STEEL STRENGTH COMPARISON:

TENSILE, COMPRESSION, TORSION, BENDING, SHEAR

The data provided in this article indicates that the common factors or 'rules of thumb' for converting tensile strength to other load cases are reasonably close.

By GREGORY FETT

The strength of steel is commonly characterized by using engineering tensile strength. Typically, a dog-bone shaped test bar is pulled in the axial direction until fracture occurs. During the test, load vs. deflection or strain is measured. Strain is the increase of the test bar gauge length divided by the initial length expressed as a percent. The common output data from the test is ultimate tensile strength, yield strength, elongation, and reduction of area (ROA). The calculations are relatively simple; load is converted to strength in terms of load per unit area by dividing by the initial cross-sectional area of the sample. Engineering tensile strength can readily be applied to other geometries loaded in tension. However, the application of engineering tensile strength to components loaded in compression, bending, torsion, or shear requires the use of a conversion factor. The reason is steel tested under these other load cases does not have the same strength as in tension when stress is calculated by conventional engineering methods. Over the years, these conversion factors or "rules of thumb" have been passed down. For example, 0.6X is commonly used to convert tensile to shear or torsion, and 2.0X to convert to bending, and 1.2X to convert to compression.

In 2009, a project was initiated to compare the strength of the same steel tested in tension, compression, shear, bending, and torsion [1]. Three different grades were evaluated: one with low strength, one with an intermediate strength, and one with high strength. This project was also the basis for an undergraduate engineering thesis.

TEST BARS

The low strength steel samples were machined from 1018 cold drawn bar with a target hardness of less the 15HRC. The intermediate strength samples were machined from 4140 pre-hardened steel bar with a specified hardness of 28-32 HRC. The high strength samples were machined from 6150 bar stock and subsequently quenched from 1,650°F (899°C) and tempered at 800°F (427°C) with a target hardness of 40-45 HRC.

The cross-sectional diameter of all samples was 6 mm. The gauge length of the tensile and torsional samples was 36 mm, and the grip ends were 12 mm squares. The height or length of the compression samples was 6 mm, and the samples were compressed to 1-2 mm. The length of the bending and shear samples was 60 mm. In bending, the distance between supports was 36 mm, and in double shear, the distance between shear points was 15 mm.

TENSILE RESULTS

The results for all samples are shown in Table 1. The calculated strength of each sample is shown as well as the average and standard deviation. The strength of the tensile samples was determined by dividing the load by the initial cross sectional area. Tensile yield strength was determined by using the 0.2% offset method. A line is drawn parallel to the initial elastic portion of the curve with a 0.2% strain offset, and where it intersects, the load curve is the yield strength. The average engineering tensile ultimate strength for the 1018, 4140, and 6150 was 83 Ksi (572 MPa), 149 Ksi (1,028 MPa), and 219 Ksi (1,510 MPa) respectively. The average tensile yield strength was 73 Ksi (502 MPa), 137 Ksi (945 MPa), and 204 Ksi (1,407 MPa) respectively. The tensile yield strength of the 6150 steel was also determined to be 197 Ksi (1,359 MPa) using the Johnson Elastic Limit or JEL method for comparison. The yield strength of all other sample groups in this study was determined using the Johnson Elastic Limit. This is another offset method where two lines intersect. A line is drawn with a 50% change in slope from the elastic line and where it intersects the curve is the yield strength. The advantage is it can be applied to situations where there is no fixed gauge length such as in compression, torsion, bending, or shear. All that is required is load vs. some form of deflection or angular rotation.

		Avg Ultimate Strength		Standard Deviation		Avg Yield Strength		Standard Deviation	
Test	Steel	Psi	MPa	Psi	MPa	Psi	MPa	Psi	MPa
Tensile	1018	82,536	569	379	3	72,761	502	1,813	13
	4140	148,931	1,027	818	6	137,279	947	1,446	10
	6150	218,525	1,507	538	4	203,775	1,405	350	2
Compression	1018	588,658	4,060	11,269	78	92,683	639	3,689	25
	4140	799,585	5,514	101,326	699	140,775	971	1,503	10
	6150	1,024,357	7,065	16,362	113	239,150	1,649	737	5
Bending	1018	204,373	1,409	2,205	15	152,118	1,049	4,164	29
	4140	303,673	2,094	2,029	14	209,780	1,447	9,024	62
	6150	437,803	3,019	5,411	37	332,244	2,291	5,492	38
Torsion	1018	58,218	402	1,203	8	31,589	218	3,663	25
	4140	95,087	656	1,912	13	60,742	419	5,097	35
	6150	130,476	900	3,418	24	92,650	639	2,703	19
Shear	1018	69,610	480	214	1	54,740	378	313	2
	4140	105,158	725	198	1	72,260	498	1,031	7
	6150	140,226	967	738	5	114,170	787	761	5

Note: Five samples were typically run for each condition. Red indicates invalid results as ultimate strength was never reached and test was arbitrarily suspended.

