The Development of Standards for Instrumented Charpy Testing

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ASTM Charpy Workshop St Louis
16th November 2008
Outline of Presentation

• Instrumented Charpy Testing
• The ASTM E24.03.03 document of 1980
• The UK Working Party and BS 6729:1987
• ESIS TC5 Committee on Impact Testing
• ESIS developed ISO standards
• Progress in ISO & ASTM
My Background

• I have worked on research and development of high-rate test methods at Imperial College London since 1980

• I started by performing instrumented Charpy tests for the ORNL HSST programme

• Chair of the European ESIS TC5 committee on impact testing since 1990

• Member of ESIS TC4 on plastics, BSI and ASTM E08 and E28 committees
Probably the oldest Charpy machine in the world – built in July 1916 – instrumented 1967 by Turner – still going strong!

Mouton Pendule Systeme Charpy Machine No 110
Instrumented Charpy Testing

Could include all these requirements:-

• Measure impact force
• Measure or calculate load point displacement
• Measure pendulum release and final angles
• Detect striker contact and crack initiation
• Calculate energy
• Validate the force calibration
• Measure COD
Timeline for the Evolution of Charpy Test Standards 1

- IIW Task Group from 1966 - ASTM E24.03.03 from 1971
- Turner & Radon at Imperial College from late 1960’s
- Buchalet PVRC/MPC Working Group Report 1975
- ASME & JTE papers by Server – 1978
- ASTM E24.03.03 Proposed Standard for $K_{p_c}$ only 1980
- ORNL HSST programme 1970’s - 80’s
- Caustics work by Kalthoff & Bohme - 1980’s
- ASTM STP 1130 Rapid Load Fracture Testing Symposium 1990
- First draft ESIS Instrumented Charpy-V from DVM & SEP methods
- First draft ESIS PC Charpy method for $K, J$ & $\delta$ 1992
Timeline for the Evolution of Charpy Test Standards 2

- ESIS & DVM PC Charpy round-robins 1993 – 95
- ESIS 20 Evaluating Material Properties Symposium 1994
- ESIS Sub-size CV method 1992 onwards
- ASTM Instrumented CV and Miniature methods 1994 onwards
- ESIS Sub-size CV round robins 1994 - 99
- Final draft of ESIS Instrumented Charpy-V -1996
- ISO 14556 Instrumented Charpy-V method published - 2000
- ESIS PC Charpy method accepted as ISO/WD 26843 - 2006
- ESIS Sub-size CV method as Annex to ISO 14556 - 2007
- ASTM PC Charpy Annexe to E1820 - 2008
ASTM E23.03.03 Instrumented Charpy Method -1980

- Based on work by Server, Shoemaker, Ireland, Wullaert and others
- For fatigue pre-cracked specimens and dynamic fracture $K_{PCI}$ before general yielding only
- For pendulum and drop tower machines
- Accurate force and impact velocity required - instrument frequency response specified in detail
- Test limited by response time $T_R - 3 \tau$
- Impact velocity range 1.2 to 4.0 m/sec

The method was never adopted by ASTM

- UK group set up to develop a full-size dynamic fracture standard
- This became the successful BS 6729:1987
- Performed modelling & a careful round-robin in 1988 - 89 on full size and Charpy specimens - ASTM STP 1130 1990
- Championed use of calibrated crack-tip straingauges for $K_d$
- In 1990 the group expanded into Europe to form ESIS TC5
ESIS TC5 Committee on Impact Testing

- Formed in 1990 to bring together European researchers & industrial users with interests in high-rate testing
- To develop appropriate test methods
- To run inter-laboratory test programs
- To write test standards
- Co-operates with Dymat, ESIS TC4 on plastics, ASTM E08 and E28, & ISO on standards issues
- 50 plus members in Europe & USA
- Has held two 1-day meetings a year for 16 years
- about 25 members attend meetings
ESIS TC5 Standards Achievements

- ISO 14556 Instrumented Charpy-V standard
- ESIS P7 High-rate Tensile method
- Sub-size Charpy-V method now in ISO 14556
- Instrumented Pre-cracked Charpy Standard with ISO
- Impact Compression method phase 2 complete
- High-rate sheet metal tensile round-robin complete
- ESIS 20:1996 publication on evaluation of material properties by dynamic testing
ESIS TC5 - ISO 14556 Instrumented Charpy-V standard

