International Specialty Conference on Cold-Formed Steel Structures

(1994) - 12th International Specialty Conference on Cold-Formed Steel Structures

Oct 18th, 12:00 AM

The Strength of Partially Stiffened Stainless Steel Compression Members

Y. Buitendag

G. J. van den Berg

Twelfth International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, U.S.A., October 18-19, 1994

THE STRENGTH OF PARTIALLY STIFFENED STAINLESS STEEL COMPRESSION MEMBERS

by

Y Buitendag[1], GJ van den Berg[2]

ABSTRACT

The instability of partially stiffened stainless steel compression members due to local buckling of the flange element or flange and lip interaction has not been studied before. In this investigation the critical local buckling and post-buckling behaviour of cold-formed partially stiffened stainless steel compression elements is studied. It ic concluded in this investigation that a plasticity reduction factor should be used to evaluate the critical local buckling stress as well as the effective width to calculate the ultimate capacity of partially stiffened stainless steel compression members.

INTRODUCTION

In recent years the use of light gauge stainless steel sections has gained increasing use in structural and architectural applications. Because of its superior corrosion resistance, ease of maintenance, favourable weight to strength ratios and an attractive appearance, stainless steels have many applications and a variety of special uses. The mechanical properties of stainless steels differ to that of carbon and low alloy steels in that it has relatively low proportional limits and different mechanical properties in tension and in compression.

Instability is often the cause of failure of steel structures. This failure will be either due to overall buckling of a member or local buckling of an element. Local buckling plays a governing role when the elements are very thin and subject to compressive, bending or shear stresses. In contrast to hot-rolled members, the cold forming process allows practically unlimited width to thickness ratios. Consequently these thin elements are subjected to local buckling before reaching the ultimate load and therefore decreasing the strength. For this reason the critical local buckling and post buckling behaviour of these elements are of major importance. Open form shapes are the most commonly used in cold-rolled sections. These sections can be classified in three typical types of elements namely:

- Unstiffened elements having one edge parallel to the longitudinal axis of the member supported and the other end completely free to rotate and deflect.

- Stiffened elements having two edges parallel to the longitudinal axis of the member supported and elastically restraint against rotation by the adjoining elements.

---

1. Research Assistant in the Materials Laboratory in the Faculty of Engineering at the Rand Afrikaans University, Republic of South Africa.

2. Associate Professor and Chairman of the Department of Civil Engineering in the Faculty of Engineering at the Rand Afrikaans University, Republic of South Africa.

- Partially stiffened elements having one edge parallel to the longitudinal axis supported by a web and the other edge partially supported by a lip.

In this investigation the critical local buckling and post buckling behaviour of cold-formed, partially stiffened, stainless steel compression elements are studied. Because of the abovementioned characteristics of stainless steels, the carbon and low-alloy steel specifications are not always directly applicable to the design of stainless steel members. Although a wide range of cold-formed thin-walled stainless steel sections have been used in the past, the stainless steel specification for the design of cold-formed structural members[1] lacks a considerable amount of design provisions in comparison with the design specification for carbon and low-alloy steels[2].

STEELS UNDER CONSIDERATION

The steels under consideration in this study are Type 304 austenitic stainless steel, Type 430 ferritic stainless steel as well as the modified Type 409 steel, designated Type 3CR12 corrosion resisting steel, locally manufactured by Columbus Stainless. These are all well known stainless steels and are produced in accordance with the ASTM Standard Specification A167-81[3] , A176-85a[4] or other equivalent specification.

THEORETICAL MODEL

Partially stiffened compression elements can be idealized with one unloaded edge simply supported by a web and elastically restrained against rotation and the other edge restraint by an edge stiffener. If the plate is perfectly flat to begin with, it will remain flat until the critical buckling stress is reached. Beyond this stress the element will deflect normal to the plane and buckle into waves. If the edge stiffener is not adequate the stiffener can also buckle into waves.

Critical buckling

The critical buckling of a thin walled element represents a change in the physical behaviour of the structure. Because of the different possible modes of buckling in the partially stiffened elements, the critical local buckling behaviour plays a greater role than in flat plate elements having ideal boundary conditions, such as simply or fixed supports at both sides.

The elastic theory of isotropic plate buckling is well understood. Using the small deflection equation of the equilibrium of plates, the critical local buckling stress can be calculated. Taking the non-linear stress strain characteristics into consideration, many investigators have suggested approximate or more exact inelastic theories for the buckling of isotropic plates. For predicting the critical local buckling stress for an isotropic plate in the non-linear range, Equation 1 can be used.

$$f_{cr} = \frac{\eta(k\pi^2 E_o)}{12(1-\nu^2)(w/t)^2} \quad (1)$$

where

f_{cr} = critical buckling stress
E_o = initial elastic modulus
ν = Poison's ratio
w = width of element
t = thickness of element

k = buckling coefficient

The buckling coefficient k depends upon the edge rotational restraint, the type of loading and the aspect ratio, (ratio of length, L, to the width, w, of the plate). The value of k for a long rectangular plate is subjected to different stress and support conditions.

Equation 1 is the result of a solution of a revised form of the classical Bryan elastic buckling equation. The effects of inelastic behaviour of isotropic materials are taken into account by the plasticity reduction factor, η, which is equal to one in the elastic range and less than one in the inelastic range.

Several theories for the determination of plasticity reduction factors have been developed and include those by Bijlaard[5] and Stowell[6]. The plasticity reduction factor as suggested by Bleich[7] for longitudinal compressed stiffened elements is widely accepted as reasonable, although somewhat conservative, being $(E_t/E_o)^{1/2}$. He has also shown that for longitudinally compressed members that has unstiffened compression elements, the plasticity reduction factor is theoretically very close to the ratio of the secant modulus to the initial modulus, (E_s/E_o). Johnson, Winter and Wang[8,9,10] showed the validity of the plasticity reduction factors for the design of cold-formed austenitic stainless steels. A plasticity reduction factor of E_t/E_o is also used in this study.

Post-Buckling

Contrary to columns and shells, plate and sheet elements possess a large strength reserve capacity after local buckling, except where local buckling occurs at stresses approaching the yield point for sharp yielding materials or at large inelastic strains for materials such as stainless steel that do not have a definite yield point. After the local buckling stress is reached, the compressed plate elements merely deform into a nondevelopable wavy surface and continue to resist an increasing load.

The failure of the member may finally be induced by yielding for a sharp yielding material and by large plastic deformation or by geometrical change for a gradual yielding type of material. For smaller values of w/t ratios, yielding will take place before the element buckles locally, since the local buckling stress increases with a decrease in width to thickness ratio, (w/t),

Because of the capacity of elements to sustain additional load after local buckling, all design procedures based on strength should take into consideration this post buckling behaviour. For design purposes, the non-uniform stress distribution over the width of the plate in the post buckling range is idealized by the effective width method, assuming the stress at the supported edge or edges as uniform over an effective width, b. This semi-theoretical effective width approach was derived by Von Karman[11].

Winter's extensive investigation into the post buckling strength of ordinary carbon steel[12,13], showed that equations such as von Karman's are only justified for ideal conditions and not on actual structural members, because of initial imperfections and residual stresses. These tend to lower the post buckling strength of the members. On experimental evidence, Winter modified von Karman's equation for effective widths for stiffened simply supported compression elements as follows:

$$\frac{b}{t} = 0.95\sqrt{\frac{\eta k E_o}{f_{\max}}}\left(1 - 0.208\,\frac{t}{w}\sqrt{\frac{\eta k E_o}{f_{\max}}}\right) \qquad (2)$$

For

$$\frac{w}{t} < 0.95\sqrt{\frac{\eta k E_o}{f_{max}}} \quad (3)$$

the section is fully effective and no reduction is necessary.