Table 1

The fracture mode of the tensile samples was a cup and cone with a decreasing shear lip around the outer diameter as the strength increased. With a cup and cone type fracture, initiation is in the cen-

ter of the cross section, and final fracture is toward the surface.

Yield strength is commonly used as the point where strain changes from elastic to plastic, causing permanent deflection. However, this is just beyond the point where permanent deflection starts to occur, but it is done this way because it is easy to determine the exact point where the two lines intersect. The point where permanent deflection starts to occur is called the elastic limit, and it is where the load vs. strain curve becomes non-linear. It is not typically used because the exact point can be a little more difficult to determine. However, this can be important during the design phase if no plastic deformation is permitted.

		Factor to Convert Tensile Strength to the Following				Hardness HRC
Steel	Strength	Compression	Bending	Torsion	Shear	
1018	Yield	1.2738	2.0907	0.4327	0.7523	14
	Ultimate	7.1321	2.4762	0.7054	0.8434	14
4140	Yield	1.0255	1.5281	0.4425	0.5264	28
	Ultimate	5.3688	2.0390	0.6385	0.7061	28
6150	Yield	1.1736	1.6304	0.4547	0.5603	45
	Ultimate	4.6876	2.0034	0.5971	0.6417	45
Average	Yield	1.1576	1.7497	0.4433	0.6130	
	Ultimate	5.7295	2.1729	0.6470	0.7304	

Red indicates invalid results as ultimate strength was never reached and test was arbitrarily suspended.

Table 2

	Average Ultimate Strength					
	Engineering Tensile		True Tensile		Bending	
Steel	Psi	MPa	Psi	MPa	Psi	MPa
1018	82,536	569	97,548	673	204,373	1,409
4140	148,931	1,027	175,498	1,210	303,673	2,094
6150	218,525	1,507	244,096	1,683	437,803	3,019

Table 3

COMPRESSION RESULTS

Ultimate strength was not able to be determined for the compression samples as they were compressed into pancakes without fracturing as the load continued to increase. The test was suspended when the pancake thickness reached 1-2 mm. Strength was determined by dividing the load by the initial cross sectional area. The average maximum strength achieved for the 1018, 4140, and 6150 based on the initial diameter was 589 Ksi (4,062 MPa), 800 Ksi (5,517 MPa), and 1,024 Ksi (7,062 MPa) respectively. These values are exceedingly high. However, they do not take into account the increasing cross-sectional area. The average JEL compressive yield strength for the 1018, 4140, and 6150 was 93 Ksi (641 MPa), 141 Ksi (972 MPa), and 239 Ksi (1,648 MPa) respectively, which is slightly higher than in tension.

TORSIONAL RESULTS

The torsional strength was determined by dividing torque by the section modulus of $\pi D^3/16$. Again, the yield was determined by using the JEL. The average torsional ultimate strength for 1018, 4140, and 6150 was 58 Ksi (400 MPa), 95 Ksi (655 MPa), and 130 Ksi (897 MPa) respectively. The average torsional yield strength was 32 Ksi (221 MPa), 61 Ksi (421 MPa), and 93 Ksi (641 MPa) respectively. These strength values are significantly lower than in tension. The fractures were all flat ductile shear fractures.

BENDING RESULTS

The three-point bending strength was determined by the equation $32M/\pi D^3$ where M=Load X Length/4. The yield was equal to the JEL. The average bending strength for 1018, 4140, and 6150 was 204 Ksi (1,407 MPa), 304 Ksi (2097 MPa), and 438 Ksi (3,021 MPa) respectively. The average bending yield strength was 152 Ksi (1,048 MPa), 210 Ksi (1,448 MPa), and 332 Ksi (2,290 MPa) respectively. These strength values are significantly higher than those in tension. In the case of 6150, the strength is higher than what is possible to reach in tension. Only one 6150 fractured; all other samples reached a maximum load and continued to deform.

SHEAR RESULTS

The double shear strength was determined by the equation Load X $0.5/\pi R^2$. The yield was determined by the JEL. The average ultimate strength for the 1018, 4140, and 6150 was 70 Ksi (483 MPa), 105 Ksi (724 MPa), and 140 Ksi (966 MPa) respectively. The average yield strength was 55 Ksi (379), 72 Ksi (497 MPa), and 114 Ksi (786 MPa) respectively. These strength values were significantly lower than in tension, and similar to those in torsion. The fractures were all flat shear type fractures across the diameter with a decreasing shear lip at the final fracture as the hardness increased.

