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COMPARATIVE BEHAVIOR OF BUILT-UP COLD-FORMED BOX SECTIONS UNDER RIGID AND FLEXIBLE END SUPPORT CONDITIONS

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Abstract:

According to section D1.2 of AISI S100-2007 for compression members composed of two sections in contact whose buckling mode involves shear forces in the connectors, a reduction must be made, $\mathrm{KL/r}$ must be replaced by $(\mathrm{KL/r})_{\mathrm{m}}$. This new modified slenderness ratio takes into account the connection weld spacing and the minimum radius of gyration of an individual shape in the built-up member. Under the provisions of section D1.2 a reduction in load capacity must be made for built-up welded box members, which are the subject of this study. An experimental investigation on 48 samples was done addressed to determine the comparative behavior under compression load of box sections composed of two C-section members in contact by seam welds with different weld spacings. The weld spacings in connections in the samples are 100 mm, 300 mm, 600 mm and 900 mm. The first set of 24 studs was tested under a rigid end support condition and the second set of 24 studs was tested using a flexible end support. The length of the samples was 900 mm with a cross-section of 100 mm x 100 mm. This configuration to form box members is widely used for columns or beams as frame and truss members. The base material thickness was 1.5 mm (gauge 16) for 24 samples and 2.0 mm (gauge 14) for the rest. The weld seams were 50 mm long in all cases except on the member ends; where they were 25 mm long. The testing done on the samples did not show a statistical reduction in the ultimate compression load capacity for these members except with a weld spacing of 900 mm and a flexible end support condition. The results of the investigation showed the reduction considered in section D1.2 section of

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AISI S100-2007 not applicable to determine the ultimate load capacity for the rest of the members.

Keywords: Built-up section, modified slenderness ratio, axial strength

1. Introduction

It is a common practice to attach two or more cold-formed single sections in order to obtain greater cross-section properties. The advantages of using cold-formed steel assembled members are well known by the building construction industry. The closed box sections allow spanning greater distances between supports and carrying heavier loads than single C-sections. This connection to conform a box is usually made by seam welds, being an easy and affordable way to do so. It is especially true in countries where the hourly wage rate for welders is low compared to others. In these countries the use of seam welds applied in-situ is widely used as a good means of coupling two single C-sections in order to make up box sections to be used for structural members as columns and beams.

Usually the spacing for these seam-weld connectors ranges from 200 mm through 600 mm for sections no wider than 300 mm. There are no certain specifications to set limits in this regard, however a good criteria supported on experimental studies will lead to an optimum process of attaching two C-sections.

2. Normative

In accordance with section C4.1 of AISI S100-2007 the nominal axial strength shall be calculated by the following equation:

$$P_n = A_e F_n \qquad Eq.1$$

where

$A_e =$ Effective area calculated at stress F_n

F_n shall be calculated as follows:

For $\lambda_c \leq 1.5$ (Inelastic buckling mode)

$$F_n = \left(0.658^{\lambda_c^2}\right) F_y \qquad Eq.2$$

For $\lambda_c > 1.5$ (Elastic buckling mode)

$$F_n = \left[\frac{0.877}{\lambda_c^2}\right] F_y \qquad Eq. 3$$

where

$$\lambda_c = \sqrt{\frac{F_y}{F_e}} \qquad Eq. 4$$

$F_e =$ The least of the applicable elastic flexural, torsional and flexural-torsional buckling stress

For sections not subject to torsional or flexural-torsional buckling as doubly-symmetric sections or closed cross-sections:

$$F_e = \frac{\pi^2 E}{(KL/r)^2} \qquad Eq. 5$$

where

$E =$ Modulus of Elasticity
$K =$ Effective Length factor
$L =$ Laterally unbraced length of member
$r =$ Radius of gyration of full unreduced cross section about axis of buckling

