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Structural steel crack propagation experimental and numerical analysis

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Abstract

This paper presents an investigation on the crack propagation testing for three grades of structural steel material. The methodology uses experimental analysis with a test setup based on the ASTM E647 standard and a compact tension (CT) test piece, and, finite element analyses (FEA) for crack propagation based on the ANSYS separating, morphing and adaptive remeshing (SMART) tool. The FEA CT modelling is first used to develop front face compliance functions to relate the crack mouth opening displacement (CMOD) to the crack length. A set of CT test pieces were manufactured and then cyclically loaded on an Instron 8801 load frame and CMOD was measured against number of cycles. The steel material fracture mechanics based fatigue property was then estimated giving the crack growth rates for the Paris Law. The FEA models were then updated with the measured Paris Law coefficients and a SMART fatigue analysis was performed numerically and compared with the experimental results. The study showed that a hybrid numerical experimental methodology can be used to estimate fatigue crack growth material properties successfully with reasonable accuracy in a controlled laboratory environment.

Keywords: structural steel; crack propagation; experimental numerical.

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1. Introduction

The selection of material for heavy industrial equipment design is critical in ensuring the structural integrity of the structures for the whole design life. Researchers study the material properties in depth, for example Igwemezie et al. for a wind turbine structure in order to ensure the selected materials are suitable when structures are subjected to variable loads and in challenging environments. Design assessments are required to ensure structural integrity. In order to understand the fatigue & fracture response of a structural design, reliable material property knowledge is essential. Additionally, equipment fatigue crack propagation and failure scenarios may need to be simulated which rely on accurate material data. For most heavy industrial equipment structural steels of various grades, such as defined in BS EN 10025 Hot rolled products of structural steels, is of relevance here. The BS EN 10025 Part 2: Technical delivery conditions for non-alloy structural steels define the minimum yield strength, tensile strength and impact energy requirements etc., however fatigue and fracture properties need further research.

The generation of specific material property data such as crack propagation rates for the purpose of simulation of structures under cyclic loading can be very costly. Fageehi et al. and Kumar et al. investigated the use of compact tension test piece experiments with analytical and numerical methods in order to estimate fatigue fracture material properties and the structural response. The use of compact tension test pieces is previously studied in depth and discussed in texts such as by Dowling as well as in the relevant standards such as in the ASTM E1820 & E647. The analytical expressions defining the CT stress intensity factors was previously developed by Srawley et al. The precision measurement of crack growth rates were also previously developed, such as by Yoder et al. for a front face compliance method and by Newman et al. for a back face compliance method. Recent study by Bain investigated the use of finite element analysis and crack propagation analysis to refine the material property measurement methodology.

This paper focuses on various grades of structural steel crack propagation rate experimental and numerical evaluation based on the compact tension test piece and the ASTM E647 standard. The Ansys Workbench Mechanical SMART (separating, morphing, adaptive, remeshing tool) fracture mechanics finite element analysis technology is initially used with estimated material properties. The CMOD (crack mouth opening displacement) gauge measurements from FEA results are related to the crack length based on the compliance of the test piece. Experimental crack propagations are performed with three grades of structural steel and the fatigue fracture material properties are evaluated in a hybrid numerical experimental methodology. The evaluated material properties were used in the crack propagation numerical analysis and results compared with experimental measurements.

Nomenclature

a	crack length
CT	compact tension (test piece)
B	thickness (for CT test piece)
W	width (for CT test piece)
α	crack length non-dimensional parameter (a/W)
ϕ	CT test piece pin diameter
CMOD	crack mouth open displacement (v)
FEA	finite element analysis
K, ΔK	stress intensity factor, range of stress intensity factor
N	number of cycles
P, ΔP	applied load, range of applied load
R	load ratio

2. Experimental and numerical methodology

This investigation combines experimental and numerical methodologies to predict material fracture fatigue crack growth property. The experimental section measures the crack propagation rate for three grades of steel using the compact tension test piece and the front face compliance based crack length estimation. The relationship between the crack mouth opening displacement (CMOD) and the crack length a is defined using a fifth order polynomial and initially the polynomial coefficients are obtained from the ASTM E647 standard. In the numerical section of this study the finite element model of the compact tension test piece is developed and the Ansys Workbench Mechanical SMART fatigue crack propagation tool is used to relate the crack length in the 3D FEA model to the CMOD based on estimated Paris Law coefficients: m & C as shown in Equation (1).

