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Crack Arrest Toughness of Weldments for Ship Structures

by

Yongqing Han

**A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of
Master of Engineering**

**Department of Civil and Environmental Engineering
Carleton University
Ottawa, Ontario
May, 1999**

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Crack Arrest Toughness of Weldments for Ship Structures

**submitted by
Yongqing Han, B.Eng.**

**in partial fulfilment of the requirements for
the degree of Master of Engineering**

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May, 1999

Abstract

Flaws are always likely to exist in welded structures and are the source of the cracks that cause brittle fracture and failure, if the temperature and loading conditions are such that they cause unstable crack growth. The provision of tough steel with known crack arrest toughness characteristics is an effective method to prevent brittle fracture.

The objective of this work is to develop a large-scale double tension test from which the Crack Arrest Toughness (CAT) data from these tests can be correlated with the corresponding data from the Compact Crack Arrest (CCA) test conducted according to ASTM E1221-88. This correlation will allow the engineers to conduct relatively inexpensive tests to obtain toughness data that is representative of the real structure.

Starter plate tests with double-side face grooves were developed to determine the conditions (starter load and temperature range) required to initiate a successful crack propagation arrest. A large-scale double tension test, including the test apparatus, the test specimen, the instrumentation and the test procedure were developed to accommodate a test section measuring 500 mm by 2000 mm that could be subjected to loads up to 3500 kN and temperatures of interests as low as -100°C . Methods for determining the crack arrest toughness for the material in a variable stress intensity field with a temperature gradient were developed.

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List of Symbols

A	Projected area of the crack
a	Crack length
a_o	Initial crack length
a_a	Crack arrest length
a_{eff}	Effective crack arrest length
a_a^{stat}	Static crack arrest length
a_a^{dyn}	Dynamic crack arrest length
B	Thickness of plate
B_N	Thickness between the bottom of the grooves on each side of surface
c	Material property constant
d	Specimen depth
E	Young's modulus
G	Energy release rate
G_a	Crack arrest energy release rate
G_{cr}	Critical energy release rate
K	Stress intensity factor
K_{eff}	Effective stress intensity factor
K_I	Stress intensity factor of Mode I
K_{Ia}	Crack arrest toughness
K_{Ia}^*	plasticity corrected crack arrest toughness

R	Crack resistant force
r	Distance from the crack tip to any arbitrary point ahead of crack tip
T	Kinetic energy
t	Specimen length
U_a	Decrease in elastic energy for initiating the crack in the plate
U_o	Elastic energy of an uncrack plate
u_x	Displacement of any arbitrary point in x direction
u_y	Displacement of any arbitrary point in y direction
u_z	Displacement of any arbitrary point in z direction
v_p	Measured plastic crack tip opening displacement
W	Width of plate
W_s	Work required to create new crack surface
β	Dimensionless constant
ϕ	Dimension correction factor
δ	Crack mouth opening displacement
δ_a	Displacement at the arrested point measured by clip gauge
κ	Property constant
μ	Shear modulus
ν	Poisson's ratio
θ	Projection angle
σ	Applied normal stress
σ_x	x-direction normal stress at any arbitrary point ahead of crack tip
σ_y	y-direction normal stress at any arbitrary point ahead of crack tip

σ_{ys}	Yield stress
σ_z	z-direction normal stress at any arbitrary point ahead of crack tip
τ_{xy}	Shear stress on xy plane
τ_{yz}	Shear stress on yz plane
τ_{zx}	Shear stress on zx plane
Π	Total potential energy of the system

Chapter 1

Introduction

1.1 Brittle Fracture, Crack Arrest Toughness and Design

Brittle fractures will occur in welded steel structures such as ships, pipes, pressure vessels and tanks if micro-crack like flaws exist, and will become unstable under certain temperature and loading conditions. Generally, brittle fractures occur by cleavage and exhibit little or no plastic deformation. Cracks or potential cracks described in Table 1.1, which result from welding, fabrication or from fatigue, can be minimized through proper detailing, good fabrication practice and inspections, but are not necessarily eliminated. The avoidance of crack initiation is referred to as fracture prevention. Alternatively or in conjunction with the above, brittle fracture failures can be minimized by specifying materials with a minimum fracture toughness for the operating temperature range or by inserting a crack arrester in critical zones of the structure to minimize the maximum length of any potential crack such that it does not cause a complete failure of that structure.

Table 1.1 Crack Types, Origins and Descriptions

Type & Origin	Description
<ul style="list-style-type: none"> • Transverse weld flaws or cracks may occur at the start or the end of a weld pass with bad surface profiles (lack of complete fusion) that may be found in either the weld metal or the heat affected zone. • Longitudinal weld flaws or cracks may occur at the root of the weld where the crack initiation toughness may be small and will generally propagate parallel to the weldment. • The surface may be irregular and depend on the variation in toughness through the weld region. • The cracks may be arrested in the base metal if it has sufficient crack arrest toughness.
<ul style="list-style-type: none"> • Cracks may occur in the region of geometric stress concentrations that act in conjunction with residual tensile stresses that set up as the weld cools and shrinks. • The cracks generally propagate into thickness, and then along the heated affected zone.
<ul style="list-style-type: none"> • Cracks may generally occur at weldments where geometric stress concentrations exist in combination with a tensile stress field that undergoes a number of load cycles (fatigue).

Crack arrest toughness is a function of temperature, tensile stress field and crack geometry (length), and is a material characteristic that describes the material's ability to absorb energy, to carry load or to deform plastically in the presence of a notch or a crack. The initial toughness and the crack arrest toughness can only be determined directly by test and are equal to stress intensity factors evaluated at the crack tip for the set of physical conditions that exist at the beginning and at the end of a crack propagation event. The stress intensity factor can be calculated either by empirical formulae related to these conditions (for a limited number of cases) or by the displacement extrapolation method based on the results of a series of finite element analyses for the physical model. The crack arrest toughness characteristics for a material are generally expressed by a toughness-temperature curve in which a transition temperature defines the change in behavior from brittle fracture to ductile rupture. Typical characteristic curves for quasi-static and dynamic loading are illustrated in Figure 1.1.

Figure 1.1 Schematic Showing Relation between Static and Dynamic Fracture

Table 1.2 gives a chronological summary of the development of the test methods for measuring the crack arrest toughness and may be categorized as either small-scale or large-scale tests. Small-scale tests are relatively inexpensive and give crack arrest toughness values which are more qualitative than quantitative. The toughness values are generally calculated from empirical relationships which are given as a function of the crack mouth opening displacement or the energy required to cause fracture. The large-scale tests model the geometry and loading of the structure more closely, giving crack arrest toughness values that are more representative of an actual structure. These tests are expensive and are normally used for validation tests for fracture assessment purposes in critical structures or to establish some correlation with standardized (ASTM) small-scale tests.

Table 1.2 List of Main Research of Test Methods for measuring the Crack Arrest Toughness

Date	Description
1951	Robertson developed a large-scale crack arrest test conducted under a temperature gradient condition. The concept of the crack arrest temperature is established.
1953	Pellini developed a small-scale drop weight test to determine the NDTT of steels. The test was standardized by ASTM as E208.
1954	The large-scale ESSO test was developed to measure the crack arrest properties in tank steels in England.
1957	The large-scale double tension test was developed by Yoshiki and Kanazawa in Japan. Cracks are initiated and then propagated into a main plate under uniform tension and at a variety of temperature conditions.
1964	The dynamic tear test (small scale) was developed in USA and was standardized by ASTM as E604.
1984	Tanaka developed the short crack arrest test (large scale) for welded joints (for low temperature storage tank applications).
1988	Based on Crosely and Ripling, the CCA test (small scale) for the determination of K_{Ia} was standardized by ASTM as E1221-88.
1990	Crosely and Ripling propose modifications for a thickness K_{Ia} quality control test (small scale).

In design, the crack arrest toughness values are used to calculate the maximum allowable stress in the structure for which flaws (micro-cracks, known to exist) of a certain length will not propagate. Toughness values can also be used to determine repair schedules for cracks that approach critical lengths in which crack propagation will occur.

1.2 Objective and Scope

The main objective of this research was to develop and conduct large-scale double tension tests to determine the crack arrest toughness values for a typical weldment of a ship structure that is subjected to varying temperatures and tensile stress fields (up to 60% of the yield value of the parent plate). These test results will be used subsequently to calibrate the crack arrest toughness values for a series of standardized compact crack arrest (CCA) tests conducted according to ASTM E1221-88/96 by Fleet Technology Limited (FTL). The research presented in this thesis includes:

- a description of the design of the loading and the restraint systems for the large-scale double tension test, as illustrated in Figure 1.2;
- a description of the design of the geometry for the large-scale double tension test specimen, including starter plate details and notch geometry (blunt and sharp saw cut, double-side grooves) required to initiate cracks within the starter plate and then to propagate these into the main plate along a known path;
- a description of a temperature control chamber designed to provide different temperatures to the starter plate and the main plate;

Figure 1.2 Schematic Diagram of the Double Tension Test in Load Frame

- a description of the instrumentation required for the determination of the crack arrest toughness values for the weldment;
- a description of the four starter plate tests required to verify the initial crack starter geometry;
- a description of the loading sequence required for the starter load and the main load to obtain successful crack propagation-arrest events,
- a description of elastic and inelastic finite element analyses required for the small-scale CCA tests conducted by FTL, the starter plate tests, and the large-scale double tension tests, to determine the crack arrest toughness values and the stress intensity factor curves for propagating cracks, where appropriate; and
- a description of the large-scale double tension test conducted to verify the design of the test apparatus, the test specimen and the test procedure.

1.3 Outline

This thesis is divided into five chapters and an appendix, including this chapter which provides the general introductory information, the objective and scope. Chapter 2 describes the application of linear elastic fracture mechanics associated with the crack arrest toughness, a summary of various small-scale and large-scale tests which have been developed for determining the crack arrest toughness, and a summary of crack arresters that are used in ship structure applications. Chapter 3 describes the small-scale Crack Tip

Opening Displacement (CTOD) and the CCA tests conducted by FTL. A summary of the test results is given along with a comparison of the crack arrest toughness values evaluated for the valid CCA tests. The four starter plate tests (two with lateral compression and two with double-side grooves) conducted at Carleton University are described. The corresponding nonlinear finite element analyses for this series of tests are described. Chapter 4 describes the design of the test setup, the test specimen, the instrumentation and the test procedure for the large-scale double tension tests. The results of the first large-scale test and a description of the revised loading procedure are also given. A summary of this thesis along with conclusions drawn is given in chapter 5. Also given is a description of the series of double tension tests to be conducted as part of future work. A complete set of drawings for the large-scale loading and restraint test apparatus is given in Appendix A.

Chapter 2

Linear Elastic Fracture Mechanics Review

2.1 General

This chapter briefly introduces the fundamental concepts of linear elastic fracture mechanics (LEFM), methods used to evaluate the stress intensity factor, a description of tests used to determine the crack arrest toughness and a description of crack arresters and associated tests.

