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INITIAL IMPERFECTION CHARACTERISTICS OF MONO- SYMMETRIC LITE STEEL BEAMS FOR NUMERICAL STUDIES

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Abstract: The aim of the present study is to investigate the initial imperfection characteristics of the new mono-symmetric LiteSteel beams (LSB) and their effects on the moment capacity. A unique manufacturing process of simultaneous cold-rolling and electric resistance welding process is used in the manufacturing of LSBs that can lead to unique initial imperfections in the form of initial geometric distortions and residual stresses. Such imperfection characteristics are unlikely to be present in conventional steel beam sections. In this study, the imperfections in LSBs were measured and their effects on the moment capacities were investigated using finite element analyses. It also included a sensitivity study of geometric imperfections and residual stresses on LSB moment capacities. This paper presents the details of this study, the results, and useful recommendations for numerical modelling, design and manufacturing of LSBs.

Keywords: *Cold-formed steel, LiteSteel Beam (LSB), Initial imperfections, Residual stresses, Nonlinear analysis.*

1. INTRODUCTION

The use of thin and high strength cold-formed steel members in buildings provides many benefits including high strength to weight ratios and cost efficiency but also presents many challenges. Australian Tube Mills formerly known as Smorgon Steel Tube Mills (SSTM) has developed a new concept of Hollow Flange Sections (HFS) using a dual electric resistance welding technology. These sections are manufactured from a single strip of high strength steel using simultaneous roll-forming and electric resistances welding. One of the hollow flange sections is a mono-symmetric hollow flange channel, known as LiteSteel Beams (LSB). Unlike the conventional hot-rolled or cold-formed steel sections, the thin-walled and high strength LSB sections are made of two torsionally rigid, closed rectangular flanges and a relatively slender web. The unique manufacturing process is likely to cause both geometric imperfctions and residual stresses, but their effect on the strength of LSBs is not fully understood. Some investigations have been undertaken on the initial imperfections and their effect on the behaviour and strength of mono-symmetric sections (Schafer and Peköz, 1999, Yang and Hancock, 2004, and Dinis et al., 2007). Mahaarachchi and Mahendran (2005) conducted a series of tests to measure the initial imperfection and residual stresses for LSBs. Their research on residual stresses was conducted for 150x45x1.6 LSB, 250x75x2.5 LSB and 300x75x3.0 LSB sections. The measured residual stresses were then expressed as a ratio of the virgin plate’s yield stress. Initial geometric imperfections were measured for 48 types of test specimen using both a Wild T05 theodolite and the imperfection measuring equipment specially designed and built at the Queensland University of Technology. However, a detailed study on the effect of each component of residual stresses and geometric imperfections has not been undertaken yet. This research was therefore undertaken to investigate in detail the various imperfections in LSBs, and their effect on the behaviour and moment capacity of LSBs based on numerical studies. This paper presents the details of this study and the results.

2. EXPERIMENTAL INVESTIGATION

2.1 Test specimens

Maharachchi and Mahendran (2005) measured the residual stresses in three LSB sections. Test results showed that the flange yield stress exceeded the nominal yield stress of 450 MPa and the web nominal yield stress of 380 MPa. They were then expressed as a ratio of the virgin plate's yield stress value of 380 MPa.

In this research, residual stress tests were conducted for 150x45x1.6 LSB sections to confirm the previous test results, and also to determine the effect of various improvements made to the LSB manufacturing processes during the last three years. Initial geometric imperfection tests were also conducted for two 200x45x1.6 LSB single sections and one 200x45x1.6 LSB back to back sections. A specimen of 3.2 m length was used in the tests.

