# Updates to Expected Yield Stress and Tensile Strength Ratios for Determination of Expected Member Capacity in the 2016 AISC *Seismic Provisions*

JUDY LIU

## ABSTRACT

The expected yield stress and expected tensile strength ratios for hollow structural sections (HSS), pipe, and steel reinforcement for steel-concrete composite construction have been updated for the 2016 AISC *Seismic Provisions for Structural Steel Buildings*. For HSS, each grade of steel, including the new ASTM A1085 specification, has its own $R_y$ and $R_t$ values. Expected yield stress and tensile strength ratios have also been defined for different grades of steel reinforcement. The revisions were based on analysis of mill test data for HSS and pipe from a number of producers and a comprehensive mill survey conducted by the Concrete Reinforcing Steel Institute (CRSI).

**Keywords:** capacity design, expected yield stress, expected tensile strength, hollow structural sections, steel reinforcement.

## INTRODUCTION

The AISC *Seismic Provisions for Structural Steel Buildings* uses a capacity design methodology for seismic force-resisting systems. For calculation of the expected capacity of a designated yielding component, the expected yield stress ratio, $R_y$, is employed, where $R_y$ is defined as the ratio of the expected yield stress to the specified minimum yield stress, $F_y$. In the 2016 AISC *Seismic Provisions*, this ratio is also used in calculations of the limiting width-to-thickness ratios for members designated as highly or moderately ductile, as well as in calculations of spacing and required strength of lateral bracing (AISC, 2016). To better estimate expected capacities associated with fracture limit states in a designated yielding member, an expected tensile strength ratio, $R_t$, was introduced in the 2005 AISC *Seismic Provisions* (Liu et al., 2007), where $R_t$ is defined as the ratio of the expected tensile strength to the specified minimum tensile strength, $F_u$.

For the 2016 AISC *Seismic Provisions*, updates were sought for expected yield stress and expected tensile strength ratios for hollow structural sections (HSS), pipe, and steel reinforcement for steel-concrete composite construction. Specifically, for HSS, there was interest in differentiating between the different grades of steel, such as ASTM A500 Grade C, which is the preferred material specification for round and rectangular HSS (Anderson et al., 2015). There was also interest in adding $R_y$ and $R_t$ values for the new ASTM A1085 specification. Further study of expected strength ratios for pipe was motivated by a potential to reduce the high ratios, which may be conservative. Mill test data for HSS and pipe were solicited and received from a number of producers. For steel reinforcement, data obtained by the Concrete Reinforcing Steel Institute (CRSI) through a comprehensive mill survey were utilized (CRSI, 2012).

Judy Liu, Professor, Oregon State University, School of Civil and Construction Engineering, Corvallis, OR, E-mail: judy.liu@oregonstate.edu

Paper No. 2016-01

## HSS AND PIPE DATA

Seven different producers provided tensile test data for rectangular HSS, round HSS, and pipe, including grades A500 Grade B, A500 Grade C, A501 Grade B, and A53 Grade B. Some data sets included material specified as A500 Grade B/C. Data for ASTM A1085 were not obtained until later in the study. Outside dimensions ranged from less than 1 in to a few samples at 120 or 250 in. Thicknesses ranged from less than 0.01 in. to 0.75 in. Data provided represented mill production from 2010–2012. A53 Grade B was the sole exception, with less than 3% of data from 2008 and less than 1% from 2013. A summary of the HSS and pipe data is provided in Table 1.

Tables 2 through 10 summarize analysis results for the different grades of rectangular and round HSS and pipe. Ratios of measured to specified minimum yield stress and tensile strengths were calculated and defined as yield ratio (YR) and tensile ratio (TR). The ratios of the measured yield stress (Y) to the measured tensile strength (T) were included, along with YR/TR. Key statistics such as the average (AVG), standard deviation (ST.DEV.), coefficient of variation (CV), maximum, and minimum were calculated. Coefficient

| Table 1. HSS and Pipe Material Specifications | | | | |
|---|---|---|---|---|
| Shape | Material Specification | Specified Minimum Yield Stress (ksi) | Specified Minimum Tensile Strength (ksi) | Data Count |
| Rectangular HSS | A500 Grade B | 46 | 58 | 31,264 |
| | A500 Grade C | 50 | 62 | 14,140 |
| | A500 Grade B/C | 46 | 58 | 3,018 |
| | A501 Grade B | 50 | 70 | 402 |
| Round HSS | A500 Grade B | 42 | 58 | 2,958 |
| | A500 Grade C | 46 | 62 | 1,149 |
| | A500 Grade B/C | 42 | 58 | 568 |
| | A501 Grade B | 50 | 70 | 196 |
| Pipe | A53 Grade B | 35 | 60 | 738 |

| Table 2. Yield and Tensile Ratios for Rectangular HSS A500 Grade B | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rect. A500 Gr. B, Count = 31264 | | | | Highly Ductile, Count = 6514 | | | | Moderately Ductile, Count = 5594 | | | |
| | YR | TR | B* (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| MAX | 2.52 | 2.04 | 60.0 | 2.17 | 1.81 | 1.27 | 1.01 | 2.28 | 1.94 | 1.27 | 1.01 |
| MIN | 1.00 | 1.00 | 0.75 | 1.01 | 1.00 | 0.72 | 0.57 | 1.00 | 1.00 | 0.77 | 0.61 |
| AVG | 1.31 | 1.26 | 6.14 | 1.36 | 1.29 | 1.06 | 0.84 | 1.32 | 1.26 | 1.06 | 0.84 |
| ST.DEV. | 0.12 | 0.09 | 3.16 | 0.13 | 0.10 | 0.08 | 0.07 | 0.12 | 0.10 | 0.09 | 0.07 |
| CV | 9% | 7% | 51% | 9% | 8% | 8% | 8% | 9% | 8% | 9% | 9% |
| *B is larger outside dimension | | | | | | | | | | | |

