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MODERN APPROACHES TO CRACK ARREST

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ABSTRACT

In modern day structures fracture initiation cannot be excluded in an absolute sense, defects may exist that when subjected to the operating stress may form brittle propagating cracks. In such cases an assessment of the crack arrest capability of the steel may be required to ensure structural integrity.

This paper aims to give a review of existing crack arrest assessment procedures discussing their respective advantages and limitations. In addition a number of modern approaches currently being developed will be introduced and their capabilities compared to existing procedures.

NOMENCLATURE

a/W	= Arrest Position
B	= Thickness (mm)
CAT	= Crack Arrest Temperature (°C)
CTOA	= Crack Tip Opening Angle (°)
$CTOA_c$	= Material Resistance to Fracture Propagation(°)
$CTOA_{max}$	= Driving Force for Ductile Propagation (°)
DWTT	= Drop Weight Tear Test
E	= Elastic Modulus (MPa)
F_a	= Force at Crack Arrest (kN)
FATT	= Fracture Appearance Transition Temperature (°C)
H_I	= Stored Elastic Energy (J)
K_{1a}	= Apparent Arrest Toughness (MPa√m)
K_{1c}	= Plane Strain Fracture Toughness (MPa√m)
L	= Effective Length (mm)
NDTT	= Nil Ductility Transition Temperature (°C)
R_s	= Mean Propagation Energy (J/mm^2)
T	= Temperature (°C)
σ	= Applied/Operating Stress (Mpa)

INTRODUCTION

In welded structures, fracture initiation is usually prevented by ensuring that the fracture toughness in the weld and heat affected zone is sufficiently high for the stress levels experienced. However local brittle zones or defects above the critical size for fracture initiation may exist, particularly in large structures where 100% inspection is impracticable or detection and sizing of defects is difficult. Furthermore, in extreme situations stresses above the design levels may be experienced which negate the minimum fracture toughness requirements of the steel. A second line of defence is required to ensure that a crack once initiated will not propagate to such an extent that complete structural failure occurs. Crack Arrest assessment is therefore most applicable to large safety critical structures, such as ships and gas pipelines, where detailed studies are justified by the need to ensure structural integrity.

BACKGROUND

While the methodology of crack initiation avoidance has been developed extensively over the years, the same rigorous approach is not available for crack arrest assessment. Crack arrest is very often circumvented by ensuring the crack initiation resistance (Fracture Toughness) is high and applying additional factors of safety.

The philosophy behind crack arrest is that if a crack initiates from, for example, a pre-existing defect, it should be arrested in the surrounding material without unduly affecting the integrity of the structure. Whilst it may be possible, through good design and the appropriate choice of material, to ensure the arrest of a propagating crack, there are difficulties in the quantification of the crack arrest capability of a steel. Over the past thirty years there have been various attempts to establish parameters on which to base the crack arrest capabilities of steel. These approaches have limitations in their applicability and so further research is ongoing to assess at new methodologies for assessing crack arrestability.

STATE OF THE ART

CHARPY IMPACT ENERGY

Standard Charpy testing gives a measure of the total energy required for both propagation and initiation, but as crack arrest is concerned only with propagating cracks the results are not directly compatible with arrest behavior. Due to their simplicity and low cost, various approaches have been developed which use small-scale Charpy data as the basis for crack arrest property evaluation.

The most common method is to define a CAT as a function of temperature for a percentage brittle FATT, nominally 50% FATT. For this approach a number of corrections have been developed which have to be applied to account for steel type, thickness and applied stress [1-3].

More recent methods have been developed which use instrumented Charpy test specimens that enable force to be recorded during the test. With this information it is possible to associate the proportions of brittle and ductile fracture area with the respective energy spent in propagation and initiation and so derive the energy used in propagating a crack once initiated.
One method uses the force vs. displacement data and applies it to a crack arrest transition criterion [4]. The criterion is based on correlations between T(Fa=4kN) and the temperature at 100Mpa√m level for a mean K_{1C} Master Curve.
Results from previous work on various steel grades [5] indicate that this approach gives accurate estimations of the crack arrest conditions for ASTM E1221, K_{1a} tests (Fig.1). However, further validation may be required in terms of large-scale tests to investigate its applicability to more structurally representative test specimens.