Where

b	=	effective width of compression element
t	=	thickness
E_o	=	initial elastic modulus
f_{max}	=	compression element edge stress
w	=	actual flat width of compression element
η	=	plasticity reduction factor
k	=	edge rotational constant
k	=	0.425 for unstiffened compression elements
k	=	4.000 for stiffened compression elements

Von Karman suggested that a reduced modulus of elasticity be used in the effective width equation to account for the inelastic behaviour. The idea of introducing a plasticity reduction factor into the effective width equation was also suggested by Needham[14], Jombock and Clark[15], and Johnson[8].

It was found through tests by Miller[16] and later revised by Winter[13] that the above equation can also be applied to unstiffened elements. The above equation can also be used for partially stiffened compression elements by varying the buckling coefficient between 0.425 for unstiffened and 4.0 for stiffened elements.

In Equation 2, the plasticity reduction factor, η, for plate buckling is the same as that used in the critical local buckling discussion, namely E_s/E_o for unstiffened elements and $(E_t/E_o)^{0.5}$ for stiffened elements. A similar approach was used by Johnson[8].

EXPERIMENTAL INVESTIGATION

A comprehensive experimental investigation on 33 zed and 33 hat sections in the different stainless steels has been carried out in order to determine the critical local buckling stresses and the post buckling capacity of partially stiffened compression flanges.

Mechanical Properties

The mechanical properties of stainless steels Type 304, 430 and Type 3CR12 steel are determined from stress-strain curves obtained from uniaxial tensile and compression tests in the longitudinal and transverse directions of rolling. The mechanical properties are determined in accordance with the procedures outlined by the ASTM Standard A370-77[17]. Average strain is measured by two strain gauges mounted on either side of the specimen in a full bridge configuration with temperature compensation.

Type 304, 430 and 3CR12 steels are all gradual yielding steels. In order to compute the initial modulus, E_o, and subsequently the proportional limit, F_p, defined as the 0.01% offset strength, and the yield strength, F_y, defined as the 0.2% offset strength, a computer program is used. The best fit straight line for the initial part of the stress-strain curve is determined through a process of iterative linear regression. The slope of this line is considered to be the initial modulus, E_o. The Ramberg-Osgood[18] equation as revised by Hill[19] is used to produce the analytical stress-strain curves for the different types of steel.

$$\varepsilon = \frac{F}{E} + 0.002\left(\frac{F}{F_y}\right)^n \tag{4}$$

where

F	=	stress
E_o	=	initial elastic modulus
F_y	=	yield strength
F_p	=	proportional limit

$$n = \frac{\log\left(\frac{\varepsilon_2}{\varepsilon_1}\right)}{\log\left(\frac{F_2}{F_1}\right)} \tag{5}$$

where

ε_1	=	proportional limit offset strain
ε_2	=	yield strength offset strain
F_1	=	proportional limit
F_2	=	yield strength

The analytical mechanical properties, determined from these stress-strain curves, for stainless steels Type 304, 430 and 3CR12 are given in Table 1.

In order to use the tangent modulus and the secant modulus to determine the plasticity reduction factors in later analysis, these values had to be determined at all levels of stress. The tangent modulus, E_t, is defined as the slope of the tangent to the stress strain curve at each value of stress. It is obtained as the inverse of the first derivative of Equation 4 with respect to stress and can be computed by using Equation 6.

$$E_t = \frac{F_y\, E_o}{F_y + 0.002nE_o\left(\frac{F}{F_y}\right)^{n-1}} \tag{6}$$

The secant modulus, E_s, is defined as the stress to strain ratio at each value of stress and can be computed by using Equation 7.

$$E_s = \frac{E_o}{1 + 0.002E_o\,\frac{F^{n-1}}{F^n}} \tag{7}$$

The stress-strain curve for longitudinal compression differs considerably from te other three stress-strain curves. It has a very low proportional limit which means inelastic member behaviour at a low stress. The analytical stress-strain curves and material properties determined for the different steels in the longitudinal compression direction is used in the analysis of the stub column tests.

Strength of Axially Loaded Columns

Stub column tests have been carried out on 33 partially stiffened singly symmetrical hat sections as well as 33 point symmetrical zed sections.

Design and Preparation of Profiles

The elements were designed such that the whole range of variables governing element behaviour are covered. It was decided to vary the flat width of the flange and keep the stiffener size and plate thickness constant.

The stub columns had to be short enough to avoid any overall buckling but long enough to permit the forming of waves in local buckling. On recommendation by Schuster, the lengths of the stub columns are taken as close as possible to 3 times the largest dimension to prevent any possible overall buckling interaction. The overall dimensions of the stub column specimens are shown in Figure 2 and the dimensions are given in Table 2.

Cold rolled sheets, 1,53 mm in thickness, were used to fabricate the zed and hat profiles. Segments were cut along the longitudinal direction of the sheets and the sections were formed through a press-brake process. The ends of the columns were cold sawed and machined flat and perpendicular to the column axis.

Two sets of strain gauges are mounted at various positions as shown in Figure 2. The first set of four strain gauges is placed at the top and bottom ends of the stub columns. These strain gauges are used for alignment of the stub-columns.

The second set of eight strain gauges are placed at midspan of the column where the first local buckling is expected to occur. The strain gauges are mounted in pairs to enable the use of the strain reversal method for the determining of the critical local buckling stresses. The placing of the pairs enables the detection of both the local buckling modes, namely the stiffener buckling mode and the local plate buckling mode.

Testing Procedure

The stub columns are placed in a 500 kN Instron universal testing machine between two specially manufactured end plates as shown in Figure 1. By using the bolts on the sides of these endplates, the position of the specimens could be adjusted in order to ensure uniaxial compression. The experimental set-up of the hat and zed specimens was different. In the testing procedure of the hat sections one ball at each end of the column was provided while only one ball on the top end was used in the testing of the zed sections.

The specimens are placed in such a way that the compression load is applied above the gross centroid of the stub column specimen. During the test set-up procedure a preload of approximately 15% of the theoretically calculated ultimate load is applied to the specimen. The strain gauges at the two quarter points are used for alignment of the specimen. This is done by adjusting the bolts in the end plates. The specimen is assumed to be axially loaded when the strain readings did not differ by more than 5% for loads up to one third of the predicted ultimate load. Knowing that the compression load applied is concentrical, the preload was removed and the actual testing of the section could proceed.

The stub column is loaded statically with a continuous loading process of 0,14 mm/sec. Readings are taken every 0.5 seconds and the stresses and their correspondent strains are recorded and stored on the computer for further analysis. The tests are continued past the forming of the local buckling waves, until there is ultimate failure of the specimen and the compression force decreased with increased strain.

RESULTS

The experimental critical local buckling stresses, F_e, and the theoretical buckling stresses, F_t, for Type 304, 430 and Type 3CR12 steels are given in Tables 3, 4 and 5. The ultimate failure loads, P_e, and the theoretical ultimate loads, P_t, for Type 304, 430 and Type 3CR12 steels are given in Tables 6, 7 and 8.

The modified strain reversal method is used to determine the experimental critical buckling stresses. This method was also used by Desmond[20], however the critical buckling stresses are obtained from the stress-strain curves of the stub columns. The ultimate capacity is taken as the maximum load that the section can resist before failure.

The experimental critical local buckling and ultimate values of the zed specimen were much higher than those of the hat specimen. Because of the "wandering centroied" problem in singly simmetrical hat specimens, the results of the zed specimens are taken as more representative of the local buckling behaviour. However both these curves correspond well to the theoretically determined values.

No strain reversals were found in specimens 01, 02, 21 and 22. These specimens were the smallest two in each range. They also had the most support at the stiffener flange junction. These specimens failed ultimately before any local buckling took place. Specimen 03 and 23 reached their ultimate capacities and their critical local buckling strengths almost at the same moment and only slight strain reversal very close to failure could be seen.

The sections with the larger w/t ratios and the smallest rotational restraints at the flange stiffener junction showed failure of the stiffener which clearly induced failure of the flange and ultimately the failure of the profile. The failures were accompanied by large deformations and extremely low critical local buckling stresses as well as ultimate capacities.

