Shear Strength of Hollow Flange Channel Beams with Stiffened Web Openings

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Twenty-First International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, USA, October 24 & 25, 2012

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Abstract

This LiteSteel beam (LSB) is a new cold-formed steel hollow flange channel section produced using a patented manufacturing process involving simultaneous cold-forming and dual electric resistance welding. The LSBs are commonly used as floor joists and bearers with web openings in buildings. Their shear strengths are considerably reduced when web openings are included for the purpose of locating building services. Shear tests of LSBs with web openings have shown that there is up to 60% reduction in the shear capacity. Hence there is a need to improve the shear capacity of LSBs with web openings. A cost effective way to eliminate the shear capacity reduction is to stiffen the web openings using suitable stiffeners. Hence numerical studies were undertaken to investigate the shear capacity of LSBs with stiffened web openings. In this research, finite element models of LSBs with stiffened web openings in shear were developed to simulate the shear behaviour and strength of LSBs. Various stiffening methods using plate and LSB stiffeners attached to LSBs using both welding and screw-fastening were attempted. The developed models were then validated by comparing their results with experimental results and used in further studies. Both finite element and experimental results showed that the stiffening arrangements recommended by past research for cold-formed steel channel beams are not adequate to restore the shear strengths of LSBs with web openings. Therefore new stiffener arrangements were proposed for LSBs with web openings. This paper presents the details of this research project using numerical studies and the results.

Keywords: *LiteSteel beams, Web openings, Hollow flanges, Shear capacity, Stiffeners, Finite element analyses, Cold-formed steel structures.*

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1. Introduction

In recent times cold-formed high strength steel members are increasingly used as primary load bearing components in residential, commercial and industrial buildings. There are many significant benefits associated with the use of lightweight cold-formed steel sections in buildings. LiteSteel Beam (LSB) is a new cold-formed steel hollow flange channel beam produced by OneSteel Australian Tube Mills (see Figure 1a) (OATM, 2008). It is manufactured from a single strip of high strength steel through the use of a combined cold-forming and dual electric resistance welding process. The effective distribution of steel in LSBs with two rectangular hollow flanges results in a thin and lightweight section with good moment capacity. Figure 1 (b) shows the application of LSBs (OATM, 2008).

(a) LSB Section (b) LSB Floor Systems

Figure 1: LiteSteel Beams (OATM, 2008)

Generally in flooring systems is to include openings in the web of floor joists or bearers so that building services can be located within them. Three standard opening sizes of 60, 102 and 127 mm are used with the currently available LSBs (OATM, 2008). Keerthan and Mahendran (2011) showed that approximately 88% of the shear force is supported by the main web element of LSB. Hence this can lead to significantly reduced shear capacities when web openings are included in LSBs. Keerthan and Mahendran (2012) investigated the shear behavior and strength of LSBs with circular web openings using experimental and numerical studies. They found that the loss of shear capacity of LSBs was found to be as high as 60% when the standard 127 mm web openings were used in 200x45x1.6 LSBs. Hence LSB manufacturers and researchers realized the need to improve the shear capacity of LSB with web openings. An optimum way to improve the detrimental effects of a large web opening is to attach appropriate stiffeners around the web openings. Currently available cold-formed steel design standards (AS/NZS 4600, 2006; AISI, 2007) and other steel framing standards

(AISI, 2004) do not provide adequate guidelines to facilitate the design and construction of stiffeners for LSBs with large web openings. Therefore experimental and numerical studies were undertaken to develop the optimum and economical stiffener arrangement for LSBs with circular web openings subjected to shear. Details of the experimental study and the results are presented in Mahendran and Keerthan (2012). In the numerical study, suitable finite element models of LSBs with stiffened web openings were developed to simulate their shear behaviour and capacity, and were validated by comparing their results with corresponding experimental results. A detailed parametric study was then undertaken using the validated finite element model to develop the optimum stiffening system for the shear capacity of LSBs with web openings. This paper presents the details of the numerical study of LSBs with stiffened web openings subject to shear, and the results.

2. Experimental Study

This section presents the details of the web stiffening arrangements attempted in Mahendran and Keerthan's (2012) experimental study, which was focused on the use of plate stiffeners with varying fastening arrangements to determine the best fastening method. Table 1 shows the details of test specimens while Figure 2 shows the stiffening arrangements used. Stiffeners were not used in Test Specimens 1 to 4.

