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Strength and Toughness Inputs to Fitness for Service Analysis of Existing Hydraulic Steel Structures

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PURPOSE: The purpose of this effort is to describe a database containing information about the strength and toughness of steel used in existing hydraulic steel structures (HSS). The lack of information about these properties often presents a barrier to conducting fitness for service (FFS) analysis. The statistical dependence between strength and toughness variables and other database fields is evaluated to assess their potential as predictive variables.

BACKGROUND: HSS are critical components of the nation's water resource infrastructure. Design, construction, and operation of HSS are governed by ER 1110-2-8157 (USACE 2009). Periodic inspection and evaluation of HSS are governed by ER 1110-2-100 (USACE 1995). In accordance with ER 1110-2-100, periodic inspections of HSS are required to detect and evaluate damage. The scope of an inspection depends, in part, upon the failure potential and consequences of failure. Those structures most likely to fail catastrophically with the highest negative consequences should receive the highest priority of inspection using more robust inspection methods. These structures typically include HSS with fracture critical members (FCM) whose failure could result in loss of life. The purpose of the inspection is to identify discontinuities in FCM. A discontinuity is an interruption of the typical structure of a material, such as lack of homogeneity in its mechanical, metallurgical, or physical characteristics. Inspection methods include visual methods and nondestructive testing. When a discontinuity is encountered in a structural member, that discontinuity must either be repaired or its acceptability within that structural member must be evaluated. If it does not meet current industry quality standards such as the American Welding Society (AWS) D1.1 or D1.5, repair is required unless acceptability can be determined through an Engineering Critical Assessment (ECA) to determine FFS.

EM 1110-2-6054 (USACE 2001) provides guidance on inspection, evaluation, and repair of HSS and includes specific procedures for FFS analysis and acceptance criteria. These methods are based largely on BS 7910:2005 (BSI 2005). Note that while acceptance criteria previously developed using BS 7910:2005 are still valid, the 2013 edition along with its addendums, BS 7910:2013+A1:2015 (BSI 2015) provides an improved methodology that is currently being considered for use in updating this guidance. There are few cases where US Army Corps of Engineers (USACE) districts have employed the FFS provisions of EM 1110-2-6054 or BS 7910:2005. Rather, the practice has been to repair the damage rather than evaluate the need for repair. This practice is costly because it leads to the repair of discontinuities that might otherwise be regarded as acceptable. There are several reasons for this tendency to repair rather than evaluate discontinuities in HSS. Implementation of ECA requires an investment of time and effort, there is a lack of familiarity and experience applying these evaluation methods, and there is a lack of confidence in the results of ECA and FFS. These factors suggest there is a need for formal training in preparation of an ECA and the application of methods of assessing FFS of HSS.

The purpose of FFS analysis is to determine the acceptability of a discontinuity in a structural member. As described in BS 7910:2013+A1:2015 (BSI 2015), this is accomplished by plotting a failure assessment diagram (FAD) on a Cartesian plane. The vertical axis is the fracture ratio, defined as the applied stress intensity factor over the material toughness, and the horizontal axis is the load ratio, defined as a reference stress over the lower yield strength of 0.2% offset yield strength. The FAD is based on the properties of the material, and its shape reflects the interaction between the two failure modes: fracture and plastic collapse. A discontinuity is acceptable if the load and fracture ratios, calculated accounting for the size and type of the discontinuity, the thickness of the component, and the loads, fall within the boundaries of the FAD.

BS 7910:2013+A1:2015 (BSI 2015) describes three options for constructing the FAD. The choice of which option to implement depends upon the extent of information on material properties that is available and the degree of conservatism that is desired. In terms of material properties, Option 1 only requires estimates of yield strength, ultimate strength, and fracture toughness as inputs to the analysis. This is the simplest and most conservative level of analysis. Option 2 requires a full, material-specific stress-strain curve at the assessment temperature. This provides a more accurate result that is less conservative than Option 1. Option 3 incorporates elastic and elastic-plastic analysis of the flawed structure as a function of the loads giving rise to primary stresses. Whereas Options 1 and 2 are generally applicable to all situations, Option 3 is only suitable for specific cases.

Information about yield strength, ultimate strength, and fracture toughness of HSS components can generally be obtained from material and fabrication certifications or by obtaining a sample from the component in question and measuring these properties in a laboratory using standard methods. Particularly with respect to HSS constructed between 1930 and 1990, material requirements were often less specific, and material properties were not as well documented as they are today. Moreover, it is generally not feasible to obtain a sample from the components of an in-service HSS because that would weaken the structure. The difficulty of obtaining information on material properties presents a barrier to implementing FFS analysis. In such cases, it is worth considering whether the better course of action is to repair the discontinuity or conduct an FFS analysis. However, when data are limiting, nominal values can be used for yield strength, ultimate strength, and fracture toughness.

When the tensile strength and fracture toughness of steel used to fabricate an HSS component are unknown, what values should be used for FFS analysis? Characteristics that are more easily observable or measured such as hardness and carbon equivalence may be correlated with these properties (Pavlina and Van Tyne 2008). Information such as age of the structure, specification of the steel, and the project's location in terms of the temperature zone as designated by the American Association of State Highway and Transportation Officials (AASHTO) may also provide helpful clues about what values to use. Most foundry specifications control for strength in the manufacturing process, but this is only recently true for toughness. Specifications evolve over time; therefore, information about the age of the structure may also be useful in selecting a value for tensile strength (AASHTO 2018).

Uncertainty about the material properties of steel can be classified as epistemic if it is attributed to a lack of knowledge and aleatory if it is attributed to natural variability. Epistemic uncertainty can be reduced by gathering more information. Therefore, it is reasonable to condition estimates of FFS inputs based on information about the structure. However, natural variability is irreducible.

