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Effect of Mounting Orientation on Testing Equipment on the Elastic Compliance of Clamped SE(T) Specimens

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1. Introduction

The structural integrity assessment is an important task to assure the safe operation of nuclear components. This paper is part of the effort to the characterization of the related fracture mechanics properties.

The Elastic Unloading Compliance technique (EUC) is frequently used to determine the instantaneous crack size (a) during fracture mechanics tests. It is based on the fact that specimen flexibility must increase with crack size, and that correlation can be modeled. Other crack measuring methods such as electric potential drop and visual inspection can also be used, but EUC is advantageous because of the following reasons [1-3]:

1 – No additional equipment is necessary. It is based on compliance (V/P), that can be determined with load (P) and displacement (V). Both of those outputs are easily obtained in modern testing equipment with load cells and clip-gauges.
2 – Complete crack behavior through thickness. Crack depth usually varies alongside the thickness of the specimen due to changes of the stress state. The center portion tends to plane strain whilst the edges, plane stress. This created a curved crack that is deeper in the center and shallower in the edges (tunneling) and this crack profile cannot be observed with visual inspection. EUC is based on the elastic behavior of the entire specimen, thus capturing the effect of the whole crack. Even though tunneling is not desirable and current standards such as the ASTM E1820 [4] limits crack curvature, several studies have been conducted to validate EUC technique in predicting correct equivalent straight crack size [1].
3 – Precision. EUC technique is shown to be as precise as other available methods.

Fracture mechanics specimens are, by nature, asymmetric across the width because of the presence of a crack. In tension specimens, such as C(T), DC(T) and, scope of this study, SE(T), this generates uneven traction loading in the specimen causing a bending moment and consequent rotation [1]. This loading may be a problem with SE(T) specimens, especially the clamped ones ($SE(T)_c$) because of the mounting fixture on the test machine.

Using the coordinate system of Fig.4 for reference, most of SE(T) specimens could only be fixed on the test machine with the crack mouth pointing in the y-direction (configuration #1) due to grip clearance. Note that the bending moment generated by this is applied across a plane with significantly less moment of inertia when compared with the crack pointing in the x-direction (configuration #2), with the grips rotated 90 degrees across the y-axis. This problem is not relevant for both other cited specimens because the usual mounting apparatus allow the crack to be positioned in configuration #2.

Experimental and numerical results are expected to differ due to machine compliance and induced bending moment. The expected outcome is to validate the assumption that mounting #2 should be prioritized for $SE(T)_c$ specimens when possible.

2. Methodology

$SE(T)_c$ specimens will be tested in both mounting orientations and compared with FEM (Finite Element Method) models. Specimens are fabricated with API 5L x65MS [5] steel (stress-strain curve shown below in Fig.1). Two specimens are analyzed with width W=25.4 mm and width-to-thickness ratio of W/B=2 and W/B=4 respectively. The tests will be conducted limiting K_1 value to 35 MPa.m$^{0.5}$ aiming to maintain minimal crack tip plasticity. This is desired so the same specimen can be evaluated at both orientations without significant changes in geometry and residual stresses.

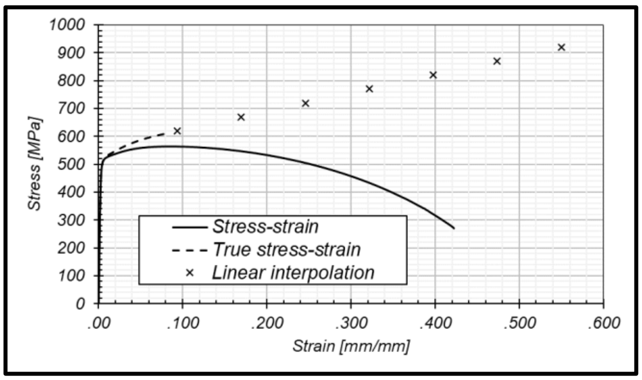

Figure 1 : API 5L x65MS stress-strain curve.

FEM models used to reproduce the specimens are constructed in Dassault Sistèmes Abaqus ® [6] software with typical symmetry conditions and spider-web mesh crack core. Standard 8-node hexahedral elements are used apart from the crack core, where 20-node hexahedral second order elements are recommended to provide accurate fracture mechanics properties. The half-thickness is discretized with 20 elements and loading is applied with displacement in the y direction at the nodes corresponding to the fixture in the loading mechanism (typical mesh shown in Fig.4).

Specimen model is built with W=25.55 mm, B=25.4 mm, a/W=0.365. In an effort to represent the effect of the machine compliance in FEM, the $SE(T)_c$ specimen is loaded with the scheme presented in Fig.2:

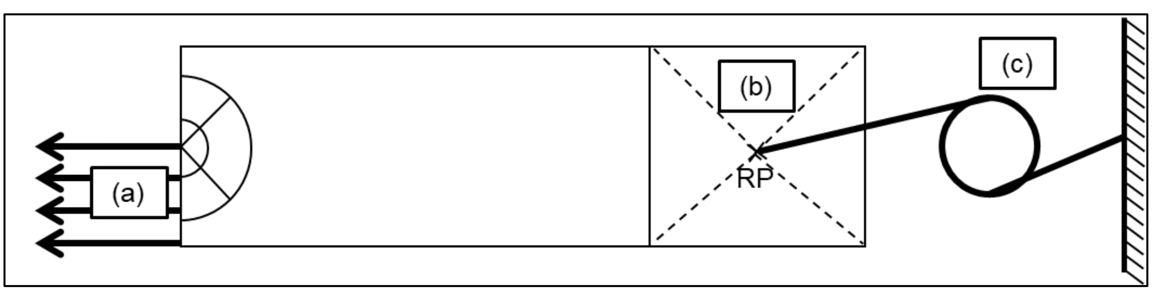

Figure 2: $SE(T)_c$ typical loading scheme.

