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The History and Importance of Impact Testing*

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Abstract: Charpy impact testing is a low-cost and reliable test method which is commonly required by the construction codes for fracture-critical structures such as bridges and pressure vessels. Yet, it took from about 1900 to 1960 for impact-test technology and procedures to reach levels of accuracy and reproducibility such that the procedures could be broadly applied as standard test methods. This paper recounts the early history of the impact test and reports some of the improvements in the procedures (standard specimen shape, introduction of a notch, correlation to structural performance in service, and introduction of shrouds) that led to this broad acceptance.

Keywords: absorbed energy, Charpy impact testing, history, impact testing, pendulum impact

Without uniformity of test results from day to day and from laboratory to laboratory, the impact test has little meaning. Over the years, researchers have learned that the results obtained from an impact test can depend strongly upon the specimen size and the geometry of the notch, anvils, and striker. To a lesser degree, impact test results also depend upon other variables such as impact velocity, energy lost to the test machine, and friction. The goal of those who have written and modified ASTM Standard Test

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Further details on the economic impact of Charpy impact testing are included in a previous version of this report published in *Standardization News*, February 1999.

Methods for Notched Bar Impact Testing of Metallic Materials (E 23) has over the years
been to standardize and control the variables associated with impact testing. This report looks at the history of impact testing, with emphasis on the key advances in understanding and application of the impact test, as reflected in the evolution of the test standard.

Impact Testing: 1824 to 1895

The earliest publication that we could find on the effects of impact loading on materials was a theoretical discussion by Tredgold in 1824 on the ability of cast iron to resist impulsive forces [*1*]. In 1849, the British formed a commission to study the use of iron in the railroad industry, which began by considering practical approaches to impact testing [*2*]. Apparently, failures of structures in the field were leading some researchers to speculate that impact loads affected materials far differently than static loads, so tensile-strength data (from slowly applied loads) was a poor predictor of performance under dynamic loads.

In 1857, Rodman devised a drop-weight machine for characterization of gun steels, and over the subsequent 30-year period, his machine was widely used to test railroad steels and for qualification of steel products [*2*]. Many of the early experiments with impact tests were performed on final product forms, such as pipes or axles. Thus they served as proof tests for a batch of material, or yielded comparative data for a new product design, or basic reference data on the impact resistance of different construction materials (such as the comparison of wrought iron to ductile iron). Instrumentation was poor for the early impact tests, so the data is often only as break or no-break for a mass dropped through a certain distance. These early drop weight tests were conducted using smooth (no notch or crack starter) rectangular bars. While the test worked well for brittle materials, where crack initiation is easy, specimens of ductile materials often just bent. LeChatalier introduced the use of notched specimens while conducting drop-weight tests in 1892 [*3*]. He found that some steels that showed ductile behavior (bending without fracture) in a smooth rectangular bar, would exhibit fragile behavior when the test specimen was notched. While the addition of a notch was a major improvement in the test method, a test procedure was needed that would provide a continuous, quantitative measure of the fracture resistance of materials. Also, substantial work was needed to develop test procedures that produced consistent data, and to answer the objections of those who doubted the value of impact testing.

1895 to 1922

This period saw the establishment of a number of national and international standards bodies, which took up the causes of developing robust test procedures and developing consensus standards for many technologies, including impact testing. One of these standards bodies was The American Society for Testing and Materials, established in

1898. Another was the International Association for Testing Materials, officially established in 1901, but this association grew out of the good response to two previous International Congresses that had been held a number of years before. These two standards bodies seem to have had a good working relationship, and the President of ASTM, Prof. H. M. Howe, also served on the Board of IATM during this time [*4*].

In 1902, only four years after the founding of ASTM, the ASTM "Committee on the Present State of Knowledge Concerning Impact Tests" published a bibliography on impact tests and impact testing machines in the second volume of the Proceedings of ASTM [*5*]. This bibliography listed more than 100 contemporary papers on impact testing published in the U.S., France, and Germany. Many of these papers contained information that was also known to the members of IATM. In fact, some of the papers had been presented and discussed at the IATM Congresses.

