that must be added to the stresses arising from in-plane bending. To calculate this transversal bending, Abbas et al. [20] introduced the C-factor method as an analytical method to be used. Lindner [24] in 1992 and Aschinger and Lindner [25] in 1997 were the first to observe the flange transverse bending of SBCWs.

Furthermore, some researchers have studied the combination of the flexural response and the shear strength of SBCWs [26]. In welding research, a few investigations have been performed on the welding between the web and the flanges, the first study conducted by Sherman and Fisher [27]. Experimentally, this study investigated three distinct web thicknesses of 25 SBCWs to determine the connected length needed between the web and the flanges. The results revealed that the horizontal folds only needed to be connected to the flanges. In addition, negligible effects on the beam stiffness and maximum capacity were observed due to the connection between the flanges and inclined folds.

Although there are numerous studies dealing with SBCWs, only a smaller number of previous studies are concerned with hybrid SBCWs, and a minor number of studies have examined the effect of flange stiffeners on beam capacity. In addition, previous studies have demonstrated the need for further investigations in the case of nonwelded inclined folds. These investigations essentially point out the most imperative parameters influencing the overall behavior and the failure mode of hybrid SBCWs with nonwelded inclined folds and, in addition, how the flange stiffeners affect the capacity and behavior of such type of beams. In the present study, the flexural behavior of a hybrid SBCW nonwelded inclined fold was analytically investigated.

Based on the experimental results of five hybrid SBCWs tested under three-line loads conducted by the authors [28], the finite element models were validated. Promising agreement was observed between the FE and experimental results. The three-dimensional (3D) FE parametric study was performed based on the validated model. The study focused on six parameters that may affect the failure mechanism of SBCW nonwelded inclined folds. The factors studied were web thickness, flange thickness, web height, flange and web steel grades, and flange transversal stiffeners. Finally, an equation is proposed to anticipate the maximum shear force for class 4 SBCWs based on the horizontal fold length.

2. Experimental Program

An experimental work was conducted to identify the factors that may affect the flexural behavior and strength of hybrid SBCWs. A summary of the experimental work is presented in this section, and more details are available in [28]. Six full-scale beams were fabricated: five SBCWs and one flat web beam. All beams were 1900 mm long with an effective span of 1800 mm and tested under three-line loads. The web height \((h_w)\), web thickness \(t_w\), flange width \(b_f\), and flange thickness \(t_f\) were 400, 3, 200, and 8 mm, respectively. The ratio \((h_w/t_w)\) of the corrugated web was 133. The compactness of the flanges in the tested specimens was measured with respect to the maximum outstanding length \((h_e + b_f)/2t_f\). In this experimental investigation, the effects of horizontal fold lengths of 200, 260, and 350 mm on SBCW behavior were examined. The corrugation depth \(h\) and the horizontal projected length of the inclined fold \(a\) were equal to 100 mm. The corrugation angle \(\alpha\) was 45°. The corrugation profiles of the specimens are shown in Figure 1.

Three steel-plate stiffeners \((400 \text{ mm} \times 200 \text{ mm} \times 8 \text{ mm})\) were used for each specimen: one was located over each support, and one was located under the concentrated load. The corrugated web was connected to the flanges with continuous 4 mm fillet welds from one side with a connection angle of 45° using gas metal arc welding. Specimens were named by a code denoting the tested parameters, where “CW,” “FW,” “IF,” “FS,” “W,” and “NW” represent “corrugated web,” “flat web,” “inclined fold,” “flange stiffeners,” “welded,” and “nonwelded,” respectively. The number following “CW” or “FW” indicates the HF or intermittent welding line length (in cm), respectively. The details of each specimen are presented in Table 1, and more details about the welding and flange stiffeners are available in [28]. The properties of the web and flange steel are presented in Table 2.