By looking at the ratio of experimental critical buckling stresses to the experimental ultimate failure loads of the specimens, it is found that partially stiffened compression elements of all three the types of steels have a considerable amount of post buckling capacity. The smaller specimens having smaller w/t ratios reached their ultimate loads without any local buckles forming, and thus had no post-buckling capacity. However, the larger the w/t ratios became, the more the specimens reached their critical buckling loads before failing and the larger the post buckling capacity of the specimens became.

Plasticity Reduction Factors

In Tables 3 to 8 the experimentally determined critical local buckling and ultimate loads are compared to the theoretical loads according to the current stainless steel specification, but using the following four plasticity reduction factors:

1. $\eta = 1$ as used in the carbon and low-alloy steel specification.
2. $\eta = E_t/E_o$
3. $\eta = (E_t/E_o)^{1/2}$
4. $\eta = E_s/E_o$.

In Figures 3 to 5 the experimental critical local buckling stresses for the zed and hat specimens are given against the different theoretical curves. In Figures 6 to 8 the experimental ultimate strengths for the zed and hat specimens are plotted against the different theoretical curves.

DISCUSSION OF RESULTS

Critical Local Buckling

The experimental critical local buckling results are in good agreement with the theoretical values when certain plasticity reduction factors are used in the calculations.

All three the steels under investigation show elastic behaviour at stresses below their proportional limits, F_p, and corresponded well to the theoretical elastical critical buckling values using a plasticity reduction factor of 1,0. However, for stresses above the different proportional limits all the steels show inelastic behaviour resulting in the flattening off of the curves. In this range the experimental critical local buckling values of Type 304 stainless steel show good agreement with both the theoretical curves using a plasticity reduction factor of E_s/E_o and $(E_t/E_o)^{1/2}$. Type 430 stainless steel correspond well to the theoretical curve using the plasticity reduction factor of E_s/E_o. Type 3CR12 steel correspond well to the theoretical values using a plasticity reduction factor of $(E_t/E_o)^{1/2}$. The experimental results does not correspond well to the theoretical results when a plasticity reduction factor of E_t/E_o is used.

Very low critical local buckling stresses are found in specimens with w/t ratios of approximately 90 and larger. The local buckling of the stiffener induces buckling in the compression flange, thus lowering the capasity of the compression flange.

Post Buckling Behaviour

The experimental results shows that partially stiffened stainless steel elements have a considerable amount of post buckling capacity which should be taken into account in the design of these members.

The post-buckling experimental results show good agreement with the theoretically calculated values. It appears that the stainless steels have a pronounce elastic and inelastic behaviour. At lower stresses the materials behave elastic. However at higher stresses, the material starts behaving inelastic and the experimental values tend to drop dramatically.

The clause in the current design specification[1] for stainless steels on partially stiffened compression members does not use a plasticity reduction factor to calculate the effective width. However in this investigation the experimental results of all three the steels compare well with the theoretical results using a plasticity reduction factor of E_s/E_o. Using the plasticity reduction factor of $(E_t/E_o)^{1/2}$ will be conservative in most cases.

SUMMARY AND CONCLUSIONS

The critical local buckling and post-buckling behaviour of partially stiffened compression flanges of Type 304, Type 430 and 3CR12 were investigated.

The experimental critical local buckling and post-buckling capacities of the specimen are in good agreement with the theoretical calculated values. However, it is found that the steels have a pronounce elastic behaviour at low stresses and inelastic behaviour at stresses above the proportional limits. This is due to the low proportional limit in the longitudinal compression direction in stainless steels, which means that inelstic behaviour of a member starts at a low stress.

It is therefor concluded that the plasticity reduction factor, E_s/E_o, should be used to evaluate the critical local buckling stress as well as the effective width to calculate the ultimate capacity of partially stiffened stainless steel compression members.

REFERENCES

1. American Society of Civil Engineers . Specification for the Design of Cold-Formed Stainless Steel Members. ANSI/ASCE. 1991.

2. American Iron and Steel Institute. Specification for the Design of Cold-Formed Steel Structural Members, 1989 Edition

3. American Society for Testing and Materials. Standard Specification for Corrosion-Resisting Chromium-Nickle Steel Plate, Sheet and Strip. ASTM Standard A167-81.

4. American Society for Testing and Materials. Standard Specification for Stainless Steel and Heat Resisting Chromium Steel Plate, Sheet and Strip. Desigation A176-85a

5. Bijlaard, P.P., Theory of the Plastic Stability of Thin Plates. Publications International Association of Bridge and Structural Engineering, Vol. 6, 1940-1941.

6. Stowell, E. Z., A Unified Theory of Plastic Buckling of Columns and Plates, NACA Tech. Note 1556, 1948.

7. Bleich, F., Buckling Strength of Metal Structures, McGraw-Hill, NY, 1952.

8. Johnson, A.L. The Structural Performance of Austenitic Stainless Steel Members, Department of Structural Engineering. Report no 327, Cornel University, 1966

9. Johnson, A.L. and Winter, G. Behaviour of Stainless Steel Columns and Beams, Journal of the Structural Division, ASCE Proceedings, Vol. 92, No. ST10. Oct,1966.

10. Wang, S.T. Cold-Rolled Austenitic Stainless Steel: Material Properties and Structural Performance, Department of Structural Engineering. Report no 334, Cornell University, July, 1969.

11. Von Karman, T., Festogjeotsprobleme im Mashinenbau, Enccyc. der math., wiss., 4, 1910.

12. Winter, G, Lansing, W, and McCalley, R.B., Jr., Four Papers on the Performance of Thin Walled Steel Structures, Eng. Esp. Sta. Cornell University, Ithaca, NY, 1950

13. Winter, G., Strength fo Thin Steel Compression Flanges, Trans. ASCE, Vol. 112, 1947.

14. Needham, R.A., The Ultimate Strength of Multiweb Box Beams in Pure Bending, Journal of the Aeronautical Siences, Vol. 22, 1955.

15. Jombock, J.R. and Clark, J.W., Postbuckling Behaviour of Flat Plates, Trans. ASCE, Vol. 127, Part 2, 1962.

16. Miller, E.A., A Study of the Strength of Short, Thin-Walled Steel Studs. MCE Thesis, Cornell Universirty, Oct. 1943.

17. American Standard for Testing of Materials. Standard Methods and Definitions for Mechanical Testing of Steel Products, Standard A370-77, 1981.

18. Ramberg, W, Osgood, W.R. Description of Stress-Strain Curves by Three Parameters, NACA Technical Note No.927, 1944.

19. Hill, H.N, Determination of Stress-Strain Relations from Offset Yield Strength Values. NACA, Technical note No.927, 1944.

20. Desmond, T.P,, Pekoz, T. and Winter, G. Edge Stiffeners for Thin-Walled Members, Journal of the Structural Division, ASCE Proceedings, Vol. 107, no. St2. 1981.