| Table 3. Yield and Tensile Ratios for Rectangular HSS A500 Grade C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rect. A500 Gr. C, Count = 14140 | | | | Highly Ductile, Count = 3736 | | | | Moderately Ductile, Count = 3042 | | | |
| | YR | TR | B* (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| MAX | 2.11 | 1.82 | 120 | 1.84 | 1.74 | 1.36 | 1.10 | 2.11 | 1.82 | 1.49 | 1.20 |
| MIN | 0.78 | 0.78 | 1.00 | 0.78 | 0.78 | 0.84 | 0.68 | 0.96 | 1.00 | 0.72 | 0.58 |
| AVG | 1.24 | 1.19 | 6.39 | 1.31 | 1.22 | 1.08 | 0.87 | 1.25 | 1.19 | 1.05 | 0.85 |
| ST.DEV. | 0.12 | 0.08 | 7.29 | 0.12 | 0.09 | 0.06 | 0.05 | 0.11 | 0.08 | 0.06 | 0.05 |
| CV | 9% | 7% | 114% | 9% | 7% | 5% | 5% | 9% | 7% | 5% | 5% |
| *B is larger outside dimension | | | | | | | | | | | |

of variation (CV) was calculated so that the data could be directly compared to existing material surveys. For A500 Grade B/C, the specified minimum values for yield stress and tensile strength for A500 Grade B were used in the calculations. The data in Tables 2 through 10 are separated into categories showing all samples for a given material specification and shape, as well as those shapes satisfying the limiting width-to-thickness ratios for compression elements for highly ductile and moderately ductile members. Limiting width-to-thickness ratios were calculated using Table D1.1 in the 2010 AISC *Seismic Provisions*. It should be noted that none of the rectangular HSS with very large outside dimensions (e.g., 120 or 250 in.) qualified as moderately or highly ductile. "Count" indicates number of samples, or data points, in each category (i.e., all, highly ductile, and moderately ductile samples).

Histograms were generated for ratios of measured to specified minimum yield stress and tensile strength. In general, the data exhibited normal distributions, as shown in Figures 1 and 2 for yield and tensile ratios for A500 Grade B

| Table 4. Yield and Tensile Ratios for Rectangular HSS A500 Grade B/C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rect. A500 Gr. B/C, Count = 3018 | | | | Highly Ductile, Count = 765 | | | | Moderately Ductile, Count = 764 | | | |
| | YR | TR | B* (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| MAX | 1.94 | 1.81 | 250 | 1.81 | 1.59 | 1.26 | 1.00 | 1.94 | 1.81 | 1.24 | 0.98 |
| MIN | 1.09 | 1.07 | 0.75 | 1.10 | 1.07 | 0.86 | 0.68 | 1.09 | 1.07 | 0.89 | 0.71 |
| AVG | 1.28 | 1.18 | 10.32 | 1.32 | 1.20 | 1.10 | 0.87 | 1.27 | 1.16 | 1.09 | 0.87 |
| ST.DEV. | 0.11 | 0.09 | 35.36 | 0.11 | 0.09 | 0.05 | 0.04 | 0.11 | 0.09 | 0.05 | 0.04 |
| CV | 9% | 8% | 342% | 9% | 7% | 5% | 5% | 9% | 8% | 5% | 5% |
| *B is larger outside dimension | | | | | | | | | | | |

| Table 5. Yield and Tensile Ratios for Rectangular HSS A501 Grade B | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rect. A501 Gr. B, Count = 402 | | | | Highly Ductile, Count = 152 | | | | Moderately Ductile, Count = 30 | | | |
| | YR | TR | B* (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| MAX | 1.63 | 1.24 | 7.87 | 1.49 | 1.16 | 1.28 | 0.92 | 1.30 | 1.11 | 1.17 | 0.84 |
| MIN | 1.03 | 1.02 | 3.54 | 1.03 | 1.02 | 0.98 | 0.70 | 1.05 | 1.02 | 1.00 | 0.71 |
| AVG | 1.18 | 1.09 | 5.36 | 1.16 | 1.08 | 1.07 | 0.77 | 1.15 | 1.07 | 1.07 | 0.76 |
| ST.DEV. | 0.10 | 0.04 | 1.35 | 0.10 | 0.04 | 0.06 | 0.04 | 0.09 | 0.03 | 0.06 | 0.04 |
| CV | 9% | 4% | 25% | 9% | 4% | 6% | 6% | 8% | 3% | 6% | 6% |
| *B is larger outside dimension | | | | | | | | | | | |

| Table 6. Yield and Tensile Ratios for Round HSS A500 Grade B | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Round A500 Gr. B, Count = 2958 | | | | Highly Ductile, Count = 2736 | | | | Moderately Ductile, Count = 143 | | | |
| | YR | TR | D (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| MAX | 3.09 | 2.43 | 12.75 | 2.03 | 1.53 | 1.41 | 1.02 | 1.69 | 1.45 | 1.33 | 0.96 |
| MIN | 0.86 | 0.91 | 0.84 | 0.86 | 0.91 | 0.82 | 0.59 | 1.07 | 1.00 | 0.93 | 0.67 |
| AVG | 1.44 | 1.19 | 3.72 | 1.45 | 1.18 | 1.23 | 0.89 | 1.37 | 1.24 | 1.10 | 0.80 |
| ST.DEV. | 0.15 | 0.11 | 2.99 | 0.15 | 0.11 | 0.09 | 0.07 | 0.13 | 0.08 | 0.07 | 0.05 |
| CV | 11% | 9% | 0.81 | 10% | 9% | 8% | 8% | 9% | 7% | 6% | 6% |

| Table 7. Yield and Tensile Ratios for Round HSS A500 Grade C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Round A500 Gr. C, Count = 1149 | | | | Highly Ductile, Count = 1070 | | | | Moderately Ductile, Count = 7 | | | |
| | YR | TR | D (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| MAX | 1.95 | 1.66 | 4.00 | 1.95 | 1.66 | 1.34 | 1.00 | 1.43 | 1.19 | 1.26 | 0.93 |
| MIN | 0.87 | 0.73 | 1.00 | 0.87 | 0.73 | 0.82 | 0.61 | 1.12 | 1.11 | 1.01 | 0.75 |
| AVG | 1.33 | 1.17 | 2.00 | 1.33 | 1.17 | 1.14 | 0.85 | 1.25 | 1.15 | 1.08 | 0.80 |
| ST.DEV. | 0.14 | 0.09 | 0.82 | 0.14 | 0.09 | 0.10 | 0.07 | 0.10 | 0.03 | 0.08 | 0.06 |
| CV | 11% | 8% | 0.41 | 10% | 8% | 9% | 9% | 8% | 2% | 8% | 8% |

