Updating Standard Shape Material Properties Database for Design and Reliability

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ABSTRACT

This paper summarizes the mechanical properties of ASTM A992 steel as determined by tests of 207 flat-strap tensile test specimens at the University of Minnesota and the University of Western Ontario carried out in accordance with ASTM A370. Samples were obtained from 38 heats of steel from eight different shapes provided by three producers. The objectives of the study were to quantify statistical parameters for the mechanical properties of A992 steel and to investigate the necessity of updating the resistance factor for steel in the AISC LRFD Specification (AISC, 1999). The lower tail of the yield strength data is accurately represented by the lognormal distribution reported by Dexter, Graeser, Saari, Pascoe, Gardner, and Galambos (2000). The ratio of the observed yield stress to the corresponding value reported on the Mill Test Report averaged 1.002, with a coefficient of variation of 0.044. The ratio of the flange yield strength to web yield strength averaged 0.95. The difference between the static yield strength and the yield strength recorded at ASTM A370 strain rates averaged 4.4 ksi. It is concluded that A992 steel has smaller bias coefficients and smaller coefficients of variation compared to the parameters for A36 steel used in the original calibration that have increased the reliability index slightly. At the AISC LRFD calibration point of a live-to-dead ratio of three, the reliability index for a braced compact beam with a resistance factor of 0.9 increases from 2.5 to 2.6 if the discretization factor is ignored or to 2.8 if the discretization factor is included. However, an increase of resistance factor from 0.90 to 0.95 is not recommended without further study.

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INTRODUCTION

Resistance factors, ϕ, presently used in the AISC Load and Resistance Factor Design (LRFD) Specification (AISC, 1999) are largely based on tensile test data for A36 steel collected in the 1960s and 1970s (Galambos & Ravindra, 1978). Since then, the processes used to make steel have changed, the producers of structural shapes are different, and the ASTM specifications for structural steel have evolved considerably.

Past steel production involved ingots produced from raw iron ore in basic oxygen furnaces. Most shapes currently produced for use in the United States are rolled from beam blanks, blooms, or near-net-shapes cast continuously. The steel is melted in electric-arc furnaces using recycled material. The continuous casting reduces the amount of rolling necessary to form the final shape, and so reduces the energy requirements and overall cost.

Most steel shapes are now produced to a single material grade specification, ASTM A992, which meets or exceeds the A36 and A572 Grade 50 (and CSA G40.21 Grades 300 and 350) specifications. The A992 specification tightens previous chemistry limits, sets new limits on residual elements, and includes the following minimum mechanical property requirements:

- yield strength, F_y: 50-65 ksi (345-448 MPa)
- minimum ultimate tensile strength, F_u: 65 ksi (448 MPa)
- maximum yield strength to ultimate tensile strength ratio, Y/T: 0.85
- minimum elongation at failure in 2 in. (50.8 mm): 21%

The change from A36 to A992 steel potentially affects the shape and character of the steel stress-strain curve because the minimum specified yield stress has increased by over 38 percent whereas the minimum ultimate tensile strength has increased by only 12 percent.

Table 1: Scope of Testing Program

Shape Designation		Size Group	No.	No. of Coupons Tested at			
				UWO		UM	
US	Metric			Flange	Web	Flange	Web
6x25	150x37	1	3	5	3	6	3
8x31	200x46	1	6	12	6	12	6
12x65	310x97	2	4	9	5	6	3
14x176	360x262	3	5	11(8)[a]	6	8	4
14x257	360x382	4	7	8(8)	10(4)	6(6)	4
24x76	610x113	2	3	5	3	6	3
30x99	760x147	2	5	12	7	6	3
36x150	920x223	2	5	11	6	8	4
Total			38	73	46	58	30

[a] number of half-thickness specimens shown in parentheses

The location of the test specimen used to verify the mechanical properties of wide flange shapes, specified in ASTM A6, has also changed. At the time of the original resistance factor calibration, the test coupon was obtained from the quarter-depth of the web. Since 1996, it has been obtained from the flange for W-shapes with flange widths of six inches (150 mm) or greater. This potentially impacts the resistance factor because the yield strength of the flange is typically less than that of the web, and so the strength of steel produced may be increased to meet minimum specified values.

To quantify the mechanical and chemical properties of current structural shape production, the Structural Shape Producers Council (SSPC) compiled an extensive database from approximately 25,000 mill test reports of A36, A572 Grade 50, and A992 material (Dexter et al., 2000). However, to fully incorporate these data into the resistance factor calibration process, it is necessary to determine the relationships between information reported on the mill test certificate and various properties of the steel.

Objectives of Research

The objectives of the research were as follows:

1. Determine various mechanical properties by tests of flat-strap tensile test specimens representing current A992 steel production. Specific objectives were:
   a. to determine the statistical parameters for the yield strength F_y, the ultimate tensile strength F_u, the *Y/T* ratio, the elastic modulus E, the strain at commencement of strain hardening ε_{st}, and the ultimate strain, ε_u;
   b. to quantify the correlation between the strength of steel in the flange of the shape and the strength in the web;
   c. to verify the accuracy of mechanical properties reported on mill test certificates, and to determine whether information in the SSPC database of mechanical properties must be rectified before being adopted for resistance factor calibration;
   d. to quantify the relationship between the yield strength observed at strain rates specified in ASTM A370 and the static yield strength, that defines the strength of steel in a structural member loaded at a very slow rate; and,
   e. to compute typical inter-laboratory precision statistics.
2. Using these findings, compute statistical parameters for the resistance of typical steel members.
3. Carry out reliability-based analyses to investigate the necessity of updating the ϕ factors, and recommend revised ϕ factors if necessary.

The study summarized in this paper was ongoing with a parallel investigation entitled "Review of the Resistance Factor for Steel" (Schmidt, 2000; Schmidt & Bartlett, 2002a, 2002b). Data have been shared between the two studies, and the findings of both studies have been progressively reviewed for consistency. Carrying out the work in parallel recognizes Canada and the United States are becoming a single marketplace for structural steel shapes. Further, it is intended that this collaboration will facilitate the ongoing harmonization of all North American steel design codes.

TESTING PROGRAM

Samples of A992 steel investigated in this study were provided by Trade ARBED Inc., Nucor-Yamato Steel Sales Corp., and Corus CIC Inc. As shown in Table 1, the samples represented a total of 38 heats of steel from eight different shapes. A total of 207 flange and web coupons were obtained from these shapes, and were tested at the University of Western Ontario (UWO) and the University of Minnesota (UM).