COMPARISON OF ALL RESULTS

Table 2 shows the comparison of ultimate and yield strength in compression, torsion, bending, and shear compared to tension. A factor for converting from tensile ultimate and yield strength is shown. Shear and torsion ultimate and yield strength are both about 0.6X tensile yield and tensile ultimate strength. Compressive ultimate strength is greater than 5X tensile ultimate strength while compressive yield strength is about 1.2X tensile ultimate strength. Bending ultimate strength is about 2.2X tensile ultimate strength and bending yield is about 1.8X tensile yield strength. The factors tend to be higher for the low strength 1018 steel and decrease as the strength increases.

The shear and torsional fractures are both flat fractures that involve shear. It makes sense the strength would be similar to each other and potentially different from tensile. In shear, the fracture initiates at the surface on one side and propagates directly across the diameter. In torsion, the fracture also initiates at the surface but in the circumferential direction and works its way inward toward the center. It also makes sense that compressive strength might be different from tensile due to the opposite loading. However, bending involves tension on one side and compression on the other and since the fracture initiates on the tension side, it would seem logical the strength might be similar to tensile strength. However, the calculated strength is approximately double in bending.

TENSION VS. BENDING

One common reason given for bending stress being higher than tensile is that in tension, the stress is the same across the entire cross section vs. in bending the stress calculated at the outer fiber. However, this should not matter. In tension or in bending, the sample will fail when the applied tensile stress exceeds the tensile strength at any given location. Tensile test bars commonly fail from the inside out on ductile steels (i.e. cup and cone fracture). This would also mean the stress is not uniform throughout the cross section. In tension, brittle steels tend to