| Table 8. Yield and Tensile Ratios for Round HSS A500 Grade B/C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Round A500 Gr. B/C, Count = 568 | | | | Highly Ductile, Count = 546 | | | | Moderately Ductile, Count = 8 | | | |
| | YR | TR | D (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| **MAX** | 1.96 | 1.53 | 6.63 | 1.96 | 1.53 | 1.36 | 0.99 | 1.42 | 1.17 | 1.22 | 0.88 |
| **MIN** | 1.07 | 1.06 | 0.84 | 1.07 | 1.06 | 0.89 | 0.65 | 1.19 | 1.08 | 1.08 | 0.78 |
| **AVG** | 1.37 | 1.14 | 4.45 | 1.37 | 1.14 | 1.20 | 0.87 | 1.30 | 1.12 | 1.17 | 0.85 |
| **ST.DEV.** | 0.11 | 0.07 | 1.48 | 0.10 | 0.07 | 0.07 | 0.05 | 0.07 | 0.03 | 0.05 | 0.04 |
| **CV** | 8% | 6% | 33% | 8% | 6% | 6% | 6% | 6% | 3% | 4% | 4% |

| Table 9. Yield and Tensile Ratios for Round HSS A501 Grade B | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Round A501 Gr. B, Count = 196 | | | | Highly Ductile, Count = 106 | | | | Moderately Ductile, Count = 40 | | | |
| | YR | TR | D (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| **MAX** | 1.43 | 1.19 | 7.63 | 1.37 | 1.19 | 1.19 | 0.85 | 1.43 | 1.19 | 1.22 | 0.87 |
| **MIN** | 1.03 | 0.99 | 3.50 | 1.03 | 0.99 | 0.99 | 0.71 | 1.05 | 1.02 | 0.99 | 0.71 |
| **AVG** | 1.16 | 1.09 | 5.85 | 1.16 | 1.09 | 1.06 | 0.76 | 1.22 | 1.11 | 1.09 | 0.78 |
| **ST.DEV.** | 0.09 | 0.04 | 1.44 | 0.09 | 0.04 | 0.05 | 0.04 | 0.10 | 0.04 | 0.06 | 0.04 |
| **CV** | 8% | 4% | 25% | 8% | 4% | 5% | 5% | 8% | 4% | 5% | 5% |

| Table 10. Yield and Tensile Ratios for Pipe A53 Grade B | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pipe A53 Gr. B, Count = 738 | | | | Highly Ductile, Count = 728 | | | | Moderately Ductile, Count = 10 | | | |
| | YR | TR | D (in.) | YR | TR | YR/TR | Y/T | YR | TR | YR/TR | Y/T |
| **MAX** | 2.06 | 1.30 | 6.63 | 2.06 | 1.30 | 1.69 | 0.99 | 1.86 | 1.14 | 1.68 | 0.98 |
| **MIN** | 1.26 | 0.97 | 1.66 | 1.34 | 0.97 | 1.30 | 0.76 | 1.26 | 0.97 | 1.26 | 0.74 |
| **AVG** | 1.60 | 1.04 | 4.06 | 1.60 | 1.04 | 1.53 | 0.89 | 1.57 | 1.04 | 1.51 | 0.88 |
| **ST.DEV.** | 0.13 | 0.05 | 1.67 | 0.13 | 0.05 | 0.08 | 0.05 | 0.20 | 0.05 | 0.15 | 0.09 |
| **CV** | 8% | 5% | 41% | 8% | 5% | 5% | 5% | 13% | 4% | 10% | 10% |

rectangular HSS. Histograms for all shapes, including some subcategories of highly ductile or moderately ductile shapes, were reported in Liu (2013).

The data were investigated for any dependency on geometric properties. Plots of ratios of measured to specified minimum yield stress versus width-to-thickness, $b/t$, and measured to specified minimum tensile strength versus $b/t$, are shown in Figures 3, 4 and 5 for A500 Grade B rectangular HSS. Figure 5 shows the measured to specified minimum yield stress for a smaller range of $b/t$. There does not appear to be a strong trend, or difference, in yield or tensile ratios for $b/t$ values above or below the moderately and highly ductile limits. Figure 6 shows some dependency on the ratio of measured to specified minimum yield stress to the larger outside dimension for very small HSS. However, the difference did not appear to be significant enough to warrant discounting small HSS in the analysis. As shown in Table 2, the average yield ratio for highly ductile shapes is 1.36 compared with 1.32 for moderately ductile shapes. Similar plots were generated, and similar observations made, for other shapes and material specifications (Liu, 2013).

The 2010 AISC *Seismic Provisions* used $R_y$ and $R_t$ of 1.4 and 1.3 for HSS and 1.6 and 1.2, respectively, for pipe, as shown in Figure 7. These 2010 $R_y$ and $R_t$ values align well with the average YR and TR values for rectangular HSS A500 Grade B (Table 2) and, in particular, for highly ductile HSS. The values compare reasonably well for YR and TR for round HSS A500 Grade B (Table 6). The values may be slightly conservative for some A500 Grade C (Tables 3 and 7). The data in Tables 4 and 8 also suggest that the 2010 $R_y$ and $R_t$ values are appropriate for cases in which Grade B is specified, but a Grade B/C is provided. Meanwhile, the data in Tables 5 and 9 suggest that even lower values could be used for A501 Grade B, but there are relatively fewer data

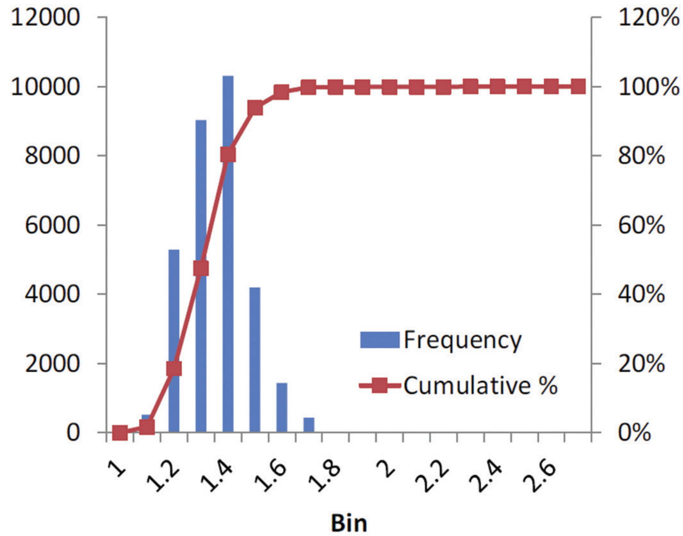


*Fig. 1. Histogram for ratios of measured to specified minimum yield stress, rectangular HSS A500 Grade B.*