3. Numerical Analysis

3.1. Development of the Numerical Model. The numerical simulations described in this section were performed using the nonlinear FE program ANSYS to conduct a parametric
analysis for the SBCW with flange stiffeners. The dimensions of the experimentally tested SBCWs at Taif University were used in the initial FE model ($b = 200$ mm, horizontal projection of IF $= 100$ mm, $a = 45^\circ$, $t_w = 2.8$ mm, and $h_w = 400$ mm). The FE elastic-plastic shell (SHELL181) was used to simulate steel. The element SHELL181 was defined by four nodes with six degrees of freedom at each node: translations in the nodal $x$, $y$, and $z$ directions and rotations about the nodal $x$, $y$, and $z$ axes. The element allowed for plasticity, creep, stress stiffening, large deflections, and large-strain capabilities. Supports and actuator were modeled using solid elements, where the contact elements were used to simulate the contact surfaces between the flanges and the supports or actuator, as shown in Figure 2(a). Some elements were used to simulate the contact between beam flanges and the support or actuator (CONTA173, to represent the deformable surface) and (TARGE170, to represent the target surface).

To model the SBCW, four simulations were conducted using mesh sizes of 100, 50, 25, and 10 mm. The results indicated that the average percentage of error relative to the experimental ultimate load yielded at 2.5% and 3.5% for element sizes of 10 mm and 25 mm, respectively. In this study, the mesh size for simulating the beam behavior was selected as 25 mm to minimize the computational time. Except for the base steel cylinder and actuator, an average mesh size of 20 mm was found to be suitable, as shown in Figure 2(b).

To obtain a unique solution, the model was constrained using the displacement boundary conditions. To ensure that the model behaved in the same manner as the experimental specimens, boundary conditions were applied at the loading and supports. The supports were modeled as roller supports. All the nodes on the bottom part of the base steel cylinder were restrained in all directions. The restrained nodes from the model are located at the following positions: (1) the prism simulate the actuator is restrained against translations in the $x$ and $z$ axes along the length of the prism from both sides of loading position. (2) The bottom part of the cylinders representing the supports is totally restrained against the translations and rotations in the $x$, $y$, and $z$ axes as shown in Figure 3.

The type of contact region is specified as frictionless contact. The contact shell face and the target face are defined as top faces to enforce the target face and the contact face to face each other to clarify the contact detection. The properties of the contact are controlled by pinball radius which specified as 10 mm, where the “Node-Normal to target” is used as detection method and the interface treatment is chosen to be “Adjust to touch.” The force applied at the top nodes of the actuator block was the actual force applied divided by the number of nodes. The total value of the load applied in each model was anticipated according to the beam ultimate load achieved by each specimen from the test, which was higher by almost 20%. The method of automatic
time stepping (or automatic loading) is one in which the applied loads are automatically determined in response to the current state of the analysis under consideration. Solver auto-time stepping technology is built in the program to adjust the model force and displacement relationship to find that optimal time increment to achieve balance. This technique employs a nonlinear static analysis with gradually increasing loads and the tangential stiffness is calculated until the imbalance forces (which are also called the residual forces/moments $R$) become acceptably small. The maximum and minimum time steps chosen were 10% to 1% from the total applied load, respectively. The values measured in the experimental tests for the material properties of the steel components (webs and flanges) were used in the FE analyses (Figure 4 and Table 2). Poisson’s ratio for steel was 0.3. In the model, steel is an isotropic material that follows a multilinear stress-strain curve (Figure 4). The elongation at yield varied between 0.001 and 0.0021 depending on the yield value for the flanges and web of the beam. An isotropic hardening behavior using a reduced modulus ($E_r$) is used to simulate the steel properties after reaching the yield strength, and this behavior continues until it attains the ultimate stress ($f_u$). After the ultimate stress, the material model follows perfectly plastic behavior. The total number of degrees of freedom for each model is ranged from 7500 to 9000, based on the horizontal fold length and the parameters studied. The Newton–Raphson solution technique is implemented to solve the nonlinear problem iteratively.

3.2. Applied Imperfections. The literature emphasizes the significant effect of imperfection on the numerical results [16]. Therefore, special attention was given to the applied imperfection shape in the current numerical simulations. The initial imperfections are the structural (residual stresses) and geometric imperfections that can be modeled by

\[
U_x = U_z = 0 \\
R_x, R_y, R_z = 0
\]

\[
U_x, U_y, U_z = 0
\]