Among the references is a report by Russell (published in 1898 and reprinted in this STP) that shows remarkable insight into the needs of the design engineers of the time and introduces quantitative measurement to the test [*6*]. He pointed out that none of the machines of the time, typically of a drop-weight design, had the ability to determine any data beyond whether the specimen broke or remained intact. Therefore, he designed and built a pendulum machine which "would measure the energy actually absorbed in breaking the test bar". His report shows a test machine that is based on the same swinging pendulum concept as those in common use today and mentions his careful analysis of the mechanics of the test, including corrections for friction losses and calculation and comparison of the centers of gravity and percussion. Since this was before the time of compact, standardized test specimens, the machine was vary large and massive, and was capable of breaking many full-size products. Besides showing a prototype of the machines used today, this report is valuable in that it includes data on over 700 tests of typical construction materials, and emphasizes the effect of the rate of loading in evaluating materials for different service conditions. Russell's pendulum impact machine finally provided a means for quantifying the energy absorbed in fracturing a test specimen for a wide range of materials and conditions. His paper nicely summarizes the test-machine technology and knowledge for material performance at the end of the past century, and so served as a benchmark for future research. To the best of our knowledge, Russell was the first to develop and demonstrate the advantages of the pendulum design for impact testing machines.

The members of IATM Commission 22 (On Uniform Methods of Testing Materials) continued to conduct research that addressed the shortcomings in the impact testing techniques, until they had developed a knowledge of most of the important factors in the test procedure. Even though many of these early machines and reports are simplistic by today's standards, they provided previously unknown data on the impact behavior of materials. France seems to have been an early adopter of impact testing for infrastructure construction standards, and so French researchers provided much data on the effects of procedure variables and were the most prolific contributors to the IATM Proceedings between 1901 and 1912. Incidentally, it was a representative from France, G. Charpy, who became the chair of the impact testing activity after the 1906 IATM Congress in

Brussels, and presided over some very lively discussions on whether impact testing procedures would ever be sufficiently reproducible to serve as a standard test method [*7*]. Charpy's name seems to have become associated with the test because of his dynamic efforts to improve and standardize it, both through his role as Chairman of the IATM Commission and through his personal research [*8*]. He seems to have had a real skill for recognizing and combining key advances (both his and those of other researchers) into continually better machine designs and consensus procedures. For example, Charpy acknowledges the benefits of Russell's pendulum design in his 1901 paper [*8*] by stating: "Russell described in a paper presented in 1897 at the American Society of Civil Engineers some 'experiments with a new machine for testing materials by impact.' The machine he is using is designed to determine the work absorbed by the rupture of a bar, for this, the ram used appears in the form of a pendulum arranged in such a way so that when it is released from its equilibrium position, it meets the test bar in passing through the vertical position, breaks it and afterward rises freely under the influence of the acquired speed. The difference between the starting height and the finishing height of the pendulum allows evaluation of the work absorbed by the rupture of the bar."

By 1905, Charpy had proposed a machine design that is remarkably similar to present designs and the literature contains the first references to "the Charpy test" and "the Charpy method". He continued to guide this work until at least 1914 [*7,9-10*]. A number of other standard machine designs and procedures were also under consideration at this time, and in 1907 the German Association for Testing Materials adopted one developed by Ehrensberger [*10*]. Because the pendulum machine had not achieved dominance yet, impact machine designers and manufacturers offered three major types; Drop Weight (Fremont, Hatt-Turner, and Olsen), Pendulum Impact (Amsler, Charpy, Dow, Izod, Olsen, and Russell), and Flywheel (Guillery).

This was a period during which the configuration and size of specimens closely approached what we use today [*7*]. Originally, two standard specimen sizes were most popular. The smaller had a cross section of 10 by 10 mm, a length of about 53 mm (for a distance of 40 mm between the points of support), a notch 2 to 5 mm deep, and a notch tip radius near 1 mm. The larger and initially more popular of these specimen sizes was scaled up by a factor of three in all these dimensions. The group favoring the larger specimen pointed out the advantage of sampling a larger cross section of the material (for reduced scatter in the data) and the difficulty of producing the small notch radius on the smaller specimen. However, the group favoring the smaller specimen eventually won because a more compact and lower-cost machine could be used, and not all structures were thick enough to produce the larger specimen. Besides specimen dimensions that are very similar to what we use today, the Commission proposed features for a standard impact procedure that included:

- limits for the velocity of the striker,
- rigid mounting to minimize vibration losses,
- a minimum ratio of anvil mass and rigidity to striker size, and
- recognition of the artificial increase in energy as ductile specimens deform around

the edges of a wide striker [*7*].

One report at the 1912 meeting [*7*] included the testimonial from a steel producer of how the improved impact test procedures had allowed them to tailor the refining processes to produce less brittle steel. The report describes a reduction by a factor of 20 in the number of production parts that were rejected for brittle performance.

