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WEB CRIPPLING STRENGTH OF MEMBERS USING HIGH-STRENGTH STEELS

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ABSTRACT

A total of 148 web crippling tests were conducted using high-strength, low-ductility Structural Grade 80 of ASTM A653 steel (former ASTM A446 Grade E steel) and tests results were evaluated along with additional 114 web crippling tests which were reported in 1986 as part of a project on Design of Automotive Structural Components Using High-Strength Sheet Steels. Four loading conditions, namely End-One-Flange (EOF), Interior-One-Flange (IOF), End-Two-Flange (ETF), and Interior-Two-Flange (ITF) conditions, were considered in the web crippling tests. Test results indicate that the tested ultimate loads for the four loading conditions were higher than the predicted loads using the AISI Specifications for the yield strength of the steels exceeding 80 ksi (551.6 MPa). The ratio of the tested ultimate load to the calculated load tends to increase with increase in the yield strength of the steels beyond 80 ksi. New modified kC_1 and kC_3 factors were developed based on the 262 web crippling tests which included the following parameters: the yield strength F_y ranged from 58.2 ksi (401.3 MPa) to 165.1 ksi (1138.4 MPa), h/t ratio from 25.99 to 208.19, R/t ratio from 1.496 to 5.696, N/t ratio from 22.70 to 88.24, N/h ratio from 0.17 to 2.02, thickness of steel sheets from 0.017" to 0.088" (0.43 to 2.24 mm), and the angle between plane of web and plane of bearing surface from 59.5 to 90 degree. Reasonable agreement was found between the tested ultimate loads and the predicted loads using the new modified kC_1 and kC_3 factors.

1. INTRODUCTION

Web-crippling failure is one of the major failure modes in cold-formed steel members at concentrated load and support locations. To prevent such a failure mode, web-crippling strength and combined web-crippling and bending strength must be checked in the design of members subject to concentrated loads or reactions. In the United States, the design for web-crippling strength and combined web-crippling and bending strength of cold-formed steel members follows the AISI design criteria (AISI 1996). These design criteria are intended to be applicable for members made of steels with yield strength up to 80 ksi (551.6 MPa) and they are mainly based on test results of members with yield strength ranging from 30 ksi (206.9 MPa) to 57 ksi (393.0 MPa) (Hetrakul and Yu 1978).

Web crippling strength of cold-formed steel beams using high-strength ductile sheet steels was studied at the University of Missouri-Rolla in 1986 as a part of an overall project on ``Design of Automotive Structural Components Using High-Strength Sheet Steels (Santaputra and Yu 1986)." The research was intended to extend the use of materials having yield strengths exceeding the limitations included in the AISI design specifications at the time.

A total of 150 hat sections and 96 I-beams were tested for four basic loading conditions, namely EOF, IOF, ETF, and ITF conditions. Additional 18 tests were also performed for the transition ranges between the basic loading conditions. For all the specimens, the yield strength of the steels ranged from 58.2 (401.3 MPa) to 165.1 ksi (1138.4 MPa), h/t ratio from 31.90 to 108.70, R/t ratio from 1.496 to 5.696, N/t ratio from 22.70 to 43.50, N/h ratio from 0.395 to 0.738, and thickness of steel sheet from 0.046 to 0.088 inches (1.17 to 2.24 mm).

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It was found that the tested ultimate loads for the four basic loading conditions were usually larger than the calculated loads using the AISI Specification, especially for the yield strength larger than 80 ksi (551.6 MPa), and the ratio of the tested ultimate load to the calculated load tended to increase with the increases in the yield strength. Based on the test results, a set of new equations were developed for predicting web crippling strength of automotive structural members made of high-strength steels. These equations have completely different formats from those presently included in Section 3.4 of the AISI Specification. The parameters used for deriving the equations ranged as follows: the yield strength from 27.5 (189.6 MPa) to 165.1 ksi (1138.4 MPa), h/t ratio from 22.4 to 259.8, R/t ratio from 0.94 to 9.77, N/t ratio from 6.77 to 79.05, N/h ratio from 0.080 to 2.406, and the thickness of steel sheets from 0.0253 to 1.148 inches (0.64 to 29.16 mm).

However until recently, web-crippling strength of cold-formed steel members using the high-strength Structural Grade 80 of ASTM A653 steel (formerly ASTM A446 Grade E steel) has not been fully investigated. The steel is widely used for roof or floor decks in the United States. The unique property of the steel, as compared to the conventional steels used for cold-formed members, is that it has a high specified yield strength (F_y=80 ksi (551.6 MPa)) and a low tensile-to-yield strength ratio (F_u/F_y=1.03). The ductility of the steel is unspecified (ASTM A446) and was reported to be smaller than the ductility requirements for the conventional steels (Dhalla and Winter 1971). Due to the lack of ductility of the steel and little knowledge about structural performance of members using the steel, the current AISI Specification requires that the strength of members should be designed based on 75% of specified yield strength of the steel or 60 ksi (413.7 MPa) whichever is larger. This design practice may preclude any potential benefit of using high strength steel for higher member flexural and web-crippling strength.