**Figure 2:** FE model and the selected mesh: (a) modeling; (b) meshed model.

**Figure 3:** Model boundary conditions.
equivalent geometric imperfections. The shapes and magnitudes of the equivalent geometric imperfection can be defined using different alternatives; one of these alternatives is the application of the first eigenmode shape. This method is used mainly because it contains the relevant failure mode, as also allowed by EN1993-1-5 [29]. Additionally, the standard permits the use of geometric imperfections based on eigenshapes. Due to manufacturing processing, the geometric fabrication tolerances in combination with residual stresses are represented by stress patterns with amplitudes equivalent to the mean values. The initial geometric imperfections in the web can generally be estimated as a value far smaller than $h_0/200$ [30]. Lelouba et al. [14] recommended considering the first buckling mode shape as a source of geometric imperfection with a magnitude equal to the web thickness. Based on an experimental program conducted to test six corrugated web steel beams, it was also reported that the residual strength is not significantly influenced by the mode of shear buckling and is estimated to be approximately 50% of the ultimate load-carrying capacity of the tested beams. In the present study, nonlinear FE models considering geometric imperfections were established and validated. The calculations were based on equivalent geometric imperfections recommended by the standard EN 1993-1-5:2006. An eigenvalue buckling analysis was conducted to obtain the first buckling mode, and then the buckling shapes were scaled to simulate the initial imperfection. In the current simulation, therefore, the initial imperfection is considered only in web buckling with an amplitude equal to 2 mm. Various failure modes were examined separately and combined to ensure an appropriate and safe side solution. Changes in the failure mode in the interaction domain were handled by using such an imperfection type. Under one concentrated load, pilot runs were performed for five simply supported beams with corrugated webs having the same span and flange dimensions as the specimens with corrugated webs studied experimentally. The loads were applied to the model by defining different load steps.

In the model, two load cases are applied to analyze the model. The first case is to induce the initial imperfection in the form of the initial out-of-plane displacement over the HF when no external load is applied. The second case is applied at the end of this first case until the ultimate load is reached. In summary, the model is subjected to two load cases during the run, as follows: (1) from the beginning to the application of the initial imperfection and (2) from the updating of the geometry with the initial imperfection to the ultimate failure.

3.3. Model Validation. To validate the FE model, the load-vertical deflection behavior, load capacities, and failure mechanics were compared with the experimental results. Table 3 shows comparisons between the experimental and numerical results. Consequently, Figures 5(a) to 5(e) present plots of the experimental and numerical load vs. the vertical deflection at the midspan of the simulated specimens. Table 3 clearly shows that the model could accurately predict the yield and maximum load and the failure modes of the tested beams. The maximum errors in the predicted yield and maximum loads were less than 12.8% and 5.6%, respectively (for yield load, mean ($\mu$) = 8.1% and standard deviation ($\sigma$) = 3.6, while for maximum load, $\mu$ = 3.2% and $\sigma$ = 1.7). Consequently, the load-deflection curves obtained from the FE model also agreed well with the experimental data for the corrugated web steel beams (Figure 5). The load-deflection plot in the linear range from the FE analysis coincided with the load-deflection plot in the linear range based on the experimental results. The FE model became slightly stiffer than the actual beam after the elastic stage. The curves indicate that, during the solution process, the structure is in equilibrium if the residual forces/moments are totally vanished; and the displacement/rotation increment $\Delta u$ in every iteration is updated. Finally, at the load level where the structure becomes unstable (convergence is not achieved), at this moment the program stopped the solution process. In some cases as shown in (Figures 5(b) and 5(e)), the program stopped at a smaller deflection than the deflection obtained from the test result, possibly due to the solution techniques implemented in this analysis. Moreover, Figure 6 shows a comparison between the experimental and numerical failure mechanisms for simulated specimens CW20IFNW, CW20IFNFS, CW35IFW, and FW35WL. The above results and comparisons ensured the capability of the simulated model to predict with good precision the overall behavior, loads, and failure modes of the tested SBCW as well of the SBCW with a flat web.