Two producers, identified hereafter as Producers A and B, sent two-foot lengths of complete shapes to the University Machine Shop at UWO. Coupons were obtained from each shape from the six locations shown in Figure 1, and were machined to the dimensions shown in Figure 2, which conform to the ASTM A370 standard (ASTM, 1997). Mill test certificates were provided by each producer that represented flange material from the same heat as each length of shape provided.

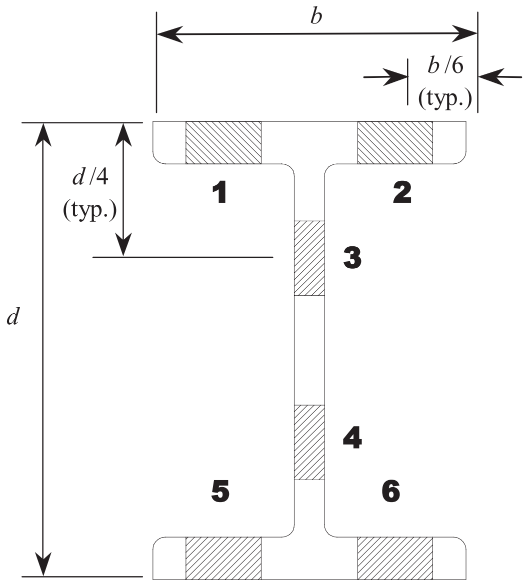
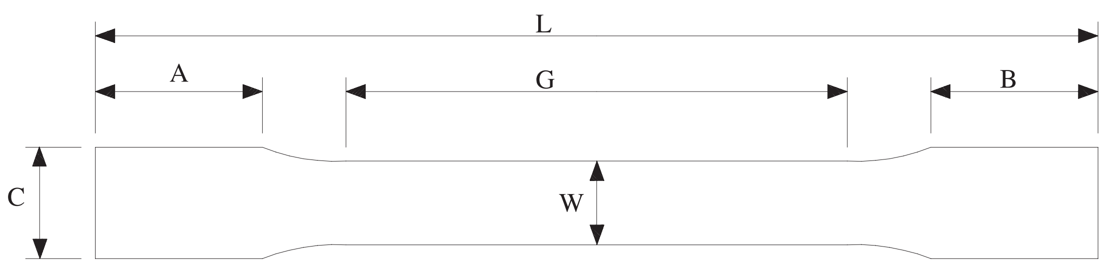


Fig. 1: Coupon locations.

The third producer, Producer C, sent web and flange coupons obtained from the locations shown in Figure 1 instead of the complete shapes. The coupons were shorter and thinner than the standard ASTM A370 sizes as shown in Figure 2. Mill test results were provided for one flange coupon from each shape, corresponding to location 6 on Figure 1.

At UM, the specimens were tested using an MTS machine with a capacity of 600 kips (2670 kN), and elongation of the reduced section was recorded using an extensometer with an 8-in. gauge length. At UWO, the specimens were tested using the Tinius Olsen Deluxe Super "L" Model 120 Universal Testing Machine, with a capacity of 120 kips (530 kN), and elongation of the reduced section were recorded using an MTS extensometer with a 2-in. gauge length. At both laboratories, load, crosshead movement, and elongation data were logged electronically. Both laboratories controlled the speed of testing as determined by the rate of crosshead separation in accordance with ASTM A370. Static yield stress readings were obtained for all coupons tested at UM in accordance with the procedure specified in SSRC Technical Memorandum #8.

The capacity of the UWO testing machine limited the maximum test specimen thickness to 1 in. (25 mm) for coupons from the material provided by Producers A and B. Some coupons from the 14-in. column shapes exceeded this limit. It was postulated that, if material strength variation is symmetric about the mid-thickness of the flange or web, milling a specimen on one side to exactly half the original



Dimension	Producer A	Producer B	Producer C
A	3 in. (75 mm)	3 in. (75 mm)	4 in. (100 mm)
B	3 in. (75 mm)	3 in. (75 mm)	3.6 in (90 mm)
C	2 in. (50 mm)	2 in (50 mm)	1.5 in. (40 mm)
G	9 in. (225 mm)	9 in. (225 mm)	3.6 in (90 mm)
L	18 in. (450 mm)	18 in. (450 mm)	12 in. (300 mm)
W	1.5 in. (40 mm)	1.5 in. (40 mm)	0.75 in. (19 mm)

Fig. 2: Coupon geometry.

Table 2: Elastic Modulus Parameters for Nominal Value of 29 000 ksi

Source	n	Bias	CoV
Current Investigation	119	0.993	0.034
Galambos & Ravindra (1978)[a]	197	1.01 to 1.02	0.010 to 0.014
Galambos (1998)[b]	341	1.036	0.045
Chernenko & Kennedy (1990)	7	1.038	0.026

[a] tension and compression coupon specimens

[b] combined results for all data presented by Galambos and Ravindra (1978)

thickness should not impact its average strength properties. Therefore half thickness coupons were fabricated for testing at UWO, and the results were compared with full thickness coupons from the same shape tested at UM. Subsequent analysis indicated no significant difference between the mechanical properties measured on full thickness specimens and those measured on half thickness specimens.

A complete summary of test results for all specimens tested at both UWO and UM is presented in Bartlett, Dexter, Graeser, Jelinek, Schmidt, and Galambos (2001).

DATA ANALYSIS

In this section, the statistical parameters for the elastic modulus, E, yield strength, F_y, ultimate tensile strength, F_u, strain at commencement of strain hardening, ε_{sh}, and strain at failure, ε_u for the tests conducted in the present investigation are presented and compared with results reported in previous investigations. The main statistical quantities investigated are the bias, the ratio of the mean value to the nominal value, and the coefficient of variation, CoV, the ratio of the standard deviation to the mean. The mechanical properties of flange and web material are presented and compared. Inter-laboratory precision statistics are also presented and compared to values published in the literature.

