Investigation of Tensile Behavior of Steel Plates and Epoxy Material Using Digital Image Correlation

Elias Toumeh [1], Ghoson Danhash[2]

1 Master student at structural civil engineering college /Homs University.

2 Head of structural engineering department at civil engineering college /Homs University.

Abstract:

This study aims to investigate the tensile behavior of steel plates and Epoxy material by employing both conventional and advanced deformation measurement techniques. Tensile deformations were monitored using the traditional linear variable differential transformer (LVDT) alongside the optical, non-contact digital image correlation (DIC) technique. The DIC method operates by capturing high-resolution images before and after deformation, allowing full-field measurement of displacements and strains without physically contacting or damaging the specimen.

Specimens were prepared by applying a high-contrast speckle pattern on the surface to facilitate accurate image tracking. Video recordings of the tensile tests were processed to extract displacement and strain data, which were then compared against the results obtained from LVDT. This comparison aimed to evaluate the accuracy, advantages, and limitations of each measurement technique, especially focusing on the effectiveness of DIC in complex hybrid steel-epoxy interfaces.

The results demonstrated strong correlation and agreement between the DIC and conventional methods, confirming DIC as a reliable tool for capturing detailed strain distributions over time. The optical technique also overcame common issues observed with contact sensors, such as slip and localized measurement errors.

This research contributes valuable insight into the application of DIC for hybrid joint testing, supporting its use in structural engineering design and numerical modeling validation, and enhancing understanding of tensile mechanics in composite materials.

Keywords:

Steel, epoxy, Digital Image Correlation DIC, tensile behavior.

دراسة سلوك الصفائح الفولاذية ومادة الإيبوكسي باستخدام تقنية ارتباط الصور الرقمية

ملخص:

تهدف هذه الدراسة إلى التحقق في سلوك مادتي الفولاذ والإيبوكسي على الشد باستخدام كل من تقنيات قياس التشوه التقليدية والمتطورة. تم رصد تشوهات المواد على الشد باستخدام محول الإزاحة التفاضلي المتغير الخطي (LVDT) التقليدي إلى جانب تقنية ارتباط الصور الرقمية (DIC) البصرية عن بعد. تعمل طريقة DIC من خلال التقاط صور عالية الدقة قبل التشوه وبعده، مما يسمح بالقياس الكامل للإزاحات والانفعالات دون التلامس الفيزيائي مع العينة أو إتلافها.

تم تحضير العينات من صفائح فولاذية بحسب {(ISO6892-1:2019) المواد المعدنية – اختبار الشد – الجزء طريقة الاختبار في درجة حرارة الغرفة}.

بأبعاد مقطع (73 mm x 6.4 mm) وبطول حر بين الفكين (Lo = 122 mm) في جهاز الشد في مخبر البيتون في كلية الهندسة المدنية في جامعة حمص.

حيث أن Lo: عادةً ($5.65\sqrt{S_0}$ or $4\sqrt{S_0}$)،

S_0: هي مساحة المقطع العرضي الأصلي

بتطبيق نمط تنقيط عالي التباين على السطح لتسهيل التتبع الدقيق للصورة. تم معالجة التسجيلات المصورة لاختبارات الشد لاستخراج بيانات الإزاحة والانفعال، والتي تمت مقارنتها بعد ذلك بالنتائج المستخلصة منLVDT ، هدفت هذه المقارنة إلى تقييم دقة ومزايا وقيود كل تقنية قياس، مع التركيز بشكل خاص على فعالية DIC على سطوح الفولاذ–الإيبوكسي الهجينة المعقدة.

أظهرت النتائج وجود توافق قوي بين طريقة DIC والطرق التقليدية، مما يؤكد أن DIC أداة موثوقة لالتقاط توزيعات الانفعال التفصيلية عبر الزمن. كما أن التقنية البصرية تجاوزت المشكلات الشائعة الملاحظة مع أجهزة الاستشعار التلامسية، مثل الانزلاق وأخطاء القياس الموضعية.

يساهم هذا البحث في تقديم رؤى قيمة حول تطبيق DIC لاختبار الوصلات الهجينة، مما يدعم استخدامه في تصميم الهندسة الإنشائية والتحقق من النمذجة العددية، ويعزز فهم ميكانيكا الشد في المواد المركبة.

