SUITABILITY OF STANDARD FRACTURE TEST SPECIMENS FOR LOW CONSTRAINT CONDITIONS

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Abstract. Test specimen selection plays a vital role in successful transformation of laboratory fracture parameter findings to the real fracture behavior of any component. The ASTM and BSI Standard test methods for measurement of fracture toughness are dominated by high constraint specimens like Compact Tension (C(T)) and Single Edge Notch Bend (SEN(B)). However, most cracks in real time structure are shallow and surrounded by low constraint. Hence, the standard specimen like Middle Crack Tension (M(T)) in ASTM and Clamped Single Edge Notch Tension (Clamped SEN(T)) specimen in BSI, yield fracture toughness value to be test specimen dependent. The Clamped SEN(T) specimen suitable for various real pipeline (low constraint conditions) application has been widely reported in literature, that however in not the case for M(T) specimen which has scarcely reported. The 3D numerical analysis of SEN(T) and M(T) specimens with an identical flaw size for fracture toughness and constraint parameters (T-stress) under linear-elastic conditions are dealt in this article. The standard specimen that emulates low constraint fracture behaviour forms the basis for recommending suitable specimen for defined real time conditions. The conservatism associated with usage of standard specimen to find fracture parameters for an application has been quantified in this work for field implementation by practitioners in fracture mechanics. Keywords: Clamped SEN(T), Fracture toughness, Low constraint condition, M(T).

1. INTRODUCTION
The structures such as pipelines and reactor pressure vessel (RPV) that are crack imbibed due to manufacturing processes and service conditions get susceptible to fracture failure [1, 2]. A regular inspection of these components becomes mandatory to ensure that crack shape and size do not reach critical proportions that damage the part/structure during operation. Growth of the crack ensues if the operating conditions are enough to overcome the material fracture toughness. However, study on replicating real time crack behaviour through laboratory test specimen has its own challenges on account of difficulty to depict true behaviour of crack under these loads. American Society for Testing and Materials (ASTM) and the British Standards Institution (BSI) have recommended standards for different crack behaviour of components based on material and loading conditions [3]. These standards quantify plane strain fracture toughness by stress intensity factor (KIC) in linear elastic conditions and J integral (J IC), Crack opening displacement (COD), Crack-tip opening angle (CTOA) in elastic-plastic conditions for Mode-I loading. Standard specimens used to replicate true nature of crack behaviour result in a conservative fracture toughness value. A single parameter from these standards to quantify crack behaviour is not adequate as it provides too little insight into the true nature of crack.

The researchers have proposed new parameters apart from fracture toughness to quantify true nature of crack under various loading conditions. The new parameters provide scope to define plasticity around crack tip in terms of stress, strain, and displacement collectively designated as constraint parameters. In case of experimental methods constraint parameters are difficult to be defined, but analytical and numerical methods for standard specimens are easy to be comprehended. The Tij stresses, Q stress, A, and A2constraint parameters are well defined in literature for measures of in-plane and out-of-plane constraints near crack tip/front [4]. Each constraint parameter has its own limitations whose discussion lies beyond the scope in this article. The defined constraint parameters along with fracture toughness quantify crack tip/front growth, under the nomenclature of two-parameter and three-parameter fracture assessment [5].
The standard specimen selection to replicate component crack-behaviour plays a vital role, apart from the chosen type of fracture assessment. Thus selection of standard specimens and their limitations to experimentally measure actual fracture toughness, on basis of prevailing constraint at real crack has led to evolution of constraint-corrected fracture assessment of structure. The numerical approach to assess fracture through constraint correction needs high skill and precise computational ability, although data related to standard specimens and values concerning crack shape and geometry are found in literature [6]. The transferability of constraint corrected assessment of standard test specimen to actual structure is extensively researched over last two decades [3, 7].