Variability is inherent in the manufacturing process, so different heats of steel manufactured to the same specification may exhibit different properties. As a result, the properties of steels used to fabricate HSS can vary from one structure to another and between different components of the same structure. Thus, a conservative approach to FFS analysis is to use a minimum value for strength and fracture toughness inputs given the range of possible values based on what is known about the structure. There is also uncertainty in minimum values. For example, BS 7910:2013+A1:2015 (BSI 2015, 46) suggests that with respect to the strength of ferritic steels, uncertainty in lower bound values for yield strength and ultimate strength can be described by coefficients of variation between 5% and 10%.

There is a downside to using conservative minimum values for strength and toughness inputs to FFS analysis. The motivation for FFS analysis is to reduce cost by distinguishing between those discontinuities in components of HSS that need to be repaired and those that do not. Using conservative input values reduces the size of the area under the FAD, making it more likely that a discontinuity that might otherwise be classified as acceptable will be classified as unacceptable. Therefore, reliance on conservative minimum values works against the objective of reducing cost and accurate specification of material properties is desirable. That said, there are also costs associated with overstating tensile strength and fracture toughness inputs to FFS analysis because that could lead to accepting a discontinuity that should be rejected.

The database described in this technical note compiles data on tensile strength and fracture toughness of steel used in HSS from a variety of sources. It is a step towards documenting the range and variability of these material properties in HSS and understanding what values might be used in FFS analysis when these material properties are unknown. This technical note describes the sources of data used to compile the database, the contents of the database, and the range and variability of strength and toughness inputs to FFS analysis. The statistical dependencies between data fields that describe inputs to FFS analysis and those that describe more easily observable characteristics of steel components are evaluated using a variance reduction analysis.

METHOD: Data were compiled from primary and secondary sources. While no particular criteria were used to exclude data from the database, an emphasis was placed on characterizing steel used in structures built between about 1930 and 1990. This corresponds to the period during which many of the HSS that might be subject to ECA and FFS analysis were constructed. Primary sources of data were reports from laboratories commissioned by USACE districts to test steel samples obtained from HSS. Secondary sources include a study of steel from bridges built between 1921 and 1981 (Connor 2017), a study of the toughness of steel specimens from Pennsylvania foundries, which was commissioned by the National Highway Administration (Roberts et al. 1974), and a study of fracture toughness in bridge steel (Collins et al. 2016a,b). Bridges have been included in this database because it was difficult to obtain a large number of observations from HSS and the specifications of materials used to construct bridges are similar to those used to construct HSS. Additionally, 10 steel samples were obtained from relict HSS and tested in the US Army Engineer Research and Development Center (ERDC) Materials Testing Center to determine their material properties. The fields contained in the database are listed in Table 1. The last row lists the number of observations from each data source, and the right-hand column lists the number of observations of each field. Table 2 lists the data fields.

Foundry specifications are known for 87% of observations described in the database. Material specifications included in the database are summarized in Table 3, which includes the number of observations of each specification in the database. Dates of release and withdrawal, minimum criteria for strength and elongation, toughness, carbon content, and carbon equivalence are provided in Table 4. To reduce the number of specifications for subsequent analysis, several specifications were grouped based on the similarity of their characteristics. ASTM A242, A440, A441, and A588 were grouped into a single category consisting of 142 observations. ASTM A514 and A517 were grouped into a single category consisting of 58 observations. The largest categories by specification in the database are in the category ASTM A242/A440/A441/A588, A36, and A514/A517. These four groups represent 83.7% of the observations of material specification.

Table 1. Number of observations in the database by data field.

Data Fields	USACE HSS Data Reports	Connor et al. 2017	Roberts et al. 1974	Collins et al. 2016	ERDC Materials Lab	Total Number of Observations
Project name	84	192	22	2	10	310
USACE district	84	0	0	0	10	94
City, state	84	192	1	18	10	305
Temperature zone	84	192	1	18	10	305
Structure type	80	190	22	6	10	308
Component	80	192	22	56	10	360
Welded or riveted	70	190	0	0	3	263
Year of fabrication	22	185	1	4	10	222
Strength	39	90	22	0	10	161
Charpy V-notch (CVN) temperature	51	154	22	74	10	311
Specification	24	191	22	70	6	313
Carbon equivalence	44	73	22	0	0	139
Rockwell hardness	16	9	0	0	10	35
Year of testing	82	11	22	74	10	199
Testing laboratory	81	9	22	0	10	122
Total Observations	84	192	22	74	10	382

Table 2. Description of data fields.

Data Fields	Description
Project name	Name of the USACE project where the structure is located or bridge.
USACE district	For HSS, the USACE District where the project is located.
City, state	City and state where the project or bridge is located.
Temperature zone	The AASHTO temperature zone where the project or bridge is located.
Structure type	The type of structure (e.g., miter gate, Tainter gate, stop log, bridge, etc.)
Component	A description of the component of the structure

Table 2. (cont.) Description of data fields.

Data Fields	Description
Welded or riveted	Whether the structure is welded or riveted.
Year of fabrication	Year the structure was fabricated.
Strength	Yield strength (ksi), ultimate strength (ksi), and elongation (%) in 2 in.[1,2]
CVN temperature	Temperature (C) at which 27 and 40 J are absorbed in a CVN test.
Specification	Standard used by the foundry when fabricating the steel.
Carbon equivalence	Equivalent carbon content of the steel as a fraction (per AWS D1.1).
Rockwell hardness	Rockwell hardness (HRB) of the steel.
Year of testing	Year the testing of material properties was conducted.
Testing laboratory	Name of the laboratory conducting the material property tests.

Table 3. Description of steel specifications represented in the database.

