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Welded High Strength Low Alloy Steels in Seismic Design

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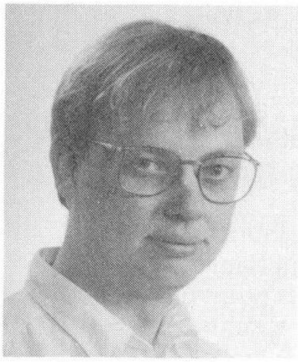

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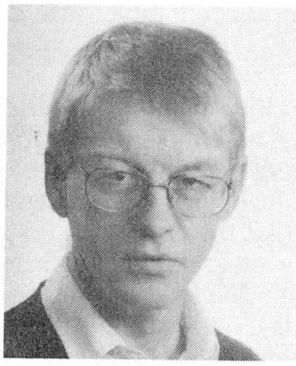

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Summary

High strength low alloy steels (HSLA) are frequently used in applications when high strength properties enable weight reduction, e.g. in long span bridges. Results of an experimental investigation show that the HAZ fracture toughness in HSLA depends strongly on the loading rate and temperature. At low and static loading rates ductile behaviour is enhanced and at increased loading rates there is a transition to brittle behaviour. Loading rates that reduce the fracture toughness significantly are frequent in buildings and bridges during a seismic event. This means that surprisingly short fatigue cracks become critical so that dissipative zones may fracture rather than deform and prevent structural collapse.

1. Introduction

In regions of high seismic risk steel structures are usually preferred because of their often superior performance in terms of strength and ductility. Structural ductility is achieved by allowing yielding in selected parts of the structure upon loading beyond a certain level, so-called dissipative zones. During severe seismic events such zones absorb seismic energy through ductile behaviour and hysteresis. Current design methods [1] recommend that connections in dissipative zones shall have sufficient strength to allow yielding of connected parts. In order to ensure this, butt welds or full penetration welds are recommended. It is obvious that this design philosophy assumes that structural elements are free from starting points for fracture, i. e. severe stress concentrators such as sharp defects and fatigue cracks. Despite current seismic design codes, serious failures of steel structures have not ceased to occur. Post-earthquake investigations [2]-[3] have pointed out that welded connections are critical locations for several types of structures. The most typical damages reported from the Kobe earthquake may be summarised as following: 1) fracture of fillet welded joints of beam to column connections, 2) column-to-column with partial joint penetration weld and 3) fillet welded joints of column to through diaphragm. Another interesting observation was that surprisingly short cracks and geometrical discontinuities provided starting points for brittle fracture.

In this work it is assumed that some insight into the cause of some of these failures can be gained through a fracture mechanics approach. Small fabrication defects, e.g. weld undercuts and slag inclusions, are almost always present in welded joints. Fatigue cracks may initiate and grow from such initial defects during normal service. Under normal service loading conditions, short fatigue cracks may exist without seriously affecting the load carrying capacity of a structure. During a seismic event structures are in general subjected to both inertia loads and high loading rates. In a previous investigation [4] it was found that loading rates just above the maximum limit prescribed in the fracture toughness testing standard ASTM E813 [5] significantly affect the fracture toughness of ordinary C-Mn structural steels. In practice that means that shorter cracks become critical and that dissipative zones may fracture rather than deform and absorb energy at increased loading rates.

The observations in [4] raised the question if similar rate effects exists in HSLA steels, particularly in HAZ material. These modern structural steels are frequently used in applications when high strength properties allow weight reduction, e.g. in long span bridges. In this paper the results of an experimental investigation of the fracture toughness of both base and HAZ material of an HSLA steel are presented. The crack driving force in terms of the J-integral [6] is evaluated for an edge cracked beam flange with the finite element method. The loading rates are, from a fracture mechanics point of view, estimated in a simple elastic frame subjected to ground acceleration. The results are discussed in connection to fracture toughness testing requirements in current design codes.

2. Material

The test material comprised both base and HAZ material of an HSLA steel. Two 16 mm plates were joined with a 1/2 V-butt weld. In order to achieve as good toughness properties as possible and to reduce residual stresses welding was performed with multi-run welds and the submerged metal arc process. The chemical composition of the base material is shown in Table 1 and the tensile properties in Table 2. The Charpy-V notch toughness of the base material is typically 30 J at -60 °C.