The design specifications for assembled members under compression loads described in the section D1.2 of the AISI S100-2007 modify the overall slenderness ratio of the built-up member according to the spacing between connection seam welds in individual shapes. If shear forces are present in the weld connector due to deformations related to the buckling mode of the member, KL/r, in the $Eq. 5$, shall be replaced by $(KL/r)_m$ as follows:

$$\left(\frac{KL}{r}\right)_m = \sqrt{\left(\frac{KL}{r}\right)_o^2 + \left(\frac{a}{r_i}\right)_o^2} \qquad Eq. 6$$

Where

$(KL/r)_o$ =Overall slenderness of the entire section about built-up member axis
$a =$ Seam weld spacing

r_i = Minimum radius of gyration of full unreduced cross-sectional area of an individual shape in a built-up member

Other studies take a different approach to determine the modified slenderness ratio of a built-up member. The AISC *Specification for Structural Steel Buildings* presents a different expression based on the work of Zahn and Haaijer (1987) to predict the behavior of built-up sections with welded connectors:

For $a/r_i > 50$

$$\left(\frac{KL}{r}\right)_m = \sqrt{\left(\frac{KL}{r}\right)_o^2 + \left(\frac{a}{r_i} - 50\right)^2} \qquad Eq.7$$

For $a/r_i \leq 50$

$$\left(\frac{KL}{r}\right)_m = \left(\frac{KL}{r}\right)_o \qquad Eq.8$$

The work of Zahn and Haaijer concludes that reduction shall be applicable when the value of a/r_i is greater than 50.

3. Experimental Investigation

The study performed by Stone and LaBoube on the behavior of built-up cold-formed steel I-sections (2005) provided the basic guidance to develop all the research on assembled box members.

Figure 1 presents both the typical stud sample for the first set rigidly supported (left) and the typical sample for the second set under a flexible end supporting condition (right). For the flexible support neoprene plates 12 mm thick at each end were used (figure 5). The experimentation focused on ultimate axial strength was performed at Universidad del Norte, Barranquilla (Colombia).

The purpose of this research was to determine the variation of the ultimate load capacity for the built-up member evaluating how it is affected by the variability in the weld spacing (distance “a” in figure 1) taking into consideration different end supporting conditions and also shedding light on determining whether current AISI provisions are applicable for cold-formed box section members.

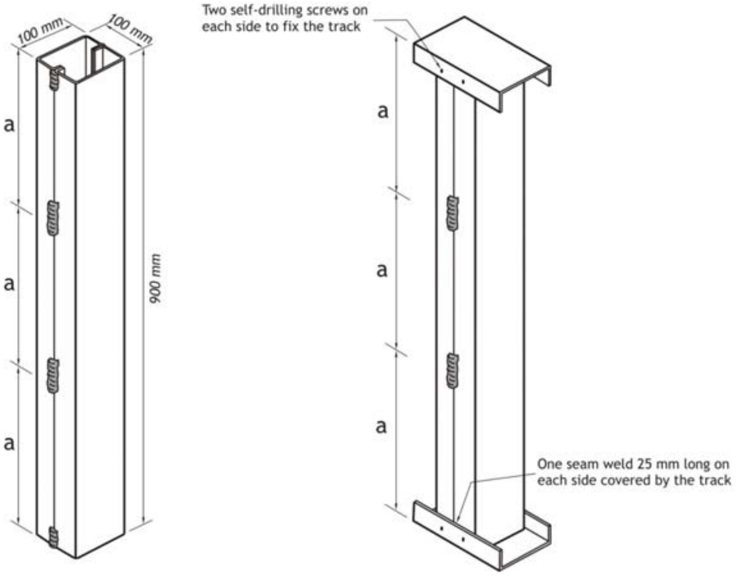

Figure 1 Typical tested sample for rigid end supports (left) and for flexible end supports (right)

The figure 2 shows the dimensions of the cross-section:

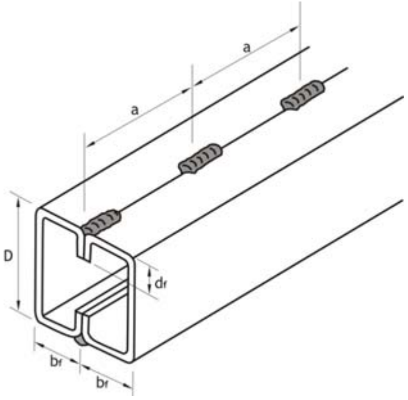

Figure 2 Typical box section

3.1 Section parameters:

The parameters of the typical section are shown in Figure 2 and their magnitudes are shown in table 1.

