Bending Tests of Hat Sections with Multiple Longitudinal Stiffeners

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BENDING TESTS OF HAT SECTIONS WITH MULTIPLE LONGITUDINAL STIFFENERS

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ABSTRACT

This paper is the first in a series of articles that report findings of the authors investigation into the behavior of cold formed steel hat sections in bending with multiple intermediate longitudinal stiffeners. Presented in this paper is the test program that was carried out at the University of Waterloo as part of a two year research program.

It is known that sections with multiple intermediate stiffeners can fail either in a local sub-element buckling mode, or alternatively, can experience an overall plate buckling mode of failure. Although both failure modes were examined, the main objective was to develop a consistently accurate and practical method of predicting the ultimate bending strength of sections which failed in overall plate buckling. Recent testing carried out by previous researchers indicates that the bending resistance of multiple stiffened cold formed steel members which fail in overall plate buckling is too conservatively predicted by the current Canadian design standard (S136-94). These researchers have also shown that the American design specification (AISI 96) is unconservative for the same sections.

Data from 18 previous test specimens were compiled and supplemented with 94 additional tests carried out at the University of Waterloo, encompassing a range of section dimensions and material properties. All test specimens were simply supported and subjected to uniformly distributed loading. The Waterloo test program consisted of hat sections that failed primarily in overall plate buckling and in a few cases also in local sub-element buckling of the compression flange. Only six of the 112 specimens were observed to have failed in local sub-element buckling, while the remainder experienced overall plate buckling at failure.

TEST PROGRAM

The test program was intended to provide experimental data on the load carrying capacity of sections subjected to uniformly distributed loads. The members tested were hat sections with intermediate stiffeners in the compression flange. Although it was considered important to investigate all possible modes of failure, the main objective of the experimental testing program was to complete a series of tests that fully explored the overall buckling mode of failure.

Of the 99 tests conducted, 94 were considered valid in this investigation. The dimensions and properties used to 'design' the test specimens were calculated in accordance with S136 (CSA S136-94, 1994), and the geometric and material properties were varied sufficiently to reasonably ensure that the overall buckling mode of failure could be investigated. Each specimen configuration was tested three times and this set of three tests comprised a series. Although each specimen within a series was not identical (due to manufacturing tolerances), the differences among them were measured and taken into account in the analysis.

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Test specimens were first 'designed' to determine the required section properties that would allow a proper investigation of the behavior of multiple stiffened sections. These specimens were then brake-formed by VICWEST Steel Inc. Four specimens were manufactured for each test series, of which at least three were used in testing.

There was of course some variability between the geometric dimensions requested and the sections that were actually manufactured, which necessitated the precise measurement of each specimen prior to testing. One problem that occurred in manufacturing of specimens was that the slenderness of some sub-elements within each section was larger than intended. Specimens were designed such that all sub-elements were of equal width, i.e., the center to center distance between stiffeners was equal. This resulted in the sub-elements adjacent to the web elements being larger in width than the interior sub-elements. The larger flat width ratios, W, of these sub-elements became the determining factor in the failure mode of the specimen.

Although the compression flange assembly and material thickness were varied among the different test series, the web height and tension flange widths were kept constant. These constant dimensions ensured that web crippling and tension failure would not occur, as well as, allowed for ease of manufacturing.

Three parameters were altered in the test specimens, as follows:

a) Flat width ratio between stiffeners ($W = w/t$);

b) Moment of inertia (I_s); and

c) Number of stiffeners (n)

The geometric parameters (a & b) were altered by changing the material thickness, overall compression flange width and stiffener dimensions (depth and width). Three material thicknesses and three different stiffener dimensions were used in conjunction with the three stiffener configurations (2, 3 and 4 intermediate stiffeners). A summary of the dimensions for all specimens can be found in Tables A.1 of the Appendix.

The flat width ratio, W, was varied in relation to the limiting plate slenderness ratio W_{lim}, calculated in accordance with S136. Likewise, the stiffener moment of inertia, I_s, was altered as a function of the adequate moment of inertia (I_a), based on S136. Summarized in Table 1 is the range of key parameters that was investigated for the corresponding test series.

The W values shown in Table 1 refer to the maximum flat width ratio that was measured for each specimen. The range of W/W_{lim} and I_s/I_a was chosen to ensure that all practical values of parameters were included.

The tests carried out as part of this research were supplemented with tests conducted by Papazian in a previous research project (Papazian, 1994). A more detailed review of Papazian's work is contained in the referenced paper.

Tensile coupon tests were conducted using an Instron material testing machine. Coupon blanks were cut from the tension flange of each specimen, and if sufficient space was available, from the compression flange. Coupon specimens were then machined to size according to ASTM A370-92. The galvanized coating was removed prior to testing using a hydrochloric acid bath. Thickness, yield, ultimate strength and percent elongation were determined from an average of three coupons per thickness. All coupon tests exhibited a sharp yielding steel with yield strengths ranging from 310 MPa (45.0 ksi) to 342 MPa (49.6 ksi). Material properties are summarized in Table A.2.

