Modelling mode I failure at crack tip with verifications using digital image correlation [version 1; peer review: 2 approved with reservations]

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Abstract

Background: Linear elastic fracture mechanics (LEFM) applies to sharp cracks, although crack sites such as holes and slots are often blunt cracks with nonzero widths. The advancement in finite element method (FEM) has enabled the calculation of stress intensity factor (SIF) for unstable crack growth prediction, regardless of crack shape and size, but the calculations often differ from contour to contour. Hence, the purpose of this work is to determine if SIFs computed using commercial FEM have experimentally verifiable advantages over the traditional stress-based modelling approaches in predicting Mode I brittle failure at blunt crack tip.

Methods: Experiments and simulations were conducted on brittle Poly(methyl methacrylate) (PMMA) plastic to compare the actual and predicted strain fields and SIFs at crack tip, and the critical force at which unstable crack growth initiates. A centrally straight cracked Brazilian disc made of PMMA was subjected to purely Mode I fracture. Its strain fields were measured from deformed speckle patterns using digital image correlation software. The same disc was modelled using plane stress model in FEM. By applying the critical force, SIFs were then computed using ANSYS pre-meshed crack method at different contours away from the crack tip. The effects of element type, mesh size and crack width on the simulated SIFs were investigated.

Results: It was found that the experimental critical load agreed well with LEFM prediction based on PMMA fracture toughness in published literature. Disc failure happened at the first sign of tensile yield at the crack tip in the finite element model with a triangle mesh. Digital image correlation clearly shows the occurrence of unstable crack growth at critical force. It also shows comparable far field strain responses to the FEM model.

Conclusions: The computed SIFs were inconsistent, and their usefulness in predicting unstable crack growth requires further
investigation.

**Keywords**
Stress Intensity Factor, Opening Mode, Fracture, PMMA, Ansys Fracture Tool

This article is included in the Research Synergy Foundation gateway.

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**Competing interests:** No competing interests were disclosed.

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Introduction

It is widely accepted that crack tip shape and crack width have significant effects on the stress intensity factor (SIF). For a crack with finite width (i.e. blunt crack), researchers are working on correction factors to account for the deviations that result from linear elastic fracture mechanics (LEFM) predictions. Although literature is abundant on the use of finite element method to predict SIF, most work focused on comparing finite element predictions and those from LEFM on sharp crack, and often not complemented by experimental observations. Also, some modelling techniques require manual node adjustment (i.e. collapsed elements or quarter-node approach) and/or complex mesh morphing strategy, and therefore not feasible for routine use by simulation analysts. SIFs calculated in finite element commercial software, such as ANSYS, often differ from contour to contour. Experimental verifications are indeed important in cases of a crack with finite width.

In recent years, digital image correlation (DIC) has enabled researchers and engineers to measure strains at minute locales and view full-field data without requiring any physical contact, or installing relatively large and expensive strain gauges. It is convenient, simple, and accurate in measuring deformation and strains in large-scale structures. Open-source programme such as GOM correlate makes 2D DIC feasible and cost-effective. Some examples of DIC usage for monitoring structural behaviour and long term reliability of materials under different loading conditions in both static and dynamic situations are as follows: Abshirini et al.’s investigation on mode I failure of Brazilian disc using DIC method, Huang et al.’s study on the flexural behaviour and crack formation in cementitious composite, UK National Physical Laboratory’s (NPL) measuring of hard-to-detect micro-crack opening in concrete structures. Recently, digital image correlation was used to evaluate fracture mode-mixity.

In this work, experiments and simulations were conducted on brittle Poly (methyl methacrylate) (PMMA) plastic to compare the actual and predicted strain fields around crack tip with finite width, and the critical force at which unstable crack growth initiates. The effects of mesh size and crack width on the simulated critical SIF were investigated. The aim of this work is to determine if SIFs computed using commercial finite element method have experimentally verifiable advantages over the traditional stress-based modelling approaches in predicting Mode I brittle failure at blunt crack tip.

Methods

Ethical approval

All procedures used in this project have been approved by the Research Ethics Committee (REC) Multimedia University (EA1682021). This work does not involve data collection from humans, human or animal experiments or vulnerable communities.