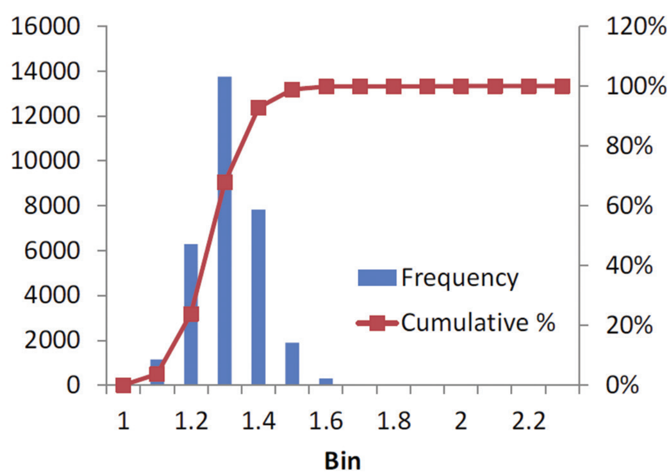


*Fig. 2. Histogram for ratios of measured to specified minimum tensile strength, rectangular HSS A500 Grade B.*

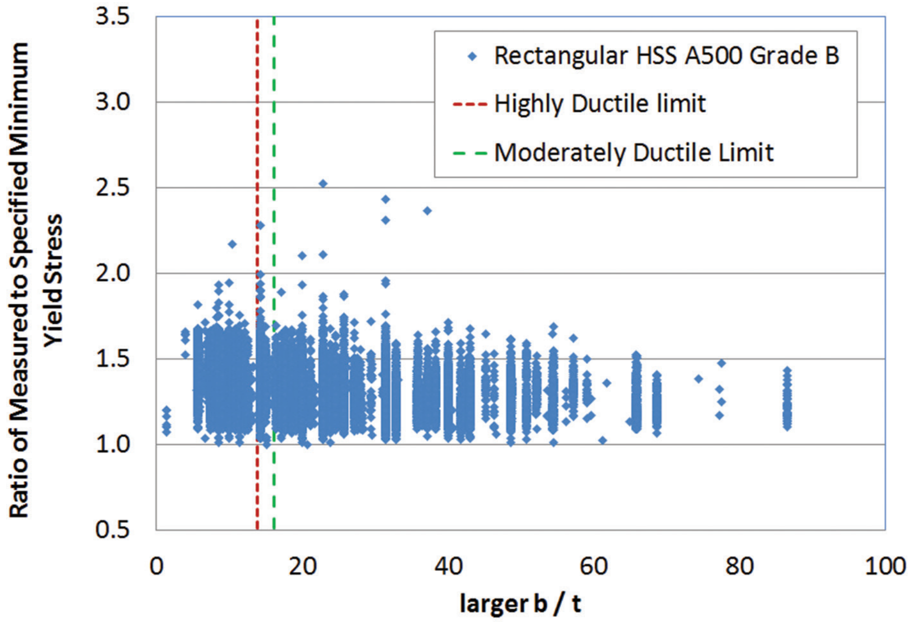


*Fig. 3. Ratio of measured to specified minimum yield stress versus larger* b/t *for rectangular HSS A500 Grade B.*

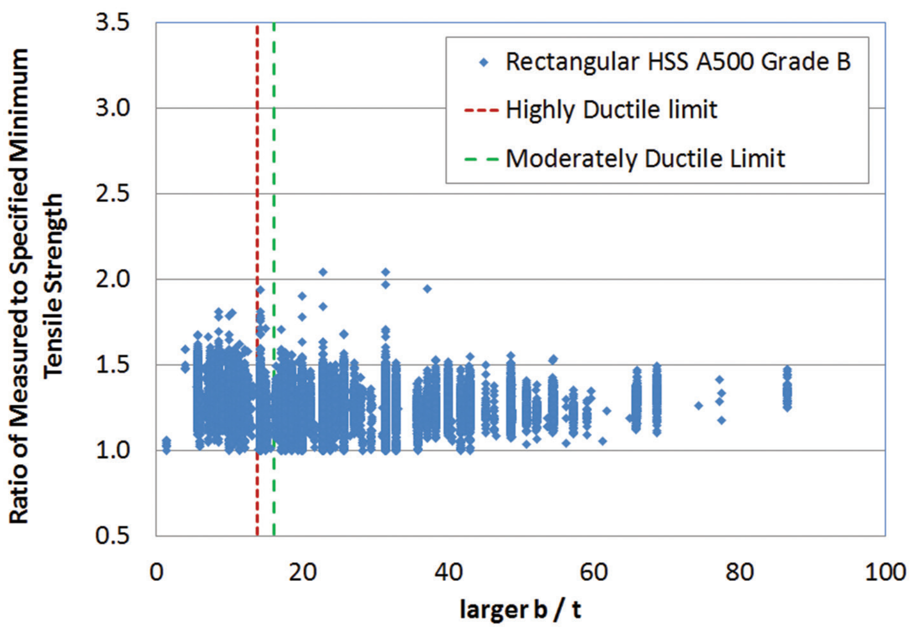


*Fig. 4. Ratio of measured to specified minimum tensile strength versus larger* b/t *for rectangular HSS A500 Grade B.*

