STATISTICAL ANALYSIS OF CHARPY V-NOTCH TOUGHNESS FOR STEEL WIDE FLANGE STRUCTURAL SHAPES

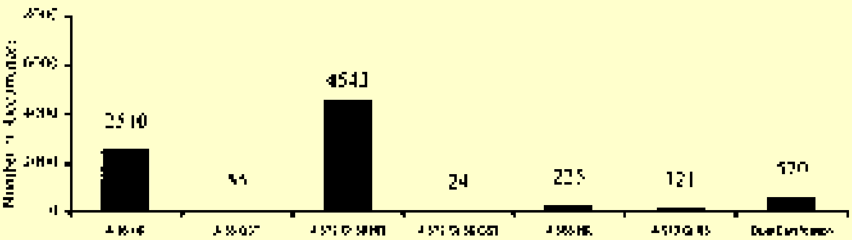

Figure 1: *Number of CVN samples reported by ASTM steel grade designation*

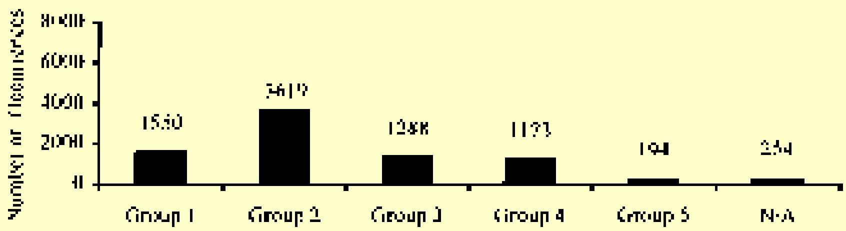

Figure 2: *Number of CVN samples reported by ASTM group shape. Data that was provided with a known steel grade, test temperature and test location but which could not be classified in an ASTM group is listed as "not available" (NA)*

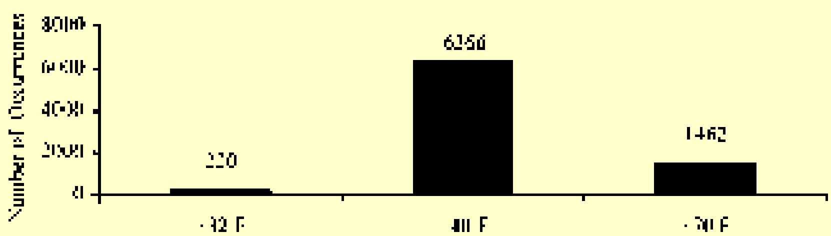

Figure 3: *Number of CVN samples reported by test temperature*

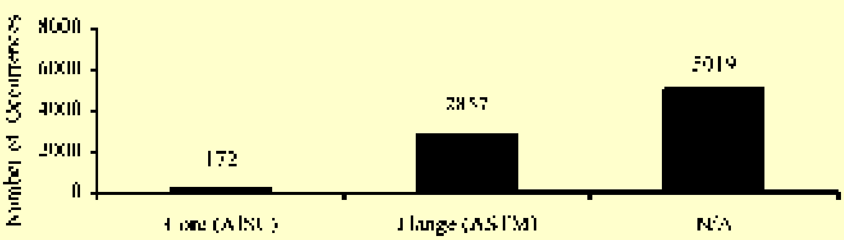

Figure 4: *Number of CVN samples reported by test location. N/A represents data for which producers did not specify a location.*

By Jacques Cattan

AFTER THE 1994 NORTHRIDGE EARTHQUAKE, QUESTIONS BEGAN TO SURFACE about the toughness of material provided for structural steel frames when no minimum values were specified. Steel shape producers advised that the material they furnished provided toughness at traditionally accepted levels and that specifying toughness would needlessly incur the cost of testing without providing any real benefit. In answer to these questions, AISC has recently studied production data to provide information on steel toughness and evaluate this issue.