Specification	Description*	Scope	Number of Observations		
			HSS	Bridge	Other
ASTM A7	Structural Steel for Bridges (S)	Carbon steel shapes, plates, and bars of structural quality for use in construction of bridges and buildings.	7	16	1
ASTM A36	Structural Steel (S)	Shapes, plates, and bars of structural quality for use in riveted, bolted, or welded construction of bridges and buildings.	9	31	22
ASTM A94	Structural Silicon Steel (T)	Special high-strength structural steel shapes, plates, and bars intended primarily for use in main stress-carrying structural members.	4	4	0
	High Strength Structural Steel (T)	High strength steel shapes, plates, and bars intended primarily for use in the construction of riveted or bolted bridges and buildings.			
ASTM A237	Alloy Steel Forgings for General Industrial Use (S)	Heat treated alloy steel forgings for general industrial use.	1	0	0
ASTM A242	High-Strength Low-Alloy Structural Steel (S)	Structural steel shapes, plates, and bars for welded, riveted, or bolted construction intended primarily for use as structural members, high corrosion resistance.	0	4	6

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[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Table 3. (cont.) Description of steel specifications represented in the database.

Specification	Description*	Scope	Number of Observations		
			HSS	Bridge	Other
ASTM A441	High-Strength Low-Alloy Columbian-Vanadium Steels of Structural Quality (S)	High strength steel shapes, plate, and bars intended primary for use in welded, riveted, or bolted construction of bridges and buildings; high corrosion resistance.	3	6	8
ASTM A514	High-Yield-Strength, Quenched and Tempered Alloy Steel Plate, Suitable for Welding (S)	Quenched and tempered steel plates less than 6 in. thick for use in welded bridges.	0	27	11
ASTM A517	Pressure Vessel Plates, Alloy Steel, High Strength, Quenched and Tempered (S)	High-strength quenched and tempered allow steel plates intended for use in fusion welded boilers and other pressure vessels.	0	8	12
ASTM A572	High-Strength Low-Alloy Columbian-Vanadium Steels of Structural Quality (S)	High-strength low alloy structural steel shapes, plates, steel piling and bars intended for riveted, bolted, or welded construction of bridges and buildings.	5	1	4
ASTM A588	High-Strength Low-Alloy Structural Steel, with 50 ksi Minimum Yield Point to 4 in. Thick (S)	High-strength low-alloy structural steel shapes, plates, and bars for welded, riveted, or bolted construction; high corrosion resistance.	0	96	13
ASTM A852	Quenched and Tempered Low-Alloy Structural Steel Plate with 70 ksi Minimum Yield Strength to 4 in. Thick (T)	Quenched and tempered high-strength low-alloy structural steel plates for welded, riveted, or bolted construction. It is intended primarily for use in welded bridges and buildings where savings in weight, added durability, and good notch toughness are important.	7	16	1
QQ-S.751a	Steel, Structural (including steel for cold-flanging) and Steel, River; (for) Ships other than Naval Vessels	Structural steel, structural steel for cold flanging, and rivet steel for ships over than naval vessels	1	0	0
Total number of observations with specifications by structure type.			30	193	83

* S = Standard; T = Tentative

Table 4. Minimum strength and toughness criteria for specifications represented in the steel database.

Specification	Year Released	Year With-drawn	Replaced By	Minimum Yield Strength, F_y (ksi)	Minimum Ultimate Strength, F_u (ksi)	Elongation % (in 2 in.)	Toughness Requirements	Carbon Content Maximum Percentage	Carbon Equivalence
ASTM A7	1901	1967	ASTM A36	30 (1901–1942), 33 (1942–1967)	60 (1901–1967)	22% (1924–1967)	None	–	–
ASTM A36	1960	–	–	36 (1960–present)	60 (1901–1967), 58 (1960–present)	23% (1960–1969), 21% (1969–present)	No mandatory requirements; may be specified by the purchaser	0.32% (1960–1966) 0.3% (1966–1975) 0.26% (1975–present)	0.33% (1960–1966) 0.31% (1966–1975) 0.27% (1975–present)
ASTM A94	1949	–	–	45 (1949–1962)	80 (1949–1962)	20% (1949–1952) 19% (1952–1966)	None	0.40%	0.41%
	1962	1966	None	50 (< 1.5 in. thick), 47 (1.5–2 in. thick), 45 (2–4 in. thick)	75 (< 1.5 in. thick), 72 (1.5–2 in. thick), 70 (2–4 in. thick)	21% (1.5–2 in. thick), 20% (2–4 in. thick)	None	0.33%	0.61%
ASTM A237	1955	1975	ASTM A668	50 to 140 *	80 to 170 *	11% to 26% *	None	–	–
ASTM A242	1980	–	–	50 (< 0.75 in. thick), 46 (0.75–1.5 in. thick), 42 (1.5–4 in. thick)	70 (< 0.75v thick), 67 (0.75–1.5 in. thick), 63 (1.5–4 in. thick)	21%	None	0.15%	0.33%
ASTM A440	1959	1979	None	50 (< 0.75 in. thick), 46 (0.75–1.5 in. thick), 42 (1.5–4 in. thick)	70 (< 0.75 in. thick), 67 (0.75–1.5 in. thick), 63 (1.5–4 in. thick)	24% (1959–1975) 21% (1975–1979)	None	0.28%	0.56%
ASTM A441	1970	1988	ASTM A572	50 (< 0.75 in. thick), 46 (0.75–1.5 in. thick), 42 (1.5–4 in. thick), 40 (4–8 in. thick)	70 (< 0.75 in. thick), 67 (0.75–1.5 in. thick), 63 (1.5–4 in. thick), 60 (4–8 in. thick)	21%	None	0.22%	0.45%

Table 4. (cont.) Minimum strength and toughness criteria for specifications represented in the steel database.