LEFM describes the stress and displacement distribution in the vicinity of the crack tip as a function of the applied normal stress, the crack geometry and orientation. One of two basic methods used in LEFM to determine the energy required to initiate a crack for a given inclusion or flaw is the energy criterion developed by Griffith (1920). Irwin (1956) continued the development of the energy approach and defined a critical energy release rate, G_{cr} (driving force), which causes the initiation of the crack. An alternate method to determine whether a crack will initiate or not, involves the comparison of a single parameter which describes the fracture characteristics, stress intensity factor K_I , with the fracture toughness of the material.

Either approach can be used to assess the resistance of a welded structure, like ships, to brittle fracture for typical weld details and weld flaws. Based on this assessment, crack arresters may be incorporated in the design to improve its crack resistance.

2.2 Linear Elastic Fracture Mechanics

2.2.1 The Griffith Energy Balance

The balanced energy approach is based on a continuous plate with a through thickness crack of length $2a$ that is subjected to a uniform tensile stress, σ , as illustrated in Figure 2.1.

Figure 2.1 A Through Thickness Crack in An Infinitely Wide Plate Subjected to Uniform Remote Tensile Stress

The total potential energy for this plate is given as:

$$\Pi = U_e - U_s + W_s \quad (2.1)$$

where, Π = the total potential energy of the plate

U_0 = elastic energy of an uncracked plate

U_a = decrease in elastic energy for initiating the crack in the plate

W_s = surface energy (the work required to create new crack surfaces)

The crack initiation occurs when the total potential energy of the plate is a minimum with respect to the projected crack area, A , and can be expressed as:

$$\frac{d\Pi}{dA} = \frac{dU_0}{dA} - \frac{dU_a}{dA} + \frac{dW_s}{dA} = 0 \quad (2.2)$$

in which the energy release rate, G , Irwin (1956) is defined as:

$$G = -\left(\frac{dU_0}{dA} - \frac{dU_a}{dA}\right) = \frac{\pi\sigma^2a}{E} \quad (2.3)$$

where,

G = the energy release rate

A = the projected area of the crack, $2aB$

σ = applied normal tensile stress

a = half of crack length

E = modulus of elasticity

and,

$$R = \frac{dW_s}{dA} \quad (2.4)$$

where,

R = the material resistance to crack propagation

When the energy release rate reaches a critical value, G_{cr} , which is equal to the material resistance, R , then a crack will initiate.

2.2.2 Stress Intensity Factor Approach

A crack solid can be loaded in one of three modes, tension, in-plane shear, out of plane shear, or in any combination of these modes, as illustrated in Figure 2.2. Mode I is the most common and is the subject of this investigation. Irwin (1957) defined the relationship between the stress and displacement near the crack tip in terms of the stress intensity factor, K , and the mode of loading.

Figure 2.2 The Three Basic Modes of Crack in Fracture Mechanics

For Mode I, the stress components and displacement at any arbitrary point “n” with respect to the crack tip, illustrated in details in Figure 2.3, is a function of its location relative to the crack tip in terms of polar coordinates, the stress intensity factor, Poisson’s ratio ν , and the value κ , and are given by equations 2.5 (a) to (f) and 2.6 (a) to (c) respectively:

Figure 2.3 Coordinate System and Stress Components Ahead of a Crack Tip

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \left[1 - \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right) \right] \quad 2.5 (a)$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \left[1 + \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right) \right] \quad 2.5 (b)$$

$$\sigma_z = 0 \quad (\text{for plane stress}) \text{ and,} \quad 2.5 (c)$$

$$= \nu (\sigma_x + \sigma_y) \quad (\text{for plane strain})$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \sin\left(\frac{\theta}{2}\right) \cos\left(\frac{3\theta}{2}\right) \quad 2.5 (d)$$

$$\tau_{yz} = 0 \quad 2.5 (e)$$

$$\tau_{zx} = 0 \quad 2.5 (f)$$

where, σ_x , σ_y , σ_z , τ_{xy} , τ_{yz} , τ_{zx} = stress components at any arbitrary point “n”.

$$u_x = \frac{K_I}{2\mu} \sqrt{\frac{r}{2\pi}} \cos\left(\frac{\theta}{2}\right) \left[\kappa - 1 + 2\sin^2\left(\frac{\theta}{2}\right) \right] \quad 2.6 (a)$$

$$u_y = \frac{K_I}{2\mu} \sqrt{\frac{r}{2\pi}} \sin\left(\frac{\theta}{2}\right) \left[\kappa + 1 - 2\cos^2\left(\frac{\theta}{2}\right) \right] \quad 2.6 (b)$$

$$u_z = 0 \quad 2.6 (c)$$

and where, u_x , u_y , u_z = displacement of any arbitrary point “n” in the x, y, z directions defined with respect to the crack tip as illustrated in Figure 2.3.

$$\nu = \text{Poisson's ratio}$$

$$\mu = \text{shear modulus}$$

$$\kappa = 3 - 4\nu \quad (\text{for plane strain}) \text{ and,}$$

$$= (3 - \nu) / (1 + \nu) \quad (\text{for plane stress})$$

$$K_I = \text{stress intensity factor for Mode I}$$

Similar to the energy approach, fracture occurs when a critical value of K_I is reached, K_{IC} , which is the fracture toughness of the material.

For standard crack geometry and loading such as that shown in Figure 2.4 or those related to standard crack arrest tests, empirical relationships have been developed for stress intensity factor, K_I , and can be expressed as:

$$K_I = \beta \sigma \sqrt{\pi a} \quad (2.7)$$

where, β = a dimensionless constant which depends on geometry and mode of loading.

a = crack length

The value β is available for other crack geometries from the "Handbook of Stress Intensity Factor" (Murakomi, 1987)

Figure 2.4 Crack Length and Loading

Note, Irwin (1957) established the following general relationship between G and K_I for plane stress and plane strain expressed by

$$G = \frac{K_I^2}{E} \text{ for plane stress, and} \quad (2.8)$$

$$G = \frac{1-\nu^2}{E} K_I^2 \text{ for plane strain} \quad (2.9)$$

2.2.3 Determination of Value of K_I by Finite Element Analysis (FEA)

The stress intensity factor for a given crack length can be calculated by the displacement and the stress extrapolation method or by the energy method from Equations 2.6, 2.5, 2.3 and 2.9 in which the displacements and stresses are evaluated by FEA. For example, the stress intensity factor evaluated using the displacement extrapolation method can be determined by:

- Calculating the stress intensity factor for any distance from the crack tip along the crack surface from the displacement solution generated by FEA, using Equation 2.6. These values are illustrated in Figure 2.5 for a 500 mm wide plate with a single-edge-crack with an initial crack length of 30 mm. For the stress extrapolation method the stress intensity factor is calculated using the stresses at a distance from the crack tip on the crack surface.
- Extrapolating the tangent to the curve to the crack tip as illustrated gives the stress intensity factor at the crack tip.

These numerical methods must be calibrated against the known empirical solutions for standard geometries. To evaluate the best method, each was compared to the solution for a single-edge-crack and a center-crack infinite plate for the FEA models as shown in Figure 2.6.

Figure 2.5 An Example of Tangent Extrapolation Method

The stress intensity factor evaluated by each method for propagating cracks with initial crack lengths of 30 mm for both a single-edge-crack and a center-crack in a finite plate are illustrated in Figures 2.7 and 2.8, respectively. Also shown is the corresponding stress intensity factor evaluated from the empirical solution for an infinite plate given by Equation 2.7. Both the stress and the displacement extrapolation methods give good correlation for single-edge-cracks with any length. For an initial crack length of 30 mm, the ratio of the stress intensity factor of the displacement extrapolation method to the classical solution is 0.9913. For the center crack model, the deviation of the stress intensity factor values evaluated by the displacement extrapolation method from those calculated by classical solutions, is related to the ratio of the crack length to the plate width. The small variation of the stress intensity factors at the initial crack length of 30 mm is again attributed to the difference in plate widths (finite, 500mm versus infinite).

versus infinite). Notwithstanding, the corresponding ratio of the stress intensity factor is 1.0624. Note, S.K. Chan et al. (1970) also concluded that the displacement extrapolation method would provide the best estimates of the stress intensity factor for any given load condition and crack geometry.

- Note, i) Two dimensional eight-node plane stress elements were used.
 ii) Initial crack length were 30 mm for both cases.

Figure 2.6 FEA Modeling for Standard Crack Geometry and Loading

Figure 2.7 Comparison of Stress Intensity Factors for a Single-Edge-Crack in a Finite width Plate Subject to Uniform Tension

Figure 2.8 Comparison of Stress Intensity Factor for a Center-Crack in a Finite width Plate subject to Uniform Tension

2.3 Crack Arrest Toughness

2.3.1 Determination of Crack Arrest Toughness

Crosely and Ripling (1969, 1975) developed an experimental method (Compact Crack Arrest Test) for measuring the crack arrest toughness based on an assumption that kinetic dynamic effects at crack propagation can be neglected. The crack arrest toughness K_{Ia} is defined as the stress intensity factor at the point of crack arrest and can be determined from the crack length and the crack opening displacement at arrest. A typical set of results illustrating the crack initiation and the arrest toughness versus a non-dimensional geometrical parameter reflecting the crack length for a given geometry is shown in Figure 2.9. Based on this data, Crosely and Ripling concluded that K_{Ia} is a material property and independent of geometry, the rate of the load increment and the crack length.

Figure 2.9 Crack Arrest Toughness versus the Different Ratios of Crack Jump Distance to the Gross Specimen Thickness (after Crosely and Ripling, 1969,1975)

The crack arrest toughness or the material's resistance against crack propagation can also be determined using an energy criterion. The change of energy per unit of the crack extension, the first two terms of Equation 2.1, gives the driving force for crack propagation and is defined as the energy release rate, G . This may be modified to account for the kinetic dynamic effect, (Hahn *et al* 1972, 1975), by including kinetic energy term,

$\frac{dT}{dA}$, as given by Equation 2.10.

$$G = -\left(\frac{dU_e}{dA} - \frac{dU_s}{dA} - \frac{dT}{dA}\right) \quad (2.10)$$

where, A = crack area

T = kinetic energy of the plate

The energy release rate G is dependent on the crack length, the applied load condition and on the geometry of the body containing the crack and can be determined using the theory of elasticity. An explanation of the effect of kinetic energy on crack propagation as illustrated in Figure 2.10 follows. The material's resistance to crack propagation is defined as surface energy per unit area of crack extension. A static analysis assumes that, if the value of G is equal to or greater than the material resistance, then the crack will propagate, otherwise, it will arrest. This is indicated by point B in Figure 2.10. For a dynamic crack propagation event, the strain energy release rate, G , drives the crack and imparts kinetic energy to the plate which is represented by the shaded area between points A and B. The crack continues to propagate to length $a = a_a^{dyn}$ even though G is less than R as the kinetic energy is recovered from the plate. G_a is the corresponding energy release rate at the arrest point and is less than the critical energy

release rate, G_c , assumed in static energy analysis. Hahn *et al.* concluded that the material resistance might be overestimated by static analysis.

