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# Toughness Requirements for Older Structural Steels

## Caractéristiques de résistance d'anciens aciers de construction

## Anforderungen an die Zähigkeit älterer Konstruktionsstähle

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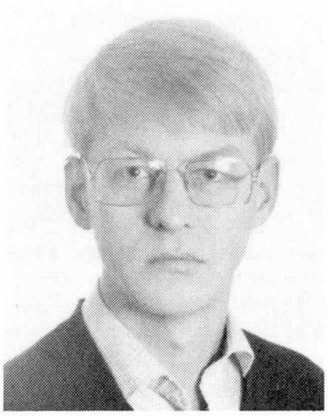

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**SUMMARY**

The Charpy-V notch toughnesses of steel from the Swedish railway bridges, 25 – 100 years old, have been found not to satisfy current National Standards requirements. Fracture toughness testing with fullthickness specimens indicate much better effective toughness of a structural part. Also, fatigue crackgrowth rate does not increase with decreasing toughness.

**RÉSUMÉ**

On a découvert que des résultats d'essais de résilience Charpy-V réalisés sur des aciers provenant d'une dizaine de ponts de chemins-de-fer suédois, datant de 25 à 100 ans, ne correspondent pas aux valeurs courantes données dans les normes nationales. D'autre part, des essais effectués sur des éprouvettes de plus grandes dimensions montrent une résistance effective plus élevée. De plus, la vitesse de propagation des fissures de fatigue n'augmente pas lorsque la résistance diminue.

**ZUSAMMENFASSUNG**

Zehn verschiedenen, zwischen 25 und 100 Jahre alten schwedischen Eisenbahnbrücken wurden Charpy-Proben entnommen, um die Kerbschlagarbeit zu bestimmen. Dabei zeigt sich, dass die damals verwendeten Stähle die in den aktuellen Normen festgehaltenen Mindestanforderungen nicht zu erfüllen vermögen. Die Ermittlung der effektiven Bauteil-Bruchzähigkeit an Probekörpern grösserer Abmessungen ergibt bei weitem vorteilhaftere Resultate. Weiter stellt man fest, dass die Rissfortschrittsrate mit abnehmender Zähigkeit nicht zunimmt.

## 1. INTRODUCTION

The one and only national limit on notch ductility came into effect some 30 years ago. In line with the Bonhomme recommendation minimum 27 J Charpy-V notch toughness is required for structural steels in general.

For many years Banverket* has collected Charpy-V notch toughness data of steels from damaged structural elements in railway bridges. The Charpy-V notch toughness of the steels, which are 25-100 years old, is typically 4-7 J at -30°C.

Williams and Ellinger reported in their investigation of the Liberty ship disasters approximately this notch toughness for fracture in combination with severe stress concentrations and welding resid-ual stresses of yield magnitude (or both) in some 30 fracture source plates (1).

The most critical parts for structural integrity of a railway bridge are often plain rolled or riveted beams in which residual stress and stress concentrations are small.

On the other hand severe stress raisers and welding residual stresses are not uncommon due to damage or unskilled repair work, etc.

Despite the very low notch toughness of the damaged steels (and most likely of a much larger number still in service) only partial but unfortunately no catastrophic failures have so far occurred.

These points have risen the question as to the safety and toughness requirements for older railway bridge steels which do not fulfill present toughness requirements.

This paper is based on technical reports on survey investigations carried out on behalf of Banverket. A group of ten steels, of various age and representative of the most brittle, were selected for further investigation. Based on the results a larger testing program has been planned, which adresses the toughness problem of older structural steels.

## 2. CHARPY-V NOTCH TOUGHNESS

The plate thickness of the investigated steels is typically 10-30 mm. Charpy V notch toughness specimens were machined from the midthickness part of the steel samples. Attempts to register the full notch toughness transition curve always yielded considerable scatter.An example for a typical steel is shown in Fig. 1.

Two series of specimens were tested. The 27 J transition temperature is around +5°C according to the first series and around -25°C according to the second. It is clear that a very large number of specimens is required to avoid an effect of the number of specimens upon the transition temperature.