Specification	Year Released	Year With-drawn	Replaced By	Minimum Yield Strength, F_y (ksi)	Minimum Ultimate Strength, F_u (ksi)	Elongation % (in 2 in.)	Toughness Requirements	Carbon Content Maximum Percentage	Carbon Equivalence
ASTM A514	1981	–	–	100 (< 2.5 in. thick), 90 2.5–6 in. thick)	110 (< 2.5 in. thick), 100 (2.5–6 in. thick)	18% (< 2.5 in. thick), 16% (2.5–6 in. thick)	None	0.21% (Gr. A)	0.61% (Gr. A)
ASTM A517	1984	–	–	100 (< 2.5 in. thick), 90 (2.5–6 in. thick)	115 (< 2.5 in. thick), 105 (2.5–6 in. thick)	16% (< 2.5 in. thick), 14% (2.5–6 in. thick)	No mandatory requirements; may be specified by the purchaser	0.21%(Gr. A)	0.61% (Gr. A)
ASTM A572	1975	–	–	42 – 65	60 – 80	17% – 24%	No mandatory requirements; may be specified by the purchaser	0.23% (Gr. 50)	0.46% (Gr. 50)
ASTM A588	1981	–	–	50 (< 4 in. thick), 46 (4–5 in. thick), 42 (5–8 in. thick)	70 (< 4 in. thick), 67 (4–5 in. thick), 63 (5–8 in. thick)	21%	No mandatory requirements; may be specified by the purchaser	0.19% (Gr. A)	0.60% (Gr. A)
QQ-S-751a	1938	1960	None	33 (Grade A and B) 30 (Grade C and D)	60 (Grade A and B) 55 (Grade C and D)	22% (Grade A and B) 25% (Grade C and D)	None	0.31% (Gr. A)	0.53% (Gr. A)

* Depends on size and class.

Fracture toughness can be estimated through the concept of the Master Curve using correlations that relate an offset temperature to the temperatures at which 27 and 40 J of energy would be released during standard Charpy V-notch (CVN) tests (McCabe et al. 2005; ASTM Standard E1921 2011; BS 7910 2005). CVN energies of 28 J and 41 J were originally used to establish this relationship, but 27J and 40J are used in the British Standard since they correspond to typical steel specifications. This approach assumes that the sigmoidal shape of the toughness-temperature curve is similar for all ferritic steels and specific material characteristics are captured in the position of the curve along the temperature axis. For those observations in the database that included CVN data, estimates of the temperatures at which 27 and 40 J of energy would be released during a CVN test were obtained by fitting CVN data to a five-parameter exponential sigmoid function:

$$CVN(T) = a + \frac{b}{\left[1+e^{-(T-c)/d}\right]^{f}} \tag{1}$$

where $CVN(T)$ is the amount of energy released at a given temperature, T, and a, b, c, d, and f are the five fitted parameters (Collins et al. 2016a,b). Each model fit involved an application of the Differential Evolution global optimization method (Price et al. 2006; Storn and Price 1997) as implemented in the R software package DEoptim (Ardia et al. 2010a,b; Ardia et al. 2020; Mullen et al. 2011). The fitted model was subsequently used to estimate the test temperatures corresponding to CVN impact test values of 27 and 40 J, respectively. Fracture toughness is estimated from an offset temperature, which is the temperature at which the material possesses a toughness of 100 MPa√m. The offset temperature is calculated as either $T_0 = T_{27J} - 18$ or $T_0 = T_{40J} - 24$, where T_{27J} and T_{40J} are the CVN test temperatures that were estimated from the fitted curve in degrees Celsius. Note that the specific value of these constants may vary depending on the thickness of the specimen. Appendix J of BS 7910:2013 (2013) describes how fracture toughness is derived from offset temperatures. Estimates of fracture toughness have not been included in the database because that calculation depends upon the thickness of the component. For most observations in the database, the thickness of the steel component from which the specimen was taken is not available. Therefore, the CVN temperatures T_{27J} and T_{40J} are used here as proxies for fracture toughness. In general, the lower the CVN temperature, the higher the fracture toughness.

The ability of the sigmoid curve to fit CVN data is illustrated in Figure 1 using CVN data obtained by testing specimens from the I-90 Cuyahoga Bridge in Cleveland, Ohio (Connor 2017) and the Calcasieu Saltwater Barrier Sector Gate in Louisiana. The standard approach is to conduct at least three replicates of a CVN test at each temperature. However, as these data show, the number of replicates and the number and range of temperatures at which CVN tests are conducted vary widely. Therefore, the steel database contains a plot showing the sigmoid fit and the data used to fit every CVN temperature model. For each case, database users are encouraged to view these plots and to independently assess the fit and validity of each temperature model visually. Due to the scatter in CVN, at least three replicates at eight temperatures are typically recommended to fit the CVN temperature models using the sigmoid function. Specimens without CVN values above and below 27J and 40J were excluded from the analysis but are included in the database.

A Bayesian network was used to analyze the degree of statistical dependence between material strength (yield and ultimate) and CVN temperature fields and other database fields, including steel specification, temperature zone, structure type, year of fabrication, carbon equivalence, and

Rockwell hardness. These fields were selected based on prior beliefs regarding the existence of dependence and the potential availability of that information for FFS analysis. The conditional probability tables were learned from the database using the expectation maximization (EM) algorithm (Dempster et al. 1977). Use of the EM method was necessitated by the prevalence of missing data in the database. Once parameterized, dependence relationships within the Bayesian network were quantified by calculating the expected reduction in variance of the strength and CVN temperature variables caused by findings at each of the other nodes (Pearl 1988). Data fields were then ranked in terms of the strength of that dependence.