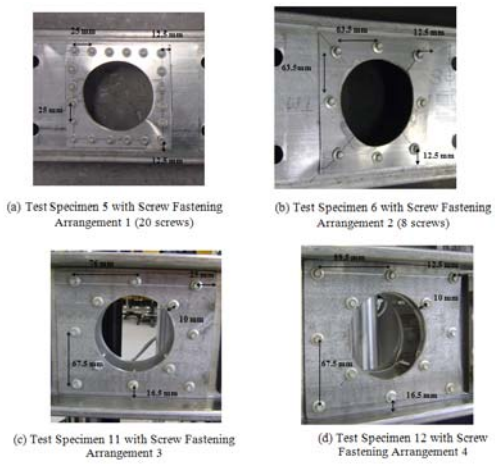
In Test Specimen 5, the web openings were stiffened with plate stiffeners based on AISI's (AISI, 2004) minimum stiffening requirements. The thickness of the plate stiffener was equal to the thickness of 200x45x1.6 LSB section while the plate stiffener extended 25 mm beyond all the edges of the web openings. The plate stiffener was fastened to the web of the LSB section with No.12 Tek screws at 25 mm spacing along the edges of the plate stiffener with an edge distance of 12.5 mm as shown in Figure 2 (a). This stiffener arrangement was defined as "Arrangement 1" (20 screws). Test Specimen 6 was assembled similar to Test Specimen 5. Here Tek screws were spaced at 63.5 mm along the edges of the plate stiffener (three screws on each side of the plate stiffener giving a total of 8 screws) with an edge distance of 12.5 mm (Figure 2 (b)). This eight screw arrangement was defined as "Arrangement 2". Since the use of plate stiffeners with a thickness equal to the LSB web thickness (1.6 mm) did not restore the original shear capacity of LSB, two and three 1.6 mm plate stiffeners (total thicknesses of 3.2 mm and 4.8 mm) were used in Test Specimens 7 and 8, respectively. The plate stiffeners' heights were also increased to match the clear LSB web height of 168 mm, which led to plate stiffener sizes of 152x168x3.2 mm and 152x168x4.8 mm. These two specimens were fastened using eight screws (Arrangement 2) as in Specimen 6. It was decided to locate the screws in the middle as implied by AISI (AISI, 2004) recommendations. Hence, unlike in Test Specimen 6, the edge distance along the horizontal edges was 16.5 mm instead of 12.5 mm while its spacing along the vertical edges was 67.5 mm instead of 63.5 mm due to the increased height of plate stiffeners.

Table 1: Details of LSB Specimens and their Test and FEA Results

Test No.	Stiffener Type	d_{wh} (mm)	t_w (mm)	d_1 (mm)	t_{Stiff} (mm)	Stiffener Size (mm)	No. of Screws	F.S.	Shear Capacity (kN)	
									Test	FEA
1	-	0	1.59	169.9	-	-	0	-	52.0	54.0
2	-	60	1.61	169.6	-	-	0	-	41.4	41.2
3	-	102	1.57	170.2	-	-	0	-	26.6	27.1
4	-	127	1.61	169.6	-	-	0	-	22.2	21.9
5	PS	102	1.59	170.1	1.6	152x152	20	A1	33.6	34.8
6	PS	102	1.57	170.2	1.6	152x152	8	A2	31.9	33.1
7	PS	102	1.56	170	3.2	152x168	8	A2	40.1	41.5
8	PS	102	1.56	170.5	4.8	152x168	8	A2	44.5	46.7
9	LSB SS	102	1.55	170.3	1.6	200x168	8	A2	40.5	42.1
10	LSB SS and PS	127	1.55	169.9	3.2	200x168, 177x168	12	A3	35.6	38.0
11	PS	102	1.56	170.1	3	202x168	12	A3	54.5	56.0
12	PS	102	1.57	170	3	202x168	12	A4	52.5	55.0
13	PS	102	1.57	168.8	3	202x168	Welding	-	67.0	66.5
14	PS	127	1.56	169.9	5.0	227x168	12	A3	47.4	49.4
15	PS	127	1.57	170	5.0	227x168	12	A5	46.3	48.1
16	PS	127	1.57	170.1	4.8	177x168	12	A3	35.6	36.8
17	PS	60	1.58	169.8	1.6	160x168	12	A3	50.5	52.5

Note: F.S. – Fastening System, PS - Plate Stiffener, LSB SS - LSB Stud Stiffener, A1- Arrangement1, t_{Stiff}, t_w- Thickness of Stiffener and LSB Web;
d_{wh} = Depth of Web Opening, d_1 = Clear Height of Web.