2.2 Initial geometric imperfections

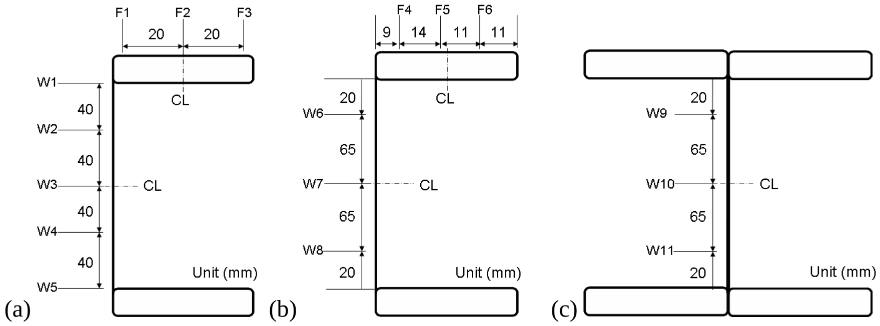
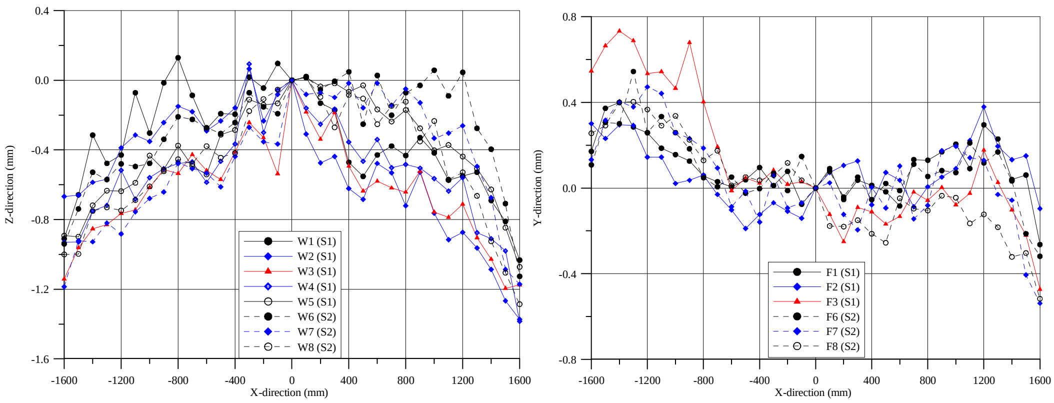


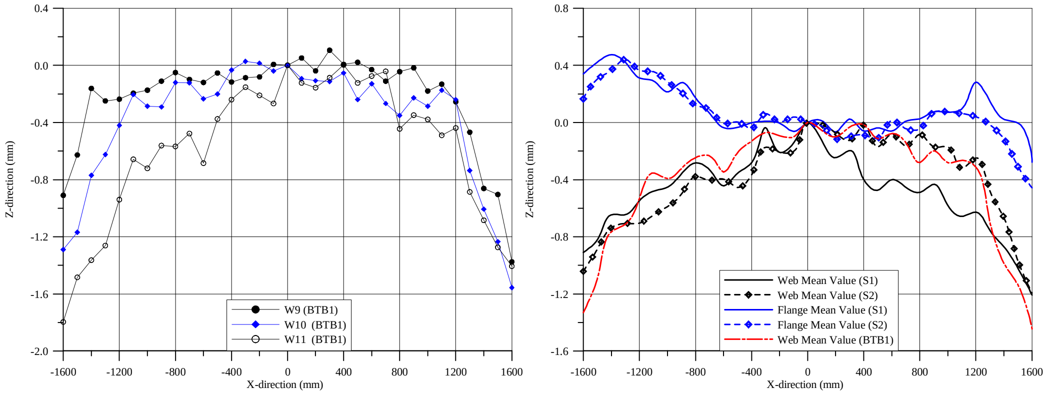
Figure 1: Locations of initial imperfection measurements (a) and (b): single LSB (c): back to back LSB

Geometric imperfection refers to deviation of a member from perfect geometry. It includes bowing, warping, and twisting as well as local deviations. In this research, the imperfection magnitudes of LSB sections were measured based on the final shape of formed sections. The imperfection measuring equipment included a levelled table with guided rails, a laser sensor, travelator to move the sensor and a data logger. Measurements were taken along five lines for single LSB web and three lines for flange in the longitudinal direction of the specimen at 100 mm intervals. The imperfection measurement locations along the length of a 3.2 m span 200x45x1.6 single LSB are shown in Figures 1 (a) and (b) while Figure 1 (c) shows the measurement locations along three lines for web in the longitudinal direction for back to back sections. Figures 2 (a) to (d) show the measured imperfections of straightness for each LSB member tested in bending.