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

The grades of structural steel selected for this study are identified here based on their nominal yield strength: 235MPa, 275MPa and 355MPa. The compact tension (CT) testing experimental data for the three grades of steel were post processed to obtain the da/dN vs ΔK , and their crack growth material property for the Paris Law m & C were estimated based on a logarithmic regression analysis. Ansys SMART FEA tool is then used again to simulate the crack propagation on the compact tension test piece based on the experimental & numerically obtained material properties comparing the experimental crack growth vs the numerical simulation of crack growth.

3. Experimental crack growth analysis

This study used compact tension test piece designs for the experimental crack growth analysis with a procedure similar to specified in the ASTM E647. The selected grades of structural steel plates of 12 or 15mm thickness are first waterjet cut and CNC machined to the required compact tension (CT) test piece design. The main dimensions for the CT test piece were: W=40mm, and B=10mm. The initial notch for a_i=10mm was electric discharge machined. An Instron 8801, 100kN load frame is setup as shown in Figure 1 (a) and used to apply a cyclic load with a mean load of 4.5kN and a load amplitude of 4.5kN. The knife edge with a thickness t=3.8mm is attached on the front face of the CT test piece for a CMOD gauge with a gauge length of 10mm as shown in Figure 1 (b). The load was cycled at 20Hz and the Instron system acquired the CMOD data together with load, position, number of cycles. The load range applied was $\Delta P = P_{max} - P_{min}$ = 9kN. The load R ratio (P_{min}/P_{max}) was zero and a constant-force-amplitude test procedure for $da/dN > 10^{-8}$ m/cycle was used. A fractured CT test piece is shown in Figure 1 (c) after the displacement limits specified on the Instron load frame is reached.

The main output from the experimental study for each steel material grade was da/dN (or $\Delta a/\Delta N$) fatigue crack growth rate which was related to the stress intensity factor range $\Delta K = K_{max} - K_{min}$. The crack length estimation was based on the front face compliance method that is discussed in the next section. The experimental evaluation of the Paris Law coefficients m and C is achieved with a best-fit straight line from a regression analysis of log(da/dN) vs log(ΔK).

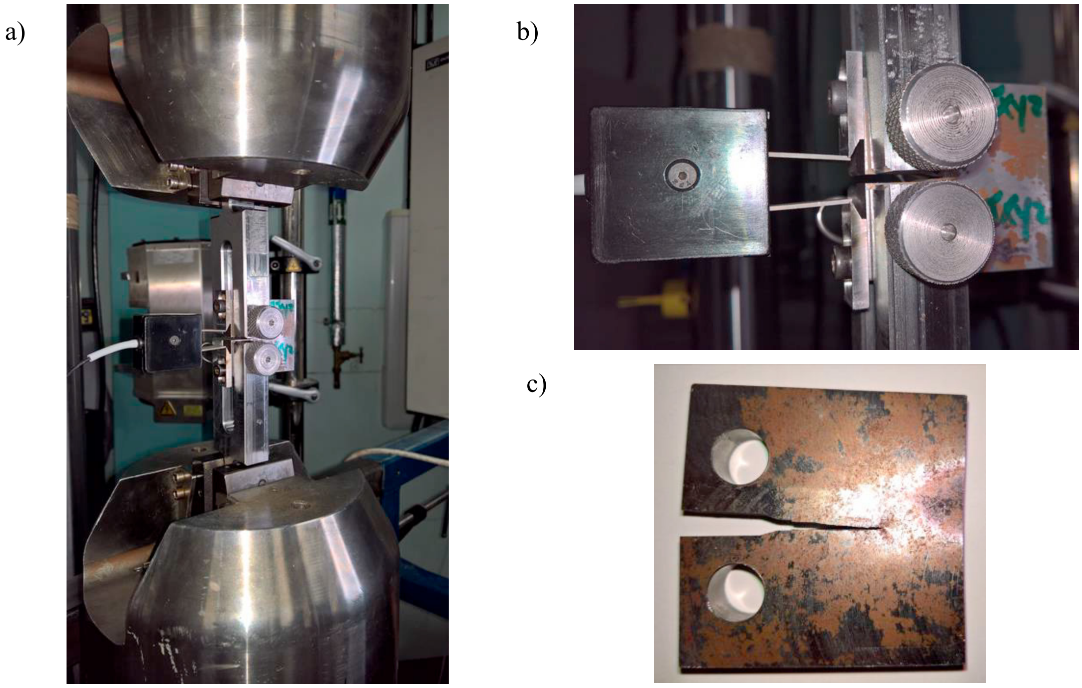

Fig. 1. (a) CT test piece assembly on the Instron 8801 grips; (b) CMOD gauge attached to the knife edges; (c) fractured CT test piece.