The study revealed that the probability of obtaining CVN values of 15 ft.-lbs. at 40 degrees F or 20 ft.-lbs. at 70 degrees F in the longitudinal direction at the standard test location when tested according to current codes and standards is high even though toughness is not required by material or design specifications for most building projects. *The full report is available from the American Institute of Steel Construction Technology & Research Department for a nominal fee of $10.00. For more information or to order a copy, please call AISC's Technology and Research Department at 312/670-5411.*

MATERIAL TOUGHNESS IS DEFINED by S.T. Rolfe and J.M. Barsom ("Fracture and Fatigue Control in Structures/Application of Fracture Mechanics," Prentice-Hall, 1977) as "the resistance to unstable crack propagation in the presence of a notch". Notch toughness is defined in C.G. Salmon's and J.E. Johnson's "Steel Structures Design and Behavior" (Harper Collins Publishers Inc., Third Edition 1990) as " the measure of the resistance of a metal to the start and propagation of a crack at the base of a standard notch, commonly using the Charpy V-Notch test". Several studies in the past have concentrated on investigating the variability of Charpy V-Notch toughness, or CVN toughness, within a steel plate or throughout the cross-section of a wide flange shape.

This report, which was prepared by AISC's Technology and Research Department and reviewed by Task Committee 115 on Materials of the AISC Committee on Specifications, describes the variability of CVN toughness data as documented by six steel shape producers over 12 to 18 months (during 1994-95) both at the standard ASTM A6/A6M flange location and the standard AISC Specification for Structural Steel Buildings Group 4 and 5 core area location. Data and information was provided by the following members of the Structural Shapes Producers Council (SSPC): Bethlehem Steel Corporation; British Steel; Chaparral Steel Company; Northwestern Steel & Wire; Nucor-Yamato Steel Company; and TradeArbed.