(a) Measured imperfection of single LSB web (b) Measured imperfection of single LSB flange

Figure 2: Measured Imperfections for 3.2 m long 200x60x2.0 LSB



(c) Measured imperfection of back to back LSB web (d) Average values for webs and flanges

Figure 2: Measured Imperfections for 3.2 m long 200x60x2.0 LSB

The overall maximum values of member imperfections are less than about 50% of the recommended limit of span/1000 (SA, 1998). The member imperfections (out of straightness) were found to be dominant than the local plate imperfections. For example, the flange imperfections were considerably smaller than the accepted limit of width/150. This demonstrates that the unique manufacturing process of LSB does not lead to geometric imperfections that exceed the currently accepted fabrication tolerances. As illustrated in Figures 2(c) and (d), it is also observed that the overall initial imperfection values were not affected by back to back assembling of LSB members.

2.3 Residual Stress distributions

In numerical analyses, idealized residual stress patterns must be used to simplify the modeling process while retaining a reasonable accuracy in strength results. For hot-rolled I-sections, the longitudinal membrane residual stress distributions shown in Figure 3 (a) are recommended by ECCS (1984) and have been adopted by numerous researchers. The assumed residual stress distribution for HFB sections is shown in Figure 3(b), based on the measured residual stresses of Doan and Mahendran (1996). They ignored the membrane component of the residual stress as it was found to be significantly less than the flexural component. This residual stress model was used by Avery et al. (2000) in predicting the flexural capacity of HFBs.

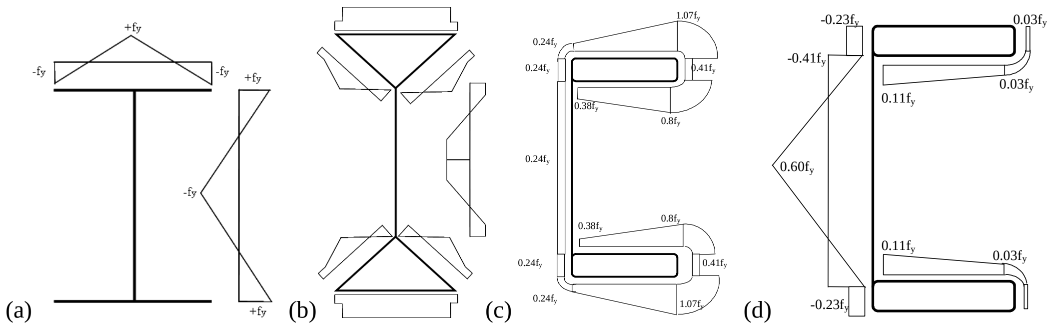


Figure 3: Residual stress distributions in (a) typical I-sections for membrane stresses (b) hollow flange sections for flexural stresses (c) LSB flexural stresses (d) LSB membrane stresses

The distributions of flexural and membrane residual stresses based on the measured residual stresses in three LSB sections are given in Figures 3 (c) and (d) (Mahaarachchi and Mahendran, 2005). Conventional open cold-formed sections made by roll-forming alone have only flexural residual stresses. However, LSB sections are different to the conventional cold-formed steel sections due to the unique dual electric resistance welding and this can lead to the generation of membrane residual stresses. Therefore it is very important that both membrane and flexural residual stresses are measured in LSB sections. The maximum flexural residual stress was recorded in the corner of the outside flange ($1.07f_y$) while the maximum membrane residual stress recorded in the web was 0.60 f_y, where f_y is the virgin plate yield stress of 380 MPa. Tensile test results showed that the average flange yield stress (516 MPa) is much higher then the virgin plate yield stress of 380 MPa due to the cold-forming process. Therefore the residual stresses recorded in the flange corners were more than the virgin plate yield stress ($1.07f_y$).

In order to confirm the residual stress distributions measured by Mahaarachchi and Mahendran (2005) and to determine the effect of improved manufacturing processes since 2005, residual stress tests of 150x45x1.6 LSBs were undertaken using the destructive method known as the sectioning method.

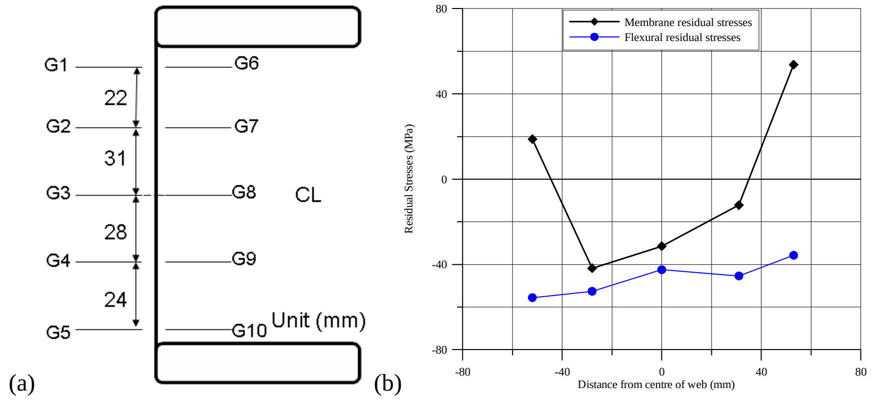


Figure 4: Measured stress distribution along the Web (After 24hrs)