1922 to 1933: The Beginning of ASTM Method E 23

ASTM Committee E-1 on Methods for Testing sponsored a Symposium in 1922 on Impact Testing of Materials as a part of the 25th Annual Meeting of the Society, in Atlantic City, New Jersey. The Symposium included a history of the developments in this area, a review of work done by the British Engineering Standards Association, several technical presentations, and the results of a survey sent to 64 U.S. testing laboratories [*11*]. Twenty-three respondents to the survey offered detailed information on topics such as the types of machines in use, the specimen dimensions, and procedures. In addition, many responded positively to a question about their willingness to develop an ASTM standard for impact testing.

Based on the information in this survey, an ASTM subcommittee began to prepare a standard test method for pendulum impact testing in 1923. This effort took until 1933, when ASTM published "Tentative Methods of Impact Testing of Metallic Materials," ASTM designation E 23-33T. (An ASTM specification of “Tentative” indicated that it was subject to annual review and was a work in progress. The tentative designation is no longer used by ASTM.) (Other countries also developed their own standards; however, we found it difficult to find their records and to track their developments.)

ASTM E 23-33T specified that a pendulum-type machine was to be used in testing and “recognized two methods of holding and striking the specimen”, that is, the Charpy test and the Izod test (where the specimen is held vertically by a clamp at one end). It did not specify the geometry of the striking edge (also known at the time as the “tup”) for either test. It stated that “the Charpy type test may be made on unnotched specimens if indicated by the characteristics of the material being tested, but the Izod type test is not suitable for other than notched specimens”. Only a V-notch was shown for the Charpy test. Although the dimensions for both types of specimens were identical with those currently specified, many tolerances were more restrictive. The units were shown as English preferred, metric optional. The committee pointed out many details that influence the test results, but because they did not have the knowledge and database needed to specify values and/or tolerances for these details, the document was issued as a tentative. The original document contains an appendix with general discussions of applications, the relation to service conditions, and comparisons between materials. As our understanding of the variables in Charpy testing has grown, ASTM E 23 has been revised repeatedly to incorporate the new knowledge.

1934 to 1940

The first revision of E 23 was issued in 1934 and it added a dimension for the radii of the anvil and specifically stated that "these specimens (both the Charpy and the Izod) are not considered suitable for tests of cast iron" referencing a report of ASTM Committee A3 on Cast Iron. The method retained the "tentative" designation.

The geometry of the Charpy striking tup, specifically the radius of the tup that contacted the specimen, was not specified in the 1934 revision. However, the minutes of the 1939 and 1940 meetings for the Impact Subcommittee of E1 state that this item was discussed and a survey was made of the geometries used in the United Kingdom and in France. Those countries had been using radii of 0.57 mm and 2 mm, respectively. For reasons that were not recorded, the members of the Subcommittee agreed to a radius of 8 mm at the 1940 meeting and ASTM E 23 was revised and reissued as E 23-41T. Two other changes that occurred with this revision were that metric units became the preferred units, and keyhole and U notches were added for Charpy-test specimens.

1940 to 1948

Impact testing seems to have been a useful technique for evaluating materials, but was not a common requirement in purchase specifications and construction standards until the recognition of its ability to detect the ductile-to-brittle transition in steel. Probably the greatest single impetus toward implementation of impact testing in fabrication standards and material specifications came as a result of the large number of ship failures that occurred during World War II. These problems were so severe that the Secretary of the U.S. Navy convened a Board of Investigation to determine the causes and to make recommendations to correct them. The final report of this Board stated that of 4694 welded-steel merchant ships studied from February 1942 to March 1946, 970 (over 20%) suffered some fractures that required repairs [*12*]. The magnitudes of the fractures ranged from minor fractures that could be repaired during the next stop in port, to 8 fractures that were sufficiently severe to force abandonment of these ships at sea. Remedies included changes to the design, changes in the fabrication procedures and retrofits, as well as impact requirements on the materials of construction. The time pressures of the war effort did not permit thorough documentation of the effect of these remedies in technical reports at that time; however, assurance that these remedies were successful is documented by the record of ship fractures that showed a consistent reduction in fracture events from over 130 per month in March 1944 to less than five per month in March 1946, even though the total number of these ships in the fleet increased from 2600 to 4400 during this same period [*12*].