الكلمات المفتاحية:
فولاذ، الإيبوكسي، ارتباط الصور الرقمية DIC، السلوك الشدّي

Introduction

Determining the stress–strain curve in material testing is a critical factor for ensuring safe structural design due to its fundamental role in characterizing material behavior under various loading conditions and identifying critical load thresholds and appropriate safety factors [Danhash et al., 2012→2024]. The

stress–strain curve is widely used in tensile testing of steel to determine essential mechanical properties such as ultimate tensile strength, yield stress, modulus of elasticity, and strain at failure. These parameters are indispensable for selecting appropriate cross-sectional dimensions and evaluating the integrated performance of structural elements. Accurate stress–strain characterization of steel is particularly vital when incorporating the data into finite element modeling programs, such as ABAQUS, to verify the reliability and predictive capability of numerical simulations [Abdulahad & Danhash, 2025], [Danhash, 2025].

Various deformation measurement techniques exist, classified based on their working mechanisms, the equipment used, and installation methods. These include electrical conversion–based devices such as linear variable differential transformers (LVDT), resistance change–based sensors like strain gauges, and advanced optical methods relying on image processing algorithms, such as digital image correlation (DIC).

Digital Image Correlation (DIC) technique

DIC is a non-contact optical method for studying surface deformations without damaging or physically interacting with the specimen. It operates by comparing digital images taken before and after the deformation of the specimen surface, allowing monitoring of displacements, strains, velocities, and accelerations in all directions over the entire surface [Gdoutos, 2022]. Initially, the specimen surface is cleaned and painted white, followed by applying a speckle pattern with approximately 50% black spray over the white background. During tensile loading, video is captured under steady lighting

conditions, with the camera positioned perpendicular to the surface and set to high resolution [Rossman et al., 2017].

The recorded video undergoes several processing steps using specialized software: excess frames are removed to include only the loading phase until failure and images are converted to grayscale. The grayscale images are then imported into software such as GOM, where numerical algorithms calculate displacements of reference points (see Figure 1) using virtual extensometers placed in areas of interest. To ensure accurate measurements, a random speckle pattern is essential on the specimen surface as a reference for the correlation algorithm. In some materials, like cement, the naturally rough surface provides an inherent speckle pattern.

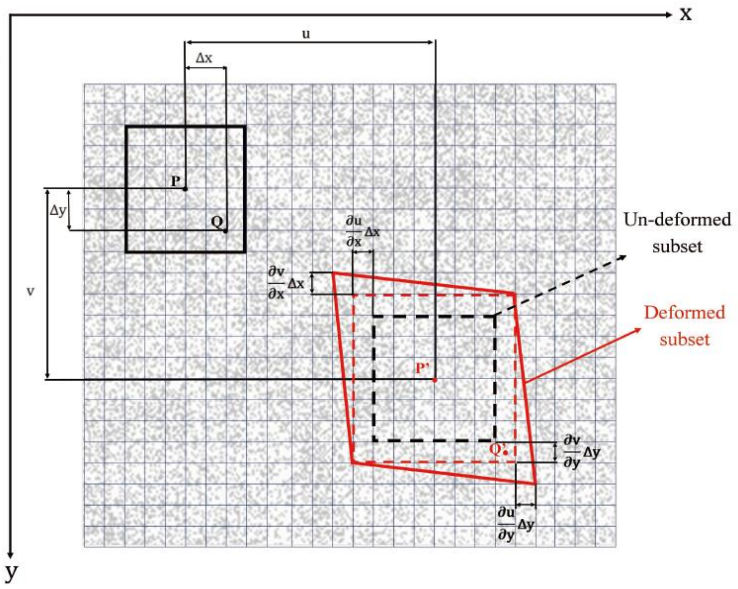


Figure 1. Principle of operation of the Digital Image Correlation (DIC) technique

Digital Image Correlation (DIC) has emerged as a reliable technique for studying the bond behavior between steel and recycled aggregate concrete, as well as for measuring strain in various materials. Research indicates that DIC-derived displacement-time curves align closely with those obtained from traditional methods like LVDT, confirming its effectiveness in experimental deformation tracking. DIC was employed to analyze bond-slip behavior in steel-recycled aggregate concrete, revealing that bond strength decreases with higher replacement ratios of recycled aggregates (Danhash et al., 2023). The study demonstrated that DIC results were comparable to LVDT measurements, validating its use in assessing bond behavior in concrete mixes with varying recycled content (Danhash et al., 2023). DIC has been validated for obtaining strain-time curves in tensile tests of steel, showing strong correlation with strain gauge measurements (Mousa et al., 2023). The technique's non-invasive nature and ability to provide full-field measurements enhance its applicability in structural testing, making it a preferred choice over traditional methods (Mousa et al., 2023).

