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The Charpy Machine Verification Program at NIST:

Ensuring the Reliability and Consistency of Charpy Machines Around the World

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Introduction

- Reliable measurements of impact energy are needed for accurate predictions of the performance of new structures, and to predict when structures are in need of replacement or repair (before catastrophic failure).
- The impact for replacement and repair scales with the more than $1T expected to be needed over the next decade to bring the US infrastructure up to safe standards. In 1978, Battelle conducted a landmark study estimating the cost of structural fractures in the US at $87.6B/year. Today, failure costs are projected to be far greater.
- Charpy impact is a standardized high strain-rate test to measure energy absorption during fracture. Periodic testing of impact machines with certified test specimens is necessary to indirectly verify machine performance.
- The Charpy Verification Project at NIST provides certified standard reference materials (SRMs) for the indirect verification of Charpy impact machines.
- The existence of this program, in conjunction with the requirements in ASTM E23, has produced a population of industrial impact machines with lower scatter than any other system in the world. This helps improving reliability predictions of bridges, buildings, railroads and other infrastructure, as well as the safety of products manufactured from structural steels such as oil and gas pipelines, heavy trucks, mining equipment, power plants and wind turbines.
- Over 1,000 machines per year in more than 60 countries worldwide are evaluated by means of NIST verification specimens for conformance with the ASTM E23 standard.

Historical Background of the Charpy Impact Test

- During the 19th century, a large number of catastrophic accidents caused by brittle failures were recorded in all industrialized countries, particularly in the rapidly-expanding railway industry.
- The use of metals for construction increased from 20 % to 80 %, at the expense of traditional materials, such as wood, brick, stone, etc.
- A new type of material (steel) was developed in the mid-1800s.
- Between 1824 and 1895, impact testing was introduced as a means to characterize the resistance of steels to impulsive forces. Pivotal moments were:
  - The design of the first drop-weight machine (T. J. Rodman, 1857).
  - The introduction of notched specimens (H. L. Le Châtelier, 1892).
- In 1895, the International Association for Testing of Materials (IATM) was founded. Committee 26 on Impact Testing was formed in 1905.
- In 1898, the American Society for Testing and Materials (ASTM) was established.

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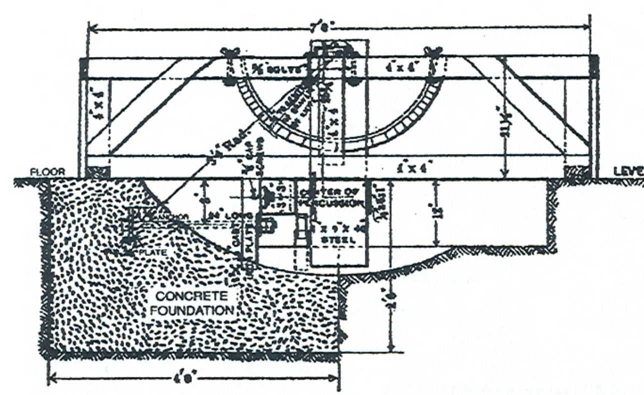
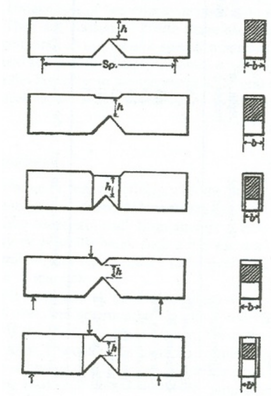
Earliest pivotal publication: Silas Bent Russell, 1898

- **Resilience**: "*work absorbed in the deformation of a material.*"
- **Impact testing machine**: "*machine which would measure the energy actually absorbed in breaking the test bar.*""
- "*This was to be done by using a hammer in the form of a pendulum.*"
- "*The difference between the height (…) before striking and (…) after striking would measure the energy absorbed in breaking the bar.*"



- Testing of tough (ductile) materials: "*To break such a bar (wrought iron) successfully, it must first be nicked.*"
- Tested materials: cast iron, paving brick (brittle); wood, bronze, aluminum, wrought iron, steel (tough).