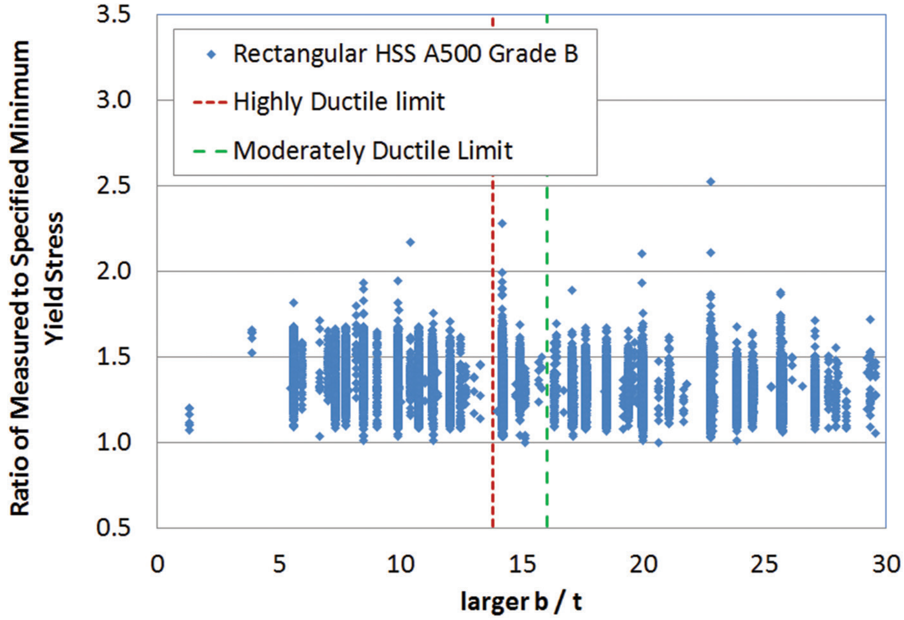


*Fig. 5. Ratio of measured to specified minimum yield stress versus larger b/t for rectangular HSS A500 Grade B, shown for* b/t *range of 0 to 30.*

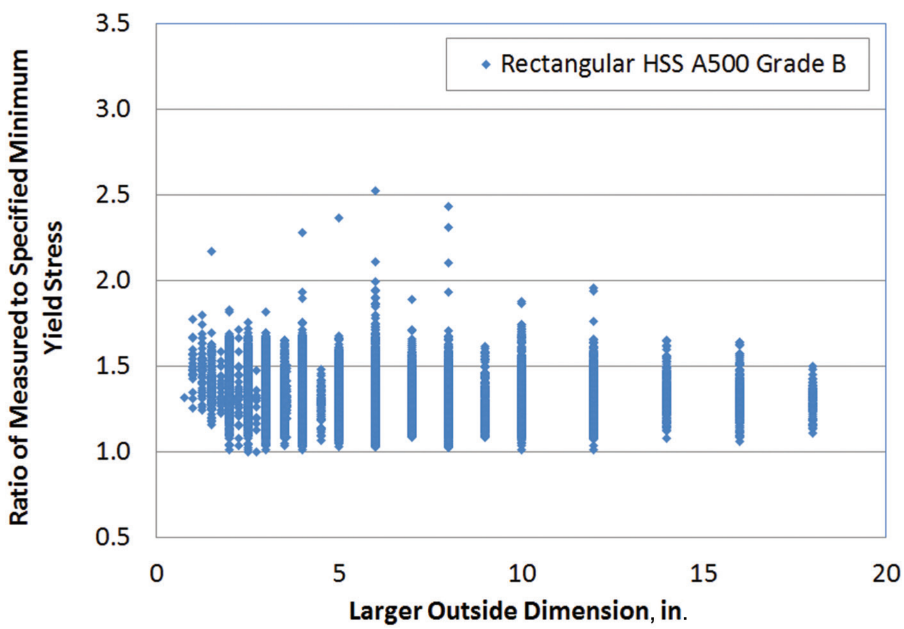


*Fig. 6. Ratio of measured to specified minimum yield stress versus larger outside dimension (in.) for rectangular HSS A500 Grade B.*

| Table 11. Comparison of Y/T and $R_yF_y/R_tF_u$ | | | |
|---|---|---|---|
| Shape | Material Specification | Mean Y/T (for Highly Ductile) | $R_yF_y/R_tF_u$ |
| HSS (Rectangular) | A500 Gr. B | 0.84 | 0.85 |
| | A500 Gr. C | 0.87 | 0.87 |
| | A500 Gr. B/C | 0.87 | 0.85 |
| | A501 Gr. B | 0.77 | 0.77 |
| HSS (Round) | A500 Gr. B | 0.89 | 0.78 |
| | A500 Gr. C | 0.85 | 0.80 |
| | A500 Gr. B/C | 0.87 | 0.78 |
| | A501 Gr. B | 0.76 | 0.77 |
| Pipe | A53 Gr. B | 0.89 | 0.78 |

points (less than 600 total for rectangular and round HSS) to support this modification.

The data for pipe were insufficient to support any modification to the existing $R_y$ and $R_t$ values. One possible change, based on the data in Table 10, could be to lower the $R_t$ value. However, these data were also primarily from one source, with relatively fewer data points than for the HSS.

Confirmation of HSS $R_y$ and $R_t$ values can also be seen in ratios of measured yield to measured tensile strength for individual specimens. Comparisons of the 2010 HSS $R_y/R_t$ (1.08) to the YR/TR values in the tables for rectangular HSS show that the 2010 $R_y/R_t$ would represent the data well, with an average YR/TR value on the order of 1.07 for rectangular HSS. The mean Y/T values may also be directly compared with the design $R_yF_y/R_tF_u$ values, as shown in Table 11. The table again shows good correlation for rectangular HSS. However, the $R_yF_y/R_tF_u$ values are lower than the mean Y/T values for round HSS and pipe, with the exception of A501 Grade B HSS. For design, this may result in an overestimation of the expected net section fracture capacity versus the expected gross section yield capacity.

## EXPECTED YIELD AND TENSILE STRENGTH RATIOS FOR ASTM A1085

The investigation of expected yield and tensile strength ratios for ASTM A1085 was challenging due to limited production. First, in the absence of a comparable data set for A1085, a subset of the A500 Grade B, Grade C, and Grade B/C data was analyzed. The data were truncated to include only those points that satisfied the minimum yield stress of 50 ksi and the maximum yield stress of 70 ksi for A1085. Then, a small set of A1085 data was obtained and also analyzed. Tables 12 through 17 summarize the yield and tensile ratio statistics for the truncated A500 data, with comparison to the original data. The values were also sorted by highly and moderately ductile sections and analyzed for any dependence on geometric properties.