Research Problem:

Tensile testing of steel plates aims to acquire the stress-strain curve, from which modulus of elasticity and yield stress are determined properties fundamental to steel design. However, challenges arise due to measurement inaccuracies, mostly caused by slipping of the steel plate within the grips of the tensile machine despite surface roughening and tack welding, resulting in erroneous displacement and strain data when using LVDT sensors attached to the grip jaws. Such issues prevent capturing precise strain-time and strain-stress relationships.

For validating the accuracy of DIC, the present study used two methods, the first involves securely welding attachment plates to the specimen surface to firmly fix the LVDT sensor, minimizing slip and measurement error; the second solution is to apply the DIC technique, which inherently eliminates slip measurement errors due to its non-contact nature.

The aim of the present study

The primary objective of this study is to validate the feasibility and accuracy of using the Digital Image Correlation (DIC) technique for strain measurement in tensile tests of steel plates, by comparing its results with those obtained from a welded-fixed LVDT sensor securely attached to the specimen surface. Additionally, the study aims to assess the effectiveness of DIC in measuring tensile elongation in two types of epoxy materials and to compare these measurements with elongation data provided by the tensile testing machine's computer software. The previous experimental curves are required in simulating the hybrid joints (steel-epoxy-CFRP) for obtaining the real behavior of the joint.

Experimental Procedure

Tensile Testing of Steel Specimens

Three steel specimens were tested with cross-sectional dimensions of 73×6.4 mm, Lo = 122 mm as shown in Figure 2. Tests were conducted using a universal tensile testing machine at the Concrete Laboratory, Faculty of Civil Engineering, University of Homs. Tensile deformations were recorded using an LVDT sensor initially mounted between the machine jaws (Figure 3).



Figure 2. The tensile experimental process of the steel plate

Initial results obtained via the LVDT, due to grip slippage during testing, produced unrealistic modulus of elasticity values (65.4 MPa).

The test was repeated with two types of measurements, where the LVDT was re-mounted directly onto the first face of the specimen (Figure 3) using welded steel attachment plates, ensuring stability and minimizing sensor drift during loading. This method, although effective, introduced localized weaknesses in thinner specimens.



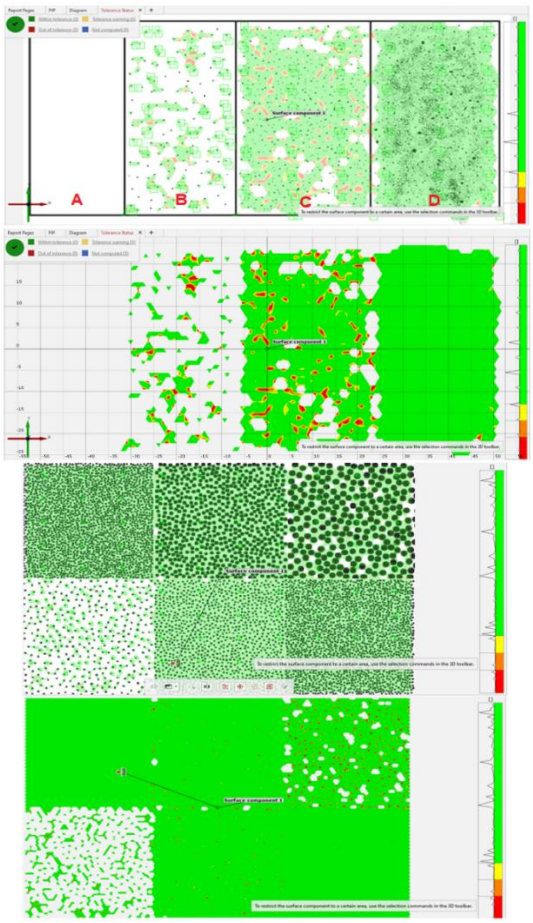
Figure 3. LVDT fixed on the steel plate

To facilitate DIC analysis, the second face of the specimen was first coated with white paint, followed by application of a black speckle pattern, and video recording was performed during loading. This two-faces measuring procedure was suggested for obtaining the elongation-time curve for the same specimen at the same time for validation DIC's measurements.

Multiple speckle pattern designs were evaluated in GOM (Figure 4) before the test, revealing that increased speckle density improved tracking quality. Pattern D was ultimately selected due to its high correlation quality, full tracking coverage, and ease of application with a brush. Sensor placement in GOM (Extensometer) is illustrated in Figure 5.