Table 1 Parameter magnitudes of the cross-section

Parameter	***Magnitude***
Stud Thickness, t	1.5 mm, 2.0 mm
Depth, D	100 mm
Flange, b_f	50 mm
Edge stiffener, d_f	15 mm
Weld seam spacing, a	100 mm, 300 mm, 600 mm, 900 mm

All the samples were 900 mm long and the tracks were made of material 1.5 mm thick. An inelastic buckling mode was expected during the test.

3.2 Test setup

The single C-sections were attached by seam welds of 50 mm long except for the seam welds on the member ends; there they were 25 mm long. The weld spacing of 300 mm is the one commonly used to attach two single C-sections. The welding work was done using electrodes E6011 meeting the specifications of the AWS *(American welding society)*. A complete penetration of the seam welds was guaranteed. Figure 3 shows the work of attaching the two single C-sections.

The first set of 24 samples was directly supported on the plates of the Universal Testing Machine. This condition simulates a rigid support for the structural members. No additional plates were used to test the samples during the first set. The second set of 24 samples was similar to the first but the end support conditions were changed. In this case neoprene plates 15 mm thick were used to simulate a flexible supporting condition (figure 5). Short tracks were fixed by self-drilling screws to the member ends to consider the real support handled in construction.

Figure 3 Attachment of two single sections

Figure 4 Test setup for the rigid support condition

Figure 5 Test setup for the flexible support condition

All the specimens were tested under compression load in the Universal Testing Machine. The criterion to stop the testing was determined by the point where failure load was reached (ultimate load capacity). The test was stopped shortly after reaching that point, at which point the force-deformation curve started decreasing.

3.3 Test procedure

The failure load, P_{test}, is the largest load that a built-up member sustained during a test. The load application was done through the centroid of the section after adjusting the samples on the bearing supports of the machine according to Figures 4 and 5. All the samples were tested under compression loads.

4. Test results

Almost all the specimens with rigid support showed local buckling near the connection welds during the test. Nevertheless they still were able to continue carrying load. The set of samples supported on the neoprene plate mainly showed local buckling at the member ends and several of them showed local buckling near the connection seam welds. Most of the specimens reached failure load after presenting notorious lateral deformations on the walls of the cross-section. At the end of the testing for the first set almost all the specimens presented a smooth curvature as shown in figure 6.

Figure 6 Typical failure mode for rigidly supported specimens

Some of the rigidly supported specimens showed a curvature different from figure 6 before reaching the failure load. Each single C-section curved smoothly in opposite directions one from another following the pattern shown in figure 7. It was mainly presented in samples with weld spacings of 600 mm and 900 mm.

Figure 7 Other failure modes for rigidly supported specimens

On the other hand the second set of specimens on flexible supports showed a local buckling at the ends. The typical curvature is described in Figure 8.