In Test Specimen 9, 200x45x1.6 LSB stud stiffeners were attached to LSB specimen with 102 mm web openings while 200x45x1.6 LSB stud stiffener and 177x168x1.6 mm plate stiffener were attached to LSB specimen with 127 mm web openings in Test Specimen 10. In these tests, the stiffener heights were again increased to that of clear web to improve the shear capacity. Arrangement 2 of eight screws was used in Specimen 9, but the edge distances and screw spacings were 16.5 mm and 67.5 mm on all four sides. The screw fastening in Specimen 10 was improved with four extra screws in the diagonal direction at 10 mm from the web opening edge, giving a total of 12 screws (Arrangement 3).



(a) Test Specimen 5 with Screw Fastening Arrangement 1 (20 screws)

(b) Test Specimen 6 with Screw Fastening Arrangement 2 (8 screws)

(c) Test Specimen 11 with Screw Fastening Arrangement 3

(d) Test Specimen 12 with Screw Fastening Arrangement 4

Figure 2: Screw Fastening Arrangements

In order to increase the shear capacity further, 3 mm thick and 202 mm wide plate stiffeners were used for the full web height of Test Specimens 11 and 12 (Figures 2 (c) & (d)). As in Test Specimen 10, four extra screws were used to attach these 202x168x3.0 mm plate stiffeners along the diagonal direction to enhance the shear capacity of LSBs. The screws were located in the middle on each side of the plate stiffener, which led to the edge distances of 25 mm and 16.5 mm and spacings of 67.5 mm and 76 mm in Test 11 (Figure 2 (c)). However, in Test Specimen 12, the edge distances were 12.5 mm and 16.5 mm (Figure 2 (d)). This arrangement of using 12 screws with a reduced edge distance of 12.5 mm was defined as “Arrangement 4”. In Test Specimen 13, 202x168x3.0 mm plate stiffeners were welded to LSBs with 102 mm web openings to determine whether welding instead of screw-fastening would produce higher shear capacities. Test Specimen 14 was used to investigate the use of thicker (5 mm) and wider (227 mm) plate stiffeners to restore the shear capacity for larger 127 mm web openings. Two 2.5 mm plates of 227x168 mm were fastened using 12 screws in Arrangement 3 as in Test Specimen 11. Test Specimen 15 is similar to Specimen 14 except in this case the plate stiffeners were attached to LSB using screws located on a circular format. This stiffener arrangement was defined as “Arrangement 5”. In Test Specimen 16 the width of plate stiffeners was reduced to 177 mm based on AISC’s (AISI, 2004) recommendations while three 1.6 mm plate stiffeners were used giving a total thickness of 4.8 mm. Test Specimen 17 was used with the smallest web opening of 60 mm for which only a single 1.6 mm plate stiffener was used.

3. Finite Element Analyses

This section illustrates the development of suitable finite element models to investigate the ultimate shear behaviour and strength of LSBs with stiffened web openings. For the numerical study, a general purpose finite element program, ABAQUS Version 6.7 (HKS, 2007), which has the capability of undertaking geometric and material non-linear analyses of three dimensional structures, was used. Finite element models were developed first with the objective of accurately simulating the actual test members' physical geometry, loads, constraints and mechanical properties reported in the experimental study of Mahendran and Keerthan (2012). This experimental study included 13 shear tests of simply supported back to back LSBs with stiffened web openings under a three-point loading arrangement as shown in Figure 3. Four tests were also conducted without stiffening the web openings, giving a total of 17 tests. Finite element models were also developed for LSBs with other types of stiffeners such as transverse and sleeve stiffeners. The cross-section geometry of the finite element model was based on the measured dimensions, thicknesses and yield stresses of 17 tested LSBs. Table 1 gives the measured dimensions of the test beams made of 200x45x1.6 LSB sections. The measured yield stresses of web, and inside and outside flange elements were 452.1, 491.3 and 536.9 MPa, respectively. The shell element in ABAQUS called S4R5 was used to simulate the shear behaviour of LSBs with stiffened web openings. R3D4 rigid body elements were used to simulate the restraints and loading in the finite element models of LSB with stiffened web openings. Convergence studies showed that an element size of 5 mm x 5 mm provided an accurate representation of shear buckling and yielding deformations. In order to get accurate results, Paver Mesh was applied around the LSB web and stiffener openings. Figure 4 shows the geometry and finite element mesh of a typical LSB with stiffened web openings.