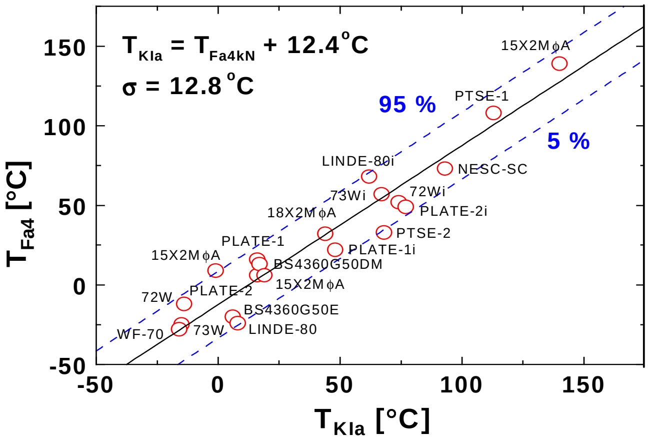

Fig.1 Correlation between Transition Criterion from Instrumented Charpy Specimens and Crack Arrest Toughness Transition Temperature of the Associated Master Curve (5).

COMPACT CRACK ARREST TEST

The most widely recognised Fracture Mechanics based crack arrest standard is ASTM E1221 [6], which is aimed at obtaining linear elastic arrest stress intensity factor K_{1a} values. The method uses side grooved wedge loaded test specimens to obtain a rapid run-arrest event under constant displacement. The values may be obtained over a range of temperatures and have been used to provide estimates of the crack arrest temperature at given levels of applied stress. In practical situations the arrest phenomenon is accompanied by the development of shear and crack tunneling. Shear is representative of plasticity and so the linear elastic K_{1a} approach may not be applicable. Regardless of this fact, experimental observations have indicated that a suitably adjusted static analysis provides a useful estimate of the arrest conditions [7].

PELLINI DROP WEIGHT TEST

In terms of the practical quantification of crack arrest capability in structural steels, the Pellini Drop Weight Test (ASTM E208)[8] is the most simple and frequently used method. The test involves the use of specimens that are welded, notched and tested using stops to restrict the deflection. The NDTT is determined by conducting impact tests over a range of temperatures. The NDTT is defined as the maximum temperature at which the brittle crack spreads completely across one or both of the ligaments either side of the weld bead. NDTT temperatures from the Pellini test are claimed to be independent of the number of runs in the weld bead, size of test piece and its orientation.

A number of corrections, which account for the structural conditions, can be applied to the NDTT in order to derive a

CAT [2,3]. The corrections required are extensive and are derived from empirical correlations rather than from rigorous physical analysis, therefore the predicted arrest temperatures tend to show extensive scatter.
Despite these reservations, the Pellini test has been useful for providing a basis for evaluating crack arrest properties for many years, due to its simplicity and general acceptance, and the test is often used for quality acceptance purposes.

DROP WEIGHT TEAR TEST

The DWTT (ASTM E436)[9] consists of a three point bend specimen containing a shallow pressed notch. The test is carried out under impact loading at a variety of temperatures and the relative proportions of ductile (shear) and cleavage (brittle) areas on the fracture surface are measured. A plot of percentage shear versus temperature can be produced.
A development of this test is the Dynamic Tear Test (ASTME604)[10] that uses a deeper notch than the DWTT. The energy absorbed in fracture, rather than the fracture appearance is recorded.
An example for the use of these testing procedures is for pipeline assessment. A typical requirement could be to ensure that the service temperature is above the 80% shear temperature from the DWTT. This would subsequently ensure that the steel is operating towards the top of the transition regime approaching the uppershelf.

One of the more recent variations of the DWTT approach is named the CTOA approach [11]. The procedure requires dynamic fracture of two sets of three point DWTT specimens having different ligament lengths, the total absorbed energy is recorded for each test and from the results a value for the $CTOA_c$ can de derived. $CTOA_{max}$ is defined as the driving force for ductile propagation and is a function of pipeline geometry and operating conditions.
The limiting condition where $CTOA_{max} = CTOA_c$ then allows a quantitative assessment to be made of the arrest/propagation conditions in gas transmission pipelines. In the case where $CTOA_{max} < CTOA_c$ then even if a crack initiates large scale ductile fracture is avoided and arrest occurs.