To create a uniformly distributed load, the specimens were placed in a vacuum chamber that was constructed specifically for this research. The vacuum chamber consisted of a wooden box sealed on all sides except at the top, as shown schematically in Figures 1 - 3. Illustrated in these figures are also the test setup and general dimensions.

Table 1 - Test Section Parameters and Corresponding Test Series

Test Section Parameters			Test Series
2 Intermediate Stiffeners	$0.5 < W/W_{lim} < 0.8$	$I_s / I_a < 1.0$	
		$1.0 < I_s / I_a < 2.5$	
		$2.5 < I_s / I_a < 4.0$	3,29*
		$I_s / I_a > 4.0$	30
	$0.8 < W/W_{lim} < 1.2$	$I_s / I_a < 1.0$	
		$1.0 < I_s / I_a < 2.5$	13,14
		$2.5 < I_s / I_a < 4.0$	4
		$I_s / I_a > 4.0$	2
	$1.2 < W/W_{lim} < 1.5$	$I_s / I_a < 1.0$	15
		$1.0 < I_s / I_a < 2.5$	11,28*
		$2.5 < I_s / I_a < 4.0$	
		$I_s / I_a > 4.0$	
3 Intermediate Stiffeners	$0.5 < W/W_{lim} < 0.8$	$I_s / I_a < 1.0$	
		$1.0 < I_s / I_a < 2.5$	17
		$2.5 < I_s / I_a < 4.0$	12,26,27*
		$I_s / I_a > 4.0$	
	$0.8 < W/W_{lim} < 1.2$	$I_s / I_a < 1.0$	
		$1.0 < I_s / I_a < 2.5$	16,22*
		$2.5 < I_s / I_a < 4.0$	6
		$I_s / I_a > 4.0$	
	$1.2 < W/W_{lim} < 1.5$	$I_s / I_a < 1.0$	18
		$1.0 < I_s / I_a < 2.5$	7
		$2.5 < I_s / I_a < 4.0$	
		$I_s / I_a > 4.0$	1
4 Intermediate Stiffeners	$0.5 < W/W_{lim} < 0.8$	$I_s / I_a < 1.0$	
		$1.0 < I_s / I_a < 2.5$	19
		$2.5 < I_s / I_a < 4.0$	8,24*
		$I_s / I_a > 4.0$	25
	$0.8 < W/W_{lim} < 1.2$	$I_s / I_a < 1.0$	
		$1.0 < I_s / I_a < 2.5$	20,23*
		$2.5 < I_s / I_a < 4.0$	10
		$I_s / I_a > 4.0$	
	$1.2 < W/W_{lim} < 1.5$	$I_s / I_a < 1.0$	21
		$1.0 < I_s / I_a < 2.5$	9
		$2.5 < I_s / I_a < 4.0$	
		$I_s / I_a > 4.0$	5

* More than one test series with similar parameters but different thicknesses

The vacuum chamber had a neoprene strip around the top edge, which helped to properly seal the chamber. An open rectangular steel frame was constructed to fit on top of the vacuum chamber and had a matching neoprene strip on it's underside. When the frame was placed on top of the vacuum chamber, the seals were aligned and ensured that adequate suction could be generated. In each test, a polyethylene sheet was placed on the top of the vacuum chamber between the two neoprene strips. By creating a suction in the vacuum chamber, the pressure differential across the polyethylene sheet exerted a pressure on the test specimens and provided a uniformly distributed load. The tension flanges of the specimens were braced at equal intervals (one-fifth points) so that the sections did not spread out as the load was applied. This bracing ensured that the section was the same section that was measured prior to testing, and that no secondary effects (geometrical deformations) needed to be taken into account.

Equal-length 2x6 wood planks were placed on top of the test specimens in an effort to induce a uniformly distributed load into the test specimens. This allowed for a measurable area of load (the area of wood planks) to be applied to the specimens, which in turn facilitated an accurate calculation of maximum moment capacity. The additional dead load due to the wood planks was measured for each test and included in the failure load of the specimen. If the compression flange of the specimen was too small, the wood blocking assembly became unstable and susceptible to twisting. In these cases, two test specimens were placed in the vacuum chamber at one-third points along the width of the vacuum chamber. This provided a stable support for the wood planks and allowed each of the test specimens to share the applied load equally.

Two load cells with a 4448 N (1000 lb) capacity each were positioned at the pin support of the specimens. In the case of double specimen tests (Figure 2), the pin supports were placed at opposite ends of the vacuum chamber. This provided some assurance that both reaction loads within a specimen were equal, even though only one reaction per specimen was measured. The two reaction measurements on different specimens confirmed that the intended uniformly distributed load was being applied to the test specimens. In the case of single specimen tests (Figure 1), load cells were used under both reactions. These tests showed equal load at the two reactions, and confirmed the quality of the test setup.