Table 1. Chemical composition of the base metal (wt %).

C	Mn	P	S	Si	Mo	N	B
.15	1.40	.025	.01	.45	.10	.015	.002

Table 2. Tensile properties of base metal at 20 °C.

ReH [MPa]	R_m [MPa]	A_5 [%]
700	780-930	14

Proportional single edge notched bend specimens (SENB) according to ASTM E813 were taken from both base and HAZ material. The notch plane was perpendicular to the rolling direction of the parent material and in the case of HAZ material, parallel to the longitudinal direction of the weld. The HAZ is usually divided into number of subzones depending on the material being welded. Each sub-zone refers to a different type of microstructure and different mechanical properties [7]. In this investigation the interest was focused on the coarse grained material adjacent to the weld metal.

3. Experimental

The quasi-static fracture toughness testing were performed in a servo hydraulic testing machine. Testing was performed at + 20 °C and -30 °C. The low temperature tests were carried out in a climate chamber. The tests were carried out under displacement control and at different displacement rates. The loading rate in this work is defined as the linear elastic stress intensity rate and is taken as a measure of how fast the crack tip region is loaded. In each test the load and load point displacement signals were recorded with a high speed data acquisition equipment. According to ASTM E813, the critical value of the J-integral, denoted J_C, characterises the onset of crack growth. The J_C values were calculated from the area under the load-displacement curves to the maximum load using the equation for three-point bend specimens:

$$J_C = 2A / Bb \qquad (1)$$

where A is the area under the load-displacement curve, B specimen thickness and b remaining ligament. A test is considered valid if the specimen thickness meets the requirement:

$$B \geq 25 J_C / \sigma_Y \qquad (2)$$

where σ_Y is the yield strength.

4. Results

For the base metal, no significant loading rate effect on the fracture toughness was observed. This material was ductile at -30 °C over the entire loading rate range investigated. Some typical load versus load point displacement recordings are shown in Fig. 1a. Crack growth was preceded by significant lateral contraction of the material ahead of the crack tip. In all tests pop-in was observed and none of the specimens fractured completely. The obtained fracture toughness is typically greater than 300 kN/m.

The HAZ material showed a brittle behaviour already at low loading rates. From an engineering point of view, all these tests were brittle. The load-displacement curves were almost linear up to the fracture load, Fig. 1b. The fracture toughness was reduced to one third of the fracture toughness at the static loading rate. For the HAZ material, all fracture surfaces showed two distinct regions, a central flat region and a region of shear lips. The central flat region was shiny and faceted and typical for brittle fracture. All tests on the HAZ material at -30 °C are summarised in Fig 2. Only one single test was performed with HAZ material at room temperature and slow loading rate. Surprisingly, this test showed brittle behaviour and the obtained fracture toughness J_C was 86 kN/m.

5. Discussion

5.1 Material behaviour

Modern methods for producing high strength structural steels with yield strength in the range 420-500 MPa are based on thermo-mechanical rolling (TM) and accelerated cooling process. For steels with yield strength in the range 600-960 MPa the QT method (quenching and tempering) is usually preferred. This is in fact the only realistic method to achieve high yield strength without adversing weldability [8]. In practise, both these methods means tightly controlled manufacturing conditions. Welding is in fact a process with quite the opposite effect. As a result of the welding thermal cycle the original microstructure and properties of the metal in a region close to the weld metal are strongly affected. It is of common knowledge that the microstructure of the grain coarse zone, above all other zones in the HAZ, determine the properties of the weld. In ordinary C-Mn structural steels, low fracture toughness is usually associated with the coarse grained HAZ and the intercritically reheated HAZ. The tests in this investigation show that the fracture toughness at the increased loading rate is further reduced of the order two thirds in the heat affected region. This result was somewhat unexpected considering the excellent properties of the base material. In fact, the fracture toughness values at the increased loading rate are of the same magnitude of order as those of the older C-Mn structural steels reported in [4].