The CTOA approach offers a simple means for determining the crack arrest properties of gas transmission pipelines; the testing procedure is simple and relatively inexpensive, especially compared to the full-scale burst tests (described later). One of the main drawbacks of the approach is the definition of $CTOA_{max}$, which is derived from the operating conditions. These conditions are variable dependent upon the type of gas being transmitted and calculating an accurate value for this driving force is difficult.
Although the approach shows great promise it is relatively new and further validation, by comparison with full-scale test data, is required if it is to become a standard testing method.

LARGE SCALE TESTING

Large-scale tests are the most structurally representative tests available.

The first large-scale tests to be developed were the Robertson [12] and ESSO test [13]. The basic concept of the test is a large plate loaded in tension, into which a brittle running crack is introduced, which subsequently runs through the plate or arrests depending upon the crack arrest properties of the plate.

These early forms of large-scale test incorporate a driven wedge as the method for initiating a brittle crack at the plate edge. Using this form of initiation device gives rise to spurious stress waves in the test specimen and so invalidates many of the results.

The double tension test was derived from the above test geometries. In contrast to the previous tests a subsidiary loading tab is used for initiation of the brittle crack, which then forms a running crack when it reaches the main body of the test specimen, (fig.2).

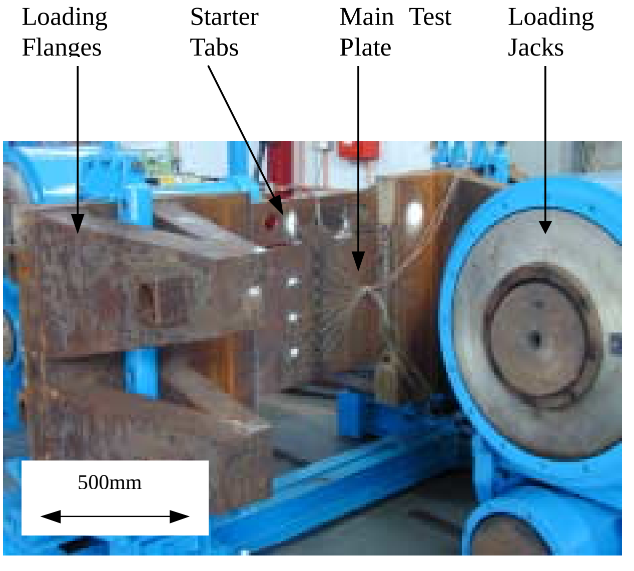

Fig.2 Double Tension Test

The tests are fully instrumented with strain gauges and thermocouples. A comprehensive history of stress and temperature can therefore be captured during the test allowing the arrest conditions to be defined accurately. The tests can be carried out under isothermal conditions or with a temperature gradient across the test specimen. Under isothermal conditions the crack will arrest immediately after initiation or run right through the plate. Incorporating a temperature gradient means the crack will initiate in a region of low toughness and propagate into material of increasing toughness. An accurate reading of temperature in the region of crack arrest can be recorded.

Unfortunately these large-scale tests are still not completely understood and wide divergences in the test results still occur between laboratories. There is no standard procedure owing to the difficulty in performing the test, laboratory testing facilities required and subsequent cost. In the majority of cases these tests are used to validate small-scale testing results as opposed for direct derivation of crack arrest capability.

Another large-scale test, applicable only to gas pipelines, is the full-scale burst test, (fig.3). As the name implies this test is carried out using full size (diameter) sections of pipeline. A crack is initiated in a low toughness section located in the centre of the test line. The crack then propagates through the adjoining sections of increasing toughness until it reaches a section with sufficient toughness for arrest to occur. The level of recorded toughness can then be specified, as the min. toughness required for crack arrest under that set of operating conditions. Of course there are many factors that effect the results of the test and so the test line is instrumented to record crack speed, gas decompression behaviour, test temperature, elastic deformation and the behaviour of backfill during the fracture process.