3. DESIGN OF SPECIMENS FOR WEB CRIPPLING TESTS

Nineteen sections were selected for studying the web crippling strength using the Structural Grade 80 steel. Of the nineteen sections, sixteen sections had single rib or double ribs with sloped webs, while three sections had only single rib and vertical webs (90 degree angle with respect to bearing surface). The main section parameters include: web flat-depth-to-thickness ratio (h/t), inside bend radius (R), and the angle between plane of web and plane of bearing surface (θ). Two types of steel sheets, namely 22 and 26 gage sheets, were used for the specimens with the sloped webs, while only 22 gage sheet was used for the specimens with the vertical webs.

The measured dimensions of all elements and the angles of all webs are given in Table 1, and the shape of the sections is shown in Figure 1. In the table, each section is designated as: t**h**R**θ*, where "t**" represents gage number (thickness), such as t22 (22 gage); "h**" represents the flat depth of the web, such as h1 (h=1.0 inch); "R**" indicates the inside bend radius; and "θ" represents the angle of the web, such as θ60 (60 degree angle).

For all the specimens, the actual h/t ratio ranged from 25.99 to 208.19, the actual w/t ratios from 35.19 to 156.03, the actual R/t ratio from 2.16 to 5.51, the actual N/t ratio from 34.48 to 88.24, the actual N/h ratio from 0.22 to 2.02, the actual angle between the plane of web and plane of bearing surface from 59.5 to 90 degree, the actual thickness of steel sheet from 0.017 to 0.029 inches (0.43 to 0.74 mm) and the actual yield strength of the steel from 103.9 (716.4 MPa) to 112.5 ksi (775.7 MPa). The average values are listed in Table 2 for all the sections.

The material properties of the Structural Grade 80 steel were determined based on a total of seventy-six tensile coupon tests (Wu, Yu, and LaBoube 1995). The tensile coupons were made of 22, 24, 26, and 28 gage steel sheets and cut from the sheets with the orientation both parallel and perpendicular to the rolling direction of the sheets. The results of the tensile coupon tests are presented in Table 3.

4. WEB CRIPPLING TESTS

A total of 148 specimens were tested at the Engineering Research Laboratory of the University of-Missouri-Rolla. Among the 148 specimens, 39 specimens were tested in EOF loading condition; 38 specimens in IOF loading condition, 36 specimens in ETF loading condition, and 35 specimens in ITF loading condition. All tests were conducted using automatic displacement control mode of the MTS 880 Test System and a data acquisition system situated in the Laboratory. For each section, two specimens were tested. If the two tested loads differed from each other for about 10%, a third test was conducted for the same section.

Under the displacement control mode, all the specimens experienced gradual failure. The out-of-plane deformation of webs for the specimens with larger h/t ratios occurred gradually at the early stage of loading and continued to increase until failure. A sudden drop of applied load due to buckling of the web was not observed during tests. The tests indicated that the low ductility of the Structural Grade 80 steel does not affect the web crippling strength of the members made of such a steel. Specimens with sloped and vertical webs performed similarly. Detailed description of test setup, test results, and structural behavior of the specimens for different loading conditions can be found elsewhere (Wu, Yu, and LaBoube 1997).

5. EVALUATION OF TEST RESULTS

The results of the 148 web crippling tests with the EOF, IOF, ETF, and ITF loading conditions were evaluated using the AISI Specification (AISI 1986), actual and specified material properties, and the measured dimensions to determine if the higher yield strength of the steel can affect web crippling strength of the members. Also evaluated are the 114 web crippling tests that were reported by Santaputra and Yu (1986) using high-strength ductile steels. The sectional properties of the 114 specimens can be found in Santaputra and Yu (1986).

5.1 EVALUATION OF TEST RESULTS WITH EOF LOADING CONDITION

The present kC_1 and kC_3 factors in Section 3.4 of the AISI Specification prior to 1996 edition for predicting the web crippling strength of cold-formed structural members are used to consider the effect of yield strength on web crippling strength of members. They are plotted in Fig. 2 with respect to yield strength of steel. For all the specimens tested in this research program, the yield strength of the steel ranged from 103.9 (716.4 MPa) to 112.5 ksi (775.7 MPa), which will result in both kC_1 and kC_3 factors being on the descending branches of the kC_1 vs. F_y and kC_3 vs. F_y curves. Thus, a modification on the kC_1 and kC_3 factors, as used by Santaputra and Yu (1986), was employed again to predict the web crippling strength of the specimens tested in this program. The modification was to remove the descending branches of the kC_1 vs. F_y and kC_3 vs. F_y curves and replace them with horizontal lines at the peak of the curves. The peak value for kC_1 was taken as 1.691 at the yield strength of 91.5 ksi (630.9 MPa) and this value was also used for the yield strength larger than 91.5 ksi. Similarly, the peak value for kC_3 was taken as 1.34 at the yield strength of 66.5 ksi (458.5 MPa) and it was used for the yield strength larger than 66.5 ksi as well. Prior to the peak values, the present kC_1 and kC_3 factors stated in the 1996 edition of the AISI Specification are used.

