Data-Driven Design Properties For Cast Carbon Steels

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ABSTRACT

Carbon steel is the most common steel alloy. Carbon steel may be the best-known industrial material for use in design for its economic value and reliability in performance. It is nonetheless challenging to find the information needed to efficiently design safe and reliable systems that are man-ufactured from carbon steel. Historically, carbon steels were considered to be the same material with the same properties and design values for all product forms such as forgings, bars, or plates, including castings. Now, design-ers want to know the properties and performance of steel components, based on the manufacturing process as well as the alloy. While the use of steel mill products allows designers to use standard mill products, based on precal-culated load capacity listed in the building construction codes, custom components like castings are more difficult to design. The designer must determine what properties and quality measures to use in the analysis of the compo-nent's safety. Often the design is based on the minimum properties required in the specification with no given context for the actual distribution of properties for these type of products. Mechanical property allowances for design, which are statistically supported for steel castings are not available. Steel Founders' Society of America (SFSA) has collected the ordinary testing results for com-mercial carbon steel heats from a variety of producers, in order to develop an extensive data set of properties. This data set has been analyzed and is compared to steel mill properties, specifications, and allowable design values, which are embedded in the American Institute of Steel Construction-Specification for Structural Steel Buildings (AISC-ASD), and the ASME Boiler and Pressure Vessel Code (ASME BPVC). This analysis demonstrates the capability of carbon steel castings to provide safe and reliable service that is compatible with steel mill products in fabrications or other structures. Statistically supported values for tensile properties for steel castings are reported and compared with other steel products. Significant find-ings show: (1) Carbon steel castings have properties compatible to other product forms such as forgings and mill products. (2) Carbon steel components meet the design allowables included in the ASME BPVC and AISC-ASD requirements with similar properties to other structural steels. (3) The use of net-effective area and a fraction of the UTS for allowable stress design by AISC is comparable to the challenge of creating thick-section complex-geometric design of steel castings. (4) The proposed limit for design, based on the ratio of yield strength to ultimate tensile strength (YS/UTS) provides a reasonable guide for safe and reliable design for steel castings as well as structural steel shapes. (5) The proposed quality index (QI) for steel casting provides satisfactory guidance for the lower bound of commercial cast alloys at 280 ksi. This is also the common upper level of specification requirements.

Keywords: carbon steel, design properties, quality index (QI), yield strength, ultimate strength, test variability, measurement bias, yield strength/tensile strength ratio, design allowables

INTRODUCTION

Carbon steel is the most basic alloy, and the dominant product made of metal that is used in commercial appli-cations. More than 80% of the steel produced by mills is carbon steel. As the most-used alloy of steel, there is inadequate published information to support and enable design engineers to exploit the full value of these common steel products safely and reliably. Design codes, notably the ASME Boiler and Pressure Vessel Code (ASME BPVC) and the structural steel American Institute of Steel Construction-Specification for Structural Steel Buildings-Allowable Stress Design (AISC-ASD), have allowed designers to use the steel mill products like pipes, plates, bars, or wide flange shapes, "I" beams, with confidence.[1,2]

For traditional uses of steel castings that are not critical, part designs become elegant over time. These products experience design flaws and inadequate material properties, which are exposed in casting failures. For other products made in limited quantities, the designs are often overly conservative to compensate for uncertainties in performance requirements and in technical information. This paper intends to help provide a technically sound basis for design, based on the properties of carbon steel castings.

Carbon steel is known as unalloyed steel in the European Union (EU), in EuroNorm (EN), or International Standards Organization (ISO) standards (ISO 4948-1).[3] These common carbon steels have less than 0.30% carbon and less than 1.00% manganese. Carbon–manganese steels with more than 1.00% manganese are carbon–manganese grades but are still considered unalloyed steels. The limits for unalloyed steels in ISO standards are shown in Table 1.

In the ASTM standards for cast steels, there are generally three compositions for carbon steel castings. ASTM specifications are given a letter, based on the committee responsible, and are numbered sequentially. The A committee was the first committee formed and covers steel and iron products. ASTM A6 is the oldest active specification; and it is a general requirements specification for steel bars, plates, shapes and sheet piling. The oldest steel casting specification is A27 which specifies carbon steel castings for general applications. The oldest mill carbon steel material standard is A36, for structural steel.

Cast carbon steel grades are found in a number of ASTM material specifications as seen in Table 2. While the required properties and composition appear different, the actual composition as produced is usually similar. The most com-mon grade produced is ASTM A216, grade WCB.[4] The heat treatment for this grade is normalizing and tempering. The other common grade is ASTM A352 grade LCB, which is quenched and tempered and requires Charpy V-notch testing (CVN). Steel castings were the first product in ASTM to limit the residual elements in carbon steel. This requirement limit can be tightened to ensure weldability by imposing an additional compositional requirement in ASTM A216 S50 or A352 S52 on the calculated carbon equivalent. Common steel casting properties are available from SFSA.[5] An explanation of the specifications cited in Table 2 are also available from SFSA.[6]

Table 1. Limits on Alloy Content for Carbon or Unalloyed Steels Defined in ISO 4948 Part 1

Specified element		Limiting value % (m/m)
Name	Symbol	Percentage
Aluminum	Al	0.10
Boron	Bo	0.0008
Bismuth	Bi	0.10
Chromium	Cr	0.30
Cobalt	Co	0.10
Copper	Cu	0.40
Manganese	Mn	1.65a
Molybdenum	Mo	0.08
Nickel	Ni	0.30
Niobium	Nb	0.06
Lead	Pb	0.40
Selenium	Se	0.10
Silicon	Si	0.50
Tellurium	Te	0.10
Titanium	Ti	0.05
Tungsten	W	0.10
Vanadium	V	0.10
Zirconium	Zr	0.05
Other specified elements (except C, N, P, and S) (each)	–	0.05

When only a maximum value is specified for the manganese content, the limiting value is 1.80%

Steel producers in the U.S.A are required to perform a tensile test for each heat that is made to ASTM steel product requirements. This tensile-test requirement originated early in the history of steel production and specification to qualify the heat of steel. Before modern automated spectrographs, chemical composition was done through titration, using wet methods. The time required to determine the chemistry of the steel and the limit on the number of elements that could be analyzed efficiently, created a challenge for early steel makers and users. To ensure that a heat was not contaminated with unexpected and unanalyzed elements, a tensile test provided assurance that the heat of steel met the expectations of that grade for the mechanical properties after heat treatment. This requirement remains and has created a massive set of producer records of composition, heat treatment, and tensile properties for common alloy steel grades.

Steel Founders' Society of America (SFSA) has collected data from these routine tests for analysis. Steel casting providers would like to give designers and users a better measure of the capability and reliability of performance of the steel castings produced. These data should provide the foundational guidance for the design of components made from common cast steel grades.

Table 2. ASTM Carbon Steel Casting Grades Summary of Composition and Properties Required

ASTM specification	Grade	Composition				Properties					Heat treat	
		C	Mn	C-Mn	Residuals	UTS, ksi	TS, ksi	El %	RA %	CVN ft-lb (°F)	Primary	Allowed
A27	N-1	0.25	0.75	Note 1A27	A781-S54						N/A	As-cast
A27	N-2	0.35	0.6	Note 1A27	A781-S54						A,N,NT,QT	
A27	U-60-30	0.25	0.75	Note 1A27	A781-S54	60	30	22	30		A,N,NT,QT	
A27	60–30	0.3	0.6	Note 1A27	A781-S54	60	30	24	35		A,N,NT,QT	
A216	WCA	0.25	0.7	Note 1A	A216	60–85	30	24	35		A,N,NT	S15 QT
A352	LCA	0.25	0.7	Note 1A	A352	60–85	30	24	35	13(-25°F)	QT	A,N,NT
A27	65–35	0.3	0.7	Note 1A27	A781–S54	65	35	24	35		A,N,NT,QT	
A757	A1Q	0.3	1	Note 1C	A757	65	35	24	35	13(-50°F)	QT	NT
A27	70–36	0.35	0.7	Note 1A27	A781–S54	70	36	22	30		A,N,NT,QT	
A216	WCB	0.3	1	Note 1B	A216	70–95	36	22	35		A,N,NT	S15 QT
A352	LCB	0.3	1	Note 1B	A352	70–95	36	22	35	13(-50°F)	QT	A,N,NT
A915/A958	SC1020	0.18–0.23	0.40–0.80	None	None	70	36	22	30			
A915/A958	SC1025	0.22–0.28	0.40–0.80	None	None	70	36	22	30			
A356	1	0.35	0.7	Note 1A27		70	36	20	35		NT	
A27	70–40	0.25	1.2	Note 1C	A781–S54	70	40	22	30		A,N,NT,QT	
A216	WCC	0.25	1.2	Note 1C	A216	70–95	40	22	35		A,N,NT	S15 QT
A352	LCC	0.25	1.2	Note 1C	A352	70–95	40	22	35	15(-50°F)	QT	A,N,NT
A757	A2Q	0.25	1.2	Note 1C	A757	70	40	22	35	15(-50°F)	QT	NT
A915/A958	SC1030	0.28–0.34	0.50–0.90	None	None	80	50	18	35			

P	S	Si	Cu	Ni	Cr	Mo	V	Total
0.035	0.035	0.80	0.50	0.50	0.50	0.25		
0.035	0.035	0.60	0.30	0.50	0.50	0.20	0.03	1.00
0.040	0.045	0.60	0.30	0.50	0.50	0.20	0.03	1.00
0.025	0.025	0.60	0.50	0.50	0.40	0.25	0.03	1.00

Note 1 A27, For each reduction below the maximum carbon of 0.01%, an increase above the maximum limit for manganese of 0.04% ius permitted up to 1.00%

Note 1 A, For each reduction below the maximum carbon of 0.01%, an increase above the maximum limit for manganese of 0.04% ius permitted up to 1.10%

Note 1 B, For each reduction below the maximum carbon of 0.01%, an increase above the maximum limit for manganese of 0.04% ius permitted up to 1.28%

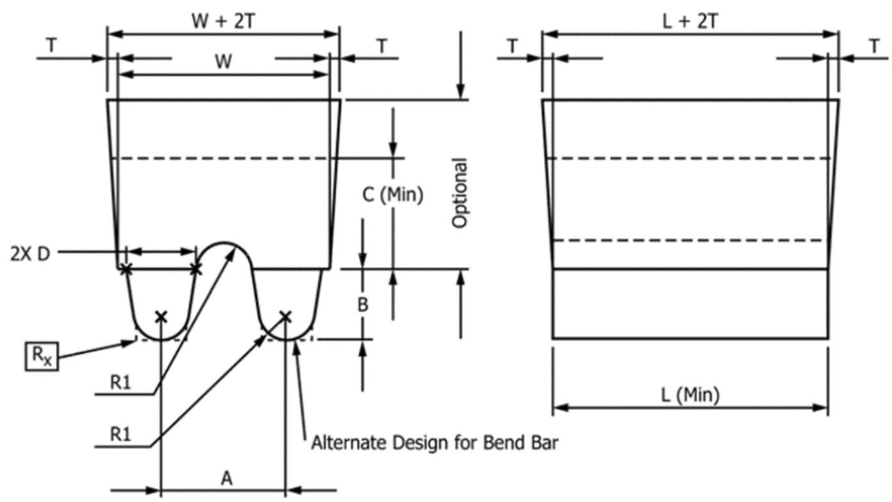
Note 1 C, For each reduction below the maximum carbon of 0.01%, an increase above the maximum limit for manganese of 0.04% ius permitted up to 1.40%

Modern users often believe that the tensile test is required to ensure that the properties of the steel product are above the specification minimum in every location. This is incorrect. To clarify, Appendix X2 in the oldest specification in ASTM still active, A6[7], states:

> ASTM A6/A 6M General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling.
> X2. Variation of Tensile Properties in Plates and Shapes
> X2.1 The tension testing requirements of specification A 6/A 6M are intended only to characterize the tensile properties of a heat of steel for determination of conformance to the requirements of the applicable product specification. Such test procedures are not intended to define the upper or lower limits of tensile properties at all possible test locations within the heat of steel. It is well known and documented that tensile properties will vary within a heat or individual piece of steel as a function of chemical composition, processing, test procedures, and other factors. It is, therefore, incumbent on designers and engineers to use sound engineering judgment when using the tension test results shown on mill test reports. The testing procedures of specification A 6/A 6M have been found to provide structural products adequate for normal structural design criteria.