In general, the yield and tensile ratios are lower for the truncated data than for the original data, suggesting lower $R_y$ and $R_t$ values for A1085. Overall, the data seem to support an $R_y$ on the order of 1.2 for A1085. However, values for highly ductile members trend higher. The yield ratios for highly ductile A500 Grade C rectangular HSS and Grade B

| Application | $R_y$ | $R_t$ |
|---|---|---|
| Hollow structural sections (HSS):<br>• ASTM A500/A500M (Gr. B or C), ASTM A501 | 1.4 | 1.3 |
| Pipe:<br>• ASTM A53/A53M | 1.6 | 1.2 |

*Fig. 7. Excerpt from Table A3.1, 2010 AISC Seismic Provisions, for HSS and pipe.*

| Table 12. Original and Truncated Data for Round A500 Grade B | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Round A500 Gr. B | Original | | Truncated (i.e., without data that does not satisfy A1085) | | | | | |
| | | | All | | Highly Ductile | | Moderately Ductile | |
| | Count = 2958 | | Count = 1870 | | Count = 1491 | | Count = 190 | |
| | YR | TR | YR | TR | YR | TR | YR | TR |
| MAX | 3.09 | 2.43 | 1.40 | 1.33 | 1.40 | 1.32 | 1.40 | 1.33 |
| MIN | 0.86 | 0.91 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| AVG | 1.44 | 1.19 | 1.23 | 1.10 | 1.25 | 1.09 | 1.16 | 1.13 |
| ST.DEV. | 0.15 | 0.11 | 0.10 | 0.06 | 0.09 | 0.06 | 0.09 | 0.06 |
| CV | 11% | 9% | 8% | 6% | 7% | 6% | 8% | 6% |

| Table 13. Original and Truncated Data for Round A500 Grade C | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Round A500 Gr. C | Original | | Truncated (i.e., without data that does not satisfy A1085) | | | | | |
| | | | All | | Highly Ductile | | Moderately Ductile | |
| | Count = 1149 | | Count = 967 | | Count = 861 | | Count = 40 | |
| | YR | TR | YR | TR | YR | TR | YR | TR |
| MAX | 1.95 | 1.66 | 1.40 | 1.34 | 1.40 | 1.34 | 1.32 | 1.28 |
| MIN | 0.87 | 0.73 | 1.00 | 1.00 | 1.00 | 1.00 | 1.03 | 1.01 |
| AVG | 1.33 | 1.17 | 1.21 | 1.12 | 1.22 | 1.12 | 1.14 | 1.12 |
| ST.DEV. | 0.14 | 0.09 | 0.10 | 0.06 | 0.09 | 0.06 | 0.07 | 0.06 |
| CV | 11% | 8% | 8% | 6% | 8% | 6% | 6% | 5% |

| Table 14. Original and Truncated Data for Round A500 Grade B/C | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Round A500 Gr. B/C | Original | | Truncated (i.e., without data that does not satisfy A1085) | | | | | |
| | | | All | | Highly Ductile | | Moderately Ductile | |
| | Count = 568 | | Count = 274 | | Count = 222 | | Count = 46 | |
| | YR | TR | YR | TR | YR | TR | YR | TR |
| MAX | 1.96 | 1.53 | 1.40 | 1.23 | 1.40 | 1.23 | 1.36 | 1.18 |
| MIN | 1.07 | 1.06 | 1.01 | 1.00 | 1.01 | 1.00 | 1.07 | 1.00 |
| AVG | 1.37 | 1.14 | 1.19 | 1.06 | 1.19 | 1.06 | 1.20 | 1.05 |
| ST.DEV. | 0.11 | 0.07 | 0.07 | 0.05 | 0.07 | 0.05 | 0.08 | 0.05 |
| CV | 8% | 6% | 6% | 4% | 6% | 4% | 6% | 5% |

| Table 15. Original and Truncated Data for Rectangular A500 Grade B | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Rectangular A500 Gr. B | Original | | Truncated (i.e., without data that does not satisfy A1085) | | | | | |
| | | | All | | Highly Ductile | | Moderately Ductile | |
| | Count = 31264 | | Count = 28048 | | Count = 5566 | | Count = 4914 | |
| | YR | TR | YR | TR | YR | TR | YR | TR |
| MAX | 2.52 | 2.04 | 1.40 | 1.53 | 1.40 | 1.49 | 1.40 | 1.53 |
| MIN | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| AVG | 1.31 | 1.26 | 1.20 | 1.13 | 1.23 | 1.14 | 1.21 | 1.13 |
| ST.DEV. | 0.12 | 0.09 | 0.09 | 0.07 | 0.09 | 0.08 | 0.09 | 0.07 |
| CV | 9% | 7% | 8% | 6% | 7% | 7% | 7% | 6% |

| Table 16. Original and Truncated Data for Rectangular A500 Grade C | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Rectangular A500 Gr. C | Original | | Truncated (i.e., without data that does not satisfy A1085) | | | | | |
| | | | All | | Highly Ductile | | Moderately Ductile | |
| | Count = 14140 | | Count = 12691 | | Count = 2913 | | Count = 2746 | |
| | YR | TR | YR | TR | YR | TR | YR | TR |
| MAX | 2.11 | 1.82 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.38 |
| MIN | 0.78 | 0.78 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 |
| AVG | 1.24 | 1.19 | 1.22 | 1.13 | 1.26 | 1.14 | 1.23 | 1.12 |
| ST.DEV. | 0.12 | 0.08 | 0.09 | 0.06 | 0.08 | 0.07 | 0.09 | 0.06 |
| CV | 9% | 7% | 7% | 6% | 7% | 6% | 7% | 6% |

| Table 17. Original and Truncated Data for Rectangular A500 Grade B/C | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Rectangular A500 Gr. B/C | Original | | Truncated (i.e., without data that does not satisfy A1085) | | | | | |
| | | | All | | Highly Ductile | | Moderately Ductile | |
| | Count = 3018 | | Count = 1857 | | Count = 559 | | Count = 425 | |
| | YR | TR | YR | TR | YR | TR | YR | TR |
| MAX | 1.94 | 1.81 | 1.40 | 1.33 | 1.40 | 1.33 | 1.40 | 1.29 |
| MIN | 1.09 | 1.07 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 |
| AVG | 1.28 | 1.18 | 1.22 | 1.09 | 1.24 | 1.10 | 1.22 | 1.09 |
| ST.DEV. | 0.11 | 0.09 | 0.07 | 0.06 | 0.07 | 0.06 | 0.07 | 0.05 |
| CV | 9% | 8% | 6% | 5% | 5% | 5% | 6% | 5% |

round HSS are 1.26 and 1.25, respectively. The data were surveyed to determine if higher yield ratios were for only for sections with small outside dimensions that might not be used in seismic applications (e.g., less than 6 in.), but there was no such trend with these data. Graphs of actual to minimum specified yield stress were also analyzed for the grades with the largest differences between highly ductile and overall $R_y$ values (rectangular Grades B and C). These results suggested that, beyond the tendency for the average values to be higher for highly ductile members, there are no particular values of thickness, $t$, or width-to-thickness, $b/t$, for which the ratios are always high. Figures 8 and 9 show comparisons of yield ratio to $b/t$ and $t$ for the truncated A500 Grade C rectangular HSS data. Similar results were obtained with the Grade B data.