The pressure in the vacuum chamber was measured by a pressure transducer, which had a measurable range of up to twenty-five inches of water 6.25 kN/m^2 [kPa] (131 psf). The two load measurements (reactions and applied pressure), provided two different methods of calculating the maximum moment applied to the specimen, which were compared against each other to confirm results.

The test setup incorporated a data acquisition system (DAS) which measured the center deflection of the specimen, four load cells and the pressure in the vacuum chamber. Readings of all measurements obtained from the DAS were taken every three seconds. The voltage output of the pressure transducer was measured by both the DAS and an independent voltmeter. The independent voltmeter ensured that the peak loads were recorded, regardless of which signal (load cell, displacement or pressure) was being measured by the DAS at the time of failure.
The two test specimens in a double specimen test were never identical and therefore only one specimen would fail at a time. The remaining specimen was then visually inspected for any plastic deformations and if undamaged, reused in subsequent tests of the same series.

Test loads were controlled by a hand operated valve, and although the rate of load application was not constant, gradual load application was subjectively controlled and varied between 0 and 0.4 kPa (8.5 psf) per second. Low rates of load application were employed during the final stages of a test as the specimens approached failure. Failure was easily anticipated by observing the load-deflection curve. The load-deflection history that was recorded using the DAS was visible on the computer monitor throughout the test. As the load deflection curve entered the inelastic

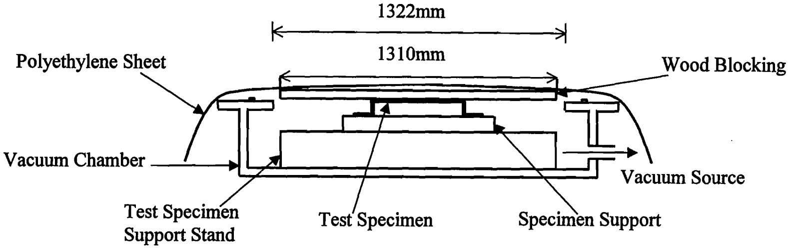

Figure 1 - Test Setup (Section Through Single Specimen Test)

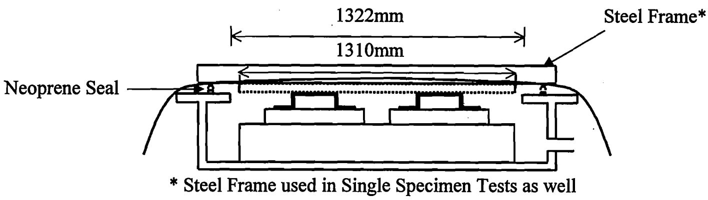

Figure 2 - Test Setup (Section Through Double Specimen Test)

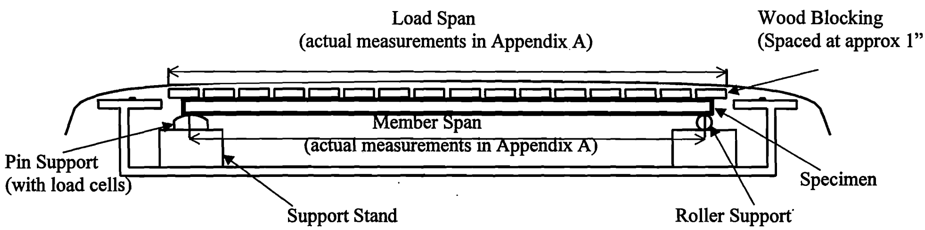

Figure 3 - Test Setup (Side Elevation)

range of response, the rate of load application was reduced to approx. 0.01 kPa (0.2 psf) per second (on average).

TEST RESULTS

The two load measurements (reaction and pressure) provided two separate methods of moment calculation. Using the maximum reaction, the failure moment could easily be calculated by assuming a uniformly distributed load. In the case of using the maximum pressure, the failure moment was calculated by assuming a tributary area and a uniformly distributed load. Although failure did not always occur precisely at midspan of the specimen, but would be within 200mm of the midspan point. The calculation of the maximum applied moment was with respect to the midspan of the specimen. The structural model used to calculate maximum moments is shown in Figure 4.

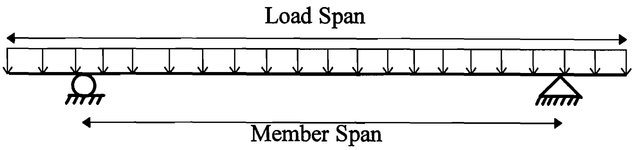

Figure 4 - Structural Model for Maximum Moment Calculation

Although the length of the wood planks was made to be as close as possible to the width of the vacuum chamber opening, there was still approximately a 12 mm (0.5") space between the wood planks and the chamber edge [6 mm (0.25") on each side]. Likewise, in the longitudinal direction, there was approximately a 140 mm (5.5") space between the wood planks and the edge. The polyethylene sheet was observed to exhibited a catenary/membrane action over this small space, therefore, the total tributary width and load span of the specimens was increased by one half of the space [6 mm (0.25"), and 70 mm (2.75"), respectively] to account for this membrane action. By adequately addressing this situation, better agreement was obtained between the two methods of maximum moment calculation. The average difference between the two methods of moment calculation was approximately 0.15%.