- Developed relatively quickly using existing German documents as a basis
- DVM 001 covered instrumentation of the machine & tup design
- SEP 1315 covered the evaluation of results
- Typical CV test record showing how characteristic force values are evaluated
- Similar evaluations for determination of displacements and energies
ESIS TC5 Sub-size Charpy-V method

- Developed in close co-operation with ASTM
- Used an existing DIN specimen design 27 x 4 x 3mm
- Alternate 5 x 5mm, 4.8 x 4.8mm and 3.3 x 3.3mm specimens
- Specimen is more dynamic, so 250kHz frequency response is needed
- Regression method for determination of Fgy
- Proved by two careful international round robins
- Originally developed as a stand-alone document, now included as Annex D of ISO 14556
Some Sub-size Charpy-V round robin results

Typical test record showing very high frequencies encountered

Repeatability and reproducibility indexes from Phase 1 results

From Phase 1 Final Report – E Lucon
ESIS 20 1996

- Excellent topical 1–day Charpy meeting held at SCK/CEN in 1994

- Resolved most of the outstanding instrumented Charpy equipment and analysis problems!

- Published as ESIS 20 in 1996 – similar to an ASTM STP
ESIS TC5 & ISO Pre-cracked Charpy method for steels and other metals up to 5.5ms\(^{-1}\)

- covers all types fracture measurements made using pre-cracked 10mm Charpy specimens at impact velocity up to 5.5ms\(^{-1}\)
- a range of test techniques to cover material behaviour from brittle to fully ductile
- analysis stays close to ISO and ASTM quasi-static methods
- Reached final form only after 15 years development!
Some ESIS TC5 PC Charpy round-robin results on BS 4360-50E steel
Some DVM round robin data on A508 Cl. 2 in the DBT zone

- Total of 384 specimens tested
- V-notch, EDF slit and fatigue pre-cracking compared

Bohme – ESIS 20
The Intended Scope of the Method

- dynamic fracture mechanics properties determined using this standard are comparable with conventional large-scale fracture mechanics results when the corresponding criteria of validity are met.

- because of the small absolute size of the Charpy specimen, this is often not the case!

- the values obtained can be used in research & development of materials, in quality control and service evaluation and to establish the variation of properties with test temperature.

### Table 2. Fracture toughness properties to be determined

<table>
<thead>
<tr>
<th>Material response/fracture behaviour</th>
<th>corresponding diagram type</th>
<th>R-curve</th>
<th>Characteristic Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>essentially linear-elastic</td>
<td>I</td>
<td>-</td>
<td>$K_{1c}$ ($K_{1d}$)</td>
</tr>
<tr>
<td>elastic plastic, unstable cleavage without significant stable crack extension [$\Delta a&lt;0.2\text{mm}$]</td>
<td>II</td>
<td>-</td>
<td>$J_{ucd}$ ($B, J$)</td>
</tr>
<tr>
<td>elastic plastic, unstable cleavage after stable crack extension [$0.2\text{mm} \leq \Delta a \leq 0.15(W-a_0)$]</td>
<td>II</td>
<td>-</td>
<td>$J_{ucl}$ ($B, \Delta a, J$)</td>
</tr>
<tr>
<td>elastic plastic, unstable cleavage after gross stable crack extension [$\Delta a&gt;0.15(W-a_0)$]</td>
<td>III</td>
<td>$J_\sigma$-R-curve</td>
<td>$J_{0.28d}$ ($J$)</td>
</tr>
<tr>
<td>elastic plastic: no unstable crack extension</td>
<td>IV</td>
<td>$J_\delta$-R-curve</td>
<td>$J_{0.28d}$ ($J$)</td>
</tr>
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</table>

In order to distinguish the dynamic properties from the corresponding static ones, the former are designated either by an additional 'd' in the subscript, or for the sake of shortness by replacing the last character of the subscript by a 'd':
Specimens and Pre-cracking

- standard test piece to ISO 148 with or without 2.0 mm [.080"] V notch
- minimum 1.0 mm [.040"] pre-crack length – can start from existing V notch
- for final 1.0 mm [.040"] of crack growth, the maximum fatigue force must not exceed $0.6 \, F_y$

$$F_y = \frac{4B[W-a_o]^2}{3S} \, R_{p0.2}$$

- ratio of minimum to maximum fatigue pre-cracking force should not exceed 0.1
- stress intensity factor at maximum fatigue force must not exceed $E \times 1.5 \times 10^{-4}m^{0.5}$