4. Numerical finite element crack growth analysis

4.1. Front face compliance method for crack length estimation

The first part of the numerical analysis was to investigate the front face compliance method for the CT test piece geometry and the experimental setup being used in this study. ASTM E647 gives the normalized crack size α as a function of plane stress elastic compliance for CT specimens. The fifth order polynomial function coefficients C_0 to C_5 as given in Equation (2) below are defined based on the measurement location of the crack mouth opening as shown in Fig. 2 below. The labels v_{x1}, v_0, v_1 and v_{LL} identify typical locations of CMOD measurements and for the present study the knife edge thickness of 3.8mm for location v_{x1} was used.

$$\alpha = a / W = C_0 + C_1 u_x + C_2 u_x^2 + C_3 u_x^3 + C_4 u_x^4 + C_5 u_x^5 \tag{2}$$

The CMOD measurement v at location v_{x1} is then used to evaluate u_x using Equation (3) below:

$$u_x = \left\{ \left(\frac{EvB}{P} \right)^{1/2} + 1 \right\}^{-1} \tag{3}$$

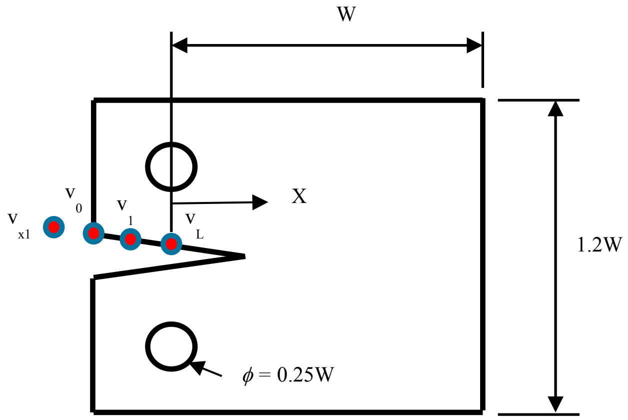

Fig. 2. CT test piece CMOD measurement locations.

The calculated u_x values can then be used in Equation (2) in order to estimate α and hence the crack length a. In order to evaluate the coefficients C_0 to C_5 for the particular CT geometry being used in this study, a linear elastic static finite element model including a fracture model was developed. Figure 3 (a) below shows the ANSYS Workbench DesignModeler 3D half-symmetric solid representation of the CT test piece (W=40mm) with a notch, and a surface body to create an initial crack length of 11mm. The finite element mesh shown in Figure 3 (b) is refined around the crack front using the sphere of influence tool and the automatic tetrahedral mesh generation using the Ansys Workbench Mechanical Fracture Mechanics tool. The load boundary conditions are specified as shown in Figure 3 (c) as bearing loads on the pin locations in opposing directions and the displacement boundary conditions are specified so that rigid body motions are avoided without over constraining the model.

The ANSYS fracture mechanics tool fatigue option allows crack propagation using the SMART method and the Paris Law material properties m and C, initially defined based on estimates from the literature. The iterative solution estimates the stress intensity factor K on the crack front, calculates the crack growth for a specified crack extension amount, adaptively remeshes the fracture model and solves until a limit in crack size or a geometry boundary is reached. The crack length, number of cycles N and the stress intensity factor K etc. can then be postprocessed. In this investigation the crack mouth opening displacement is also tracked and a relationship between crack length is defined as a polynomial function similar to the ASTM E647 approach.