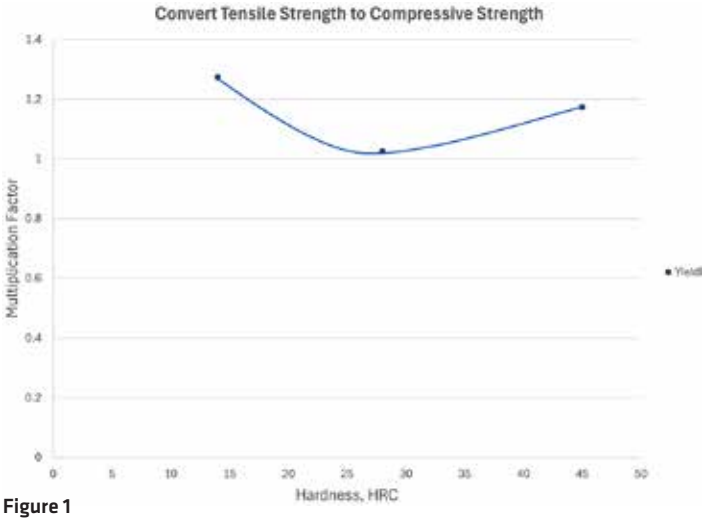

Figure 1

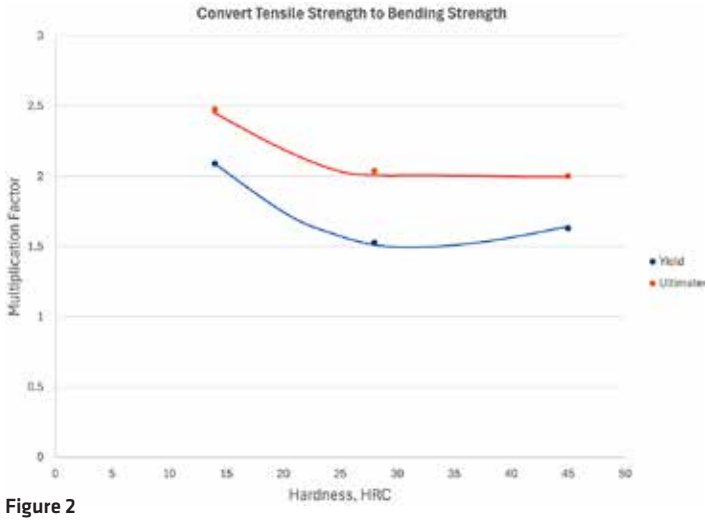

Figure 2

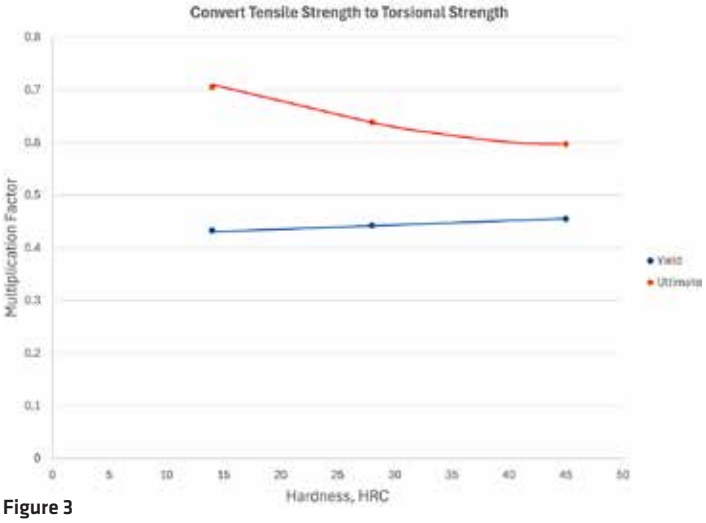

Figure 3

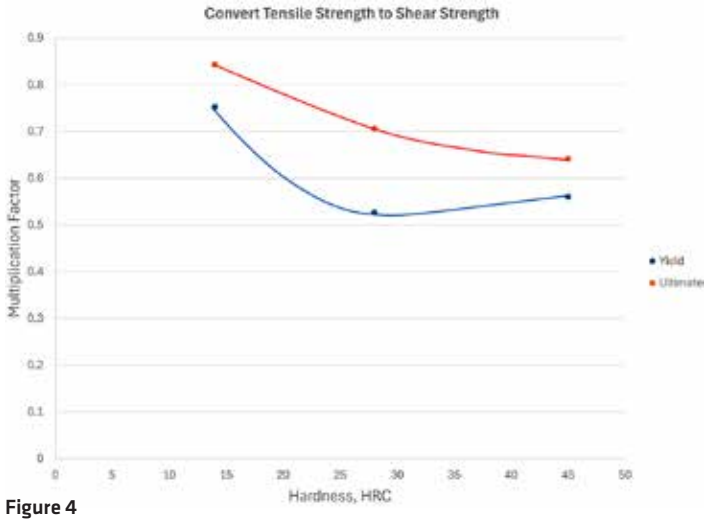

Figure 4

fracture from the surface as do brittle steels in bending. The fractures are identical, yet the calculated strength is still significantly higher in bending (i.e. 1541, oil quenched, no temper, 6mm diameter, 3 point bending, 57 HRC, average ultimate 431,034 psi or 2973 MPa) [1].

Another common reason is in tension, the fracture is free to find the weakest spot in the cross section while in bending, the fracture is forced to the side in tension. However, this would mean there should be a large variation in bending results from sample-to-sample and eventually the fracture would occur at the weakest spot. This does not happen. Also, if a small degree of bending is introduced during a tensile test, the strength does not double, but instead it decreases. It does not seem these reasons are valid.

A more logical explanation for higher strength in bending compared to tension might be in tension, the original cross section decreases as stress increases, and the calculated stress is not the true stress. This is especially true with ductile steels that exhibit a large degree of plasticity and a large ROA. Table 3 shows a comparison of engineering and true tensile ultimate strength to bending ultimate strength. True tensile strength is a little closer to bending strength; however, a large gap still exists. Another possible explanation for the large difference between tensile and bending strength is the method being used to calculate bending stress is not correct. Stress is simply a calculation, and different methods can be used to calculate bending stress. For example, industry gear stress calculations can vary significantly on the same gear [2]. With AGMA, Gleason, and ISO methods, the difference in calculated bending can vary by more than 2X. In one case, the gear bending strength and low cycle and high cycle fatigue life is more closely associated with tensile strength, and in the other, it is associated with traditional bending strength. These methods have been used for a long time, and they all work.

SUMMARY

The data provided here indicates that the common factors or "rules of thumb" for converting tensile strength to other load cases are reasonably close. However, the factors do vary with hardness and strength. Figures 1, 2, 3, and 4 show the conversion or multiplication factors vs. hardness to convert tensile strength to compressive, bending, torsional, or shear strength. For compression only, yield strength is shown, as ultimate strength was never reached. In general, the factors are higher for the lower hardness samples. The factors are also different for ultimate and yield strength with the yield being lower.

REFERENCES

[1] Unpublished work done by G. Fett, courtesy of Dana Corporation, circa 2008.

[2] J. Langhart M. Bolze, "Bevel Gear Strength Rating: The Appropriate Combination of FEM with Rating Standards," Gear Solutions, December 2022.

ABOUT THE AUTHOR

Gregory Fett retired from Dana Corporation in 2016 where he was chief materials engineer for nearly 35 years. He has done considerable research and authored numerous publications in the areas of carburized and induction hardened steels. He currently is a materials engineering consultant at Fett Engineering LLC. For more information, contact him at fetteng@gmail.com.