Steel casting tensile test specimens are required for most grades ordered to ASTM requirements. The grades in Table 2 reference either ASTM A703 or A781 for the general requirements.[8,9] These general requirement standards reference ASTM A1067 for the test coupon used for test material.[10] ASTM steel grades use test coupons to provide material from standard keel blocks, shown in Figure 1.

The test coupon is required to be cast in the same heat and heat-treated following the same procedure used for the castings when ordered as an ASTM steel cast grade. Unlike high-production consumer products, the small lot size and limited production means that the keel block test coupon is used for a wide variety of steel alloy grades, subjected to a range of possible heat treatments and used for castings of complex geometries. It is the responsibility of the customer and designer to relate the steel grade and expected properties to the design and service requirements. This is noted in both ASTM A703 and A781.



Feature	4–leg design		2–leg design	
	in.	mm	in.	mm
A	2¼	60	2¼	60
B	1¼	35	1¼	35
C	2	50	2	50
D	1¼	35	1¼	35
E	Optional	Optional	Optional	Optional
W	8⅜	215	3⅞	100
T	*	*	*	*
L	5 min.	125 min.	5 min.	125 min.
R1	½	12.5	½	12.5
Rx	0 – 1⁄16	0 – 2	0 – 1⁄16	0 – 2

*Use of and size of taper is at the discretion of the foundry

Figure 1. ASTM A1067/A1067M test coupons for steel castings.

Table 3. Repeatability and Reproducibility of Tension Testing Steel ASTM A105 and Brinell Hardness Testing

Property	Average	In Lab Repeatability Standard Deviation	Between Lab Reproducibility Standard Deviation	Repeatability 95%	Reproducibility 95%
Tensile Strength ksi	86.57	0.60	1.27	1.68	2.68
Yield Strength ksi	59.66	0.83	1.44	2.31	4.03
Elongation % 4D	29.10	0.76	0.98	2.13	2.76
Reduction of Area %	65.59	0.84	1.26	2.35	3.53
HBW _10/3000	197.71	4.47	6.72	12.51	18.80
HBW _10/3000	291.25	2.08	6.93	5.83	19.42
HBW _10/3000	502.21	4.74	12.40	13.28	34.71

Table 4. SFSA RR 17 Variability of Tensile Testing in Keel Blocks

Property	Double Leg Keel Block			Multi-leg Keel Block (48 legs)		
	Mean	Standard Deviation	Repeatability 90%	Mean	Standard Deviation	Repeatability 90%
Tensile Strength ksi	78.56	0.656	2.042	78.46	0.629	1.181
Yield Strength 0,2% ksi	44.03	1.126	4.888	43.77	1.136	3.845
Elongation % 4D	31.50	1.60	3.40	28.90	1.90	4.00
Reduction of Area %	53.60	1.90	12.70	46.20	4.30	8.30

> Note in A703 and A781 testing requirements: Information on the relationship of mechanical properties determined on test coupons obtained as specified in XX with those obtained from the casting may be found in The Steel Casting Handbook, Fifth Edition, Steel Founders' Society of America, pp. 15-35 through 15-43, 1980.[11]

This question is addressed in a summary of published work on the testing of cast steel heats on expected cast product properties.[12]

TENSILE TESTING LIMITATIONS

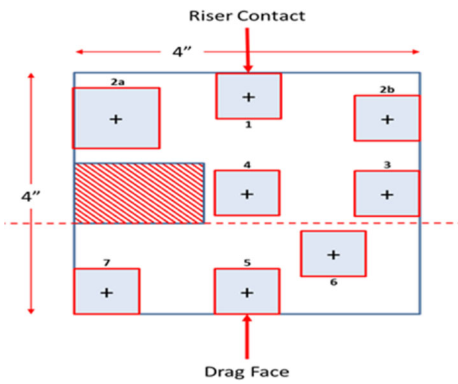
All tests including tensile tests give results that vary. The test results include not only the signal, the value of interest, but also noise, a variation that is not attributable to the property of interest. Tensile test results have limited accuracy and precision. This is true for the test, even when the material is not variable. ASTM recognizes this limitation of testing, that tensile testing does not give an invariant accurate value. In ASTM test methods, a statement of their precision and bias is required. The Form and Style Manual for ASTM Standards in Section A.21 makes this statement mandatory.[13] For tensile testing, this is included in several publications and codified in ASTM E8 Appendix X1.[14–17] The same type of information for Brinell hardness testing is reported.[18] The repeatability and reproducibility of tensile test properties and Brinell Hardness testing is given in Table 3.

Test uncertainty for ASTM A105, a steel cited in ASTM E8 X1 to determine tensile test precision and bias, has similar properties to the cast steels in the SFSA data. The variability of testing alone for ultimate tensile strength (UTS) is from 1.27 to 2.68 ksi. For yield strength (YS), it is higher; 1.44 to 4.03 ksi. For elongation (El), the variability is from 0.76 to 2.76% and higher for reduction of area (RA), 1.26 to 3.53%. The Brinell hardness test (HBW), which has a reproducibility for 198 HBW for a 10-mm tungsten carbide ball indenter with a load of 3000 kgf is 18.80 as shown in Table 3.

In addition to the test variability on identical material, testing steel products has other confounding factors in measuring the tensile properties. These include the variation of properties by location, the size of the microstructure compared to the test specimens, and the quality of the test bar.

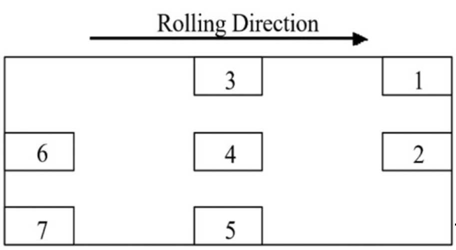
The variability of tensile testing has been a perennial concern for steel casting producers and users. It was the subject of early research sponsored by SFSA. A carbon steel heat was cast in a standard test block, similar to the block in Figure 1. A second keel block with 48 legs was tested out of the same heat. Twelve samples were tested and reported. The results of these tests are in Table 4. Note that the double leg keel block tensile test results have a repeatability similar to the reproducibility seen in test uncertainty of the tensile test itself.

Table 5. Variation of Tensile Properties in Different Locations in a Test Block



Alloy	ID	Gage Diameter	UTS ksi	YS ksi	Elongation %	RA %
WCB	0719-1	0.25″	72.9	41.5	33	54
WCB	0719-2A	0.505″	74.3	43.1	35	66
WCB	0719-2B	0.25″	75.9	44.8	35	69
WCB	0719-3	0.25″	76.0	49.9	35	69
WCB	0719-4	0.25″	73.9	42.9	34	65
WCB	0719-5	0.25″	76.0	44.7	35	70
WCB	0719-6	0.25″	74.8	43.6	35	67
WCB	0719-7	0.25″	75.5	47.2	34	68

Table 6. Variation of Tensile Strength in Different Locations for 79 Structural Steel Plates



	avg	max	min
UTS ksi			
Std	1.18	2.82	0.29
Range	3.17	7.70	0.80
YS ksi			
Std	1.72	6.19	0.26
Range	4.69	16.30	0.70

In this required testing, test samples that had visible porosity, inclusions or other features that would affect the test results were discarded. Many of the early property data sets were cleaned up by discarding data that appeared to be in error. Since the intent of the tensile test in ASTM steel standards is to characterize the heat of steel and not the test bar quality, non-representative test bars with these features are discarded and replaced with results from sound bars. This is formalized in ASTM A703 Clause 13 and A781 Clause 12.[8,9]

Compliant heats of steel have more than just the testing variability, as seen in the variation in Table 4. SFSA has been analyzing the properties of various locations in test blocks used for compliance testing of heavier section castings. Properties from a 4x4 inch test block are shown in Table 5. The sample test bar used for the reported properties is WCB 0719-2A and located in the red checked section in the block drawing. The variations in different test block locations are common in production testing. The strength levels routinely vary by 10 ksi, and the El varies by 3%, and the reduction of area varies by 10%.

The variation of tensile properties by location is not a factor unique to casting. A statistical study of structural plate mechanical properties was conducted with samples taken from seven locations, as seen in Table 6. For each plate, the standard deviation and range of values were calculated. This table indicates the average for all plates, the minimum and maximum value for the standard devia-tion, and the range. The average range of values for UTS was 3.17 ksi and for YS was 4.69 ksi. The maximum range in a single plate for UTS was 7.70 ksi and for YS was 16.30 ksi. This data set does not report El or RA but only the YS/UTS as a measure of ductility. As declared in the ASTM A6 X2 note, the properties in steel products vary by loca-tion, and the specification tests for the heats are no guar-antee that the required minimum properties will be present in every location in the product.[19]

ANALYSIS OF CARBON STEEL PROPERTIES FOR DESIGN AND PERFORMANCE

STRENGTH

Typical design strategies for steel casting components for static loads use YS as the design-limiting property. Cast components are designed not to exceed the YS when subjected to the highest anticipated load in service or in possible or expected misuse. Finite Element Analysis (FEA) modeling is used to assess the service loads on proposed designs. Some fraction of the YS is used to qualify the design as fit for service. This fraction becomes lower if the component is critical or if it is subjected to fatigue loading. A common design value to use is one half of the YS since that gives a generous margin of safety, offers an approximation of the fatigue limit for many steels, and provides an approximation of the maximum shear loading from the performance loads on the compo-nent. Castings are also often given an additional casting factor, reducing the allowed load, in order to deal with the quality uncertainty in their performance.

Since the UTS is the most repeatable and reproducible tensile test measurement, in this work, it was evaluated and then used to categorize the data. Using UTS has another benefit: it is fundamentally related to hardness. Hardness is a tool available to purchasers to confirm the properties in a casting shipment or at a location of interest in the part. Showing the relationship of other properties to UTS is a useful tool set for understanding performance and capability of steel cast grades.

