

HSS

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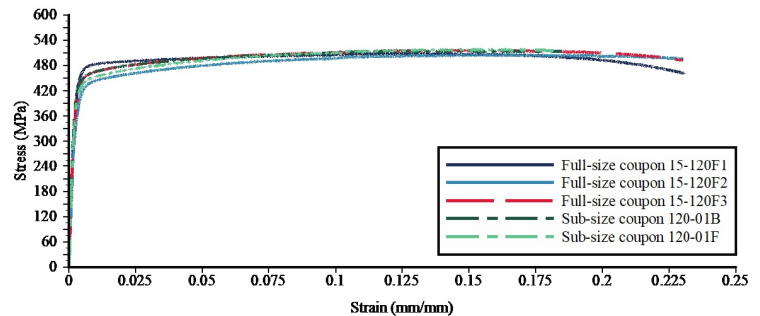
MECHANICAL PROPERTIES OF HSS CORNERS VERSUS FLATS

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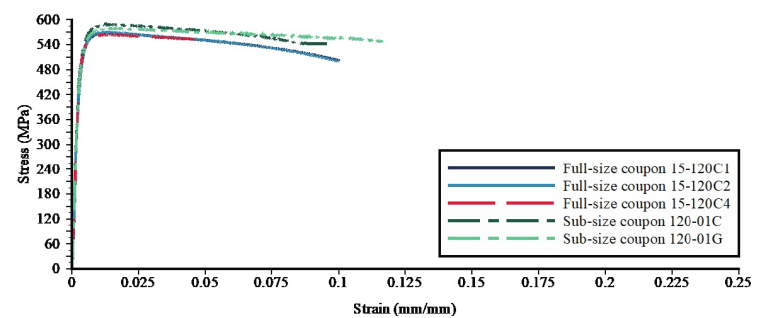
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It is well known that cold-formed square and rectangular HSS have a very high degree of cold working, and this raises the overall cross-section yield strength considerably. Relative to the flats, the cold forming causes an increase in the corner yield stress, an increase in the ultimate tensile strength and a decrease in the ductility (measured by the elongation at rupture). These mechanical properties vary with HSS width/depth and thickness, corner radius, grade and type of hot-rolled coil material, and by production method. This article hence summarizes mechanical property data from cold-formed HSS measured at the University of Toronto laboratories, over many projects. Typical engineering stress-strain curves for tensile coupons, taken longitudinally from four corners and three flats of a single cold-formed HSS member, are shown in Figure 1 (Ritchie et al., 2017a). Note that strain is actually dimensionless and $6.89 \text{ MPa} = 1 \text{ ksi}$.

Representative mechanical properties, from both the flats and corners, are of particular interest for refining designs for dynamically loaded HSS, including blast, impact and seismic applications (Ritchie et al., 2017b). With regard to seismic loading, the capacity of the corners to withstand repeated inelastic load cycles is important when HSS are used as energy-dissipative braces. Also, the elevated yield stress in the corners is currently being investigated as a rationale for an increased F_y value for seismic design of such braces. (Recall that the nominal or minimum F_y guaranteed by the HSS producer is based on tensile coupons taken from the flats). Corner property data is also important to advance the science of hot-dip galvanizing cold-formed HSS.



(a) coupons taken from the flats



(b) coupons taken from the corners

Figure 1: Static stress-strain curves from tensile coupon tests on HSS 120x120x6 (HSS $4\frac{3}{4} \times 4\frac{3}{4} \times \frac{1}{4}$)

TESTING METHOD

Standard longitudinal tensile coupons, cut from the three flat sides excluding the weld seam and from the corners of square/rectangular HSS, have been machined to a specified dog-bone shape and tested under displacement control in a quasi-static manner in accordance with ASTM standards E8 (2016) and A370 (2017). The yield stress was determined using the 0.2% strain offset method, strain was measured over a prescribed gage length using a clip-gage extensometer, and elongation at failure (rupture strain) was determined after tests were completed by joining the fractured pieces together and recording the change in gage length divided by the initial gage length, as shown in Figure 2.

For the corner coupons, the correct curved shape (as in the parent HSS) was maintained during tensile testing by placing a curved block to fit snugly inside the corner radius, so that the coupon ends would not flatten when gripped by the universal testing machine. This is important, in order that the tensile behavior of the tested corner samples reflects the in-situ corner behavior.