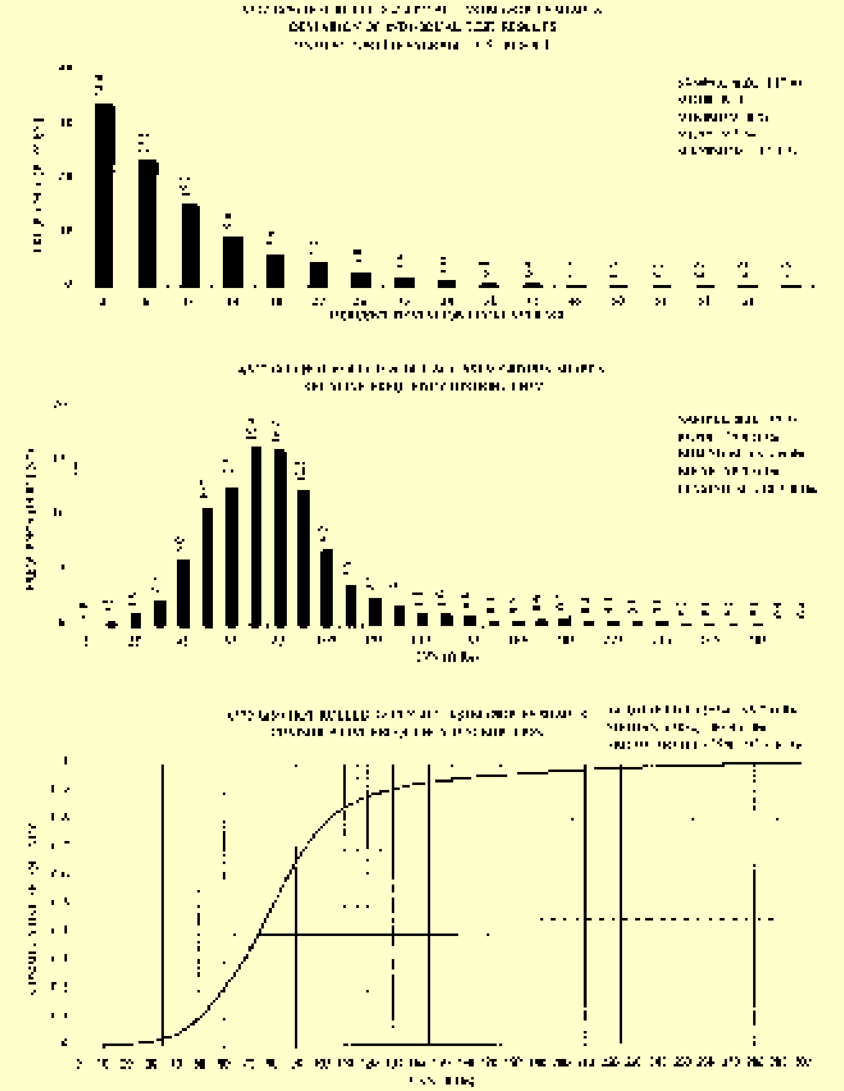

Chart 1: *Typical distribution chart for A572 Gr. 50 hot rolled at 40 degrees F and including all ASTM shapes*

Fracture Mechanics

Structural steels can reach a strength limit state in one of two manners: brittle or ductile. A ductile response is preferred, especially for high seismic conditions, because it is gradual, provides energy dissipation and overload protection. Steel fracture is dependent on the rate of loading, the ambient temperature and any constraints applied to the material that would restrict plastic deformations. Slower loading rates, higher temperatures, and fewer constraints all increase material toughness. Additional factors affecting the fracture resistance of a component are geometry and surface conditions, the presence and size of existing discontinuities or crack initiators. Bridge structures have long been identified as being susceptible to fatigue and fracture and hence, material toughness has been recognized as an important property for these exposed conditions. The toughness demands for enclosed buildings subject to wind and gravity loads, which are considered static, are relatively less severe than for bridges or for larger members in welded moment frames subject to high seismic loads.

To properly evaluate the toughness of a material the theory of fracture mechanics, which is widely covered in the literature, can be used. One common parameter is the energy absorbed by the material during fracture of a steel test specimen subject to a standard test. In a CVN test a small bar specimen with a milled notch is struck by a fast moving hammer, the energy that is absorbed in breaking the test sample is measured. CVN testing is documented in supplement (S5) of the ASTM A6/A6M specification and the test is performed according to the ASTM A370 specification on a sample collected according to the ASTM A673 specification. A

Table 1: Statistical parameters of examined distributions

Steel Grade	Test Temp. (deg. F)	ASTM Shape Group	Sample Size	Mode (ft.-lbs.)	Min. (ft.-lbs.)	Mean (ft.-lbs.)	Max. (ft.-lbs.)	1st Quartile (ft.-lbs.)	Median (ft.-lbs.)	3rd Quartile (ft.-lbs.)
A36 QST	32	ALL	21	162	91	151	204	137	160	168
A36 HR	32	ALL	73	130	91	150	241	124	145	169
A36 HR	40	ALL	2011	66	16	112	286	65	98	147
		1	421	100	20	116	272	79	113	146
		2	1057	239	16	130	286	77	117	176
		3	315	36	19	86	240	63	77	98
		4	218	54	16	54	193	41	51	62
A36 HR	70	ALL	426	239	22	95	253	43	70	124
		1	262	43	25	59	177	36	50	75
		2	59	69	59	122	253	83	97	138
		3	24	239	25	200	240	235	239	239
		4	81	240	22	158	240	99	177	221
A572 Gr 50 QST	32	ALL	24	N/A	101	136	182	122	138	149
A572 Gr 50 HR	32	ALL	15	N/A	106	140	170	135	142	147
A572 Gr 50 HR	40	ALL	3930	79	16	91	288	64	80	97
		1	400	58	16	84	259	58	73	95
		2	2181	80	18	93	288	71	85	102
		3	813	86	16	83	280	65	82	96
		4	453	60	17	66	155	53	63	77
		5	83	49	29	62	155	47	59	71
A572 Gr 50 HR	70	ALL	598	47	15	61	241	31	51	74
		2	37	124	31	135	237	89	134	194
		3	90	74	31	76	202	56	68	91
		4	364	50	17	57	241	34	51	68
		5	104	26	15	33	116	23	27	32
A588 HR	40	ALL	223	21	16	140	290	71	129	204
		2	182	54	18	148	290	82	145	215
		3	41	N/A	16	103	249	58	75	155
A913 Gr65 QST	32	ALL	87	156	92	141	212	122	142	158
A913 Gr65 QST	70	ALL	34	48	33	61	108	45	57	79
Dual Certified	40	ALL	202	43	17	53	121	37	51	67
		1	142	38	17	51	121	35	48	63
		2	55	43	24	59	116	43	58	74
Dual Certified	70	ALL	368	65	15	59	131	41	55	74
		1	322	53	15	55	131	37	53	69
		2	46	65	60	86	123	67	91	99