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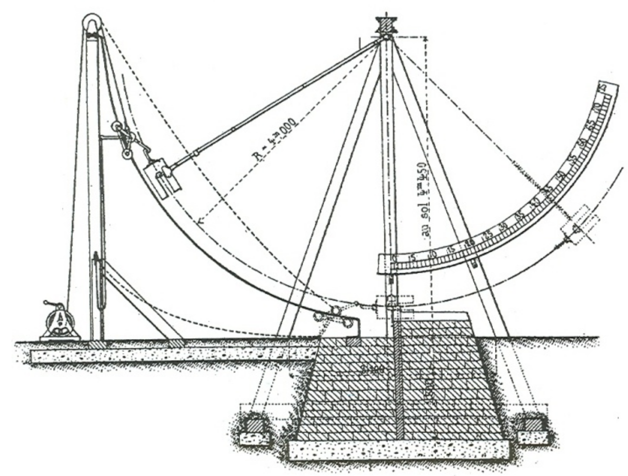
Second pivotal publication: George A. A. Charpy, 1901

- "*It is therefore extremely important to standardize in a rigorous way shape and dimensions of the notch.*"

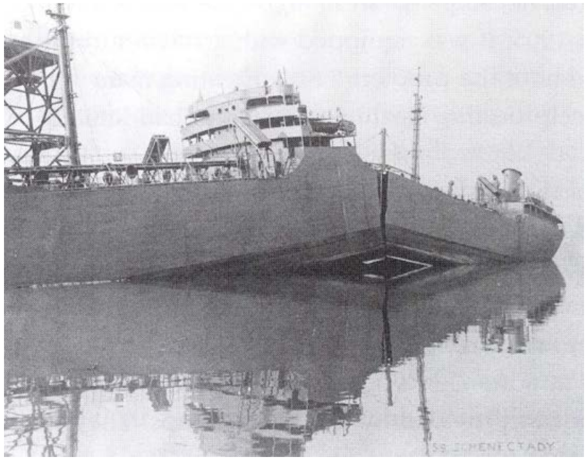
- "*The bar is subjected to a series of impacts from a constant height and we count the number of impacts needed to provoke rupture, as well as the angle at which rupture takes place. These two data allow a very clear ranking of the different metals.*"
- "*The loss due to passive resistances can be easily evaluated by performing a free swing and following the reduction of the freely swinging pendulum.*"



- The first edition of ASTM E23 came out in 1933 as ASTM E23-33T (Tentative).

Catastrophic failures during WW2: the Liberty Ships (1941-1948)

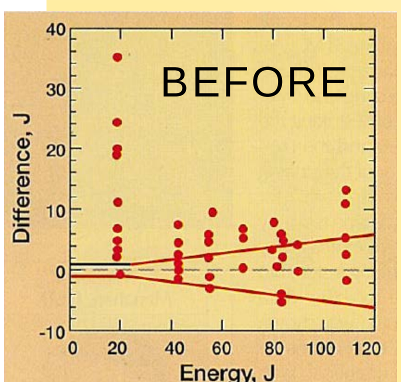
- In the late 1930s, at the outbreak of WW2, impact testing was not yet commonly included in material specifications and construction standards.
- During WW2, a large number of failures occurred in Liberty ships (cargo ships) – over 20 % fractured from February 1942 to March 1946.
- A 1948 report by the National Bureau of Standards established a correlation between the impact properties of the fractured plates and the likelihood of brittle fracture. No such correlation was found with tensile properties or microstructure.



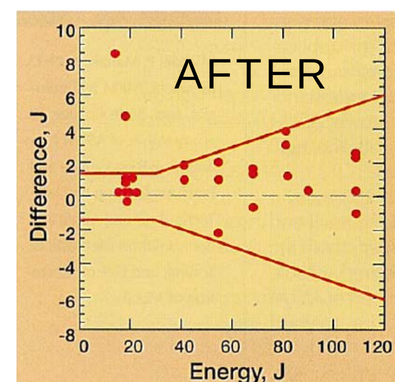
- A minimum toughness (absorbed energy) requirement of 15 ft-lb (~ 20 J) was established in the report.