Elastic Modulus

The statistical parameters for elastic modulus from the 119 specimens tested at UWO are shown in Table 2. The elastic modulus for each coupon was determined by: graphing the recorded load-elongation data; identifying data in the elastic region that were not affected by any initial slip of the specimen in the testing machine grips; and, fitting a straight line to these data by least-squares regression. Scatter plots indicated no discernible trend between the elastic modulus, E, and either the specimen thickness, t, or yield strength, F_y. The final statistical parameters for E, shown in Table 2, based on a nominal value of 29,000 ksi (200 000 MPa), are a bias of 0.993 and a CoV of 0.034. As shown in the table, these parameters are similar to those obtained in previous investigations.

Yield Strength

The current edition of ASTM A370 (ASTM, 1997) permits the yield strength of steel to be determined by several different methods. It is permissible to report the upper yield point, F_{yu}, which corresponds to the drop of the beam of older testing machines, or the yield plateau stress, which can be determined using the 0.2 percent offset or 0.5 percent absolute elongation methods. The yield plateau stress, F_y, was adopted as the basis for the definition of the yield strength in the present investigation because not all steels exhibit an upper yield point. At both laboratories, F_{yu} and F_y values were recorded for all specimens tested to quantify the difference between the yield strengths as obtained by these definitions.

Yield strengths reported on mill test certificates correspond to specimens loaded at relatively high strain rates specified in ASTM A370. These must be converted to static yield strengths observed for zero strain rates, F_{ys}, that are more appropriate for design because the majority of loads on structures are essentially static. Conventionally, the static yield strength has been assumed to be four ksi (28 MPa) less than the strength observed at normal testing rates (Galambos & Ravindra, 1978; Kennedy & Gad Aly, 1980). Static yield stress readings were obtained for all coupons tested at the UM in accordance with the procedure specified in SSRC Technical Memorandum #8 (Galambos, 1998).

An initial review of the yield strength data indicated that the average strengths reported by UWO were approximately 0.4 ksi less than those reported by UM. The rate of loading at UM was approximately twice that at UWO, which accounts for approximately half of the difference. Before the overall yield strength parameters were computed, the inter-laboratory precision was computed using criteria presented in ASTM E691 (ASTM, 1992) for the 27 shapes that had two flange specimens tested by each lab. The repeatability standard deviation, a measure of the within-laboratory variability, ranged from 0.16 to 2.33 ksi (1.1 to 16.1 MPa) and averaged 0.75 ksi (5.2 MPa). The reproducibility standard deviation, a measure of the between-laboratory variability, ranged from 0.21 to 2.33 ksi (1.5 to 16.1 MPa), and averaged 1.19 ksi (8.2 MPa). The

Table 3: Flange Yield Strength Parameters for Nominal Value of 50 ksi

Source	Producer	Grade	n	$\bar{x}$ (ksi)	s (ksi)	Bias	CoV
Current Investigation	A	A992	106	54.1	2.3	1.082	0.043
	B	A992	10	61.5	2.1	1.231	0.034
	C	A992	15	56.9	1.9	1.138	0.033
	overall	A992	131	55.0	3.1	1.100	0.056
Dexter et al. (2000)	D	A992	4 942	52.0	2.2	1.04[a]	0.042
	E	A992	10 794	56.0	2.9	1.12	0.052
	F	A992	2 873	58.0	2.7	1.16	0.046
	G	A992	987	58.5	3.3	1.17[a]	0.056
	H	A992	407	52.5	1.9	1.05[a]	0.037
	overall	A992	20 295	55.8	3.2	1.116	0.058
Jaquess & Frank (1999)	I	A572	4	49.0	0.6	0.980	0.013
	J	A572	19	52.5	1.7	1.050	0.033
	K	A572	14	54.8	2.2	1.097	0.040
	L	A572	22	56.8	4.6	1.136	0.081
	overall	A572	59	54.4	3.9	1.088	0.071
Frank & Read (1993)	overall	A572	13 536	54.9[b]	4.9[b]	1.097	0.0089

[a] value shown is 0.97 x reported upper yield point value
[b] value shown is 0.95 x reported web yield strength value

within-laboratory consistency statistic, k, a measure of the relative within-laboratory variability, ranged between 0.163 and 1.413 with an average value of 0.780 for the specimens tested at UWO and between 0.064 and 1.405 with an average of 1.025 for the specimens tested at UM. These values are just less than the average values reported in ASTM E8 (ASTM, 1996) for metal specimens and so were combined to give one large data set. No adjustment was made to account for the rate of loading because the rates adopted at each laboratory conform to ASTM A370.

The statistics for the combined set of flange yield strengths are shown in Table 3. Generally there is remarkable consistency between the parameters obtained in the current investigation and those reported for A992 by Dexter et al. (2000), and for A572 Grade 50 steel by Jaquess and Frank (1999) and Frank and Read (1993). Regression analysis of flange data indicated that the differences between mean strengths for material from Producers A, B and C are statistically significant. However, as shown in the

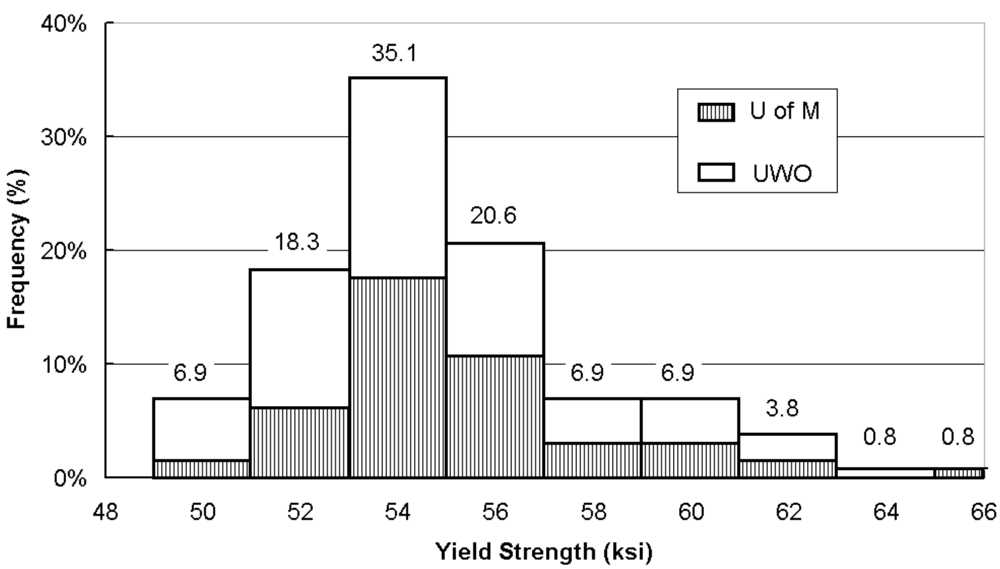


Fig. 3: Histogram of yield strength data.