Figure 2.10 Relation Between Static Analysis and Dynamic Analysis Method

Practically, it is very difficult to quantify the kinetic energy return. It was suggested by Crosely and Rippling that the effect of the kinetic energy component on a crack arrest event is small. Hence, ASTM adopted the CCA test as a standard method for measuring the crack arrest toughness.

2.4 Crack Arrest Tests

There are two principal design philosophies for the avoidance of brittle fracture:

- to design the structure such that crack initiation is prevented; and /or
- to specify fracture tough steels and to design the structure with details that will arrest brittle cracks.

The first requires considerable effort and does not guarantee that the brittle fracture will not occur during the service life of the structure. This is especially true for continuous all-welded steel structures, in which weld flaws, residual stresses, embrittle region and stress concentrations exist and will be the source of fatigue cracks. Unexpected impact forces may also cause ruptures and tear cracks in the steel structures.

The provision of fracture-tough steels with appropriate structure detailing is the most practical means to minimize the number of cracks and to arrest the propagating cracks. This requires an understanding of fatigue, brittle fracture and methods for evaluating the crack toughness of steel for conditions associated with the structure service life (varying temperatures and tensile stress fields). The crack arrest toughness can only be evaluated by the tests (small-scale tests or large-scale tests). A summary of these tests and of structural details that act as crack arresters are presented in the following sections.

2.4.1 Small – Scale Crack Arrest Tests

The main objective of small-scale crack arrest tests is to provide a standardized and inexpensive method which can be used to characterize the crack arrest toughness of a material. The most widely used tests are the Charp-V-Notch test (CVN), the Nil-Ductility-Temperature Transition test (NDTT), the Dynamic Tear test (DT), the Double Cantilever Beam test (DCB), the Tapered Double Cantilever Beam test (TDCB) and the Compact Crack Arrest Test (CCA). The description of test specimen and discussion for each type of test is given in Figure 2.11 and Table 2.2, respectively.

The CVN, NDTT and DT give a measure of crack arrest toughness in the form of a temperature transition curve expressed in terms of absorbed energy versus temperature.

Empirical relationships relating the crack arrest toughness with the absorbed energy must be used to classify notch toughness for a given steel. Data from the remaining tests can be used to calculate the stress intensity factor at the arrest point (crack arrest toughness) using basic fracture mechanics.

Of this group, the CCA test has been standardized by ASTM since it is the most reliable and reproducible, and is not as affected as are the alternative test methods by the dynamics of crack propagation. The crack arrest toughness values determined from these tests have been used to evaluate existing structures for their susceptibility to brittle fracture and to design structures with the appropriate crack arrest toughness.

Figure 2.11(a) Small-Scale Test Types

Figure 2.11(b), (c) Small-Scale Test Types

Figure 2.11(d), (e), (f) Small-Scale Test Types

Table 2.2 Summary of Small-Scale Tests

Type of Test	Description of Test	Measurement and Discussion
Charpy-V Notch (CVN) (ASTM E23-96)	<ul style="list-style-type: none"> • A pendulum mechanism is used to strike the test specimen illustrated in Figure 2.11(a) with a known mass and velocity to determine the energy required to cause brittle fracture. • A series of tests at different temperatures must be conducted to determine the transition temperature (temperature which initiates brittle fracture mode). 	<ul style="list-style-type: none"> • Although the test is fast, simple and relatively inexpensive to conduct, the energy absorbed by test specimen (for all specimens failed by brittle fracture) only gives a measure of the crack arrest toughness. Some empirical relationships have been developed but may not be applicable to all load cases. • The percentage of the fracture surface in shear and the corresponding lateral expansion at the specimen impact gives a measure of brittleness. • The measured energy versus temperature gives a temperature transition curve and only serves as a qualitative estimate of the crack arrest toughness since it does not account for the impact load.
Nil-Ductility Transition Temperature Test (NDTT) (ASTM E208)	<ul style="list-style-type: none"> • Impact loads from a drop test are applied to a standard test specimen supported by the apparatus shown schematically in Figure 2.11(b). A brittle weld bead with a saw cut made on the face opposite of the face being struck is designed to embrittle the material to initiate a crack on impact. • Maximum deformation is limited and tests are conducted at various temperature until fracture can not be obtain 	<ul style="list-style-type: none"> • The measured energy versus temperature gives a temperature transition curve and serves as qualitative test to crack arrest toughness.
Dynamic Tear Test (DT) (ASTM E604)	<ul style="list-style-type: none"> • Impact loads from a drop test are applied to standard specimens with dimension and the sharp notch geometry shown in Figure 2.11(c). Tests are conducted on specimens at various temperatures and the kinetic energy to cause fracture is recorded. 	<ul style="list-style-type: none"> • The measured energy versus temperature gives a temperature transition curve and serves as qualitative test to crack arrest toughness.

Table 2.2 Summary of Small-Scale Tests (Cont'd)

Type of Test	Description of Test	Measurement and Discussion
Double Cantilever Beam Test (DCB) & Tapered Double Cantilever Beam Test (TDCB)	<ul style="list-style-type: none"> The geometry of various types of test specimens are illustrated in Figure 2.11(d) and (e). There are no standard dimensions for either the DCB or the TDCB tests. Blunt notches, chevron notch or fatigue cracks are used for crack initiation in both types. Face grooves are used to direct the crack growth along a known path. A static load is applied to open and propagate a crack within the specimen. The crack mouth opening displacement is measured by clip gauge. 	<ul style="list-style-type: none"> The stress intensity factor at initiation and crack arrest toughness can be calculated from the data measured during the test. This test method has not been standardized, as it may be susceptible to dynamic effects and as tests have shown unstable crack paths that tend to branch.
Compact Crack Test (CCA) (ASTM E1221-96)	<ul style="list-style-type: none"> The geometry of the CCA test specimen is illustrated in Figure 2.11(f). A brittle weld bead may be placed notch tip to promote crack initiation. Face grooves generally produce uniform crack fronts and stable crack path. CMOD result from a wedge loading with split pins and is measured with a clip gauge. 	<ul style="list-style-type: none"> Crack arrest temperature can be calculated as function of crack length and CMOD as defined by ASTM E1221-96. This test has been standardized since crack path is relatively stable. The dynamic effects have been determined to be small relative to other tests. The CCA gives the lower bound value of K_{Ia}.

2.4.2 Large-Scale Crack Arrest Tests

Large-scale tests have been developed to study crack arrest toughness for sections with geometry, weld, temperatures and loading conditions, similar to those in realistic structures. Note, the large-scale tests are generally conducted in conjunction with less expensive small-scale tests to establish correlations between these two. Of this group, the double tension test is considered to be the best for the determining crack arrest toughness since:

- the dynamic effects and influence of starter plate load are minimized,
- the main plate load (applied stress) and hence the stress intensity factor field can be controlled, and
- the test can be conducted under either isothermal temperature conditions or temperature gradient conditions.

A summary of five different large-scale test types including the geometry of the test specimen, the test description, the loading condition, the measurements and the data evaluation are given in Figure 2.12 and Table 2.3.

Figure 2.12(a), (b) Large Scale Test Types

Figure 2.12(c), (d) Large Scale Test Types

Figure 2.12(e) Large Scale Test Types

Table 2.3 Summary of Large-Scale Tests

Type of Test	Description of Test	Measurement and Discussion
Robertson Test (1953)	<ul style="list-style-type: none"> • The dimensions, sharp notch geometry and loading for the test specimen are illustrated in Figure 2.12(a). • The crack is initiated from impact load applied to the outstanding lug on one side as shown. • Tests are conducted under either temperatures gradient or isothermal temperature condition. 	<ul style="list-style-type: none"> • Temperature gradient, impact load, uniform transverse load and crack length are measured. • The test gives the lowest temperature associated with crack arrest. • The determination of the crack arrest is ambitious. • The test gives qualitative data and is of limited value since impact load may influence the results.
Esso Test (1955)	<ul style="list-style-type: none"> • The dimensions, sharp notch geometry and loading for the starter and test sections are illustrated in Figure 2.12(b). • The brittle crack is initiated by driving a wedge into the V-shaped notch. This may be a pressed notch and placed close to brittle weld bead to promote the crack initiation. • The test is conducted under isothermal temperature condition. 	<ul style="list-style-type: none"> • The test gives the lowest temperature associated with the crack arrest. • The Esso test has not been used extensively since the test results may be effected by stress waves on the test plate.
Double Tension Test	<ul style="list-style-type: none"> • The dimension, notch geometry and loading for the main and starter plate are illustrated in Figure 2.12(c). • A pressed notch or brittle weld bead could be used to promote the crack initiation at notch tip. • The test can be conducted under isothermal temperature or temperature gradient condition. 	<ul style="list-style-type: none"> • The press notch yields the localized compressive residual stress in brittle region. • Test results are only valid for tests in which cracks can be initiated and subsequently arrested in the main plate. • The crack arrest toughness can be calculated using the displacement method or estimated form the empirical equation, which are function of the measured crack length and applied stress.

Table 2.3 Summary of Large-Scale Tests (Cont'd)

Type of Test	Description of Test	Measurement and Discussion
Dual Plate Double Tension Test	<ul style="list-style-type: none"> The dimension, notch geometry and loading for the main, starter plate and brittle weld section are illustrated in Figure 2.12(d). Tests are usually conducted at low temperature. 	<ul style="list-style-type: none"> The test was specifically developed to simulate crack events in storage tanks so that the crack arrest toughness for these steels subject to low temperature could be evaluated. The crack arrest toughness is estimated from empirical equations, which are function of applied stresses and crack length.
Short Crack Arrest Test (1982)	<ul style="list-style-type: none"> The dimension, notch geometry and loading conditions for the starter and main plate for two different configurations are illustrated in Figure 2.12(e). The starter plate is welded to center of weld line to test plate on top of a brittle weld bead. A face groove machined on the opposite of the starter plate to create a stable crack path. 	<ul style="list-style-type: none"> The test configuration minimize the dynamic effects of stress waves and simplifies the calculation for crack arrest toughness which is based on empirical formulation given as function of crack length and applied load. The bending effect in the test plate due to the starter load is not considered.

2.5 Crack Arresters

2.5.1 Concept

The two principle methods for arresting cracks in structures are to increase the fracture resistance of the material locally or to decrease the crack driving force by inserting tough material or by welding stiffeners across potential crack paths. A diagram of a plate under a constant tensile load with an initial crack and no crack arresting components is shown in Figure 2.13 along with the corresponding energy release rate curve for a propagating crack (shown by the dashed-line). As described in section 2.3.1, when the energy release rate exceeds the critical value, G_c , then the crack will propagate. As the crack propagates, a portion of the strain energy released becomes kinetic energy stored in the plate. An increasing energy release rate greater than the critical value of G_c is indicative of a crack that will propagate completely across the plate.

