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Crack Initiation Prediction in Rock Samples using Digital Image Correlation

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Summary

Crack initiation is important in rock mechanics because it is the first stage in the process of rock failure. Understanding the mechanisms of crack initiation can help engineers predict when and where rock failure is likely to occur, which can inform decisions about design and safety. Crack initiation in rocks can be studied using image processing techniques. Image processing involves the analysis and manipulation of digital images to extract meaningful information. This can be done through techniques such as digital image correlation (DIC), which allows for the measurement of displacement and strain fields in rocks under different loading conditions. Therefore, this paper presents a study aimed at predicting tensile crack initiation in rock samples using DIC. The study used rock specimens of Marble and Travertine and performed direct tensile strength tests to determine their strength characteristics. To do that, the DIC technique was employed to measure the rock surface displacement field under direct tensile stress. Afterwards, the divergence of this field was calculated to identify the location of crack initiation. The results showed that the regions with the maximum positive divergence value reflect the pure relative expansion of the surface, thereby helping in identifying the location of crack initiation.

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Introduction

Digital Image Correlation (DIC), is a non-contact measurement image processing technique used to determine the displacement and strain fields of a material by comparing two or more digital images of a specimen under test. It involves tracking the movement of certain features in the specimen between images, and then using the information to calculate displacement and strain fields (Eichhorn, Bowman, Haigh, & Stainer, 2020). DIC can be used in rock mechanics to study the behaviour and properties of rock materials. It can provide quantitative information about the deformation and strain patterns in rock specimens subjected to various loading conditions, making it a valuable tool for investigating the mechanical properties of rocks. The technique can be used to measure the displacement fields on rock surfaces and provide information about the stress-strain behavior, failure modes, and other important mechanical properties of rock materials. DIC has been used by a number of researchers to study the rock surface displacement field and to gain insights into the mechanics of rock materials (Moazzami, Ayatollahi, & Akhavan-Safar, 2020; Tudisco, et al., 2015). While DIC has been widely used to study the deformation and strain fields in rock specimens, only a limited number of studies have focused on using the technique to study tensile crack propagation, and there are relatively few studies that have specifically investigated crack initiation. This may be due to the technical challenges associated with measuring the very small displacements and strains that occur at the early stages of crack initiation (Liwang , Haibo , Xiaofeng, Di , & Guokai , 2020). Besides, direct tensile (DT) tests are typically more difficult than compressive tests for several reasons, such as: specimen preparation, loading direction, and failure mode (Huang, et al., 2021; Kittitep & Sippakorn, 2010).

Therefore, in this paper we would like to invest in methods that could find the crack initiation under tensile stress before it is noticeable through visual inspection. Thus, the objective is to use DIC and mathematical surface displacement divergence to predict the initiation of cracks in rock samples subjected to tensile stress. To do that, the DIC is first employed to calculate the surface displacement field, followed by the calculation of the divergence of this field. The results show that the divergence field accurately reflects the pure relative expansion of the surface, which helps in identifying the location of crack initiation.

Method

In this study, the process of locating crack initiation is divided into three stages: the direct tensile strength test, the deployment of DIC, and the calculation of divergence (as shown in ***Figure 1***). The stages are presented individually and then gradually interconnected.

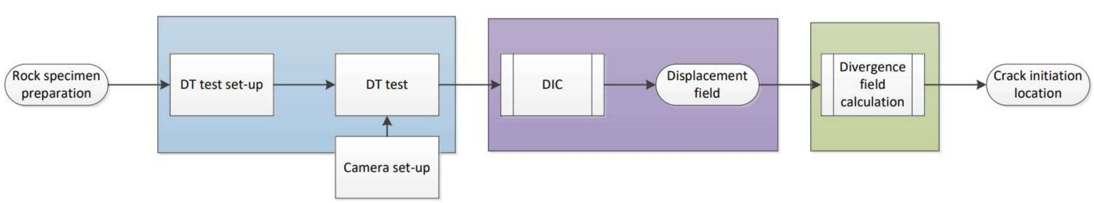

***Figure 1** Proposed method diagram.*

Rock specimen preparation

In this study, 80 rock specimens of Marble and Travertine were utilized, and were obtained following the ISRM standard for coring (54, 65, and 75 diameters with a height-to-diameter ratio of 2 and 2.5). These rocks are widely used for building views and thus, it is crucial to assess their tensile strength. If it is found to be insufficient, measures must be taken to reinforce it or avoid its collapse, ensuring the safety of those in the vicinity. This underscores the importance of determining the tensile strength of these rock types.