The ABAQUS classical metal plasticity model was used in all the FE analyses. When the measured strain hardening in the web element as reported in Keerthan and Mahendran (2011) was used in FEA, the shear capacity improvement was less than 1%. Hence it was not considered in our analyses. Measured yield stresses were used in the finite element analyses. The elastic modulus and Poisson's ratio were taken as 200,000 MPa and 0.3, respectively. Simply supported boundary conditions were implemented in the finite element models of LSBs with stiffened web openings. The vertical translation was not restrained at the loading point. Figure 5 shows the applied loads and boundary conditions of the FE model. Shear test specimens included a 75 mm wide plate at each support to prevent lateral movement and twisting of the cross-section. These stiffening plates were modelled as rigid bodies using R3D4 elements. The motion of the rigid body can be prescribed by applying boundary conditions at the rigid body reference node. Hence simply supported boundary conditions were applied to the node at the shear centre to provide an ideal pinned support.

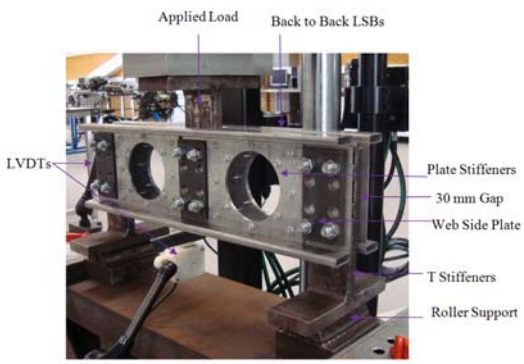
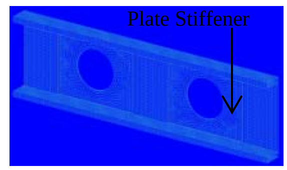
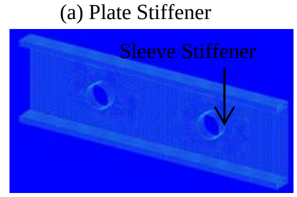


Figure 3: Experimental Set-up

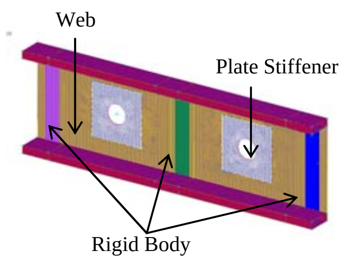


(a) Plate Stiffener

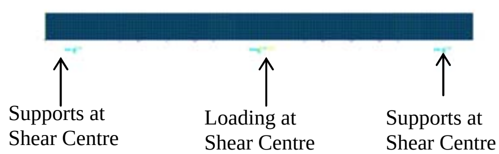


(b) Sleeve Stiffener

Figure 4: Finite Element Models of LSB



(a) Rigid Body



(b) Applied Loads and Boundary Conditions (Plan View)

Figure 5: Applied Loads and Boundary Conditions

Mahendran and Keerthan's (2012) tests showed that there were no screw fastener failures. Hence this was assumed in all the finite element analyses used here. The screw fasteners connecting the LSB to the stiffeners (Plate or LSB stud stiffeners) were not explicitly simulated in the finite element model. Instead they were simulated using perfect Tie MPCs, which makes all active degrees of freedom equal on both sides of the connection. The fabrication tolerance limit of $d_1/150$ was used as imperfection in the numerical models of LSBs. The critical imperfection shape was introduced by ABAQUS *IMPERFECTION option with the shear buckling eigenvector obtained from an elastic buckling analysis. Preliminary FEA showed that the effect of residual stresses on the shear capacity of LSBs without openings is less than 1% (Keerthan and Mahendran, 2011).

Therefore the effect of residual stresses on the shear capacity of LSBs with stiffened web openings is also likely to be very small. It was thus decided to neglect the residual stresses in the FEA of LSBs with stiffened web openings.