A fracture tough material (arrest plate) welded across the potential crack path increases the resistance locally such that it is greater than the energy release rate, as illustrated in Figure 2.14 by the resistance for the arrest plate R_A . The kinetic energy stored in the base plate will propagate the crack a short distance into an arrest plate. If the arrest plate is too narrow (less than the width of the horizontal shaded area) then the crack will propagate right through.

The energy release rate curve for the alternative method where a stiffener is welded across the potential crack path is shown in Figure 2.15. The stiffener prevents crack opening, reduces the energy release rate to values below the resistance of the material and it absorbs the kinetic energy return, arresting the crack.

Figure 2.13 Energy Released Rate for a Propagating Crack under Constant Load

Figure 2.14 Energy Release Rate Curve for Base Plates with Arrest Plates

Figure 2.15 Energy Release Rate Curve for Base Plate with Stiffeners

2.5.2 Crack Arrester Tests and Evaluation

Crack arrester tests are required to evaluate the effectiveness of the various methods used to arrest crack and to develop the appropriate design guidelines and rules. Example tests and results summarized by T. Kanazawa (1972) are given in Figure 2.16.

The tests are modeled after the large-scale double tension test with a main plate subjected to uniform tension and a starter plate in which the crack is initiated. Various crack arresters are applied to the main plate and intercept a propagating crack. For each test, the crack arrest toughness was determined as function of crack length from the data acquired from the double tension tests. The corresponding stress intensity factors for the sections without crack arresters were determined analytically and are shown on the same diagrams given in Figure 2.16, along with the stress intensity factor calculated from the test for sections with crack arresters. Crack arrest generally occurs a short distance beyond the point in which the stress intensity factor falls below the crack arrest toughness, K_{Ia} .

2.5.3 Application

Crack arresters are being applied to nuclear pressure vessels, liquid or gas storage tanks, pipelines, offshore structures and ships to provide additional resistance against brittle fracture. The common types of crack arresters (M. Kanninen *et al*, 1976) including arrest strakes, stiffeners, welded patches and bolted patches are illustrated in Figure 2.17.

Figure 2.16(a) The Crack Arrester Types

(b) Crack Arresters Models with Welded Patches or Riveted Patches

Figure 2.16(b) The Crack Arrester Types

Figure 2.16(c) The Crack Arrester Types

The arrest strake shown in Figure 2.17(a) is comprised of fracture tough steel which has a toughness greater than the surrounding plates or is of greater plate thickness which decreases the stress intensity factor level (increase resistance). Both of these are commonly used in the marine industry. The stiffener arresters illustrated in Figure 2.17(b) are commonly used to reinforce openings, improve the fatigue performance and increase fracture resistance. The patch crack arresters illustrated in Figure 2.17 (c) and (d) are generally used as a temporary repair to arrest existing cracks. Although not commonly used, it is possible to suppress the growth of cracks by introducing through thickness compression around the crack tip in the form of bolted patch plates. Welded patches will increase the resistance locally by decreasing the stress intensity field which diminishes the probability of crack propagation for existing cracks.

Figure 2.17(a), (b) Crack Arresters

Figure 2.17 (c), (d) Crack Arresters (Cont'd)

Chapter 3

Small Scale Test Programme

3.1 General

Small-scale tests give a measure of the crack arrest toughness of a material with respect to any given temperature. From this data, the temperature transition curves and the crack arrest toughness of the steel or weld (with prescribed welding procedures) can be determined and compared to the specified toughness values, to determine the acceptability of the material for a given application. The test data may be used for design or they may be used to conduct toughness or safety assessments of welded structures such as ship hulls, bridges, storage tanks and pressurized containers. The major drawback of the small-scale test is that the data are more qualitative than quantitative, since the loading is generally indirect and the specimens are not tested in a uniform or gradient tensile stress field indicative of real loading conditions.

The small scale tests for this investigation will be used to characterize the crack arrest toughness for typical butt welds in ship structures, and to define the experimental parameters (notch geometry, temperature, stress field) for the large-scale test. Finite element analyses were conducted for all small-scale tests and for the starter plate tests, to give corroborating evidence and to determine the stress intensity factor and the crack arrest toughness values. A description of each analysis is given in the appropriate section.

The weldment (full penetration groove weld for butt joints) and the corresponding weld procedure for the crack arrest toughness being investigated, are illustrated in Figure 3.1.

- weld metal designation, E71T-1

Figure 3.1 Welding Procedure for Full Penetration Groove Weld

The pre-heat, number and sequence of weld passes and weld preparation geometry (weld root face length and root distance) have been developed or specified to minimize the weld distortions and to provide complete fusion for the root passes. The root distance was determined to be 4 mm. Welds for two root face lengths of 3 mm and 1 mm, referred to as the *W1* and the *W2* series respectively, were made. Of these only the *W2* series provided complete fusion without flaws. All welds were made perpendicular to the rolling direction of the parent plate.

3.2 Compact Crack Arrest Test of the Weld Metal

All CCA and CTOD tests described in section 3.2 were conducted by Fleet Technology Limited as part of the investigation of the crack arrest toughness characteristics for weldments of ship structures.

3.2.1 Geometry and Notch Embrittlement

Twenty-two compact crack arrest tests were conducted in accordance with either the method described by Crosely and Rippling (1991) or the ASTM standard E1221-88/96, to obtain the fracture toughness characteristics of the weld metal for the temperature ranging from -15°C to 20°C . To determine the dimensions of the CCA test specimen given as a function of W , and the allowable range of crack mouth opening displacement, a series of the Crack-Tip Opening Displacement tests (CTOD) were conducted in accordance with British Standard 5762, on the machined specimen comprised of weld metal. The test specimen, the loading and the boundary conditions are illustrated in Figure 3.2.

The results from five tests of series W2, for temperature 0°C to 19°C are labeled in Table 3.1. The crack tip opening displacements between points 'c', shown in Figure 3.2, were calculated from the relative displacements between points 'b'. The elastic and the plastic CTODs of the specimen at failure were determined from the load-CTOD curve and are summarized in Table 3.1 along with the failure types. Based on the geometry and plastic CTOD, the crack arrest values can be calculated using Equation 3.1 and are listed in Table 3.1.

Note, t = thickness of plate
 $d = 2t$
 $a = t$

Figure 3.2 Crack-Tip Opening Displacement Test Specimen

Table 3.1 Estimated Crack Arrest Toughness from FTL

Specimen	Temp. (°C)	a/d	Elastic CTOD (mm)	Plastic CTOD (mm)	Type of Failure	K_{IC} (MPa√mm)
W2-1-2	0	0.339	0.027	0.050	δ_c	100
W2-1-3	0	0.318	0.029	0.097	δ_c	86
W2-1-4	19	0.326	0.030	0.109	δ_m	N / A
W2-1-5	19	0.332	0.031	0.135	δ_m	N / A
W2-1-6	0	0.323	0.026	0.100	δ_c	84

- Note:
1. δ_c , δ_m , δ_k are defined as CTOD value at unstable cleavage fracture (no evidence of ductile tearing), CTOD value at first attainment of maximum load and CTOD value at unstable cleavage fracture after ductile tearing, respectively.
 2. N/A means not applicable.

$$\delta = \frac{K_{IC}^2(1-\nu^2)}{2\sigma_y E} + \frac{0.4(d-a)v_p}{0.4d+0.6a} \quad (3.1)$$

where,

a = crack length, mm

t = specimen thickness, mm

d = specimen depth, mm

σ_y = yield stress of weld metal, MPa

v_p = measured plastic CTOD, mm

Tests W2-1-4 and W2-1-5 were conducted at 19°C and were classified as δ_m type failure, since the specimens were failed by stable ductile tearing at the maximum load. The calculation for K_{Ic} using Equation 3.1 is not applicable for this case. The dimension, W , can now be calculated from Equation 3.2 using K_{Ic} from CTOD tests.

$$W \geq 2.83 (K_{Ic} / \sigma_y)^2 \quad (3.2)$$

where, W = width of specimen as illustrated in Figure 3.2

From these calculations, three sets of specimens with sizes based on W equal to 100 mm, 200 mm and 300 mm were made. All other dimensions, with equations given in Figure 3.3, are calculated as function of W .

To initiate the crack, two different initiation starters were employed. The first is an embrittlement of a Chevron notch by a local through-thickness plastic pre-compression of 5% in the region of the notch tip followed by “strain aging”, and a heat treatment of 250°C for one hour. The second is embrittlement at the notch tip by the application of a brittle weld bead made by using Foxdur 350 or Foxdur 500.

Note: $H = 0.6 W \pm 0.005 W$
 $L = 1.25 W - t$
 $0.3 W \leq a_0 \leq 0.375 W$
 $S \leq W / 10$
 $D = 0.3 W$

Figure 3.3 Dimension of Full-Thickness Compact Crack Arrest Test Specimen

3.2.2 Test Setup and Instrumentation

Pictures of the test specimen in the testing machine identifying the supports, the split pin and wedge, the digital temperature controllers, the temperature insulation box, the liquid nitrogen conduit and the displacement gauge are shown in Figure 3.4 (a) and (b). The test specimen was instrumented with two thermocouples welded to the top surface of specimen as shown in Figure 3.5. A single strain gauge was installed on the side of the test specimen as shown, and was used to trigger the high-speed data

acquisition system once the crack was initiated. A clip gauge was attached at points 'd' at a distance of $0.35W$ from the loading line as illustrated in Figure 3.5. Measured displacement from the displacement gauge gives the crack mouth opening displacement corresponding to the applied load and the crack propagation event.

Liquid nitrogen was released into the insulated box from the tank through a conduit until the target test temperature was reached and maintained for a minimum of 15 minutes. The CCA tests were conducted under an isothermal temperature condition.

3.2.3 Test Procedure, Results and Discussion

For each test, the wedge was loaded and driven into the split pins to cause brittle fracture and crack propagation. The response of the strain gauge triggered the data acquisition system to record the load and CMOD at the time of crack propagation. These were also recorded graphically on a chart.