Specimen

Centrally straight crack Brazilian discs (CSCBD), commonly used to investigate the fracture toughness in various materials were prepared according to dimensions in Figure 1. The PMMA discs were machined to a diameter of 60 mm and 15 mm thick. The centre notch was of 2 × 15.5 mm in length and 1 mm in width. PMMA had been chosen in this study due to its brittle nature and the vast amount of related publications. Specimen dimensions were specified in compliance with ASTM D3967-95a requiring a thickness to diameter ratio \(t/d\) within the range of 0.2-0.75 and ASTM E 399-90 requiring the specimen to be sufficiently large compared to the crack length and the plastic zone size. The benefit of using a Brazilian Disc specimen is that it is much easier to prepare than other specimens because of its simple geometry, and the uniaxial compression test is relatively easy to set up.

The quality of DIC results depends mostly on the resolution of the speckle pattern. Fine speckle pattern, a good focusing lens and a high resolution (10 MP) camera are essential for DIC to track the random speckle pattern with accuracy. The specimen was first sprayed with a layer of plastic primer followed by white spray paint before the black speckle pattern was applied. Spray painting was used to apply random speckle patterns, as shown in Figure 2. Natural drying under sunlight took place before subsequent application of paints.

Compression test and digital image collection

Figure 3 shows the test setup. Compression was applied to CSCBD until fracture using Instron 3367 universal testing machine, at speeds of 1 mm/minute and 5 mm/minutes, respectively. During the compression test, the camera was mounted onto the tripod and calibrated using a built-in spirit level to ensure the image sensor was aligned perpendicular to the region of interest. In the setup, a high brightness LED light was used to illuminate the surface of the specimen. The camera was set to capture one image per second in black and white. Both the image acquisition and compression testing were carried out simultaneously. Image acquisition was started one to three-seconds before load application. Images and force data were synchronized during post-processing. GOM Correlate was used to perform the DIC.
Figure 1. (a) Brazilian disc and crack tip polar coordinate system; (b) Actual disc dimensions.

Figure 2. Fine speckle pattern on a 60 mm Brazilian disc.

Figure 3. Setup for compression test and digital image collection.
LEFM and numerical analysis

According to,\textsuperscript{10} critical SIF of Mode I fracture, $K_I$, can be computed using equation (1).

$$K_I = \frac{P}{RB} \sqrt{\frac{a}{\pi} Y_I(a/R)}$$  \hspace{1cm} (1)

where $P$ is the critical load at fracture, $R$ is the radius of the disc, $a$ is the semi crack length, $B$ is the thickness of the disc and $\theta$ is the angle of crack relative to load, which is zero in this study. $Y_I$ is a geometry factor and is a function of crack length ratio ($a/R$) and the crack angle $\theta$.

Ansys Mechanical Workbench was used to simulate the compression test. Plane stress model was used, as the finite element results do not show significant differences from those of plane strain model. This is expected as the specimen dimensions meet the requirement of small plastic zone for plain strain consideration (i.e. ASTM E 399-90),\textsuperscript{12} and will not be further discussed in this paper. The material properties of PMMA are summarized in Table 1.\textsuperscript{15}

A force was applied through a rigid top plate in contact with the specimen, which was supported by yet another rigid plate at the bottom. Pre-meshed crack approach and linear elements were adopted. Ansys fracture tool, which calculates SIF using contour integration,\textsuperscript{16} was used to compute SIFs on 6 contours around the crack tip.

As the quality of the mesh directly affects the accuracy and speed of the solution, a finer mesh was used around the crack tip since it was the region of interest. In this study, the effects of element type (i.e. triangles vs. quadrilaterals), minimum element size at crack tip (i.e. 50 $\mu$m, vs. 2.5 $\mu$m) and crack width (i.e. 1.0 mm and 0 mm) on stress-strain contour and SIF were investigated. Figure 4 shows the different meshes on the CSCBD model. Quadratic elements reported lower SIF values, and will not be presented in this study.

Table 1. Material properties of PMMA.