Once the test moments were calculated, each test series was scrutinized to identify any significant discrepancies. The average failure moment for the majority of test series was found to be well within 10% of any individual test within the series. Also, it was determined that the coefficient of variation for the majority of test series was generally less than 6.5%. In three cases however, both of these general trends were violated. In test series 22 (4 specimens), the coefficient of variation was 8.4% and test specimen 22-1 was approximately 12.4% less than the average. Once this specimen was removed from the series, the coefficient of variation fell to 1.7% and all specimens were within 2% of the series average. Likewise, test series 25 (4 specimens) had a coefficient of variation of 10% and test specimen 25-4 was approximately 11.6% less than the series average. Also, test specimen 25-3 was approximately 11.6% greater than the series average. Removal of this specimen resulted in a coefficient of variation of 0.5% and all specimens in test series 25 reverted to within 2% of the series average.

It was noted that the test setup for these three test specimens were not ideal and the above observations appeared to confirm this discrepancy. It was consequently decided that these three specimens would not be included in subsequent analysis, which reduced the number of useful tests to 91. Table A.3 contains individual test results, while Table A.4 contains the test results from the Papazian testing program.

The predominant mode of failure for each of the experimental specimens was recorded at the time of testing, and categorized as either local or overall buckling. The presence of the wood planks made it impossible to observe the initiation of buckling and the onset of failure during the test. Failure modes were determined by inspection of the specimen *after* the test was completed, and it was observed that most sections failed via overall buckling. It was observed that overall buckling was generally characterized by a sudden failure mechanism, while local buckling had a tendency to be more gradual. The position of the failed hat-section was also measured with respect to the centerline of the section.

Test Series 1, 2 and 5 experienced local buckling while overall buckling was the failure mechanism of the remaining test specimens.

CONCLUSIONS

Presented in this paper are the experimental results of the testing program that was conducted at the University of Waterloo. This paper forms an important part of the second paper by the authors, entitled "Analysis of Hat Sections with Multiple Longitudinal Stiffeners". It is believed that these tests accurately quantify the behavior of cold formed steel hat sections with multiple intermediate longitudinal stiffeners subjected to bending. Although the majority of test specimens were observed to experience the overall buckling mode of failure, three test series (six specimens) failed in local buckling. The data obtained from this testing program helps to form a sufficiently large data bank to properly investigate the overall buckling mode of failure of these types of sections. Furthermore, the test data corresponding to specimens that failed in local buckling, will also help to establish the limits of section properties that define the governing failure mode of a section. Consult the second paper for analysis details

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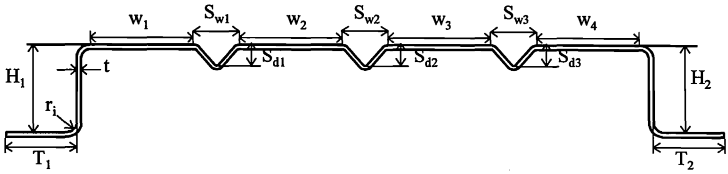
APPENDIX



n = number of intermediate stiffeners

Figure A.1 - Typical Specimen Dimension Notations

Table A.1a - Test Specimen Dimensions

Specimen ID	t (mm)	n	T_1 (mm)	T_2 (mm)	H_1 (mm)	H_2 (mm)	w_1 (mm)	w_2 (mm)	w_3 (mm)	w_4 (mm)	w_5 (mm)
1-1	0.59	3	80	80	48	48	24	12	12	25.5	-
1-2	0.59	3	79.5	79.5	48	48	25	12	12	26	-
1-2	0.59	3	79.5	79.5	48	48	25	12	12	26	-
2-2	0.59	2	79	80.5	48	49	20	11.5	20	-	-
2-3	0.59	2	79	80.5	48	49	20	11.5	20	-	-
3-1	0.59	2	69.5	70.5	54.5	55	13	9	13	-	-
3-2	0.59	2	69.5	71	54.5	55	12.5	9.5	13	-	-
4-1	0.59	2	75.5	82.5	54	55	18	13	10	-	-
4-4	0.59	2	79	80	54.5	55	21	18.5	11.5	-	-
5-1	0.59	4	78.5	78	47.5	49	28	17	18	17.5	28
5-2	0.59	4	83	79	48	49	26.5	17	17.5	18.5	28
5-3	0.59	4	79	83	48.5	49	28	18	18	18	27
6-1	0.59	3	81	79	55	55	16	12	12.5	16.5	-
6-2	0.59	3	81.5	78.5	54	55	15.5	13.5	12.5	16	-
7-1	0.59	3	80	79.5	54	55	24	23	22	25	-
7-2	0.59	3	80.5	79	54	55	23	22.5	22	25	-
7-3	0.59	3	80	80	54	54	26	22	22.5	25.5	-
8-1	0.59	4	80	79.5	54	55	14	14.5	13.5	14	14
8-2	0.59	4	80.5	79	54	55	14	14	14	14.5	12.5
8-4	0.59	4	81	80	53	55	14	13	14	14.5	13.5
9-1	0.59	4	81	80	54	54.5	25.5	25	24	23	27
9-2	0.59	4	80.5	79	54	55	25.5	25	24	23.5	25.5
9-4	0.59	4	79	79.5	54	55	26.5	25.5	23	24	26
10-1	0.59	4	71	70	54	54	15.5	11	7.5	10	18.5
10-3	0.59	4	72	70	54	54	14.5	11	11	8.5	17
10-4	0.59	4	70	71	54	54	16	11	10	9	16.5
11-1	0.59	2	81	79.5	54	55.5	26	21.5	27	-	-
11-2	0.59	2	81	79.5	54	55	25	23	26.5	-	-
11-4	0.59	2	80	79	54	55	26	24	26	-	-