(a) Loading is applied via displacement (for all models, 0.5 mm loading followed by a 0.05 mm unloading to measure compliance). Note that since uniform displacement applied to the crack plane nodes, symmetry conditions are still maintained.
(b) A reference point (RP) is constrained with the grip area of the specimen. Only one torsional degree of freedom is allowed.

(c) torsional spring, with configurable stiffness, joins the reference point to ground with a torsional degree of freedom. Five values of spring stiffness are used in this first moment to show the impact of such value in fracture mechanics data.

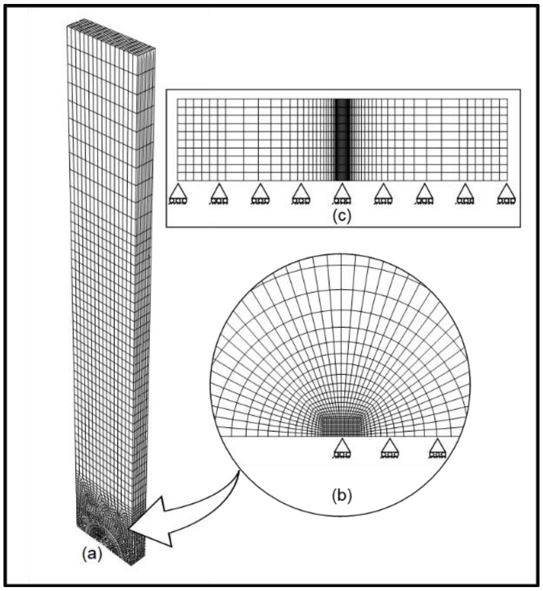

Figure 3 : Typical $SE(T)_c$ mesh.

For estimation purposes only, the test machine frame was roughly modeled with the specimen in both configurations using Autodesk Inventor ® [7] software. Two simple FEM analysis with tetrahedral elements, linear elastic material and simplified boundary conditions were conducted to compare the impact of a bending moment applied on the x-axis and y-axis of the machine, representing respectively configuration #1 and #2.

3. Results and Discussion

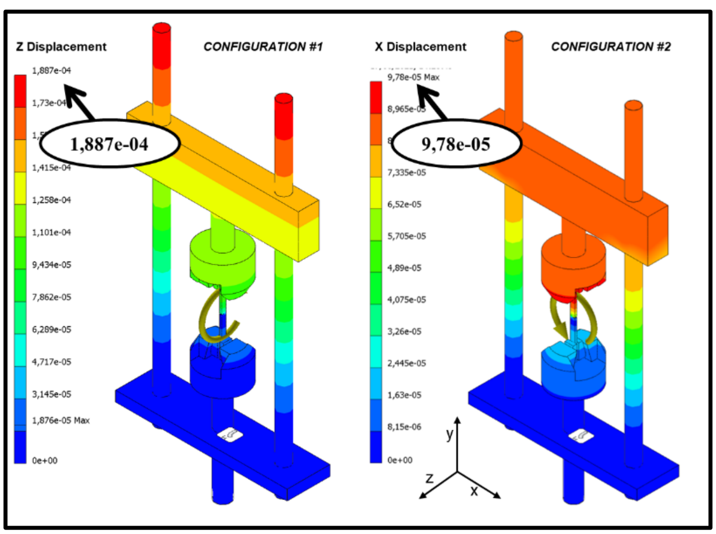

Figure 4 : Machine stiffness estimation results

It is presented first the estimation of machine maximum displacement results conducted in Autodesk Inventor ® [7] in Fig.4. Please note that this does not accurately represents the test machine and should not be used quantitatively. With a uniform 100 Nmm bending moment applied to the crack tip, the maximum displacement in configuration 1# was one order of magnitude higher of that observed on configuration #2, measuring 1.877E^{-4} mm versus 9.78E^{-5} mm.

SE(T)$_c$ specimen simulation results are presented in Table 1. It is show spring stiffness (representing machine stiffness, Nmm/rad), CMOD (mm), specimen compliance (mm/N), normalized compliance and a/W estimation using Moreira curve fitting polynomial (mm/mm). Five spring stiffness values with different order of magnitude were used since machine compliance should be significantly different in both orientations.

Table 1: Clamped SE(T) models simulation results

Stiffness	**CMOD**	**Compliance**	**µ**	**a/W**
2.60E+05	1.097	1.031E-06	0.387	0.300
2.60E+06	1.049	1.108E-06	0.379	0.313
2.60E+07	0.923	1.263E-06	0.363	0.337
2.60E+08	0.870	1.288E-06	0.361	0.341
2.60E+09	0.864	1.288E-06	0.361	0.341

4. Conclusions

- Machine stiffness is significantly higher in the XY plane when compared with the YZ plane (Fig.6).
- Machine stiffness affects the results of tension specimens, exemplified by SE(T)$_c$ in this work (Tab.1). With increasing value, a/W prediction tends to stabilize, thus it must be desirable, concluding that configuration #2 might be optimal for SE(T)$_c$ specimens tests.
- Fracture mechanics properties could be affected by mounting orientation of SE(T)$_c$ specimens.

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[7] Autodesk Inventor [Computer software]. 2020. Retrieved from Figure 4 : Machine stiffness estimation results.