Even if it were possible to find an unambigous transition temperature the large scatter still implies the question: What constitutes the effective toughness of a structural element?

If the scatter means that the toughness is inhomogeneous on a scale larger than the Charpy specimen, then Charpy notch toughness data is most probably not suitable for toughness requirements of such steels.

*) Swedish National Rail Administration

## 3. CHEMICAL COMPOSITION

Chemical analysis of the steels is shown in Table 1. All steels are carbon steels. The carbon content is low, usually 0.05-0.10 %, manganese in the range 0.2-0.8 %. The silicon content is typical for rimmed steel, whose inhomogeneous composition is well known. The sulphur and phosphorus contents are not high considering the age of the steels. The total amount of the residual alloying elements (Cr, Ni, Cu) is in the range 0.03-0.15 %. The nitrogen content is 0.004-0.013 %, where N above 0.010 % may cause embrittlement. The Mo and Al contents have also been checked and found to be less than 0.01 and 0.001 % respectively.

| Steel | C | Si | Mn | P | S | Cr | Ni | Cu | N |
|---|---|---|---|---|---|---|---|---|---|
| SJ2 | 0.06 | 0.01 | 0.39 | 0.067 | 0.035 | 0.01 | 0.04 | 0.08 | 0.013 |
| SJ4 | 0.05 | 0.01 | 0.46 | 0.058 | 0.032 | 0.01 | 0.04 | 0.07 | 0.012 |
| SJ5 | 0.15 | 0.01 | 0.81 | 0.060 | 0.062 | 0.03 | 0.05 | 0.01 | 0.007 |
| SJ6 | 0.07 | 0.01 | 0.61 | 0.039 | 0.028 | 0.02 | 0.04 | 0.01 | 0.007 |
| SJ7A | 0.04 | 0.01 | 0.40 | 0.047 | 0.037 | 0.01 | 0.04 | 0.05 | 0.010 |
| SJ7B | 0.03 | 0.01 | 0.45 | 0.045 | 0.037 | 0.02 | 0.04 | 0.04 | 0.007 |
| SJ8 | 0.10 | 0.01 | 0.63 | 0.071 | 0.071 | 0.02 | 0.04 | 0.01 | 0.011 |
| SJ9 | 0.15 | 0.02 | 0.27 | 0.068 | 0.020 | 0.02 | 0.01 | 0.05 | 0.004 |
| SJ10 | 0.19 | 0.02 | 0.22 | 0.030 | 0.010 | 0.01 | 0.01 | 0.01 | 0.011 |

Table 1 Chemical analysis wt%

## 4. FRACTURE TOUGHNESS

To obtain an alternative estimate of the effective toughness of a structural member, fracture toughness testing was carried out. Full thickness Compact specimens were cut from plates or beam flanges and subsequently fatigue precracked at room temperature. The crack plane is always perpendicular to the rolling direction of the parent steel. Specimen data are given in Table II.

| Steel | Form | Year | W(mm) | B(mm) |
|---|---|---|---|---|
| SJ2 | I-beam | 1915 | 160 | 27 |
| SJ4 | -"- | 1920 | 128 | 20 |
| SJ5 | -"- | 1940 | 240 | 27 |
| SJ6 | -"- | 1940 | 160 | 15 |
| SJ7A | plate | 1922 | 128 | 14 |
| SJ7B | -"- | 1922 | 128 | 14 |
| SJ8 | I-beam | 1940 | 160 | 19 |
| SJ10 | L-profile | 1900 | 60 | 20 |
| SJ11 | I-beam | 1919 | 100 | 26 |

Table II Fracture toughness specimen data

Fracture toughness testing was carried out according to ASTM Standard E813-87 when applicable (2). The test temperature was -30°C. During a test the load versus load point displacement curve was registered. Although the registered curves in general were non-linear, no evidence of stable crck growth was found. For each curve $J_c$ was evaluated according to Merkle and Corten (3).