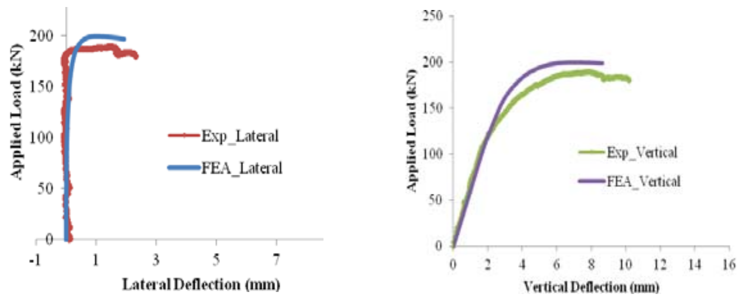
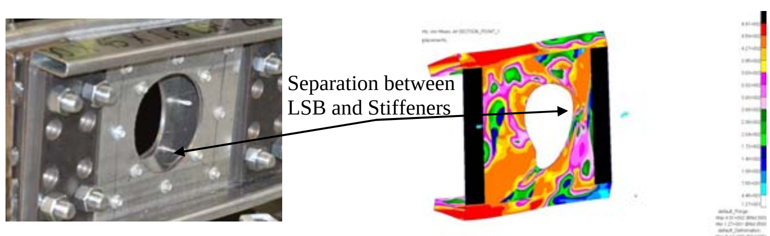
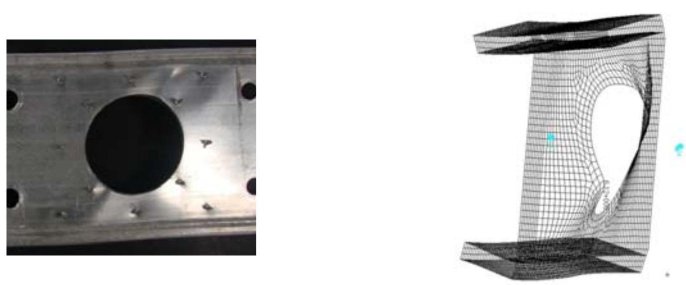


Figure 6: Plot of Applied Load versus Deflections for Test Specimen 14



(1) Experiment (2) FEA

(a) Stress



(1) Experiment (2) FEA

(b) Deformation

Figure 7: Failure Modes of Test Specimen 11

It is necessary to validate the developed finite element models for non-linear analyses of LSBs with stiffened web openings. This was achieved by comparing the non-linear analysis results with the results obtained from the shear tests (Mahendran and Keerthan, 2012). This comparison was intended to establish the validity of the shell element model in the modelling of initial geometric imperfections and shear deformations, and associated material yielding. The FEA results were compared against those from testing, with particular attention given to the ultimate load, load-deflection curves and failure mechanism. Table 1 presents a summary of the ultimate shear capacity results of LSBs with stiffened web openings from FEA and tests. The mean and COV of the ratio of test to FEA ultimate shear capacities are 0.97 and 0.021. This indicates that the finite element model developed in this study is able to predict the ultimate shear capacity of LSBs with stiffened web openings with very good accuracy. Figure 6 shows the FEA results in the form of load versus deflection for 200x45x1.6 LSB with 127 mm stiffened web openings (Test Specimen 14) and compare them with corresponding experimental results while Figure 7 shows the shear failure modes of Test Specimen 11. These figures demonstrate a good agreement between the results from FEA and experiments.

4. Effects of Using Different Type of Stiffeners with LSBs

In this section, the use of various types of stiffeners, namely, plate stiffeners, LSB stud stiffeners, sleeve stiffeners and transverse stiffeners, was investigated to determine the shear capacity improvements by using finite element analyses.

4.1. Transverse Stiffeners

Transverse stiffeners are generally used in hot-rolled steel sections and are welded to the web. Welding in cold-formed steel sections is difficult and hence this stiffener is not a practical option. In order to investigate the effect of the thickness of transverse stiffeners on the shear capacity, finite element analyses of 200x45x1.6 LSBs with 60 and 127 mm web openings were undertaken with varying stiffener thicknesses. Figure 8 shows the failure modes of LSBs with 3 mm transverse stiffeners while Figure 9 shows the finite element analysis results in the form of shear capacity of LSBs versus thickness of transverse stiffeners. Figure 9 shows that transverse stiffeners are not adequate to restore the shear strengths of LSB with larger web openings (127 mm). Hence it was decided not to recommend the use of transverse stiffeners for LSBs with large web openings.