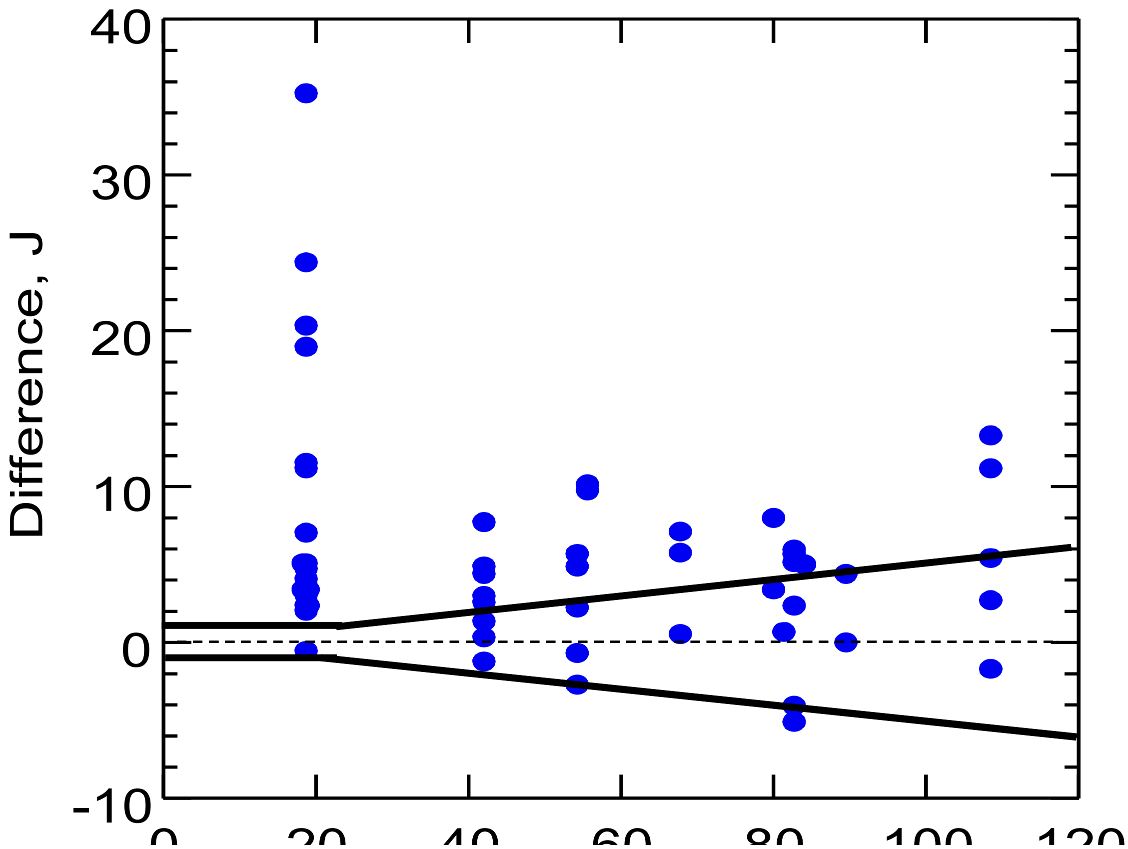
After the war, the National Bureau of Standards released its report on an investigation of fractured plates removed from some of the ships that exhibited these structural failures and so provided the documentation of the importance of impact testing [*13*]. The NBS study included chemical analysis, tensile tests, microscopic examination, Charpy impact tests, and reduction in thickness at the actual ship fracture plane. A notable conclusion of the report was that the plates in which the fracture arrested had consistently higher impact energies and lower transition temperatures than those in which the fractures originated. This was particularly important because there was no similar correlation with chemical composition, static tensile properties (all steels met the ABS strength requirements), or microstructure. In addition, the report established 15 ft-lb (often rounded to 20 J for metric requirements) as a minimum toughness requirement, and recommended that "some criterion of notch sensitivity should be included in the specification requirements for the procurement of steels for use where structural notches, restraint, low temperatures, or shock loading might be involved", leading to a much wider inclusion of Charpy requirements in structural standards.

1948 to Present

By 1948, many users thought that the scatter in the test results between individual machines could be reduced further, so additional work was started to more carefully specify the test method and the primary test parameters. By 1964, when the ASTM E 23 standard was revised to require indirect verification testing, the primary variables responsible for scatter in the test were well known. In a 1961 paper, Fahey [*14*] summarized the most significant causes of erroneous impact values as follows: (1) improper installation of the machine, (2) incorrect dimensions of the anvil supports and striking edge, (3) excessive friction in moving parts, (4) looseness of mating parts, (5) insufficient clearance between the ends of the test specimen and the side supports, (6) poorly machined test specimens, and (7) improper cooling and testing techniques. While the machine tolerances and test techniques in ASTM E 23 addressed these variables, it was becoming apparent that the only sure method of determining the performance of a Charpy impact machine was to test it with standardized specimens (verification specimens).