In addition to the load deflection curves and failure mode comparison mentioned above, another verification for the finite element model was conducted. Using the experimentally recorded strain, the stress resulting from the model was compared with the experimental stress for specimen CW20IFNW. Figure 6(a) shows the load strain curve recoded during the test procedure until flange buckling. From this figure, the top flange started to buckle at 141 kN, while it completely buckled at 197 kN. From the recorded strain, the corresponding compressive stresses to these loads are 103 MPa to 144 MPa. The section could not develop the yield moment because the beam section is classified as class 4 according to the slenderness classification
Table 3: Comparisons of the experimental and numerical results.

| Specimen ID   | Experimental results | Numerical results | Comparisons |
|---------------|----------------------|-------------------|--------------|
|               | $P_y, \text{Exp. (kN)}$ | $P_y, \text{Num. (kN)}$ | $P_u, \text{Exp. (kN)}$ | $P_u, \text{Num. (kN)}$ | Failure mode | Failure mode | Error in $P_y$ (%) | Error in $P_u$ (%) |
| CW20IFNW     | 141                  | 151               | 197           | 208           | WB + FB     | WB + FB     | 7.1             | 5.6              |
| CW20IFNFS    | 162                  | 170               | 225           | 228           | WB + FB     | WB + FB     | 4.9             | 1.3              |
| CW35IFNW     | 145                  | 162               | 217           | 225           | WB + FB     | WB + FB     | 11.7            | 3.7              |
| CW35IFW      | 178                  | 185               | 245           | 248           | FB          | FB          | 3.9             | 1.2              |
| FW35 WL      | 125                  | 141               | 178           | 185           | WB*         | WB          | 12.8            | 3.9              |
|平均          | —                    | —                 | —             | —             | —           | —           | $\mu = 8.1$ | $\mu = 3.2$ |
|标准偏差      | —                    | —                 | —             | —             | —           | —           | $\sigma = 3.6$ | $\sigma = 1.7$ |

Error in $P_y(\%) = \frac{P_y, \text{Num} - P_y, \text{Exp}}{P_y, \text{Exp}} \times 100$ and error in $P_u(\%) = \frac{P_u, \text{Num} - P_u, \text{Exp}}{P_u, \text{Exp}} \times 100$. WB = web buckling; FB = flange buckling.
Figure 5: Comparisons between the experimental and numerical results: (a) specimen CW20IFNW; (b) specimen FW20IFNWF; (c) specimen CW35IFNW; (d) specimen CW35IFW; (e) specimen FW35 WL.

Figure 6: Continued.
stated in EC3 [29]. The compressive stress obtained from the FE model at the top flange was 138.14 MPa at a complete flange buckling load (Figures 6(a) and 7(a)). The percentage of error between the FE model and the experimental results was less than 4%. This result demonstrated that the model could simulate the CWSB behavior with an acceptable degree of accuracy.

Furthermore, the FE stress-strain relationship was described herein in two different places (the most affected places of the model). The first place was located at the web horizontal panel close to the load position, whereas the second was located at the midspan of the top flange.

In the web horizontal panel, the stress-strain relationship was almost identical for all specimens and could be represented by the following three stages. In the first stage, the stress increased linearly with increasing strain until the beginning of local web buckling. Throughout the second stage, the stress remained almost constant while the strain increased. In the third stage, with increasing applied load, the strain increased rapidly compared to the stress increase until total web local buckling occurred. Furthermore, the strain at the top flange of the modeled beam CW20IFNW was plotted for different loading stages (Figure 6(a)). The flange behavior can be divided into two main stages. In the first stage, a linear stress-strain relationship was observed from zero until almost 50% to 60% of flange yield stress (based on horizontal fold length), whereas in the second stage, the strain increased faster than stress until visible flange buckling occurred. Figure 7(b) shows the stress-strain relation obtained from the experimental tests and FE model at the top flange of beam CW20IFNW. The figure ensured good agreement between the numerical and experimental stress-strain curves for the top flange. This comparison emphasized the ability of the proposed numerical model to precisely capture the overall behavior of the CWSB items of load capacity, failure modes, stains, etc.