Obviously these tests are the most accurate and yield the most applicable property data of all the tests available for gas pipelines, but unfortunately this is accompanied by their complexity and the extremely high cost of the test.

Fig.3 Full scale Burst Test

INTERMEDIATE DOUBLE TENSION TEST

As previously discussed the double tension test is the most structurally representative laboratory test available, however, the cost of the test and laboratory capability required are high.

An intermediate scale double tension test is currently being developed as an alternative to the double tension test with the aim of reducing the equipment required and time taken to carry out the test, subsequently significantly reducing the cost [14].
Once fully developed and validated, the test procedure will be used as the basis for crack arrest property evaluation, incorporating a structurally representative test specimen. The test procedure could also be used in the same manner as Pellini testing, as a release test for minimum property requirements.

The test specimen is a direct scaling of the double tension test specimen and is presented in Fig.4 Initiation is achieved using a scissor type jack, which is inserted between the starter tabs.

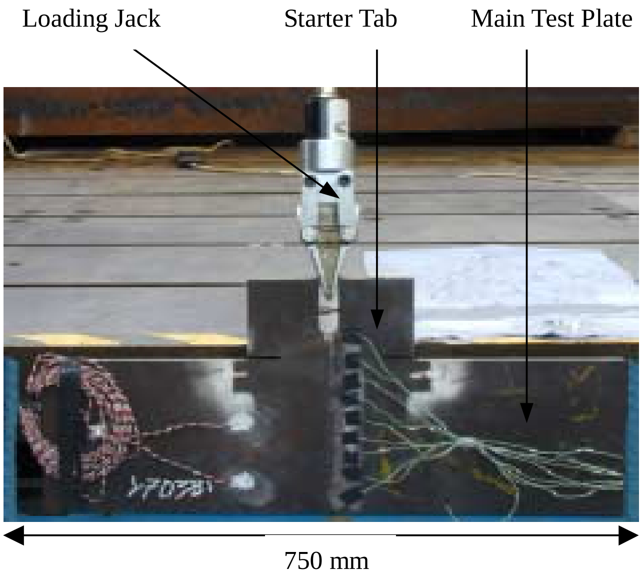

Fig.4 Intermediate Double Tension Test Specimen

An integral part of the test specimen is the starter tab. More importance is placed on achieving a low toughness region for initiation in the tab than for the full-scale tests as the jack used has a lower load capacity. At present a number of methods are being investigated including introducing a brittle weld and undercooling the tab region. The ideal would be to introduce a fatigue pre-crack in the notch region, due to the geometry of the specimen this is extremely difficult and has yet not been achieved.

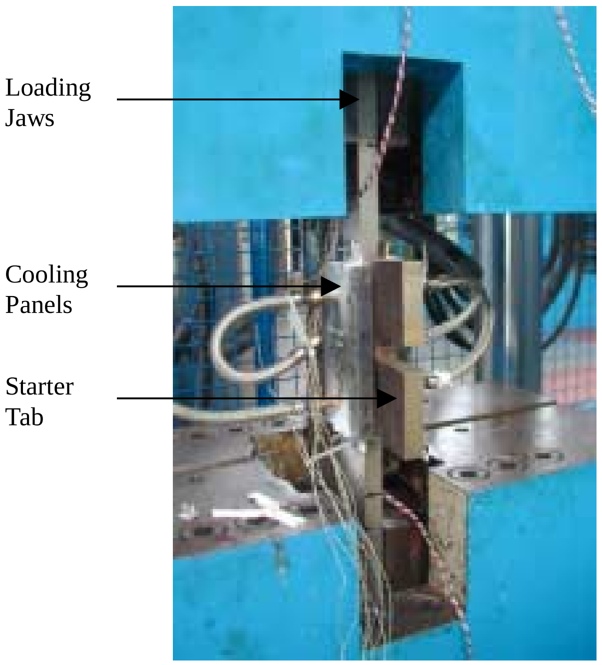

Fig.5 Intermediate Double Tension Test Set-up

The tests are instrumented in the same manner as the double tension test, measuring the main applied load, displacement, initiation jack load, temperatures and stresses in the main plate at a number of positions.
The main benefit from this test is that a standard hydraulic test machine is used, for which no rigorous preparation and welding is required in the test set-up, Fig.5

Initial tests carried out on Grade A ship plate are promising, the results indicate that a successful arrest event can be achieved and that the results are comparable to those achieved using the full scale double tension tests, fig.6.