Table 4: Flange Yield Strength for Various Shape Groups

ASTM Group	n	$\bar{x}$ (ksi)	s (ksi)	Bias	CoV
1	35	54.0	1.3	1.08	0.025
2	63	55.4	3.2	1.11	0.058
3	19	56.4	3.9	1.13	0.069
4	14	53.7	3.4	1.07	0.064

table, the between-producer variation noted in the current study is similar to that observed in past studies.

Table 4 shows the yield strength statistical parameters for the various ASTM Shape Groups investigated. The mean strengths for specimens from Group 2 and three shapes tended to be slightly larger than those from Group 1 and 4 shapes. However, it is difficult to make strong inferences here because the numbers of specimens from each producer in each group category were not constant, and so any difference between producers may influence any difference between ASTM group categories. Also, Schmidt (2000) documented the use of different chemical compositions for different thickness ranges of steel plate produced to a single specification: it is probable that a similar variation of chemical composition of steel produced for different shape groups may occur in practice. No trend between yield strength and coupon thickness was observed.

Figures 3 and 4 show the frequency histogram and cumulative distribution values of yield strengths, respectively, for the 131 flange coupons tested in the current investigation. Figure 4 also shows the 20,259 data points from the SSPC survey and the lognormal fit corresponding to a mean strength of 55.8 ksi and a CoV of 0.058 as reported by Dexter et al. (2000). The horizontal axis of Figure 4 is the natural logarithm of the yield strength, and the vertical axis is the Z value from the standard normal distribution, so a population with a lognormal distribution plots as a straight line on the figure. Although the yield strength values do not plot as a straight line, the values in the lower tail with $-2 \leq Z \leq -1$ are linear and close to the distribution reported by Dexter et al. (2000). The data also imply that the distribution may be truncated at F_y = 50 ksi, or $\ln(F_y)$ = 3.91, because the sample Cumulative Distribution Function (CDF) is nearly vertical at that point. Thus the distribution reported by Dexter et al. (2000) is very suitable for reliability analysis because it provides an excellent fit to much of the lower tail and, conservatively, neglects any truncation at the specified yield stress value.

The observed yield strengths of the flange coupons were on average very consistent with the values reported on the mill test certificates. For the 131 flange specimens tested, the ratio of observed yield strength to that reported on the

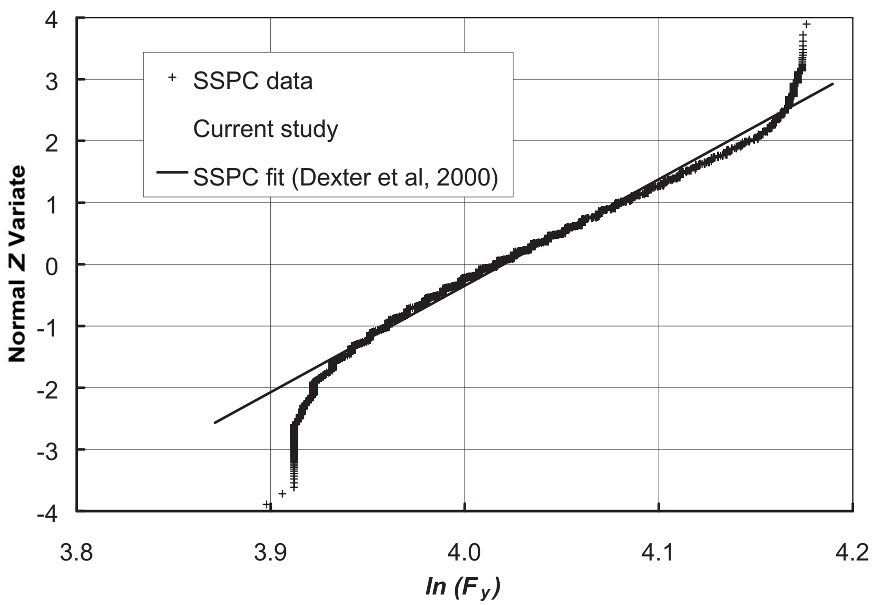


Fig. 4: CDF for yield strength data.

Table 5: Flange Ultimate Tensile Strength Parameters for Nominal Value of 65 ksi

Source	Producer	Grade	n	$\bar{x}$ (ksi)	s (ksi)	Bias	CoV
Current Investigation: UM	A, B	A992	58	72.4	3.3	1.113	0.045
Current Investigation: UWO	A, B, C	A992	73	71.0	3.8	1.092	0.054
Current Investigation (combined)	A	A992	106	70.4	2.5	1.084	0.036
	B	A992	10	80.4	2.0	1.238	0.025
	C	A992	15	73.8	1.7	1.135	0.023
	overall	A992	131	71.6	3.7	1.101	0.051
Dexter et al. (2000)	D	A992	4 942	72.8	2.5	1.12	0.035
	E	A992	10 794	72.2	2.9	1.11	0.040
	F	A992	2 873	76.7	2.3	1.18	0.030
	G	A992	987	76.7	3.6	1.18	0.047
	H	A992	407	73.5	2.4	1.13	0.032
	overall	A992	20 295	73.5	3.2	1.13	0.044
Jaquess & Frank (1999)	I		4	70.1	0.6	1.079	0.008
	J		19	71.0	2.4	1.092	0.034
	K		16	73.0	1.9	1.123	0.027
	L		22	73.3	3.5	1.128	0.047
	overall	A572	61	72.3	2.9	1.113	0.040
Frank & Read (1993)	overall	A572	13 536	75.6	6.2	1.163	0.082

mill certificate ranged from 0.91 to 1.18, with a mean value of 1.002 and a coefficient of variation of 0.044.