3.4. Design of the Parametric Study. The previous FE model was proven to be effective in predicting the behavior of SBCWs. Accordingly, this previous FE model can be used to investigate the effect of different parameters that influence the behavior and capacity of SBCWs with deeper insights. In this parametric study, the effects of web thickness, web yield strength, web depth, flange thickness, flange yield strength, and stiffeners on SBCW behavior and loads were studied. The details of the simulated beams and the studied parameters are listed in Table 4. Hence, the objective of this parametric study was to investigate the different aspects of the system behavior, such as the stiffness, ultimate load.
capacity, and failure mode, by changing the studied parameters. The studied parameters were classified into 6 groups (Table 4). In group 1, four SBCWs with different web thicknesses (2, 4, 5, and 6 mm) were simulated. In group 2, three SBCWs with different web yield strengths (400, 450, and 500 MPa) were simulated. In group 3, three SBCWs with different web heights (450, 550, and 650 mm) were simulated. Conversely, in group 4, four SBCWs with different flange thicknesses (7, 9, 10, and 12 mm) were simulated. In group 5, four SBCWs with different flange yield strengths (250, 275, and 300 MPa) were also simulated. Finally, in group 6, using the validated FE model, two cases with different stiffener heights (Figures 8(a) and 8(b)) and stiffener numbers (Figures 8(c) and 8(d)) were considered. In this study, the $h_s/h_w$ value was varied between 35% and 85% to investigate the effect of the flange-stiffener height on the

**Table 4: The specimen configurations for the parametric study.**

| Group no. | Specimen ID | $N_s$ (-) | $H_s$ (mm) | $H_F$ (mm) | $h_s$ (-) | $h_w$ (mm) | $t_w$ (mm) | $f_{y,w}$ (MPa) | $f_{y,f}$ (MPa) | Tested factor |
|-----------|-------------|-----------|------------|------------|-----------|------------|------------|----------------|----------------|---------------|
| Control   | CW20IFNW    | 0         | 0          | 200        | 100       | 384        | 3          | 420            | 8              | 225           |
| Group 1   | Bw2Y420     | —         | —          | 200        | 100       | 384        | 2          | 420            | 8              | 225           |
|           | Bw4Y420     | —         | —          | 200        | 100       | 384        | 4          | 420            | 8              | 225           |
|           | Bw5Y420     | —         | —          | 200        | 100       | 384        | 5          | 420            | 8              | 225           |
|           | Bw6Y420     | —         | —          | 200        | 100       | 384        | 6          | 420            | 8              | 225           |
| Group 2   | Bw3Y400     | —         | —          | 200        | 100       | 384        | 3          | 400            | 8              | 225           |
|           | Bw3Y450     | —         | —          | 200        | 100       | 384        | 3          | 450            | 8              | 225           |
|           | Bw3Y500     | —         | —          | 200        | 100       | 384        | 3          | 500            | 8              | 225           |
| Group 3   | Bw3H450     | —         | —          | 200        | 100       | 450        | 3          | 420            | 8              | 225           |
|           | Bw3H550     | —         | —          | 200        | 100       | 450        | 3          | 420            | 8              | 225           |
|           | Bw3H650     | —         | —          | 200        | 100       | 450        | 3          | 420            | 8              | 225           |
| Group 4   | B07Y420     | —         | —          | 200        | 100       | 384        | 3          | 420            | 7              | 225           |
|           | B09Y420     | —         | —          | 200        | 100       | 384        | 3          | 420            | 9              | 225           |
|           | B10Y420     | —         | —          | 200        | 100       | 384        | 3          | 420            | 10             | 225           |
|           | B12Y420     | —         | —          | 200        | 100       | 384        | 3          | 420            | 12             | 225           |
| Group 5   | B08Yf250    | —         | —          | 200        | 100       | 384        | 3          | 420            | 8              | 250           |
|           | B08Yf275    | —         | —          | 200        | 100       | 384        | 3          | 420            | 8              | 275           |
|           | B08Yf300    | —         | —          | 200        | 100       | 384        | 3          | 420            | 8              | 300           |
| Group 6   | BS1Hs150    | 1         | 150        | 200        | 100       | 384        | 3          | 420            | 8              | 225           |
|           | BS2Hs150    | 2         | 150        | 200        | 100       | 384        | 3          | 420            | 8              | 225           |
|           | BS3Hs150    | 3         | 150        | 200        | 100       | 384        | 3          | 420            | 8              | 225           |
|           | BS1Hs250    | 1         | 250        | 200        | 100       | 384        | 3          | 420            | 8              | 225           |
|           | BS1Hs350    | 1         | 350        | 200        | 100       | 384        | 3          | 420            | 8              | 225           |

**Figure 7:** Comparison between experimental and numerical for specimen CW20IFNW: (a) experimental strain results; (b) stress-strain curve.
flange resistance. In the FE parametric study, the consistency in the models was maintained such that the only variable parameter was the stiffener conditions. In the parametric study, beam CW20IFNW was fixed as the control beam. BZ_he results for the simulated beams in the parametric study were compared with the results for the considered control beam.