$$K = \frac{F \cdot S}{\sqrt{(B \cdot B_N) \cdot W^{1.5}}} \cdot f[a/W]$$

- when the fatigue pre-cracking of a specimen is performed at a temperature $T_1$ and then tested at a temperature $T_2$, $K_{\text{max}}$ should be factored by the ratio $R_{p0.2} \left[T_1\right] / R_{p0.2d} \left[T_2\right]$, $F_y$ should be evaluated from the lowest value of $R_{p0.2} \left[T_1\right]$ and $R_{p0.2d} \left[T_2\right]$.
- an approximate equivalent strain rate can be calculated using

$$\dot{\varepsilon} = \frac{R_{p0.2}}{t_f E}$$

this provides strain rate values at the edge of the plastic zone ahead of the crack tip - more conservative
• for materials with a linear force-displacement test record prior to unstable fracture as in Figure 1 Type I, the force $F_{cd}$ at fracture is used instead of $F_y$ to check that the fatigue pre-cracking requirements have been met.

• experience has shown for a wide variety of steels that a fatigue pre-crack can be initiated in a Charpy specimen using an initial mean force of $2\text{kN}$ and a range of $\pm1\text{kN}$ at $a/W$ of 0.3 which are then both progressively reduced by equal amounts to a level of 0.7kN over the final 0.5mm of crack growth.

• initial crack length $a_0$ normally in the range $0.3 < a_0/W < 0.55$

• if the results in terms of $J$ or $d$ are to be directly comparable with full size standard fracture toughness values such as $J_{0.2B_l}$ or $\delta_{0.2B_l}$ then $a_0/W$ must be in the range $0.45 < a_0/W < 0.55$. Otherwise shorter crack lengths may be more advantageous.

• an Impact Response Curve for $0.28 < a_0/W < 0.32$ may be established - **Annex 2**

• specimens may be side-grooved to a depth of 1.0 mm on each side - **recommended** for all J-R tests.
Flowchart for selection of Test and Analysis method

Instrumented Precracked Charpy Test

Fracture behaviour

Unstable Figure 1 types I or II

Stable Figure 1 types III or IV

Interrupted test

Test method

Complete fracture

I

Figure 1 type

II

Interrupted test

Test method

Complete fracture

I

Dynamic evaluation
Annex 2

Quasi-static linear-elastic fracture mechanics
ISO/DIS 12135

Dynamic evaluation
Annex 2

Quasi-static elastic-plastic fracture mechanics
ISO/DIS 12135

Multi-specimen evaluation method
Annex 3

repeat test with different $\Delta a$

Single-specimen evaluation method
Annex 4

$K_{Qd}$

validity Annex 6

$K_{1d}$

validity Annex 6

$J_{ud(B)}$

validity Annex 6

$J_{ucd(B)}$

validity Annex 6

$J_{ud(B)}$

validity Annex 6

$J_{0.2Bd}$, $\delta_{0.2Bd}$
Annex 1 - Testing Machines

• several types of testing machines can perform the tests but not all machines can perform all types of test

• the *recommended* machine is the instrumented Charpy pendulum according to ISO 14556, modified to have a variable pendulum release position and a variable striking velocity up to 5.5 ms\(^{-1}\) [216 in/sec or 18 ft/sec]

• special pendulum machines can be used - fixed anvil/moving striker or fixed striker/moving anvil - and with the specimen fixed or moving.

• falling weight testing machines - may be spring assisted - no restriction on impact velocity or mass of falling weight. The striker is normally instrumented to determine force-time or force-displacement curves

• servo-hydraulic testing machines have no restriction on impact velocity, which is normally infinitely variable up to some maximum value. The striker is normally instrumented to determine force-time or force-displacement curves

• for tests evaluated by the impact response curve or crack tip strain gauge methods a standard non-instrumented Charpy pendulum impact testing machine to ISO 148 Part 2 may be used - an independent method to determine the moment of impact / time to fracture is required

• other testing machines which can comply with the calibration and other requirements are not excluded
Test Procedures

• tests are performed similarly to standard Charpy ISO 148
• force-displacement diagram recorded according to ISO 14556 to determine key data values $F_m$, $F_{cd}$, $W_m$ & $W_t$
• reduced impact velocity down to 1m/sec is allowed
• Crack length is measured by 5-point or preferably by Area Average
• if time to fracture < 5T independent time measurement required – use Annex 2
• for interrupted multi-specimen tests for R-curves – use Annex 3
• for estimating single specimen R-curves – use Annex 4
• Annex 5 gives guidance on determining fracture toughness from R-curves
• Annex 6 gives validity criteria for transferability
• Annex 8 summarises the fracture mechanics principles
Annex 2: For short times to fracture