ASTM and BSI recommend few standard specimens for high and low constraint conditions. High constraint specimens in these standards are Compact Tension (C(T)), Single Edge Notch Bend (SEN(B)), Disc Shaped compact (DC(T)), and Arc Shaped Tension (A(T)). These standard specimens ensure minimum fracture toughness for various geometry of crack under linear elastic fracture mechanics conditions (LEFM). The real practical components susceptible to fracture still use this fracture toughness value leading to design conservatism. Most practical components are under low constraint conditions and possess high toughness for shallow cracks. To overcome the conservatism associated with test specimen, BS 8571:2018 suggests usage of low constraint Single Edge Notch Tension (SENT) specimen [8]. BS 8571:2018 ensures single fracture toughness value for metallic materials under LEFM (in-terms of COD) condition and a resistance curve (R- curve) for ductile materials under Elastic-Plastic Fracture Mechanics (EPFM) condition.

Similarly, ASTM E2472 – 12(2018) recommends Middle Crack Tension (M(T))/ Center-Cracked Tension (CCT) specimen to measure fracture toughness (in-terms of CTOA) for metallic materials under EPFM condition [9]. Both standards are defined (or revised) recently, to acquire fracture toughness data of low constraint to replicate real practical situations. The ASTM standard for metallic materials on low constraint condition under LEFM regime has not been developed with a standard specimen for single value of fracture toughness. The non-usage of SENT specimen in ASTM standards has compelled researchers choose M(T) as low constraint specimen but only under EPFM conditions.

S. Cicero et al. [10] reviewed the fracture assessment of low constraint specimen adopted by industry. The available fracture assessment methods considered ensured structure safety at the expense of excessive conservatism. Matthias Verstraete et al. [11] have suggested a framework to select efficient laboratory test specimen for large scale structure with fracture toughness data adopted to compare different fracture toughness trajectories of laboratory test specimen. The authors recommended suitable test specimen based on preparation cost, time, material needed, and required test capabilities. Zhu X K et al. [12] have reviewed that many researchers claimed suitability of clamped SEN(T) through experimental, numerical and analytical methods for fracture assessment in low constraint applications. However, lack of SEN(T) based ASTM standards necessitates thoughtful relook and comparison of low constraint specimen like M(T) and SEN(T).

Yan Di et al. [13] have suggested use of modified C(T) specimen to measure CTOA for X80 pipeline steel with recommendation for successful conduction of ASTM E1820 test. J.M. Warrenet al. [14] have used Finite Element Analysis (FEA) to predict failure of C(T) and M(T) specimens on basis of CTOA fracture criteria. Lu, L. and Wang, S [15] have conducted tests on C(T) and M(T) specimens for various thicknesses (plane stress and plane strain) to collect K-R curves by ASTM E1820. A novel method was proposed to find CTOA from K- R experimental data. Similarly, K. Lu and T. Meshi [16] have investigated T-stress variation in Center-Cracked Tension (CCT) specimens for various values of the ratios of crack length to width (a/W) and thickness to width (B/W) of the specimen as per ASTM E2472. The T-stress components were negative for all a/W, and B/W considered in the numerical study. The extensive analysis of M(T) specimen is reported in literature, unlike the constraint comparison of M(T) with SENT (low constraint) specimen that finds scarce reported work. The research gap for selection of appropriate standard and test specimens based on application can be helpful if constraint comparison between similar standard test specimens were available.
The selection of standard specimen for low constraint application on SENT and M(T) becomes crucial owing to limited literature available, necessitating user to draw better interpretations with respect to their suitability for an application. A thorough 3D numerical analysis was performed on identical flaw size, fracture toughness and constraint parameters under LEFM conditions for both specimens. A comparison of the constraint parameters through Tij stresses at the crack front were conducted for various a/W ratio. The equations of both specimens for fracture toughness and Tij stress preferred 3D analysis to be adopted. The low constraint specimen was recommended based on constraint parameter trajectory and fracture toughness for various a/W for both standard specimens.