3.5. Results of the Parametric Study

3.5.1. Load Capacities and Failure Modes. The results for the simulated beams in the parametric study are listed in Table 5. The web thickness affected the yield and maximum loads and failure modes of the SBCW. As the web thickness was less than or equal to 4 mm, the failure of the SBCW was web buckling (WB) followed by flange buckling (FB). In contrast, increasing the web thickness to 5 mm and 6 mm changed the failure mode from WB + FB to FB only. Compared to CB, the beams with web thicknesses equal to 2, 4, 5, and 6 mm experienced yield loads equal to 93%, 117%, 126%, and 128%, respectively, while the maximum loads were 94%, 114%, 118%, and 121%, respectively. Increasing the web thickness up to 200% of the CB web thickness increased the load capacity by 21% over the load capacity of the CB (Table 5). Conversely, the increase in web yield strength from 420 to 450 MPa increased the yield and ultimate load.

![Diagram](https://via.placeholder.com/150)

**Figure 8**: Parameters studied: (a) flange stiffener height (250 mm) \((h_s/h_w = 62.5\%)\); (b) flange stiffener height (350 mm) \((h_s/h_w = 85\%)\); (c) number of flange stiffeners (two); (d) number of flange stiffeners (three).
capacities of the SBCW by approximately 26% and 12%, respectively, while increasing the web yield strength from 450 to 500 MPa had no effect on the yield and maximum as the failure was due to flange buckling failure. Increasing the web height also increased the load capacities of the SBCW as it delayed or prevented flange buckling and decreased the compressive stress on the flanges. Increasing the web height from 384 mm to 450, 550, and 650 mm increased the SBCW yield load by 9%, 18%, and 20%, respectively, while the SBCW ultimate load increased by 10%, 16%, and 22%, respectively. Increasing the web height up to 69% over that of the CB increased the load capacity of the SBCW by 22%. Effects of the flange properties (flange thickness, flange yield strength, and flange stiffeners) on the SBCW are also summarized in Table 5. Decreasing the flange thickness by 1 mm (from 8 to 7 mm) decreased the yield and ultimate loads of the SBCW by 13%, 21%, and 26%, respectively, while the ultimate loads increased by 10%, 15%, and 20%, respectively, over that of CB as the failure mode changed from WB + FB to WB only. A comparison between the web and flange dimensions on the behavior of the CWSB showed the higher effectiveness of the flange dimensions on the load capacity and failure modes of the CWSB. Conversely, the effect of the material properties of the web and flanges had nearly similar effects on the CWSB behavior.

As was observed from the experimental results, the flange stiffeners had a great effect on the SBCW behavior and load capacity. In this parametric study, more flange stiffener configurations were studied. Increasing the flange thickness or using the flange stiffeners had higher effects on enhancing the yield and ultimate loads of the SBCW than increasing the web dimensions or the yield strengths of the web and flanges. Effects of the flange-stiffener height on the flange normal stress and buckling are shown in Figures 9(a) and 9(b). Additionally, the effects of the number of flange stiffeners on the flange buckling and ultimate normal stress limit were investigated by varying the locations and number of flange stiffeners. Flange stiffeners were recommended to be located only in