The tested ultimate loads of the 39 specimens with the EOF loading condition were compared with the calculated loads using the modified kC_3 factor. The ratio of the tested ultimate load to the calculated load is plotted with respect to the yield strength, F_y, for the specimens tested in this program and additional 30 specimens reported by Santaputra and Yu as shown in Fig. 3. It is shown in the figure that the ratio of the tested ultimate load to the calculated load tends to increase with increases in the yield strength of steel, especially when the yield strength is larger than 80 ksi. It is noted that the load ratios are all larger than 1.0, ranging from 1.25 to 2.91. This indicates that using the modified kC_3 for predicting the web crippling strength of the specimens made of high-strength steels is conservative for the EOF loading condition and the predicted strengths become more conservative with increases in the yield strength.

5.2 EVALUATION OF TEST RESULTS WITH IOF LOADING CONDITION

The tested ultimate loads of the 38 specimens with the IOF loading condition were compared with the calculated loads using the modified kC_1 factor, and the tested ultimate moments of the specimens obtained in the same loading condition were compared to the calculated moments using the AISI Specification and a yield strength reduction factor obtained elsewhere (Wu, Yu, and LaBoube 1996). The ratio of the tested ultimate moment to the calculated moment is plotted with respect to the ratio of the tested ultimate load to the calculated load for the specimens tested in this program and for additional 36 specimens reported by Santaputra and Yu as shown in Fig. 4. The envelope for combined web crippling load-moment interaction as specified in Section 3.5 of the AISI Specification is also shown in Fig. 4. It is noted in the figure that most of the tested data fall outside of the envelope, indicating it is conservative to use the modified kC_1 factor for predicting the web crippling strength of the specimens made of high-strength steels in the IOF loading condition.

5.3 EVALUATION OF TEST RESULTS WITH ETF LOADING CONDITION

strength, F_y, for the 36 specimens tested in this program and 24 specimens reported by Santaputra and Yu as shown in Fig. 5. It is noted in the figure that the ratio of the tested ultimate load to the calculated load has a tendency to increase with increases in the yield strength of steel except for the yield strength of 165 ksi (1137.7 MPa). The load ratios for the specimens tested in this program tend to be higher than those reported by Santaputra and Yu. It is apparent that all the load ratios are larger than 1.0 and range from 1.22 to 2.81, indicating that using the modified kC_3 for predicting the web crippling strength of the specimens made of high-strength steels is also conservative for the ETF loading condition.

5.4 EVALUATION OF TEST RESULTS WITH ITF LOADING CONDITION

The tested ultimate loads of the 35 specimens with the EOF loading condition were compared with the calculated loads using the modified kC_1 factor. The ratio of the tested ultimate load to the calculated load is plotted with respect to the yield strength, F_y, for the 35 specimens tested in this program and for additional 24 specimens reported by Santaputra and Yu as shown in Fig. 6. The figure indicates that the ratio of the tested ultimate load to the calculated load tends to increase with increases in the yield strength of steel, especially when the yield strength is larger than 80 ksi. The load ratios range from 0.84 to 2.17. All load ratios with the yield strength larger than 80 ksi are greater than 1.0.

6. DEVELOPMENT OF MODIFIED kC$_1$ AND kC$_3$ FACTORS

The comparison between the tested ultimate web crippling loads to the calculated web crippling strength using the modified kC_1 and kC_3 factors and the AISI Specification, as discussed in Section 5, demonstrates that even with the largest kC_1 and kC_3 values that are allowed in the Specification for predicting web crippling strength, the tested ultimate loads tend to be higher than the calculated loads for most of the 262 specimens with the four basic loading conditions. Therefore, it may be necessary to develop new modified kC_1 and kC_3 factors for predicting the web crippling strength of the members made of high-strength steels.

6.1 DEVELOPMENT OF NEW MODIFIED kC$_1$ AND kC$_3$ FACTORS

It is found that the h/t ratios of the specimens included in this study does not appear to have a significant effect on the web crippling strength of the specimens for the four loading conditions. Even though these h/t ratios cover a wide range of values represented in practice, they are still within the limit specified in the AISI Specification. The parameter that significantly affect the web crippling strength of the specimens, as observed in Section 5, is the yield strength of sheet steel. The present AISI equations for web crippling strength are mainly based on tested specimens with yield strength less than 60 ksi, while the yield strength used for this study is more than 100 ksi. The effect of yield strength of a steel on the web crippling strength of structural members is reflected in the kC_1 and kC_3 factors in Section 3.4 of the AISI Specification. These factors are written as:

For the IOF and ITF loading conditions,

$$k\,C_1 = \frac{F_y}{33}\left(1.22 - 0.22\,\frac{F_y}{33}\right) \tag{1}$$

where $k=F_y/33$.

For the EOF and ETF loading condition,

$$k\,C_3 = \frac{F_y}{33}\left(1.33 - 0.33\,\frac{F_y}{33}\right) \tag{2}$$

where $k=F_y/33$.

For a better prediction of web crippling strength of the members made of both high- and low-strength steels, the kC_1 and kC_3 factors need to be modified. Two things are considered for developing the new modified kC_1 and kC_3 factors. Firstly, the new equations should be able to represent the part of the existing equations which have been valid in practice for many years. Secondly, a lower bound solution is preferred.