DUCTILITY

To ensure that the component does not have a sudden failure, the steel part is expected to demonstrate some deformation prior to failure. To ensure yielding prior to failure, El is used as a measure of safety in the design. El is not a material property directly used in design but gives an indication of the ability of the steel to plastically deform when loaded beyond the yield strength prior to fracture for a standard uniaxial small-uniform-cross-section tensile bar. In many steel casting components, thick sections and geometric constraint on steel casting designs limit the amount of plastic deformation when the casting is loaded to failure. Even ductile failures in thick-section constrained component geometries do not exhibit much deformation when loaded to failure.

No fundamental property of ductility can be used in design that is characterized in a standard tensile test. When ductility is measured by elongation and reduction of area, the values needed are based on experience or rules of thumb but not on the performance needs. Steel is a safe material with structural steels having elongations in excess of 10%, allowing traditional strength-based designs. The value of 10% is a common rule of thumb for metals to be treated as performance limited by strength and not by ductility. A typical design text indicates that the elongation needs to exceed 5%, and the strength in tension and compression needs to be the same for a metal to be considered ductile.[20]

Elongation and reduction of area both measure relatively uniform plastic deformation and then severe local deformation, after necking begins. Non-uniform material or geometric features like machining marks develop stress concentrations that localize failure and reduce the measured gross elongation or reduction of area. This is seen when notched tensile samples are tested.

STRESS CONCENTRATION

This stress concentration effect in notched tensile bars is well known and has been extensively studied to understand fatigue and fracture. In fatigue, it was traditionally expressed as a notch sensitivity. For fracture, the testing of fracture toughness with carefully designed specimens that are used to provide adequate constraint in order to develop plane strain, evaluates the resistance to cracking. For crack-resistant steels, dynamic tear tests are used in pipeline steels and naval vessels, to evaluate not only the ability of the alloy to resist initiating a crack but to stop crack propagation.

For common structural steels, stress concentration localizes the plastic deformation response to the load. The inability for the bulk sample to deform to retain constant volume or Poisson's Ratio requires a higher load to yield but allows less plastic deformation in failure. This can be seen in Figure 2, where the effect of a notch of increasing severity is shown.[21] As the notch becomes sharper, the stress concentration increases, and the strength increases, while the elongation drops.

This notch effect is apparent in routine tensile tests when the test bar is not sound. If the test bar has a large inclusion or porosity, the El drops dramatically. The strength levels are less affected, unless the inclusion or porosity is large, relative to the bar's loaded gage section area.[22–24] This is due to the inclusion or porosity acting as a geometric notch, not as a material property, so that the unsound bar acts like the notched bar shown in Figure 2.

This effect can be seen in some published work on through-thickness properties in steel products.[25] After the Norridge earthquake with many steel frames failing at the beam-column connections, through-thickness properties of steel mill shapes became an area of interest. For steel mill products containing normal quantities of sulfur and oxygen as second-phase inclusions, the rolling process deforms these inclusions. If the inclusion starts after solidification as a sphere, it becomes an elongated pancake in the direction

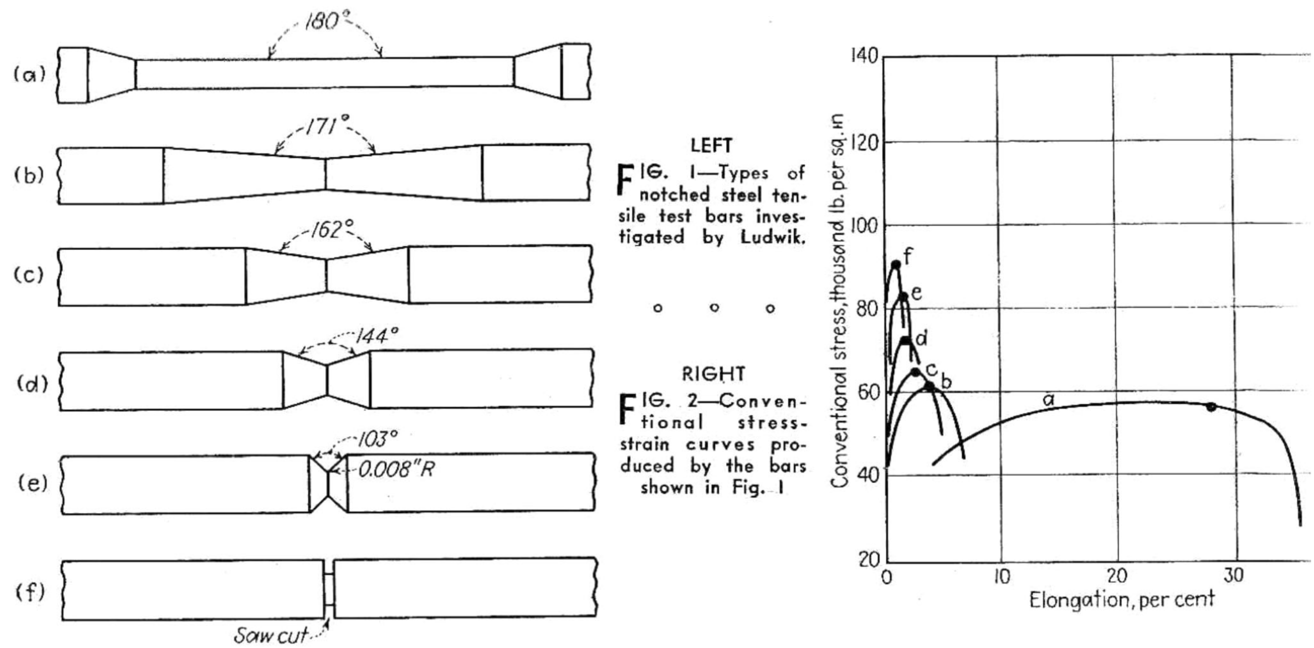


Figure 2. Effect of notch on the strength and elongation of soft steel.

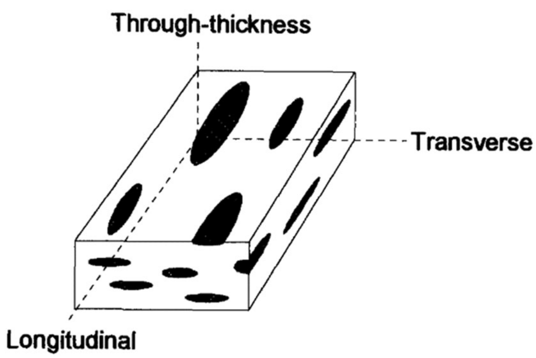


Figure 3. Effect of rolling on inclusion shapes in steel mill products.

of rolling as seen in Figure 3. The properties of strength and ductility are improved longitudinally in the direction of rolling, modestly reduced in the transverse direction, and most reduced in the through-thickness direction, also called the short transverse.[25]

This evaluation utilized data from plates, shapes, and continuous-cast strands to compare properties in these product directions. There was little difference in strength and ductility between the properties in the longitudinal and transverse directions for these products. The majority of the data showed that the through-thickness UTS strength exceeded 0.95 of the longitudinal UTS. Considering the full data set, a conservative value for the through-thickness UTS would be used as 0.80 of the longitudinal UTS. The YS of the through thickness for design is recommended to be 0.90 of the YS in the longitudinal direction.[25] This is shown in Figure 4.

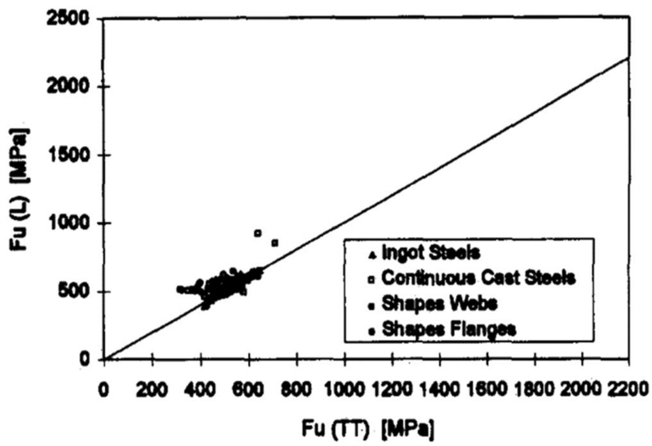
The graph on strength underplays the effect on the strength, at 500 MPa (72.5 ksi) in the longitudinal direction; the through-thickness UTS is as low as 300 MPa (43.5 ksi). The through thickness RA values are consistently well below the longitudinal values. These reductions were shown to be the effect of the sulfur content of the steel as seen in Figure 5.

YIELD STRENGTH-ULTIMATE TENSILE STRENGTH RATIO

As structural steel users have tried to incorporate higher-strength steels in designs, the problem of safety in designs that have stress concentrations has been an issue of concern. In bolted connections, the failure of an overloaded connection often will occur at the bolt hole with little shear or other evidence of plastic deformation prior to failure. To ensure safe and reliable designs in component geometries that may not deform but have been shown to be safe and reliable, the YS/UTS has been used.[22]

Some specification limits on the YS/UTS ratio are shown in Table 7. [22,26]An effort has been undertaken to develop a design approach that utilizes the ratio to ensure an adequate design. This effort has proposed an upper bound of the ratio for design, as shown in Figure 6. [22,26] This upper bound can be used to assess the structural steel and steel casting data sets.

Since all products have a range of quality features that limit performance, from point defects in the crystal structure to gross porosity or segregation, SFSA work has been done to determine what effect quality details have on component performance.



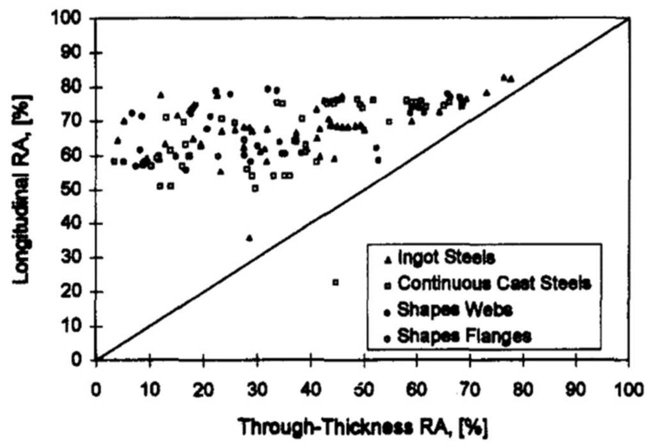


Figure 4. The differences of ultimate strength and reduction of area between samples tested in the longitudinal and through-thickness directions.