The cross-sectional dimensions in the gage length of flat tensile coupons were carefully measured using a micrometer. For the curved corner coupons, the cross-sectional area in the reduced-width gage length can be determined by either: (i) weighing a sample, carefully cut at the gage marks and dividing the mass obtained by the initial gage length and the nominal density of rolled steel = 7850 kg/m^3 (CISC 2016) or 490 lb/ft^3 (AISC 2017); or (ii) placing the cross-section of a cut-and-machined sample from the elastic gage region (as done in Figure 2) on a flat-bed scanner and then determining the area using CAD software. The cross-sectional areas can also be checked with the equation given in Section 7.2.3 of ASTM E8 (2016), using the measured outside corner radii and the widths and thicknesses of the specimens (which is considered a less accurate method).



Figure 2: Curved corner coupon, fitted together after testing to determine elongation at fracture. Then, the coupon is sectioned at the gage marks (elastic region) to measure the cross-sectional area.

TEST DATA

The results of mechanical property tests on 23 cold-formed HSS members are given in Table 1, where each entry is generally the average from several coupons from the flat portions, or several coupons from the corner regions, of that member. The material tested has been obtained from multiple producers across North America and Europe. The data has been compiled from theses by: Dixon (1983), Bruno (1984), Poloni (1985), Frater (1986, 1991), Sun (2014), Fan (2017) and Ritchie (2017).

Ref.	HSS Designation	Specification and Grade	Manuf. Process	F_{yf} ksi	F_{yc} ksi	$\frac{F_{yc}}{F_{yf}}$	F_{uf} ksi	F_{uc} ksi	$\frac{F_{uc}}{F_{uf}}$	ϵ_{ff} %	ϵ_{fc} %	$\frac{\epsilon_{fc}}{\epsilon_{ff}}$
Fan	8x8x1/4	ASTM A500 Gr B/C	CF	56.4	78.5	1.391	73.8	86.9	1.177	28.7	17.6	0.613
Fan	8x8x3/8	ASTM A500 Gr B/C	CF	57.9	74.5	1.288	75.4	87.6	1.162	30.6	21.9	0.716
Sun	6x6x1/2	ASTM A500 Gr B/C	DF	61.9	89.2	1.440	75.7	94.1	1.243	35.6	21.4	0.601
Sun	6x6x1/4	ASTM A500 Gr B/C	DF	58.3	78.2	1.341	68.6	82.2	1.199	32.2	14.5	0.450
Sun	6x6x1/2	CSA G40.20 Gr 50	CF	66.3	85.6	1.291	86.9	98.0	1.129	24.1	21.7	0.900
Sun	6x6x1/4	CSA G40.20 Gr 50	CF	49.3	70.1	1.421	65.0	76.6	1.179	33.1	16.5	0.498
Sun	6x6x1/2	CSA G40.20 Gr 50	CFSR	70.1	82.7	1.180	87.9	92.4	1.051	30.0	27.4	0.913
Sun	6x6x1/4	CSA G40.20 Gr 50	CFSR	52.6	67.2	1.275	67.3	77.0	1.144	34.1	21.1	0.619
Ritchie	150x150x10	EN10219 Gr 355J2	CF	50.5	62.8	1.244	74.3	70.6	0.951	32.3	17.8	0.551
Ritchie	150x150x8	EN10219 Gr 355J2	CF	58.5	96.3	1.648	73.0	108.6	1.489	31.4	19.4	0.618
Ritchie	120x120x8	EN10219 Gr 355J2	CF	60.9	75.6	1.240	72.4	84.1	1.162	31.8	19.3	0.607
Ritchie	120x120x5	EN10219 Gr 355J2	CF	61.9	81.7	1.319	75.1	88.6	1.180	30.1	13.4	0.445
Ritchie	120x120x6	EN10219 Gr 355J2	CF	61.5	77.2	1.255	74.0	83.7	1.131	30.0	15.9	0.530
Ritchie	80x80x3	EN10219 Gr 355J2	CF	63.1	78.2	1.239	77.2	85.6	1.109	27.9	12.5	0.448
Ritchie	60x60x3	EN10219 Gr 355J2	CF	65.1	76.4	1.174	79.2	84.6	1.068	26.1	15.3	0.586
Dixon	8x6x3/16	CSA G40.20 Gr 50	CFSR	56.9	78.0	1.372	73.7	90.8	1.232	31.2	19.0	0.609
Dixon	10x10x3/8	CSA G40.20 Gr 50	CFSR	57.3	73.5	1.284	73.7	86.9	1.179	22.6	21.7	0.960
Poloni	10x4x3/16	CSA G40.20 Gr 50	CFSR	55.5	66.1	1.191	71.4	77.0	1.079	28.2	20.0	0.709
Bruno	4x4x1/4	CSA G40.20 Gr 50	CFSR	51.5	76.0	1.476	66.1	76.0	1.149	38.0	-	-
Bruno	7x5x3/16	CSA G40.20 Gr 50	CFSR	57.6	74.5	1.295	71.6	74.5	1.040	40.0	-	-
Frater	5x5x3/8	CSA G40.20 Gr 50	CFSR	61.8	72.1	1.167	72.5	81.5	1.124	-	-	-
Frater	8x8x1/2	CSA G40.20 Gr 50	CFSR	48.6	63.8	1.313	67.0	78.0	1.165	-	-	-
Frater	8x8x1/2	CSA G40.20 Gr 50	CFSR	52.1	66.3	1.273	70.5	79.6	1.130	-	-	-