Uniaxial tensile testing data (at room temperature), Charpy-V notch toughness and fracture toughness are given in Table III.

| Steel | $R_{eL}$ (MPa) | $R_m$ (MPa) | $A_5$ % | Charpy-V notch toughness 1) $C_v$(J) | Fracture toughness $J_c$(kN/m) |
|---|---|---|---|---|---|
| SJ2 | 246 | 386 | 32 | 4.8*) | 22 |
| SJ4 | 230 | 365 | 38 | 5.3*) | 145 |
| SJ5 | 239 | 449 | 34 | 6.9 | 22 |
| SJ6 | 233 | 380 | 39 | 6.6 | 122 |
| SJ7A | 253 | 388 | 25 | 5.9 | >400 |
| SJ7B | 258 | 394 | 29 | 4.1 | 177 |
| SJ8 | 239 | 439 | 31 | 5.9 | 21 |
| SJ9 | 330 | 486 | 23 | 5.3 | 28 |
| SJ10 | 258 | 440 | 25 | 5.3 | 15 |
| SJ11 | 263 | 385 | 34 | 3.4 | 8 |

*) Test temperature 0°C
1) Mean of three measurements

Table III Charpy notch toughness and fracture toughness

## 5. FATIGUE CRACK GROWTH

The most brittle steel, SJ11, of the ten investigated was selected for fatigue testing. Low cycle fatigue crack growth in Compact specimen was recorded at room temperature.da/dN versus ΔK data were analyzed according to Paris´law and the fatigue threshold was determined. The results are given in Table IV.

| Test no | $\Delta K_{th}$ ($MN/m^{3/2}$) | C | n |
|---|---|---|---|
| 1 | 8.8 | $3.76\ 10^{-12}$ | 3.2 |
| 2 | 6.5 | $2.60\ 10^{-12}$ | 3.3 |
| 3 | 5.5 | $3.20\ 10^{-12}$ | 3.2 |

C and n are the constants in Paris´law for da/dN in m/cycle.

Table IV Low cycle fatigue crack growth

## 6. DISCUSSION

The relationship between fracture toughness ($J_c$) and notch toughness ($C_v$) for the steels in this investigation is compared with others in Fig. 2.

All steels are tougher according to $J_c$ than to $C_v$ compared to the corresponding relationship for homogeneous steels (6). The steels in this investigation might be divided into two groups depending upon the relation between $J_c$ and $C_v$.

In the first group the steels are twice to four times tougher according to $J_c$ and to $C_v$. The steels in this group are brittle both according to Charpy-V notch toughness and to fracture toughness.

In the second group the steels are more than ten times tougher according to $J_c$ and $C_v$. The steels are in fact brittle according to $C_v$ and ductile according to $J_c$.

We assume this is because the toughness of these steels is (very) inhomogeneous, particularly in the second group. In rolled steel the toughness varies across the

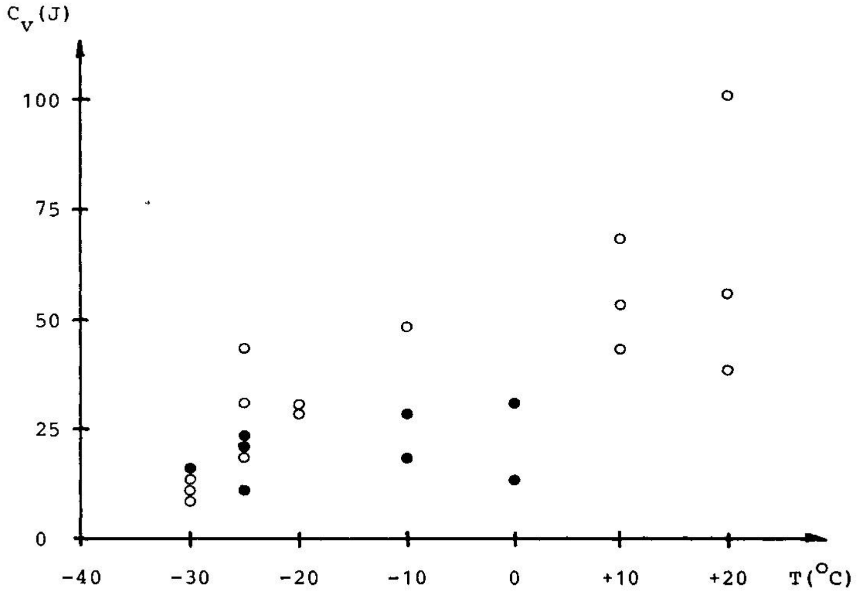


Fig 1. Charpy-V notch toughness for two specimen series of a given material. o Ser no 1. ● Ser no 2.