Figure 4 (a) shows the locations of strain gauges used in the web element of 150x45x1.6 LSB. The final residual stresses were calculated from the difference between the strain gauge readings before cutting and those obtained after 24 hours following cutting. The residual stress components of LSB we element are shown in Figure 4(b). The results show that the membrane stresses in the web caused by the welding of the section are considerably smaller ($0.15f_y$ versus $0.60f_y$) than those measured by Mahaarachchi and Mahendran (2005). In fact the flexural residual stresses in the web element have also been reduced. This may be the result of improved LSB manufacturing process in the last few years.

3. FINITE ELEMENT ANALYSIS

3.1 Element type and Mesh

Taking advantage of the advanced capability of ABAQUS, all modelling considered both geometrical and material nonlinearities, an elasto-plastic material model and large displacements based on the total Lagrangian formulation. The nonlinear shell finite element (S4R) was used in the modeling of LSBs. This element is a thin and thick, shear flexible, isoparametric quadrilateral shell with four nodes and six degrees of freedom per node, updated Lagrangian framework, applicable large strain and bilinear interpolation schemes.

Elastic shell elements were used for eigenvalue buckling analyses, and plastic shell elements allowing for large deflection behavior were used in non-linear buckling analyses. By varying the element size, the adequacy of finite element mesh used in the model was studied. It was found that good simulation results could be obtained by using the element size of approx. 8 mm × 4 mm (length by width) for web and flanges.

3.2 Boundary conditions

The idealized boundary conditions used by Kurniawan (2008) for simply supported boundary condition were used here with a uniform bending moment. For the present elastic and nonlinear finite element analyses the following boundary conditions are applied where T[x, y, z] indicates translational constraints, and R[x, y, z] indicates rotational constraints about x-, y-, and z-axis, respectively; A “0” indicates constraint, and “-”

indicates no constraint. The pin support at the end was modeled by restraining appropriate nodes degrees of freedom T[-, 0, 0] and R[0, -, -]. To simulate the symmetric condition support at the middle of span, the following nodes degrees of freedom T[0, -, -] and R[-, 0, 0] were restrained. This combination simulates a simply supported condition with warping free and local flange twist restraint conditions. To simulate a uniform end moment across the section, linear forces were applied at every node of the beam end, where the upper part of the section was subject to compressive forces while the lower part was subject to tensile forces. The required uniform bending moment distribution within the span was achieved by applying equal end moments using linear forces at the end support.

3.3 Effect of geometric imperfections

Real beams are not perfectly straight and are associated with geometric imperfections, which may affect their buckling behaviour and strength. The initial imperfection shape was introduced by ABAQUS *IMPERFECTION option with the critical buckling eigenvector obtained from an elastic buckling analysis. For intermediate and long spans, the critical mode is lateral distortional and lateral torsional buckling and hence the node that has the maximum out-of-plane deformation from elastic buckling analysis will be usually given the largest imperfection magnitude of span/1000, which is the AS4100 fabrication tolerance.

Table 1(a) shows that the measured imperfections based on this study and Mahaarachchi and Mahendran (2005) are within the manufacturer’s fabrication tolerance limits (SSTM, 2005). There are eight different kinds of imperfections and associated tolerances as shown in Table 1 (a). It is realized that the initial imperfections depend on the aspect ratio of web, flange width as well as other factors such as material properties, welding condition, and rolling process. Available measurements show that although the initial imperfection distribution is quite complex, overall member imperfection is predominant in the longitudinal direction. Also, for lateral buckling analysis member imperfections are critical. Hence the critical overall imperfection including lateral displacement, twist rotation, and cross section distortion was adopted in numerical studies. However, the effect of localized cross-section or plate imperfections (C4 to C7 in Table 1(a)) is not known. Hence the fabrication tolerances of these imperfections shown in Table 1(a) were also used in the FEA, but without any overall member imperfection. Tables 1 (b) and (c) show that the moment capacity loss due to the cross-section or plate imperfections is considerably less than that due to the use of L/1000. Therefore it is recommended to conservatively adopt the fabrication tolerance of span/1000 for overall member imperfection in the lateral buckling analysis of LSBs. This also implies that as long as LSBs are manufactured within the current SSTM tolerances of various imperfections shown in Table 1(a), the use of L/1000 in the numerical analyses is adequate.