Table A.1a - Test Specimen Dimensions (continued)

Specimen ID	t (mm)	n	T_1 (mm)	T_2 (mm)	H_1 (mm)	H_2 (mm)	w_1 (mm)	w_2 (mm)	w_3 (mm)	w_4 (mm)	w_5 (mm)
12-1	0.59	3	69	70	54.5	55	11	11	10	10	-
12-3	0.59	3	69	70	54	54.5	11.5	10.5	12	9	-
12-4	0.59	3	70.5	70	54.5	55	10	11	9.5	12	-
13-1	0.89	2	70.5	70.5	56.5	57	23.5	23	24	-	-
13-3	0.89	2	71	70	56.5	56.5	26	23	23.5	-	-
13-4	0.89	2	70	71	55.5	55	24.5	22.5	25.5	-	-
14-2	0.89	2	82	81.5	56.5	56	25	24	24.5	-	-
14-3	0.89	2	82	81	56	55.5	25	24	26	-	-
14-4	0.89	2	80.5	79.5	57	57	26.5	23	25	-	-
15-2	0.89	2	83	83.5	57	57	38.5	36.5	39.5	-	-
15-3	0.89	2	83	82.5	56.5	56	39.5	35.5	39	-	-
15-4	0.89	2	81.5	82	56	56	40.5	35.5	42	-	-
16-1	0.89	3	83	82.5	55	56	29.5	25	26.5	28.5	-
16-2	0.89	3	82.5	83	55.5	56	29	25	26	29	-
16-3	0.89	3	83.5	83.5	56	56	29.5	25	25	28	-
17-1	0.89	3	73	73	56	57	22	17.5	17.5	22	-
17-2	0.89	3	73	73.5	55.5	55.5	24	17	17	23	-
17-3	0.89	3	72.5	73	56.5	57.5	22	17.5	17.5	22	-
18-2	0.89	3	84	84	56	56	40	38.5	39	40	-
18-3	0.89	3	85	84	56	56.5	38	39	38.5	38.5	-
18-4	0.89	3	84	84	55	55	40	38	38	40	-
19-1	0.89	4	75.5	75.5	56	57	20.5	20.5	20.5	20	21
19-2	0.89	4	76	75	56	56.5	20	20	20.5	20	20
19-3	0.89	4	76	75	56	56.5	20	20.5	20.5	20.5	19.5
20-2	0.89	4	84.5	84	56	55.5	21	26	27.5	26.5	22
20-3	0.89	4	83.5	84	56.5	56.5	21.5	26	26.5	27	21
20-4	0.89	4	83	83	57	56	21	26.5	26.5	26.5	22
21-2	0.89	4	82	82.5	56	56	41.5	38	38	38.5	42
21-3	0.89	4	84	84.5	56	57	40	38	38	38	39
21-4	0.89	4	84.5	85	56	57	40	38	38	38	39
22-1	1.48	3	84	84.5	57	56.5	59.5	51.5	53.5	60.5	-
22-2	1.48	3	83	85	57	56.5	61.5	50.5	51	60	-
22-3	1.48	3	84	85	57	56	60.5	51	51	61	-
22-4	1.48	3	83	84.5	57	56	61	51	50	61	-
23-1	1.48	4	83	85	56.5	56	60.5	52.5	52	51	60.5
23-2	1.48	4	84.5	86	57	56	60.5	52.5	52	52	60.5
23-3	1.48	4	85	86.5	57	57	61.5	52.5	52.5	52	59.5
23-4	1.48	4	84.5	85.5	57	56	62	51.5	52.5	52	60

PREDICTION OF FAILURE MODE

Consider the current S136-94 approach, whereby local buckling is considered to occur when

$$W > W_{lim} \tag{7}$$

where: $W = w_{max} / t$

$$W_{lim} = 0.644\sqrt{\frac{kE}{f}}$$

w_{max} = largest sub-element width ; k =4

The specimens that were observed to have failed in local buckling had W/W_{lim} in excess of 1.32. However, there were also specimens that had $W/W_{lim} > 1.3$ which did not experience local sub-element buckling. At the very least, it would appear that when considering multiple intermediate stiffeners, the maximum allowable W/W_{lim} ratio for applying overall plate buckling procedures should be increased from 1 to 1.3. Based on the limited data (six specimens), this increase would be considered conservative since some specimens would be subjected to local sub-element buckling equations even though their actual failure mode would be overall plate buckling.