Table 1. Mechanical Properties

Mechanical Properties	TT	LT	TC	LC
Modulus of Elasticity E_o (GPa)				
TYPE 3CR12	206.26	189.24	204.93	218.89
std	0.02	0.02	0.09	0.09
TYPE 430	197.24	179.89	214.67	213.71
std	0.03	0.01	0.02	0.05
TYPE 304	192.90	200.02	213.79	232.25
std	0.03	0.03	0.05	0.04
Yield Strength F_y (MPa)				
TYPE 3CR12	315.89	271.86	311.92	314.82
std	0.02	0.01	0.01	0.04
TYPE 430	352.08	315.51	394.15	370.47
std	0.01	0.00	0.04	0.04
TYPE 304	284.87	293.36	323.04	328.32
std	0.02	0.01	0.02	0.04
Proportional Limit F_p (MPa)				
TYPE 3CR12	274.22	202.66	296.50	198.31
std	0.03	0.05	0.04	0.07
TYPE 430	311.31	237.22	352.75	244.62
std	0.04	0.02	0.03	0.09
TYPE 304	215.78	187.71	224.79	160.61
std	0.03	0.03	0.09	0.07
Ultimate Strength F_u (MPa)				
TYPE 3CR12	449.47	416.90		
std	0.01	0.01		
TYPE 430	507.38	476.27		
std	0.00	0.00		
TYPE 304	706.64	733.67		
std	0.01	0.01		
50 mm Elongation (%)				
TYPE 3CR12	31.28	34.47	-	-
std	0.01	0.01		
TYPE 430	24.58	27.28		
std	0.03	0.02		
TYPE 304	71.65	68.15		
std	0.01	0.02		

LT Longitudinal Tension
TT Transverse Tension
TC Transverse Compression
LC Longitudinal Compression

Table 2. Average Overall Dimensions of Hat and Zed Specimens

CODES	t mm	D_s mm	B mm	C mm	D mm	D_s mm	D_s/w	w/t	Length mm
HAT 01 ZED 01	1.53	20.0 20.2	49.8 50.0	62.6 61.6	49.7 50.3	20.0 20.2	0.46	28.5	240
HAT 02 ZED 02	1.53	20.1 20.1	59.6 59.6	72.9 71.3	59.5 61.2	19.9 20.1	0.37	35.0	240
HAT 03 ZED 03	1.53	20.0 20.0	69.8 70.8	81.4 81.2	69.9 69.8	19.9 20.1	0.31	42.0	240
HAT 04 ZED 04	1.53	20.1 20.0	79.3 79.8	91.8 92.3	79.6 79.7	20.1 20.1	0.27	48.0	400
HAT 05 ZED 05	1.53	20.1 20.2	89.2 89.4	102.0 101.5	89.6 89.5	20.1 20.1	0.24	54.5	400
HAT 06 ZED 06	1.53	20.2 20.2	99.7 99.6	111.2 110.8	100.1 99.6	20.1 20.2	0.21	61.0	500
HAT 07 ZED 07	1.53	19.9 20.3	110.1 110.1	122.9 121.0	110.3 110.1	20.0 20.2	0.19	68.0	500
HAT 08 ZED 08	1.53	20.0 20.2	119.9 120.5	132.2 131.3	120.2 120.9	20.0 20.3	0.17	75.0	500
HAT 09 ZED 09	1.53	19.6 19.9	130.6 130.5	142.5 142.1	130.5 130.3	19.9 19.7	0.16	81.3	500
HAT 10 ZED 10	1.53	19.7 20.3	140.4 140.3	152.9 152.6	140.2 140.0	19.9 19.9	0.15	87.7	500
HAT 11 ZED 11	1.53	20.0 20.0	149.9 150.3	162.3 162.0	150.0 150.2	20.0 20.0	0.14	94.2	500

Symbols as shown in Figure 1

t' - thickness of web plate = 1.6 mm
r - corner radius = 2.22 mm
w/t - flat width to thickness ratio of compression flange
D_s/w - ratio of edge stiffener size to flat width of flange

Table 3: Critical Local Buckling Analysis of Stainless Steel Type 304

Code	w/t	D_s/w	A_g mm^2	F_e MPa	F_{t1} $\eta = 1$ MPa	F_{t2} $\eta=E_s/E_o$ MPa	F_{t3} $\eta=(E_t/E_o)^{0.5}$ MPa	F_{t4} $\eta=(E_t/E_0)$ MPa	F_e/F_{t1}	F_e/F_{t2}	F_e/F_{t3}	F_e/F_{t4}
H01	28.5	0.46	383.7	-	-	-	-	-	-	-	-	-
H02	35.0	0.37	445.6	-	-	-	-	-	-	-	-	-
H03	41.8	0.31	506.0	175.9	328.3	253.8	235.4	194.3	0.54	0.69	0.75	0.91
H04	48.1	0.27	569.4	190.0	317.5	223.3	206.1	175.2	0.60	0.85	0.92	1.08
H05	54.3	0.24	629.9	123.0	244.7	194.3	180.0	156.9	0.50	0.63	0.68	0.78
H06	61.2	0.21	694.0	127.4	188.9	162.7	152.4	137.0	0.67	0.78	0.84	0.93
H07	68.1	0.19	760.1	122.5	144.4	135.4	128.6	118.7	0.85	0.90	0.95	1.03
H08	74.4	0.17	816.7	97.7	120.6	114.3	110.3	103.9	0.81	0.85	0.89	0.94
H09	81.4	0.16	883.2	76.0	97.6	95.1	93.0	89.2	0.78	0.80	0.82	0.85
H10	87.7	0.15	942.8	62.9	82.5	80.9	79.9	77.6	0.76	0.78	0.79	0.81
H11	94.0	0.14	1003.9	44.5	70.3	69.7	69.0	67.5	0.63	0.64	0.65	0.66
								Mean	0.68	0.77	0.81	0.89
								Coefficient of Variation	17.1	11.8	12.1	13.7
Z01	28.7	0.46	383.2	-	-	-	-	-	-	-	-	-
Z02	35.2	0.37	447.0	-	-	-	-	-	-	-	-	-
Z03	42.3	0.31	506.4	-	-	-	-	-	-	-	-	-
Z04	48.0	0.27	570.3	-	-	-	-	-	-	-	-	-
Z05	54.5	0.24	633.4	193.3	246.2	193.4	178.6	156.2	0.79	1.00	1.08	1.24
Z06	61.1	0.21	692.5	172.3	190.0	162.8	152.5	137.3	0.91	1.06	1.13	1.25
Z07	68.1	0.19	761.4	155.6	148.4	135.4	128.6	118.7	1.05	1.15	1.21	1.31
Z08	75.5	0.17	824.0	153.3	119.5	110.9	107.3	101.5	1.28	1.38	1.43	1.51
Z09	81.5	0.16	883.7	101.6	99.3	94.8	92.5	89.0	1.02	1.07	1.10	1.14
Z10	87.9	0.15	950.5	70.7	83.2	80.6	79.5	77.4	0.85	0.88	0.89	0.91
Z11	94.5	0.14	1001.2	64.3	70.4	68.7	68.0	67.0	0.91	0.94	0.95	0.96
								Mean	0.97	1.07	1.11	1.19
								Coefficient of Variation	15.7	14.3	14.8	16.1

Table 4: Critical Local Buckling Analysis of Stainless Steel Type 430

Code	w/t	D_s/w	A_g mm^2	F_e MPa	F_{t1} $\eta = 1$ MPa	F_{t2} $\eta=E_s/E_o$ MPa	F_{t3} $\eta=(E_t/E_o)^{0.5}$ MPa	F_{t4} $\eta=(E_t/E_0)$ MPa	F_e/F_{t1}	F_e/F_{t2}	F_e/F_{t3}	F_e/F_{t4}
H01	28.5	0.46	379.8	-	-	-	-	-	-	-	-	-
H02	35.0	0.37	442.2	-	-	-	-	-	-	-	-	-
H03	41.8	0.31	502.4	246.1	366.2	262.1	291.9	238.5	0.67	0.94	0.84	1.03
H04	48.1	0.27	566.8	195.9	283.9	232.7	254.1	216.8	0.69	0.84	0.77	0.90
H05	54.4	0.24	628.0	166.8	219.7	200.9	211.3	191.9	0.76	0.83	0.79	0.87
H06	61.2	0.21	684.4	132.7	168.6	163.5	165.9	160.3	0.79	0.81	0.80	0.83
H07	68.1	0.19	756.2	127.4	131.3	130.4	131.0	129.3	0.97	0.98	0.97	0.99
H08	74.5	0.17	815.6	84.0	107.8	106.5	106.8	106.3	0.78	0.79	0.79	0.79
H09	81.2	0.16	877.2	68.8	86.4	87.6	87.9	87.7	0.80	0.78	0.78	0.78
H10	88.0	0.15	943.6	58.3	71.8	73.2	73.2	73.0	0.81	0.80	0.80	0.80
H11	94.1	0.14	1000.3	47.0	63.0	62.8	62.8	62.7	0.75	0.75	0.75	0.75
								Mean	0.78	0.84	0.81	0.86
								Coefficient of Variation	10.4	8.5	7.7	10.6
Z01	28.8	0.46	384.7	-	-	-	-	-	-	-	-	-
Z02	35.6	0.37	445.4	-	-	-	-	-	-	-	-	-
Z03	42.7	0.31	509.5	-	-	-	-	-	-	-	-	-
Z04	48.3	0.27	573.0	241.6	276.5	232.0	252.4	216.4	0.87	1.04	0.96	1.12
Z05	54.5	0.24	631.5	197.0	216.5	200.0	210.8	191.2	0.91	0.99	0.93	1.03
Z06	61.2	0.21	691.5	-	-	-	-	-	-	-	-	-
Z07	68.0	0.19	759.1	-	-	-	-	-	-	-	-	-
Z08	75.2	0.17	832.7	164.3	106.3	104.4	104.3	104.5	1.54	1.57	1.58	1.57
Z09	81.4	0.16	881.1	-	-	-	-	-	-	-	-	-
Z10	87.8	0.15	948.2	100.7	74.1	73.4	73.4	73.4	1.36	1.37	1.37	1.37
Z11	94.2	0.14	1001.2	99.9	63.3	62.7	62.7	62.5	1.58	1.59	1.59	1.60
								Mean	1.25	1.31	1.29	1.34
								Coefficient of Variation	24.3	19.6	22.5	17.3