To investigate the correlation between the flange yield strength and the web yield strength, data were analyzed from 64 specimens where two or three flange coupons and one or two web coupons from the same shape were tested. The ratio of average flange yield strength to web yield strength ranged from 0.85 to 1.21. The difference between flange and web strength was relatively small for all shape groups except Group 2, where the ratio of flange to web yield strength was 0.90 on average. The lack of difference for most shape groups is different from what has been reported previously, and can perhaps be attributed to the web being less worked (reduced) in beam-blank rolling as in bloom-based rolling. The lack of reduction could cause a web to be less strong, offsetting the usual effect of webs gaining strength because they are thinner. On average, for all shape groups, the mean flange-to-web strength ratio had a mean of 0.953 and a CoV of 0.064. These findings are consistent with the five per cent allowance considered in past investigations (Galambos & Ravindra, 1978; Kennedy & Gad Aly, 1980). Jaquess and Frank (1999) reported 95 percent for most producers, but data from one producer with widely varying flange-to-web yield strength ratios increased the overall average to 98 percent. This producer uses the Quenched and Self-Tempered (QST) process, accounting for the difference in the flange-to-web-strength ratio.

To investigate the relationship between the upper yield point and the yield (plateau) strength, data from all 207 web and flange specimens tested at both laboratories were analyzed. The upper yield point, where it existed, was consistently greater than the yield plateau strength, ranging from 0 to 5.2 ksi (0 to 36 MPa) with a mean difference of 1.8 ksi (12.4 MPa) and a standard deviation of 1.2 ksi (8.0 MPa).

To investigate the difference between the yield strength observed at a typical testing strain rate and the static yield strength, data from 86 web and flange specimens tested at UM were analyzed. On average the static yield strength was 4.41 ksi (30.4 MPa) less than the yield strength observed at typical testing rates, with a standard deviation of 0.59 ksi (4.1 MPa). This average value is very consistent with that assumed in past calibration studies (Galambos & Ravindra 1978; Kennedy & Gad Aly, 1980). It is slightly greater than that for A572 Grade 50 steel where a difference of approximately 2.44 ksi (16.8 MPa) was reported for 101 flange and web specimens (Jaquess & Frank, 1999).

Ultimate Tensile Strength

An initial review of the ultimate tensile strength data indicated that the strengths reported by UM averaged 2.6 ksi (18 MPa) greater than those reported by UWO. Inter-laboratory precision was again computed for the 27 shapes that had two flange specimens tested by each lab. The repeatability standard deviation ranged from 0.04 to 1.30 ksi (0.3 to 10.7 MPa) and averaged 0.51 ksi (3.5 MPa). The reproducibility standard deviation ranged from 1.30 to 2.68 ksi (8.9 to 18.5 MPa) and averaged 1.19 ksi (8.2 MPa). The within-laboratory consistency statistic, k, ranged between 0.065 and 1.315 with an average value of 0.693 for the specimens tested at UWO and between 0.520 and 1.413 with an average of 1.143 for the specimens tested at UM. The repeatability is less than the average value for metal specimens reported in ASTM E8 (ASTM, 1996) but the average reproducibility exceeds the average value in ASTM E8 by a factor of approximately two. We are unable to find any rational explanation for this difference.

The data from the tests at UM and UWO are therefore presented separately and together in Table 5. Despite any difference between the UM and UWO results, there is again general consistency between the parameters obtained for the combined data sets from the current investigation and those reported for A992 by Dexter et al. (2000), and for A572 Grade 50 steel by Jaquess and Frank (1999) and Frank and Read (1993). Regression analysis indicated that the differences of the mean ultimate tensile strengths for material from Producers A, B and C are statistically significant. However, as shown in the table, the between-producer variation noted in the current study is similar to that observed in past studies.

Figures 5 and 6 show the frequency histogram and sample cumulative distribution, respectively, of ultimate tensile strengths for the specimens tested at UM and UWO. It also shows the ultimate tensile strengths of the 20,259 coupons from the SSPC survey and the lognormal fit corresponding to a mean strength of 73.3 ksi and a CoV of 0.043 as reported by Dexter et al. (2000). The data from the current study are not lognormal, although a lognormal distribution can be readily fitted to the lower four-fifths of the data, say for $Z \leq 1$. The upper fifth of the distribution deviates from lognormal, perhaps due to the effect of combining material from different producers. The distribution reported by Dexter et al. (2000) has a slope (and therefore a CoV) that is consistent with the data from the present investigation, and has ordinates that are in the order of two percent larger than suggested by the data.

The observed ultimate tensile strengths of the flange coupons were on average very consistent with the values reported on the mill test certificates. For the 131 flange specimens tested, the ratio of observed ultimate tensile strength to that reported on the mill certificate ranged from 0.91 to 1.08, with a mean value of 0.996 and a coefficient of variation of 0.030.

To investigate the correlation between the ultimate tensile strengths of the flange and the web, data were analyzed from 64 specimens where two or three flange coupons and one or two web coupons from the same shape were tested. The ratio of average flange ultimate tensile strength to web ultimate tensile strength ranged from 0.93 to 1.17, with a mean of 0.986 and a CoV of 0.037.

The ratio of the yield to ultimate tensile strength, *Y/T*, was also investigated. For the 131 flange coupons tested, the *Y/T* ratio had a mean value of 0.768, a standard deviation of 0.026, and a maximum value of 0.830. For the 76 web coupons tested, the mean *Y/T* ratio was 0.789, with a maximum of 0.862 and a standard deviation of 0.039. Six web coupons exceeded the limit of 0.85 specified for flanges in ASTM A992, but not by much.

Strains

Table 6 summarizes the strain at the commencement of strain hardening for the flange and web specimens tested at UWO and UM. The coefficients of variation are reasonably stable at about 0.3 as shown. A statistically significant relationship was noted between the strain at the onset of strain hardening and the thickness of the coupon, as shown in Figure 7. The figure also illustrates the scatter of the data, which made analysis of other trends in the data difficult.

Table 7 summarizes the ultimate strain values for all 207 specimens tested. The average ultimate strains for steel supplied by Producer B were significantly less than those for steel supplied by Producers A and C, and there was a

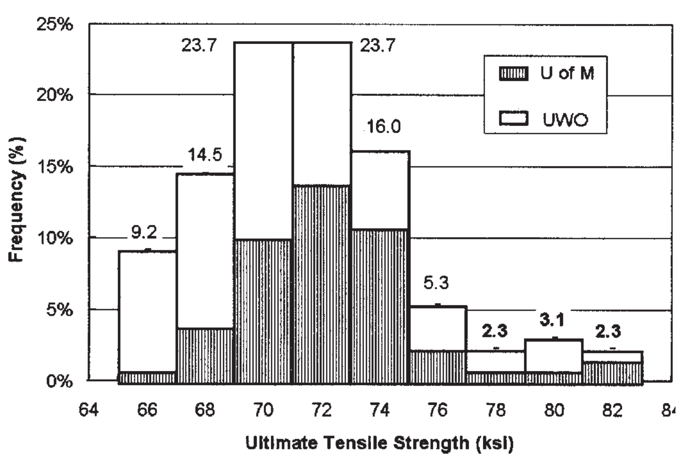


Fig. 5: Histogram of ultimate tensile strength data.