The need of reducing variability: introducing verification testing

- During the late 1940s/early 1950s, critics of impact testing often referred to the scatter of test results, claiming it was an inherent characteristic of the test.
- On the other hand, many ASTM E23 users were convinced that the scatter between individual machines could by significantly reduced by addressing and eliminating the primary variables responsible for the scatter.
- In 1955, D. E. Driscoll from the Watertown Arsenal demonstrated that most of the variability could be eliminated by rigorous testing and accurate maintenance of the testing machine.



- Limits of 1 ft-lb (1.4 J) and 5 % were set for individual machines (expected to be met by 90 % of the machines).
- In 1964, ASTM E23 was revised to require indirect verification testing.



The Charpy Machine Verification Program: from the Watertown Arsenal to NIST

- In the 1960s, the U.S. Army (Watertown Arsenal, Watertown MS → became United States Army Materials and Mechanics Research Center, AMMRC, in 1968) started the Charpy machine verification program.
- In 1989, NIST took over the program and the three Charpy machines owned by AMMRC were transferred to Boulder, Colorado.
- These three Charpy machines (one was replaced in the mid 1990s) are defined in ASTM E23 as reference Charpy impact machines for the establishment of reference absorbed energy values in the US.
- Every year, NIST evaluates the impact verification results for more than 1,000 industrial machines in more than 60 countries.
- <u>Principle of Charpy machine verification</u>: if the impact test results (average value) from an industrial machine agree with the reference absorbed energy value established at NIST within the larger of 1.4 J or 5 %, the machine is certified in accordance with ASTM E23.

The operation of the Charpy Verification Program: Pilot Lot testing

- One of our qualified vendors heat-treats a lot of 1,200-2,000 specimen blanks (*i.e.*, slightly oversized and unnotched).
- They machine 100 Charpy specimens from heat treated blanks and send them to NIST for pilot lot testing.
- 30 randomly selected specimens are checked for compliance with NIST dimensional requirements (stricter than E23) and their hardness is measured.
- 75 randomly selected specimens (including the 30 above) are tested on the three reference machines (25 tests per machine).
- The results are collected and statistically analyzed (grand mean, standard deviation, standard error, sample size).
- If:
  a) The specimens are dimensionally acceptable.
  b) The grand mean of the absorbed energy is within the expected range for the specific energy level (low, high, or super-high).
  c) The sample size is lower than or equal than 5.0,

the pilot lot is accepted, and the vendor proceeds with the Production Lot.

Index of the variability of impact test results.

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The operation of the Charpy Verification Program: Production Lot testing

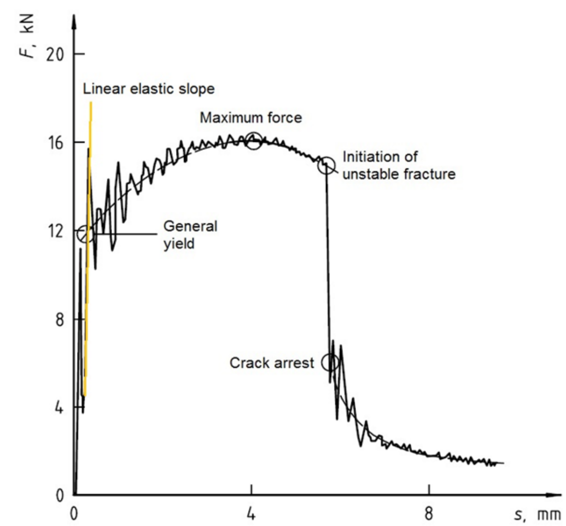
- The vendor machines the remaining 1,100-1,900 specimen blanks into Charpy specimens and ships them to NIST for production lot testing.
- The certification of the production lot is similar to that of the pilot lot:
  a. Dimensional measurements and hardness measurements on 30 randomly selected specimens.
  b. Impact testing of 75 randomly selected specimens (including the 30 above) on the three reference machines (25 tests per machine).
  c. Statistical analysis of the absorbed energy results, including calculation of the sample size for comparison with the acceptable limit (5.0).
- If the results are acceptable:
  a. The lot is officially accepted.
  b. The reference value of absorbed energy is calculated (KV_{ref}), as well as its standard (u_c) and expanded uncertainty (U).
- Specimens are shipped to NIST Gaithersburg (SRM) for packaging and sale.