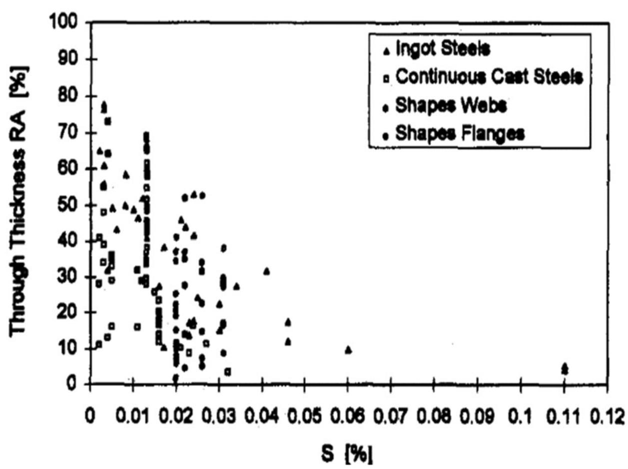


Figure 5. The effect of sulfur content on the through-thickness reduction of area.

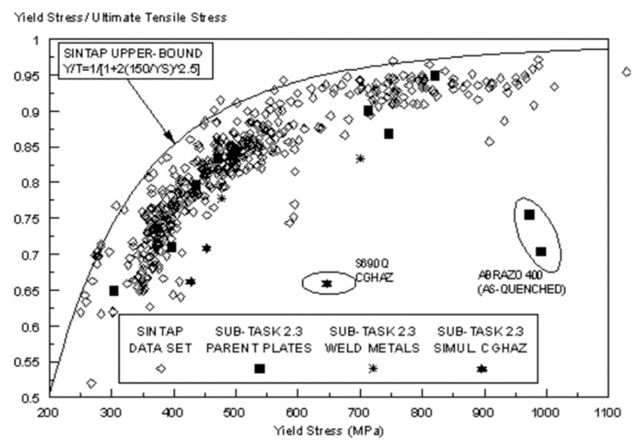


Figure 6. Yield strength/ultimate tensile strength ratio as a function of yield strength.

Historically, quality details were considered independently from material properties. Mechanical properties were developed for the steel, with tensile tests on sound bars. Quality limits on performance were managed by requiring NDT levels on parts.

Steel products have interdendritic segregation and micro-porosity, which affect the tensile properties. Larger inclusions, segregation or porosity can have a more severe effect, lowering the properties of steel products locally. One benefit of rolling or forging the steel in the process is that it reduces the segregation and porosity and gives the product more uniform properties.

In Figure 7, cast steel bar tensile specimens were made with sound bars, bars with varied sizes of NDT surface indications, and bars with holes drilled halfway through the thickness of the bar.[27,28] The NDT indications were shallow and did not significantly reduce the cross section of the bar. The holes drilled in heat 2 gave the lowest values for UTS and El, significantly lower than NDT indications of the size of the hole diameter. Indications and holes over 0.1 inches reduced the El dramatically, as seen in Figure 7. The non-sharp drilled holes having the largest effect showed that this is a case of geometric stress concentration causing local plastic collapse and not cracking due to a sharp notch causing sudden failure below the YS. This work is consistent with recent publications identifying the effect of local quality on component performance.[29]

In other work given in Table 8, large cast plate samples that were sound or that were unsound and contained radiographic indications were tested.[30] The maximum indication length, perpendicular to the loading direction, was measured and then the samples were tested. The plates were either 15 or 18 inches long, 5 inches wide and 1 inch thick. Test samples were 0.75 inches thick, 3.4 inches wide, with a uniform gage of 6 inches. The radiographic indication measurement was the percentage of the width of the test bar. Only two samples showed YS values below the sound bar, and the lowest value was 92% of the sound value. As expected, ductility dropped significantly. The test specimen

Table 7. Limits to YS/UTS Ratio for Mill Products in Accordance with Various Design Codes

Code and application	Country	Maximum allowed Y/T ratio
API 5L (Pipeline)	USA	0.93
HSE Offshore (Guidance Note)	UK	0.70
BS 5950 Buildings	UK	0.84
Eurocode 3 (Buildings and Bridges)	EU	0.91
BS 5400 (Bridges)	UK	0.83
NS3472 (NPD) (Offshore)	UK	0.83
EPRG (European Pipeline Working Group)	EU	0.88–0.93
DIN 18800 Construction Code	D	0.813
EU-RID Rules (Tankers for carriage of dangerous goods)	EU	0.85
Ship building, Pressure Vessels, Storage Tanks	–	No Limits Specified

with largest indication fraction, E4, gave a low ductility but had a low YS/UTS ratio. The indication was 57.69% of the specimen width, the El was still above 10%, and the YS/UTS was 0.68. The low YS/UTS ratio shows that the even with the largest RT indication, the material was ductile.

QUALITY INDEX

Aluminum casting producers have developed a QI to assess the performance of their standard alloys. This index combines the UTS with the El to indicate the onset of necking in the tensile test. It has been used as a method to monitor aluminum quality that may be compromised by porosity. Due to this use in aluminum, the effect of test bar quality could be measured by using the concept of a quality index. This factor has been proposed for use in steel castings.[31,32]

Similar to the study of the effect of surface quality indications identified during NDE, SFSA has evaluated test samples with indications, drilled holes, and sound samples in order to explore the concept of the QI. This allows the assessment of the effect of surface quality limitations on the tested tensile properties. Based on an analysis of ASTM A148 and the results of this testing, a QI was proposed:

$$QI = UTS\ (ksi) + 150 * \log(El\%) \qquad \text{Eqn. 1}$$

This proposed QI factor is plotted in Figure 8.[31–33] The lines in the graph are lines of constant QI and where they cross the UTS axis at 1% EL is the QI value in psi. The 1025 and 70-40 data for sound bars slightly exceed the QI of 300,000 psi or 300 ksi. As expected from Figure 7, large indications decrease the EL significantly but have a small effect on UTS, until they compromise the cross section. As expected, the samples in Figure 7 also have lower QI values.

SFSA TENSILE DATA SET ANALYSIS

As noted above, carbon steel is the dominant alloy class for all steel production. It represents over half the steel produced for steel casting production. SFSA has collected over 15,000 data points of cast carbon steels in the normalized and tempered (NT) and quenched and tempered (QT) conditions. At a minimum, the data for each heat contains the chemical composition and the tensile properties. These test results come from the spectrographic analysis of the heat for chemistry and a tensile test from the standard keel block. The type of heat treatment was given but not process details.

This analysis separates the alloys into two groups corresponding to the two most common heat treatments: normalized and tempered (NT) or quenched and tempered (QT). Most of the heats are ASTM A216 Grade WCB. This category also includes other similar compositions and requirements for NT processed heats as seen in Table 2. For the analysis, this group of data is designated WCX NT. For carbon steels that are QT commonly requiring higher strength or having minimum toughness requirements supported by Charpy testing, the carbon steel is typically ordered to ASTM A352 Grade LCB and this group of data is designated LCX QT.

The assessment of steel casting with routine tensile testing has limitations. Efforts to predict or control properties that exceed the capability of the tests or the uniformity of the material are not possible. One challenge from current information technology-driven techniques like artificial intelligence or machine learning, is overfitting: predicting properties with a precision that exceeds the measurement capability.

Apart from the limitations of testing and sampling to determine the performance of a steel heat and the products made, the bias involved in testing can corrupt the usefulness of the data in production records. Bias is not necessarily a dishonest falsification of test results. When test results marginally fail to comply with the specification requirements, it is natural and correct to review the results to make sure that the failure to meet the requirement was an accurate assessment.[34–36] In tensile testing; the ability to remeasure elongation, re-evaluate the test chart, or even to discard a sample that has a machining mark or flaw, introduces bias. This bias toward compliance is most evident when the properties measured are close to the limits of the specification requirements.

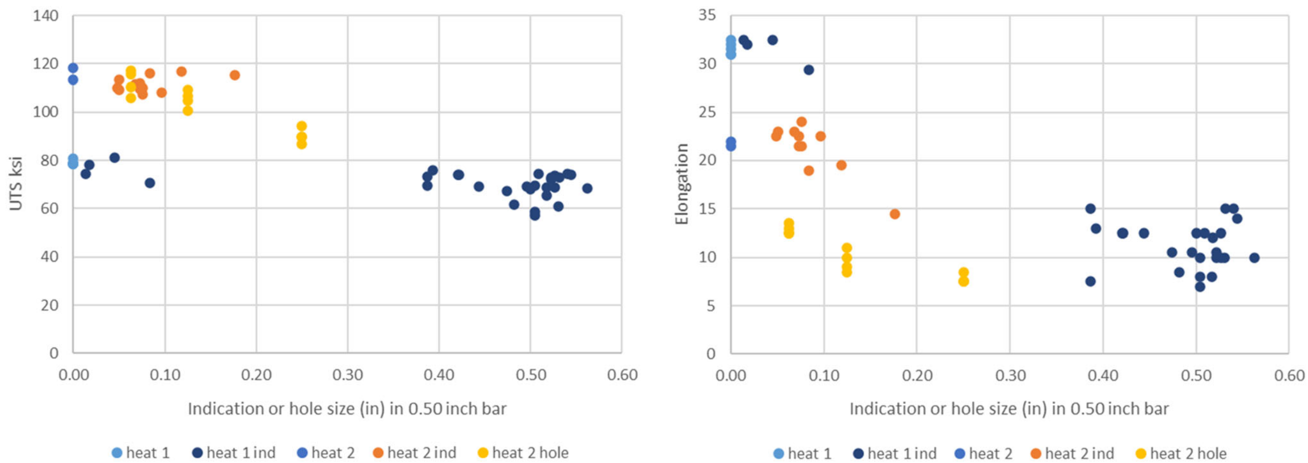


Figure 7. Two heats of cast steel with sound bars, bars with NDE indications and bars with drilled holes.

Table 8. Tensile Properties of Sound and RT Indications Plate Samples that Were Tensile Tested

Plate ID	Max. Ind. Fraction	Elastic Modulus (ksi)	Yield Stress 0.2% (ksi)	UTS (ksi)	Elongation
D1	46.15	26,096	51.01	NA	NA
D2	45.19	25,109	55.65	83.05	16.00
D3	50.00	26,055	56.35	83.49	16.30
D4	44.23	25,260	54.39	80.41	12.80
D5	35.58	19,907	54.15	83.51	17.10
E1	42.31	22,796	47.75	78.61	19.60
E2	45.19	23,586	53.38	81.52	13.80
E3	50.96	24,971	51.53	77.17	15.00
E4	57.69	25,927	52.52	76.24	13.80
E5	49.04	24,518	50.65	78.88	17.00
Sound data	NA	27,600	51.76	80.65	22.00

So, a critical task of data base management, prior to assessment and technical modeling, is to do initial evaluations to identify data entries that should not be included in the critical analysis or modeling efforts. One approach, documented in ASTM E178, is the practice for dealing with outlying observations.[37] This process divides the reasons to drop a data point from analysis into physical reasons known as an outlier or a statistical test that iden-tifies outliers with no known physical reason but a reason is assumed to exist. For critical design values, it is common to do a statistical lower-bound property value based on three standard deviations below the mean property value of the pertinent full data set. For technical performance or engi-neering information, two standard deviations are used to exclude outliers in order to get the cleanest signal for the properties of the data set.