A new set of equations for the kC_1 and kC_3 factors were developed based on the available 262 web crippling tests that included the following parameters: the yield strength F_y ranged from 58.2 ksi (401.3 MPa) to 165.1 ksi (1138.4 MPa), h/t ratio from 25.99 to 208.19, R/t ratio from 1.496 to 5.696, N/t ratio from 22.70 to 88.24, N/h ratio from 0.17 to 2.02, thickness of steel sheets from 0.017" to 0.088 (0.43 to 2.24 mm)", and the angle between plane of web and plane of bearing surface from 59.5 to 90 degree. The modified kC_1 and kC_3 factors are expressed as follow:
For the IOF and ITF loading conditions,

$$k\,C_1 = \frac{F_y}{33}\left(1.13 - 0.13\,\frac{F_y}{33}\right) \tag{3}$$

where $k=F_y/33$ and $F_y \leq 143.4$ ksi (988.7 MPa). When F_y equals to 143.4 ksi, the kC_1 reaches a peak value of 2.46 and remains as 2.46 for the yield strength larger than 143.4 ksi.

For the EOF and ETF loading conditions,

$$k\,C_3 = \frac{F_y}{33}\left(1.20 - 0.20\,\frac{F_y}{33}\right) \tag{4}$$

where $k=F_y/33$ and $F_y \leq 99.0$ ksi (682.6 MPa). When F_y equals to 99.0 ksi, the kC_1 reaches a peak value of 1.80 and remains as 1.80 for the yield strength larger than 99.0 ksi.

The two equations have the same derivative at the yield strength of 16.5 ksi (113.8 MPa) where the present kC_1 and kC_3 equations in the AISI Specification also have the same derivative. The modified equations for the kC_1 and kC_3 factors are shown in Fig. 2 as compared to the present equations. The figure indicates that Equations 3 and 4 are almost identical to Equations 1 and 2 for the yield strength less than 40 ksi (275.8 MPa). The difference between Equations 3 and 4 and Equations 1 and 2 is also small for the yield strength between 40 and 60 ksi (413.7 MPa). This allows the new modified factors to be used for predicting web crippling strength of the members made of low-strength steels (less than 60 ksi) as the present AISI equation does.

It is noted that for the IOF and ITF loading conditions, the peak value of the new modified kC_1 factor is about 1.45 times larger than the peak value of the present kC_1 factor, while for the EOF and ETF loading conditions, the peak value of the new modified kC_3 factor is about 1.34 times larger than the peak value of the present kC_3 factor. As a result, the new modified factors lead to more economical design as compared to using the present kC_1 and kC_3 factors.

6.2 COMPARISON OF TESTED ULTIMATE LOADS WITH PREDICTED LOADS USING THE NEW MODIFIED kC_1 AND kC_3 FACTORS

To evaluate the validity of the new modified kC_1 and kC_3 factors, the tested ultimate loads for the 148 specimens tested in this program and the 114 specimens reported by Santaputra and Yu (1986) were compared to the calculated loads using the new modified factors for the four loading conditions. The ratio of the tested ultimate load to the calculated load is plotted with respect to F_y for the EOF, ETF, and ITF loading conditions as shown in Figures 7, 8, and 9, respectively. The comparison for the combined moment and web crippling load is illustrated in Fig. 10 for the IOF loading condition.

For the specimens tested in the EOF and ETF loading conditions, the ratio of the tested ultimate load to the calculated load using the new modified kC_3 factor still tends to be larger than 1.0. The load ratio ranges from 0.93 to 2.17 for the specimens with the EOF loading condition and from 0.96 to 2.09 for the specimens with the ETF loading condition. The use of the new modified kC_3 factor leads to a conservative solution, but considerable improvement has been made on predicting the web crippling strength using high-strength steels.

For the specimens tested in the IOF loading condition, a large number of tested data still fall outside of the web crippling load-moment interaction envelope, indicating a conservative solution and a reasonable agreement between the tested data and the calculated values using the new modified kC_1 factor and the yield strength reduction factor.

For the specimens tested in the ITF loading condition, the ratio of the tested ultimate load to the calculated load using the new modified kC_1 factor tends to be larger than 1.0 for the specimens tested in this program, but the ratio is relatively lower for some specimens tested by Santaputra and Yu. The load ratio ranges from 0.72 to 1.56 with an average of 1.11. Reasonable agreement between the tested ultimate loads and the calculated loads is achieved.

7. SUMMARY

Based on studies of 148 web crippling tests conducted in this program and additional 114 web crippling tests reported by Santaputra and Yu (1986) using high-strength cold-formed steels, major findings are summarized as follows:

(1) The web crippling tests conducted in this program and those reported in 1986 indicated that the tested ultimate loads for the four loading conditions were higher than the predicted loads using the AISI Specification with the modified kC_1 and kC_3 factors (1.691 for kC_1 when F_y exceeds 91.5 ksi (630.9 MPa) and 1.34 for kC_3 when F_y exceeds 66.5 ksi (458.5 MPa)) and the high yield strength of the steels (exceeding 80 ksi). The ratio of the tested ultimate load to the calculated load tends to increase with further increase in the yield strength of the steel beyond 80 ksi (551.6 MPa). Therefore, it is conservative to use the kC_1 and kC_3 factors in Section 3.4 of the AISI Specification for predicting web crippling strength of structural members with yield strength exceeding 80 ksi.