2. STANDARD SPECIMENS AND DIMENSIONS

The 3-D models of Clamped SEN(T) and M(T) specimens are shown in Figure 1, with both specimens under remote tension that ensures Mode-I loading. In clamped SEN(T) specimen, H refers to specimen height (daylight of the specimen), H* is the clamped distance referred to as gripped region held by the machine, a is the initial crack length before loading, W is the specimen width, and B is specimen thickness. H/W=10 and H*/W = 4 were considered as per BS 8571:2018 also adopted by C. Bassindale et al. [17]. The square cross-section (B=W) was considered in this work. Similarly, for M(T) specimen, according to ASTM E2472 –12(2018), 2a was initial crack length before loading, 2W was specimen width, 2H was specimen height and B was specimen thickness. In both specimens, P or σ was applied remote load. Though in ASTM E2472 –12(2018) clamped M(T) specimen was recommended, direct loading without clamp also resulted in identical values with negligible variation (<0.1%) compared to clamped M(T). The further analysis had M(T) specimen without clamp for easy and refined mesh purposes.

![Figure 1. Standard Specimens (a) Clamped SEN(T) (b) M(T)](image)

Analytical solution for clamped SEN(T), suggested by Zhu’s [18] closed-form polynomial was used to compare the obtained results. Zhu proposed a sixth-order polynomial to obtain geometrical factor F(a/W) that further resulted in KI value based on equation (1). Similarly, for M(T) specimen, closed-form solution mentioned in equation (2) was used [19] for comparison with obtained results.

\[ K_I = \frac{\sigma}{\sqrt{2\pi a}} F \left( \frac{a}{W} \right) \]  
\[ K_I = \sigma \sqrt{\pi a} F \left( \frac{a}{B} \right) \]

The geometry factor F(a/W) depends on standard specimen type, crack length, and specimen width.
3. FINITE ELEMENT MODEL AND ANALYSIS METHODOLOGY

3.1 Model Parameters and Computational Procedure

The comparative study of standard specimen fracture toughness in terms of constraint level at crack front with real structure was adopted by virtue of taking both clamped SEN(T) and M(T) specimens with identical initial crack length and thickness. Since real structure (pipe) has a definite thickness with variable crack length as defects, thickness of both specimens were kept constant, and only a/W was varied. Crack length to width ratio (a/W) was varied between 0.25 to 0.7 in increments of 0.05 keeping the specimen thickness as 25.4mm. Other geometrical parameters were derived as per standard relationship. Structural steel with Young’s modulus of 207 GPa and Poisson’s ratio 0.3 was used during the study [17].

Abaqus 6.14-1 commercial FE package was used for all numerical calculations and computational analysis [20]. Fatigue pre-crack was modeled considering seam crack to ensure a sharp crack structure. To maintain crack front singularity, collapsed elements with 0.25 mid-node shift towards crack was used [21]. The counter integral method was used to evaluate both stress intensity factor and Tij-stresses. T11-stress represents stress parallel to crack faces used as a constraint parameter. Similarly, T33-stress was evaluated by relationship in equation (3). In equation (3) E represents Young’s modulus, ε33 strain in the z-direction, and ν poisson ratio. Both T11 and T33 stresses confirm measurement of in-plane and out of plane constraints at crack tip/front in LEFM[22].

\[ T_{33} = E \varepsilon_{33} + \nu T_{11} \]

The Tensile load (P) on clamped SEN(T) and equivalent remote stress (σ ) for M(T) Specimen were applied. The load considered in the analysis confirmed the LEFM condition at the crack front [23]. To Simulate boundary conditions for clamped regions only load direction movement was allowed and other degrees of freedom was restricted.

3.2 Finite Element Model & Mesh

In case of clamped SEN(T), half symmetry model and in M(T), a quarter symmetry model was used. A typical half symmetry model with FE mesh for clamped C(T) specimen for a/W= 0.5 is shown in Figure 2. Similarly, quarter symmetry FE meshed model of M(T) specimen for a/W=0.5 is shown in Figure 3. Twenty-node quadratic brick elements with reduced integration (C3D20R) were used in the analysis [20]. Near crack front, these nodes were collapsed at one end (near the crack tip side) for efficient replication of singularity. The dense mesh was used near crack front surface and structured mesh maintained in the entire FE model for both specimens. The number of elements was between 8,000 and 20,000 for all a/W considered in both specimens. More details about the mesh generation in cracked models can be obtained from Abaqus Manual [24].
Standard mesh convergence was performed for both specimens. The stress intensity factor (SIF) values were unaffected beyond certain significant fine mesh refinement at the crack front. The SIF value deviation for mesh refinement was examined and maintained within 0.1% for the entire investigation.