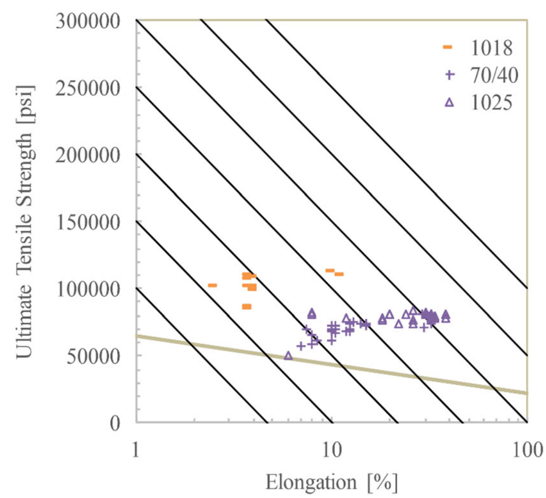


Figure 8. Quality index for steel with cast carbon and mill steels data plotted.

The distribution of ultimate tensile strength in the data sets are shown in Figure 9. The strength of the LCX QT grades is higher than the WCX NT grades as expected from the heat treatments. For these grades, 70 ksi is the minimum requirement for ultimate strength of the standard, and 95 ksi is the maximum allowed. The lower, flat section at 70 ksi and the upper flat section at 95 ksi are the result of the bias from these specification limits. Tensile tests that are outside of this range are discarded and not retained in the data set. The use of the data distribution to determine the standard deviation allows a lower bound value to be identified for the properties even with the discarded outliers.

For WCX NT grades, if the composition is low in alloy content, then the tempering cycle for the heat treatment can be lowered to raise the strength level to meet the minimum requirement. This leads to a large group at 70 ksi. For both the WCX NT and LCX QT, if the grade is alloy rich, and the test shows strength above the maximum limit of 95 ksi, the heat treat can be modified and redone to reduce the

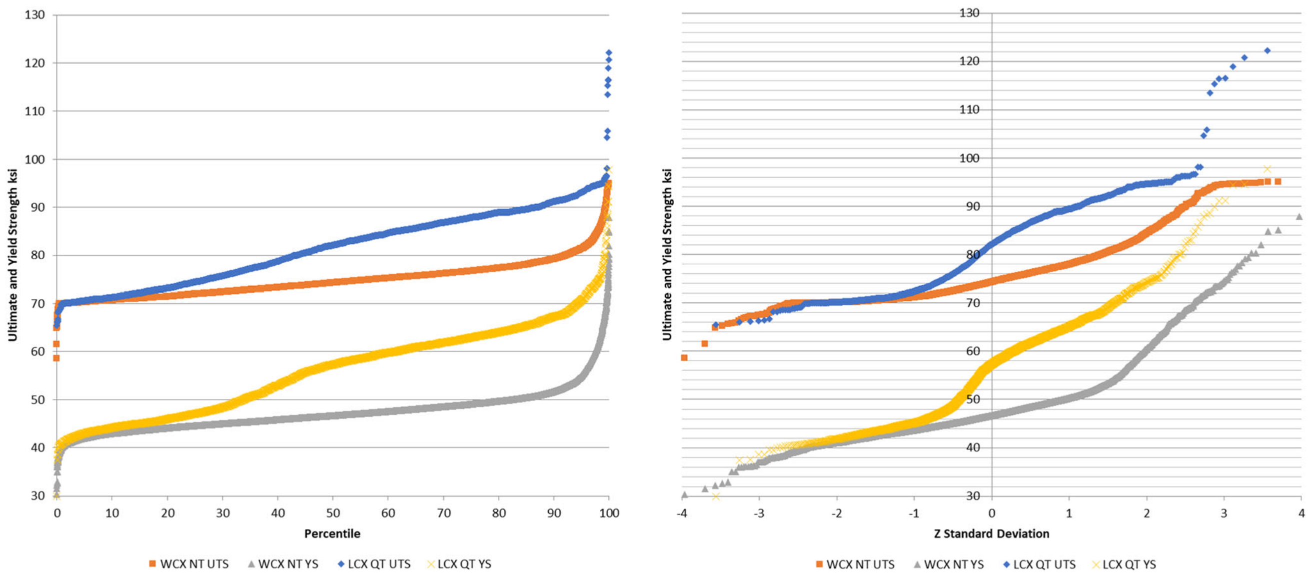


Figure 9. Probability distribution of ultimate and yield strength of carbon steel cast grades, (a) percentiles on the left (b) normal probability on the right.

strength and meet that requirement. This gives the flat section at 95 ksi.

For the LCX QT grades, CVN testing for toughness is a requirement when this grade is ordered to ASTM A216. To meet this requirement, the grade may be heat treated to a lower strength, in order to marginally meet the minimum strength required to maximize the toughness of the heat. This gives the flat section at 70 ksi for the LCX QT grades at low strengths. Properties below 70 ksi or above 95 ksi are not used to certify compliance and can be dropped from the commercial records. This should not materially affect the distribution lower limit set by the bulk of the data enclosed within the two standard deviation section.

For safety-critical designs, a lower bound for strength might be selected at three standard deviations below the mean. For WCX NT, this would give a design value for UTS of 67.5 ksi and for YS a value of 37.0 ksi. For a two standard deviation, lower bound design strength for a general application would be 70.1 ksi for the UTS and 41.0 ksi for YS. A three-standard deviation lower bound value for LCX QT would be 66.3 ksi for UTS and 38.6 ksi for YS. It would be 70.1 ksi for UTS and 41.8 ksi for YS for a two-standard deviation lower bound design strength. It is worth noting that the two standard deviation lower bound UTS and YS levels for LCX and WCX are just above the common specification minimum requirements.

The common requirement for minimum yield strength for these alloys is 40 ksi but some grades only require 36 ksi as seen in Table 2. This is seen in Figure 9 in the flat section at 40 ksi. Recall that heats that are close to the requirement are often re-examined or retested and only if they comply

Table 9. Structural Steel Average Properties by Bins from UTS

UTS, ksi	YS, ksi	El %	YS/ UTS	Count
62.71	36.50	36.40	0.582	9
66.53	43.32	31.70	0.649	9
73.55	51.51	32.20	0.700	9
76.71	55.61	30.80	0.725	9
79.35	51.83	28.90	0.653	9
81.07	58.82	31.00	0.725	9
83.46	62.03	30.80	0.743	9
87.30	65.47	29.80	0.750	9
89.79	69.44	27.40	0.773	9
92.02	68.52	25.60	0.745	9
93.06	74.34	21.60	0.799	9
93.86	74.19	23.75	0.790	11
Average standard deviation				
0.88	4.73	4.24	0.056	
Data standard error correlated with UTS	5.15	4.57	0.063	
Data R^2 for correlation with UTS	0.83	0.37	0.457	
Data slope for correlation with UTS	1.15	–0.35	0.006	
Data intercept for correlation with UTS	–34.76	57.62	0.253	

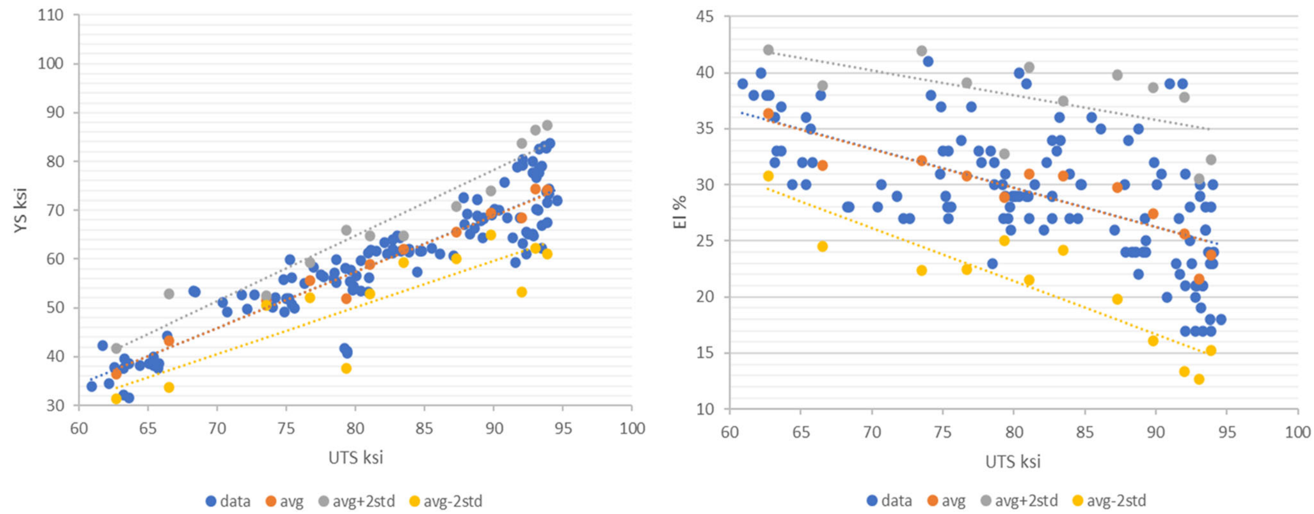


Figure 10. Structural steel of YS and El based on UTS including the full data set, the bin average and that bin average plus and minus 2 times the standard deviation.

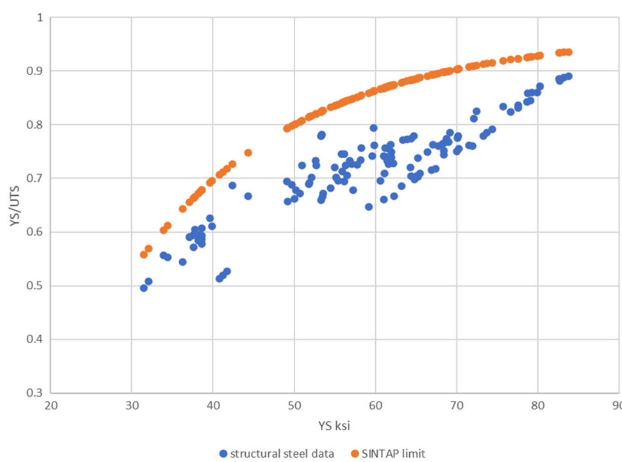


Figure 11. Structural steel plot of YS/UTS ratio of data set including the proposed upper limit from SINTAP.

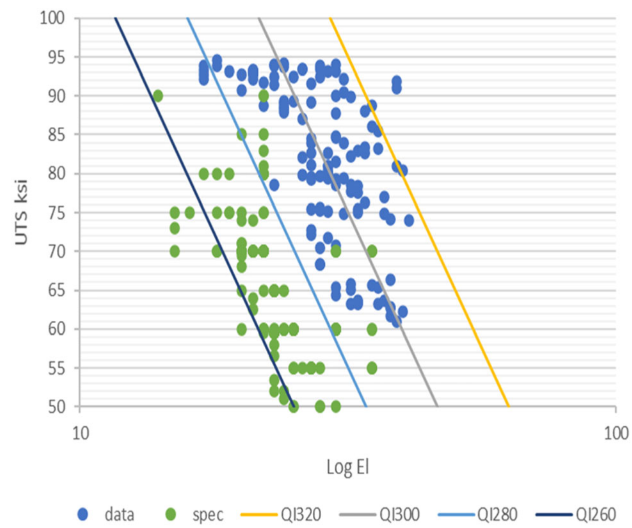


Figure 12. Structural steel plot of QI based on data set including common specification for minimum properties of structural carbon steel alloys.

are added to the data set. This common compliance bias is ubiquitous in commercial testing.