Much of the work that showed that impact tests did not have inherently high scatter, and could be used for acceptance testing, was done by Driscoll at the Watertown Arsenal [*15*]. Driscoll's study set the limits of 1 ft-lb (1.4 J) and ∀ 5%, shown in Figures 1 and 2. The data superimposed on these limits in Figures 1 and 2 are the initial verification results gathered by Driscoll for industrial impact machines to evaluate his choice of verification limits. In Figure 1, the verification results for the first attempt on each machine are shown: only one machine fell within the ∀ 1 ft-lb (1.4 J) limit proposed for the lower energy range. Results for retests on the same machines after maintenance are shown in Figure 2. Driscoll's work showed the materials testing community that not all machines in service could perform well enough to meet the indirect verification requirements, but that most impact machines could meet the proposed requirements if the test was conducted carefully and the machine was in good working condition. With the adoption of verification testing, it could no longer be convincingly argued that the impact test had too much inherent scatter to be used as an acceptance test.

Early results of verification testing showed that 44% of the machines tested for the first time failed to meet the prescribed limits, and it was thought that as many as 50% of all the machines in use might fail [*16*]. However, the early testing also showed that the failure rate for impact machines would drop quickly as *good* machines were repaired, *bad*

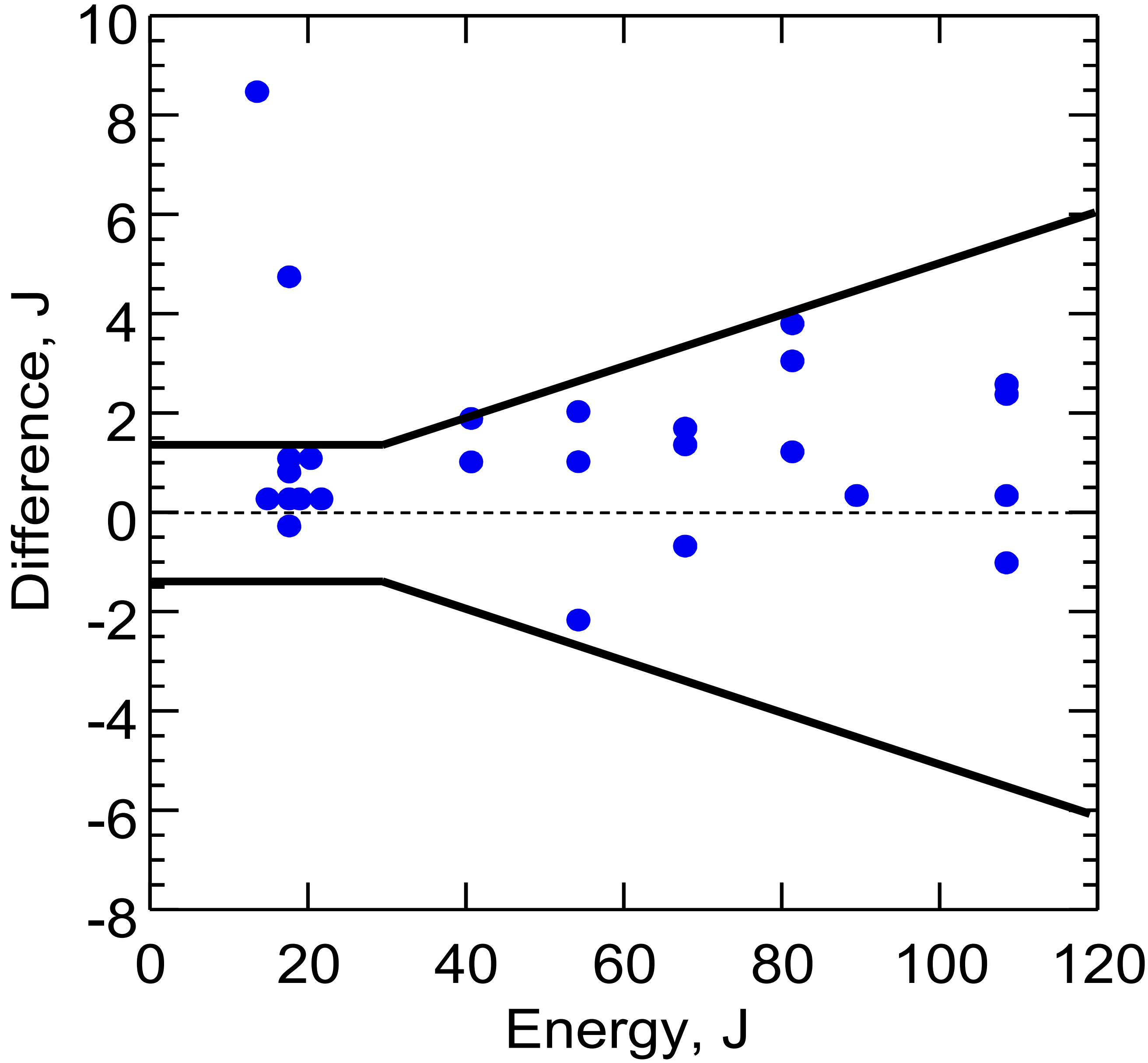


machines were retired, and more attention was paid to testing procedures. It was estimated that approximately 90% of the machines in use could meet the prescribed limits of ∀ 1 ft-lb (1.4 J) or ∀ 5%. Recently acquired verification specimen data, shown in Figures 3 through 5, confirm these predictions. Failure rates for verification tests at low, high, and super-high energy ranges are currently estimated to be 12, 7, and 10%, respectively [*17*].

Overall, the incorporation of verification limits in ASTM E 23 has greatly improved the performance of impact machines, so that data collected using ASTM E 23 machines can be compared with confidence. ASTM E 23 is still the only standard in the world, to our knowledge, that requires very-low-energy impact specimens (between 15 and 20 J) for verification, and as shown by the data in Figure 1, results obtained using machines in need of maintenance can vary by more than 100% at this energy level. In effect, the limits imposed by ASTM E 23 have produced a population of impact machines that are arguably the best impact machines for acceptance testing in the world.

