ENHANCED EVALUATION OF TENSILE BEHAVIOR IN STEEL FIBER REINFORCED CONCRETE VIA DIC-BASED INDIRECT TENSILE TESTING

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RESUMEN

Este estudio presenta una modificación del ensayo brasileño, diseñado para medir la resistencia a tracción de cubos de hormigón reforzado con fibras, utilizando piezas de carga en forma de T y una rótula que minimiza la excentricidad. Esta configuración garantiza la estabilidad de la muestra, una carga centrada con precisión y una propagación predecible de las fisuras. Un sistema de correlación digital de imágenes (DIC) permite un análisis preciso del hormigón reforzado con fibras de acero, identificando los puntos de inicio de las fisuras y las cargas correspondientes. Los resultados experimentales validan el DIC como una alternativa superior a las bandas extensométricas, respaldado por el software GOM. La metodología proporciona datos cualitativos del DIC, capturando deformaciones principales y el comportamiento local durante las pruebas de tracción indirecta. Se observó fisuración en la matriz en aproximadamente el 60% de la resistencia a tracción, destacando la sensibilidad del DIC para detectar el inicio de la fisuración. El uso combinado de las piezas en forma de T, la rótula y el sistema DIC mejora significativamente la evaluación del comportamiento a tracción y el comportamiento en fractura del hormigón.

ABSTRACT

This study introduces an innovative Brazilian test method for measuring the tensile strength of concrete cubes using a novel T-shaped loading mechanism with a hinge arrangement. This setup ensures specimen stability, precise load centering, and predictable crack propagation. A Digital Image Correlation (DIC) system enables accurate analysis of steel fiber-reinforced concrete, identifying crack initiation points and corresponding loads. The experimental results validate DIC as a superior alternative to traditional strain gauges, supported by licensed GOM software. The methodology provides qualitative DIC data, capturing major strains and local behavior during indirect tensile tests. Matrix cracking was observed at approximately 60% of tensile strength, showcasing DIC's sensitivity to early fracture detection. The combined use of the T-shaped mechanism and DIC system significantly improves the evaluation of concrete's tensile performance and fracture behavior.

PALABRAS CLAVE: Prueba brasileña modificada, inicio de fisura, DIC, SFRC
KEYWORDS: Modified Brazilian test, crack initiation, DIC, fracture behavior, SFRC

1. Introduction

The tensile strength of concrete is a critical parameter in structural design and performance evaluation, as it directly influences the durability and load-bearing capacity of concrete structures. While the direct tensile test is recognized as the most accurate method for determining tensile strength, its application is limited in practice due to the challenges associated with uniformly applying tensile loads to concrete specimens. This limitation has led to the widespread adoption of indirect testing methods, with the Brazilian test being one of the most commonly used approaches [1,4,5]. The Brazilian test, also referred to as the splitting tensile test or diametral compression test, involves applying a compressive load along the diameter of a cylindrical or cubic specimen. This induces tensile stresses along the loaded diameter, ultimately resulting in specimen failure.

Despite its simplicity and cost-effectiveness, the traditional Brazilian test is not without drawbacks. Key limitations include:

- Difficulty in accurately identifying the onset of cracking.
- Uneven crack propagation in both faces of the specimen.

To address these challenges, this study introduces a modified Brazilian test setup that aims to enhance the reliability and scope of tensile strength evaluation. The modifications include:

- A novel T-shaped loading mechanism with a hinge arrangement to improve specimen stability and ensure precise load application.
- The incorporation of Digital Image Correlation (DIC), a non-contact optical technique capable of accurately capturing surface displacements and strains.

By integrating these innovations, the proposed approach provides a more comprehensive understanding of concrete's tensile strength and fracture behavior, paving the way for improved structural assessments.

2. Materials & Methodology

2.1 Mix Proportion

The materials used in this study were carefully selected to ensure consistency and reliability in experimental results. The composition is detailed in Table 1. The concrete mix was designed to achieve high performance, incorporating key components such as cement, water, superplasticizer, air-occluded reducer, limestone powder, and aggregates.

The compressive strength of the concrete was measured using standard specimens: cylindrical samples with dimensions of 150 mm in diameter and 300 mm in height yielded a mean compressive strength of 56.7 ± 1.8 MPa, while 100 mm × 100 mm cubic specimens demonstrated slightly higher strength at 58.6 ± 3.4 MPa. The elastic modulus was determined to be 32.9 ± 0.8 GPa, reflecting the material's stiffness under applied stress. The steel fibers used in the mix had a length of 35 mm, contributing to the enhanced tensile performance of the concrete.

The compressive strength and elastic modulus of the concrete were determined according to standard procedures[1,5,6].

Table 1. Composition of Materials.

Material	**kg/m³**
Cement	380
Water	182
Superplasticizer	3.800
Air-Occluded Reducer	1.518
Limestone Powder	90
Fine Aggregate (0–4 mm)	950
Coarse Aggregate (4–12 mm)	525
Coarse Aggregate (12–20 mm)	225
Steel Fiber	47.1

2.2 Modified Brazilian Test Setup

The modified Brazilian test setup employed in this study is depicted in Figure 1. The key features of this setup are:

•Cubic concrete specimens (100 mm × 100 mm × 100 mm) were chosen for their advantageous fiber alignment compared to cylindrical specimens

•T-shaped loading devices were used to apply the compressive load to the specimen.