Displacement–time data were extracted from the LVDT via Excel (Figure 6) and from DIC-processed GOM data (Figure 7). The results showed strong agreement between LVDT and DIC measurements. Stress–strain curves

generated from both methods yielded modulus of elasticity $E = 200.4 \times 10^3 [MPa]$ and yield stress $Fy = 343\ [MPa]$, see (Figure 8).



(a) (b)

Figure 4. Speckle patterns density investigated in GOM

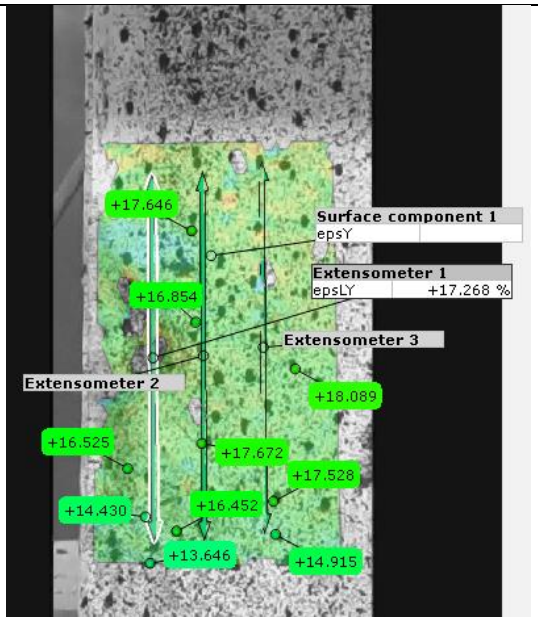


Figure 5. Sensors placement in GOM (Extensometers)