While ASTM E 23 is used around the world, there are other forums for the development of global standards. One of these, the International Organization for Standardization, ISO, allows qualified representatives from all over the world to come together as equal partners in the resolution of global standardization problems [*18*]. ISO Committee TC 164 handles the topic of Mechanical Testing, and its Subcommittee SC 4 handles toughness testing. While this subcommittee has developed and maintains ten standards on toughness testing, perhaps the most pertinent is *ISO Standard R 442:1965 Metallic Materials - Impact Testing - Verification of Pendulum Impact Machines*. This standard covers the Charpy test and is presently undergoing balloting for revision. An important feature of this document is that it recognizes Charpy testing with both the 2-mm and 8-mm radius striker. There are other regional and national standards that specify impact testing procedures, such as the Japanese standard, JIS Z2242, *Method for Impact Test for Metallic Materials*.

Figure 1 - The deviation and energy values obtained for the first round of tests on industrial machines. The deviation is calculated as the difference between the results of the Watertown Arsenal machines and the industrial machines. These data were originally published by D.E. Driscoll, Reproducibility of Charpy Impact Test, ASTM STP 176, 1955.



Typical Applications Today

Nuclear

Since it is impractical to measure the fracture toughness of large specimens throughout the life of a nuclear power plant, surveillance programs use Charpy and tensile specimens to track the embrittlement induced by neutrons. The economic importance of the Charpy impact test in the nuclear industry can be estimated by noting that most utilities assess the outage cost and loss of revenue for a nuclear plant to be in

Figure 2 - The deviation and energy values for the second and third rounds of tests on industrial machines. The data shows that all but two of the machines tested were able to pass the 1.4 J or 5% criteria after appropriate repairs were made. These data were originally published by D. E. Driscoll, Reproducibility of Charpy Impact Test, ASTM STP 176, 1955.

the range of $300,000 to $500,000 per day. If Charpy data can be used to extend the life of a plant one year beyond the initial design life, a plant owner could realize revenues as large as $150,000,000. Further, the cost avoidance from a vessel related fracture is expected to be in the billion-dollar range. To date, the NRC has shut down one U.S. plant as a result of Charpy data trends. It is important to note that this plant's pressure vessel was constructed from a one-of-a-kind steel and is not representative of the U.S. reactor fleet.