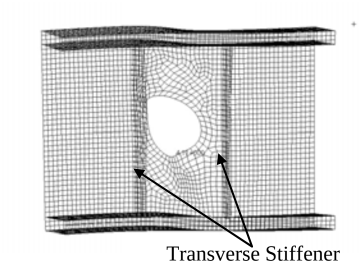


Figure 8: Shear Failure Modes of 200x45x1.6 LSB with 60 mm Web Openings and 3 mm Transverse Stiffeners

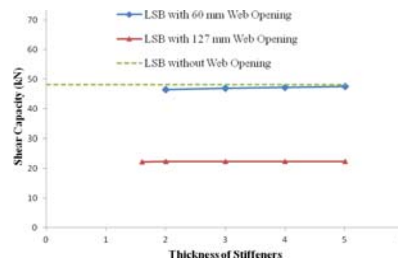


Figure 9: Shear Capacity of LSB versus Thickness of Transverse Stiffeners

4.2. Sleeve Stiffeners

The sleeve stiffener was proposed based on its ability to restrain the free edge of web openings. The thickness of the sleeve stiffeners was considered to be the same as the LSB web thickness. However, its length was varied (10, 20 and 25 mm) to determine its effect on the shear capacity of 200x45x1.6 LSBs with 60 mm web openings. The results show that the length of the sleeve stiffeners (10 to 25 mm) did not play a significant role on the shear capacity of LSB with web openings. Figure 10 shows the failure mode of 200x45x1.6 LSB with 60 mm web openings and 20 mm sleeve stiffeners while Figure 11 shows the shear capacities of LSBs with varying web opening sizes and 20 mm sleeve stiffeners, which indicate that sleeve stiffeners are not adequate to restore the shear strengths of LSB with larger web openings (102 and 127 mm). Hence it was decided not to recommend the use of sleeve stiffeners for LSBs with large web openings.

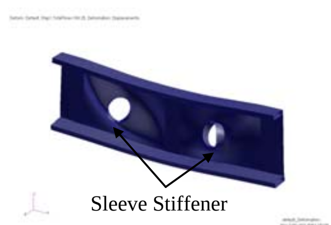


Figure 10: Shear Failure Mode of 200x45x1.6 LSB with 60 mm Web Openings and 20 mm Sleeve Stiffeners

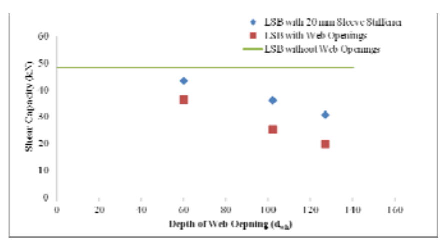


Figure 11: Shear Capacities of LSBs with varying Web Opening Sizes and 20 mm Sleeve Stiffeners

4.3. LSB Stud Stiffeners

The LSB stud stiffener is attached to the web around the opening by fastening with No.12 Tek screws. Effect of LSB stud stiffeners on the shear capacity of LSBs with web openings was investigated using finite element analyses and Tests 9 and 10, and the results are shown in Table 1. The FEA and test results showed that LSB stud stiffener systems were able to obtain about 80% of the shear capacity of LSB without web openings (52 kN) in the case of 102 mm web openings. Since the thickness of LSB stud stiffener is equal to the web thickness, LSB stud stiffeners are not adequate to restore the shear strengths of LSB with large web openings. Hence LSB stud stiffeners are not recommended for LSBs with large web openings.

4.4. Plate Stiffeners

Mahendran and Keerthan (2012) undertook experimental studies to investigate the effect of plate stiffeners on the shear capacity of LSB with web openings. They found that plate stiffener is the optimum stiffener for LSBs with web openings. However, the number of shear tests was limited (17 shear tests). Hence in order to determine the optimum plate stiffener sizes, finite element models of LSBs with web openings stiffened with plate stiffeners in shear were developed to simulate their shear behaviour and strength. They were then validated by comparing their results with available experimental test results (Mahendran and Keerthan, 2012) and used in a detailed parametric study.