NOTE: HR = Hot Rolled; QST = Quenched Self-Tempered

minimum value of 15 ft.-lbs. at the test temperature taken to be 40 degrees F is traditionally used for structural steel applications. This criteria was developed in the mid 1940s and the reader is referred to Chapter 13 of Rolfe and Barsom's book, "Fracture and Fatigue Control in Structures" for further information.

In addition to ASTM, the AISC LRFD Specification (1993) Section A3.1.c requires testing for ASTM A6/A6M Group 4 and 5 shapes when used for certain applications. The testing is conducted in accordance with the ASTM A6/A6M, Supplement S5. Several additional requirements are set by the AISC Specification, including sampling from the core location and a required minimum average value of 20 ft.-lbs. absorbed energy at 70 degrees F. AISC does not currently require any similar CVN properties for other shapes or other applications used for interior building construction under static conditions.

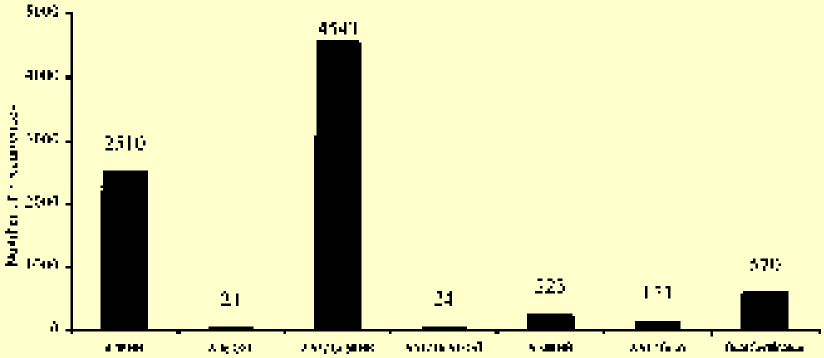

Figure 5: Distribution of CVN samples used to determine the statistical parameters in Table 1. Comparing Figures 1 and 5 reveals that 36 values were not used. The 36 values not used came from shapes or heats which did not fit clearly an ASTM grade or group studied here. In essence, the statistical analysis was performed on 8,012 data points each representing the average of three CVN tests.

CVN values are a material qualification which are not directly used in AISC design equations. Engineers are advised that CVN values are to be used in conjunction with other properties of the material, its design and fabrication and should not be the only measure of the material adequacy.

Sample Data Base

Data was submitted from heats produced in 1994 and 1995. The sample consisted of an unidentified mix of heats ordered with toughness requirements and heats tested for internal quality control purposes. The data for this study is considered representative of the present and future shape production as confirmed to AISC in writing by the six participating producers. The test samples were full size samples taken from the ASTM standard flange location or from the AISC core location, all in the longitudinal—or rolling—direction. The tests were done at one of three temperatures: 32 degrees F, 40 degrees F and 70 degrees F. Only wide flange structural shapes were considered and grouped by web thickness according to the ASTM A6/A6M. As shown in Figures 1 through 5, the steel grades evaluated are:

- A36 HR (Hot Rolled)
- A36 QST (Quenched and Self-Tempered)
- A572 Gr50 HR
- A572 Gr50 QST
- A913 Gr65 QST
- A588 HR
- Dual grade (A36 and A572 Gr50)

ASTM A673 defines a test as the average of three specimens. Most data reported to AISC was the three required test values and the average of these three values. The total number of CVN values reported to AISC was 21,330. Also, the total number of average CVN values reported by the producers to AISC was 8,048. (Multiplying the number of average CVN values by three does not correspond to the total number of CVN values reported since one producer did not provide individual CVN values but provided only the average CVN).