<table>
<thead>
<tr>
<th>Young’s Modulus (MPa)</th>
<th>Poisson’s Ratio</th>
<th>Density (g/cm$^3$)</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Compressive Yield Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>0.37</td>
<td>1.18</td>
<td>62</td>
<td>104</td>
</tr>
</tbody>
</table>

Figure 4. Equivalent strain fields in different meshes (a) Triangle mesh, crack width = 1.0 mm; (b) Quadrilateral mesh, crack width = 1.0 mm; (c) Zoom in at crack of (b); (d) Quadrilateral fine mesh, zoomed in at crack; (e) Triangle mesh, crack width = 0 mm, zoomed in at crack; The scales in (c), (d) and (e) are comparable.
Results
Experiments on CSCBD show consistent critical load ranging from 4212 N to 4502 N, with no significant differences due to the two different speeds. With the dimensions in Figure 1, using equation (1), $K_i$ turns out to be between 0.91 to 0.98 MPa × $\sqrt{m}$. Figure 5 shows the DIC of two samples at the initiation of unstable crack.

It is well-known that finer mesh tends to increase the predicted stresses at the singularity sites of crack tips, even well before the critical load. Therefore, predicting the critical load by studying the magnitude of stresses at crack tip had not been a viable option. The conventional practice in predicting unstable sharp crack growth is to obtain the SIF using LEFM at the crack front and compare it with the critical stress intensity factor (i.e. fracture toughness) of the material. However, in this FEM study simulating both a blunt crack and a sharp crack, the SIFs predicted by the model differ vastly from one contour to the next. These values are presented in Figure 6 for different meshes (i.e. Tri for triangles, Qua for quadrilaterals, Qua_Fine for fine quadrilaterals) and crack widths (CW). Results for blunt crack models of triangle and quadrilateral meshes almost overlapped in Figure 6.

Nevertheless, it was found that triangle mesh at the 1.0 mm-wide rounded crack was less sensitive towards stress concentration at crack tip. The onset of unstable crack in the experiment coincided with the onset of yielding at crack tip in the mesh, i.e. when the Mises stress based factor of safety is less than unity, as shown in Figure 7. The factor of safety in this case is the ratio of yield strength to Mises stress. And PMMA, being, a brittle material, fractures close to its yield strength.

Figure 5. DIC on sample specimens displaying strains normal to crack path.

Figure 6. SIFs (in Pa × $\sqrt{m}$) of 5 contours around crack tip for different meshes.
Figure 8 shows the stress fields at crack tips for both blunt and sharp cracks in different meshes. They were mostly comparable for the blunt cracks, but only the quadrilateral fine mesh captured the stress singularity well at the sharp crack tip.

Figure 7. Mises-stress based factor of safety around crack tip for different models. Factor of safety in the red regions is less than unity (a) Triangle Mesh; (b) Quadrilateral Mesh; (c) Quadrilateral Fine Mesh.

Figure 8. Mises stress (in Pa) around sharp and blunt crack tip in (a) triangle meshes (b) quadrilateral meshes (c) quadrilateral fine meshes.
The Mises strain field recorded in DIC at impending crack growth is now compared with that predicted in finite element models, namely the triangle and quadrilateral meshes, both with 1.0 mm crack width (See Figure 9). Comparison of the Mises strain values as recorded in the DIC and that predicted by the models were made along two different paths. Path A crosses the stress concentration at crack tip along the horizontal axis, whereas path B is parallel to path A and crosses the specimen centroid.

**Discussion**

The critical SIFs obtained from the experiment, in the range of 0.91 to 0.98 MPa × √m, are consistent with 0.87-1.20 MPa × √m reported by Choi et al., 1.02 MPa × √m reported by Zhou et al., and 1.17 MPa × √m (37.1 MPa × √mm) by Lerch et al. This implies the applicability of LEFM for the blunt “notch root-radius” of 0.5 mm of PMMA in this study and validates the experimental procedures in the present study.

The SIFs obtained from the finite element models were significantly lower from the actual values ranging from 0.87 to 1.17 Pa × √m reported elsewhere. The sharp crack models showed poorer predictions—their SIFs in the first contours being closest to the actual values. This correlates with the sharp drop of peak stresses away from the singularity of the sharp crack tips, in contrast with the more gradual drop in stress values at the blunt crack tip without singularity (see Figure 8). Although all models captured the rise of stress or strain amplitude at crack tips (see Figures 4, 7 and 8), the different attempts made using different element types and sizes did not improve the SIF predictions. This finding implies
that the practice of predicting unstable crack growth using SIFs computed by commercial FEM, such as the pre-meshed crack approach of Ansys fracture tool in this case, begs a closer examination, and experimental verifications.\textsuperscript{21} There is evidence that the interaction integral approach used in the pre-meshed crack approach to determine SIFs may not be as accurate as that using the J-integral approach or the modified Virtual Crack Closure Technique.\textsuperscript{22}