Two methods are available:

1. Impact Response Curve due to Kalthoff & Bohme – measure time to fracture only usually with an uncalibrated crack tip strain gauge or magnetic sensor

2. Calibrated crack tip strain gauge measures applied force at fracture – requires static calibration
Annex 3: Multiple-specimen R-curves

- limit the available impact energy of the pendulum or drop weight such that it is sufficient to produce a certain stable crack extension, but not to break the specimen fully

- by choosing different energy levels in a series of tests on nominally equal specimens, a series of different crack extensions are produced

- with the corresponding J-values they form the J-R-curve

- for ferritic steels in the transition zone, a Cleavage R-curve is also possible
Annex 4: Single-specimen R-curves

three methods available for estimation which give reproducible results

1. Basic key curve [Ernst/Joyce/Bohme]

\[ J(\Delta a(s)) = \frac{\eta(a_0)}{B_N \cdot b} \cdot \int_0^s F(s) \cdot ds \]

2. Analytical 3-parameter approach [Schindler]

\[ J(\Delta a) = \left( \frac{2}{p} \right)^{\frac{1}{p}} \cdot \frac{\eta(a_0)}{B_N (W-a_0)^{1+p}} \cdot W^p \cdot W_{mp}^{1-p} \cdot \left[ 1 - \frac{(0.75 \cdot \eta(a_0) - 1) \cdot \Delta a}{W-a_0} \right]^{\Delta a^p} + \]

\[ \frac{K_i^2 (F = F_{n_0} a_0)}{E} (1-V^2) \]

3. Normalisation method [Landes & E1820]

\[ F_{N(i)} = \frac{F(i)}{W B_e \left[ \frac{W-a_{b(i)}}{W} \right]^q} \]

and

\[ S'_{pl(i)} = \frac{S_{pl(i)}}{W} = \frac{(S(i) - F(i) C(i))}{W} \]
Annex 5: determining characteristic fracture toughness $J_{0.2Bd}$

- guidance note on appropriate use of $J_{0.2Bd}$ and $J_{id}$
- dynamic blunting line adapted from ISO 12135

$$J(\Delta a) = s_1 \Delta a = 3.75 \ R_{md} \ \Delta a$$

where $R_{md}$ is the dynamic UTS

$$R_{md} = \frac{F_m \cdot S}{(W - a_0)^2 \ B_N}$$

as determined from a dynamic Charpy V test
Annex 6: Validity criteria 1

Plane Strain Fracture Toughness

\[ K_{ld} \leq 0.4 \cdot \sqrt{W-a_0} \cdot R_{pd} \]

where \( R_{pd} \) denotes the dynamic yield stress obtained at an instrumented Charpy V test according to ISO 14556 at the same temperature.

In case \( R_{pd} \) is not available, it can be estimated by

\[ R_{pd} = \frac{F_{gy} \cdot S}{(W-a_0)^2 B_N} \]
Annex 6: Validity criteria 2

Initiation of Cleavage Fracture

\[ J_{ucd} \leq \frac{\sigma_{fd} \cdot (W - a_0)}{100} \]

where \( \sigma_{fd} \) denotes the plastic flow-stress under the actual strain rate, i.e. the dynamic equivalent of the static flow stress as used in ISO 12135 (or ASTM E 1820, respectively), being defined as the mean value of the static yield stress and the tensile strength.

\( \sigma_{fd} \) can be estimated by:

\[ \sigma_{fd} = \frac{F_m \cdot S}{(W - a_0)^2 B_N} \]
Annex 6: Validity criteria 3

• Onset of Ductile Tearing

\[ J_{0.2Bd} \leq \frac{\sigma_{fd} \cdot (W - a_0)}{25} \]

• Note: \( J_{ucd} \) and \( J_{0.2Bd} \) cannot be treated as transferable to larger structures. \( Jc-, Ju- Juc \)-values determined in the transition range are size sensitive parameters and only valid for the specimen thickness tested, see ISO 12135.
A partial list of contributors to
Charpy Standards development 1980 - 2008

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Summary of the ISO & ASTM Charpy Standards Position

- ISO 14556 Charpy V now available with Sub-size Annex
- ISO/CD 26843 Pre-cracked Charpy should be published in 2010
- ASTM Charpy V and Miniature Standards recently balloted, should be available 2009
- ASTM Pre-cracked Charpy Annex to E1820 recently balloted
Thank you for listening – any questions?