4. RESULTS AND DISCUSSION

The values of $K_I$ for both clamped SEN(T), and M(T) specimens were calculated using equations (1) and (2) for various $a/W$ considered. But these values suited for 2-D specimen considered. The 3-D model indicated maximum $K_I$ along crack front (present analysis) and $K_I$ at crack tip (from equations (1) and (2)) for both specimens with reference to $a/W$ considered as shown in Figure 4. These equations do not consider the effect of constraint originated due to specimen thickness. The present $K_I$ (max $K_I$) results on 3-D model have higher values in comparison to Zhu’s solutions for all $a/W$ considered for clamped SEN(T). Similarly, for M(T) specimen, all $a/W$ resulted in higher $K_I$ values as compared to analytical results. Higher $K_I$ in 3-D analysis was attributed to constraint present near the crack front and can be further quantified by constraint parameters.

Similarly, maximum value of $T_{11}$ obtained from present analysis and $T_{33}$ (using equation (3)) along the crack front for both specimens is shown in Figure 5. In both specimens, the $T_{11}$ and $T_{33}$ values were negative indicating the low constraint specimen. In clamped SEN(T), $T_{11}$ increased with increase in $a/W$ and a reverse trend was observed for out-of-plane constraint, $T_{33}$. Similar kind of variation was observed in Z. Liu et al. [25]
However, for M(T) specimen, $T_{11}$ and $T_{33}$ both decreased with increase in $a/W$ and are in agreement with Henry and Luxmoore [26]. Clamped SEN(T) specimen’s $T_{11}$ value increasing nature with $a/W$, making it vulnerable in-plane constraint specimen compared to that of M(T).

For a given load and a flaw size, selection of laboratory standard specimen influence on fracture toughness values and their constraint at the crack front, can be compared using normalized values of $K_I$, $T_{11}$ and $T_{33}$. The Figure 6 shows variation of normalized $K_I$ (in terms of $F(a/W)$) and normalized T-stress with $a/W$ for both specimens. The trajectory of $F(a/W)$ was higher in Clamped SEN(T) compared to M(T) specimen, also the trajectory of normalized $T_{11}$ was also higher in clamped SEN(T). However, normalized $T_{33}$ values of M(T) were higher and trajectory attained a similar magnitude for higher $a/W$ with clamped SEN(T). The out-of-plane constraint effect was almost same in both specimens because of slight difference between $T_{33}$ trajectories. Overall, M(T) specimen constraint values/trajectory exhibited low constraint values as compared to clamped SEN(T) for same crack length and specimen thickness. Based on numerical analysis, the M(T) specimen was a better representation of low constraint compared to clamped SEN(T).
To avoid numerical calculations and complex analysis for both specimens, it was proposed to develop equations (3) and (4) for $F(a/W)$, $T_{11}$, and $T_{33}$ based on curve fitting. The error analysis on the proposed equations and numerical findings indicated proposed equations to have a maximum of 1.3% and a minimum of 0.002% error. The results strongly indicated the suitability of proposed equations as an alternative to complex simulations and numerical analyses.

5. CONCLUSIONS

The conclusions based on the computational studies to compare two different standard specimens used for low constraint conditions in terms of constraint trajectory are presented. The 3-D analysis of both the specimens for the same load and flaw size was considered to estimate the $K_I$ and $T$-stresses parameters. In most cases, maximum $K_I$ and $T$-stress were at center of crack front line owing to crack-tunneling effect at the center. Based on numerical analysis, the M(T) specimen was a better representation of low constraint compared to clamped SEN(T). But preparation of M(T) specimen compared to Clamped SEN(T) was challenging due to fatigue pre-crack initiation and experimental measurement of $K_I$.

The numerical analysis requires fine mesh and complex simulation to analyze crack geometry and extract the required parameters. The proposed SEN(T) and M(T) mathematical equations based on computational studies avoids complex simulations to offer an easier investigation to practitioners in the field of fracture mechanics. The margins of error associated with these equations are within acceptable industrial margins.

6. ACKNOWLEDGMENTS

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