Charpy SRMs currently on sale

SRM number	Description	Energy/Force Level
2092	Low-energy Charpy (NIST verification)	14 J to 20 J
2093	Low-energy Charpy (self-verification)	
2096	High-energy Charpy (NIST verification)	88 J to 136 J
2097	High-energy Charpy (self-verification)	
2098 (out of stock)	Super-High energy Charpy (NIST verification)	176 J to 244 J
2112	Dynamic force verification (self-verification)	24 kN (nominal)
2113	Dynamic force verification (self-verification)	33 kN (nominal)
2216	Miniaturized low-energy KLST Charpy (self-verification)	1.59 J – 2.43 kN
2218	Miniaturized high-energy KLST Charpy (self-verification)	5.65 J – 1.78 kN
2219	Miniaturized super-high energy KLST Charpy (self-verification)	10.08 J – 1.79 kN

A new twist for Charpy testing: Force Verification Specimens

- Additional information can be obtained from a Charpy impact test if the machine striker is instrumented with strain gages (instrumented Charpy tests).
- The electrical signal of the strain gages allows measuring the elastic deformation of the striker, which can be correlated to the force applied to the specimen during the impact test.
- The force-time record from an instrumented Charpy test resembles that of a tensile test.
- SRMs 2112 and 2113 (launched in 2012), as well as SRMs 2216, 2218, and 2219 (launched in 2014) allow customers to verify their instrumented Charpy machines by comparing their results with the reference maximum forces provided in NIST certificates.



An important distinction: NIST Verification vs. Self-Verification

NIST Verification (SRM 2092, 2096, 2098)

- Customer tests NIST specimens (minimum two energy levels, 5 specimens in a set) and fills out a questionnaire about their equipment and test results.
- Customer packages broken specimens and returns them back to NIST in Boulder with complied questionnaire.
- Charpy Program Coordinator (Ray Santoyo) examines results and broken specimens to establish if verification is successful.
- Ray sends customer an official NIST letter certifying that:
  - (verification successful) machine is compliant with ASTM E23 requirements, or
  - (verification unsuccessful) machine is not verified, and suggesting correctional measures, based on the visual examination of broken specimens.

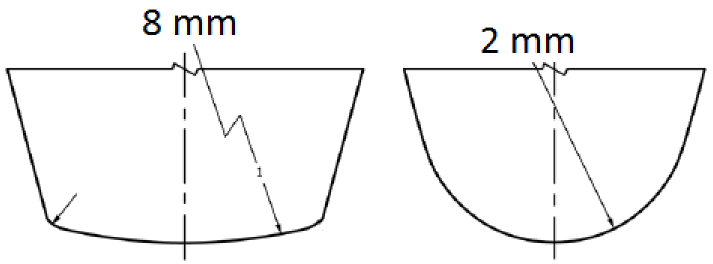
Self-Verification (SRM 2093, 2097, 2112, 2113, 2216, 2218, 2219)

- When buying SRMs, customer receives certificates including reference values (absorbed energy or force) and uncertainties, but no questionnaire.
- After testing specimens, customer checks if machine is successfully verified by comparing results with reference values and E23 limits (1.4 J or 5 %).
- NIST does not provide post-test service (official letter, examination of broken specimen, troubleshooting advice).

Future directions of the NIST Charpy Machine Verification Program

- Verification of Charpy machines equipped with 2 mm strikers (radius of the striking edge = 2 mm)
  - SRM 2197: low-energy level, self-verification
  - SRM 2198: high-energy level, self verification

  available in 2018.



- Change of the test temperature from -40 °C to room temperature (21 °C ± 1 °C).
- Transition from:
  - a conventional approach to measuring absorbed energy (height, or angle of rise, of the swinging pendulum after fracturing the specimen);

  to:

  - a more scientific, SI-traceable approach (energy calculated under the instrumented force-displacement test record).

  What is required: a reliable procedure for dynamically calibrating instrumented Charpy strikers (study currently in progress).