A very small set of A1085 data was also obtained and analyzed. There were 24 samples of ASTM A1085 steel and 31 samples of dual-grade (A1085/A500 Grade C) steel. The data set included round and rectangular HSS, with thicknesses ranging from 5⁄16 in. to 7⁄8 in. and outside dimensions ranging from 4 to 16 in. Table 18 shows yield and tensile ratio statistics. These data support an $R_y$ on the order of 1.2 for A1085 and 1.2 or lower for $R_t$. Unfortunately, with so few data points, plots of yield and tensile ratios versus $b/t$ were inconclusive.

## YIELD AND TENSILE STRENGTH RATIOS FOR REINFORCING BAR

Data for A615 Grade 60, A615 Grade 75, A706 Grade 60, and Dual A615/A706 Grade 60 bars were studied with respect to expected yield and tensile strength values. For A615 Grade 60, particular attention was paid to the most commonly used bar sizes (nos. 7–11). Data had been submitted by domestic reinforcing steel producers and were estimated by CRSI to represent approximately 90% of total production in 2011 (CRSI, 2012).

Table 19 shows the number of data points and the total weight in tons for each grade of steel. Each data point represented one heat of steel, and a weight representing the size of that heat was tabulated. From this information, weighted average values, weighted standard deviations, and weighted coefficients of variation (CV) were calculated, along with maximum and minimum values. Histograms were generated for yield and tensile strengths for all grades. In general, the data exhibited normal distributions (Liu, 2013).

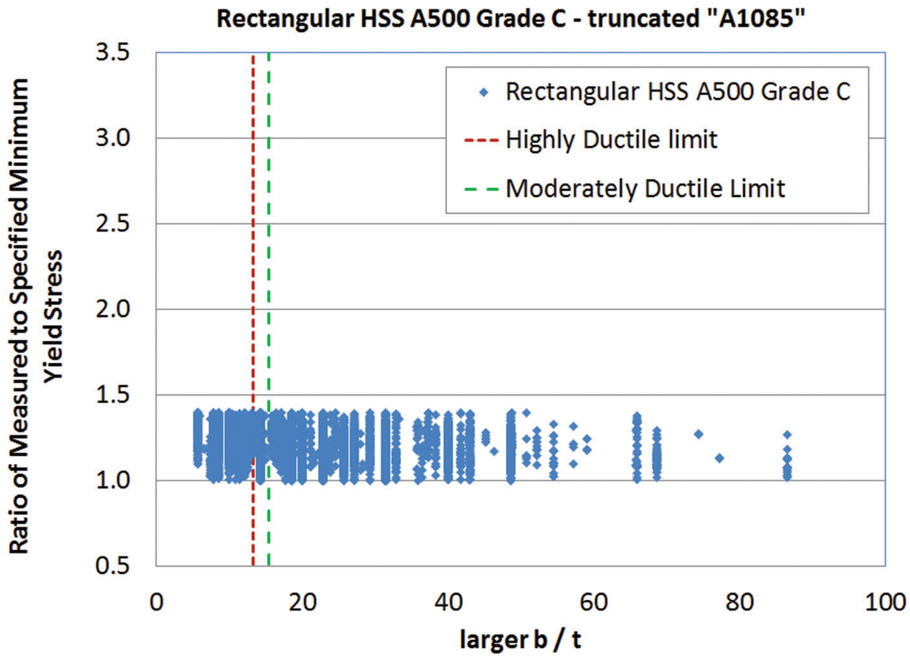


*Fig. 8. Yield ratio versus* b/t *for truncated A500 Grade C (rectangular HSS) data.*

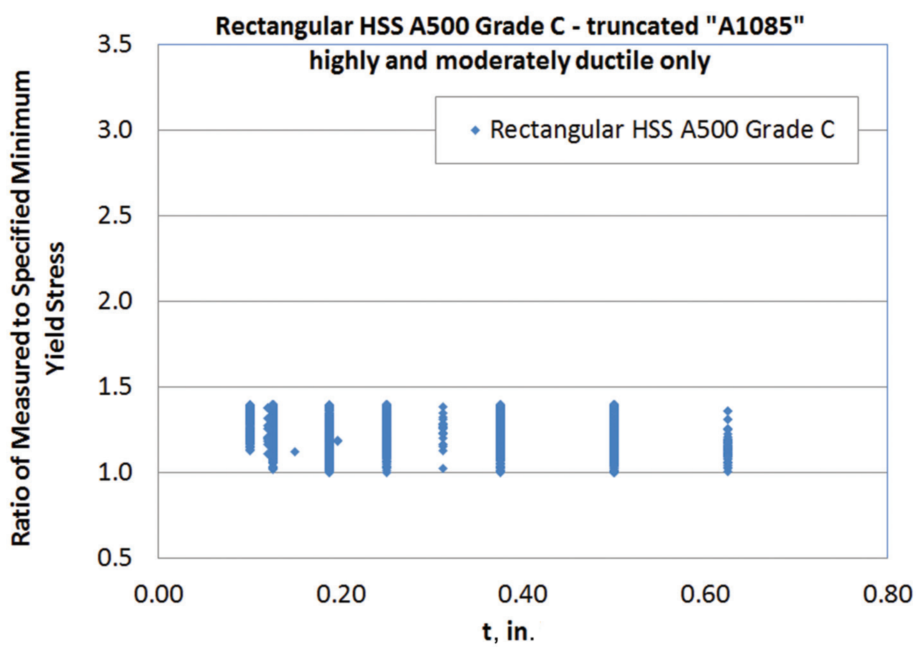


*Fig. 9. Yield ratio versus thickness,* t, *for truncated A500 Grade C (rectangular HSS) data.*

| Table 18. Yield and Tensile Ratios for ASTM A1085 Data | | | | |
|---|---|---|---|---|
| | Dual-Grade (A1085/A500 Grade C) | | A1085 Only | |
| | Count = 31 | | Count = 24 | |
| | YR | TR | YR | TR |
| **MAX** | 1.33 | 1.23 | 1.28 | 1.23 |
| **MIN** | 1.06 | 1.04 | 1.13 | 1.04 |
| **AVG** | 1.21 | 1.14 | 1.19 | 1.12 |
| **ST.DEV.** | 0.07 | 0.05 | 0.04 | 0.05 |