A purely empirical analysis reveals that if the sub-element width in Equation 5 is taken as the spacing between stiffeners and the maximum allowable W/W_{lim} ratio is increased to 2.4, then only the specimens that actually did undergo sub-element buckling would be subjected to the local sub-element buckling equations. Although this procedure fits the data well, it would be more prudent at this time, due to the limited data available, to simply increase the W/W_{lim} ratio (as currently defined in S136-94) to 1.3.

CONCLUSIONS

Based on the evaluation of current design documents (S136-94 and AISI 96), it has been established that the current S136-94 procedure is not adequate in predicting the ultimate bending strength of sections with multiple intermediate stiffeners. Furthermore, it was shown that the current procedure isolates sections into three distinct regions depending on the strength of the stiffener and slenderness of plate sub-elements. When considering specimens with inadequate stiffeners, the current procedure produces overly conservative estimates (approximately 70%) of section strength. For specimens that are considered as failing in local sub-element buckling ($W > W_{lim}$), the S136-94 procedure actually *overestimates* the section strength and predicts strengths that are approximately 17% unconservative. With the specimens that are considered as failing in overall plate-buckling ($W < W_{lim}$), the S136-94 approach yields predictions that are conservative by a factor of about 50% (on average).

The AISI 96 procedure is similar to the S136-94 approach except for the manner in which the equivalent thickness is calculated for sections subjected to overall plate-buckling. Consequently, the same results as with S136-94 are obtained when considering sections with inadequate stiffeners and sections with large plate sub-elements ($W > W_{lim}$). For sections with $W < W_{lim}$, the AISI 96 procedure uses an equivalent plate thickness approach which is based on an equal moment of inertia philosophy. With the S136 approach on the other hand, one calculates an equivalent thickness based on an equal elastic buckling load. It was found that the AISI 96 approach (equal moments of inertia) yields unconservative results for section strength (5% on average).

A different method of strength prediction was developed based on the energy formulation of Lind (Lind, 1973). This previous work provided the basis for the current equivalent thickness approach used in S136-94. The resulting predictions of section strength were found to be sufficiently accurate with an average test to predicted moment ratio of 1.02 and a coefficient of variation of 10 percent.

Through the course of the investigation it was found that the current method of predicting the failure mode using the W/W_{lim} ratio is considerably conservative. The range of sub-element slenderness (W = w/t) over which the standards assume local buckling as the governing failure mode were found to be incorrect. The limiting value of 1 was found to commit sections to sub-element buckling equations when in fact the sections were observed to fail in overall plate buckling. Based on the data available, it was found that increasing the limiting W/W_{lim} ratio to 1.3 would provide a more accurate assessment of the actual failure mode without sacrificing safety (i.e. predicting overall failure when local buckling occurs). This modification would still improperly consign some sections to local buckling equations, but allow for a 30% increase in sub-element slenderness.

Another empirical method of predicting the failure mode was also developed as a part of this research (Acharya, 1997). This method involves using the existing W/W_{lim} ratio with a minor variation. It was determined that by increasing the limiting ratio to 2.4 and redefining W in W / W_{lim} to be equal to the ratio of the stiffener spacing to the thickness, accurate predictions of failure mode could be made.

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Table A.1b - Additional Test Specimen Dimensions (continued)

Specimen ID	S_{W1} (mm)	S_{W2} (mm)	S_{W3} (mm)	S_{W4} (mm)	r_{i1} (mm)	r_{i2} (mm)	S_{d1} (mm)	S_{d2} (mm)	S_{d3} (mm)	S_{d4} (mm)
26-1	32.5	31.5	31	-	1.52	1.52	13	14	13.5	-
26-2	30.5	31.5	32	-	2.02	1.52	13	13.5	14	-
26-3	33	30	31.5	-	2.02	1.52	13.5	13	13	-
26-4	31.5	30	32	-	2.52	1.52	13	13	14	-
27-1	30.5	30.5	31.5	-	1.02	1.52	12.5	14	13.5	-
27-2	33	32	34	-	2.52	2.52	13	13	13	-
27-3	31	30	30	-	1.52	2.52	13	13	13	-
27-4	31	30.5	31	-	1.52	2.02	13	13.5	13.5	-
28-1	30.5	31	-	-	1.52	1.52	13.5	13	-	-
28-2	30	30	-	-	1.52	1.02	13	13	-	-
28-3	29.5	31	-	-	1.52	1.02	13	13.5	-	-
28-4	30	30	-	-	1.02	2.02	13	13	-	-
29-1	30	29.5	-	-	2.02	2.02	12.5	12	-	-
29-2	32	31	-	-	2.52	3.02	13	12.5	-	-
29-3	32.5	31	-	-	1.52	2.02	12.5	12	-	-
29-4	31	31	-	-	1.52	2.02	12.5	13	-	-
30-1	30	31	-	-	1.52	2.02	12	12.5	-	-
30-2	32	31	-	-	1.52	2.02	13	13	-	-
30-3	29	32.5	-	-	2.02	2.52	10.5	13	-	-
30-4	32.5	31.5	-	-	1.52	1.52	13	12	-	-