CVN Statistical Analysis

A set of data can be characterized by the following principle statistical parameters:

- Sample size
- Minimum value
- Mode (value that occurs most frequently)
- Mean (sum of all the values divided by the sample size)
- Maximum value
- The range of values (the difference between the maximum value and the minimum value)
- Standard deviation (measure of scatter).

A set of data can be further characterized by statistical information obtained from a cumulative distribution such as:

- The first quartile (value below which 25% of the data lies and above which 75% of the data is located)
- The median (value above and below which 50% of the sample is located)
- The third quartile (value below which 75% of the data lies and above which 25% of the data is located)
- Finally, theoretical statistical distributions can be fit to the data and tested, but this was not done in this report.

For the statistical analysis the data was divided by steel grade, by temperature and by size group as shown in Table 1. Table 1 shows the steel grade, the test temperature, the sample size, and the statistical results obtained. Included in Table 1 are the following:

- The mode of the data
- The minimum value
- The mean
- The maximum value
- The first quartile
- The median
- The third quartile

Figure 5 shows the distribution of the CVN samples used to determine the statistical parameters in Table 1. If the reader compares Figures 1 and 5 he/she will notice that 36 values were not used. The 36 values not used came from shapes or heats which did not fit clearly an ASTM grade or group studied here. In essence, the statistical analysis was performed on 8012 data points each representing the average of three CVN tests.

When possible the deviation of the individual test values from the reported average test value were computed and plotted in the charts provided in Appendix A of the full Report. These values represent the scatter of each test with respect to the group average CVN value reported; the means of these deviations vary

Table 2: Observed probabilities of exceedance

Steel Grade	Test Temp. (Degrees F)	ASTM Shape Group	Observed Prob. Of Exceedence 15 ft.-lbs. (%)	Observed Prob. Of Exceedance 20 ft.-lbs. (%)
A36 QST	32	ALL	100	100
A36 HR	32	ALL	100	100
A36 HR	40	ALL	99	97
		1	100	97
		2	100	99
		3	100	99
		4	96	95
A36 HR	70	ALL	100	95
		1	100	95
		2	100	100
		3	100	94
		4	100	97
A572 Gr 50 QST	32	ALL	100	100
A572 Gr 50 HR	32	ALL	100	100
A572 Gr 50 HR	40	ALL	100	99
		1	99	99
		2	100	99
		3	98	98
		4	100	99
		5	100	99
A572 Gr 50 HR	70	ALL	95	87
		2	100	100
		3	100	100
		4	96	89
		5	85	60
A588 HR	40	ALL	98	97
		2	99	98
		3	97	95
A913 Gr65 QST	32	ALL	100	100
A913 Gr65 QST	70	ALL	100	100
Dual Certified	40	ALL	99	94
		1	98	94
		2	100	99
Dual Certified	70	ALL	98	94
		1	98	93
		2	100	100

NOTE: HR = Hot Rolled; QST = Quenched Self-Tempered

from 3 to 17% and are usually of the order of 10 to 12% of the average. For each steel grade, test temperature, and ASTM Shape Group, a relative frequency distribution and a cumulative frequency distribution are plotted, as shown in Chart 1. For convenience, the cumulative frequency distributions are plotted on a larger sheet in Appendix B of the full Report (a smaller version is shown in Chart 2). These charts allow the reader to directly read the probability of exceeding a given CVN value based on the data itself (not a theoretical fitted distribution). A certain steel grade, at a certain temperature and a certain ASTM Shape Group may not be presented due to the small sample of available data, which makes a statistical analysis not valid, or because it simply is not rolled.