5.2 Application of results

Steel frameworks have many practical applications, such as buildings and bridges. A steel frame essentially consists of beams and columns joined by connections. For the design of structures, the maximum values of relative displacement, relative velocity and absolute acceleration of the response vibration are the most important parameters. Consider for example a simple elastic frame with two columns of height L and with a rigid top beam subjected to a piecewise linear acceleration spectrum, Fig 3. The mass of the top beam is here assumed 8 ton and the total stiffness 900 kN/m. The input load is a total period of 3 s of strong ground motion with a peak ground acceleration of 0.3 g. A numerical solution routine based on the central difference method [9], can be used to solve the equation of motion provided that the time step is considerably smaller than the natural period of the structure. The calculated displacement versus time is shown in Fig. 3. The maximum loading rate in terms of linear elastic stress intensity rate can be estimated from the slope of the displacement curve for some different crack lengths. According to elementary frame analysis, the stress rate at the beam ends can be expressed as

$$\dot{\sigma} = \frac{\dot{M}}{W_x} = \frac{6EI}{W_x L^2}\dot{u} \qquad (3)$$

where E is the elastic modulus, I the moment of area, du/dt the displacement rate and W_x the bending resistance. The linear elastic stress intensity rate for a beam flange with an edge crack is approximately given by

$$\dot{K}_I = \dot{\sigma}\sqrt{a\pi} f(a/W) \qquad (4)$$

where a is the crack length, W the flange width and $f(a/W)$ a dimensionless geometry function. With $W_x = 1680\ \text{cm}^3$, $I = 25\ 166\ \text{cm}^4$ and $L = 11.2$ m, the maximum loading rate for the case investigated is typically 242-343 MPa$\sqrt{\text{m}}$/s for crack lengths 25-50 mm. Even if the response of a real structure is more complicated, this simple example indicates that the loading rate in an elastic frame work is higher than the maximum rate prescribed in current fracture toughness standard (ASTM E813) and within the range of reduced fracture toughness.

5.3 Crack driving force J

The path independent J-integral, is widely used as a criterion in fracture mechanics to determine the onset of crack growth. In this work a finite element model of a beam flange with an edge crack was used to investigate the influence of crack length and stress level on the crack driving force J. For the calculations the finite element program ADINA [10] was employed. The model was composed of 286 eighth-nodes elements and plain strain conditions were adopted. In the crack tip elements 1/r strain singularities were obtained by collapsing the crack side nodes on to one point in the unloaded state. The material model was plastic-multilinear and with data points in general agreement with typical tensile tests on HSLA. About 100 time increments were used through one loading history. The J-integral was calculated for eight contours through the Gauss integration points of the elements surrounding and at different distances from the crack tip.

The calculated value of J versus nominal stress is shown in Fig. 4 for different crack lengths. The lowest fracture toughness data observed in this investigation is marked by a dashed line. Assume that a 25 mm deep fatigue crack exists in a beam element and that the fracture toughness is approximately $J_c \approx 20$ kN/m. That means that a nominal stress level of $\sigma_O/\sigma_Y \approx 0.3$ is sufficient to initiate crack growth. This example shows that already short fatigue cracks are critical and that sufficient fracture toughness is a necessary requirement to achieve global ductility.

6. Conclusions and further work

Further experimental work is necessary to determine the fracture toughness of HAZ material under different welding conditions, loading rates and temperatures. One single test indicated brittle material behaviour already at room temperature. This indication is, if general, of importance for most applications. To determine loading rates from a fracture mechanics point view in some typical structures subjected to ground motion, is another interesting study in prospect. However, based on the findings in this investigation, the following conclusion can be drawn:

The fracture toughness of HSLA base and HAZ material depends strongly on the loading rate.

Fracture toughness is strongly reduced at loading rates above the maximum limit prescribed in ASTM E813.

In common structures loading rates caused by earthquakes often exceed the maximum loading rate prescribed in fracture toughness testing standards.

A necessary condition for global ductility of structures is sufficient local fracture toughness properties of structural elements and connections.