### Table 5: The results of the parametric study.

| Group no. | Specimens ID | $P_{y,n}$ (kN) | $\mu_y$ (%) | $P_{u,n}$ (kN) | $\mu_u$ (%) | Failure mode |
|-----------|--------------|----------------|-------------|----------------|-------------|--------------|
| Control   | CW20IFNW     | 141            | —           | 197            | —           | WB + FB      |
| Group 1   | Bw2Y420      | 131            | 93          | 186            | 94          | WB + FB      |
|           | Bw4Y420      | 165            | 117         | 225            | 114         | WB + FB      |
|           | Bw5Y420      | 178            | 126         | 233            | 118         | FB           |
|           | Bw6Y420      | 180            | 128         | 238            | 121         | FB           |
| Group 2   | Bw3Y400      | 135            | 96          | 194            | 98          | WB + FB      |
|           | Bw3Y450      | 177.5          | 126         | 220            | 112         | FB           |
|           | Bw3Y500      | 177.5          | 126         | 222            | 113         | FB           |
| Group 3   | Bw3H450      | 154            | 109         | 216.5          | 110         | WB + FB      |
|           | Bw3H550      | 166            | 118         | 228.8          | 116         | FB           |
|           | Bw3H650      | 168.9          | 120         | 239.5          | 122         | FB           |
| Group 4   | B07Y420      | 124            | 88          | 177            | 90          | FB           |
|           | B09Y420      | 175            | 124         | 233            | 118         | WB + FB      |
|           | B10Y420      | 210            | 149         | 258            | 131         | WB           |
|           | B12Y420      | 275            | 195         | 305            | 155         | WB           |
| Group 5   | B08YF250     | 159            | 113         | 217.6          | 110         | WB + FB      |
|           | B08YF275     | 171            | 121         | 227            | 115         | FB           |
|           | B08YF300     | 177            | 126         | 237            | 120         | FB           |
| Group 6   | BS1Hs150     | 157.5          | 112         | 225            | 114         | WB + FB      |
|           | BS2Hs150     | 199.8          | 142         | 278.5          | 141         | WB + FB      |
|           | BS3Hs150     | 210.5          | 149         | 378            | 192         | WB           |
|           | BS1Hs250     | 189.5          | 134         | 254.7          | 129         | WB + FB      |
|           | BS1Hs350     | 208.5          | 148         | 328.5          | 167         | WB + FB      |

$\mu_y = \frac{P_{y,any}}{P_{y,CB} \times 100}$ and $\mu_u = \frac{P_{u,any}}{P_{u,CB} \times 100}$; any = any specimen and CB = control specimen.

225 MPa (CB) to 250, 275, and 300 MPa increased the yield load by 13%, 21%, and 26%, respectively, while the ultimate loads increased by 10%, 15%, and 20%, respectively, over that of CB as the failure mode changed from WB + FB to WB only. A comparison between the web and flange dimensions on the behavior of the CWSB showed the higher effectiveness of the flange dimensions on the load capacity and failure modes of the CWSB. Conversely, the effect of the material properties of the web and flanges had nearly similar effects on the CWSB behavior.

As was observed from the experimental results, the flange stiffeners had a great effect on the SBCW behavior and load capacity. In this parametric study, more flange stiffener configurations were studied. The yield loads of the SBCW with 1, 2, and 3 flange stiffeners that were 150 mm high increased by 12%, 42%, and 49%, respectively, while the ultimate loads increased by 14%, 41%, and 92%, respectively, over that of CB. Conversely, using one stiffener with 250 and 350 mm heights increased the yield loads by 34% and 48%, respectively, while the ultimate loads increased by 29% and 67%, respectively, over that of CB. From the above results, increasing the flange thickness or using the flange stiffeners had higher effects on enhancing the yield and ultimate loads of the SBCW than increasing the web dimensions or the yield strengths of the web and flanges. The effects of the flange-stiffener height on the flange normal stress and buckling are shown in Figures 9(a) and 9(b). Additionally, the effects of the number of flange stiffeners on the flange buckling and ultimate normal stress limit were investigated by varying the locations and number of flange stiffeners. Flange stiffeners were recommended to be located only in
the HF s close to the line load. Three stiffeners were used to maximize the number of flange stiffeners along the HF. The first and second stiffeners were located at the intersection lines between the IF and HF, and the third was fixed at the middle of the HF length. The number of transverse stiffeners significantly affected the flange buckling and ultimate normal stress limit of the SBCW, as shown in Figures 9(c) and 9(d). Beam BS3Hs150 (with three 150 mm flange stiffeners) experienced the highest load capacity of the simulated beams because of the effect of the stiffeners on delaying or preventing flange buckling (Table 5 and Figure 9(d)). The number of stiffeners or increasing the stiffener heights had a great influence on the load capacity and failure mode of the SBCW (Table 5). Moreover, the use of three flange stiffeners prevented FB failure.