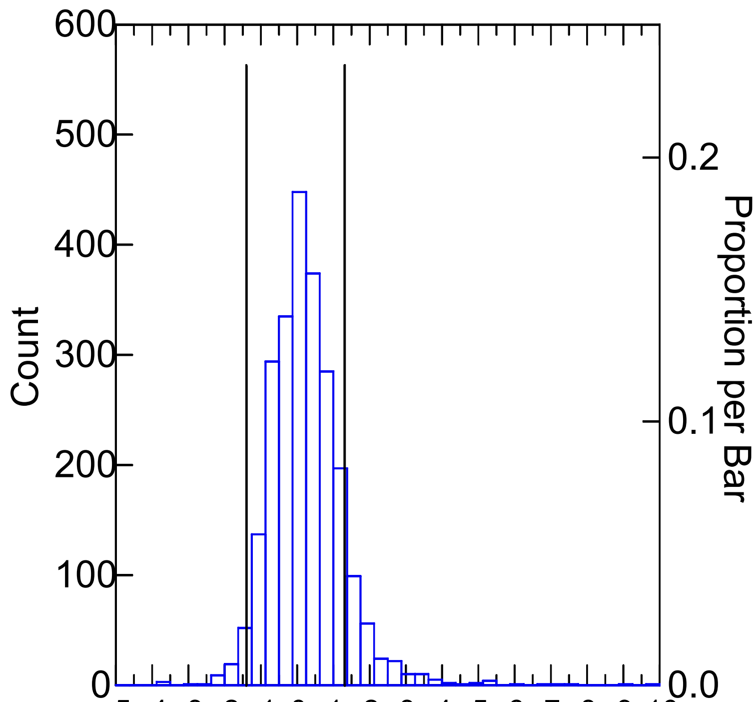
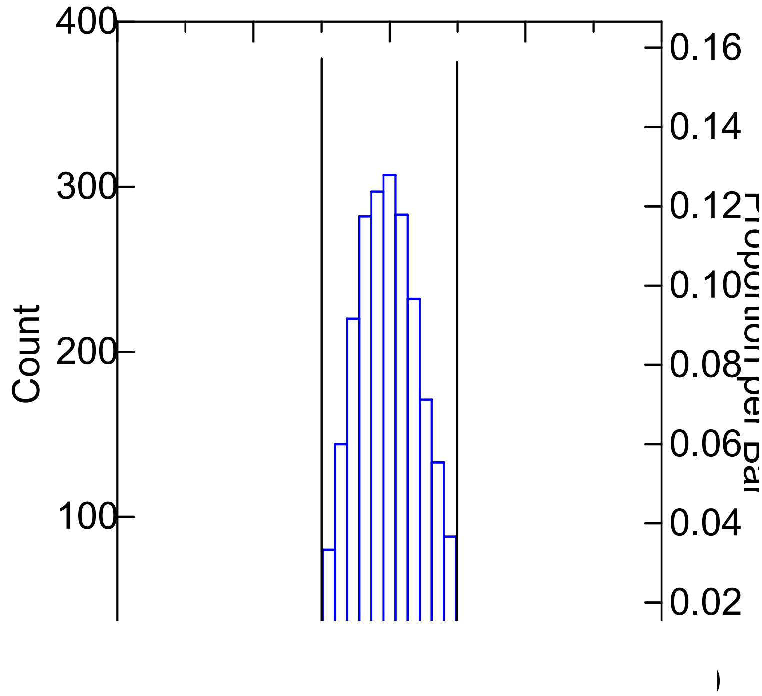


Figure 3 - Distribution of low-energy verification data. Data for 1995-1997. Approximately 2400 tests; each test is an average of five specimens. The vertical lines at ∀1.4 J represent the acceptance criteria.



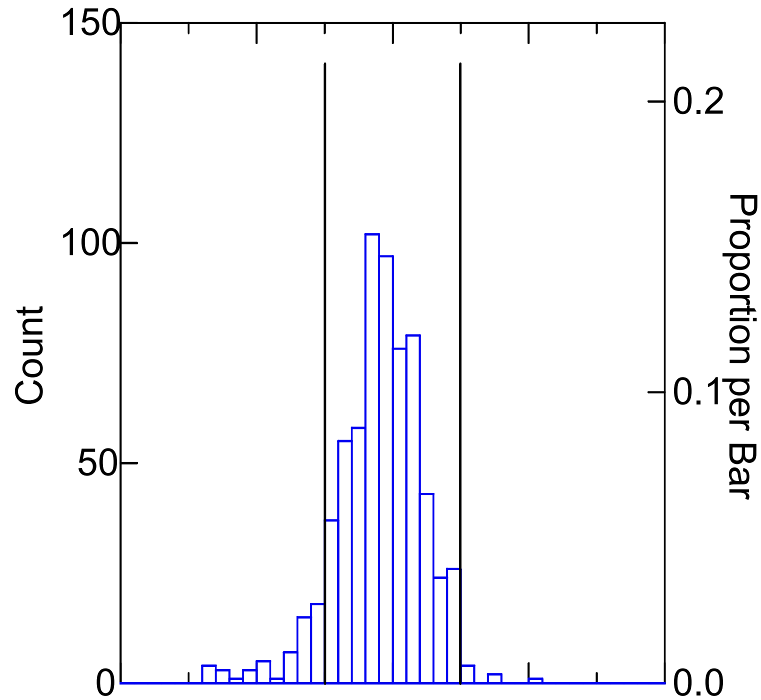


Figure 5 - Distribution of the super-high energy verification data. Data for 1995-1997. Approximately 650 tests. Each test is an average of five specimens. The vertical lines at ∀5% represent the acceptance criteria.