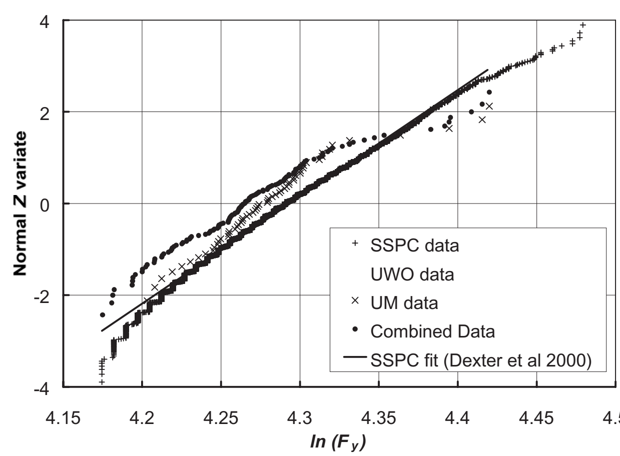


Fig. 6: CDF for ultimate tensile strength data.

Table 6: Strain at Commencement of Strain Hardening

	n	$\bar{x}$ ($\mu\varepsilon$)	s ($\mu\varepsilon$)	CoV
Flange	131	22290	6324	0.284
Web	76	24875	7352	0.296
Overall	207	23239	6817	0.293

Table 7: Ultimate Strain

	n	$\bar{x}$ ($\mu\varepsilon$)	s ($\mu\varepsilon$)	CoV
Flange	131	158745	15668	0.099
Web	76	151452	17196	0.114
Overall	207	156067	16583	0.106

slight negative correlation between the coupon thickness and the ultimate strain.

The mean value, $\bar{x}$, standard deviation, s, and the coefficient of variation of the percent elongation at failure are shown in Table 8. Due to the different specimen geometries, as shown in Figure 2, elongations were measured using a two-in. gauge length for specimens provided by Producer C or using an eight-in. gauge length for specimens provided by Producers A and B. The different measurement technique causes the strains for Producer C's specimens to appear larger than the others, because the post-ultimate elongation concentrated in the necking area is independent of the gauge length, and so larger percent elongations at failure are computed for shorter gauge lengths. There was no significant correlation between the percent elongation at failure and the coupon thickness.

PRELIMINARY RELIABILITY ANALYSIS

Commentary Section A5 of the AISC LRFD specification (AISC, 1999) states that the point at which the LRFD criteria are calibrated to the previous Allowable Stress Design (ASD) criteria is L/D = 3 for braced compact beams in flexure and tension members at yield. For the resistance factor, ϕ, equal to 0.9, the implied reliability index β at this calibration point is approximately 2.6 for members. The following equation, numbered A-C5-3 in the commentary, is used to define β:

$$\beta = \frac{\ln(R_m / Q_m)}{\sqrt{V_R{}^2 + V_Q{}^2}} \tag{1}$$

where R_m and V_R are the mean value and coefficient of variation of the resistance, respectively, and Q_m and V_Q are the mean value and coefficient of variation of the total load effect. In this section, new resistance distributions based on the material properties of steel presented in Section 3 will be derived and reliability indices corresponding to ϕ = 0.90 and 0.95 will be computed.

ASCE 7-98 (ASCE, 2000) specifies a dead load factor of 1.2 and a live load factor of 1.6 for the basic combination of dead plus live load. To assess the impact of changing the resistance factor, Equation (1) was rearranged to give the reliability index, β, for a given live-to-dead load ratio, L/D, and ϕ as follows:

$$\beta = \frac{1}{\sqrt{V_R^2 + V_Q^2}} \ln\left[\frac{R_m}{\phi R_n}\left(\frac{1.2 + 1.6 \quad (L/D)}{(D_m/D) + (L_m/L)(L/D)}\right)\right] \tag{2}$$

where D_m and L_m are the mean dead and live load effects, respectively, and R_n is the nominal resistance.

Statistical parameters for the effects of dead load and live load due to use and occupancy were obtained from the literature. The dead load effect was assigned bias D_m/D = 1.05 and V_D = 0.10 in accordance with Ellingwood, Galambos, MacGregor, and Cornell (1980). An equivalent lognormal distribution was fit to the upper tail of the Gumbel distribution for maximum office live load in a 50-year reference period reported by Ellingwood and Culver (1977), with resulting parameters L_m/L = 0.93 and V_L = 0.288. (As a check, analyses were repeated with L_m/L =1.0 and V_L = 0.25 as reported by Ellingwood et al. (1980) and similar β values were obtained).

Three sets of reliability analyses were carried out, using the resistance parameters shown in Table 9. The resistance factors used in the original calibration did not include any factor for discretization. This is conservative (e.g. Technical Memorandum #10 in Galambos, 1998), so the current calibration check has been carried out for two cases: one neglecting discretization and the other considering it.

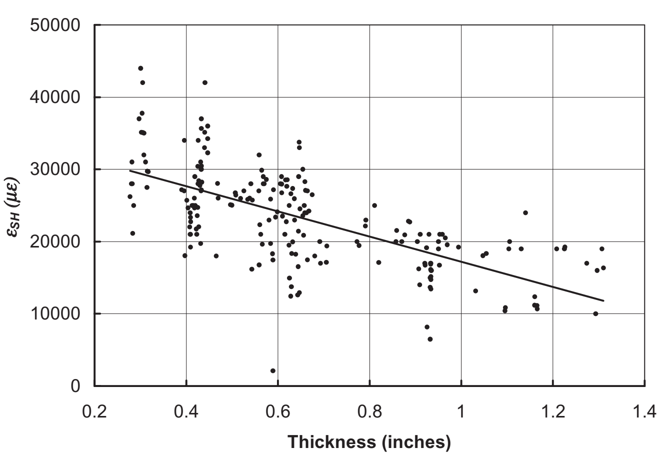


Fig. 7: Strain at onset of strain hardening versus coupon thickness.