Table A.2 - Material Properties of Test Specimens

Test Series	t (mm)	F_y (MPa)	F_u (MPa)	% Elong.
1 to 12	0.59	310	364	37.1
13 to 21	0.89	342	363	38.8
22 to 30	1.48	342	369	35.6

Note: E = 203 000 MPa (29,443 ksi) was used in all analysis calculations. Percent elongation was based on a 50 mm gauge length.

Table A3 - Test Setup Dimensions and Test Results

Specimen ID	Member Span (m)	Load Span (m)	Mod. Load Span (m)	Max. Press. (kPa)	Max. Reac. (N)	Load Cell Moment (N.m)	Press. Moment (N.m)	M_{test} (N.m)
1-1	2.65	2.75	2.82	1.18	1167	724	776	750
1-3	2.66	2.75	2.82	1.11	1203	752	737	745
1-4	2.66	2.75	2.82	1.26	1332	832	833	832
2-2	2.65	2.75	2.82	0.35	1464	908	-	908
2-3	2.65	2.75	2.82	1.39	1417	879	918	898
3-1	2.67	2.84	2.91	1.47	1433	871	948	909
3-2	2.67	2.84	2.91	1.36	1541	936	913	924
4-1	2.67	2.84	2.91	1.41	1529	929	948	939
4-4	2.65	2.75	2.82	1.46	1392	863	916	890
5-1	2.65	2.75	2.82	1.02	1061	658	708	683
5-2	2.64	2.82	2.89	1.17	1165	696	743	720
5-3	2.65	2.825	2.895	1.11	1223	735	745	740
6-1	2.67	2.85	2.92	1.46	1498	906	924	915
6-2	2.67	2.84	2.91	1.53	1606	976	998	987
7-1	2.66	2.82	2.89	1.54	1761	1070	1053	1061
7-2	2.65	2.82	2.89	1.74	1796	1082	1104	1093
7-3	2.66	2.82	2.89	1.45	1639	995	944	970
8-1	2.65	2.82	2.89	1.64	1753	1056	1041	1048
8-2	2.65	2.82	2.89	1.68	1706	1028	1073	1050
8-4	2.65	2.82	2.89	1.78	1849	1114	1126	1120
9-2	2.65	2.82	2.89	1.59	1708	1029	1036	1032
9-4	2.65	2.82	2.89	1.61	1756	1058	1044	1051
10-1	2.63	2.82	2.89	1.63	1719	1018	1029	1023
10-3	2.63	2.82	2.89	1.62	1789	1060	1016	1038
10-4	2.63	2.82	2.89	1.78	1869	1108	1107	1107
11-1	2.62	2.82	2.89	1.46	1603	942	917	929
11-2	2.63	2.82	2.89	1.38	1515	898	883	890
11-4	2.63	2.82	2.89	1.44	1615	957	911	934
12-1	2.62	2.82	2.89	1.60	1688	991	998	995
12-3	2.63	2.82	2.89	1.53	1685	998	969	984
12-4	2.63	2.82	2.89	1.54	1673	991	969	980
13-1	2.63	2.82	2.89	3.39	3391	2009	2045	2027
13-3	2.63	2.82	2.89	3.34	3353	1987	1996	1991
13-4	2.63	2.82	2.89	3.12	3045	1804	1868	1836
14-2	2.63	2.82	2.89	3.53	3815	2261	2104	2182
14-3	2.63	2.82	2.89	3.49	3711	2199	2076	2138
14-4	2.63	2.82	2.89	3.35	3492	2069	2000	2035
15-2	2.63	2.82	2.89	3.45	3603	2135	2016	2076
15-3	2.63	2.82	2.89	3.48	3710	2198	2079	2139
15-4	2.62	2.82	2.89	3.40	3654	2147	2017	2082

Note:
1) Test Series 1 to 21 were double specimen tests with a modified tributary width of 0.658 m per specimen
2) Test Series 22 to 30 were single specimen tests with a modified tributary width 1.316 m per specimen
3) See Figure 4 for illustrations of Load Span and Member Span

Table A.3 - Test Setup Dimensions and Test Results (continued)