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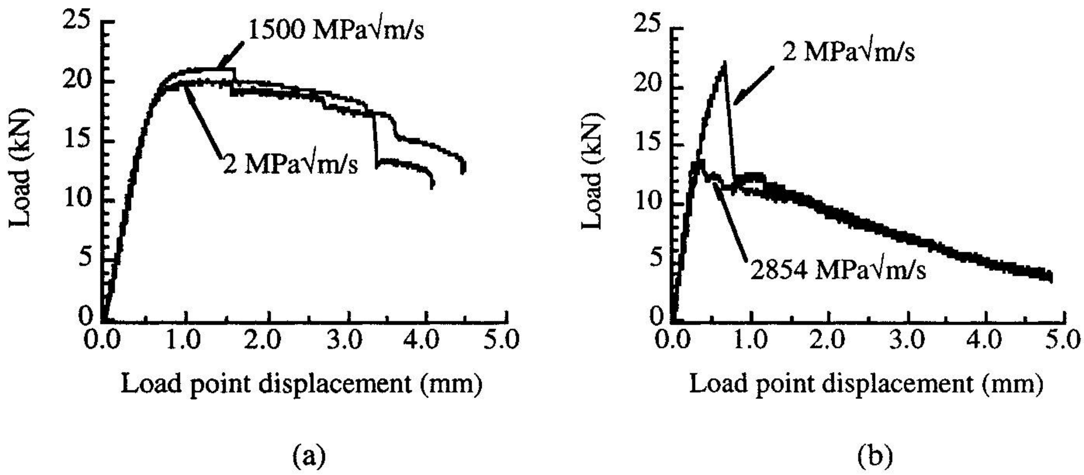

Fig. 1 Load versus load point displacement, a) base metal and b) HAZ material.

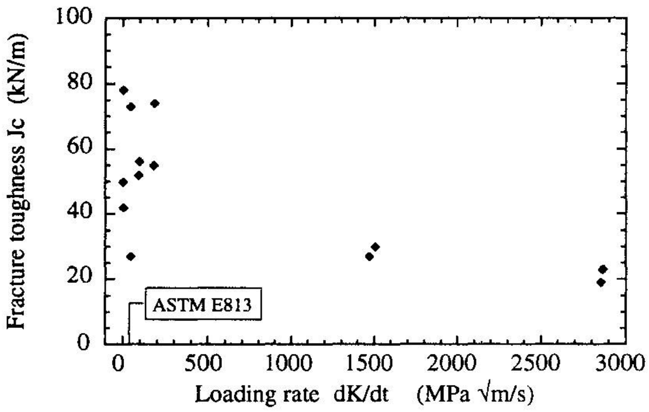

Fig. 2 Influence of loading rate on HAZ fracture toughness at temperature -30 °C.

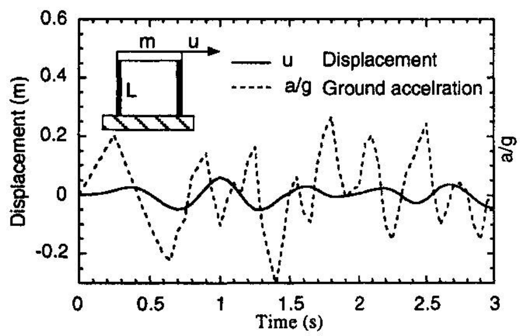

Fig. 3 Response of a simple elastic frame work subjected to ground acceleration.

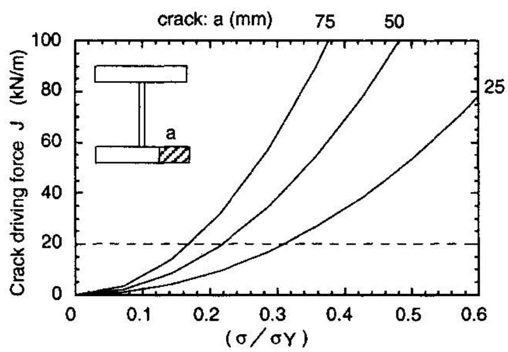

Fig. 4 Crack driving force J versus stress for some different crack lengths, σ_Y *= 700 MPa.*