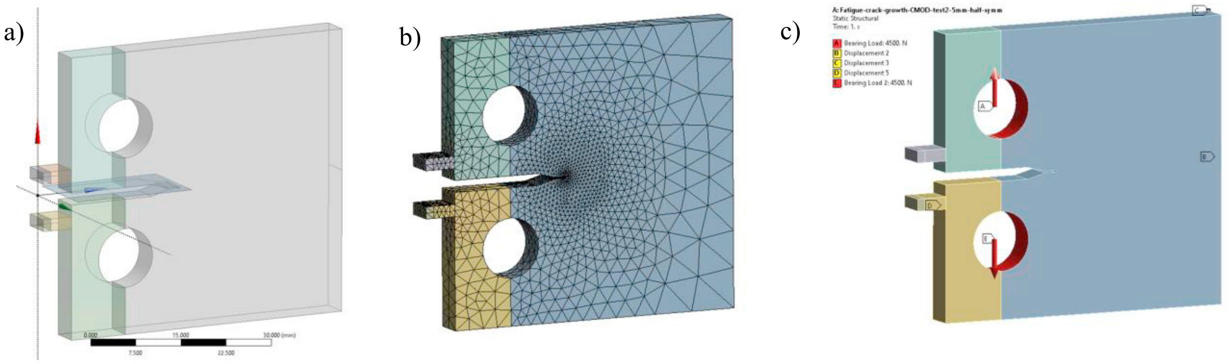

Fig. 3. (a) finite element solid model with crack plane; (b) meshed geometry; (c) load and displacement boundary conditions.

4.2. FEA numerical CT tests for specific structural steel material grades

The relationship between the CMOD and crack length is first established for the specific CT geometry and knife edge location as defined in Section 4.1. The experimental CMOD gauge data from the Instron cyclic load crack growth tests are then postprocessed which allows the estimation of crack length *a* and the crack growth rate *da/dN*. The stress intensity range of *ΔK* is also calculated based on Equation (4).

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} \left(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4\right) \tag{4}$$

The next step in the process for estimating the specific material Paris Law properties is to perform a regression analysis of the logarithmic *da/dN* vs *ΔK* data. This is repeated for the specific grades of steel experimental data as required. The Paris Law material data are then entered in the ANSYS material database and the crack growth finite element analysis is repeated. The output from the numerical analysis, such as the crack length *a* vs number of cycles *N* is then compared against the experimental values.

5. Results and discussion

The ANSYS Workbench Mechanical SMART CT test piece numerical analysis was first used to establish the front face compliance relationship. The deformation probe on the FEA model tracked the displacement of the knife edge position as the crack propagated as shown in Figure 4 (a) below. This data is then used to evaluate the CMOD vs non-dimensional crack length parameter α. The fifth order polynomial curve fits relating u_x to a for 3D FEA and ASTM E647 is shown in Figure 4 (b). The polynomial coefficients obtained from the 3D FEA based compliance function to the ASTM E647 plane stress based compliance function are compared in Table 1 below. The difference between the plane stress approximation and 3D FEA analysis is relatively small for this CT test piece geometry, however the methodology given here can be used to establish compliance relationships when geometry and knife edge positions differ from the standard.

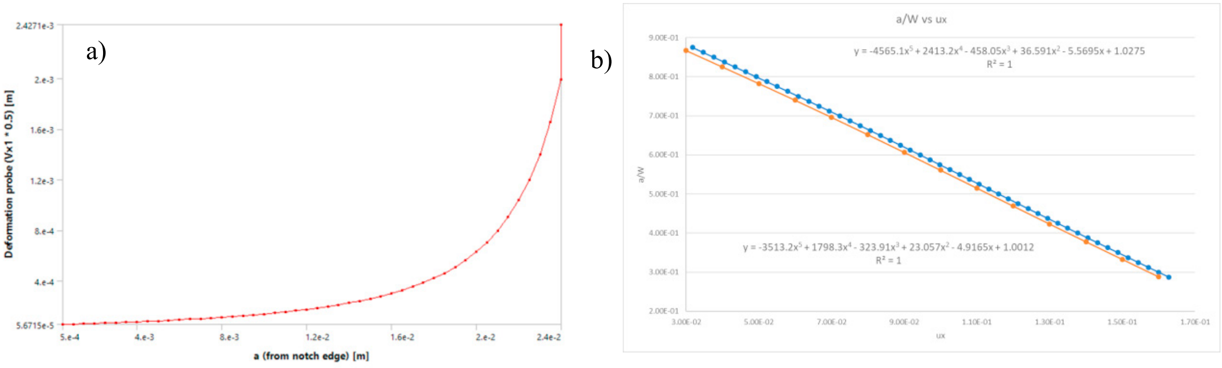

Fig. 4. (a) deformation probe from 3D FEA model for CMOD vs crack length a; (b) curve fit relating u_x to a for 3D FEA and ASTM E647.

Table 1. Front face compliance fifth order polynomial function coefficients based on ASTM E647 and 3D FEA.