(2) New modified kC_1 and kC_3 factors were developed based on the 262 web crippling tests, which included the following parameters: the yield strength F_y ranged from 58.2 ksi (401.3 MPa) to 165.1 ksi (1138.4 MPa), h/t ratio from 25.99 to 208.19, R/t ratio from 1.496 to 5.696, N/t ratio from 22.70 to 88.24, N/h ratio from 0.17 to 2.02, thickness of steel sheets from 0.017" to 0.088" (0.43 to 2.24 mm), and the angle between plane of web and plane of bearing surface from 59.5 to 90 degree. Reasonable agreement was found between the tested ultimate loads and the predicted loads using the new modified kC_1 and kC_3 factors. The solutions tend to be conservative.

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APPENDIX

NOTATIONS

The following symbols are used in this report:

E = modulus of elasticity, 29500 ksi.
F_y = specified yield strength of sheet steel.
F_u = specified tensile strength of sheet steel.
h = flat width of web.
$k = F_y/33$
R = inside bend radius.
t = thickness of sheet steel.
w = flat width of compression flange.
θ = angle between planes of the web and bearing surface.

Table 1 Measured Dimensions of Specimens

Type of Specimen (#)	$L_{1,2}$ (in.)	$L_{2,3}$ (in.) ($\theta_{2,3}$ in degree)	$L_{3,4}$ (in.)	$L_{4,5}$ (in.) ($\theta_{4,5}$ in degree)	$L_{5,6}$ (in.)	$L_{6,7}$ (in.) ($\theta_{6,7}$ in degree)	$L_{7,8}$ (in.)	$L_{8,9}$ (in.) ($\theta_{8,9}$ in degree)	$L_{9,10}$ (in.)
t26h0.75R3/32θ60 (1)	1.060	0.910 (61,62)	1.200	0.901 (61.5,60)	2.193	0.908 (61.5,60.5)	1.184	0.912 (60.5,61)	1.075
t26h0.75R3/64θ60 (2)	1.029	0.850 (61,61.5)	1.110	0.853 (61.5,60)	2.109	0.840 (62,60.5)	1.104	0.838 (60.5,61)	1.027
t26h1.5R3/32θ60 (3)	1.065	1.670 (60,60)	2.184	1.658 (61,60)	2.201	1.651 (61,61)	2.200	1.648 (61,63)	1.076
t26h1.5R3/64θ60 (4)	1.035	1.591 (60,60)	2.110	1.581 (60,60)	2.125	1.594 (60.5,60)	2.118	1.583 (59.5,61)	1.046
t22h0.75R5/64θ60 (5)	1.089	0.929 (60,61.5)	1.195	0.934 (61.5,58.5)	2.183	0.951 (60,60)	1.188	0.935 (60,62)	1.080
t22h0.75R1/16θ60 (6)	1.064	0.851 (60,61)	1.128	0.873 (61.5,61)	2.105	0.852 (60.5,60)	1.130	0.867 (60,61)	1.054
t22h1.5R5/64θ60 (7)	1.071	1.696 (58.5,60.5)	2.204	1.673 (61,58)	2.171	1.677 (59.5,60)	2.207	1.667 (60,61)	1.094
t22h1.5R1/16θ60 (8)	1.030	1.612 (59.5,60)	2.105	1.619 (60.5,59)	2.142	1.619 (60,60)	2.128	1.613 (60,61)	1.044
t22h2R5/64θ60 (9)	1.066	2.184 (60.5,61.5)	2.192	2.165 (62.5,60)	2.165	2.183 (60,60.5)	2.204	2.156 (60,63)	1.104
t22h2R1/16θ60 (10)	1.030	2.105 (59,60)	2.120	2.094 (60.5,60)	2.172	2.117 (59.5,60)	2.117	2.102 (60,60.5)	1.055

Note: See Figure 1 for dimensions. 1 inch = 25.4 mm.

Table 1 Measured Dimensions of Specimens (Continued)

Type of Specimen (#)	$L_{1,2}$ (in.)	$L_{2,3}$ (in.) ($\theta_{2,3}$ in degree)	$L_{3,4}$ (in.)	$L_{4,5}$ (in.) ($\theta_{4,5}$ in degree)	$L_{5,6}$ (in.)	$L_{6,7}$ (in.) ($\theta_{6,7}$ in degree)	$L_{7,8}$ (in.)	$L_{8,9}$ (in.) ($\theta_{8,9}$ in degree)	$L_{9,10}$ (in.)
t22h3R5/64θ60 (11)	1.082	3.201 (59,61.5)	3.190	3.188 (60,61)	1.103				
t22h3R1/16θ60 (12)	1.050	3.100 (60,61)	3.150	3.113 (60,61)	1.047				
t22h4.5R5/64θ60 (13)	1.077	4.681 (61,62.5)	3.183	4.676 (61,62)	1.102				
t22h4.5R1/16θ60 (14)	1.040	4.619 (61,61)	3.108	4.617 (60.5,61.5)	1.057				
t22h6R5/64θ60 (15)	1.083	6.174 (63,63)	3.177	6.162 (61,64)	1.107				
t22h6R1/16θ60 (16)	1.045	6.118 (61,61)	3.126	6.088 (60,62)	1.050				
t22h1.5R1/8θ90 (17)	1.142	1.793 (90,90)	2.324	1.780 (89,90)	1.126				
t22h3R1/8θ90 (18)	1.132	3.327 (90,91)	3.282	3.302 (90,90)	1.154				
t22h4.5R1/8θ90 (19)	1.124	4.817 (89.5,91)	4.833	4.805 (90,90.5)	1.140				

Note: See Figure 1 for dimensions. 1 inch = 25.4 mm.