| Table 19. Reinforcing Bar Data Analyzed | | |
|---|---|---|
| Material Specification | Data Count | Weight (tons) |
| A615 Grade 60 | 19,860 | 1,054,190 |
| A615 Grade 75 | 2,174 | 147,930 |
| A706 Grade 60 | 5,810 | 320,708 |
| Dual A615/A706 Grade 60 | 1,328 | 132,315 |

| Table 20. Yield and Tensile Strength Data for A615 Grade 60 Bar | | | | |
|---|---|---|---|---|
| Bar Size | Data Count | Weight (tons) | Yield Ratio (Weighted Average) | Tensile Ratio (Weighted Average) |
| 3 | 1,794 | 136,863 | 1.18 | 1.21 |
| 4 | 12,225 | 810,826 | 1.18 | 1.17 |
| 5 | 16,321 | 1,059,469 | 1.17 | 1.17 |
| 6 | 11,445 | 747,669 | 1.17 | 1.18 |
| 7 | 4,555 | 297,294 | 1.17 | 1.18 |
| 8 | 5,233 | 343,707 | 1.18 | 1.16 |
| 9 | 3,743 | 243,603 | 1.19 | 1.17 |
| 10 | 2,791 | 171,807 | 1.19 | 1.15 |
| 11 | 3,538 | 231,539 | 1.19 | 1.15 |
| 14 | 131 | 8,247 | 1.20 | 1.14 |
| 18 | 56 | 3,167 | 1.24 | 1.17 |
| ALL sizes | 61,832 | 4,054,190 | 1.18 | 1.17 |
| 7 to 11 only | 19,860 | 1,287,950 | 1.18 | 1.16 |

The 2010 AISC *Seismic Provisions* used $R_y$ and $R_t$ values of 1.25 for all steel reinforcement (AISC, 2010). Analysis of the CRSI data supported lower expected yield stress and tensile strength ratios for the grades investigated (Liu, 2013). Table 20 summarizes data for A615 Grade 60 bars, showing average yield and tensile ratios less than 1.20 for the entire data set. The average value for the no. 18 bars was 1.24, but the expected yield ratio for a subset of more common bar sizes (nos. 7–11) averaged less than 1.20. Similar results were obtained for all grades, with the exception of A615 Grade 75, which had an average yield ratio of 1.11. Meanwhile, the CRSI database only included 11 samples for A706 Grade 80 bars, but those data suggested similar yield and tensile strength ratios as for A706 Grade 60 bars. Similarly, the 21 samples for A615 Grade 80 bars showed similar yield and tensile strength ratios as for the A615 Grade 75 bars (CRSI, 2012).

| Table 21. HSS and Steel Reinforcement $R_y$ and $R_t$ Values in the 2016 *Seismic Provisions* (AISC, 2016) | | |
|---|---|---|
| **Application** | $R_y$ | $R_t$ |
| ***Hollow Structural Sections (HSS)*** | | |
| ASTM A500 Grade B | 1.4 | 1.3 |
| ASTM A500 Grade C | 1.3 | 1.2 |
| ASTM A501 | 1.4 | 1.3 |
| ASTM A53 (Pipe) | 1.6 | 1.2 |
| ASTM A1085 | 1.25 | 1.15 |
| ***Steel Reinforcement*** | | |
| A615 Grade 60 | 1.2 | 1.2 |
| A615 (Grades 75 and 80) | 1.1 | 1.2 |
| A706 (Grades 60 and 80) | 1.2 | 1.2 |

## EXPECTED YIELD AND TENSILE STRENGTH RATIOS FOR THE 2016 *SEISMIC PROVISIONS*

The data for steel reinforcement and HSS were used to refine the $R_y$ and $R_t$ values in the 2016 *Seismic Provisions* (Table 21). The original $R_y$ and $R_t$ of 1.4 and 1.3 for HSS were kept for ASTM A500 Grade B and ASTM A501, respectively. These values corresponded well to calculated yield and tensile ratios for A500 Grade B. With relatively few data points, the information for A501 was insufficient to justify lower $R_y$ and $R_t$ values. A53 pipe data confirmed the original $R_y$ of 1.6. The limited data were insufficient, however, to justify an $R_t$ value lower than 1.2. Data for ASTM A500 Grade C motivated reductions of $R_y$ and $R_t$ to 1.3 and 1.2. Investigation of limited A1085 data in combination with A500 grades that satisfied A1085 limits on yield stress formed the basis for $R_y$ and $R_t$ values of 1.25 and 1.15. Steel reinforcement data supported $R_y$ and $R_t$ values of 1.2 for all grades investigated, except for an $R_y$ of 1.1 for A615 Grades 75 and 80.

## ACKNOWLEDGMENTS

This study was conducted with support from the American Institute of Steel Construction. The author would like to thank AISC staff and members of AISC Task Committee 9 (Seismic Design)—in particular, Subcommittee 6 on Composite Construction and Subcommittee 3 on Materials—for their technical assistance. Special thanks to the steel producers who provided data and to Tony Johnson, CRSI, for sharing their mill database.

## REFERENCES

AISC (2010), *Seismic Provisions for Structural Steel Buildings,* ANSI/AISC 341-10, American Institute of Steel Construction, Chicago, IL.

AISC (2016), *Seismic Provisions for Structural Steel Buildings,* ANSI/AISC 341-16, American Institute of Steel Construction, Chicago, IL.

Anderson, M., Carter, C.J. and Schlafly, T.J. (2015), "Are You Properly Specifying Materials?" *Modern Steel Construction,* AISC, February.

CRSI (2012), *CRSI Mill Database: 2011 Annual Summary Report,* Concrete Reinforcing Steel Institute, Schaumburg, IL.

Liu, J., Sabelli, R., Brockenbrough, R. and Fraser, T. (2007), "Expected Yield Stress and Tensile Strength Ratios for Determination of Expected Member Capacity in the 2005 AISC Seismic Provisions," *Engineering Journal,* AISC, Vol. 44, No. 1, First Quarter, pp. 15–26.

Liu, J. (2013), "Updates to Expected Yield and Tensile Strength Ratios," *Report to the American Institute of Steel Construction,* Chicago, IL, November, 40 pages.