Specimen ID	Support Span (m)	Load Span (m)	Mod. Load Span (m)	Max. Press. (kPa)	Max. Reac. (N)	Load Cell Moment (N.m)	Press. Moment (N.m)	M_{test} (N.m)
16-1	2.62	2.82	2.89	3.51	3468	2037	2069	2053
16-2	2.64	2.82	2.89	3.65	3648	2180	2180	2180
16-3	2.64	2.82	2.89	3.61	3652	2182	2169	2176
17-1	2.64	2.82	2.89	3.61	3565	2130	2157	2144
17-2	2.64	2.82	2.89	3.64	3827	2287	2183	2235
17-3	2.64	2.82	2.89	3.47	3497	2090	2075	2083
18-2	2.64	2.82	2.89	3.56	3702	2212	2143	2178
18-3	2.64	2.82	2.89	3.44	3509	2097	2076	2086
18-4	2.64	2.82	2.89	3.30	3490	2085	1994	2039
19-1	2.64	2.82	2.89	3.64	3661	2187	2191	2189
19-2	2.64	2.82	2.89	3.61	3759	2246	2168	2207
19-3	2.64	2.82	2.89	3.71	3732	2230	2220	2225
20-2	2.64	2.82	2.89	3.60	3626	2166	2155	2161
20-3	2.64	2.82	2.89	3.50	3538	2114	2103	2108
20-4	2.62	2.82	2.89	3.47	3528	2073	2054	2063
21-2	2.64	2.82	2.89	3.67	3795	2268	2220	2244
21-3	2.63	2.82	2.89	3.49	3491	2068	2085	2076
21-4	2.63	2.82	2.89	3.52	3604	2135	2113	2124
22-1	2.67	2.84	2.91	3.24	6562	3986	4001	3994
22-2	2.64	2.84	2.91	4.05	8160	4835	4819	4827
22-3	2.64	2.84	2.91	3.99	7976	4726	4759	4742
22-4	2.64	2.80	2.87	3.93	7677	4626	4702	4664
23-1	2.64	2.82	2.89	4.16	8206	4903	4966	4934
23-2	2.65	2.82	2.89	4.13	8042	4846	4967	4906
23-3	2.64	2.82	2.89	4.03	7833	4680	4830	4755
23-4	2.64	2.82	2.89	3.65	7221	4314	4380	4347
24-1	2.64	2.82	2.89	3.74	7080	4231	4650	4440
24-2	2.64	2.82	2.89	3.63	7312	4369	4337	4353
24-3	2.64	2.82	2.89	3.73	7479	4469	4459	4464
24-4	2.64	2.82	2.89	3.94	7751	4631	4700	4665
25-1	2.64	2.84	2.91	0.16	411		4265	4265
25-2	2.64	2.82	2.89	3.57	7235	4323	4273	4298
25-3	2.64	2.82	2.89	4.10	8090	4834	4878	4856
25-4	2.64	2.82	2.89	3.14	6398	3823	3784	3804
26-1	2.64	2.82	2.89	3.78	7548	4510	4512	4511
26-2	2.64	2.81	2.88	3.91	7785	4671	4689	4680
26-3	2.64	2.82	2.89	4.00	7921	4733	4763	4748
26-4	2.64	2.82	2.89	4.08	8085	4831	4852	4841

Note:
1) Test Series 1 to 21 were double specimen tests with a modified tributary width of 0.658 m per specimen
2) Test Series 22 to 30 were single specimen tests with a modified tributary width 1.316 m per specimen
3) See Figure 4 for illustrations of Load Span and Member Span

Table A.3 - Test Setup Dimensions and Test Results (continued)

Specimen ID	Support Span (m)	Load Span (m)	Mod. Load Span (m)	Max. Press. (kPa)	Max. Reac. (N)	Load Cell Moment (N.m)	Press. Moment (N.m)	M_{test} (N.m)
27-1	2.64	2.82	2.89	3.50	7202	4303	4200	4252
27-2	2.64	2.82	2.89	3.56	7296	4360	4255	4307
27-3	2.64	2.82	2.89	3.76	7590	4535	4480	4508
27-4	2.64	2.82	2.89	3.57	7259	4337	4267	4302
28-1	2.64	2.82	2.89	3.99	7970	4762	4751	4757
28-2	2.64	2.82	2.89	4.11	8118	4850	4886	4868
28-3	2.64	2.82	2.89	3.69	7308	4367	4406	4387
28-4	2.64	2.82	2.89	4.16	8230	4917	4965	4941
29-1	2.64	2.82	2.89	4.30	8504	5081	5111	5096
29-2	2.64	2.82	2.89	4.08	8083	4829	4840	4835
29-3	2.64	2.82	2.89	3.87	7648	4570	4610	4590
29-4	2.64	2.82	2.89	4.05	8076	4825	4801	4813
30-1	2.64	2.82	2.89	3.29	6879	4110	3994	4052
30-2	2.64	2.82	2.89	3.78	7644	4567	4505	4536
30-3	2.64	2.82	2.89	3.40	6956	4156	4074	4115
30-4	2.64	2.82	2.89	3.84	7678	4587	4567	4577

Note:
1) Test Series 1 to 21 were double specimen tests with a modified tributary width of 0.658 m per specimen
2) Test Series 22 to 30 were single specimen tests with a modified tributary width 1.316 m per specimen
3) See Figure 4 for illustrations of Load Span and Member Span