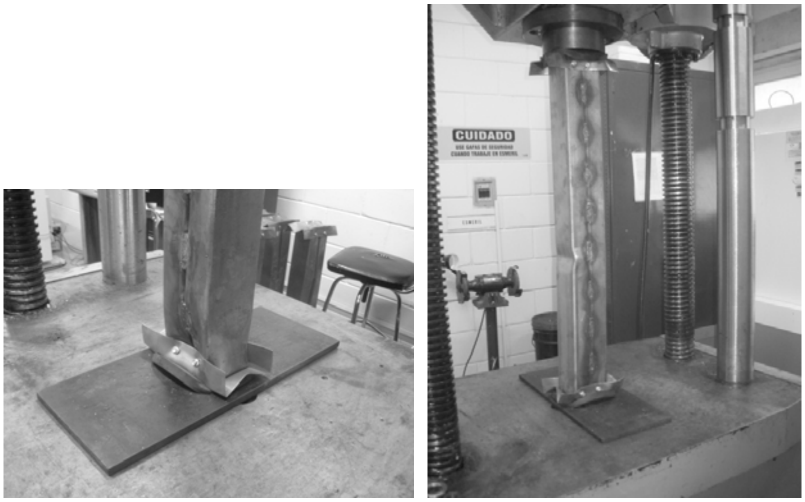

Figure 8 Local buckling at ends for samples with flexible supports (left) and buckling close to seam welds along the specimen (right).

The specimens with seam weld spacing of 900 mm on flexible supports presented a deformation as shown in figure 9. Each C-section member curved in opposite direction one from another limiting the maximum load capacity of the member. There was a significant statistical reduction in the maximum load capacity for these samples.

Figure 9 Failure curvature mode typical on samples with flexible supports and welds spaced 900 mm (there was a reduction in the maximum load capacity under this configuration)

Table 2 Built-Up Compression-Member Test Results for rigid supports

Reference	Weld spacing (mm)	P_{test1}, Failure load (kN)		
		1st test	2nd test	3rd test
Box 100x100-1.5 mm	100	131.4	141.6	133.2
Box 100x100-1.5 mm	300	133.1	134.0	129.8
Box 100x100-1.5 mm	600	131.0	123.6	121.1
Box 100x100-1.5 mm	900	141.9	130.2	144.3
Box 100x100-2.0 mm	100	240.1	265.4	256.9
Box 100x100-2.0 mm	300	264.0	267.9	264.1
Box 100x100-2.0 mm	600	263.8	246.2	263.9
Box 100x100-2.0 mm	900	257.5	269.6	263.9

Table 3 Built-Up Compression-Member Test Results for flexible supports

Reference	**Weld spacing (mm)**	**P_{test2}, Failure load (kN)**		
		1st test	**2nd test**	**3rd test**
Box 100x100-1.5 mm	100	131.2	125.8	129.7
Box 100x100-1.5 mm	300	120.9	128.2	121.4
Box 100x100-1.5 mm	600	124.8	121.8	129.7
Box 100x100-1.5 mm	900*	115.8	119.5	118.2
Box 100x100-2.0 mm	100	239.4	247.8	251.8
Box 100x100-2.0 mm	300	250.8	262.9	259.5
Box 100x100-2.0 mm	600	243.6	253.3	254.9
Box 100x100-2.0 mm	900*	238.3	235.8	240.0

*These samples presented a significant statistical reduction in the average of the maximum load capacity

Table 2 and Table 3 summarize the failure loads for each specimen. These tables collect all the maximum loads obtained from the tests for rigid and flexible supports. The results of the first set of samples, under a rigid support condition, are summarized in table 2 (P_{test1}). Table 3 presents the results obtained from the second set of samples according to a flexible support condition (P_{test2}). In figures 10 and 11 several load-deformation curves obtained from tests present combined results from both sets of samples as a comparison of the top loads sustained during tests.

Figure 10 and Figure 11 show the difference presented between the results for samples under flexible versus rigid support conditions. These curves describe the behavior presented during the test for specimens with weld spacing of 900 mm before reaching the failure load (maximum load capacity). For this spacing there was a significant statistical difference between the failure load obtained from rigid and flexible supports for both 1.5 mm and 2.0 mm thicknesses.

5. Data Analysis

The results of failure load from the first set, P_{test1}, and the second test, P_{test2}, were compared one to another. Figure 12 and Figure 13 show separately the difference presented due to the different seam weld spacings in the cold-formed samples from material 1.5 mm and 2.0 mm thick. The P_{test2}/P_{test1} ratio establishes the variation of the maximum load capacity between the second and the first test.