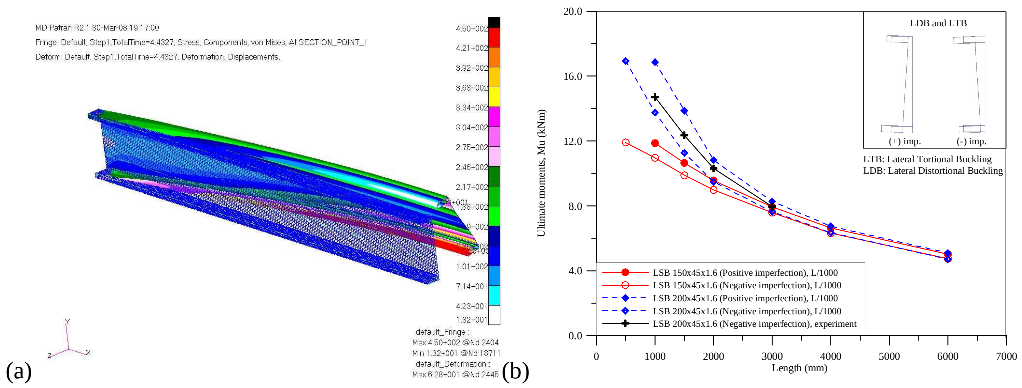


Figure 5: (a) Typical von Mises stress distribution at ultimate moment, (b) The results of imperfection value and direction on LSB Ultimate moments under uniform moment conditions

LSB is a mono-symmetric section, and hence the imperfection direction may also affect its ultimate strength. A typical von Mises stress distribution at ultimate moment is shown in Figure 5 (a). The results of geometric imperfection value and direction on LSBs’ ultimate strengths under uniform bending moment are shown in Figure 5 (b). The negative imperfections cause a maximum of 22 and 8% reduction to the ultimate strengths of 200x45x1.6 (slender section) and 150x45x1.6 (non compact section) when compared with positive imperfection for the lateral distortional (intermediate spans) and lateral torsional buckling (long spans). The ultimate strengths of 200x45x1.6 (slender section) based on the measured initial imperfection value are about 4 to 8% higher than that for the negative imperfection value of span/1000. Hence negative imperfections must be used in the numerical studies and design of LSBs.

Table 1(a): Comparison of fabrication tolerance vs. measured imperfections for lateral buckling analysis