Table 8: Elongation at Failure

		n	$\overline{x}$ (%)	s (%)	CoV
Flange	Producers A + B	57	28.9	2.7	0.092
	Producer C	15	44.3	3.0	0.067
	Combined	72	32.1	6.9	0.215
Web	Producers A + B	30	26.2	3.5	0.134
	Producer C	16	40.3	7.1	0.176
	Combined	46	31.1	8.4	0.270
Overall	Combined	118	31.7	7.5	0.236

Table 9: Resistance Parameters for Reliability Analysis

Factor	Original Calibration		Current Calibration			
			No Discretization		With Discretization	
	bias	CoV	Bias	CoV	Bias	CoV
Geometric	1.00	0.05	1.00	0.034	1.00	0.034
Material	1.05	0.10	1.028	0.058	1.028	0.058
Professional	1.02	0.06	1.02	0.06	1.02	0.06
Discretization	1.00	0.00	1.00	0.00	1.05	0.043
Total	1.07	0.127	1.049	0.090	1.101	0.100

The effect of discretization is a factor in steel design that generally improves the resistance statistics. When a designer chooses a section with factored resistance greater than or equal to the sum of the factored load effects, extra capacity is usually provided because only discrete shapes are available to resist the continuum of applied load effects. For example, the light dotted line with markers in Figure 8 shows the ratio of the factored braced compact beam bending resistance to the factored demand versus the factored demand for 174 W shapes listed in the beam selection tables of the AISC LRFD *Manual of Steel Construction* (AISC, 1993). The vertical line that defines the left side of each peak represents a transition point where the capacity of a shape becomes insufficient and the next larger shape, with excess capacity, must be selected. For the range of capacities shown, the average discretization factor is 1.027 with a coefficient of variation of 0.022. If the set of possible shapes is reduced to the 47 most efficient shapes that provide the necessary capacity and have the least weight, represented by the heavy line in Figure 8, the average discretization factor is 1.051 with a coefficient of variation of 0.043. These values represent an upper bound on the discretization effect, and so have been adopted for one of the current calibration checks, as shown in Table 9.

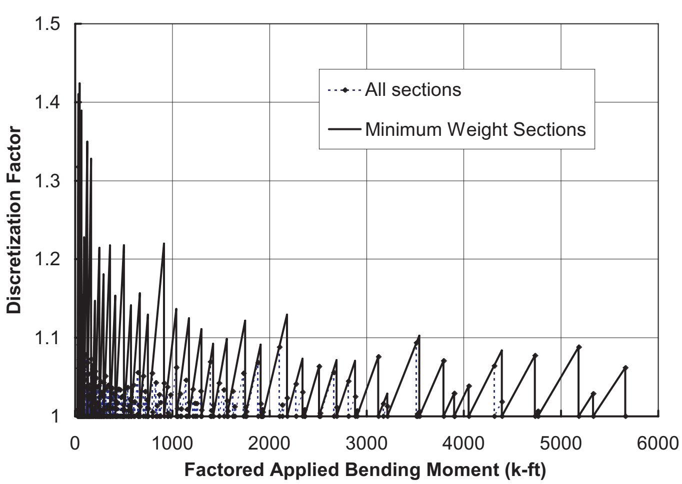


Fig. 8: Discretization factor for braced compact beams.

The resistance parameters shown in Table 9 under the heading "Original Calibration" are as presented in Appendix C of Ellingwood et al. (1980). The material factor represents the static yield strength of the flanges of rolled W-shapes (Galambos & Ravindra, 1978). The professional factor quantifies any model error in the resistance equation, and is computed from the ratio of an experimental result to the predicted value for that test as computed using the actual geometric and material properties of the specimen. The mean value of the professional factor, 1.02, seems low if significant strain hardening can occur in the flanges of a braced compact beam, and values as high as 1.10 have been adopted for calibration of other steel resistance factors (Kennedy and Gad Aly, 1980; Schmidt & Bartlett, 2002b).

The resistance parameters shown in Table 9 for the current calibration were selected recognizing that the main focus of the current study is the impact of new material properties on the resistance factor. The statistical parameters for geometric properties, in this case the plastic section modulus, *Z*, are as reported in recent studies (Schmidt & Bartlett, 2002a; Jaquess & Frank, 1999) of geometric tolerances in rolled W-shape production. The material property statistics based on the SSPC study data (Dexter et al., 2000): the mean yield strength reported for 20,295 ASTM A992 steel coupons of 55.8 ksi (Table 3) has been reduced by 4.4 ksi (Section 3.2) to give an equivalent mean static yield strength of 51.4 ksi and an associated bias coefficient of 1.028. The uncertainty of the conversion to static yield strength has been assumed negligible, so the coefficient of variation of the static yield strength equals the value reported in the SSPC study, 0.058.

The variation of the reliability index, β, with the live-to-dead load ratio, *L/D*, is shown in Figure 9. The lower boundary of the shaded areas on the figure represent the β values for the case where discretization is neglected and the upper boundary represents the case where discretization is included. The range of β values computed for $\phi = 0.95$ straddle the set of values computed using the resistance parameters adopted for the original calibration. If ϕ is maintained at 0.90, the range of β values fall above that obtained using the resistance parameters from the original calibration. At the calibration point of *L/D* = 3, the β value computed using the resistance parameters from the original calibration is 2.52. For the new resistance parameters, the corresponding β values range between 2.61 and 2.77 for $\phi = 0.9$ and between 2.37 and 2.54 for $\phi = 0.95$.

Thus the new statistical parameters for A992 steel give slightly higher reliability indices than those adopted for the original calibration, but they are insufficient by themselves to permit increasing the resistance factor from 0.90 to 0.95 unless the full beneficial effect of the discretization factor is assumed. Further studies might be carried out to review the professional factors for steel shapes and to broaden the investigation to consider other load combinations and resistance categories. At this stage it can simply be stated that A992 steel has smaller bias coefficients and smaller coefficients of variation compared to the parameters for A36 steel used in the original calibration, and the new parameters have increased the reliability index slightly.