Notes:

HSS Designation: in. x in. x in., or mm x mm x mm for European sections

Manufacturing Process: CF = continuous-formed; DF = direct-formed; CFSR = continuous-formed + stress-relieved by heat treatment at 850°F

(450°C) or higher, followed by cooling in air
 F_{yf} and F_{yc} = yield stresses measured in the flat and corner positions, respectively, by the 0.2% strain offset method

F_{uf} and F_{uc} = ultimate stresses measured in the flat and corner positions, respectively

ϵ_{ff} and ϵ_{fc} = elongation at failure (fracture) measured in the flat and corner positions, respectively

Table 1: Static tensile test results for longitudinal coupons taken from the flats and corners of cold-formed square/rectangular HSS

All HSS tabulated are cold-formed, generally by the popular continuous forming method into a circular shape and then shaping to a square/rectangular size (CF). In some cases these sections were subsequently stress-relieved by heat treatment to 850°F or higher, followed by cooling in air (CFSR), which is an option available with ASTM A1085 Supplementary Requirement S1 (ASTM 2013a) and CSA G40.20/G40.21 Class H (CSA 2013). Two of the sections in Table 1 were direct-formed to square/rectangular shape (DF) from flat coil material. As the DF process produces a different strength and ductility distribution around the cross section compared to the CF process, the two DF sections have been omitted from the subsequent statistical analysis given below.

The HSS full-section average tensile strength, F_{yave} , can be computed by considering the yield stresses of the flat and corner regions from Table 1, weighted according to their respective contributions to the cross-sectional area, by:

$$F_{yave} = CF_{yc} + (1-C)F_{yf}$$

Equation (1)

where C is the ratio of the corner areas to the full cross-sectional area of the HSS member, F_{yc} is the yield stress of the corner regions, and F_{yf} is the yield stress of the flats.

In Figures 3, 4 and 5, test data from Table 1 are shown in green for CF, red for CFSR, and blue for DF. Figure 3 shows the distribution of the corner-to-flat yield stress ratios, for which the mean for the 21 CF/CFSR sections is 1.30 and the coefficient of variation (COV) is 8.7%. Interestingly, the F_{yc}/F_{yf} ratios are generally similar for both CF and CFSR HSS, indicating that heat treatment tends to stress relieve the corners and flats in a proportional manner.