Table 2 Properties of the Specimens

Specimen	Thickness (in.)	F_y (ksi)	Average h/t	Average w/t	Average R/t	Average θ (degree)
t26h0.75R3/32θ60	0.017	112.5	45.72	62.44	5.51	61
t26h0.75R3/64θ60	0.017	112.5	45.29	60.69	2.76	61
t26h1.5R3/32θ60	0.017	112.5	89.78	121.27	5.51	61
t26h1.5R3/64θ60	0.017	112.5	89.02	120.01	2.76	60.1
t22h0.75R5/64θ60	0.029	103.9	28.02	36.79	2.69	60.4
t22h0.75R1/16θ60	0.029	103.9	25.99	35.24	2.16	60.6
t22h1.5R5/64θ60	0.029	103.9	53.60	71.81	2.69	59.8
t22h1.5R1/16θ60	0.029	103.9	52.07	69.34	2.16	60
t22h2R5/64θ60	0.029	103.9	70.55	71.44	2.69	61
t22h2R1/16θ60	0.029	103.9	68.93	69.42	2.16	59.9
t22h3R5/64θ60	0.029	103.9	105.86	105.70	2.69	60.4
t22h3R1/16θ60	0.029	103.9	103.44	104.94	2.16	60.5
t22h4.5R5/64θ60	0.029	103.9	156.93	105.35	2.69	61.6
t22h4.5R1/16θ60	0.029	103.9	155.53	103.46	2.16	61
t22h6R5/64θ60	0.029	103.9	208.19	105.05	2.69	62.8
t22h6R1/16θ60	0.029	103.9	206.73	104.08	2.16	61
t22h1.5R1/8θ90	0.029	103.9	50.97	69.52	4.31	90
t22h3R1/8θ90	0.029	103.9	103.67	102.55	4.31	90
t22h4.5R1/8θ90	0.029	103.9	155.28	156.03	4.31	90

Note: 1 inch = 25.4 mm. 1 ksi= 6.895 MPa.

Table 3 Material Properties of 22, 24, 26, and 28 Gage Steel Sheets

Direction	Gage	Thickness (in.)	0.2% Offset Yield Strength F_y (ksi)	Tensile Strength F_u (ksi)	Tensile-to-Yield Ratio F_u/F_y	Local Elongation in 1/2-in. Gage Length (%)	Uniform Elongation Outside Fracture (%)	Elongation in 2-in. Gage Length (%)
Parallel to Rolling Direction	22	0.029	103.9	107.7	1.04	11.98	1.29	3.67
	24	0.024	110.1	116.4	1.06	9.33	1.23	2.69
	26	0.017	112.5	115.9	1.03	9.13	0.77	2.40
	28	0.015	111.0	116.1	1.05	7.89	1.04	2.77
Perpendicular to Rolling Direction	22	0.029	119.6	121.2	1.02	7.29	0.41	1.99
	24	0.024	126.0	128.5	1.02	6.40	0.35	1.78
	26	0.017	129.7	132.6	1.02	3.78	0.43	1.32
	28	0.015	127.3	130.1	1.02	3.78	0.43	1.38

Note: All the steel sheets were made of the Structural Grade 80 of ASTM A653 Steel. 1 inch = 25.4 mm. 1 ksi = 6.895 MPa.