•3D-printed plastic cushions with a low elastic modulus were placed between the loading device and the specimen to ensure even load distribution and minimize stress concentrations.

•A hinge mechanism was incorporated into the loading device to allow for minor angular adjustments and ensure precise load centering, minimizing eccentricity.

The width of the bearing surface on the T-shaped loading device was set to 15% of the cube's side length (b = 0.15L) to balance stability with the desired stress distribution. The experiments were conducted using a 1 MN servohydraulic universal testing machine [8].

2.3 Digital Image Correlation (DIC) System

A 2D-DIC system was integrated into the Brazilian test setup to capture and analyze the full-field deformation, crack nucleation, and propagation in SFRC specimens [2,3]. The DIC system consisted of:

•High-resolution cameras to capture images of the specimen surface during loading.

•A random speckle pattern applied to the specimen surface to provide distinct features for the DIC algorithms to track.

•GOM Correlate software, a licensed DIC software package used for processing the captured images and calculating displacement and strain fields

2.4 Strain Guages

In addition to the DIC system, strain gauges were attached to two opposing faces of the specimen to provide comparative data and validate the DIC measurements. The strain gauges used were HBM K-CLY4-0100-1-120-3-005, chosen for their high accuracy and temperature compensation capabilities.

2.5 Testing Procedure

The cubic SFRC specimens were loaded in compression in displacement control using the modified Brazilian test setup. During loading, images of the specimen surface were captured by the DIC system, and strain data was recorded from the strain gauges. The loading was continued until the specimen failed, typically by splitting along the loaded surface [7].

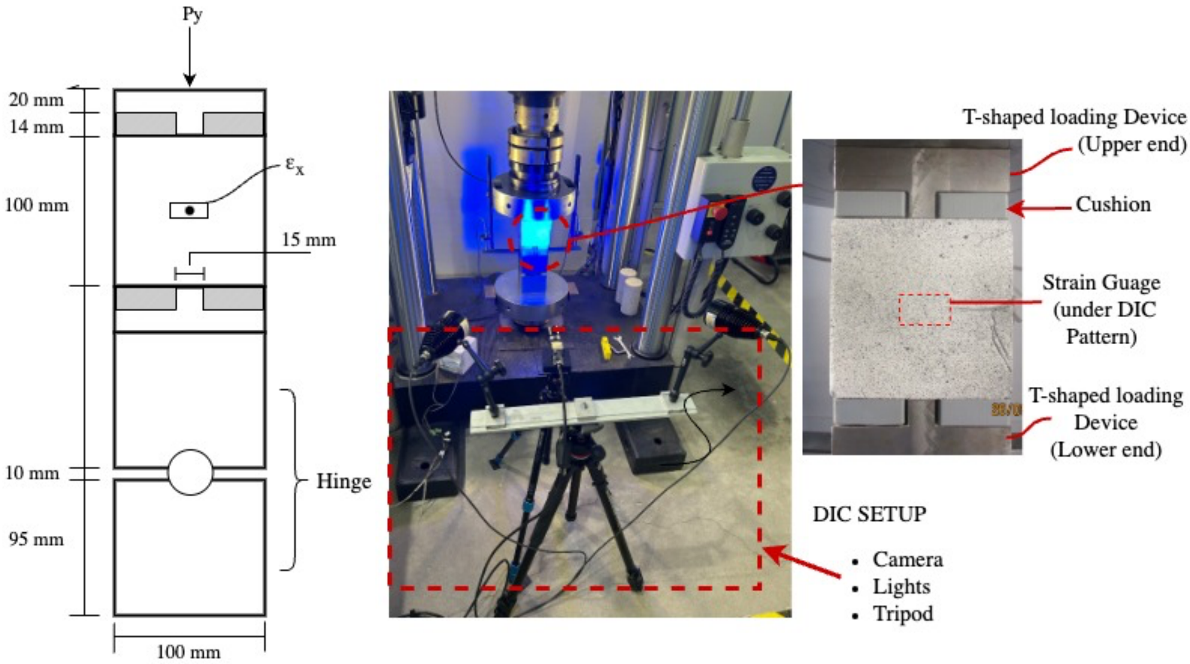

Figure 1 : Experimental setup of the Modified Brazilian Test configuration with integrated DIC system.