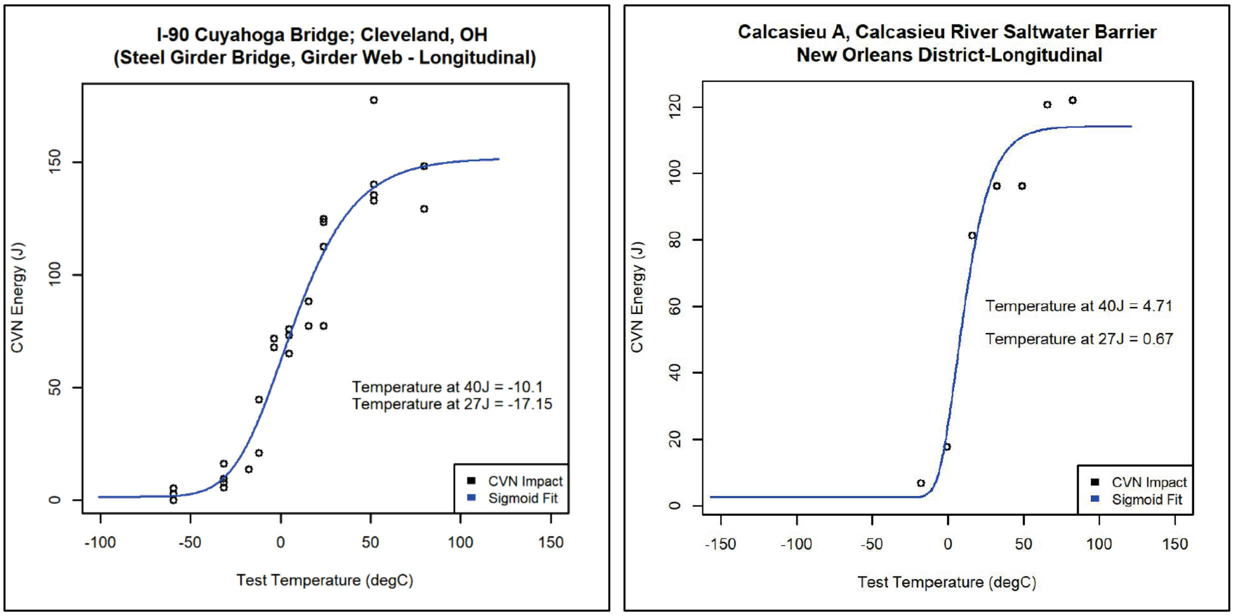

Figure 1. Examples of sigmoid curves fit to CVN test results.

RESULTS: Data on yield strength and ultimate strength are summarized in Table 5. Data on CVN temperatures at 27 and 40 J are summarized in Table 6. Each table reports the number of observations by specification, the mean, and where more than one observation is available, the standard deviation and the minimum or maximum value, whichever represents the conservative extreme. The column labeled "Spec. Min." in Table 5 is the minimum value for yield strength and ultimate strength given in the specification. The specifications for strength can vary with thickness, and because the database contains limited information on the thickness of tested components, the minimum strength is reported over all thicknesses categories in the specification. With exception of ultimate strength of A94 steel, the minimum of the observed data on tensile strength satisfies the specification requirements. The conformance of these values suggests that, given knowledge of the specification of a steel component, the minimum yield and ultimate strength values described in the specification might be used as conservative, lower bounds for FFS analysis. A similar observation is more difficult to make for CVN temperature estimates in Table 6 because there are no corresponding specifications for maximum CVN temperatures at 27 and 40 J.

Table 5. Tensile strength data summary by specification.

ASTM Specification	Yield Strength (F_Y, ksi)					Ultimate Strength (F_U, ksi)				
	N	Mean	Std. Dev.	Min.	Spec. Min.*	N	Mean	Std. Dev.	Min.	Spec. Min.*
A7	18	41.2	6.0	33.7	30.0	18	67.2	7.5	60.4	60.0
A36	25	41.8	3.4	36.7	36.0	25	68.4	4.1	60.9	58.0
A94	6	52.9	4.8	45.8	45.0	6	84.9	14.2	56.8	70.0
A237	1	79.5	-	79.5	50.0	1	131.2	-	131.2	80.0
A242/440/441/588	46	60.0	5.9	45.0	42.0	46	85.1	7.3	72.0	60.0
A514/517	29	115.6	6.0	105.9	90.0	26	124.1	4.7	115.1	100.0
A572	6	54.8	10.3	46.0	42.0	6	77.8	13.3	66.5	60.0
Unclassified	26	47.8	20.1	23.9	-	26	74.5	20.3	59.2	-
All Observations	157	62.9	28.0	23.9	-	154	85.1	22.0	56.8	-

The database contains no observations of yield strength or ultimate strength for specifications: A852 and QQ-S.751a. (*) Spec Min is the minimum required tensile strength for all thicknesses specified. (**) The database contains observations for which the specification is SAE 1035, but these are not reported in the table. The Unclassified category includes observations for which strength data were available, but for which the ASTM specification was unknown.

Table 6. CVN temperature data summary by specification.

ASTM Specification	Temperature (C) at 27 J (T_{27}, C)				Temperature (C) at 40 J (T_{40}, C)			
	N	Mean	Std. Dev.	Max.	N	Mean	Std. Dev.	Max.
A7	4	21.6	25.4	41.6	4	30.4	24.7	51.3
A36	44	-1.6	13.7	31.7	42	5.6	14.9	34.3
A242/440/441/588	46	-14.6	23.0	47.4	45	-5.3	24.5	55.3
A514/517	24	-37.3	56.9	111.0	21	-30.5	43.1	62.7
A572	6	-19.2	21.8	15.8	6	-10.6	24.6	29.4
Unclassified	8	6.2	11.8	15.53	8	14.9	11.9	26.4
All Observations	132	-12.2	32.6	111.0	126	-3.7	29.0	62.7

The database contains no observations of CVN temperature for the following specifications: A237, A586, A94, and QQ-S.751a. The database contains observations for which the specification is SAE 1035 or ASTM A852, but these are not reported in the table. The Unclassified category includes observations for which CVN data were available, but for which the ASTM specification was unknown.