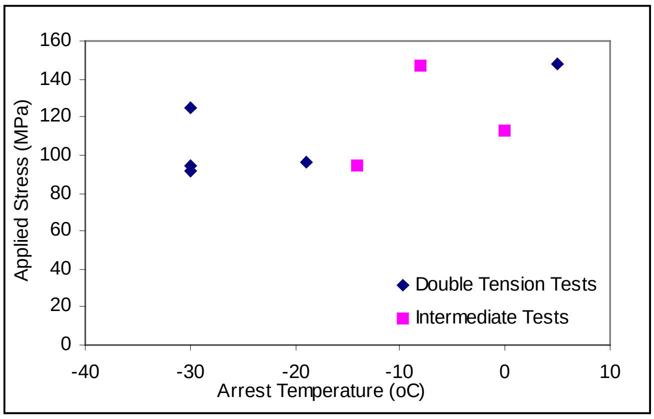

Fig.6 Full and Intermediate Scale Double Tension Test Results for Grade A Ship Steel

ENERGY BALANCE APPROACH

An energy balance approach has been developed which offers potential advantages over other methods in that it can predict the arrest conditions in terms of both temperature and length of arrested crack. The approach was developed from a similar approach applied to gas pipelines [15].

In essence the approach depends on establishing the balance between the dynamic fracture propagation energy from small-scale laboratory tests and the total static energy in the loaded components of the structure.
The total available energy in the structure is defined by

$$H_i = \sigma^2 L / 2E \qquad \text{.....(1)}$$

and the energy balance is given by

$$a/W = H_i / 2R_s \text{ [16]} \qquad \text{.....(2)}$$

At crack arrest the energy required for fracture is not simply that involved in extending a straight crack front at a specific location and temperature, but must include that for the whole of the crack, in particular the shear lips in the tunneled zone. Crack arrest is retrospective and the relevant properties are those of the crack already propagated, unlike initiation where the relevant properties are those of the unbroken ligament.

It follows that the small-scale property required is the mean energy required for propagation, which is equivalent to the energy used as the crack propagates through the specimen.
At this moment there are two possible methods for determing this, one is from instrumented charpy tests as described previosly and the other is by using dynamic tear tests.

The Dynamic Tear Test procedure developed is similar to that given in ASTM E604-1983 [10]. Full plate thickness specimens are used. Crack arrest properties are dependent upon the microstructural condition of the steel, in particular the outer edges of the plate, which influence the shear lips, and degree of crack tunneling. It is therefore important that full thickness specimens are used if a truly representative result is to be obtained.
Instead of a pressed notch as recommended in the standard, a fatigue crack is introduced at the notch to eliminate the energy used in initiation.

Using equation (2) the crack arrest temperature and length of arrested crack can be predicted. Obviously if the structure is under isothermal conditions then the position for arrest cannot be specified as one temperature is applicable to all positions in the structure.

A number of large-scale double tension tests have been carried out as validation for the approach throughout its development. The results for two ship steels, Grade A and AH32, in terms of predicted and actual positions and temperatures are presented in figs.7-8 [3,13].
In terms of predicted arrest position, the approach needs further development since many of the data lie outside the ± 0.2 boundary. In terms of temperature, however, the approach accurately predicts the arrest temperature to within 10^{o}C.
It is important to remember that in large scale testing using a temperature gradient, a relatively small distance can represent a large difference in temperature, this goes some way to explaining why the predicted arrest positions appear inaccurate when compared to the predicted and actual arrest temperatures.