In addition to having the compliance bias and non-normal character, the lack of precision in commercial testing and the narrow ranges allowed for the properties results in data that is inherently noisy. The UTS measured in different locations in a block reported in Table 5 is 73 to 76 ksi or varies by 3 ksi. This is more than 10% of the entire range allowed for carbon steel, 70 to 95 ksi.

This project evaluation of cast carbon steels considers the UTS, YS, El and HBW as key properties for design and material qualification. There are a number of common relationships between these properties that are characteristic of other product forms made from carbon steel. Using the SFSA data set allows comparison of cast grades to other product forms and design values. Many of these common relationships rely on the UTS measurement.

This includes the yield strength/ultimate strength ratio (YS/UTS), the correlation of hardness and ultimate strength, and the combination of ultimate strength and elongation in a Quality Index (QI).

STRUCTURAL STEEL PROPERTIES

The variability of YS and El compared to UTS is not a casting data issue but is similar to the noise seen in data for structural steels.[38] The data for structural steels was binned in groups of 9 data points because of the limited data published. Bins were used to calculate average and variability that were about 10% of the data based on ultimate strength as shown in Table 9. This data is shown in Figure 10.

Table 10. WCX Normalized and Tempered Average Properties of Commercial Alloys by Bins from UTS Including a Count of Number of Entries in the Last Column

Count	UTS, ksi	YS, ksi	%El	YS/UTS
9	63.21	43.90	31.1	0.695
9	67.07	42.71	32.9	0.637
13	67.74	43.20	32.5	0.637
20	68.99	44.88	32.0	0.641
914	70.21	44.09	34.0	0.622
1766	70.99	44.64	33.6	0.622
1431	72.00	45.07	32.7	0.623
1391	72.98	45.64	32.7	0.622
1404	73.96	46.50	32.3	0.624
1430	74.99	47.43	32.0	0.629
1386	75.97	47.90	31.6	0.630
1138	76.97	48.97	31.5	0.635
768	77.91	49.66	31.5	0.636
562	78.93	50.31	31.4	0.635
338	79.95	51.67	31.1	0.639
257	80.98	51.85	30.8	0.638
165	81.93	52.34	30.8	0.635
112	82.93	52.96	30.0	0.639
69	83.99	55.45	30.3	0.670
69	84.96	58.18	29.7	0.669
51	85.96	57.44	29.1	0.664
37	87.00	57.78	30.3	0.652
34	87.90	60.65	29.7	0.699
18	89.07	56.53	27.8	0.651
43	89.63	61.12	28.1	0.706
14	90.86	63.12	30.1	0.717
5	91.77	65.43	27.7	0.720
18	92.90	62.62	27.7	0.660
20	94.14	65.85	27.3	0.726
14	94.76	67.90	29.9	0.727
Std	0.40	4.96	10.31	0.06

The last row has the average standard deviation for the bin for each property included.

The standard deviation for each bin is averaged and presented below the property data. For the UTS, this is small because the bin is defined by the UTS, and the standard deviation is the width and dispersion in the bin. For the other properties, the standard deviation shows the variability of the property at a similar UTS. The standard error is a similar measure of how far data points are from the regression line with UTS. Comparing the average standard deviation for the bin with the standard error gives a measure of how variable the measurement or property is for

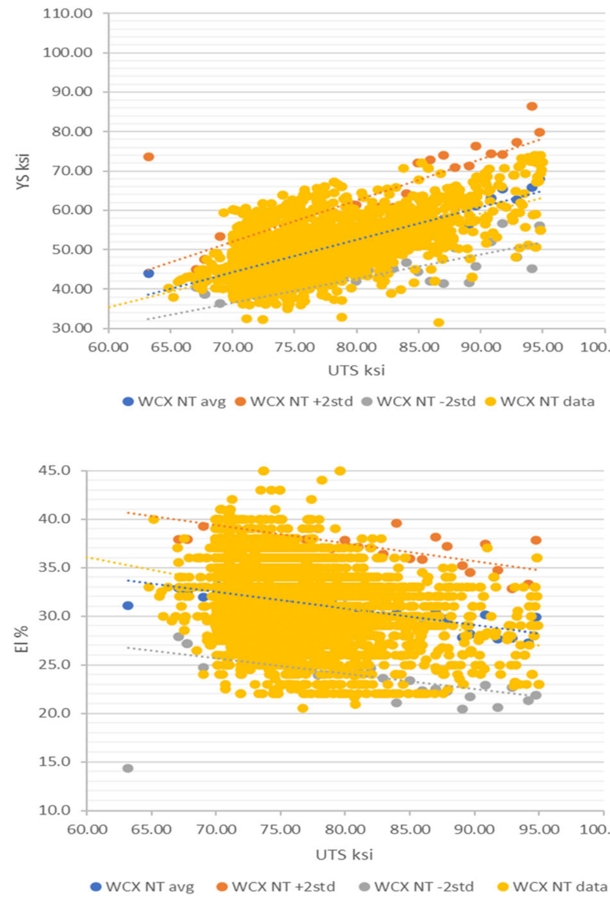


Figure 13. WCX normalized and tempered plot of YS and El based on UTS including the full data set, the bin average and that bin average plus and minus 2 times the standard deviation.

nominally the same steel. For example, the YS has an average standard deviation of 4.73 ksi and the regression gives the standard error of the regression to be 5.15 ksi. These values are larger than the test uncertainty of those from the test block or early variability studies. This is expected since these are not tests from the same heats or the same products. This is a useful data set to compare to the SFSA data set below which has similar make up.

One of the first relationships that can be evaluated in carbon steel products is the one between yield and ultimate strength. For a single alloy grade with a common heat treatment, YS should be tightly correlated to UTS. Few recent data sets of common structural steel properties are available but one set which was developed after the World Trade Center disaster provides limited data on common structural steels.[38] This set includes the UTS, YS, El, and RA and allows an analysis parallel to the SFSA data set.

Structural steels are welded onsite into structural fabrications, so they are predominantly carbon steels with alloy limitations. This makes them a good comparison for the cast carbon steels in the SFSA data set. The relationship

Table 11. WCX Normalized and Tempered Regression Equations of Commercial Heats for the Data and Averages for UTS

	Independent factor "x"	Dependent factor "y"	Slope	Intercept	R^2	Standard error	Bin avg standard deviation
WCX NT data	UTS, ksi	YS ksi	0.80	−12.39	0.63	2.20	
WCX NT avg	UTS, ksi	YS ksi	0.83	−13.74	0.95	1.81	4.96
WCX NT +2std	UTS, ksi	YS ksi	1.05	−21.48	0.69		
WCX NT -2std	UTS, ksi	YS ksi	0.61	−6.00	0.59		
WCX NT data	UTS, ksi	El %	−0.26	51.56	0.09	2.90	
WCX NT avg	UTS, ksi	El %	−0.17	44.58	0.75	0.92	3.35
WCX NT +2std	UTS, ksi	El %	−0.19	52.39	0.45		
WCX NT -2std	UTS, ksi	El %	−0.16	36.78	0.22		
WCX NT data	UTS, ksi	YS/UTS	0.0020	0.4800	0.06	0.0289	
WCX NT avg	UTS, ksi	YS/UTS	0.0025	0.4546	0.45	0.0258	0.0617
WCX NT +2std	UTS, ksi	YS/UTS	0.0033	0.5192	0.09		
WCX NT -2std	UTS, ksi	YS/UTS	0.0018	0.3900	0.05		

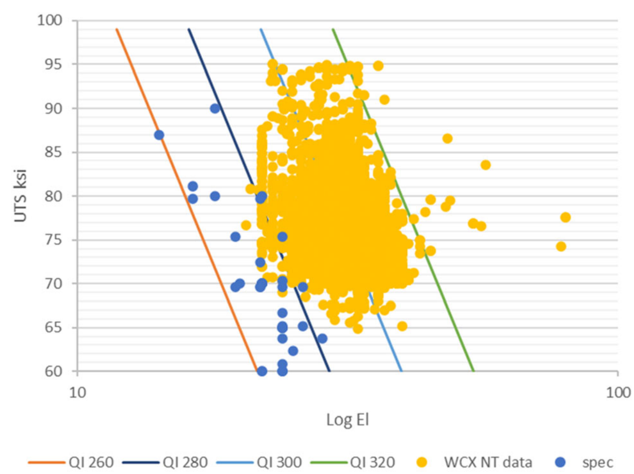


Figure 14. WCX normalized and tempered plot of Quality Index based on UTS including the full data set, and the bin average and includes the specification requirements of common cast steel grades.

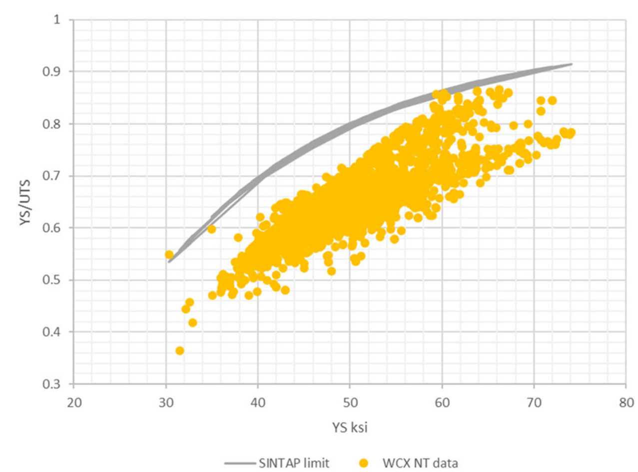


Figure 15. WCX normalized and tempered plot of YS/UTS ratio based on YS including the full data set, the bin average and that bin average plus and minus 2 times the standard deviation and includes the maximum allowed ratio based on The SINTAP analysis.

between the YS, EL, and UTS for the structural steels cited are shown in Figure 10.[38]

The ductility as measured by the El decreases as the strength level increases. The average standard deviation for El for the UTS bins is 4.24% and the standard error for the linear regression is 4.57%. This is shown in Table 9 and Figure 10. The variation for El is much more significant than for yield strength. The R^2 value of 0.37 shows the effect of the slight slope and the large scatter. This is consistent with the difficulty in the measurement and the test uncertainty.[38] The data for the structural steels we used to calculate the YS/UTS ratio and plotted with the upper limit for the ratio proposed by SINTAP in Figure 11. As the yield strength increases, the ratio increases. This curve is not linear and approaches 1 at high YS levels. This could be a factor used in specifications to define the upper UTS allowed for a heat. This factor is used as an upper bound measure of safety for geometric sections that are constrained and would experience stress concentrations if loaded to failure. The inability to deform due to this stress concentration would finally result in failure at the ultimate strength. An upper bound for the ratio for safety was given in Table 7 and shown in Figure 6.