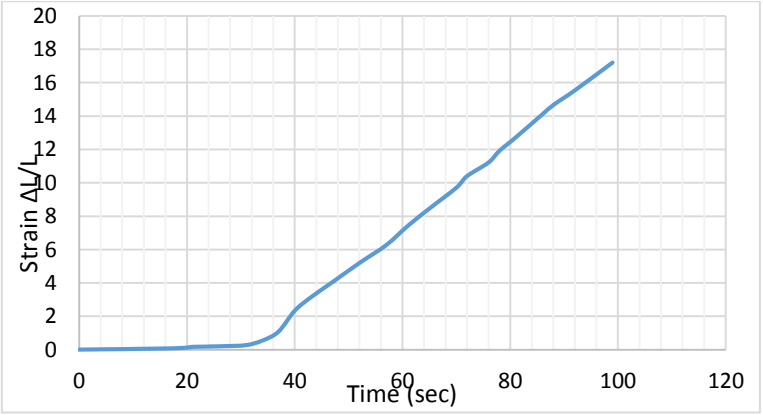


Figure 6. Stress–Time curve obtained from LVDT

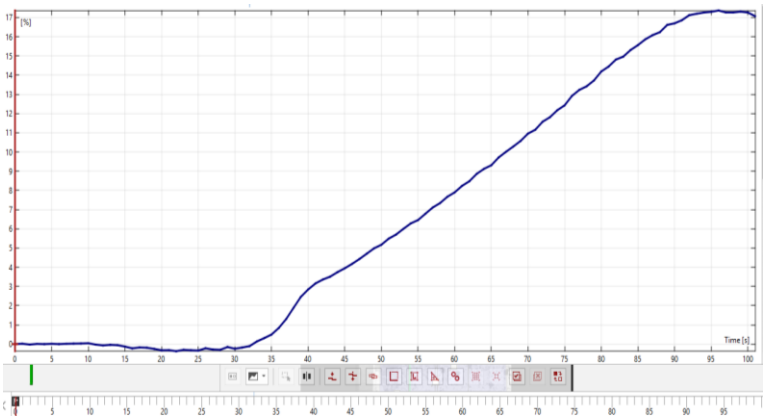


Figure 7. Stress–Time curve obtained from DIC

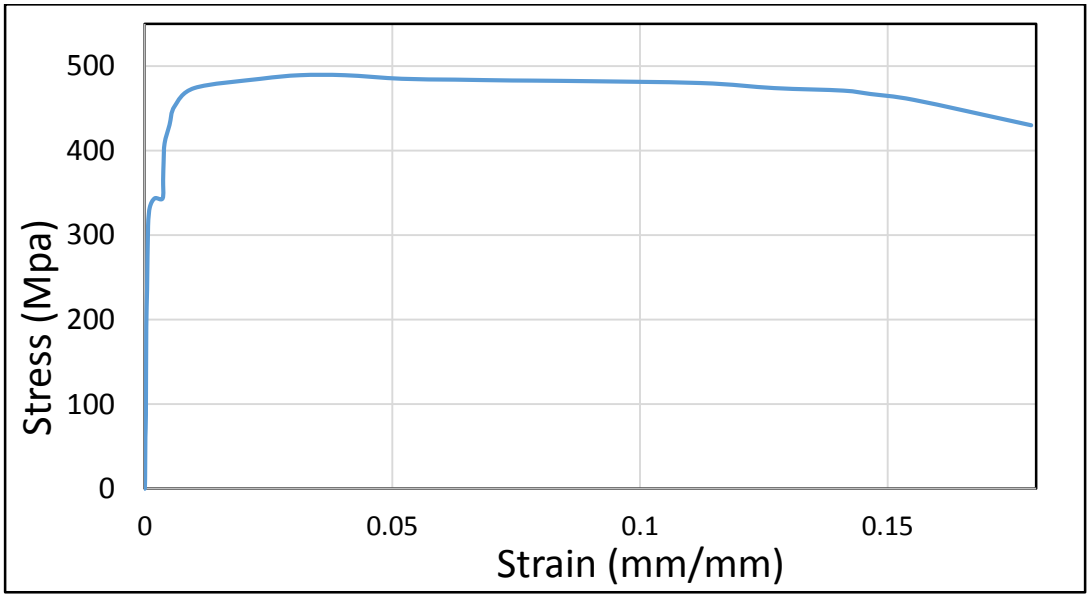


Figure 8. Stress–strain curve for steel plate

Tensile Testing of Epoxy Specimens

Sikadur–31 Epoxy

Three specimens (dog–bone) shape of Sikadur–31 epoxy were tested, conforming to ASTM C 881–78 Type 1, Grade 3, Class B + C specifications

with thickness of 4 mm and , Overall length: 165 mm (6.5 inches) Length of measurement: 50 mm (2 inches) , Width at the narrow section: 13 mm (0.5 inches) a mixing ratio of 2:1. as shown in Figure 10. Speckle patterns were applied, allowing GOM software to easily register reference points for vertical displacement tracking. Displacement–time curves obtained from the tensile machine (Figure 11), calculated from machine-connected computer software, closely matched those derived from DIC analysis, as shown in Figure 10.

Stress-strain curve then was obtained (Figure 12) enabling the calculating the tensile strength and fracture energy (required for finite element method), which is the area under the stress–strain curve, approximated by the triangle formed from maximum stress before failure and corresponding elongation. The average measured tensile strength was 8.39 [MPa].