Table 5: Critical Local Buckling Analysis of Stainless Steel Type 3CR12

Code	w/t	D_s/w	A_g mm^2	F_e MPa	F_{t1} $\eta = 1$ MPa	F_{t2} $\eta = E_s/E_o$ MPa	F_{t3} $\eta = (E_t/E_o)^{0.5}$ MPa	F_{t4} $\eta = (E_t/E_0)$ MPa	F_e/F_{t1}	F_e/F_{t2}	F_e/F_{t3}	F_e/F_{t4}
H01	28.7	0.46	384.4	-	-	-	-	-	-	-	-	-
H02	35.0	0.37	447.0	-	-	-	-	-	-	-	-	-
H03	41.6	0.31	503.8	-	-	-	-	-	-	-	-	-
H04	48.0	0.27	562.9	201.9	301.0	233.9	210.9	189.9	0.67	0.86	0.96	1.06
H05	54.2	0.24	627.3	171.4	231.6	204.9	187.8	173.1	0.74	0.84	0.91	0.99
H06	61.3	0.21	691.6	139.1	175.4	168.0	158.9	151.9	0.79	0.83	0.88	0.92
H07	67.9	0.19	753.8	131.5	138.2	136.9	133.3	129.7	0.95	0.96	0.99	1.01
H08	74.5	0.17	817.5	114.0	110.0	111.9	110.6	109.4	1.04	1.02	1.03	1.04
H09	81.7	0.16	878.8	70.7	89.9	90.5	90.5	90.1	0.79	0.78	0.78	0.78
H10	87.8	0.15	941.1	58.4	76.4	77.4	77.0	76.9	0.76	0.76	0.76	0.76
H11	94.2	0.14	1001.7	49.9	65.6	65.5	65.5	65.6	0.76	0.76	1.31	0.76
								Mean	0.81	0.85	0.95	0.92
								Coefficient of Variation	13.8	10.4	17.1	13.3
Z01	28.8	0.46	384.4	-	-	-	-	-	-	-	-	-
Z02	35.2	0.37	447.0	-	-	-	-	-	-	-	-	-
Z03	42.1	0.31	503.8	-	-	-	-	-	-	-	-	-
Z04	48.5	0.27	574.2	207.8	286.9	231.9	208.7	188.7	0.72	0.90	1.00	1.10
Z05	54.6	0.24	627.3	190.8	230.7	202.6	186.1	171.8	0.83	0.94	1.03	1.11
Z06	61.2	0.21	691.9	180.9	177.5	168.3	159.4	151.1	1.02	1.07	1.13	1.20
Z07	68.1	0.19	757.2	163.0	140.2	168.9	132.8	129.1	1.16	0.97	1.23	1.26
Z08	74.9	0.17	822.6	169.3	113.0	110.0	109.3	108.0	1.50	1.54	1.55	1.57
Z09	81.2	0.16	883.2	137.2	93.6	92.2	91.9	91.5	1.47	1.49	1.49	1.50
Z10	87.6	0.15	947.3	93.1	77.9	77.4	77.4	77.2	1.20	1.20	1.20	1.21
Z11	94.7	0.14	1000.0	85.4	64.8	64.9	65.0	64.9	1.32	1.32	1.31	1.32
								Mean	1.15	1.18	1.24	1.28
								Coefficient of Variation	21.5	18.7	14.3	12.5

Table 6: Post Buckling Analysis of Stainless Steel Type 304

Code	w/t	D_s/w	A_g mm²	P_e kN	P_{t1} $\eta = 1$ kN	P_{t2} $\eta=E_s/E_o$ kN	P_{t3} $\eta=(E_t/E_o)^{0.5}$ kN	P_{t4} $\eta=(E_t/E_0)$ kN	P_e/P_{t1}	P_e/P_{t2}	P_e/P_t	P_e/P_{t4}
H01	28.5	0.46	383.7	111.9	126.0	107.2	105.3	78.2	0.89	1.04	1.06	1.43
H02	35.0	0.37	445.6	118.0	142.1	118.6	116.5	80.9	0.83	0.99	1.01	1.46
H03	41.8	0.31	506.0	114.4	153.0	124.7	120.9	82.6	0.75	0.92	0.95	1.38
H04	48.1	0.27	569.5	125.6	164.9	128.7	124.5	84.0	0.76	0.98	1.01	1.50
H05	54.3	0.24	629.9	109.2	175.1	131.4	127.0	84.9	0.62	0.83	0.86	1.29
H06	61.2	0.21	694.0	111.8	185.5	133.3	128.7	85.4	0.60	0.84	0.87	1.31
H07	68.1	0.19	760.1	120.4	189.1	134.1	129.3	85.3	0.64	0.90	0.93	1.41
H08	74.4	0.17	816.7	128.3	192.9	135.5	130.7	85.8	0.67	0.95	0.98	1.50
H09	81.4	0.16	883.2	121.9	195.4	136.2	131.3	85.9	0.62	0.90	0.93	1.42
H10	87.7	0.15	942.8	113.3	197.7	136.9	131.9	86.0	0.57	0.83	0.86	1.32
H11	94.0	0.14	1003.9	88.0	199.8	137.7	132.5	86.2	0.44	0.64	0.66	1.02
								Mean	0.67	0.89	0.92	1.37
								Coefficient of Variation	17.9	11.7	11.2	9.4
Z01	28.7	0.46	383.2	119.6	125.6	107.1	105.2	78.3	0.95	1.12	1.14	1.53
Z02	35.2	0.37	447.0	119.7	140.9	117.6	115.7	80.7	0.85	1.02	1.03	1.48
Z03	42.3	0.31	506.4	135.5	152.2	124.3	120.5	82.5	0.89	1.09	1.12	1.64
Z04	48.0	0.27	570.3	139.9	167.6	130.1	125.9	84.6	0.83	1.07	1.11	1.65
Z05	54.5	0.24	628.6	152.1	174.9	131.4	127.0	84.9	0.87	1.16	1.20	1.79
Z06	61.1	0.21	690.7	155.3	185.0	133.2	128.6	85.3	0.84	1.17	1.21	1.82
Z07	68.1	0.19	758.6	152.0	190.0	134.6	129.9	85.6	0.80	1.13	1.17	1.78
Z08	75.5	0.17	817.9	144.3	193.0	135.6	130.7	85.8	0.75	1.06	1.10	1.68
Z09	81.5	0.16	881.4	132.0	195.8	136.5	131.5	86.0	0.67	0.97	1.00	1.53
Z10	87.9	0.15	944.3	119.0	198.2	137.3	132.2	86.2	0.60	0.87	0.90	1.38
Z11	94.5	0.14	1005.2	141.0	200.0	137.8	132.7	86.2	0.71	1.02	1.06	1.64
								Mean	0.80	1.06	1.10	1.63
								Coefficient of Variation	12.5	7.99	7.92	8.08