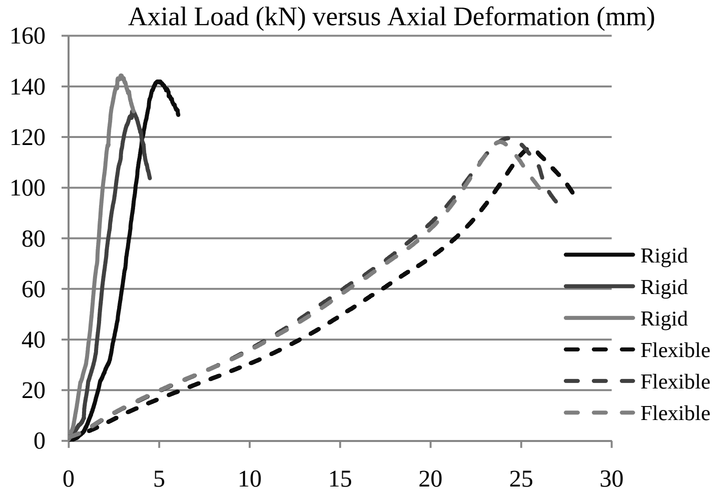

Figure 10 Comparative behavior of samples under Rigid versus Flexible support conditions for box members 100 x 100 – 1.5 mm and weld spacing of 900 mm.

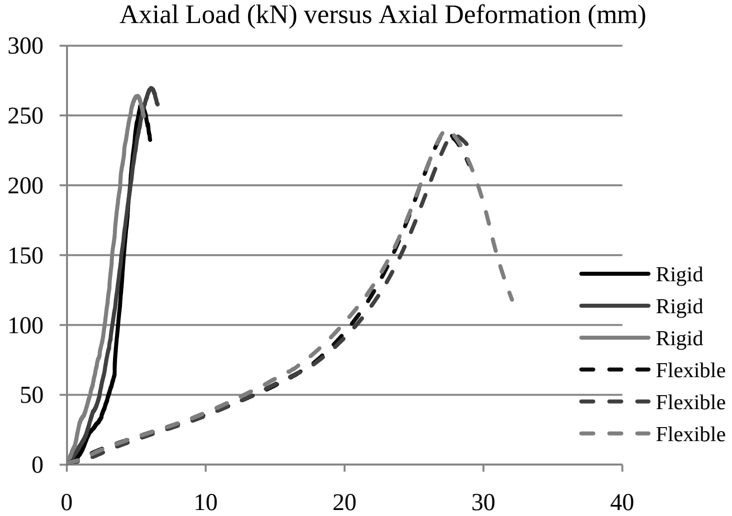

Figure 11 Comparative behavior of samples under Rigid versus Flexible support conditions for box members 100 x 100 - 2.0 mm and weld spacing of 900 mm.

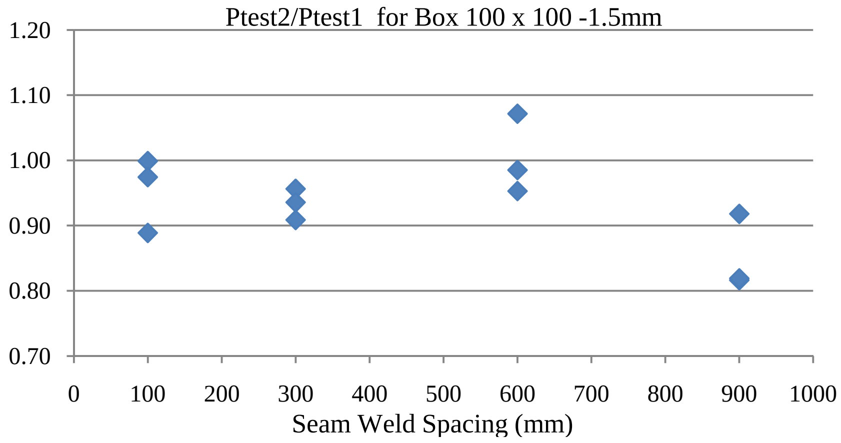

Figure 12 Comparison between the maximum load capacity (failure load) under a flexible and a rigid support condition. Cold-formed box section of 100 mm x 100 mm and thickness material 1.5 mm.