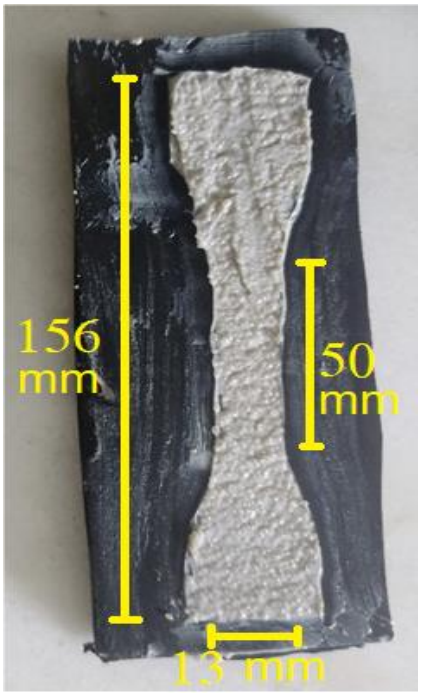


Figure 9: Epoxy sample dimensions

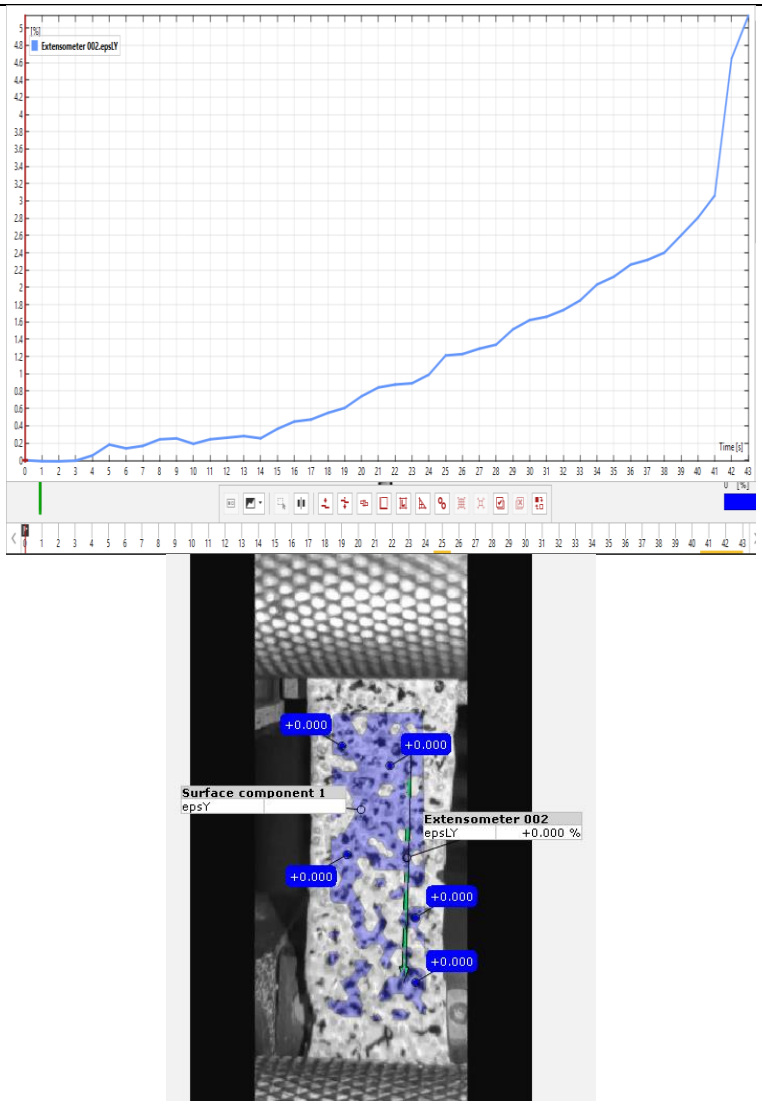
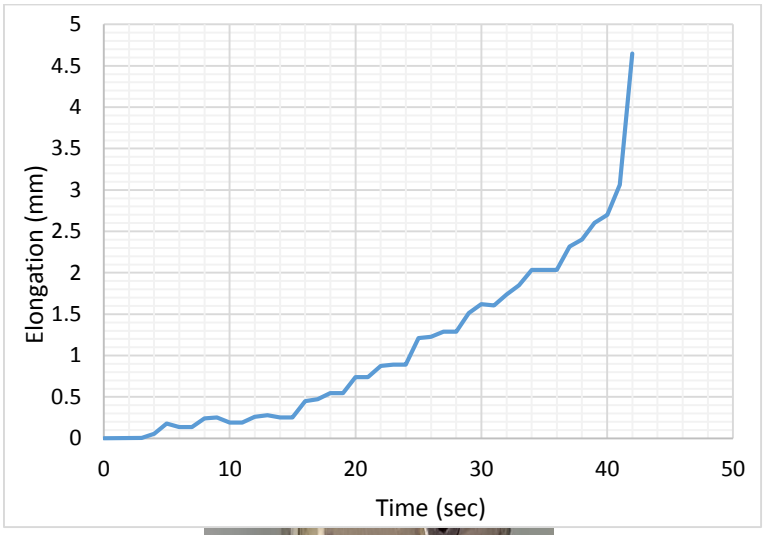