Figure 7 shows that both the coarse and fine meshes of quadrilateral elements are able to capture noticeable yielding zones at crack tip equally well, whereas the triangle mesh displays yielding only at a single node. The insensitivity of triangle elements towards stress concentration at the blunt crack tip actually helps failure prediction in the present scenario. Yielding at a single node provides a clear-cut indicator for FEM analysts to determine the onset of failure. On the contrary, the larger yielding zones in quadrilateral element models obscure the precise moment of impending fracture, since the question of how large a yielding zone needs to be to signify failure cannot be answered easily. Further case studies to take advantage of the triangle mesh insensitivity towards stress concentration may lead to a simple yet experimentally verifiable practice in predicting crack tip failures on brittle materials such as PMMA.

It can be seen from Figure 9 that the equivalent strains captured by the DIC matched reasonably well (i.e. to the same order of magnitude) with those predicted by the finite element models. DIC managed to capture the stress concentration around the crack tip even better than the models. However, the small strains at far field regions seemed to chatter. The general agreement between DIC and the model predictions verifies the models.

**Conclusions**

The following are the conclusions:

1) The critical SIF computed using LEFM, based on the critical loads of failed CSCBD specimens with blunt cracks, agreed well with the published critical SIF values in the literature.

2) Despite the limitation of traditional stress-based approach in predicting the onset of failure induced by stress concentration or singularity at blunt and sharp crack tip, respectively, the triangle mesh in this study predicted a single node yielding precisely at the onset of unstable crack growth in the experiment. Other crack scenarios may be investigated to determine if triangle mesh insensitivity may lead to the deployment of a simple and practical stress-based approach to predict the onset of crack growth.

3) Both the coarse and fine quadrilateral meshes captured the stress concentration at crack tip well but failed to produce accurate or consistent SIFs at the crack tip using the pre-meshed crack approach of Ansys fracture tool. The reliability of using SIFs computed by the FEM as crack growth predictors deserves scrutiny.

4) SIFs computed using ANSYS pre-meshed crack method have not shown experimentally verifiable superiority over traditional stress-based modelling approaches in predicting Mode I brittle failure at the blunt crack tip.

**Data availability**

**Underlying data**


This project contains the following underlying data:

- Figure 9-PhiM-Summary.xlsx
- Ansys_Mechanical_New.zip
- GOM.zip

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

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References


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Version 1

Reviewer Report 01 November 2021

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For decades, Linear elastic fracture mechanics (LEFM) has been used to study the behaviour of cracks in mechanical components and structures. Commercial finite elements (such as ANSYS and ABAQUS) have been used to either substantiate experimental results or provide further insights in this field.

In this study, the authors carried out experimental test and numerical modelling on centrally straight cracked Brazilian discs (CSCBD) prepared from polymethyl methacrylate (PMMA) and compared their strain fields and stress intensity factors (SIF) generated at crack tip under purely Mode I loading. The strain fields from the experiment were measured using a digital image correlation (DIC) software. While pre-meshed crack method in ANSYS was used to obtain similar information. Effects of varied element types, mesh sizes and crack widths on the simulated SIFs were examined.

The following must be addressed to make this study and its presentation comprehensive and reliable to be indexed:

1. In the introduction, the authors made some generalized/assumed statements without providing ample citations. These statements are as follows:
   ○ (a) "...researchers are working on correction factors to account for the deviations that result from linear elastic fracture mechanics (LEFM) predictions"
   ○ (b) "Although literature is abundant on the use of finite element method to predict SIF".
   ○ (c) "...some modelling techniques require manual node adjustment (i.e. collapsed elements or quarter-node approach) and/or complex mesh morphing strategy".
   I suggest for each statement at least 3 citations should be provided to substantiate these statements.
2. The experimental work was reasonably explained in detailed unlike the ANSYS Simulation. The authors need to provide more details on how the simulation was conducted such that it can be reproducible. For instance, boundary conditions used were not mentioned. They only reported, "a force was applied through...". What was the quantity of the force used and how was it applied? Was there any coefficient of friction applied at the contact points? What kind of supports were used? Was it a fixed or moveable support in certain direction? What mesh controls did they use for their meshing, including the finer mesh that was reported.