The characteristic load–CMOD curves for the first load cycle are illustrated in Figure 3.6. The tests are only considered to be valid if the CMOD is within the range of $\delta_{\min}$ and $\delta_{\max}$. These limits were calculated from Equation 3.3 for the ratios of a/W equal to 0.5 and 0.8, respectively.

$$\delta_{\min, \max} = \frac{K_{Ic} W^{1/2}}{E f(a/W)} \quad (3.3)$$

$$\text{where, } f(a/W) = \frac{2.24[1.72 - 0.9(a/W) + (a/W)^2][1 - (a/W)]^{1/2}}{[9.85 - 0.17(a/W) + 11.0(a/W)^2]}$$

(a) Overall View

(a) Close-up View

Figure 3.4 CCA Test Specimen Setup

Figure 3.5 Location of Thermocouples and Strain Gage on CCA Test Specimen

Figure 3.6 Typical Load - CMOD Curves

The most common load–CMOD curve is shown in Figure 3.6(a). For tests with a small number of distinct short crack propagation events and a crack mouth opening displacement value less than the minimum allowable value, δ_{min} , the load must be increased until the CMOD lies between the two limits. The test is considered to be valid only if the load can be sustained between these CMOD limits as illustrated in Figure 3.6(b). The last type, illustrated in Figure 3.6(c), results in a large number of short crack propagation events. Equation 3.4 is used to calculate K_{Ia} and is based on the CMOD, δ_a , as illustrated in each of these Figures 3.6(a), (b), (c).

$$K_{Ia} = \delta_a E f(a/W) / W^{1/2} \quad (3.4)$$

This value can be corrected using Equation 3.5 to take into account the small plastic zone at crack tip.

$$K_{Ia}^* = K_{Ia} [1 - 0.04 \phi^2 (1 - a/W)^{1/2}] \quad (3.5)$$

Where, K_{Ia}^* = plasticity corrected crack arrest toughness

ϕ = dimension correction factor and is equal to $E \delta_a / \sigma_{ys} W$

δ_a = displacement at the arrested point measured by clip gage

For tests in which δ_{max} is reached without any crack, ASTM Standard E1221-88/96 suggests that the specimen be unloaded and reloaded with a new maximum CMOD equal to δ_a given by Equation 3.6. If there is no crack, the procedure is repeated until the maximum CMOD, given by Equation 3.7, is reached. If brittle fracture occurs in any cycle, the crack arrest toughness is evaluated as before using Equation 3.4 and 3.5. Five

other conditions listed in ASTM Standard E1221-88/96 and reproduced in Table 3.2 must be met for the test to be valid. Four of these (i, ii, iv, v) are relevant to this series of tests and are related to the crack propagation length. The third (iii) condition imposes a minimum plate thickness requirement that gives the plane strain condition along the crack front and is not applicable to this case.

$$\delta_i = [1.0 + 0.25(i-1)] \left[\frac{0.69 \sigma_y W \sqrt{B_N / B}}{E f(a/W)} \right] \quad 3.6$$

where, i = load cycle number

B_N = thickness between the bottom of the grooves on each side of surface

B = thickness of plate

$$[\delta]_{\text{limit}} = \left[\frac{1.50 \sigma_y W \sqrt{B_N / B}}{E f(a/W)} \right] \quad 3.7$$

Table 3.2 Test conditions for Validity of ASTM Standard E1221-88/96

Designations	Condition	Description
(i)	$W - a_e \geq 0.15 W$	Unbroken ligament
(ii)	$W - a_e \geq 1.25 (K_{Ic} / \sigma_y)^2$	Unbroken ligament
(iii)	$B \geq (K_{Ic} / \sigma_y)^2$	Thickness
(iv)	$a_e - a_0 \geq 2 N$	Crack-jump length
(v)	$a_e - a_0 \geq (K_0 / \sigma_y)^2 / 2 \pi$	Crack-jump length

The test results are summarized for all tests with one load cycle and those that required multiple load cycles in Table 3.3 and 3.4, respectively. Measured plate thickness, temperature, average crack length and CMOD are listed for each test. Crack arrest toughness values are calculated for all valid tests. Invalid tests are identified. The blanks indicate that either the crack was not initiated or that the crack was terminated at the end of the brittle weld.

The measured crack length was determined from the average length of the cracked surface, which was identified by heat tinting. Heat tinting is a process, which marks the crack surfaces with colours that result from exposure to a torch flame in which the steel temperature is kept between 270°C and 300°C for approximately one hour. Subsequently, the specimen is cooled with liquid nitrogen, fractured into two parts and the crack length was measured. A typical load – CMOD curve and fracture surfaces are illustrated in Figure 3.7 and 3.8, respectively.

The valid crack arrest toughness values for all tests (single and multiple cycles) are plotted in Figure 3.9 as a function of temperatures and give average values of 90.6 MPa $\sqrt{m}$ and 107.7 MPa $\sqrt{m}$ for temperatures of –10°C and 0°C, respectively. Regardless of the embrittlement method or the type of brittle weld used for the crack initiation, cracks could not be initiated for temperatures equal to or greater than 10°C, indicating a tough material. Due to the natural scatter (variability) in the CCA toughness test data and the fact that there were so few successful tests in this series, it is difficult to make any conclusive statements about the success of the crack initiating techniques used.

Figure 3.7 Typical Load vs CMOD Curve

(a) Single Load Cycle of CCA Test (CCA W2(1)3) at -10°C

(b) Single Load Cycle of CCA Test (CCA W2(2)2) at -10°C

(c) Multiple Load Cycle of CCA Test (CCA W2(2)2) at -10°C

(d) Multiple Load Cycle of CCA Test (CCA W2(3)2) at 10°C

Figure 3.8 Typical Fracture Surfaces

Figure 3.9 Crack Arrest Toughness vs Temperature

Table 3.3 CCA Test Results of Field Metal (W2) Specimens (Single Load Cycle)

	Test Identification	Temp. ($^{\circ}\text{C}$)	a_a / W	CMOD (mm)	K_{Ia} ($\text{MPa}\sqrt{\text{m}}$)	K_{Ia}^* ($\text{MPa}\sqrt{\text{m}}$)	Validity Requirement
$W = 100 \text{ mm}$	CCAW2(1)-1 [#]	0	0.542	1.083	128.6	120.7	Valid
	CCAW2(1)-2 [#]	0	0.487	0.919	119.7	112.8	Valid
	CCAW2(1)-3 ⁺	0	0.558	0.8	92.8	89.7	Valid
	CCAW2(1)-4 ⁺	-10	0.537	0.657	80.7	78.6	Valid
	CCAW2(1)-5 [*]	0					No Crack
	CCAW2(1)-5 [*]	-15	0.675	1.476	141.5		Invalid by (i)
$W = 200 \text{ mm}$	CCAW2(2)-4 [*]	21					No Crack
	CCAW2(2)-4 [*]	10					No Crack
	CCAW2(2)-5 [*]	10	0.395				Invalid by (ii, iv, v)
	CCAW2(2)-6 ⁺	20					No Crack
	CCAW2(2)-7 ⁺	0					No Crack

Note: the symbols [#], ⁺ or ^{*} indicate that the crack initiating conditions refer to through the thickness compression/strain aging, Foxdur 500 brittle weld bead and Foxdur 350 brittle weld bead, respectively.

Table 3.4 CCA Test Results of Field Metal (W2) Specimens (Multiple Load Cycle)

W	Test Identification	Temp. (°C)	a_o / W	CMOD (mm)	K_{Ia} (MPa $\sqrt{m}$)	K_{Ia}^* (MPa $\sqrt{m}$)	Validity Requirements
100 mm	CCAW2(2)-1 ⁺	0					No Crack
	CCAW2(2)-2 ⁺	-10	0.517	0.772	107.0	102.3	Valid
	CCAW2(2)-3 ⁺	-10	0.483	0.714	99.3	95.3	Invalid by (iv)
	CCAW2(3)-5 ⁺	-10					No Crack
	CCAW2(3)-6 [*]	-10	0.53	0.724	94.1	90.8	Valid
200 mm	CCAW2(2)-6 [*]	10					No Crack
	CCAW2(2)-7 [*]	10					No Crack
300 mm	CCAW2(3)-1 [*]	10					No Crack
	CCAW2(3)-2 [*]	10					Invalid by (v)
	CCAW2(3)-3 [*]	10					No Crack
	CCAW2(3)-4 [*]	10					No Crack

Note: the symbols ⁺ or ^{*} indicate that the crack initiating conditions refer to Foxdur 500 brittle weld bead and Foxdur 350 brittle weld bead, respectively.

It was anticipated at the onset of the small-scale test program that the CCA tests would demonstrate the best crack starter method to be used in the double tension test and to give appropriate crack arrest toughness values to characterize the fracture toughness of the weldment being investigated. These tests demonstrated that the crack starter methods were not very successful, and indicated that the cracks are likely to terminate at the interface between the brittle weld metal and the test weld metal (incomplete fusion), or that they have low toughness values, which is equivalent to a buildup of insufficient energy to propagate the cracks from the starter plate to the main plate. As the results were unsuccessful, other crack starter methods were developed as part of the starter plate test series, which simulated more closely the plate and notch geometry of the large-scale double tension test.

The K_{Ia} and K_{Ia}^* calculation for the CCA tests as given by equations 3.4 and 3.5 reproduced from ASTM Standard E1221-88/96 is semi-empirical. To compare the toughness of the weld material from the successful CCA tests with those from the starter plate tests or from the large-scale double tension tests, the data from the CCA tests (CMOD and crack length) must be used as input to a finite element analyses and the K_{Ia} values calculated using the displacement method.

A 2-dimensional solid model replicating the CCA test specimen geometry is illustrated in Figure 3.10. Elastic analyses were performed for each successful test and the stress intensity factor at the arrest point (crack arrest toughness) was calculated. These values are illustrated in Figure 3.11 as open circles and triangles and correspond to the solid shapes for the K_{Ia}^* values calculated by Equation 3.5. The crack arrest toughness evaluated by displacement method are higher than those determined from ASTM E1221-88/96 with the average increase of 1.387 and 1.291 for -10°C and 0°C , respectively.

Table 3.5 CCA Test Results and FEA Results

	Test Identification	K_{Ia}^* , by Eq. 3.5 ($\text{MPa}\sqrt{m}$)	K_{Ia} , by FEA ($\text{MPa}\sqrt{m}$)
-10°C	W2(2)-2	102.3	126.8
	W2(3)-6	90.8	119.0
	W2(1)-4	78.6	105.1
0°C	W2(1)-1	120.7	172.7
	W2(1)-2	112.8	148.2
	W2(1)-3	89.7	127.3

Figure 3.10 CCA Test Specimen 2-Dimensional Model

Figure 3.11 Comparison of Crack Arrest Toughness Values Evaluated by ASTM 1221-88/96 and the Displacement Method

3.3 Starter Plate Tests and FEA Results

3.3.1 General

Four starter plate tests with two different crack starter methods were conducted to determine which method would be the most effective for the large-scale double tension test. The first method involved embrittlement of the weld metal by lateral compression through the thickness up to 15%. The concept of through thickness compression is to use a significant portion of the strain energy density of the material (through the net section) through plastic deformation making it brittle. With an embrittled starter plate section at the crack tip of lower fracture toughness, the large-scale double tension test could be conducted under isothermal conditions and have the crack terminate in the tougher weld metal in the main plate outside the embrittled weld region.

The second method provides double-side face grooves made on either side of the plate over a length which the initial crack will be propagated. The grooves create a state of plane strain through the net section (induces brittle behaviour), and reduces that section which increases the stress intensity factor values locally. The combination of these two effects drives the crack to propagate along the desired plane (center of weld). Since the stress intensity factor value at the crack tip is higher than that of a plate without a reduced section (double-side grooves), and since the large-scale double tension test has an increasing stress intensity factor field for propagating cracks, the large-scale test with this crack starter method must be conducted under a temperature gradient. The remaining portion of this section presents the FEA and the test results for both crack starter methods.