Figure 10. Elongation–time curve obtained from DIC for Sikadur–31 Epoxy



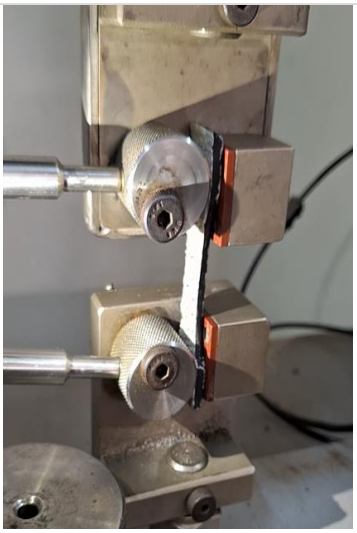


Figure 11. Elongation–time curve for Sikadur–31 Epoxy from tension machine

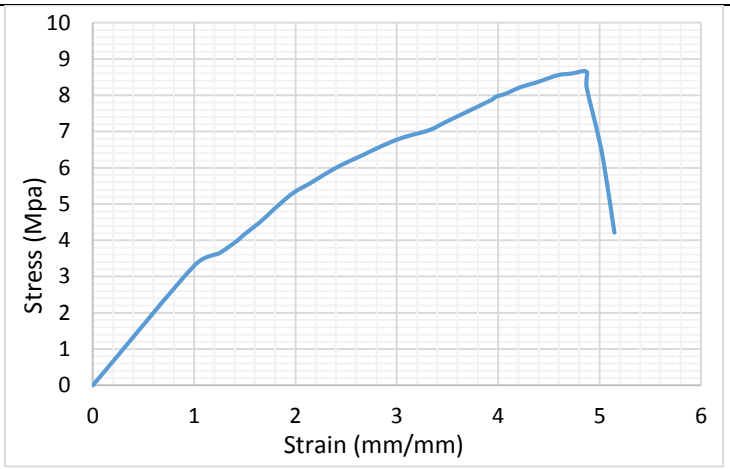


Figure 12. Stress–strain curve for Sikadur–31 Epoxy from tension machine

Ekostik Epoxy

Three specimens of fast–curing Ekostik epoxy were tested, with a 1:1 mixing ratio and thickness of 4 mm, to evaluate tensile strength and mechanical performance. Displacement–time curves obtained via DIC processing (Figure **13**) were in excellent agreement with curve recorded by the tensile machine (Figure 14). Stress–strain curves produced for these specimens confirmed the accuracy of DIC measurements. The average measured tensile strength was 6.82 [MPa], see (Figure 15).