Compliance function	C_0	C_1	C_2	C_3	C_4	C_5
ASTM E647	1.0012	-4.9165	23.057	-323.91	1798.3	-3513.2
3D FEA	1.0275	-5.5695	36.591	-458.05	2413.2	-4565.1

The crack length vs number of cycles obtained from postprocessed experimental data is shown in Figure 5 below for the three grades of steel. The loading phase on the Instron load frame for this data include the initiation of the crack from the starter EDM machined notch. The initial 20k load cycles show the crack growing around 1mm from the initial EDM machined size of 10mm to 11mm. The crack length estimated from the experimental data for this phase is relatively noisy and will not be reliable. Once there is an established crack front the crack propagation data is relatively smooth. Figure 5 indicates that the material grades corresponding to 235 and 275MPa nominal yield strength have similar response whereas the 355MPa yield strength material grade had a slower crack growth rate.

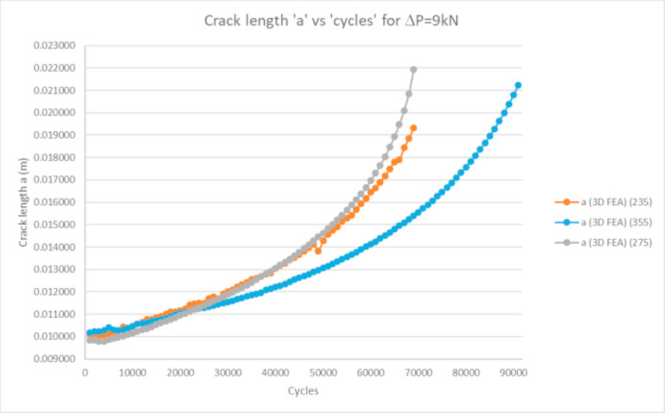

Fig. 5. CT test piece crack length *a* vs number of cycles for three grades of structural steel for *ΔP*=9kN.

The crack growth and corresponding stress intensity factor data are then used to evaluate the Paris Law material properties as show in Table 2 below. The next step was to use the evaluated material property in a CT test piece analysis and compare numerical and experimental crack growth. Figure 6 below shows that the numerical prediction of the crack growth is relatively close to the experimental values for the Grade 3 material.

Table 2. Paris Law material property estimates for the selected grades of structural steel.

Grade	Nominal Yield Strength (MPa)	m	C ((m/cycle)/(Pa m$^{0.5}$)^m)
Grade 1	235	2.5306	2.13E-26
Grade 2	275	3.2227	1.47E-31
Grade 3	355	2.6664	1.62E-27

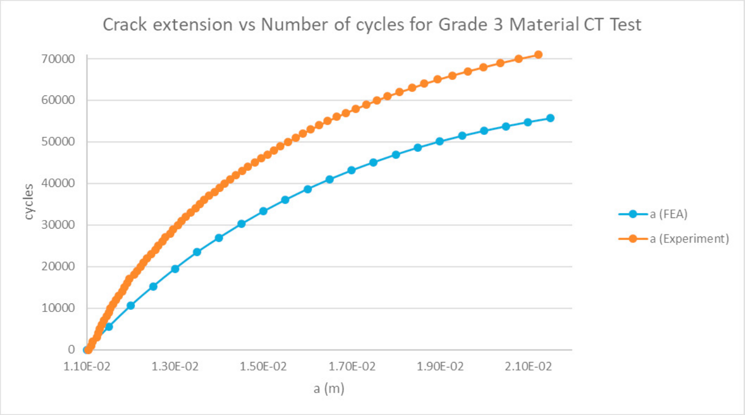

Fig. 6. Crack extension vs predicted number of cycles with Grade 3 material property estimate.

6. Conclusions

This investigation has shown that the 3D compact tension test piece FEA with the Ansys Workbench Mechanical SMART fracture tool can successfully create a compliance relationship to estimate crack length from experimental CMOD data. Three grades of structural steel were investigated for crack growth rates. The material fatigue crack growth analysis for stress intensity factor $\Delta K > 20$ MPa $m^{0.5}$ range is achieved with relatively short duration experiments on the Instron load frame. However, for lower stress intensity factor range the crack growth data is relatively noisy. Longer duration fatigue fracture tests will be required for lower stress intensity factor ranges.

Crack growth rates near threshold stress intensity factor levels required for a very high cycle fatigue (VHCF) design would be very costly due to load frame machine time required. The CMOD instrumentation for low crack growth rates would also require increased precision and would be susceptible to noise. Noise in data is found to reduce precision of material property estimation and further statistical analysis will be required with multiple test pieces. However, the presented investigation results showed that the developed hybrid analysis methodology combining numerical and experimental data can give flexibility to handle other non-standard test piece designs, for example for subsize CT geometries.

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