The global mean, standard deviation, and minimum or maximum values for tensile strength and CVN temperature in the database are shown in the last row of Tables 5 and 6. These are calculated from all observations in the database, including those without information on ASTM specification. In the absence of information on the specification of the steel used to fabricate a structural component, these values might be used as conservative inputs to FFS analysis. The difference between these values and the corresponding minimum or maximum values by specification suggests that the absence of information about the specification of the steel used to fabricate a structural component could lead to an overly conservative FFS analysis. The maximum CVN temperature for

ASTM A514/A517 steel comes from a 1975 study from the Federal Highway Administration and the California Department of Transportation investigating the variability in fracture toughness of A514/A517 plate following the brittle fracture of a tension flange in a large steel box-girder bridge during construction (Hartbower and Sunbury 1975). The study found that the toughness of A514/A517 plates fabricated before 1970 may be very low due to the typical melting practice of the time. After 1970, toughness requirements were incorporated into ASTM A517 and the AASHTO Interim Specifications for Bridges, and the study found that plates fabricated to the newer specifications had substantially higher fracture toughness.

Results of the dependence analysis are summarized for yield strength and ultimate strength in Table 7 and for the CVN temperatures at 27 and 40 J in Table 8. Each table lists the expected reduction in variance of strength or CVN temperatures caused by findings at each of the other nodes representing information that might be known about the steel used to fabricate a structural component. For both strength and CVN temperature, the strongest dependence is with steel specification. For strength variables, this is not surprising because yield and ultimate strength are both controlled for in the manufacturing specifications. Historically, fracture toughness has not been controlled for in specifications, and this probably explains why the percent variance reduction for CVN temperature is much lower than it is for tensile strength. Despite this, of the variables considered in this analysis, steel specification has the strongest degree of dependence with CVN temperature. For strength, the second highest strength of dependence is with structure type, and the third highest is with carbon equivalence (Table 7). However, these two variables carry similar weight. The strength of dependence between strength and other variables tends to be much lower. For CVN temperature, carbon equivalence is the second most important variable. Year of fabrication and structure type are roughly tied for third place in terms of their importance (Table 8). Note that these relationships can only be investigated for observations that include both data fields (e.g., strength and ASTM specification or CVN temperature and carbon equivalence).

Table 7. Results of variance reduction analysis for strength variables.

Database Variable	**Yield Strength (FY, ksi)**		**Ultimate Strength (FU, ksi)**	
	Variance Reduction	**Percent Variance Reduction (%)**	**Variance Reduction**	**Percent Variance Reduction (%)**
Specification	556.1	48.0	297.0	25.6
Structure	229.4	19.8	160.1	13.8
Carbon Equivalence	195.8	16.9	104.0	8.96
Temperature Zone	48.27	4.2	67.58	5.82
Year of Fabrication	43.26	3.7	16.22	1.4
Rockwell Hardness	22.17	1.9	12.59	1.1

Table 8. Results of variance reduction analysis for CVN temperature variables.

Database Variable	CVN Temperature @ 27 Joules (T27, C)		CVN Temperature @ 40 Joules (T40, C)	
	Variance Reduction	Percent Reduction (%)	Variance Reduction	Percent Reduction (%)
Specification	493.0	21.7	456.4	21.6
Carbon Equivalence	377.6	16.6	185.8	8.8
Year of Fabrication	163.1	7.2	142.3	6.7
Structure	150.0	6.6	116.6	5.5
Temperature Zone	46.6	2.1	19.4	0.9
Rockwell Hardness	0.5	0.0	0.9	0.0

The dependence between tensile strength, specification, and carbon equivalence can be seen in Figure 2. Observations of yield strength and carbon equivalence are plotted in a Cartesian plane, and each point is color coded by steel specification to show the range of values in the dataset by specification. While there are not enough observations of any one specification to infer the limits of either yield strength or carbon equivalence, observations of yield strength and carbon equivalence are clearly clustered by specification. For example, A514/517 steel has yield strengths in the range 105–130 ksi while A7 steel has yield strengths between 35–60 ksi. Similarly, the cluster of points representing A36 steel can be clearly distinguished between the cluster representing A242/440 steel. Across specifications, higher carbon equivalence is associated with higher yield strength. However, this relationship does not appear to hold within specifications. Results are only shown here for yield strength because results for ultimate strength would show much the same thing.

The dependence relationships between CVN temperature at 27 J, carbon equivalence, and steel specification are illustrated in Figure 3. Observations are color coded by specification. The clustering of CVN temperature by specification is not as strong as in Figure 2. This reflects the weaker dependence between these two variables. There is an apparent negative correlation between CVN temperature and carbon equivalence. Lower CVN temperatures are associated with higher fracture toughness, so those steels with higher carbon equivalence appear to have higher fracture toughness.

The dependence between yield strength, CVN temperature at 27 joules, and steel specification are plotted in Figure 4. The clustering of points by specification is not as distinct as in Figure 2. Although tensile strength and fracture toughness are generally assumed to be negatively correlated, this figure suggests a positive correlation between these two material properties. In addition, the observations of A514/517 steel stand out as having both high strength and high fracture toughness. However, this positive correlation does not appear to hold for observations within any particular steel specification. This figure only includes observations for which both the strength and the CVN temperatures are known. Since some studies specifically investigated only one of these properties, the other is unknown for a number of observations.