Figure 4 - Distribution of high energy verification data. Data for 1995-1997. Approximately 2400 tests. Each test is an average of five specimens. The vertical lines at ∀5% represent the acceptance criteria.

Nonetheless, with decisions like this based on the Charpy test, the importance of ASTM E 23 and the restraints it applies cannot be overemphasized.

Steel

The Charpy V-notch (CVN) test specimen and associated test procedure is an effective cost-saving tool for the steel industry. The specimen is relatively easy to prepare, many specimens can be prepared at one time, various specimen orientations can be tested, and relatively low-cost equipment is used to test the specimen. In many structural steel applications, the CVN test can be used: (1) as a quality control tool to compare different heats of the same type of steel, (2) to check conformance with impact requirements in standards, and (3) to predict service performance of components. Also, CVN test information can be correlated with fracture toughness data for a class of steels so that the results of fracture-mechanics analyses can be compared with the material toughness.

CVN data have many uses, such as during the design and construction of a bridge or an offshore oil platform. Before full-scale production of the steel order can begin, the supplier needs to demonstrate to the buyer that the steel plate is capable of meeting certain design criteria. The process begins by making the steel grade and then testing a portion of the plate to determine if all required criteria are met. Also, steel mill equipment imposes limitations on plate size; therefore, individual steel plates need to be welded together in the field to produce lengths which can reach deep into ocean waters. Small sections of the sample plate are welded together, and fracture mechanics tests are conducted to determine the crack tip opening displacement (CTOD) toughness in the heat affected zone (HAZ) and in areas along the fusion line where the weld metal meets the base metal. Then, a steel supplier might correlate the CTOD test results with CVN 50% ductile-brittle transition temperature (DBTT). By agreement between the customer and supplier, this correlation can allow the steel supplier to use the Charpy test instead of the more expensive and time-consuming CTOD testing.

Continuing Standardization Efforts

Even after 100 years, the Charpy impact test procedures still have room for improvement. The ASTM E 23 standard has recently been redrafted to provide better organization and to include new methods such as in-situ heating and cooling of the test specimens. Two new related standards are also under development through ASTM Task Group E 28.07.08, "Miniature and Instrumented Notched Bar Testing", which was formed a little more than two years ago. The first standard covers miniature notched bar impact testing and relies on many of the existing practices related to test machine requirements and verification as specified in existing standard E 23. The second standard is focused on instrumented testing, where strain gages attached to the striker provide a force-deflection curve of the fracture process for each specimen. Research is focused on using these data to obtain plane strain fracture toughness as well as other key test parameters. Upon acceptance of the standard by ASTM, both the existing E 23 standard and the new miniature notched bar standards would reference the instrumented impact standard.

The state of the art in impact testing continues to advance in other parts of the world also. ISO is balloting a standard (14556) on instrumented impact testing, there is work in Europe on miniature Charpy specimens, and ESIS is investigating the use of pre-cracked Charpy specimens for determining fracture toughness. It can be expected that harmonization efforts will bring some of this work into E 23 in the future.

Conclusion

The ASTM E 23 standard is a document that continues to improve as our technical knowledge increases. Several years ago, at the ASTM Symposium on "The Charpy Impact Test: Factors and Variables" [*19*], a bystander was overheard to say: "I see that there is a Symposium on the Charpy Test; what can be new there?" Since then, the document has been updated twice and is currently being revised to reflect new developments and to make it more "user friendly." Although ASTM E 23 has been a useful standard for many years, it continues to be a "work in progress," a work used extensively to help evaluate existing and new materials for products and structures -- a test to ensure safety as well as to reduce the initial and lifetime costs for structures. Knowledge which will help make the test more accurate and reliable is continually being gained. New technologies such as miniaturization of the test, instrumenting the striker to obtain additional data, and developing mechanics models to enable extraction of plane strain fracture toughness will be areas of development over the next 100 years. We anticipate that the benefits from the application of E 23 during the next 100 years will overshadow the benefits from those in the past 100 years.

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