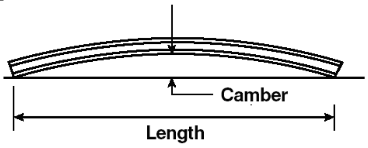
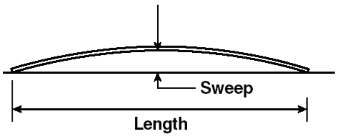
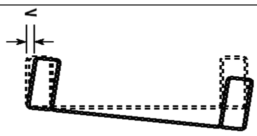
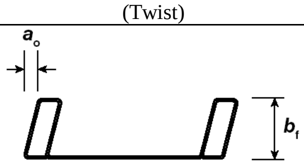
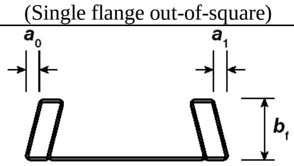
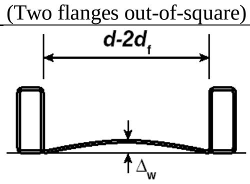
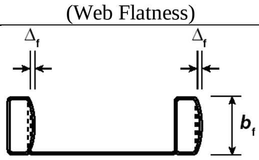
Case	Illustration	LSB (mm)	SSTM Fabrication tolerance (mm)	Measured initial imperfection values (mm)
C1	 (Camber)		≤ length / 500	-
		150x45x1.6	2.0 (L=1000mm)	-
			4.8 (L=2400mm)	1.6 (L=2400mm)
			6.0(L=3000mm)	2.1 (L=3000mm)
		200x45x1.6	C	-
			8.0 (L=4000mm)	1.9 (L=4000mm)
C2	 (Sweep)		≤ length / 500	-
		150x45x1.6	2.0 (L=1000mm)	-
			4.8 (L=2400mm)	2.6 (L=2400mm)
			6.0(L=3000mm)	3.2 (L=3000mm)
		200x45x1.6	2.0 (L=1000mm)	-
			8.0 (L=4000mm)	2.9 (L=4000mm)
C3	 (Twist)		≤2 +0.5 per m length	-
		150x45x1.6	3.2 (L=2400mm)	1.3 (L=2400mm)
			3.5(L=3000mm)	1.4 (L=3000mm)
		200x45x1.6	4.0(L=1000mm)	1.0 (L=4000mm)
C4	 (Single flange out-of-square)		a_0 or a_1 ≤0.02 b_f	-
		150x45x1.6	0.9 (L=1000mm)	-
		200x45x1.6	0.9 (L=1000mm)	-
C5	 (Two flanges out-of-square)		a_0 + a_1 ≤0.03 b_f	-
		150x45x1.6	1.35 (L=1000mm)	-
		200x45x1.6	1.35 (L=1000mm)	-
C6	 (Web Flatness)		Δ_w≤ (d – 2d_f) / 150	-
		150x45x1.6	0.8 (L=1000mm)	-
		200x45x1.6	1.133 (L=1000mm)	-
C7	 (Flange flatness)		Δ_f≤ 0.01 b_f	-
		150x45x1.6	0.45 (L=1000mm)	-
		200x45x1.6	0.45 (L=1000mm)	-

Table 1(b): Effect of local fabrication tolerances vs. Commonly used overall imperfection on LSB strength

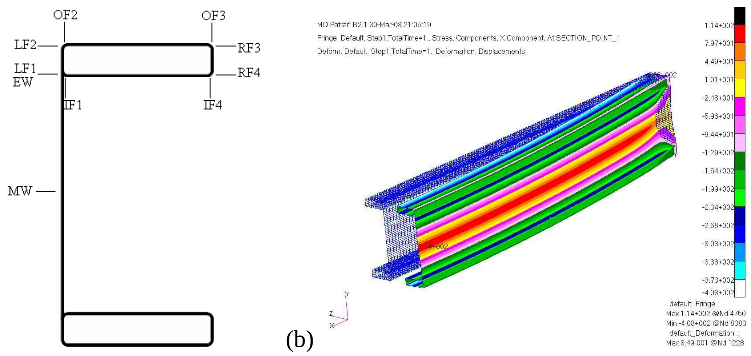
Method		Smorgon Steel Tube Mills (SSTM) (2005)				SA (1998)
Tolerance		Local	Local	Local	Local	Overall Imperfection
		$0.02b_f$	$0.03b_f$	$(d-2d_f)/150$	$0.01b_f$	FEA (L/1000)
		C4	C5	C6	C7	
150x45x1.6	Mu	12.136	12.00	12.00	12.00	**10.963**
	SSTM/SA	1.107	1.095	1.095	1.095	-
200x45x1.6	Mu	15.079	15.015	14.951	15.015	**13.743**
	SSTM/SA	1.097	1.093	1.088	1.093	-

Table 1(c): Effect of fabrication tolerances vs. Commonly used overall imperfection on LSB strength

Method		Smorgon Steel Tube Mills (SSTM) (2005)					SA (1998)	
Tolerance		Camber	Sweep	Sweep	Camber (L/500) + Local		Overall imperfection	
		L/500	L/500	L/1000	C1+C4+C6+C7	C1+C5+C6+C7	FEA (L/500)	FEA (L/1000)
		C1	C2	C2				
150x45x1.6	Mu	11.775	11.369	11.910	12.00	11.91	**10.151**	**10.963**
	SSTM/SA	1.074	1.037	1.086	1.095	1.086	0.926	-
200x45x1.6	Mu	15.015	16.924	16.860	15.01	14.89	**12.788**	**13.743**
	SSTM/SA	1.093	1.231	1.227	1.093	1.083	0.931	-

3.4 Effect of residual stresses

Flexural residual stresses are commonly used in the numerical studies of mono-symmetric and/or symmetric cold-formed steel beams. However, only a limited number of studies have been reported for mono-symmetric beams. In this section a sensitivity study of residual stress on the ultimate strength of LSBs under pure bending is presented.