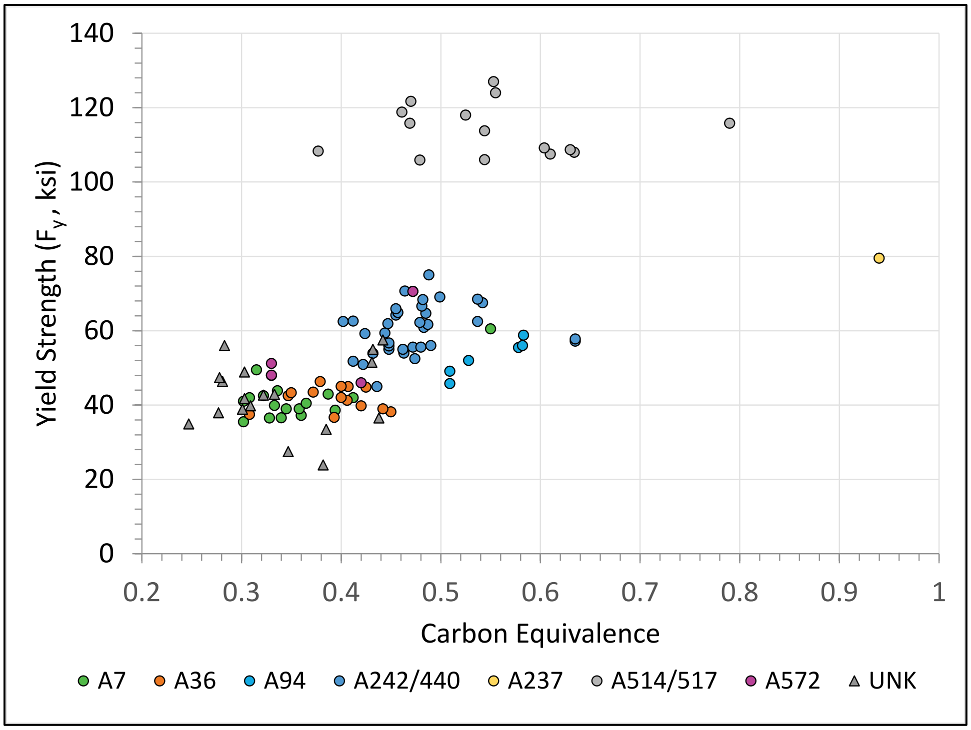

Figure 2. Yield strength and carbon equivalence by material specification.

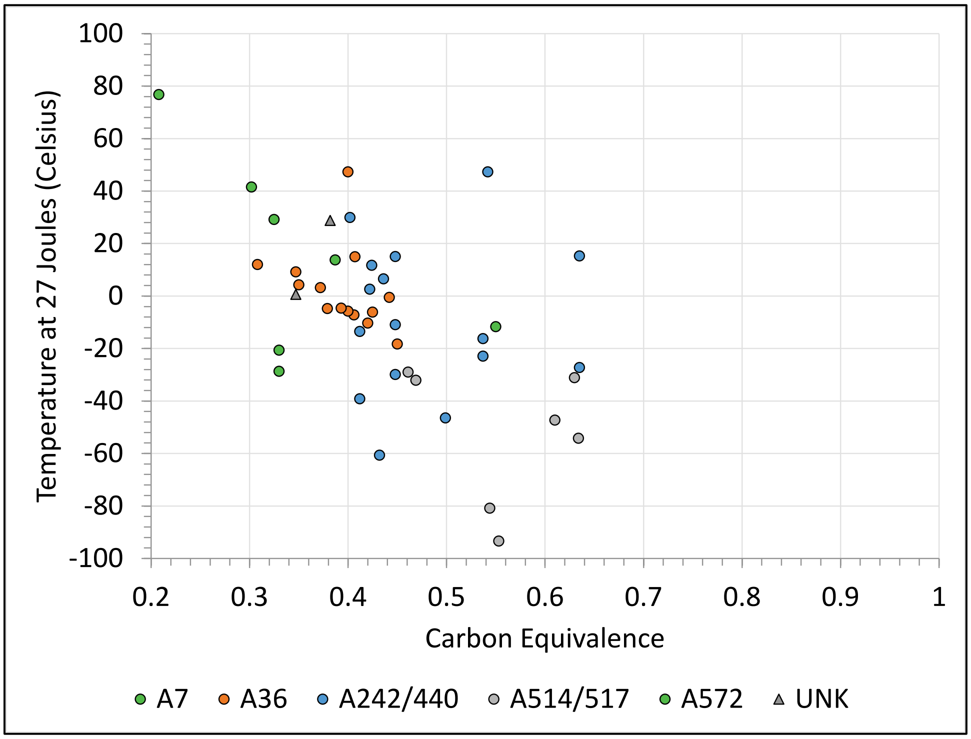

Figure 3. CVN temperature at 27 J and carbon equivalence by material specification.