Direct tensile strength test

The direct tensile strength tests were performed using a 100-ton universal servo-controlled machine at the rock mechanics laboratory of Amirkabir University. The tests were carried out using specially designed hard steel tension jaws to apply pure tension. The specimens were attached to the steel jaws using resin glue, which also included two flexural hinges to mitigate flexural forces (as shown in ***Figure 2***). Note that, this stage and the specimen preparation are coloured blues in ***Figure 1***. The average tensile strength was found to be 2.62 for Marble and 2.98 for Travertine, indicating that Travertine is harder than Marble. The strength characteristic of these rock types is summarized in ***Table 1***.

Figure 2 *A DARTEC 9600 universal machine (left), The flexural tension jaw (right).*

Table 1 *Strength characteristics of rocks*

Rock Type	Number of Sample tested	Mean UCS (MPa)	Max UCS (MPa)	Min UCS (MPa)	Mean DT (MPa)	Max DT (MPa)	Min DT (MPa)	Mean PLI (MPa)
Marble	40	18.49	28.98	11.42	2.62	3.75	1.89	1.81
Travertine	40	19.14	28.32	13.28	2.98	5.18	1.03	2.04

Digital image correlation technique

To carry out the DIC steps and measure the rock surface displacement field, a system comprised of two 24-megapixel cameras connected to a desktop computer was employed. The cameras were mounted on stands to prevent vibrations, placed one meter from the loading machine (***Figure 3 (a)***). Adequate lighting was provided by LED lamps to illuminate the specimen surface. In cases where the rock sample did not possess adequate surface colour variations for DIC processing, special markers were placed on the specimen surface (***Figure 3 (b)***). This setup remained unchanged throughout the entire direct tensile test procedure, from the start to the failure of the rock, enabling the tracking of specimen volume changes, crack initiation, and rupture. The captured videos were then converted to images (30 images per second), and the DIC technique was applied to calculate the displacement field.

Figure 3 *a) DARTEC and cameras configuration b) Dotted Travertine specimen.*

Divergence field calculation

In this study, after calculating the displacement field, the crack initiation was located by calculating the field divergence. Divergence is a concept in mathematics, particularly in vector calculus, that refers to the measure of how much a vector field "flows apart" from a given point. The divergence of a vector field can be determined by adding up the variations in the values of the vector along the axis parallel to its components. In other words, it represents the degree to which the vectors in a vector field tend to move away from each other *(Kawabe, Maruya, Fleming, & Nishida, 2015)*. Hence, it provides valuable information about the crack in a few frames prior to its initiation. For a two-dimensional vector field, A, consisting of the horizontal component A_x and the vertical component A_y in Cartesian coordinates, the divergence can be calculated using the formula provided (***Equation 1***).

$$\nabla . A = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} \quad \text{(Equation 1)}$$

Results and discussions

This research focuses on finding a method to detect crack initiation under direct tensile strength using a DIC method in combination with field divergence. The results demonstrated that in ¾ ultimate tensile strength, the divergence field starts to show a positive value of divergence in some areas. For more than 80 percent of the tested samples the maximum positive value for divergences indicates the crack initiation location. ***Figure 4*** demonstrates a sample tensile output that indicates the crack initiation location (marked a with red curve). Note that the displacement field rapidly changes around this region that validates the locating. These findings agree with the results of previous research, that suggests using the DIC can be beneficial for rock crack propagation studies. Besides, it proves that the divergence field that is often used in fluid mechanics for locating low and high-pressure regions is applicable to other material movement investigations. Further studies are necessary to confirm the findings of this study. First of all, we need more advanced cameras to capture higher resolution images with more frames per second. Next, we suggest further studies with more rock specimens under compressive stress as well. Finally, we recommend the investigation of other mathematical methods to track the crack propagation and characterization such as crack depth, orientation, and length.

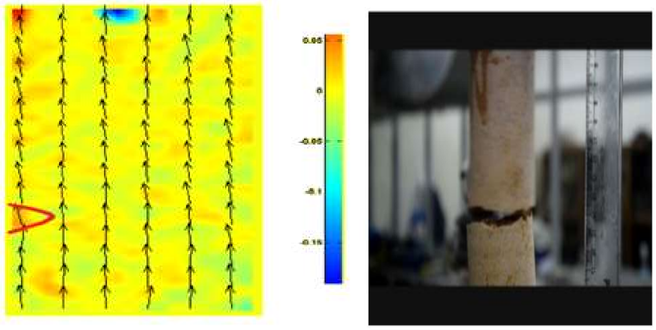

Figure 4 *The divergence field and the crack initiation location before rupture (left), The rock specimen after rupture (right)*

Conclusions

In conclusion, this research aimed to find a method for detecting crack initiation under direct tensile strength using the DIC method combined with field divergence. The results showed that for over 80% of the tested samples, the maximum value for divergences indicated the crack initiation location. The findings of this study align with previous research and demonstrate the potential benefits of using the DIC method for rock crack propagation studies. However, further research is necessary to confirm these results, including the use of advanced cameras, more specimens under compressive stress, and the investigation of other mathematical methods for crack characterization.

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