3.3.2 Lateral Pre-Compression of the Weld

Based on the results from the CCA tests conducted by Fleet Technology Limited and others (commercial research for which complete references were not available), the weldments for two starter plate tests (*STP1* and *STP2*) were pre-compressed with hardened rollers using deformation control to the values of 10% and 15%.

Pictures of the test setup for the pre-compression of the weld and an end view of starter plate *STP2* with 15% pre-compression are shown in Figure 3.12(a) and (b), respectively. Although a significant portion of the strain energy density for the net section is used by pre-compression, the material surrounding this pre-compressed or plastic zone remains elastic and restrains the plastified material from lateral extension due to Poisson effect, placing a portion of this zone into residual compression across the potential crack face.

This residual pre-compression across the interface was verified by a nonlinear FEA of the pre-compression event on a quarter model of starter plate, weldment, and roller group as shown in Figure 3.13. The mesh density, the loading, and the boundary condition are also shown in this figure. Contact elements were used between the hardened roller and the weldment surfaces to provide the proper interaction between two as the roller was pushed into the plate. The von Mises strain and normal stresses across the potential crack face for a plate subject to 15% pre-compression are shown in detail in Figure 3.14 and 3.15 for the area bounded by dash line in Figure 3.13.

Figure 3.14 clearly shows a significant von Mises strain (strain energy density) which extends from the mid-thickness of the plate to the edge of the plate in the region of the last point of contact between the roller and the plate. This band does not lie along the

potential crack face and may cause the crack to diverge from the desired path. Figure 3.15 clearly illustrates the residual compression across the potential crack face through approximately 40% of the thickness extending from surface to the middle of the plate. Cracks do not propagate through residual compression zones. However, there are significant tensile normal stresses on the outside surface between the weld metal and parent plate. Brittle cracks may propagate along this interface if a crack runs into this zone.

Figure 3.12 Test Setup of Lateral Pre-Compression of Weld and the Lateral Deformation after the 15% Pre-Compression

The question still remains, whether or not, the effects of embrittlement outweigh the effects of residual compression producing an effective crack starter method. This can only be answered by test.

Figure 3.13 3-Dimensional FEA Model for Pre-Compression Indented by a Hardened Steel Roller

Figure 3.14 Normal Stress across the Potential Crack Face, 15% Pre-compression

Figure 3.15 von Mises Strain, 15% Pre-Compression

The dimensions of the starter plate specimen, the notch geometry, the lateral pre-compression and the location of the strain gauges are illustrated in Figure 3.16(a). The test specimen was installed in the 1700 kN Tinius Olsen testing machine as shown in Figure 3.16(b). The notch and the starter crack detail including the blunt and sharp cracks are shown in Figure 3.16(c). The instrumentation (strain gauges and thermocouples) was connected to the data acquisition system. The local temperature control chamber was installed and liquid nitrogen was pumped into the chamber to bring the steel to the design temperature.

For the starter plate *STP1*, with a 10% lateral pre-compression and initial temperature of -10°C , a crack could not be initiated even with a starter load of 900 kN. The test specimen was removed, laterally pre-compressed to 15% and re-tested at the temperature of -20°C . The ductile branching cracks propagated a very short distance out of the compression zone away from the tip of sharp crack at a load of 850 kN, as illustrated in Figure 3.17. This test was considered unsuccessful.

The second starter plate test *STP2* with a lateral pre-compression with 15% was tested at -40°C . The ductile branching cracks developed at a load of 831 kN and propagated right across the width of specimen along the heat-affected zone as shown in Figure 3.18. The crack evaded the compression zone and fractured through the region where significant normal tensile stresses and von Mises strains exist (not of the region of interest). The fracture surface was very irregular and was most likely affected by the microstructure of the weld metal and the variation in toughness of the material in the heat affected zone. This test was also considered unsuccessful and clearly indicates that the pre-compression is not a viable crack starter method.

Figure 3.16 Starter Plate Test Setup

Figure 3.17 Ductile Branching Crack – Starter Plate Test, *STP1*

Figure 3.18 Crack Location – Starter Plate Test, *STP2*

3.3.3 Double-Side Face Grooves

A three-dimensional solid FEA model was developed for starter plates with double-side face grooves and is shown in Figure 3.19. Elastic analyses were conducted for a starter load of 700 kN with varying crack lengths and two different groove depths, 3 mm and 5 mm, to evaluate the stress intensity factor as function of the crack propagation and the depth of groove. The stress intensity factor corresponding to the fracture load obtained from the tests give the initial crack toughness. At the end of the groove there is a transition zone in which the groove depth diminishes to zero.

Figure 3.19 Double-Side Face Groove Finite Element Model

Figure 3.20 Stress Intensity Factor versus Depth of Grooves

The stress intensity factor values were calculated using the displacement extrapolation method. The results of these analyses are illustrated in Figure 3.20 along with the comparable curves of the calculation for a full thickness starter plate without double-side face grooves. The transition length is illustrated by shaded vertical band. As illustrated, with increasing groove depths, the stress intensity factor value also increases, and maps onto the full thickness plate curve shortly after the transition zone. For starter plates with increasing depths of the double-side face grooves, the load required to initiate the cracks will be smaller (inversely proportional to the increase in the stress intensity factor) for any given temperature. The analyses also confirm that the material along the probable face is in a state of the triaxial tension.

Two starter plate tests *STP3* and *STP4* with 3 mm deep double-side face grooves, as illustrated in Figure 3.20, were conducted at temperatures of -42°C and -10°C , respectively. The test procedure was the same as that for the other starter plate tests. For *STP3*, a brittle crack was initiated at load of 403 kN and propagated approximately 80mm. This resulted in a relaxation of the load system and an apparent drop in the applied load. The load was then increased to 410 kN, at which the crack propagated completely through the main plate tab along the groove. The corresponding fracture surface is illustrated in Figure 3.21(a).

For *STP4*, as the specimen was loaded, the crack popping sounds were heard at 680 kN and 710 kN. At a load of 841 kN, the crack propagated through the main plate tab. As previously described in section 3.4.1, the double-side face grooves cause the material through the net section to become more brittle and forces the crack to propagate along the groove. The corresponding fracture surface is illustrated in Figure 3.21(b). Examination of the crack surfaces for both *STP3* and *STP4* revealed straight crack fronts with no apparent tunneling. The initial toughness associated with *STP3* and *STP4* are $77 \text{ MPa}\sqrt{\text{m}}$ and $159 \text{ MPa}\sqrt{\text{m}}$, respectively.

In conclusion, the double-side face grooves caused a brittle fracture through the net section and force the crack to propagate along the groove as intended. This crack starter method will be used for large-scale double tension tests. Based on this limited data, it is anticipated that the temperature of -20°C in the starter plate region for the double tension test will correspond to a crack-initiating load of approximately 700 kN. This load level should provide sufficient energy to propagate the crack into the main plate.

Figure 3.20 Side View of Double-Side Face Grooves

(a) Starter Plate Test, STP3

(b) Starter Plate Test, STP4

Figure 3.21 Crack Surfaces for Starter Plate

Chapter 4

Large Scale Double Tension Test Programme

4.1 Objective and Scope

The objectives of this thesis were to design the test apparatus for the large-scale double tension test specimen shown in Figure 4.1, to outline the testing procedure and to develop the instrumentation and analytical tools to determine the crack arrest toughness of weldments. As part of this thesis, one large-scale test was conducted to confirm the test design. Others will be tested at a later date (part of a ongoing research project), to complete a matrix of crack arrest toughness values for varying temperature and tensile stresses. In addition, a series of finite element analyses were conducted on 3-dimensional solid model of the large-scale double tension test with double-side grooves to determine:

- the stress intensity factor curves (evaluated using the displacement extrapolation method) as a function of the crack length, the starter load and the main plate tensile load. These results will be used subsequently to determine both the initial crack toughness and the crack arrest toughness of the weld metal, and,
- the crack load sequence for the starter and the main plate load that minimizes the shear stress between the starter plate and the main plate.

Details of the test apparatus, the instrumentation, the test procedure, the discussion of the interpretation of the results of the first prototype large-scale test and the discussions of all corresponding analyses are given in the following sections.

Figure 4.1 Large-Scale Double Tension Test Specimen with Double-Side Grooves

4.2 Stress Intensity Factor Curves and Data Interpretation

A series of elastic analyses were performed using the finite element analysis program, ANSYS 5.4, to determine the stress intensity factor curves as a function of the crack length, the starter load and the main plate load, for the large-scale double tension test specimen in Figure 4.1. The corresponding 3-dimensional solid FEA model of half of the specimen taken about the line of symmetry consists of 11490 elements and 14630 nodes, and is illustrated in Figure 4.2. SOLID45 elements were used for both the parent steel plate and for the weld metal. A description of the SOLID45 element's characteristics is given in Table 4.1

Table 4.1 SOLID45 Element Description

Element Geometry	Element Characteristics
<ul style="list-style-type: none"> • 8 Corner nodes • 3D Space • DOF: Translations in x, y, and z-Directions 	<p>SOLID45</p> <ul style="list-style-type: none"> • Models three-dimensional solid structures; • The element has plasticity, large strain, and stress-stiffening capabilities; • Steel and weld characteristics are modelled by Young's modulus and Poisson's ratio.

The boundary conditions, the loading and the elastic material properties are summarized in Figure 4.3. The test load will be introduced and taken out of the main plate through four pins in a thickened section at the either end of the specimen. To verify that this loading could be modeled by uniform load across the end of the specimen without changing internal force distribution along the weld, FE analyses were conducted

on the full-section for both sections. As anticipated no differences were found, hence the simpler loading case was used for the main plate and is illustrated in Figure 4.3. The load distributed on the starter plate approximates the pin-load on the hole and is statically equivalent to the starter plate load. Along the line of symmetry, the nodes were restrained from the displacement in the y -direction. Three additional nodes, as indicated in Figure 4.3, were restrained from the displacement in the x and z -directions to restrict rigid body rotations without restricting deformation along the line of symmetry.

For this particular example, a series of FEA were conducted with the anticipated starter load of 700 kN required to initiate the crack in conjunction with four different main loads which give normal tensile stress in main plate equal to $0.0\sigma_y$, $0.25\sigma_y$, $0.4\sigma_y$, $0.5\sigma_y$, $0.625\sigma_y$ where σ_y is specified as yield stress of parent main plate steel. For each combination of the starter load and the main plate load, a series of analyses were conducted releasing the y -direction displacement restraint of the nodes along the potential crack face simulating the crack propagation. For each of these analyses, the displacement method, as described in section 2.2.3, was used to calculate the stress intensity factor. The results of this series of analysis give the set of stress intensity factor curves illustrated Figure 4.4. Each curve required 17 analyses. Also shown on this figure are the locations of the crack tip, the gap plate section, the start of the main plate, the transition zone, and the end of the double-side face grooves.

The initial stress intensity factor for this group of curves ranges from $142 \text{ MPa}\sqrt{m}$ to $150 \text{ MPa}\sqrt{m}$, which is in the anticipated range of the crack initiation toughness of a starter plate with a temperature of -20°C as interpolated from starter plate *STP3* and *STP4*.