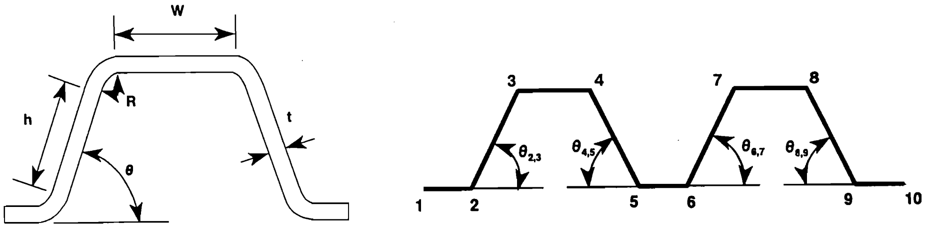

Fig. 1 Cross Section of Test Specimen

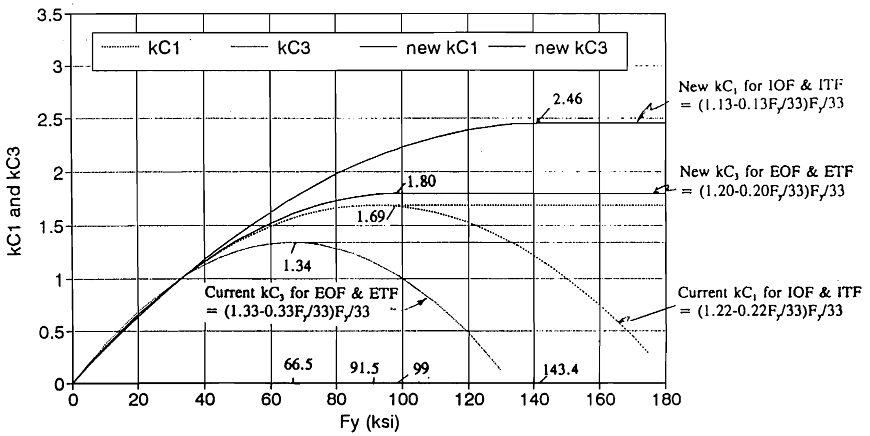

Fig. 2 kC_1 and kC_3 Factors vs. F_y

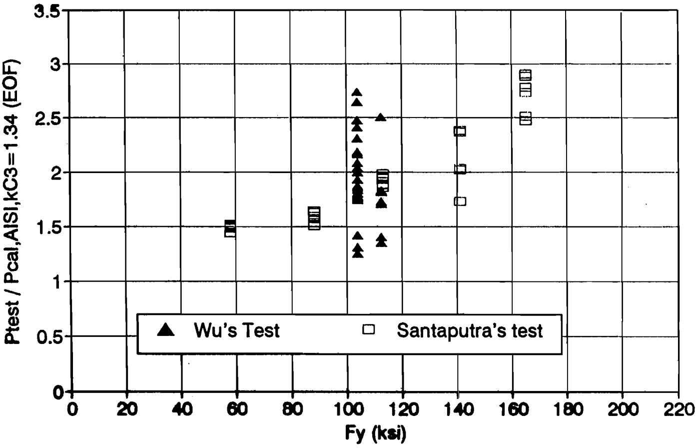

Fig. 3 Ratio of Tested Load to Calculated Load Using AISI Specification vs. F_y for EOF Condition

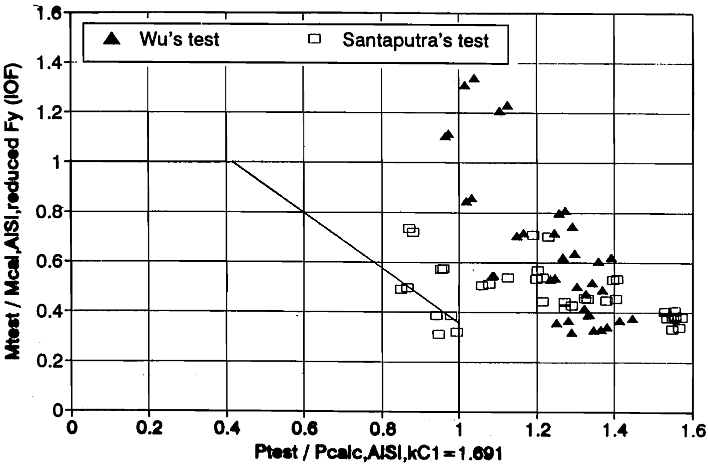

Fig. 4 Web Crippling and Moment Interaction for IOF Condition (Using Reduced F_y for Calculated Moment)

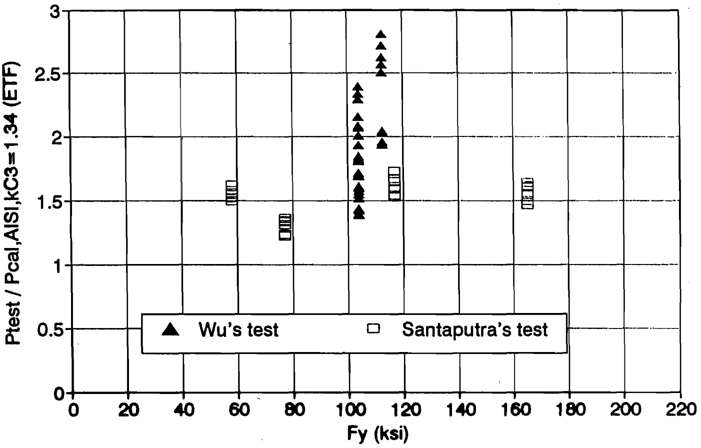

Fig. 5 Ratio of Tested Load to Calculated Load Using AISI Specification vs. F_y for ETF Condition

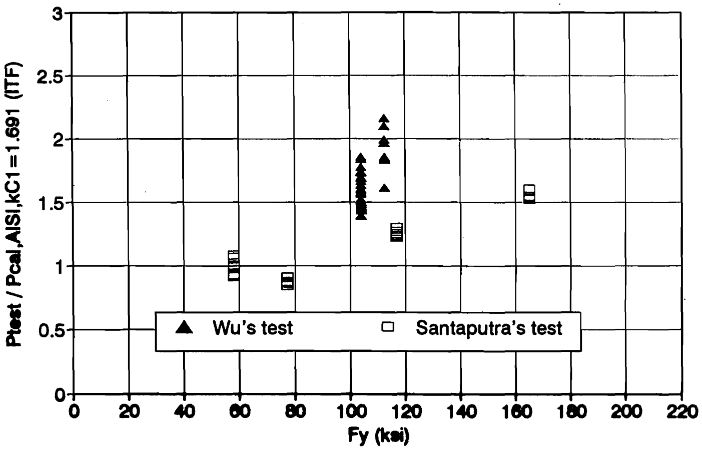

Fig. 6 Ratio of Tested Load to Calculated Load Using AISI Specification vs. F_y for ITF Condition