In order to simulate Test Specimen 5, plate stiffener dimensions and screw fastening arrangement were adopted based on AISI (AISI, 2004) (Arrangement 1). However, FEA and experimental results show that Test Specimen 5 only reached about 65% of the shear capacity of LSB section without web openings (34.8 kN vs 52 kN). Hence FEA and test results showed that the plate stiffeners established as per AISI (AISI, 2004) recommendations are not adequate to restore the shear strengths of LSB with web openings. In order to investigate the effect of screw spacing, Tests 5 and 6 were simulated with 152x152x1.6 mm plate stiffeners attached with different screw spacings (Arrangements 1 and 2). Table 1 shows that the use of screw fastening arrangement with more screws (20 versus 8 screws) only increased the shear capacity of LSBs by about 5%. Table 1 shows that the shear capacity of LSB with web openings increases with thicker and larger plate stiffeners while it did not change much due to reduced screw spacing. The FEA and test results showed that thicker and wider stiffeners of full web height are needed to fully restore the shear capacity of LSBs.

In summary, FEA and test results in Table 1 show that plate stiffeners with dimensions equal to web opening width and depth plus 100 mm, screw fastened using Arrangement 3, are needed to restore the original shear strength of 200x45x1.6 LSBs. Their thicknesses have to be a minimum of 1.6 mm and 3.0 mm for these LSBs with 60 mm and 102 mm web openings, respectively. However, detailed parametric studies should be undertaken to determine predictive equations for the required stiffener thicknesses for all LSB sections.

5. Optimum Plate Stiffeners for LSBs with Web Openings

Previous sections have shown that plate stiffeners using screw fastening Arrangement 3 are the most suitable stiffening system for LSBs with web openings. A detailed parametric study was therefore undertaken based on the validated finite element model to develop suitable sizes of optimum plate stiffeners. In this study, nominal LSB dimensions were used while an aspect ratio of 1.5 was used. Five LSB sections, 150x45x1.6 LSB, 150x45x2.0 LSB, 200x45x1.6 LSB, 300x75x2.5 LSB and 300x75x2.0 LSB, with four web opening sizes (60, 102, 119 and 127 mm) were selected in this parametric study with an aim to determine the optimum plate stiffener thickness in each case.

Figure 12 shows the FEA results in the form of shear capacity of LSB with 102 mm stiffened web openings versus number of screws while Figure 13 shows the FEA results in the form of shear capacity of LSB with stiffened web openings versus stiffener thickness for 200x45x1.6 LSB with 102 web openings. Figure 12 indicates that plate stiffeners with 12 screws (Arrangement 3) are the optimum screw fastening arrangements. Figure 13 shows that the optimum plate stiffener thickness is 3.0 mm for 200x45x1.6 LSB with 102 mm web openings. Finite element analysis results also show that 1.6 mm and 4.0 mm are the optimum plate stiffener thicknesses for 200x45x1.6 LSB with 60 mm and 119 mm web openings, respectively. Experimental results also confirmed that plate stiffeners with Arrangement 3 (12 screws) were the optimum stiffening arrangements and 1.6 mm and 3.0 mm were the optimum stiffener thicknesses for 60 mm and 102 mm web openings, respectively. The optimum plate stiffener thicknesses in each case were obtained from finite element analysis results. In order to obtain the optimum plate stiffeners thickness, stiffeners thickness were increased from 1.6 mm to 8.0 mm.

Finite element analysis results showed that 5 mm plate stiffeners fastened using Arrangement 3 were almost (93%) able to restore the full shear capacity of 200x45x1.6 with 127 mm web openings. In this case, the depth of web opening to the clear height of web ratio (d_{wh}/d_1) is 0.75, which exceeds the limiting value of 0.70 in AS/NZS 4600 (SA, 2005). In order to obtain the full shear capacity, the depth of web opening to the clear height of web ratio (d_{wh}/d_1) was limited to 0.70 based on finite element analysis results.

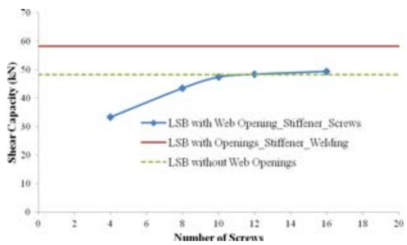


Figure 12: Effect of Number of Screws on the Shear Capacity of 200x45x1.6 LSB with 102 mm Web Openings