(a) Dimension and Mesh of Large-Scale Specimen

(b) Detail Illustrating Elements through the Thickness in the Groove

Figure 4.2 FEA Model for Large-Scale Test Specimen with Face Grooves

Material Properties <ul style="list-style-type: none"> Elastic material properties for steel and weld metal $E_s = 200500 \text{ MPa}$ $E_w = 210000 \text{ MPa}$ $\nu = 0.286$ 	Model Properties <ul style="list-style-type: none"> Number of Nodes = 14630 Number of Element = 11490
Loading <ul style="list-style-type: none"> Uniformly distributed load across the end of specimen as shown above Equivalent distributed pin-load as shown in detail above 	Boundary Condition <ul style="list-style-type: none"> y-direction constraints across the centerline of weld x and z-direction constraints on point 'a' and z-direction constraint on point 'b'

Figure 4.3 Details of FEA Model for Large-Scale Test Specimen

Figure 4.4 Stress Intensity Factor vs Crack Propagation

Because of the double-side grooves, all curves show an increasing stress intensity factor as the crack propagates through the starter plate into the main plate, and have slopes greater than any other portion of the curve. With the exception of the two curves associated with no load in the main plate and the curve with a tensile normal stress of $0.25\sigma_{sy}$, the others show an increasing stress intensity factor field as the crack propagates through the main plate.

There are only two distinct sets of testing conditions in which the cracks can be arrested in the main plate. The first set involves tests conducted under isothermal conditions in which the crack arrest toughness value is constant as illustrated by the horizontal dashed line in Figure 4.5(a). At a starter plate load of approximately 700 kN, the stress intensity factor at the crack tip exceeds the crack arrest toughness and the crack propagates until the stress intensity factor curve falls below the crack arrest toughness value as indicated by point 'a' on the stress intensity factor curve for a main plate load. The magnitude of the crack arrest toughness value will be equal to the stress intensity factor value for the measured crack length, which is located at point 'a'.

The second set of test conditions involve the tests in which the test specimen is subjected to a temperature gradient (the starter plate to the main plate) as shown in Figure 4.5(b). The corresponding crack arrest toughness curves can be drawn and overlayed (dashed line) on the stress intensity factor curves as indicated in Figure 4.5(b). The shape of this curve for a temperature greater than 0°C has to be defined, and is shown in the figure as an extrapolation of known data. The points on this portion of the curve can only be established by tests. For example, a test with a main load of $0.5\sigma_y$ is conducted with a temperature gradient curve and stress intensity factor curve, shown in Figure 4.5.

Figure 4.5 Data Interpretation and Design

A starter plate load 700 kN initiates the crack and propagates into the main plate to a distance that coincides with a point in which the calculated stress intensity factor curve falls below the crack arrest toughness value of material as indicated by point 'b'. Crack arrest toughness values and temperatures can be estimated from graphs (a) and (b) for a given crack length.

4.3 Large-Scale Double Tension Tests

4.3.1 Test Specimen Description

Seven large-scale double tension test specimens, as illustrated in Figure 4.1, were flame cut, welded and machined by Fleet Technology Limited (FTL). Only one of these was tested as part of this thesis. The specimens were cut from the parent plate material of ship steel with the rolling direction coinciding with long dimension of the test specimen. The full penetration groove weld was made, according to the description in section 3.2.1, along the line of symmetry of test specimen. For clarity, the general locations for both thermocouples and strain gauges are shown without dimensions and identification numbers. The notch geometry and double-side grooves for the large-scale double tension tests are identical to that which was developed by starter plate tests, and are shown in Figure 4.1.

4.3.2 Test Set-Up

The schematic diagram of the test specimen in the load frame along with the 500T and 200T hydraulic actuators, the end restraints, the load plates, the high-strength rods,

the distributed beams, the couplers and the turn buckle are illustrated in Figure 4.6. The instrumentation, the temperature control chamber and the data acquisition systems are not shown for clarity. A complete set of the design drawings for these elements is given in Appendix A.

The 200T and 500T actuators can be controlled independently of each other and displaced by load control or stroke control. The starter load is applied by the 200T actuator on the top of the stiffened distributing beam through another series of distributing beams, high-strength plates and pins to the starter plate. This mechanism is self-aligning and ensures that the load is applied vertically and parallel to the length of the test specimen. The remaining components consisting of a stiff transition plate, a turnbuckle and a base plate-fixture to transmit the force from the starter plate to the strong floor. The 500T actuator is used to apply a uniform tensile normal stress to the main plate. Through a coupler, and stiff transition plate and four pins to the test specimen. Pins are also used to transmit the reaction force to the main base plate and then to the strong floor. Both sets of pins have been aligned vertically and horizontally to ensure that the load is transmitted into the main plate with out bending about either principle axis of its cross-section. An assembled view of the test specimen with the temperature control chamber is shown in Figure 4.7.

Figure 4.8 illustrates a section view of the temperature control chamber. A 25 mm thick section of Styrofoam is used as an internal insulation to separate chamber 1 and chamber 2. Two independent liquid nitrogen distribution pipes were used to distribute the liquid nitrogen uniformly in each chamber. The outlet holes are 3 mm in diameter and are located uniformly along the pipe at 30 mm. Each pipe is fed from a separate liquid

nitrogen tank with its own temperature pressure control valve so that the temperatures in each chamber can be controlled independently.

Figure 4.6 Schematic Diagram of the Double Tension Test In Load Frame

Figure 4.7 Assemble View of Large-Scale Test

Figure 4.8 Section View of the Temperature Control Chamber

4.3.3 Instrumentation and Measurement

Two different data acquisition systems were used to measure the applied load, the strains and the temperatures. The loads, the strains and the temperatures were determined by the pressure transducers, 13 strain gauges and 30 thermocouples with locations and identification numbers illustrated in Figure 4.9 (photograph of specimen with thermocouples, strain gauges and cooling pipes) and 4.10.

The high speed *GaugeScope* data acquisition has six channels and is used to measure the two loads and the strain response from four strain gauges with numbers 1 to 4. The system is set to record 45000 readings over the period of 0.25 of a second when

one of strain gauges is triggered by a $392\ \mu\epsilon$ drop that results from the strain release due to a crack propagation event. Strain gauge number 1 is the trigger gauge.

The nine strain gauges (numbers 4 to 13) have been located at a distance of 45mm mm from the centerline of the weld to measure the strains. This series of strains gives a distribution across the width of the main plate, which can be used to estimate the crack length. Figure 4.11 illustrates a typical series of strain distributions for initial condition and for different crack propagation lengths.

Figure 4.9 Thermal Couples, Strain Gauges and Cooling Pipes

Figure 4.10 Location and Identification of Strain Gauges and Thermal Couples

(a) Strain Distribution without Crack Initiation

(b) Strain Distribution with Crack just Entering the Main Plate

(c) Strain Distribution with Crack Reaching the end of Face Groove

(d) Strain Distribution with Crack Propagate 100mm into Main Plate

Figure 4.11 Strain Distributions for Varying Crack Lengths

4.3.4 Measurement of Temperature Gradients

A series of temperature gradients were measured prior to conducting the first large-scale test to establish the effectiveness of the internal insulation barrier and to ensure that the temperature in both chambers can be controlled and repeated. Each of three temperature gradient curves associated with temperatures of -20°C to 0°C , -20°C to -10°C and -10°C to 10°C in chamber 1 and 2 respectively are illustrated in Figure 4.12. The temperature gradient curves were very stable and had a gradient which extended approximately 150 mm from the crack tip into the main plate. The internal insulation barrier effectively isolated the two chambers with a significant temperature drop from one side to the other.

4.3.5 Large-Scale Double Tension Test and Discussion

The first large-scale double tension test *LSP1* with double-side face grooves and a 15 mm long initial crack (10 mm blunt saw cut and 5 mm sharp saw cut) was tested with temperature of -20°C and 10°C for the starter plate and the main plate, respectively.

Once these temperatures were stable (about 2 to 3 hours of cooling), the load was applied in the following sequence. With the starter plate disconnected, 3000 kN was applied to the main plate. The starter plate was then connected and made fast with the turnbuckle and then the starter plate load was applied. At a magnitude of 740 kN, a brittle crack propagated approximately 15 mm along the weldment. The starter plate load was then increased and a brittle shear failure occurred at 800 kN. The resulting fracture is illustrated in Figure 4.13(a) and (b).

Figure 4.12 Temperature Gradient Curves

(a) Side View of Crack Propagation

(b) Brittle Crack Surface

Figure 4.13 Brittle Crack Propagation

The deviation of the fracture from its initial path through to the gap was a result of excessive localized shear that was induced by differential shear and is a function of loading sequence. The displacement along the length of the test specimen and the corresponding shear stress associated with the initial main load and the subsequently applied starter load up to 700 kN are shown in Figures 4.14(a), (b). The figure clearly illustrates that shear distortion between the starter plate and the main plate, and the large shear stress (equal to or greater than shear yield) in the fracture region. As a result, crack arrest toughness can not be calculated.

4.3.6 Modified Load Sequence

Recognizing this failure mode and verifying its occurrence analytically resulted in a re-definition of the load sequence to minimize the shear distortion along the length of the weldment and the shear stresses in the gap plate section associated with the failure of the first specimen. After alignment of the test specimen, connection of the data acquisition, and establishment of the ambient temperature for both the starter plate and the main plate, the first load step is to make the specimen fast with all the connections in the load reaction systems. The second load step is to apply a small initial contact starter load and main load in proportion to the relative stiffness for both the starter plate and the main plate. The remaining load increments, which bring the starter load and main load to their target values, will be applied in the same ratio. If the crack is not initiated, then additional load can be applied to the starter plate alone. This small increment in the starter load should have little effect in increasing the shear stresses in the region where the first specimen failed. The load sequence is summarized in Table 4.2 and the

corresponding displacements and shear stress are shown in Figure 4.15 and 4.16, respectively.

This load sequence will be used for other large-scale double tension test that will be conducted as part of future work in a continuing study.

Table 4.2 Applied Load for Each Load Step

Load Steps	Applied Load (kN)	Total Load (kN)
1	10	50
2	100	500
3	200	1000
4	300	1500
5	450	2000
6	600	2500
7	700	3000
8	840	3000

Load Step 1: Main load = 3000 kN Starter load unconnected	Load Step 2: Main load = 3000 kN Starter load = 700 kN
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Figure 4.14 Contour Diagrams for Test Load Step

Figure 4.15 Contour Diagrams for Displacement in the y-Direction

Step 5: Main load = 2000 kN Starter load = 450 kN	Step 6: Main load = 2500 kN Starter load = 600 kN	Step 7: Main load = 3000 kN Starter load = 700 kN	Step 8: Main load = 3000 kN Starter load = 840 kN
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Figure 4.15 Contour Diagrams for Displacement in the y-Direction (Cont'd)

Figure 4.16 Contour Diagrams for Shear Stresses across the Gap Plate Section

Figure 4.16 Contour Diagrams for Shear Stresses across the Gap Plate Section (Cont'd)

Chapter 5

Summary, Conclusions, and Future Work

5.1 Summary

Since flaws are always likely to exist, then brittle fractures will continue to occur in welded structures under temperatures and loading conditions that produce unstable crack growth. Consequently, it is important for engineers to be able to characterize the toughness accurately and then to provide steel and weldments with sufficient toughness to prevent crack propagation. The toughness values determined from large-scale tests are most representative of real details and structures. These tests are not always possible nor economical, hence it is important to determine the relationship between toughness values determined from small-scale tests and those obtained from large-scale tests. This then will allow engineers to conduct relatively inexpensive small-scale tests to obtain toughness data that can be used for the design and crack arrest toughness assessment of real structures.