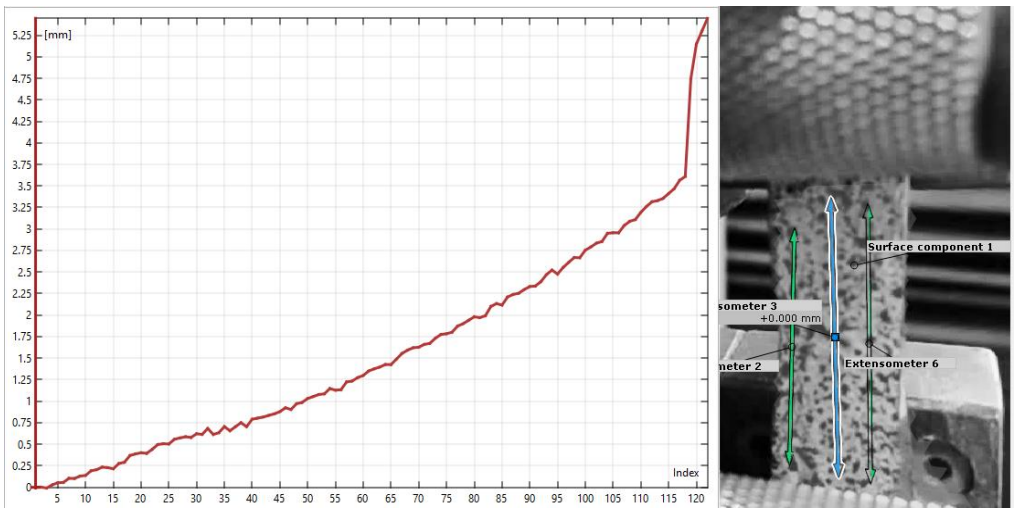


Figure 13. Stress–elongation curve for Ekostik Epoxy from DIC

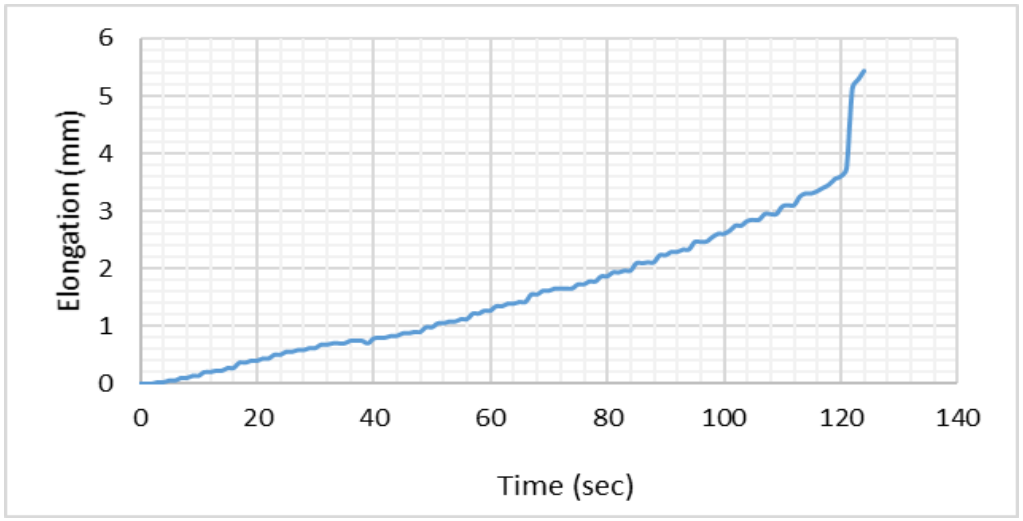


Figure 14. Stress–elongation curve for Ekostik Epoxy from tension machine

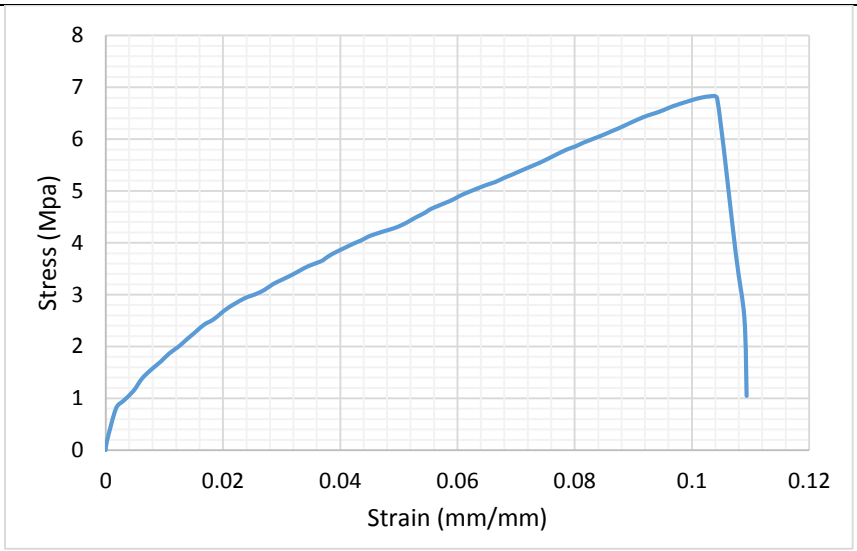


Figure 15. Stress–stress curve for Ekostik Epoxy from tension machine

Conclusion

The experimental program yielded a comprehensive comparison between the digital image correlation (DIC) technique and the conventional linear variable differential transformer (LVDT) method for tensile deformation measurement in steel and epoxy specimens. Data analysis confirmed that the DIC method is capable of producing highly accurate strain and displacement measurements, closely matching results from LVDT recordings under controlled conditions.

For steel specimens, tensile deformations recorded by DIC demonstrated strong numerical agreement with those obtained from LVDT sensors. The displacement–time and stress–strain curves generated from both methods exhibited nearly identical slopes in the elastic region, leading to consistent

modulus of elasticity values $E = 200.4 \times 10^3$ and yield stresses $F_y = 343\ [MPa]$. This correlation validates the reliability of DIC for steel testing and indicates that, when properly configured, DIC provides comparable precision to well-secured contact sensors, even under conditions where specimen grip slippage may compromise LVDT accuracy.

Similarly, a stress–strain diagram for the epoxy material was obtained, and a strong agreement was observed between the time-based deformations monitored using the DIC technique and the time-based deformation values obtained from the tensile testing machine.

The intrinsic advantage of DIC in such cases stems from its non-contact nature, which eliminates mechanical interference and measurement error caused by relative movement between the sensing device and specimen.
The accuracy of DIC was found to be highly dependent on optimal speckle pattern application and calibration through GOM software's correlation quality metrics. Tests revealed that low-density or unevenly distributed speckles reduced the number of reliable reference points, resulting in incomplete strain maps and localized tracking errors. Improving speckle uniformity.
DIC testing provided operational advantages over LVDT measurements when applied to steel specimens. The procedure required only the stable mounting of a video camera and appropriate lighting, as opposed to the more labor-intensive LVDT setup, which demanded welding of steel attachment plates to ensure sensor stability during loading. This welding not only consumed additional preparation time but also introduced potential structural

discontinuities in thin specimens, thereby risking premature failure or altered mechanical behavior.

In contrast, DIC's optical setup involved no direct contact with the specimen, minimizing risk of physical interference and preserving material integrity. These practical benefits underscore DIC's suitability for testing materials where sensor attachment is challenging, specimen geometry is irregular, or contact measurement could induce unwanted mechanical effects.

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