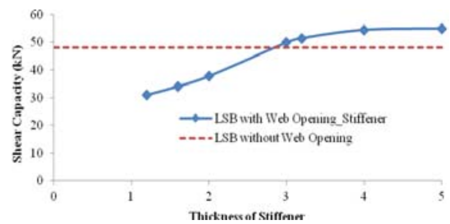


Figure 13: Shear Capacity of 200x45x1.6 LSB with 102 mm Web Openings

Based on the numerical and experimental results reported in the previous sections, it is now proposed that the width of the optimum plate stiffener is d_{wh}+100 mm and its height is lesser of clear web height (d_1) and d_{wh}+100 mm. This optimum stiffener arrangement is an improvement of the recommendations of AISI (AISI, 2004) and Sivakumaran (2008). It shows that LSBs were able to restore the original strength and stiffness when the optimum stiffener arrangements were used around the web openings. Keerthan and Mahendran (2011) proposed suitable predictive equations for the shear capacity of LSB without web opening (V_v). These equations can be used for LSBs with stiffened web openings when the optimum stiffening system proposed here is used around the web openings. Figure 14 shows the plot of optimum plate stiffener thickness to web thickness ratio (t_{Siff}/t_w) versus depth of web opening to clear height of web (d_{wh}/d_1). Equations 1 to 3 are also proposed for the sizes of optimum plate stiffeners based on the numerical and experimental results. They provide a lower bound to plate stiffener thickness (t_{Stiff}) and thus ensure a safe design of LSBs with stiffened web openings.

$$t_{Stiff} = \left[3.52\left(\frac{d_{wh}}{d_1}\right) + 0.035\right]t_w \quad 0.24 < \frac{d_{wh}}{d_1} \leq 0.70 \tag{1}$$

$$w_{Stiff} = d_{wh} + 100 \tag{2}$$

$$h_{Stiff} = \text{Lesser of } d_1 \text{ or } d_{wh} + 100 \tag{3}$$

where t_{Stiff}, w_{Stiff} and h_{Stiff} = Thickness, Width and Height of plate stiffeners, respectively. d_{wh} = Depth of web openings, d_1= Clear height of web

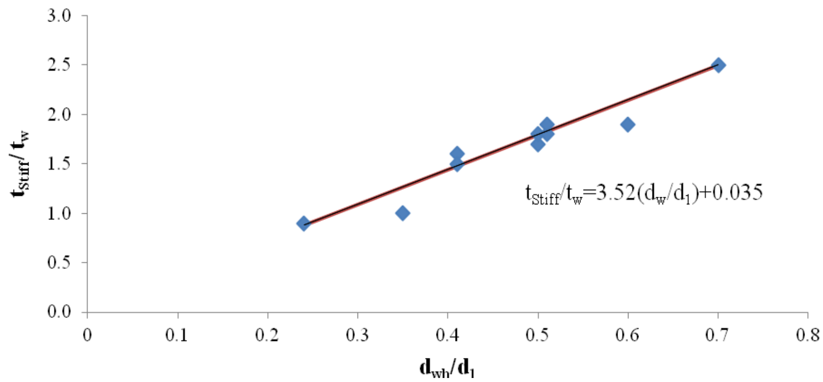


Figure 14: Plot of Plate Stiffener Thickness to Web Thickness Ratio (t_{Stiff}/t_w) versus Depth of Web Opening to Clear Height of Web (d_{wh}/d_1)

6. Conclusions

This paper has presented a detailed investigation into the shear capacity of LSBs with stiffened web openings using numerical studies. Suitable finite element models were developed and validated by comparing their results with corresponding test results. The developed nonlinear finite element model was able to accurately predict the shear capacities, plots of load-deflection and failure modes of LSBs with stiffened web openings. Both numerical and experimental study results show that the plate stiffeners based on the recommendations of AISI (AISI, 2004) are not adequate to restore the shear strengths of LSB with web openings. New plate stiffener systems with optimum sizes and screw-fastening arrangements have been proposed to restore the shear capacity of LSB with web openings based on the results from both experimental and numerical studies. New equations have been proposed for LSB designers to determine the optimum plate stiffener thickness as a function of d_{wh}/d_1.

Acknowledgements

The authors would like to thank Australian Research Council and OneSteel Australian Tube Mills for their financial support, and the Queensland University of Technology for providing the necessary facilities and support to conduct this research project. They would also like to thank Mr Ross Dempsey, Manager - Research and Testing, OneSteel Australian Tube Mills for his technical contributions, and his overall support to this research project.

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