Table 7: Post Buckling Analysis of Stainless Steel Type 430

Code	w/t	D_s/w	A_g mm^2	P_e kN	P_{t1} $\eta = 1$ kN	P_{t2} $\eta=E_s/E_o$ kN	P_{t3} $\eta=(E_t/E_o)^{0.5}$ kN	P_{t4} $\eta=(E_t/E_0)$ kN	P_e/P_{t1}	P_e/P_{t2}	P_e/P_{t3}	P_e/P_{t4}
H01	28.5	0.46	379.8	112.1	138.0	117.5	109.8	72.3	0.81	0.95	1.02	1.55
H02	35.0	0.37	442.2	113.0	152.1	130.4	115.3	74.3	0.74	0.87	0.98	1.52
H03	41.8	0.31	503.7	130.7	163.9	135.4	118.8	75.5	0.80	0.97	1.10	1.73
H04	48.1	0.27	566.8	131.9	177.8	140.1	122.1	76.6	0.74	0.94	1.08	1.72
H05	54.4	0.24	628.0	131.8	189.5	142.8	123.9	77.2	0.70	0.92	1.06	1.71
H06	61.2	0.21	684.4	110.4	193.7	144.2	124.8	77.3	0.57	0.77	0.88	1.43
H07	68.1	0.19	756.2	133.1	198.3	146.0	125.9	77.5	0.67	0.91	1.06	1.72
H08	74.5	0.17	815.6	134.0	201.3	147.2	126.7	77.7	0.67	0.91	1.06	1.72
H09	81.2	0.16	861.1	111.9	201.0	146.6	126.2	77.3	0.56	0.76	0.89	1.45
H10	88.0	0.15	943.6	114.0	204.8	148.2	127.2	77.6	0.56	0.77	0.90	1.47
H11	94.1	0.14	1000.3	105.0	207.4	149.4	128.1	77.9	0.51	0.70	0.82	1.35
								Mean	0.67	0.86	0.99	1.58
								Coefficient of Variation	15.0	10.3	9.4	8.8
Z01	28.8	0.46	381.3	122.4	138.0	117.8	110.0	72.5	0.89	1.04	1.11	1.69
Z02	35.6	0.37	442.5	-	-	-	-	-	-	-	-	-
Z03	42.7	0.31	506.7	149.4	165.2	136.1	119.3	75.7	0.90	1.10	1.25	1.97
Z04	48.3	0.27	567.1	149.6	176.7	139.6	121.7	76.4	0.85	1.07	1.23	1.96
Z05	54.5	0.24	627.5	169.6	188.7	142.6	123.7	77.1	0.90	1.19	1.37	2.20
Z06	61.2	0.21	685.0	-	-	-	-	-	-	-	-	-
Z07	68.0	0.19	753.8	-	-	-	-	-	-	-	-	-
Z08	75.2	0.17	817.4	154.3	201.4	147.2	126.7	77.7	0.77	1.05	1.22	1.99
Z09	81.4	0.16	876.5	-	-	-	-	-	-	-	-	-
Z10	87.8	0.15	942.5	152.7	205.9	148.9	127.7	77.8	0.74	1.03	1.20	1.96
Z11	94.2	0.14	1001.2	152.5	207.7	149.6	128.2	77.9	0.73	1.02	1.19	1.96
								Mean	0.83	1.07	1.22	1.96
								Coefficient of Variation	8.5	5.1	5.9	7.0

Table 8: Post Buckling Analysis of Stainless Steel Type 3CR12

Code	w/t	D_s/w	A_g mm^2	P_e kN	P_{t1} $\eta = 1$ kN	P_{t2} $\eta=E_s/E_o$ kN	P_{t3} $\eta=(E_t/E_o)^{0.5}$ kN	P_{t4} $\eta=(E_t/E_0)$ kN	P_e/P_{t1}	P_e/P_{t2}	P_e/P_{t3}	P_e/P_{t4}
H01	28.7	0.46	384.4	108.0	120.9	103.0	97.4	64.6	0.89	1.05	1.11	1.67
H02	35.0	0.37	447.0	111.4	135.6	114.0	104.0	66.3	0.82	0.98	1.07	1.68
H03	41.6	0.31	503.8	-	-	-	-	-	-	-	-	-
H04	48.0	0.27	562.9	125.5	155.7	122.5	109.9	68.3	0.81	1.02	1.14	1.84
H05	54.2	0.24	627.3	-	-	-	-	-	-	-	-	-
H06	61.3	0.21	691.6	122.9	176.1	127.0	113.2	69.1	0.70	0.97	1.09	1.78
H07	67.9	0.19	753.8	124.9	180.0	128.2	114.0	69.2	0.69	0.97	1.10	1.81
H08	74.5	0.17	817.5	129.4	182.5	128.8	114.4	69.2	0.71	1.00	1.13	1.87
H09	81.7	0.16	878.8	117.6	185.1	129.7	114.9	69.3	0.64	0.91	1.02	1.70
H10	87.8	0.15	941.1	115.0	187.6	130.6	115.6	69.4	0.61	0.88	1.00	1.66
H11	94.2	0.14	1001.3	86.0	189.8	131.4	116.1	69.5	0.45	0.65	0.74	1.24
									0.70	0.94	1.04	1.69
								Coefficient of Variation	17.5	11.9	11.1	10.5
Z01	28.8	0.46	384.0	111.6	120.8	102.5	96.9	64.5	0.92	1.09	1.15	1.73
Z02	35.2	0.37	447.0	124.8	135.4	113.1	103.9	66.4	0.92	1.10	1.20	1.88
Z03	42.1	0.31	504.4	136.8	145.4	118.9	107.2	67.4	0.94	1.15	1.28	2.03
Z04	48.5	0.27	566.8	138.6	154.8	121.8	109.4	68.0	0.90	1.14	1.27	2.04
Z05	54.6	0.24	627.3	148.4	166.9	125.6	112.2	68.9	0.89	1.18	1.32	2.17
Z06	61.2	0.21	689.6	165.0	176.0	127.1	113.2	69.1	0.94	1.30	1.46	2.39
Z07	68.1	0.19	751.4	162.0	180.4	128.5	114,2	69.3	0.90	1.26	1.42	2.34
Z08	74.9	0.17	819.0	155.9	184.1	129.8	115.1	69.5	0.85	1.20	1.35	2.24
Z09	81.2	0.16	878.5	162.0	186.6	130.5	115.6	69.6	0.87	1.24	1.40	2.33
Z10	87.6	0.15	941.3	163.9	188.4	131.0	115.9	69.6	0.87	1.25	1.41	2.36
Z11	94.7	0.14	1000.0	143.9	189.2	131.1	115.9	69.4	0.76	1.10	1.24	2.07
								Mean	0.89	1.18	1.32	2.14
								Coefficient of Variation	5.5	5.87	7.2	9.5