(a) (b)

Figure 6: (a) Residual stress values (b) Residual stresses distributed in LSB FE model

The idealized residual stresses were modelled using the ABAQUS *INITIAL CONDITIONS option, with TYPE = STRESS, USER. The user defined initial stresses were created using the SIGINI Fortran user subroutine. Residual stress values and patterns of 150x45x1.6 LSB (non-compact section) based on Mahaarachchi and Mahendran's (2005) models, and the shape of initial imperfection that is adopted and combined without loads in the same step from the first elastic buckling mode are shown in Figure 6(b). Table 2 and Figure 6(a) show the applied membrane and flexural residual stresses at each point of LSB.

Table 2: Membrane and flexural residual stresses in 150x45x1.6 LSB model as a percentage of yield stress

Model	Membrane residual stresses									
	Web		Left side of the Flange		Outside of the flange		Right side of the flange		Inside of the flange	
	MW	EW	LF1	LF2	OF2	OF3	RF3	RF4	IF4	IF1
Case 1 1)	0.24fy	-0.41fy	-0.23fy	-0.23fy	-	-	0.03fy	0.03fy	0.03fy	0.11fy
Case 2	0.55fy	-0.55fy	-	-	-	-	-	-	-	-
Case 3	-	-	-0.23fy	-0.23fy	-	-	0.03fy	0.03fy	0.03fy	0.11fy
Case 4	0.55fy	-0.55fy	-0.23fy	0.23fy	-	-	-0.03fy	0.03fy	0.08fy	-0.08fy
Case 5	0.55fy	-0.55fy	-0.23fy	0.23fy	0.08fy	-0.08fy	-0.03fy	0.03fy	0.08fy	-0.08fy
Case 6 2)	0.15fy	-0.15fy	-0.23fy	-0.23fy	-	-	0.03fy	0.03fy	0.03fy	0.11fy
Case 7 2)	0.15fy	-0.15fy	-	-	-	-	-	-	-	-
	Flexural residual stresses									
Case 8	0.24fy	0.24fy	0.24fy	0.24fy	0.24fy	1.07fy	0.41fy	0.41fy	0.8fy	0.38fy

Table 3: Effects of residual stresses on the ultimate moments of LSB

150×45×1.6LSB (1500mm)	Ultimate moments M_u (kNm)				Ratio		
	without RS	Memb.	Flex.	Memb. +Flex.	Memb. RS/ without RS	Flexural RS/ without RS	Mem.+Flex. RS/ without RS
Case 1 1)	9.97	9.38	9.07	8.71	0.941	0.910	0.874
Case 2	9.97	9.93	9.07	9.07	0.996	0.910	0.910
Case 3	9.97	9.29	9.07	8.71	0.932	0.910	0.874
Case 4	9.97	9.61	9.07	8.89	0.964	0.910	0.892
Case 5	9.97	9.74	9.07	9.02	0.977	0.910	0.905
Case 6 2)	9.97	9.29	9.07	8.71	0.932	0.910	0.874
Case 7 2)	9.97	9.93	9.07	9.07	0.996	0.910	0.910

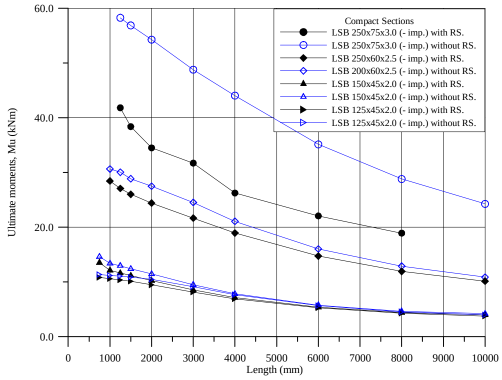
Notes: 1) The modified ideal residual stresses model of Mahaarachchi and Mahendran (2005), 2) Present measured experimental residual stresses

Effects of membrane residual stresses on LSB ultimate moments are shown in Table 3 for 150x45x1.6LSB of 1.5m span. The results show that the ultimate moment is governed by flexural residual stress components (compare the ratios in columns 6 and 7 of Table 3). When both membrane and residual stresses were included, the strength ratio was reduced from 0.910 to 0.874, which is not as severe as expected. The web membrane stress values were varied considerably for Cases 1 to 7, but their effect on the ultimate moments was found to be not significant (compare Cases 2 and 7). Comparison of Cases 2 and 3 clearly demonstrates that the membrane stress in the flange had a greater effect on strength than that due to web membrane residual stress. Also, it is observed that the outside membrane stress in flanges is not critical when the ultimate moments are compared for Cases 4 and 5.