SUMMARY AND CONCLUSIONS

This report summarizes the mechanical properties of ASTM A992 steel as determined by tests of 207 flat-strap tensile test specimens at the University of Minnesota and the University of Western Ontario carried out in accordance with ASTM A370. Samples were obtained from 38 heats of steel from eight different shapes provided by three producers. The objectives of the study were to quantify statistical parameters for the mechanical properties of A992 steel,

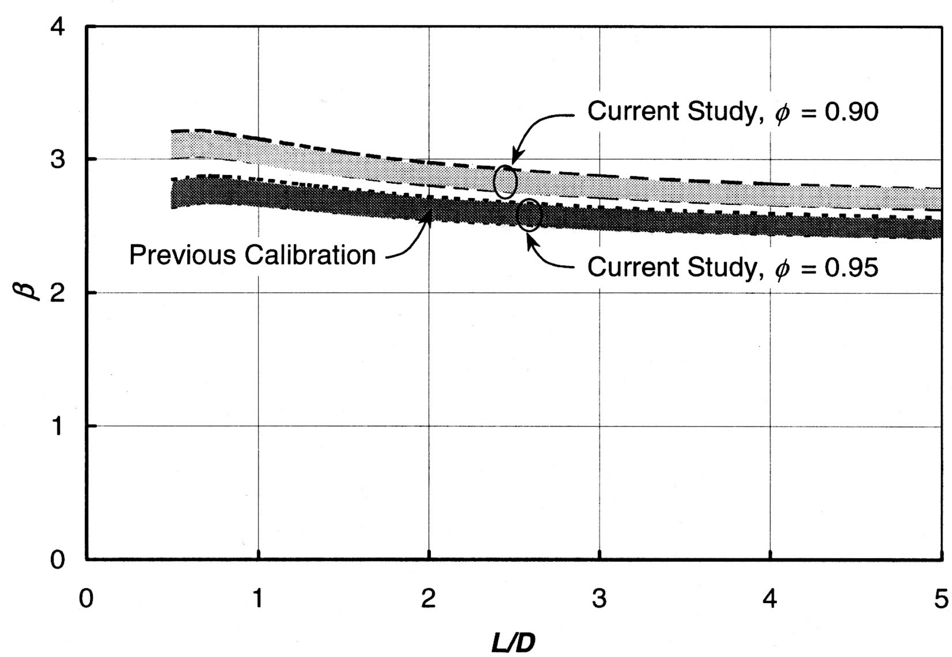


Fig. 9: Variation of ϕ with L/D, braced compact beams.

investigate the correlation of the strengths of web and flange material, verify the accuracy of information reported on mill test certificates, quantify the rate-of-loading effect on yield strength, compute inter-laboratory precision statistics, and carry out reliability-based analyses to investigate the necessity of updating the resistance factor for steel in the AISC LRFD Specification (AISC, 1999).

The conclusions of the study are as follows:

1. The elastic modulus of A992 steel with a nominal value of 29,000 ksi has a bias of 0.993 and a coefficient of variation of 0.024. These parameters are similar to those observed previously for A36 and A572 Grade 50 material.
2. The yield strength of 131 flange coupons, corresponding to rates of loading specified in ASTM A370, averaged 55.0 ksi (379 MPa) with a standard deviation of 3.1 ksi (21.4 MPa). The differences between the mean strengths of steel provided by the three producers were statistically significant. These findings are consistent with recent studies by others of A992 (Dexter et al., 2000) and A572 Grade 50 (Jaquess and Frank, 1999) steels. The lower tail of the data was particularly well represented by the lognormal distribution with a bias of 1.116 and a coefficient of variation of 0.058 reported by Dexter et al. (2000).
3. The ratio of flange yield strength to web yield strength was nearly one except for ASTM Shape Group 2, where the average value was 0.90. Overall the mean ratio was 0.953 and a coefficient of variation of 0.064. These findings are consistent with the 5 percent allowance considered in past investigations (Galambos & Ravindra, 1978; Kennedy & Gad Aly, 1980).
4. The difference between the static yield strength and the yield strength recorded at testing rates specified in ASTM A370 averaged 4.41 ksi (30.4 MPa), with a standard deviation of 0.59 ksi (4.1 MPa). This average value is very consistent with that assumed in past calibration studies (Galambos & Ravindra 1978; Kennedy & Gad Aly, 1980).
5. The ultimate tensile strength of 131 flange coupons averaged 71.6 ksi (494 MPa) with a standard deviation of 3.7 ksi (25.5 MPa). The differences between the mean ultimate tensile strengths of steel provided by the three producers are statistically significant. These findings are reasonably consistent with recent studies by others of A992 (Dexter et al., 2000) and A572 Grade 50 (Jaquess & Frank, 1999) steels.
6. The ratio of the yield to ultimate tensile strength averaged 0.768, with a standard deviation of 0.026 for the flange coupons and averaged 0.789, with a standard deviation of 0.039. Six web coupons and no flange coupons exceeded the limit of 0.85 specified for flange coupons in ASTM A992.
7. On average, values reported on mill certificates corresponded closely to the material properties determined in the investigation. The ratio of the observed yield strength to that reported on the mill certificate ranged from 0.91 to 1.18, with a mean value of 1.002 and a coefficient of variation of 0.044. The ratio of observed ultimate tensile strength to that reported on the mill certificate ranged from 0.91 to 1.08, with a mean value of 0.996 and a coefficient of variation of 0.030.
8. The resistance parameters for a braced compact A992 steel beam are a bias of 1.049 and a coefficient of variation of 0.090 if the discretization factor is neglected, or a bias of 1.101 and a coefficient of variation of 0.100 if the discretization factor is considered.
9. At the calibration point of $L/D = 3$ used to calibrate the AISC LRFD specification, the β values for a braced compact A992 beam range between 2.61 and 2.77 for $\phi = 0.9$ and between 2.37 and 2.54 for $\phi = 0.95$. The target b value computed at this calibration point using the resistance parameters from the original calibration is 2.52. Thus the new statistical parameters for A992 steel give slightly higher reliability indices than those adopted for the original calibration, but they are insufficient by themselves to permit increasing the resistance factor from 0.90 to 0.95 unless the full beneficial effect of the discretization factor is assumed.
10. A992 steel has smaller bias coefficients and smaller coefficients of variation compared to the parameters for A36 steel used in the original calibration that have increased the reliability indices slightly. However, an increase of resistance factor from 0.90 to 0.95 is not recommended without further study.

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