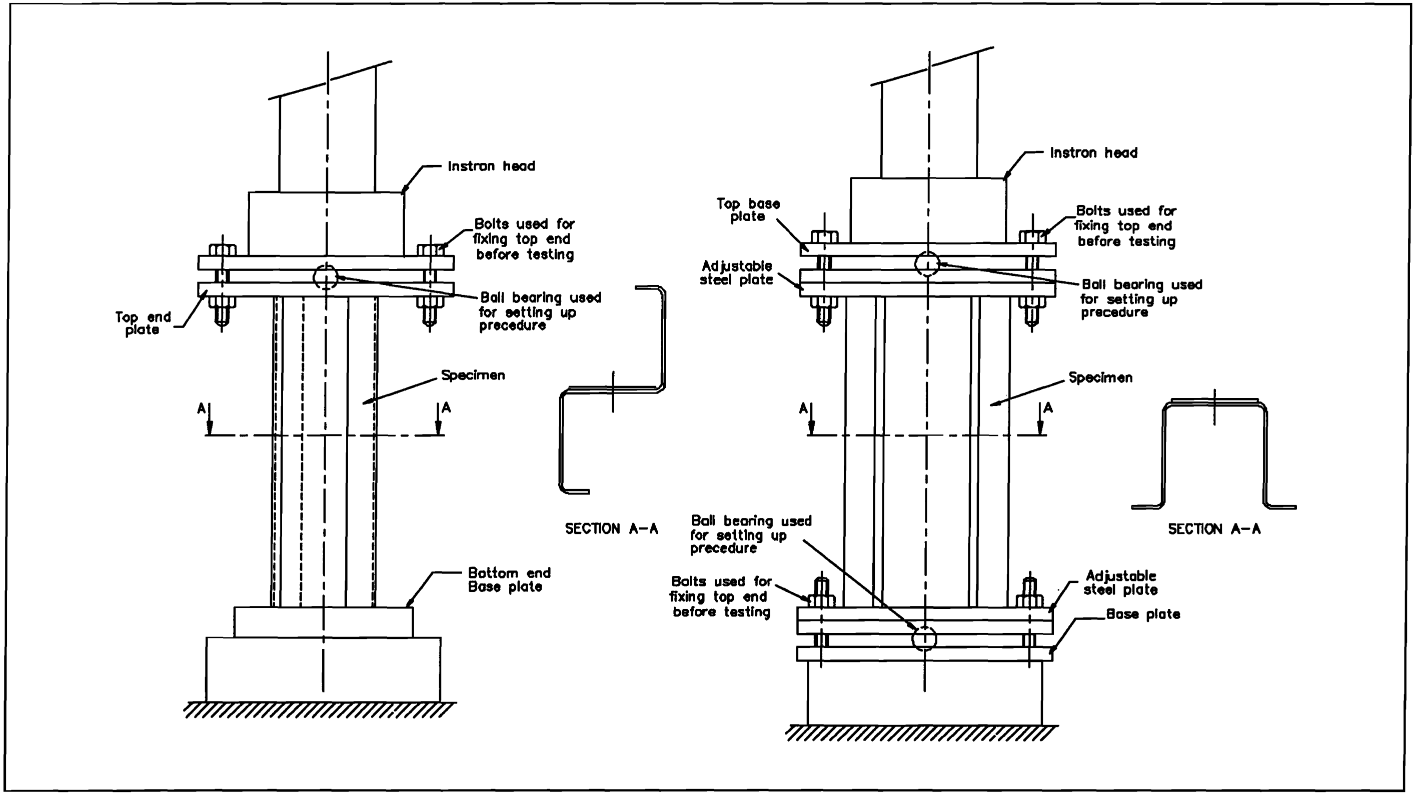

Figure 1 Experimental Setup for Hat and Zed Sections

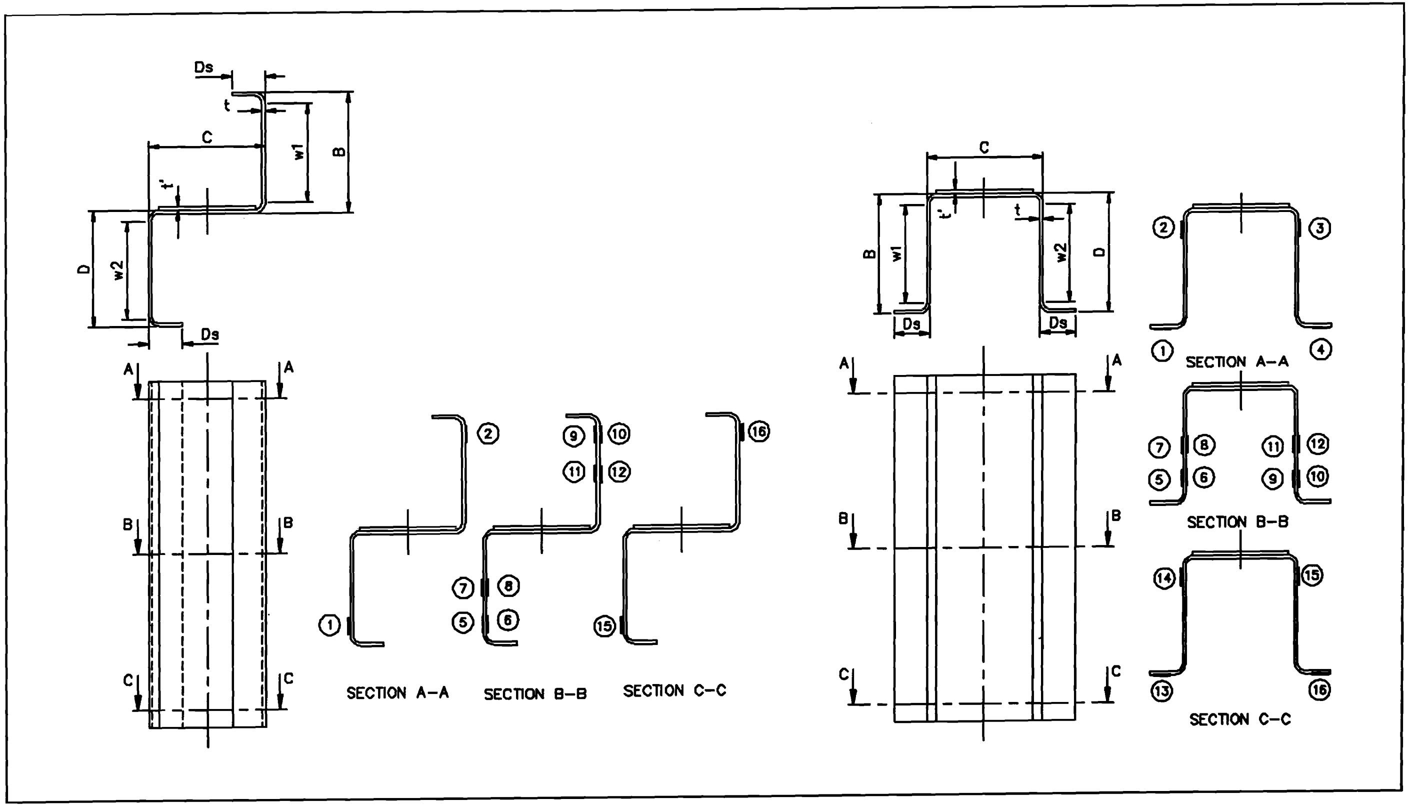

Figure 2 Layout of Strain Gauges and Dimensions of Hat and Zed Sections

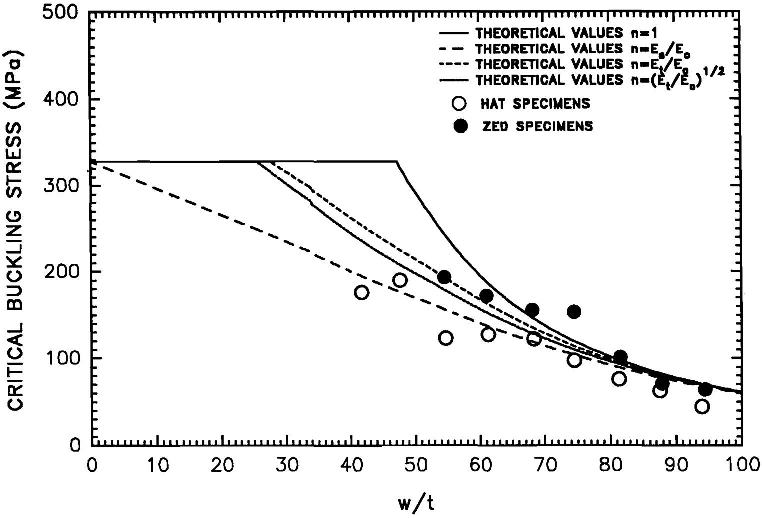

FIGURE 3 CRITICAL BUCKLING STRESS VS w/t RATIO

FOR TYPE 304 STAINLESS STEEL

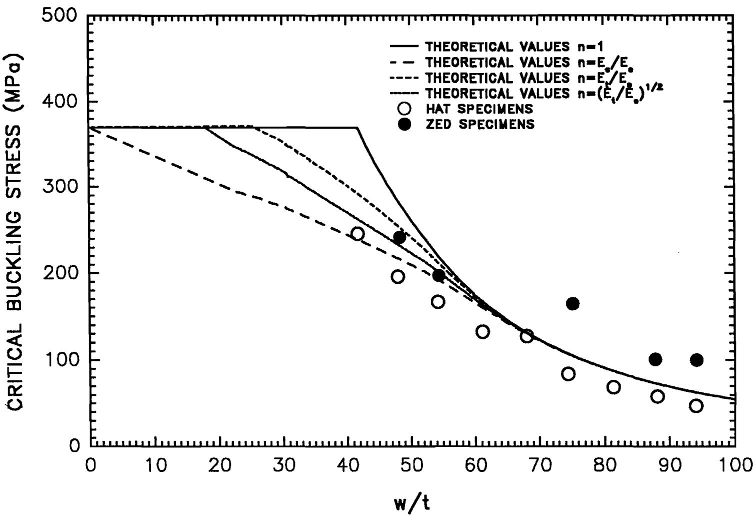

FIGURE 4 CRITICAL BUCKLING STRESS VS w/t RATIO