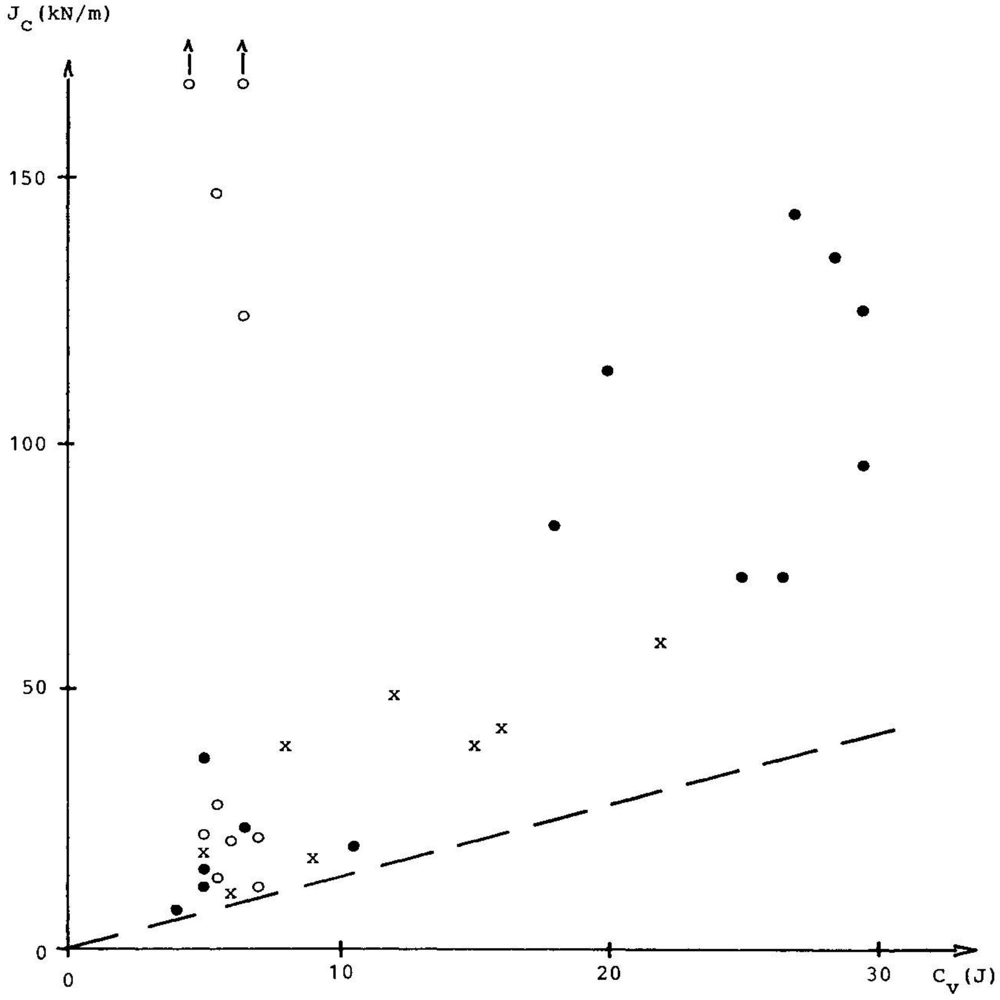


Fig 2. Fracture toughness $J_c$ and Charpy-V notch toughness $C_V$. o This investigation, x Ref (4), ● Ref (5). - - - Ref (6).

thickness and is higher near the surface than in the middle. The thickness distribution may also vary from point to point in the rolling plane.