Table 12. LCX Quenched and Tempered Average Properties of Commercial Alloys by Bins from UTS Including a Count of Number of Entries in the Last Column

Count	UTS, ksi	YS, ksi	El%	YS/UTS
12	68.80	42.23	29.6	0.614
95	70.20	44.66	34.0	0.636
186	70.99	44.98	33.7	0.634
135	72.02	45.48	33.4	0.631
126	73.02	45.66	32.4	0.625
99	73.98	47.07	32.8	0.636
109	75.01	47.75	32.1	0.637
96	75.95	48.64	32.0	0.640
88	76.97	50.35	30.8	0.654
94	77.92	51.22	30.9	0.657
74	79.00	52.97	30.7	0.671
75	80.02	55.27	29.9	0.691
76	80.94	56.72	29.7	0.701
100	82.01	57.61	28.7	0.702
104	83.00	58.17	29.2	0.701
100	83.98	59.75	28.3	0.711
118	85.04	60.24	28.0	0.708
109	85.97	61.11	27.4	0.711
123	87.01	62.15	27.4	0.714
120	87.97	63.36	27.3	0.720
162	89.02	65.91	26.6	0.740
97	89.93	65.37	26.9	0.727
69	91.08	65.15	26.1	0.715
71	91.95	66.38	26.3	0.722
38	93.04	68.58	27.1	0.737
41	94.08	71.08	24.8	0.756
48	94.76	69.99	24.9	0.739
Std	0.27	3.98	2.90	0.05

The last row has the average standard deviation for the bin

These graphs and the correlation of YS and EL to UTS allows the determination of the linear regression equation and the goodness of fit using the data sets and these are included in Table 9.

The other proposed factor is the proposed QI for steel castings. The QI in Eqn. 1 was calculated and is presented in Figure 12. Interestingly, the division between the lower bound of common structural steel properties and the upper bound of specification requirements are at a QI of 280 ksi.

ANALYSIS OF THE WCX NT DATA

The WCX NT data set is the largest in the SFSA collection reflecting its position as the most common steel grade made as a casting. The average properties for each 1 ksi bin of UTS is given in Table 10. The counts of number of data points for each row are in the first column and show that the great bulk of the heats have UTS values from 70 to 80 ksi.

The first WCX NT graph, Figure 13, shows the data with a bin average line and the average plus and minus two standard deviations for both UTS with YS and El. The linear regression results and statistical fit are given in Table 11.

These WCX points were plotted using the concept of QI in Figure 14. The quality index allows the comparison of the production data in the SFSA group with the common ASTM cast carbon steel property requirements for UTS and EL. This figure shows the specification requirements define the lower bound of expected properties at a QI of 280.

Table 13. LCX Quenched and Tempered Regression Equations of Commercial Heats for the Data and Averages for UTS

	Independent factor "x"	Dependent factor "y"	Slope	Intercept	R^2	Standard error	Bin avg standard deviation
LCX QT data	UTS, ksi	YS ksi	1.06	−30.12	0.86	3.25	
LCX QT avg	UTS, ksi	YS ksi	1.11	−34.33	0.99	0.89	3.98
LCX QT +2std	UTS, ksi	YS ksi	1.22	−35.14	0.94		
LCX QT -2std	UTS, ksi	YS ksi	1.00	−33.52	0.96		
LCX QT data	UTS, ksi	El %	−0.36	58.55	0.48	2.86	
LCX QT avg	UTS, ksi	El %	−0.32	55.76	0.88	0.98	2.90
LCX QT +2std	UTS, ksi	El %	−0.37	65.69	0.87		
LCX QT -2std	UTS, ksi	El %	−0.27	45.82	0.76		
LCX QT data	UTS, ksi	YS/UTS	0.0045	0.31	0.46	0.0406	
LCX QT avg	UTS, ksi	YS/UTS	0.0052	0.26	0.93	0.0116	0.0485
LCX QT +2std	UTS, ksi	YS/UTS	0.0054	0.34	0.69		
LCX QT -2std	UTS, ksi	YS/UTS	0.0050	0.18	0.80		

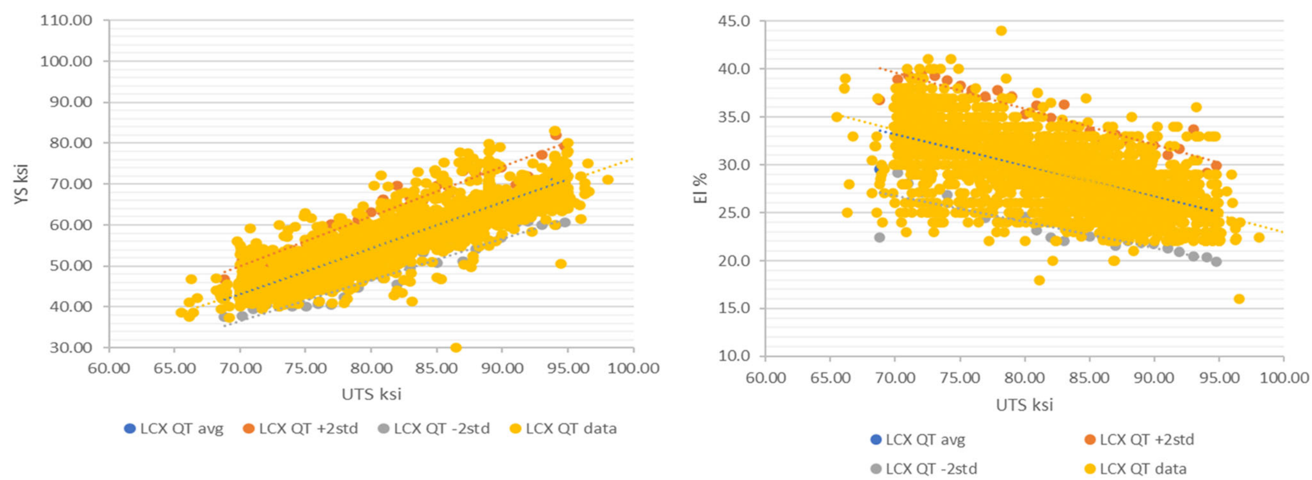


Figure 16. LCX QT plot of YS and El based on UTS including the full data set, the bin average and that bin average plus and minus 2 times the standard deviation.

The YS/UTS ratio allows an estimate of safety, since part failure would occur at UTS and YS is commonly used as the basis of design. The SINTAP equation shown in Fig-ure 6 shows how this ratio increases, approaching a value of one at higher strength steel grades. To avoid strength levels that might compromise safety, especially in large complex components, SINTAP developed the upper bound for the YS/UTS ratio as a function of YS shown in Fig-ure 15. Like the structural steel grades, the great majority of heats comply with their YS/UTS ratio by falling below the limit.

The relationships between the common tensile properties using UTS as the primary sorting property is given in Table 11. This table gives the slope, intercept, and R^2 value for the WCX data. The data can be compared to the regression equation for the bin averages in Table 10. The upper and lower bounds were also assessed using the average plus or minus two standard deviations for each bin. A linear regression analysis was performed with UTS as the independent variable and this provided the standard error for each relationship. Standard error is a standard deviation measure of how far the points are in the "y" or dependent direction from the mean line of the regression. This can be done for both the line from the full data set and from the line through the average data. As expected, the averaging has already mitigated the variability of the "y" factor, so the standard error of the average of the line is not meaningful. The standard error of the full data set linear regression and the standard deviation average from the bins

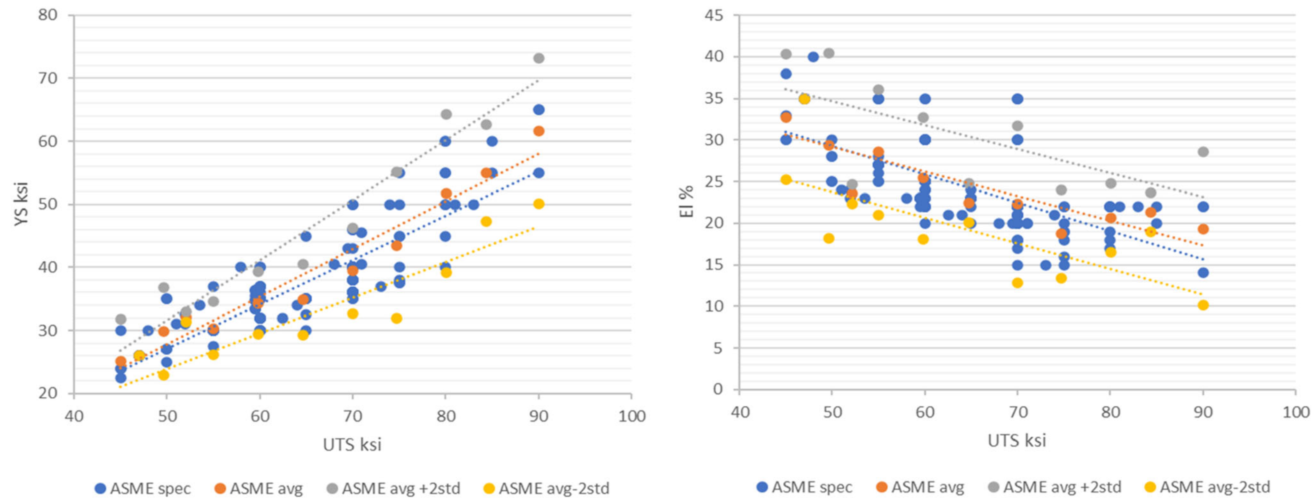


Figure 17. ASME specification plot of YS and El based on UTS including the full data set, the bin average and that bin average plus and minus 2 times the standard deviation.

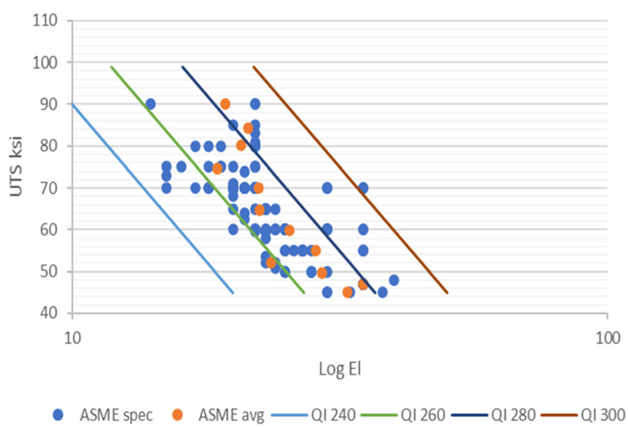


Figure 18. ASME specifications plot of Quality Index based on UTS including the full data set, the bin average and that bin average plus and minus 2 times the standard deviation.

should be related since both measure the variability of the dependent variable when located by the independent variable. The values for WCX NT in Table 11, LCX QT in Table 12 and structural steels in Table 9 are similar. There is no indication that these ordinary properties of steel castings are lower or more variable than modern structural steels.