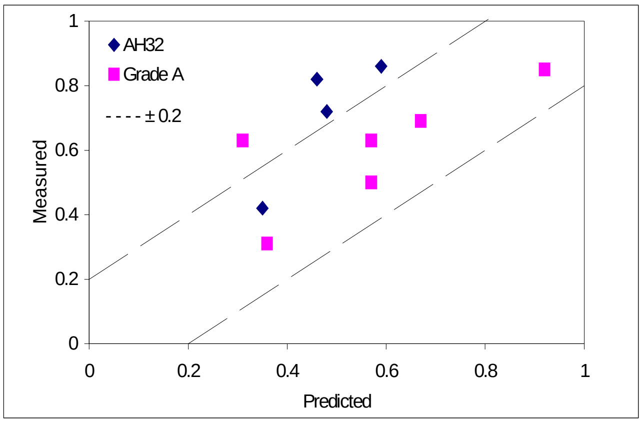

Fig.7 Predicted vs. Measured a/W Results for Large Scale Tests

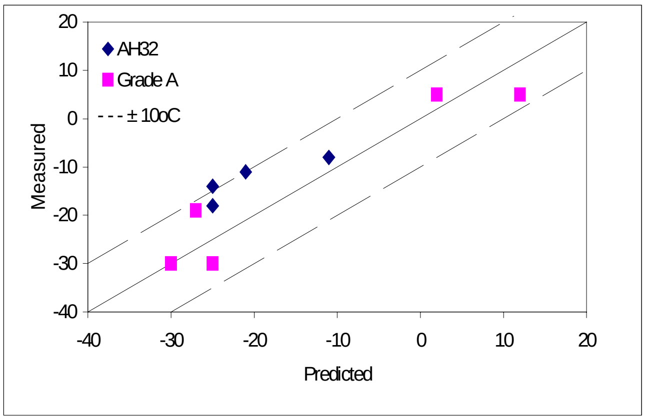

Fig.8 Predicted vs. Measured Temperature Results for Large Scale Tests

Recent work has produced a direct comparison of three procedures for crack arrest incorporating the large-scale test results described above [17]; the results are presented in Tables 1 and 2.

Material	Grade A				
Code	A1	A2	A3	A4	A5
B(mm)	15	15	15	15	15
σ (MPa)	149	99	158	200	148
CAT(°C)	5	-30	-38	12	5
Predicted Energy Balance CAT	2	-25	-12	11	12
Predicted Charpy CAT	-40	-74	-28	8	-13
Predicted Pellini CAT	-11	-18	-30	1	-12

Table 1. Comparison of Approaches for Grade A large Scale Results

Material	AH32		
Code	H1	H2	H3
B(mm)	25	25	25
σ (MPa)	211	164	190
CAT(°C)	-8	-13	-18
Predicted Energy Balance CAT	-11	-25	-25
Predicted Charpy CAT	-24	-56	-25
Predicted Pellini CAT	-33	-40	-38

Table 2. Comparison of Approaches for AH32 large Scale Results

The results give an indication of the comparative accuracy of each approach. The energy balance approach offers greater accuracy over the other two empirical methods, which when combined with the ability to predict arrest positions in the structure, promotes the approach as an attractive means for crack arrest assessment.

CONCLUSIONS

The methods available for crack arrest assessment have been discussed together with their relative benefits and restrictions.

In many cases it may be deemed sufficient to ensure that crack initiation is avoided by ensuring the fracture toughness of the material used is sufficiently high for the operating conditions experienced by the structure. In safety critical applications it may be necessary to assess the crack arrest capability of the materials in addition to its static fracture toughness properties.

The type of analysis and level to which the assessment is taken depends upon the level of accuracy required, type of data required and most importantly cost.

A simple approach such as Pellini NDTT is attractive in cases where a first approximation of the minimum operating temperature for certain structural conditions is required. The specified temperature can then be used to ensure arrest occurs at some point in the structure. Obviously the exact geometrical position for arrest cannot be specified and so further analysis would be required to ensure the structural integrity of remaining un-broken section of the structure.

In safety critical applications a more detailed assessment may be required, a number of test procedures are available for example Pellini and ASTM E1221, and the results can be accumulated to give sufficient data for assessment.
In some cases it may be necessary to carry out a number of large-scale tests to ensure that the results represent as closely as possible the service conditions of the structure.

A great deal of research has been performed and is continuing in the area of crack arrest aimed at developing accurate prediction methods using small-scale testing data applicable to any form of structure of component.

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