A description of all known small-scale and large-scale tests that have been developed to determine crack arrest toughness values are given in Chapter 2. From the small-scale test series, the CCA is considered to be the most reliable and has been standardized as ASTM E1221-88/96. As a result, this test method was selected for this investigation. Twenty-two small-scale CCA tests were conducted by FTL to

characterize the crack arrest toughness of a typical weldment for ship structures. These tests were conducted with different geometry as defined by CTOD tests and, with different crack starters for a series temperatures according to ASTM E1221-88/96. Six were considered to be valid and gave average crack arrest toughness values at -10°C and 0°C of $90.6 \text{ MPa}\sqrt{m}$ and $107.7 \text{ MPa}\sqrt{m}$, respectively.

Four starter plate tests of the same geometry, steel and welds that were used for the large-scale double tension tests were conducted to obtain the conditions and notch geometry required to propagate a crack across the full width. Two of these were tested with crack starter details that involved lateral pre-compression and strain aging. This method proved to be unsuccessful since the pre-compression placed the material across the potential crack path into residual compression. This was verified by the corresponding finite element analysis. The starter plate test with double-side grooves proved successful and bounded the starter load and temperature ranges required to successfully initiate a crack propagation event.

Chapter 4 describes the test apparatus, test specimen, instrumentation, test procedure and the method for evaluating test data for the large-scale double tension test that was developed to obtain crack arrest toughness values for weldments subject to varying temperature and tensile stresses. Based on the prototype test in which the gap plate failed in shear, a new load sequence was determined analytically. The load sequence describes the application of starter and main plate loads such that the target loads are achieved while minimizing the shear across the gap plate and promoting crack growth along the desired crack path (through the net section between the double-side grooves).

5.2 Conclusions

Based on the information presented in the literature, the test data and the results of the numerical investigations presented, it can be concluded that:

- The small-scale CCA tests are more qualitative than quantitative since there is a significant scatter in the crack arrest toughness data. The magnitude of the scatter may be attributed to indirect loading, non-uniform tensile fields and material variability associated with the weld. These values should be calibrated with large-scale tests.
- The ratios of the stress intensity factor calculated using the displacement extrapolation method (based on the displacement of modes in the region of the crack tip as determined by FEA), to that determined by classic methods for a single-edge-crack and a center-crack with semi-infinitely wide plates and uniform tensile stress field are 0.991 and 1.062, respectively. The displacement extrapolation method gives the best estimate of stress intensity factor of the three methods investigated.
- Six valid CCA tests were conducted with crack starter conditions consisting of either brittle weld beads (Foxdur 350 or Foxdur 500) or through thickness compression with “strain aging”.
- The average values crack arrest toughness at -10°C and 0°C , evaluated using the empirical relationship given in ASTM Standard E1221-88/96 are $90.6 \text{ MPa}\sqrt{m}$ and $107.7 \text{ MPa}\sqrt{m}$, respectively.

- The ratios of the average crack arrest toughness determined by displacement extrapolation method to that determined from ASTM E1221-88/96, are 1.387 and 1.291 for -10°C and 0°C , respectively.
- Lateral compression of the weld to “embrittle” the region around the crack as a crack starter method was ineffective, as there was residual compression across the potential crack path.
- Double-side face grooves in starter plate test proved to be an effective crack starter method. These grooves enhance the embrittlement by creating a state of plane or triaxial tensile stress along the potential crack path. The groove also directs the crack along the desired crack path.
- The initial toughness for the start plate with double-side grooves for temperature of -40°C and -10°C were determined to be $77 \text{ MPa}\sqrt{m}$ and $159 \text{ MPa}\sqrt{m}$, respectively.
- Based on the measured crack length and stress intensity factor curve for a given starter and main load, both the initial toughness and crack arrest toughness can be determined for the large-scale double tension test subjected to either isothermal or temperature gradient conditions.
- Based on the results of FEA on the large-scale double tension test specimen, it was determined that the normal strain distribution across the welds of the main plate gives a good measure of crack length.
- The prototype large-scale double tension test failed by a brittle shear failure through the gap plate section, which led to a modified load

procedure to minimize shear distortion across the gap. It is anticipated that the cracks for subsequent tests will propagate along the desired path.

5.3 Recommendations and Future Work

The future work involves the completion of six more large-scale double tension tests with varying magnitude of main plate loads (given a function of the yield stress for the main plate) and temperatures. The stress intensity factor curve for each particular test condition will be calculated using the displacement extrapolation method. For each test, the crack length will be measured. The crack arrest toughness value is equal to the stress intensity factor at the tip of the arrested crack.

Subsequent to completing this series of tests, a comparison can be made with the crack arrest values derived by the same analytical means for the CCA tests. This entire series, including both small-scale and large-scale tests, needs to be conducted for other materials, to broaden the data base and to confirm the correlation between crack arrest toughness values obtained from the either method.

References

Anderson, T.L. 1995. **Fracture Mechanics – Fundamentals and Applications**, Second Edition. CRC Press Inc.

ANSYS. 1998. **Release 5.4, ANSYS Analysis Guides**. ANSYS. Inc., Houston, Pennsylvania, USA

ANSYS. 1998. **Release 5.4, ANSYS Elements Manual**. ANSYS. Inc., Houston, Pennsylvania, USA

ANSYS. 1998. **Release 5.4, ANSYS Theory Manual**. ANSYS. Inc., Houston, Pennsylvania, USA

ASTM E1221-96. 1996. **Standard Test Method for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia} , of Ferritic Steels**. American Society of Testing and Materials.

ASTM E208-95a. 1996. **Standard Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels**. American Society of Testing and Materials. pp. 293.

ASTM E23-96. 1996. **Standard Test Methods for Notch Bar Impact Testing of Metallic Materials**. American Society of Testing and Materials. pp. 136.

ASTM E604-83. 1996. **Standard Test Method for Dynamic Tear Testing of Metallic Materials**. American Society of Testing and Materials. pp. 512.

Barsom, John M. & T.Rolfe, Stanley 1987. **Fracture and Fatigue Control in structures**. Second Edition. Prentice-Hall, Inc.

Bonenberger, R. J. 1994. **Development of a Chevron-Notch Crack-Arrest Specimen**. A Bell & Howell Company

Broek, David 1987. **Elementary Engineering Fracture Mechanics**. Fourth Edition. Kluwer Academic Publishers.

Chan, S.K., Tuba, I.S. and Wilson, W.K., 1970. **On the finite element method in linear fracture mechanics**, Eng. Fract. Mech., 2 pp.61-79.

Crosley, P.B. and Ripling, E.J. 1990. A Quality Control Test for Selecting Materials to Arrest Fast-Running, Full-Thickness Cracks. *Journal of Testing and Evaluation*, Vol. 18, No. 6, Nov. pp. 396-400.

Crosley, P.B. and Ripling, E.J. 1969. Dynamic Fracture Toughness of A533 Steel. *Journal of Basic Engineering*, September, pp. 525.

Crosley, P.B. and Ripling, E.J. 1975. Plane Strain Crack Arrest Characterization of Steels. *Journal of Pressure Vessel Technology*, November. pp. 291.

Crosley, P.B. and Ripling, E.J. 1980. A Compact Specimen for Plane Strain Crack Arrest Toughness Testing. *Journal of Testing and Evaluation*. Vol. 8, Jan. pp. 25-31.

Granville, B.A. 1994. Short Crack Arrest Tests – Analysis and Discussion. Contract 003SQ.23440-1-9202, March, pp.26

Granville, B.A. 1989. Evaluation of Short Crack Arrest Test Techniques. Contract 003SQ.23440-1-9202, June, pp.23

Granville, B.A. 1993. Development of Crack Arrest Approaches to Material Specification. Contract 003SQ.23440-1-9202, March, pp.34

Hahn, G.T., Hoagland, R.G., Kanninen, M.F. and Rosenfield, A.R. 1975. Crack Arrest in Steels. *Engineering Fracture Mechanics*, Vol. 7 pp. 583-591.

Kanninen, M.F. 1974. Adynamic Analysis of Unstable Crack Propagation and Arrest in the DCB Test Specimen. *International Journal of Fracture*. Vol. 10, No.3, September, pp. 415.

Lay M.G., 1982. *Structural Steel Fundamentals*. Australian Research Board.

Murakami, Y., 1987. *Stress Intensity Factor Handbook*, Pergamon Press.

Ship Structure Committee, 1976. A Study of Ship Hull Crack Arrest System., U.S. Coast Guard Headquarters, Washington D.C. Report No. SSC-265.

Wiesner, C.S. and Hayes, B. 1984 A Review of Crack Arrest Tests, Models and Applications. TWI, UK.

Appendix A

Design Drawings for the Load and Reaction Test Apparatus for the Large Scale Double Tension Tests

A.1 Formal Design Drawings for Large-Scale Test

A complete set of fabrication drawings for the load and reaction apparatus is given in this appendix. These have been designed for starter and main plate loads of 1200 kN and 3500 kN, respectively. All parts are fabricated from CANAM MANAC Group and machined by Science Technology Center (STC) at Carleton University.

Figure A1 illustrates an assembly view of the reaction transition fixture associated with starter load and main load. The details of each parts are illustrated in Figure A2 and A3 respectively. Parts SP6, SP7 and SP8 shown in these figures are designed to carry 1200 kN. Parts SP3 and SP5 are designed to transfer 3500 kN.

Figure A4 illustrates the connection between the stiff transition plate and the top of the test specimen. Fabricating details and dimensions of SP1 and SP3 are illustrated in Figure A5.

Figure A6 and A7 show the two views of the starter load test assembly from the actuator to the starter plate. The high-strength pin and rod dimensions and identification numbers are given in Figure A8. All machining and weld details are

given in these figures. As assembly view of test frame with the large-scale double tension test specimen is illustrated in Figure 1.2.

Figure A1 Assembled View of the Base Plate

Figure A3 Dimensions, Machining and Welding Details of Stiff Transition Plates

Figure A4 Assembled View of the 500T Fixture on the Top of the Specimen

Figure A5 Dimensions, Machining and Welding Details of Stiff Transition Plate

Figure A7 Distributing Beams - DB1 and DB2