ANALYSIS OF THE LCX QT DATA

There are fewer reported data points for the LCX QT set, with about 2500, than for the WCX NT set. As mentioned above, LCX materials are used both for providing a low-cost carbon steel with toughness or to gain higher strengths than can be obtained by normalizing and tempering as in the WCX materials. As with WCX, the average LCX bin data is presented in Table 13. The structure of the table is the same with the bin properties and the average bin standard deviation in the last row. The regression equations from the data set are included in Table 12.

The graph of YS, El, and UTS is in Figure 16. The slope of the data is higher for the LCX QT compared to the WCX NT, as seen in Figures 9 and 13. This can also be seen in the regression analysis comparing the slope values in Tables 11 and 12. This is also seen with the higher values on average for the YS/UTS for LCX QT than WCX NT (Figures 17, 18, 19).

The ductility as measured by El is slightly higher for LCX QT at low strengths but has a larger negative slope than the data for WCX NT, also seen in Figures 9 and 13. The El is more related to strength in LCX QT than WCX NT, as seen in the regression R^2 values for the data set. The LCX data correlating El to UTS having an R^2 value of 0.48 compared to a value of 0.09 for WCX NT. The QI for LCX QT like WCX NT, shows that the commercial heat data lower bound is at the upper bound of common specification requirements in Figure 20 at a QI of 280.

The LCX QT material with higher strength can also be evaluated using the SINTAP limit on the YS/UTS ratio as a function of YS, shown in Figure 19. Like the WCX, the YS/UTS ratio for LCX data falls below the upper limit proposed by SINTAP.

COMPARISON OF STRUCTURAL MILL STEELS, WCX NT AND LCX QT WITH DESIGN GUIDELINES AND SPECIFICATIONS

Comparing WCX and LCX property results, from thousands of commercial heats, shows that they are consistent

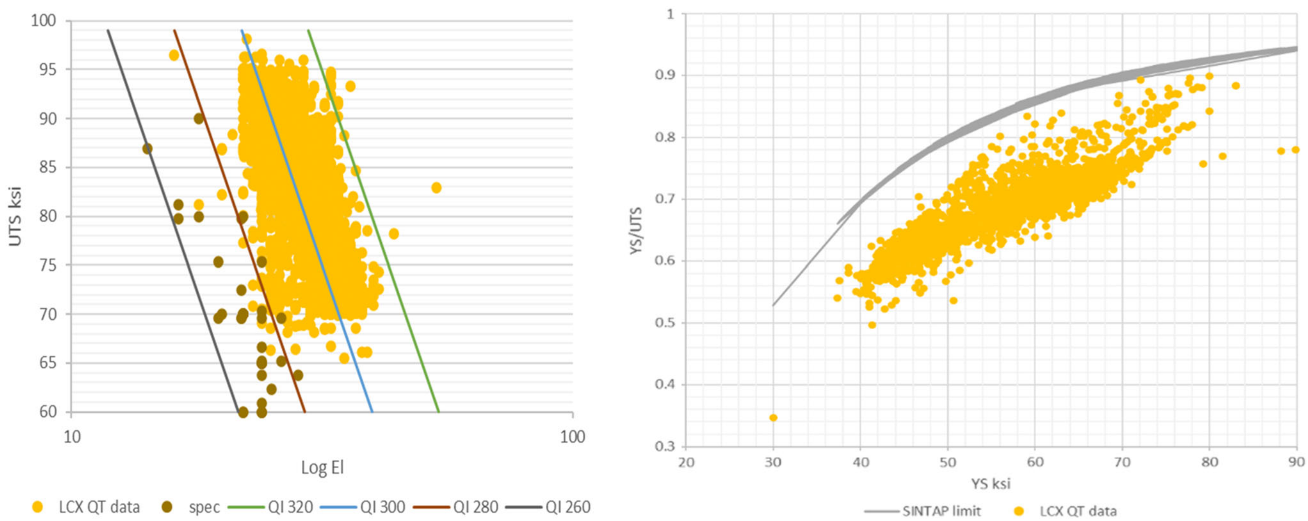


Figure 19. LCX QT plot of (a) the Quality Index based on UTS and (b) the YS/UTS ratio based on YS including the full data set, the bin average and that bin average plus and minus 2 times the standard deviation includes the specification requirements of common cast steel grades.

Figure 20. Comparison of the different steel tensile properties and requirements using the regression equa-tion for the average yield strength minus 2 standard deviations. The top line is the UTS plotted and the points at the bottom are the ASME BPVC design allowables. The average ASME spec requirement is given with the steel group data. The AISC-ASD design values are also shown.

Table 14. ASME Specification Properties of Commercial Alloys by Bins from UTS Including a Count of Number of Entries in the Last Column

Count	UTS	YS	El	YS/UTS
4	45.00	25.13	32.75	0.558
7	47.00	26.00	35.00	0.553
6	49.67	29.83	29.33	0.601
4	52.13	32.13	23.50	0.616
13	55.00	30.35	28.54	0.552
41	59.83	34.37	25.44	0.575
12	64.71	34.88	22.42	0.539
40	69.99	39.41	22.28	0.563
10	74.70	43.50	18.70	0.582
9	80.11	51.67	20.67	0.645
3	84.33	55.00	21.33	0.652
3	90.00	61.67	19.33	0.685
Std	0.69	4.12	3.07	0.060

The last row has the average standard deviation for the bin for each property included.

with the properties for similar alloys for structural steel. All of these carbon steel materials have similar properties, and so they also have similar specification requirements.

ASME BPVC gives material specifications for many steel grades with strength requirements and assigns allowable design stresses for these materials. The ASME specifica-tions can be evaluated in the same way as the steel groups above, recognizing that these are minimum requirements. These specification requirements have been analyzed in bins, based on the UTS requirements in Table 14. A regression analysis of ASME specification requirements for carbon steels for the correlations with UTS is shown in Table 15. The comparison of the UTS and YS or El requirements are shown in Figure 17. The strength levels are lower, since they are the minimum requirements. The ductility requirements are also lower, as expected.

The QI values for the specifications are shown in Figure 18. The QI values for the lowest levels of structural steel grades were about 280 ksi for all the carbon steel grades evaluated. The ASME specification requirements given in the figure shows that 280 ksi for the QI is a reasonable upper bound minimum requirement for the carbon steel

Table 15. ASME Specification Regression Equations for the Data and Averages for the Bins of UTS

	Independent factor '*x*'	Dependent factor '*y*'	Slope	Intercept	R^2	Standard error	Bin avg standard deviation
ASME data	UTS, ksi	YS ksi	0.70	−7.94	0.74	4.21	
ASME avg	UTS, ksi	YS ksi	0.76	−10.10	0.95		4.12
ASME +2std	UTS, ksi	YS ksi	0.95	−15.94	0.94		
ASME -2std	UTS, ksi	YS ksi	0.56	−4.20	0.85		
ASME data	UTS, ksi	El%	−0.34	46.29	0.42	4.03	
ASME avg	UTS, ksi	El%	−0.30	44.11	0.74		3.07
ASME +2std	UTS, ksi	El%	−0.29	49.04	0.48		
ASME -2std	UTS, ksi	El%	−0.31	39.19	0.53		
ASME data	UTS, ksi	YS/UTS	0.0015	0.48	0.06	0.0609	
ASME avg	UTS, ksi	YS/UTS	0.0021	0.46	0.48		0.0599
ASME +2std	UTS, ksi	YS/UTS	0.0034	0.48	0.43		
ASME -2std	UTS, ksi	YS/UTS	0.0008	0.43	0.42		

Table 16. Comparison of Average and Average Minus 2 Standard Deviations for YS of Structural, WCX and LCX Steel with ASME BPVC and AISC-ASD Requirements and Design Values

Minimum required UTS	ASME average YS required	ASME allowable strength	AISC Gross Area 0.60 YS	AISC effective net area 0.50 UTS	Structural steel average YS	LCX QT average YS	WCX NT average YS
65.00	32.20	18.42	22.54	32.50	39.99	38.78	39.61
				−2 std	35.43	31.48	33.65
95.00	49.00	27.36	35.14	47.50	74.49	70.58	63.61
				−2 std	63.93	61.48	51.95

grades. This suggests that developing specification for carbon steel grades could use QI values of 280 ksi to set the minimum El for a given UTS value.

The structural steel mill products and cast steel grades of carbon and manganese steels have been shown to have similar properties in this analysis.

How do they compare to the design allowables used? Two common sources of strength values for design are the ASME BPVC and the structural fabrication code in AISC-ASD.

The allowable stresses for the ASME BPVC was correlated as approximately 30% of the grade's required minimum UTS. The correlation has a R^2 value of 0.95 with a standard error of 0.67 ksi which is less than the tensile test value uncertainty. Surprisingly, the allowable stresses are less correlated with the minimum required yield strength with an R^2 value of 0.71 and a standard error of 1.68 ksi.

The AISC-ASD sets the allowable stress for tension elements at two general strength values for design. For the mill products with a full cross section, the suggestion is 0.60*YS for the gross area of the product. For sections with reduced cross section, like areas in beams with slots or bolt holes, the suggestion is 0.50*UTS for the effective net area, considering the area of the holes or slots.[2]

All of these steel groups and requirements and design allowables can be compared in Table 16 and Figure 20. All factors are compared to the required UTS, the top line is the UTS plotted against the UTS. The YS of the steel grades all exceed the ASME BPVC YS requirements at UTS levels of 65 and 95 ksi, in Table 16. The ASME BPVC allowables and the AISC-ASD allowables are similar and plotted based on the UTS. The allowables are also less than the lower bound of expected YS properties, as determined by the average YS values minus 2 standard deviations at the given UTS levels. The AISC-ASD effective net area UTS requirement is at or below the average YS minus two standard deviations for all the carbon steel grades.

The top line is the UTS value used for the analysis, and the points at the bottom are the allowable design stress in the

ASME BPVC. The lowest line is the AISC-ASD allowable 0.60*YS for the gross area in tension.

The lower bound of commercial practice identified by the average minus two standard deviations for structural steels, WCX and LCX, were similar to the ASME minimum YS required, based on the UTS requirement. This was also the location of the AISC-ASD allowable 0.50*UTS effective net section allowable stress, at or near the minimum YS requirement. The YS/UTS ratios are higher in every case than 0.50, so the allowable stress for the 0.50*UTS is below the YS for the effective net area and becomes a smaller fraction of the YS at higher strength levels as the YS/UTS ratio approaches 1.

CONCLUSIONS

An SFSA data set of commercial heats of carbon steel for casting production was collected and used to compare with structural steel tensile properties.

1. Steel casting commercial carbon steel heats were like structural steels in lower bound design values for UTS, YS, and El.
2. For a given UTS value, the standard deviation of YS for these steels was between 3.96 and 4.98 ksi.
3. For a given UTS value, the standard deviation of El for these steels was between 3.9 and 4.2%.
4. The YS/UTS ratio limit for safe use, proposed by SINTAP and found in Table 7, was applicable to structural steels and the cast grades.
5. All steel, including cast grades, retained a margin of safety for the allowable YS for both the ASME BPVC and the AISC-ASD design methodologies.

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