FOR STAINLESS STEEL TYPE 430

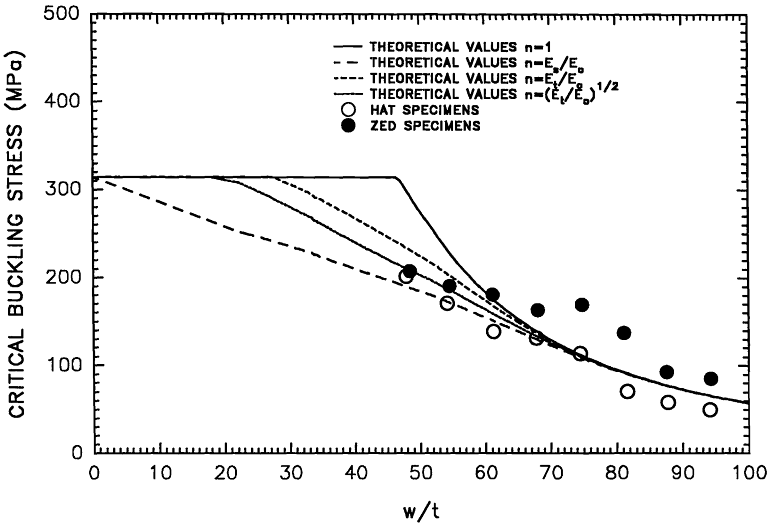

FIGURE 5 CRITICAL BUCKLING STRESS VS w/t RATIO FOR TYPE 3CR12 CORROSION RESISTING STEEL

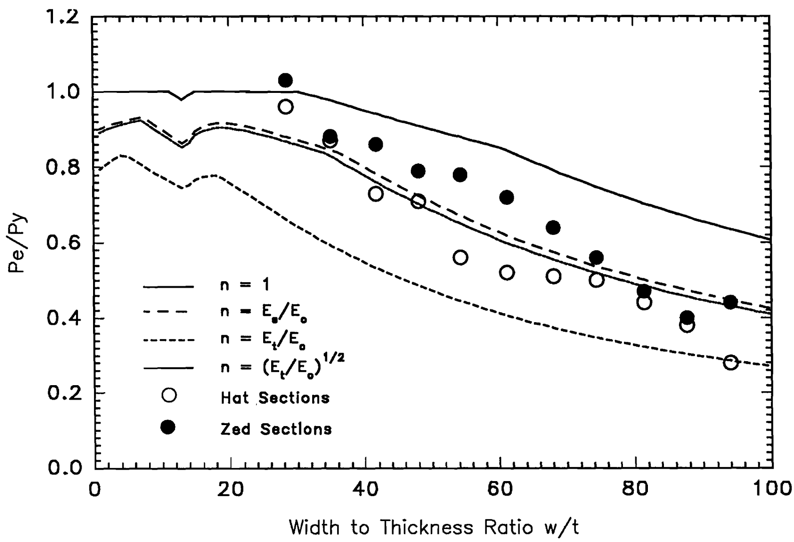

Figure 6 Ultimate Strength for Stainless Steel Type 304

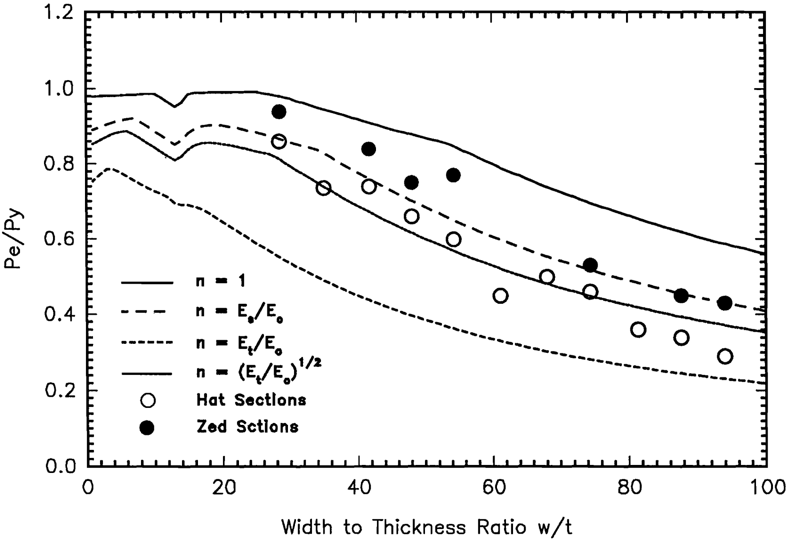

Figure 7 Ultimate Strength for Stainless Steel Type 430

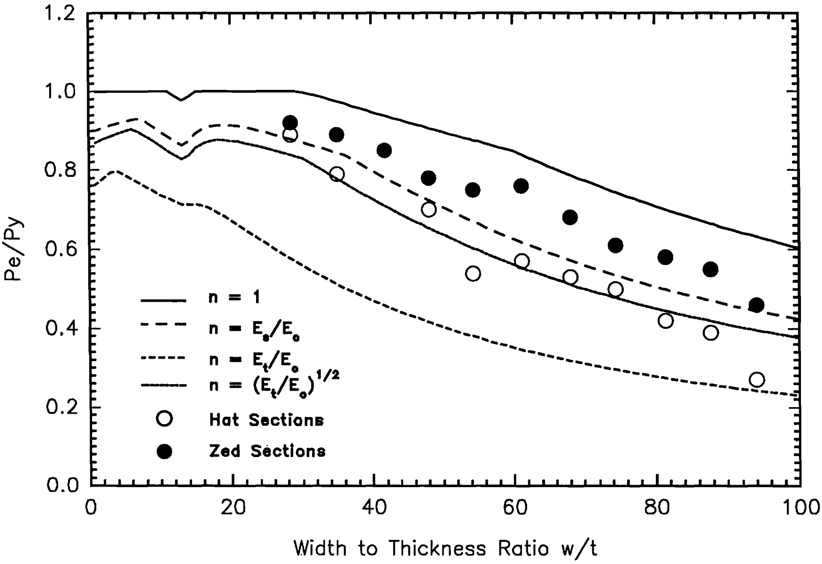

Figure 8 Ultimate Strength for Type 3CR12 Steel