Related Coverage In The AISC Manuals

In order to put material toughness and the conditions that increase susceptibility to brittle fracture in an overall context, the AISC Manual of Steel Construction, pages 1-4 through 1-6 in the most recent 1989 ASD 9th Edition and the 1993 LRFD 2nd Edition, pages 1-6 through 1-9, have introductory sections intended to overview the potential problems and provide some general and specific guidelines.

Conclusions

The inherent statistical variability of steel production warrants higher target properties than the required minimum values, and this is reflected in the generally high CVN means are generally higher and range from 33 ft.-lbs. at 70 degrees F for A572 Gr. 50 hot rolled group 5 shapes to 200 ft.-lbs. at 70 degrees F for A36 hot rolled group 3 shapes. Table 2 contains the observed probability of exceeding a CVN value of 15 ft.-lbs. at 40 degrees F or 20 ft.-lbs. at 70 degrees F. These probabilities were obtained from the cumulative distribution curves. The values in Table 2 are given for each steel grade including all ASTM groups.

It is clear from the given data curves that, in general, the probability of obtaining CVN values greater than 15 ft.-lbs. at 40 degrees F or 20 ft.-lbs. at 70 degrees F in the longitudinal direction at the standard test location when tested according to current codes and specifications is high, even though toughness is not usually a required material property for buildings. The 1993 AISC specification requires minimum CVNs in limited applications of thick material. Other

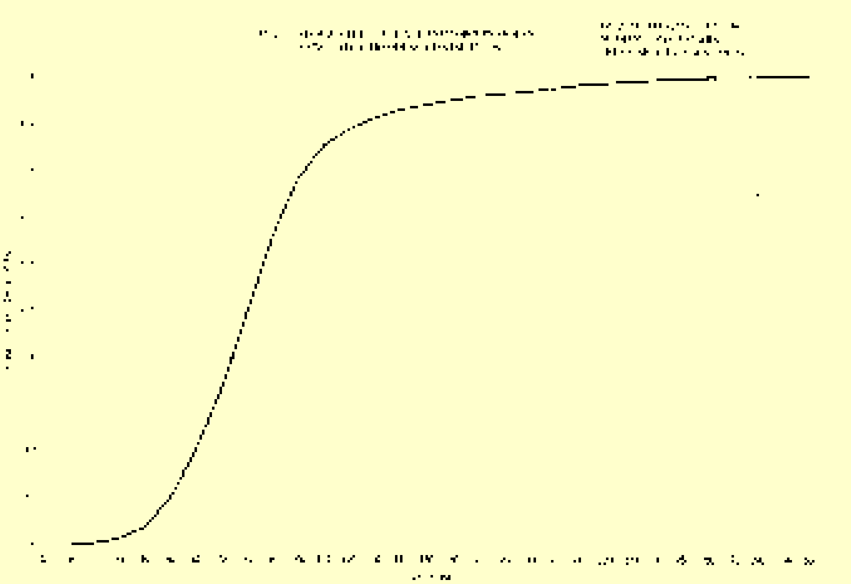

Chart 2: Typical cumulative distribution chart. Shown here is A572 Gr. 50 hot rolled at 40 degrees F and including all ASTM shapes

steel members furnished without specified minimum CVN values can be expected to provide the toughness anticipated in designs using the 1993 AISC Specification. The reader should know high material toughness values may not by themselves compensate for special conditions, poorly designed details, bad fabrication or inadequate inspection and usage.

Developments continue to occur, especially for high seismic construction in design concepts and material. AISC will remain involved and will endeavor to keep the design community advised of any changes in practice.

Jacques Cattan is a staff engineer at AISC, Inc.

Analysis of fracture toughness data for modified SA508 Cl2 in the ductile-to-brittle transition region. In: Fracture Mechanics: Twenty-First Symposion, ASTM STP 1074. (Edited by: Gudas, J., Joyce, J. and Hackett, E.), Philadelphia, U.S.A., 238â€“263.Google Scholar.Â An analysis of the temperature and rate dependence of Charpy V-notch energies for a high nitrogen steel. International Journal of Fracture 37, 197â€“215.Google Scholar. Tweed, J. and Knott, J. (1983).