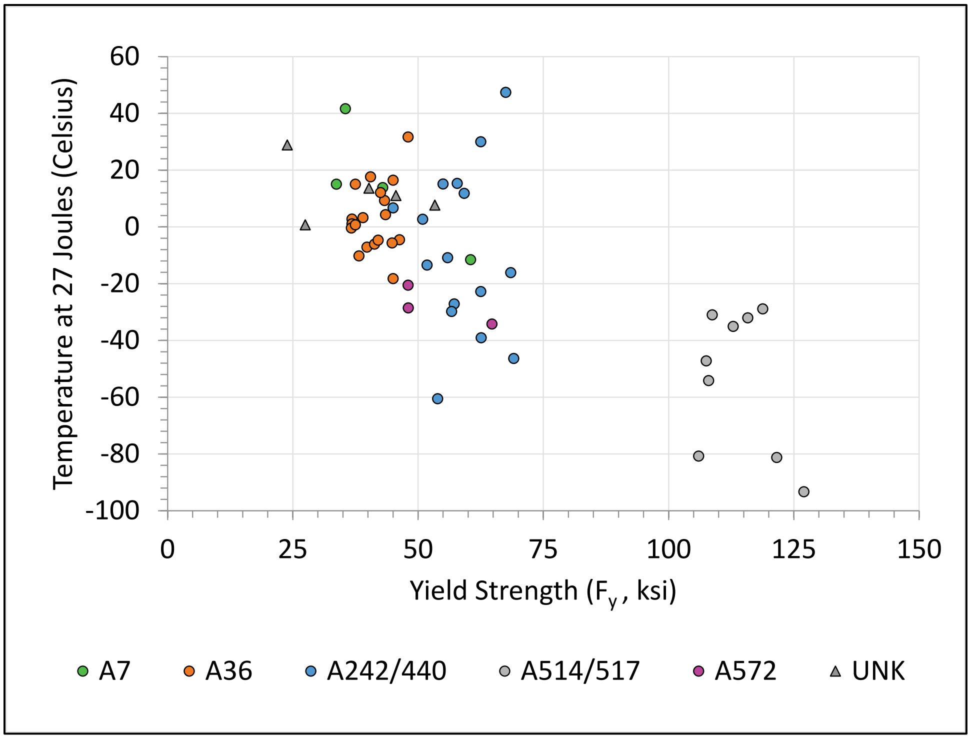

Figure 4. Yield strength and temperature at 27 J by material specification.

CONCLUSION: A database has been compiled to provide information on the tensile strength and fracture toughness of different types of steel used in HSS with an emphasis on the period between 1930 and 1990. The database is motivated by the need to provide inputs for FFS analysis as described in BS 7910:2013+A1:2015 (BSI 2015). The database incorporates the results of laboratory tests to estimate tensile strength and the CVN test temperatures at which 27 and 40 J would be released during standard CVN tests. CVN test temperatures are negatively correlated with fracture toughness and these values serve as a proxy for fracture toughness. These data were collected by USACE districts during studies of HSS and by a variety of other sources during studies of bridges in the United States. This database is currently housed on a SharePoint site and will be made available to structure engineers at the district level through the Structural Community of Practice.

With one exception, these data show that steel used in HSS exhibits tensile strengths that conform to their specifications. Measured tensile strength is greater than or equal to the minimum tensile strength described in those specifications. Therefore, if the specification of a steel component is known, the lower bounds of yield strength and ultimate strength described in those specifications might reasonably be used as a conservative estimate of tensile strength. Historic specifications for structural steel did not describe minimum values for fracture toughness. However, a variance reduction analysis showed strong statistical dependence between CVN temperature and both steel specification and carbon equivalence. This suggests that in the absence of site-specific data on fracture toughness, information on steel specification might be used to estimate a conservative upper bound on CVN temperature. This value could then be used to derive an estimate of fracture toughness for FFS analysis. However, a more complete and comprehensive database than is described here would be needed to establish those relationships.

If more modern FFS analysis methods will be used to make decisions about the need for repair of damaged HSS, there is a need for information about the material properties of steel used in constructing those HSS. Because this information was not well documented between 1930 and 1990, and destructive testing of fracture critical members of HSS is rarely an option, other sources of information will be needed. One potential source of this information is information about steel used in other HSS. A database describing the material properties of steel used in other HSS has been developed for this purpose.

Data were compiled from across USACE districts. Laboratory reports were identified through the voluntary responses of individuals to data calls issued through the Structural Community of Practice and through personal contacts. Data collection would have benefited from a systematic way to identify laboratory reports available within the agency, such as a central repository or library. Creating a digital repository to collect and catalog laboratory reports in the future is one way forward. However, this does not address the lack of information about existing structures built from 1930 to 1990. Laboratory reports that are available on these structures are often printed on paper, buried in desk drawers or in closets, and there is no systematic way to retrieve them.

The second challenge to address in compiling a central source of information on material properties is overcoming differences in testing standards, laboratory techniques, data curation standards, and data formats across data sources. These differences pose a significant challenge for those who attempt to compile data from multiple sources. For data users, this creates ambiguity and uncertainty about how that data should be interpreted. At a minimum, a database should report material properties of interest, the uncertainty in those estimates, the methods and standards used in estimating those properties, and the pedigree of the laboratory or organization publishing those results. The original documents from which data were extracted should also be preserved and made accessible to users who wish to refer to the original sources.

Compiling data on material properties of different steels and making them available for use in FFS analysis a realistic option. However, these data still need to be translated into estimates of tensile strength and fracture toughness that can be used in FFS analysis of a specific HSS. Many such predictive models and correlations already exist in the literature. Their applicability to HSS should be evaluated. While the variance reduction analysis described in this tech note shows a strong relationship between tensile strength, CVN temperature and carbon equivalence, the dependencies appear to be stronger across specifications than within specifications. Given the sparsity of this database, no attempts were made to use these data to fit predictive models or correlations specifically for HSS.

ADDITIONAL INFORMATION: Data on steel properties from hydraulic steel structures was compiled by Jarrod H. Milligan, structural engineer, USACE, Walla Walla District. Additional data on the properties of bridge steels were contributed by Robert J. Connor, Purdue University, and William Collins, University of Kansas, from their research databases. Zackery B. McClelland and Kyle P. Dunsford of the ERDC Materials Testing Center analyzed specimens of steel from relict hydraulic steel structures. This technical note was prepared by Martin T. Schultz, ERDC Environmental Laboratory; Brian E. Skahill, ERDC Coastal and Hydraulics Laboratory; Leslie E. Campbell, USACE New Orleans District; Phillip W. Sauser, USACE Northwestern Division; and Ramsay D. Bell, USACE Portland District. The research was supported by the ERDC Navigation

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