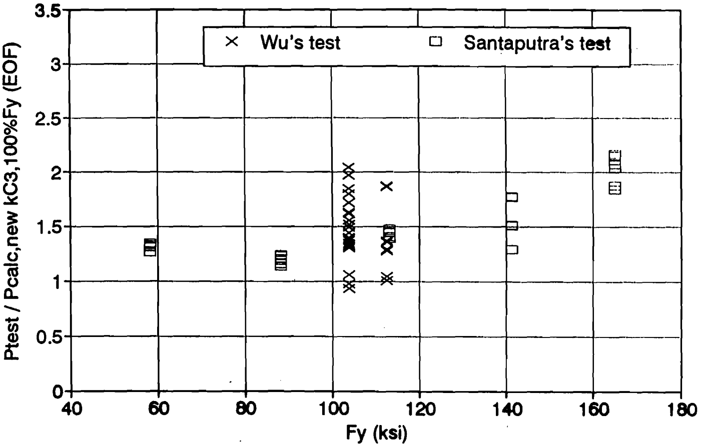

Fig. 7 Ratio of Tested Load to Calculated Load Using New kC_3 and Actual Yield Strength vs. F_y for EOF Condition

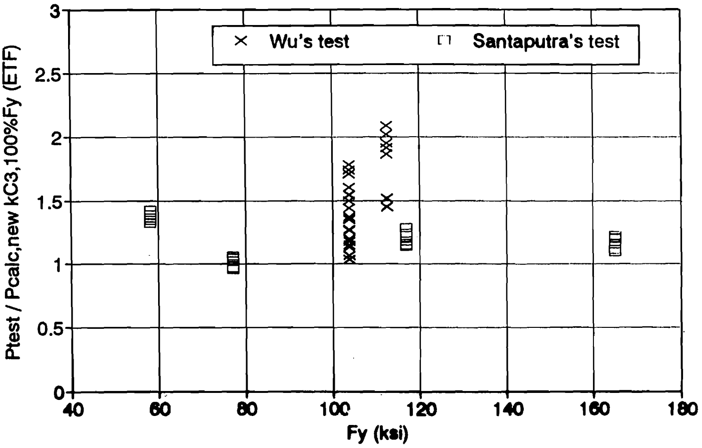

Fig. 8 Ratio of Tested Load to Calculated Load Using New kC_3 and Actual Yield Strength vs. F_y for ETF Condition

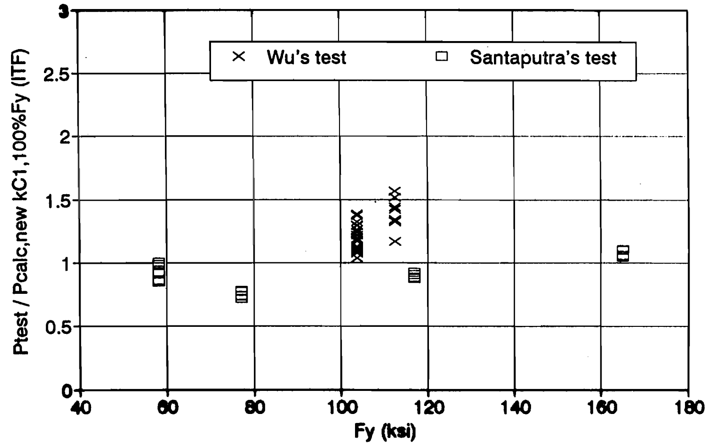

Fig. 9 **Ratio of Tested Load to Calculated Load Using New kC_1 and Actual Yield Strength vs. F_y for ITF Condition**

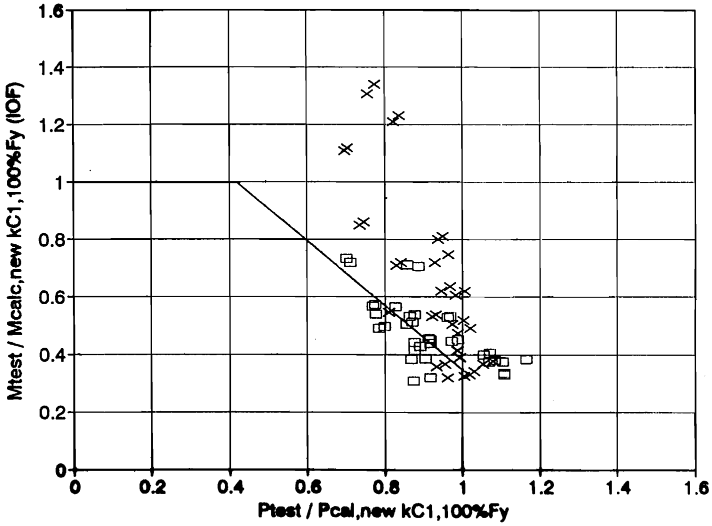

Fig. 10 **Web Crippling and Moment Interaction** for IOF Condition and Using New kC_1 and Actual Yield Strength