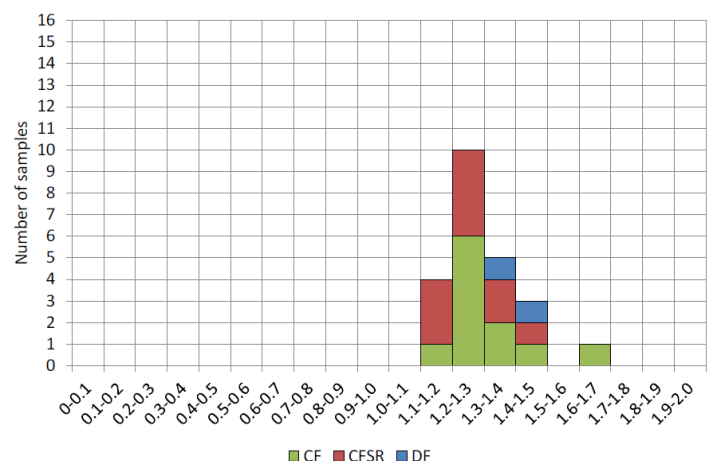


Figure 3: Corner-to-flat yield stress ratios, F_{yc} / F_{yf}



Figure 4 shows the distribution of the corner-to-flat ultimate tensile stress (strength) ratios, for which the mean for the 21 CF/CFSR sections is 1.14 and the COV is 8.8%. Again, there is a similar trend for both the CF and CFSR sections tested. The strength enhancement for the corners, relative to the flats, is much less for the ultimate stress than the yield stress.

Figure 5 shows the distribution of the corner-to-flat fracture strain ratios, for which the mean of 16 CF/CFSR sections with available data is 0.65 and the COV is 24.6%. This illustrates the severe loss in ductility in the corner regions, relative the flats (which is the specified location for test samples for the producer to show compliance with the manufacturing specification). Once again, the CFSR data points are located within the spread of the CF data points.

The four CSA G40.20 HSS in Table 1 tested by Sun (2014) are of particular interest because, for both the HSS 6x6x1/2 and HSS 6x6x1/4 sizes, the CF section is the parent of the CFSR section (i.e. the latter was produced from the former by heat treatment). Although the sample size is small (two HSS), both show that heat treatment causes a small reduction in F_{yc} / F_{yf} , a small reduction in F_{uc} / F_{uf} , and a small increase in $\epsilon_{fc} / \epsilon_{ff}$.

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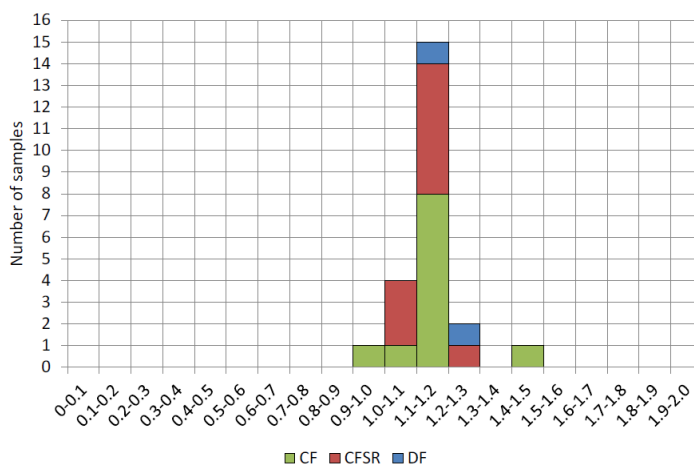


Figure 4: Corner-to-flat ultimate tensile stress ratios, F_{uc} / F_{uf}

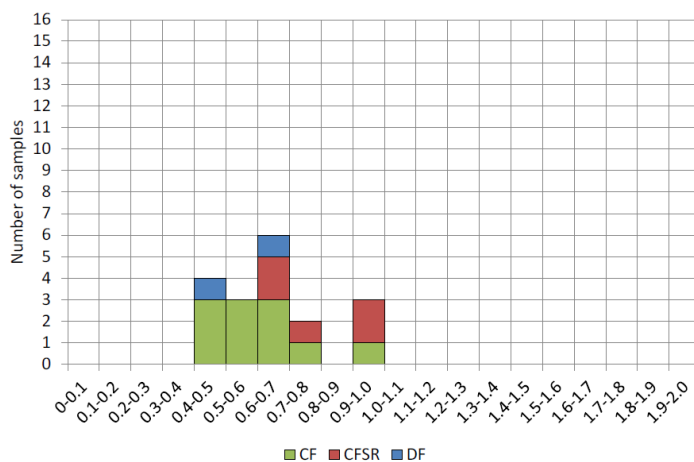


Figure 5: Corner-to-flat fracture strain ratios, $\epsilon_{fc} / \epsilon_{ff}$