3.5.2. Load-Deflection Behaviors. The load deflection curves of the simulated SBCW were affected differently by the studied parameters. The SBCW stiffness increased as the web thickness increased as the increase in web thickness increased the beam inertia and decreased the beam shear deflection (Figure 10(a)). In contrast, although increasing the web yielding strength increased the beam loads, the web yield strength had slight effects on the SBCW stiffness, as the beam inertia was affected only by the beam dimensions (Figure 10(b)). Conversely, as the web height increased, the SBCW stiffness increased as increasing the web height increased the beam inertia and decreased the beam shear deflection, thus increasing the SBCW stiffness (Figure 10(c)). Moreover, increasing the flange thickness greatly increased the SBCW stiffness, as it greatly affected the beam inertia (Figure 10(d)). Furthermore, increasing the flange yield strength increased the SBCW stiffness (Figure 10(e)). Finally, the $h_f/h_w$ ratio significantly affected the load-deflection curve of the SBCW, as shown in Figure 10(f). Using a flange stiffener increased the SBCW stiffness, as the stiffeners could delay or prevent the out-of-plane displacement of the SBCW. In contrast, increasing the number of flange stiffeners and their heights had trivial effects on the SBCW stiffness, although it had great effects on the load capacities and toughness of the SBCW (Figure 10(f)).

3.5.3. Relationship between Horizontal Fold Length and Shear Capacity. This section presents the relationship between the horizontal fold length and the corresponding maximum shear force that SBCWs with nonwelded inclined folds can sustain until failure. This study is based on three different values of horizontal fold length (200, 260, and 350 mm)
Figure 10: The load deflection curves for the simulated beams in the parametric study and the CB: (a) effect of web thickness; (b) effect of web yield strength; (c) effect of web height; (d) effect of flange thickness; (e) effect of flange yield strength; (f) effect of stiffeners height and numbers.
In this study, a simulated model was verified using an experimental study to adopt the behavior of SBCWs with different configurations. The effects of web thickness, web yield strength, web depth, flange thickness, flange yield strength and stiffeners on the SBCW behavior, load capacity, stiffness, failure modes, and strain were studied, and the following conclusions were adopted.

As the web thickness increased to 5 mm and 6 mm, the failure mode changed from WB + FB to FB only. Increasing the web thickness up to 200% of the CB web thickness increased the load capacity by 21% over the load capacity of the CB. Conversely, the increase in web yield strength from 420 to 450 MPa increased the yield and ultimate load capacities of the SBCW by approximately 26% and 12%, respectively, while increasing the web yield strength from 450 to 500 MPa had no effect on the yield and maximum as the failure was due to flange pickling failure.

Increasing the web height decreased the compressive stress in the top flange, which could delay or prevent flange buckling. The parameters studied related to the web characteristics (dimensions and material properties) had a maximum increase in the load capacity by 22% for beams with a 650 mm web height.

For the flanges, increasing the flange thickness changed the failure mode from WB + FB to FB only. Thus, increasing the flange thickness by approximately 67% over the flange thickness of CB increased the yield and ultimate loads by 95% and 55% over the yield and ultimate load of CB. Conversely, increasing the flange yield strength from 225 MPa to 300 MPa increased the yield and ultimate loads by 26% and 20%, respectively, over the yield and ultimate load of CB, and the failure mode changed from WB + FB to WB only.

The number of stiffeners or increasing the stiffener height had a great influence on the load capacity and failure mode of the SBCW. For SBCWs with 150 mm flange stiffeners, the use of 1, 2, and 3 stiffeners increased the load capacity by 14, 41, and 92% over the load capacity of CB. Moreover, increasing one stiffener with different heights (150, 250, and 350 mm) increased the load capacity of the SBCW by 29 and 67% over the load capacity of the CB. Furthermore, the use of three flange stiffeners prevented FB failure. In addition, increasing the flange thickness and the flange yield strength or using flange stiffeners increased the SBCW stiffness compared to the SBCW stiffness of CB.

The proposed equation can anticipate the shear capacity of SBCWs obtained from the experimental and FE analyses to an acceptable degree of accuracy.

**Data Availability**

All experimental and numerical data are available from the authors upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Authors’ Contributions**

A.E., I.S., and Y.A. contributed to conceptualization, validation, and original draft preparation; A.E. and I.S. contributed to methodology, software, formal analysis, investigation, visualization, and supervision; Y.A. and I.S. contributed to resources and project administration; I.S. contributed to data curation and writing-review and editing; Y.A. contributed to funding acquisition. All authors have read and agreed to the published version of the manuscript.

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