According to the values presented in Figure 12 and a statistical analysis there is no noticeable reduction in the maximum load capacity due to the greater spacing between the seam welds. For both end support conditions the statistical values of failure load are about the same magnitude except for the 900 mm spacing with a flexible end support. This latter spacing showed a reduced capacity with a flexible support compared to that with an end rigid support. The reduction considered in the section D1.2 of the North American Specification (AISI S100-2007) due to the weld spacing would not be applicable to predict the failure load up to a weld spacing of 600 mm no matter the type of support. In other words, the actual overall slenderness ratio of the entire section might not be modified due to the weld spacing as it is less than or equal to 600 mm.

For the seam weld spacing of 900 mm the results obtained from the second set of samples with flexible supports are, by an average of 15%, below the values obtained with rigid supports for the material 1.5 mm thick. This indicates that it may be necessary to use a reduction in the load capacity, using the same weld spacing or greater, following the provisions of section D1.2 of the American Specification.

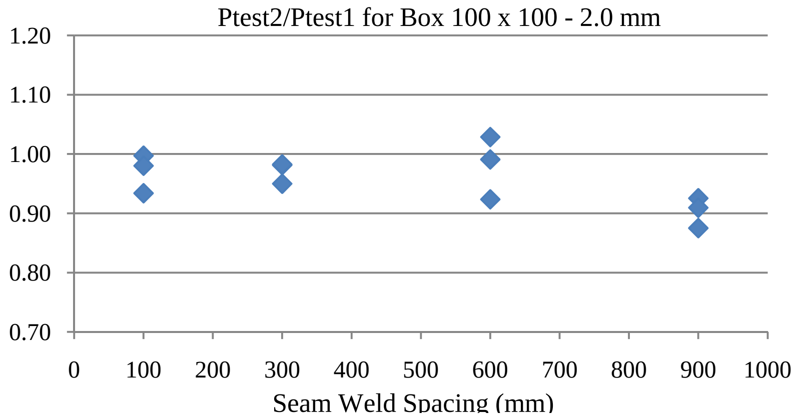

Figure 13 Comparison between the maximum load capacity (failure load) under a flexible and a rigid support condition. Cold-formed box section of 100 mm x 100 mm and thickness material 2.0 mm.

According to the values presented in Figure 13 and a statistical analysis there is no noticeable reduction in the maximum load capacity due to the greater spacing between the seam welds. For both end support conditions the statistical values of failure load are about the same magnitude except for the 900 mm spacing with a flexible end support. This latter spacing showed a reduced capacity with a flexible support compared to that with an end rigid support. The reduction considered in section D1.2 of the North American Specification (AISI S100-2007) due to the weld spacing would not be applicable to predict the failure load up to a weld spacing of 600 mm no matter the type of support. In other words, the actual overall slenderness ratio of the entire section might not be modified due to the weld spacing as it is less than or equal to 600 mm.

For the seam weld spacing of 900 mm the results obtained from the second set of samples with flexible supports are, by an average of 10%, below the values obtained with rigid supports for the material 2.0 mm thick. This indicates that it may be necessary to use a reduction in the load capacity, using the same weld spacing or greater, following the provisions of section D1.2 of the American Specification.

6. Conclusions

The analysis of the results obtained from the 48 specimens shows that the modified slenderness ratio is not always necessary for material 1.5 mm and 2.0

mm thick and therefore the actual slenderness ratio could be used to compute the ultimate load capacity for these structural members if the seam weld spacing is less than or equal to 600 mm since there is not a significant statistical reduction in the failure load in laboratory tests.

The values were slightly affected by the type of support but this reduction did not represent a significant statistical difference except for the samples on flexible supports with a seam weld spacing of 900 mm. Disregarding this latter spacing there is no need to use the modified slenderness ratio to determine the maximum load capacity of the members under consideration no matter the type of support.

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