In a full thickness fracture toughness specimen the entire toughness distribution in the thickness direction is represented along the crack front. Thus $J_c$ obtained with full thickness specimens represents the effective toughness of a plate or beam flange, etc.

A Charpy specimen on the other hand has always fixed dimensions.In our investigations the Charpy specimens were always machined on all sides and taken from the mid-thickness. A Charpy specimen therefore only represents a small part of, most linkely, low toughness material.

This effect would also explain the fact that no catastrophic failures have occured in spite of Charpy notch toughness no better than that associated with the Library ship disasters. The question as to the real safety of the steels has however not yet found an answer.

To ensure plain strain conditions at a crack tip in elastic-plastic fracture toughness testing the condition $t > \alpha J_c \sigma_y$ has been proposed (7). t is specimen thickness, $\alpha$ a numerical constant in the range 25-50 and $\sigma_y$ is flow stress.

Now to obtain a minimum toughness requirement we simply turn this condition around and require that

$$J_c > \beta\sigma_y t$$

where $\beta$ is a dimensionless constant for the time beeing put to 0.02. This toughness is just enough to prevent plain strain conditions at a crack tip. The conditions means that if a structure fails, it fails in a ductile manner, whatever the size of a crack.

It is interesting to note that this condition is fulfilled by the steels in our second group but not by those in the first.

Although the steel selected for fatigue testing is the most brittle, its crack growth data is typical for structural steel. This means that fatigue cracks do not grow faster in a low-toughness structural steel.

The fatigue threshold is also typical but there is some scatter.

The crack growth data is a mean value over several mm of growth and thus local variations, if any, are levelled out. The threshold, on the other hand, involves propagation over a very small distance and thus local variations may strongly affect its value. The treshold scsatter is thus a further indication of an inhomogeneous material.

A low fatigue threshold and a small critical crack size means of course reduced residual life in spite of typical crack growth data.

## 7. FUTURE WORK

The structural elements from which damaged parts have been collected are mostly plain rolled or riveted beams of various cross-sections but with heights not exceeding 500 mm. If there is an effect of size upon fracture behaviour then data for large structures (ships) may not be applicable to smaller structures (beams). It is doubtful whether it is possible to check this by using Charpy even for an ideally homogeneous material.

In the fracture thoughness testing program some amount of plastic deformation, although in some cases very samll, always preceeded fracture. If a ductility criterion is to be based upon $J_c$ then the amount of plastic deformation predeeding fracture must be of such an extent that an effect of size upon $J_c$ may be expected.

To determine the minimum toughness requirement for a (small) specimen that corresponds to a given safety for a (large) structural member full scale bend testing of HEB 400 beams has been organized. Experimental validation of the condition (a) is part of this work. The results will be reported in a forthcoming paper.

REFERENCES

1. WILLIAMS M.L.& ELLINGER G.A., Investigations of Structural Failures of Welded Ships. The Welding Journal 32(10), Research Supplement, 1953, pp 498-527.
2. ASTM Standard E813-87, Standard Test for $J_{Ic}$, a Measure of Fracuture Toughness, Annual Book of ASTM Standards. ASTM, Philadelphia, 1987.
3. MERKLE J.G. & CORTEN H.T., a J-Integral Analysis for the Compact Specimen. Journal of Pressure Vessel Technology, Nov.1974, pp 286-292.
4. MARANDET B & SANZ G, Étude par la mécanique de la rupture de la ténacité d´aciers a résistance moyenne fournis en forte épaisseur. Révue de Métallurgié, Avril 1976, pp 359-383.
5. SSAB Technical report SF 154/83 on correlation between $K_{Ic}$ and $C_v$. In Swedish.
6. SAILORS R.H. & CORTEN H.T., Relationship Between Material Fracture Toughness Using Fracture Mechanics and Transition Temperature Tests. ASTM STP 514, ASTM, Philadelphia, 1973, pp 164-191.
7 MCMEEKING R.M. & PARKS D.M., On Criteria for J-Dominance of Crack-Tip Fields in Large-Scale Yielding. ASTM STP 668, ASTM, Philadelphia, 1979, pp 175-194.

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