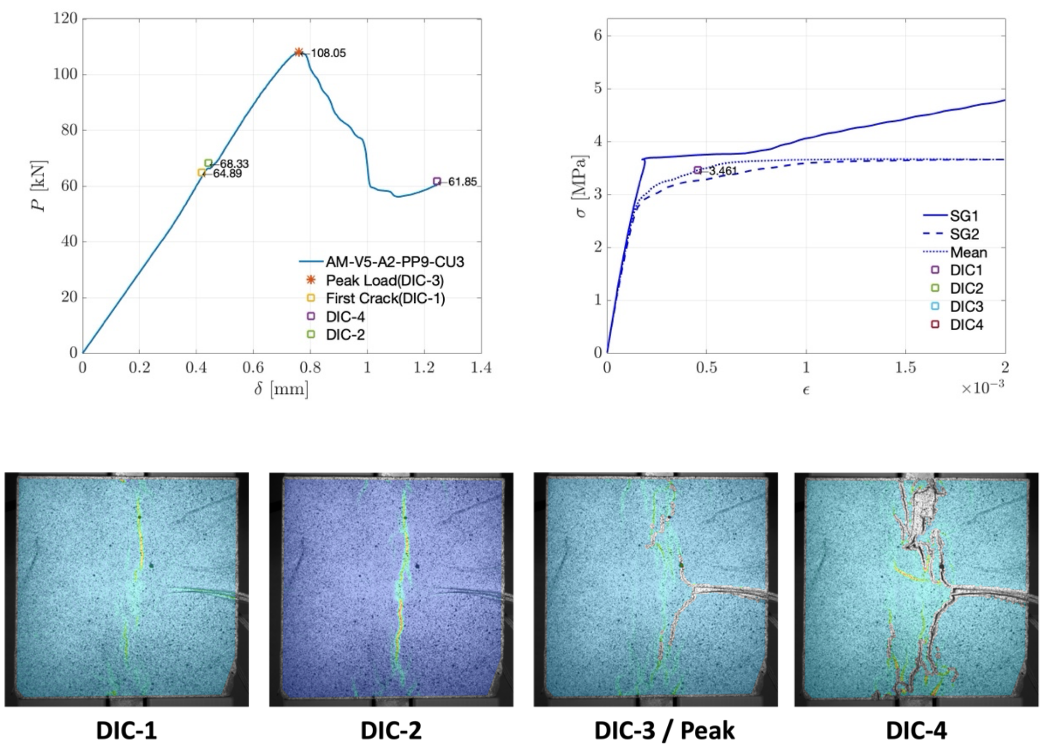

Figure 2 : Load-displacement curves and corresponding DIC strain fields (DIC-1 to DIC-4) illustrating fracture behavior and strain localization at critical load stages.

3. Results and Discussion

3.1 Crack Initiation Detection

The DIC system proved highly effective in detecting the initiation of micro-cracks in the SFRC specimens, a critical aspect often difficult to capture with traditional methods. Crack initiation was observed at a crack opening displacement of approximately 0.4 micrometers, which was corroborated by the strain gauge data.

The load-displacement curves obtained from the Brazilian tests exhibited a characteristic drop in load, indicating the onset of significant cracking shown in figure 2a. This drop in load corresponded with the rapid increase in strains measured by the strain gauges positioned at the center of the specimen, further confirming the initiation of cracking

3.2 Crack Propagation Analysis

The DIC system allowed for detailed visualization and analysis of crack propagation throughout the loading process. Representative DIC images captured at different stages of loading, (shown in Figure 2b) clearly show the evolution of the crack from initiation to complete specimen failure. These images provide valuable insights into the fracture behavior of SFRC under indirect tensile loading.

3.3 Tensile Strength and Cracking Stress

The modified Brazilian test setup combined with the DIC analysis enabled accurate determination of the indirect tensile strength of the SFRC. The average peak load from the tests was used to calculate the tensile strength according to the relevant standards. The research determined that the initial cracking stress in the SFRC was approximately 4.5 MPa, while the tensile strength was 7.4 MPa. Notably, matrix cracking was observed to occur at approximately 60% of the SFRC's tensile strength, highlighting the DIC system's sensitivity in detecting early fracture.

3.4 Advantages of the DIC System

The study demonstrated the DIC system's effectiveness as a superior alternative to traditional strain gauges for several reasons:

•Full-field measurement: DIC provides displacement and strain measurements across the entire specimen surface, offering a more comprehensive understanding of deformation behavior than strain gauges, which only provide point measurements.

•Non-contact measurement: The non-contact nature of DIC eliminates the potential for influencing the specimen's response, which can occur with attached strain gauges.

•Early crack detection: The DIC system's high sensitivity enables detection of micro-cracks at very early stages, even before significant load drops or visible cracks appear.

4. Conclusions

This research highlights the effectiveness of a novel approach to the Brazilian test for evaluating the tensile strength of concrete, particularly SFRC. The key findings are:

•The modified Brazilian test setup, featuring a T-shaped loading mechanism with a hinge arrangement, ensures specimen stability, precise load centering, and uniform crack initiation in both sides.

•The integration of the DIC system enables accurate and detailed measurement of deformation, crack initiation, and propagation, providing valuable insights into the fracture behavior of concrete.

•The DIC system surpasses traditional strain gauges in providing full-field, non-contact measurements and exhibits superior sensitivity in detecting early-stage micro-cracks.

•The combination of the modified test setup and DIC technology offers a comprehensive and robust framework for assessing concrete's tensile performance, significantly enhancing our understanding and evaluation capabilities.

These findings have significant implications for the field of concrete testing and structural design, paving the way for more accurate and reliable assessments of concrete's tensile behavior.

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