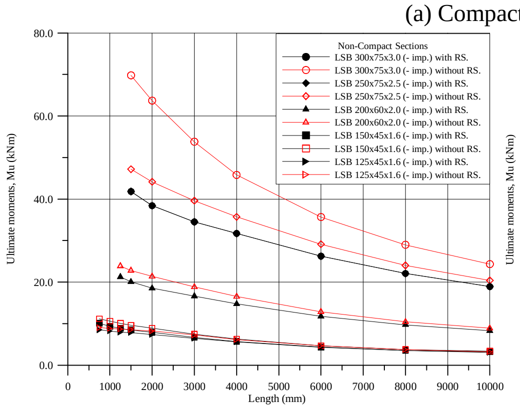
Figure 7 shows the effect of residual stresses on the ultimate strength of each LSB section with varying span under uniform bending moment. For this purpose, Mahaarachchi and Mahendran's ideal residual stress model was used. It is evident that welding induced and cold-forming residual stresses reduce the LSB ultimate strength significantly, but it is interesting to note that the ultimate strength reduction characteristic due to residual stresses differ as a function of span for all sections. Their effect is minimal for longer spans.

In summary the use of flexural residual stresses alone in the numerical studies of LSBs can give reasonable estimation of their moment capacity. However, accurate estimates could be obtained if membrane residual stresses are also included in the analyses. For this purpose a simpler distribution than specified by

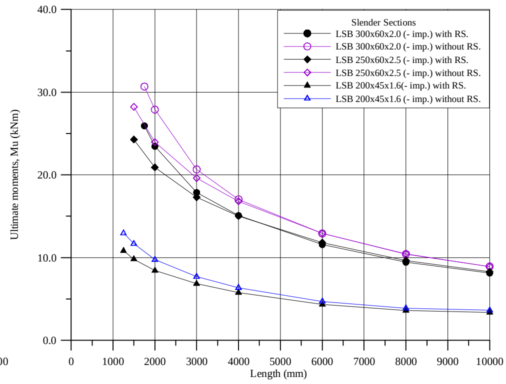
Maharachchi and Mahendran (2005) could be used with reduced values for web membrane residual stresses as measured in this study, ie. Case 7.



(a) Compact section



(c) Non-compact section



(d) Slender sections

Figure 7: Effect of residual stress on the ultimate moment capacity of LSBs

Electric resistance welding process in LSB manufacturing is considered to have introduced the additional membrane stresses in the cold-formed LSBs. However, it appears that the LSB manufacturer has improved the manufacturing process as the measured membrane stresses in this research are considerably smaller than those measured on LSBs about three years ago. Considering the smaller effect of membrane residual stresses on LSB strength, there may not be a need to further improve the manufacturing process to reduce the level of residual stresses in LSBs. However, any attempt to reduce the flexural residual stresses in LSBs due to cold-forming actions will be beneifical.

4. CONCLUSION

The unique LSB manufacturing process of simultaneous cold-forming and electric resistance welding resulted in specific initial imperfections (initial geometric imperfections and residual stresses). This could significantly affect the moment capacity of LSBs. This paper has presented the details of initial imperfections present in LSBs and their effects on the moment capacity of LSBs. Following are the main outcomes:

1. The unique manufacturing process of LSB does not lead to geometric imperfections that exceed the currently accepted fabrication tolerances.
2. The measured geometric imperfection values can be used in the numerical modelling of LSB to improve its accuracy in simulating the flexural behaviour of LSBs.

3. Inclusion of the maximum initial geometric imperfection value based on the overall member fabrication tolerance in the critical elastic buckling mode is adequate to predict the ultimate moment capacity of LSBs under uniform bending moment conditions for design purposes.
4. The effect of flexural residual stresses on the moment capacity of LSBs was found to be greater than that due to the membrane component of residual stress. The LSB moment capacity was found to be not sensitive to the membrane residual stresses in the web element. Based on the numerical studies reported here, a simplified residual stress distribution can be used in the numerical studies of LSBs without a greater loss of accuracy to the moment capacity results.

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