Also, on the ANSYS simulation, did the authors carry out a mesh convergence study on the meshes used. Using different types of element types without checking the quality of the meshes can always give a wrong result. Considering the disparity of the SIFs result from this study with that of the experiment and also those reported in previous articles, it is really a notable concern that must be properly addressed. I quote the authors in their words in the discussion: "The SIFs obtained from the finite element models were significantly lower from the actual values ranging from 0.87 to 1.17 Pa×√mPa×√m reported elsewhere".

I strongly would propose that the authors properly revisit how their ANSYS simulation was done to ensure they do an accurate job that can be reliable and reproducible. The work they did is not that novel, hence, it is expected they should have similar results with what have been reported, if it was accurately done.

Even though the authors claim that using plane stress model do not show significant difference in FE results, I differ with them. ANSYS workbench and mechanical were primarily designed for 3D simulations. Doing a 2D simulation may not give you the best of results. For instance, in this study, the experiment was done using a CSCBD with 15 mm thickness. This was totally ignored in the 2D FEM, which may have an effect in the results generated. Also in 2D, you cannot apply boundary conditions to mimic actual experiment scenario. Hence, you will always get a difference between experiment and computational results.

3. The authors kept on using these wrong words: "Mises stress and Mises strain". There is nothing like Mises stress or strain. It is von Mises stress or von Mises Strain. In ANSYS, it is the Equivalent von Mises stress or Equivalent von Mises strain.

4. The title of figure 6 is contrasting to the result displayed. The unit of the reported SIFs is different from what is on the title.

Overall, I will strongly recommend that the authors go back and redo the ANSYS simulation in such a way that it will accurately simulate the experimental set-up, be reproducible and the results obtained can be reliable.

Therefore, the conclusions they presented in this paper cannot be relied upon since there are unresolved concerns on how the simulation was performed.

**Is the work clearly and accurately presented and does it cite the current literature?**
Partly

**Is the study design appropriate and is the work technically sound?**
Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Fitness-for-service assessment, Failure Analysis, Mechanical Behaviour of Materials.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 22 October 2021

https://doi.org/10.5256/f1000research.76684.r96352

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The concept of linear elastic fracture mechanics (LEFM) has been widely used in practical engineering analyses to study the mechanical behavior of cracked structures/components. Numerical fracture mechanics has appeared to play an essential role in the development of LEFM and has become a useful tool to researchers. Current computational advancement with interactive features permits researchers to study the fracture phenomena in more details.

The Authors attempted to evaluate the SIFs of a centrally straight cracked Brazilian disc made of Polymethyl methacrylate (PMMA) under purely Mode I loading using a commercial finite element based software of ANSYS Workbench. Two-dimensional finite element models of using the quadrilateral and triangle elements were developed. Experimental works on the centrally straight cracked Brazilian disc (PMMA) were carried out. The strain fields were then measured from...
deformed speckle patterns using the digital image correlation (DIC) software. The pre-meshed

crack method in ANSYS Workbench was used to generate meshing around the crack boundaries.

Mode I (opening mode) SIF is the predominant stress field parameter at the crack tip. Even though

the numerical modelling for 2D cracked problems has been established, any updates on the

numerical fracture mechanics are always sought.

The comparisons between the numerical modelling and experimental results are desired in the

engineering analysis.

To benefit the readers, the following comments should be addressed for improvement:

○ In general, the Authors should take the opportunity to refine the explanations/texts on the

findings for clarity, especially with regard to the blunt and sharp crack tips.

○ In this present manuscript, the SIFs for the sharp cracks by the FEM were observed to be

inconsistent. The inconsistencies may be due to the sensitivity of the use of the pre-meshed

method. Therefore, the Authors are encouraged to use the ANSYS APDL to model cracks

(sharp crack tip) in which the crack boundaries may be defined coincidently. Next, the

findings obtained by the ANSYS Workbench and APDL may be compared.

○ The use of DIC should be explained in more details and the discussion on the results should

be further elaborated.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Fracture mechanics, fatigue and failure analysis

I confirm that I have read this submission and believe that I have an appropriate level of

expertise to confirm that it is of an acceptable scientific standard, however I have
significant reservations, as outlined above.

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