subsequent pull-out of individual fibers, which is revealed on the fracture surface [13,14]. Collectively, these factors contribute to ply-level fracture toughness that is more than three times greater than that of a single fiber. When a compressive loading is applied in the fiber direction, the possible failure will be in two ways: shear-driven fiber failure or fiber kinking. The precise form of failure seen is determined by elements such as the existence of shear loads, which might occur as a result of localized fiber misalignment. Shear failure causes bending ahead of the fracture point, which eventually results in fiber kinking failure [15,16].

An intralaminar crack occurs entirely within a single ply, usually parallel to the fibers. It can be caused by a variety of factors, including fiber breakage, matrix cracking, and fiber-matrix debonding. Interlaminar cracks, as opposed to those that occur within a single ply, occur between the plies. They are essentially layer separations that are frequently caused by shear stresses, impact damage, and defects in production. Translaminar cracks, on the other hand, penetrate the whole thickness of the laminate, potentially initiating an intralaminar or interlaminar crack and propagating through several plies. The fracture surface produced by intralaminar matrix cracking that grows longitudinally emphasizes that the estimated toughness of such failure modes is close to that of their interlaminar counterparts [17,18]. The critical strain energy release rates correlated to such failures are inherent material features that necessitate extensive characterization to fully comprehend the damage tolerance of the material system under investigation. The primary focus in the characterization of translaminar fracture is on toughness measurement of multidirectional laminates made from UD or 2D woven composite material structures [19,20]. In such conditions, the determined toughness is influenced by the lay-up configuration and results from a large number of constituent plies failing in combinations of the aforementioned failure causes. Only those tests associated with compact tension, three/four-point bending experiment, and extended compact tension tests show stable crack propagation in the samples among the numerous specimen configurations used in the literature [21 23]. Crack growth stability is crucial for generating resistance curves (R-curves), which track variations in the critical strain energy release rate as damage evolves. Compact Tension (CT) is extensively used for assessing translaminar fracture toughness in composite materials. This configuration has been widely employed for characterizing laminates comprising a diverse range of materials, including carbon/epoxy, carbon/carbon, carbon/PEEK, and boron/aluminum. A common approach for data analysis involves calculating the critical stress intensity factor, K_{Ic}, following the ASTM E399 guidelines for metallic materials [24]. Nevertheless, it s important to note that these attributes, which are dependent on the lay-up, have limited practical utility since they don t capture intrinsic material qualities. Several studies introduced the concept of an intrinsic material property known as K_{Ic0}, which represents the fracture toughness of the 0°-lamina within a composite laminate, irrespective of the lay-up configuration [25,26]. This concept draws from classical lamination theory, where the stress endured by the 0°-lamina in a laminated composite ($_{0c}$) is related to the applied stress on the laminate ($_c$) through the layer elastic property. Notably, this same parameter connects K_{Ic} and K_{Ic0}, underscoring that K_{Ic0} is indeed an intrinsic material attribute. In order to determine the fracture toughness related to translaminar tensile and compressive failure modes, researchers have employed diverse methods and specimen configurations. These studies have yielded invaluable insights into the behavior of composites subjected to various loading conditions [27].

The 3D Digital Image Correlation (DIC) method is included as one of the new advancements to the known 2D DIC, highlighted with additional features such as the ability to characterize composites using full-field measurement of deformation and strain with precision at the micro-level [27]. This is due to the difficulties in manufacturing of FRP composite structure through prepreg layup, Towpreg fibre winding, or even automated fibre placement by robots, etc., which creates the composite surface very rough with meso-scale 3D bumps, resulting in imprecision when 2D DIC is used to measure deformation and strain at a specified surface. On the other hand, 3D DIC uses two cameras [28] with specially adjusted parameters to capture and resolve the error of surface roughness, and provide accurate measurement of the strain field on the composite surface [29].

Literature study highlights the lack of research and technical difficulties in the determination of fracture properties of 0° CFRP lamina, in which the limitation of the standard method for full characterization of UD lamina properties is discussed. Considering the gap of study in the proper determination of fiber-bundle properties in the form of the 0°-FRP lamina in elastic to damage states, this study aimed at using 3D DIC system capability to capture the true strain field at the surface and around the notch tip of specially prepared CFRP laminate specimen, to record/measure the mechanism of deformation to fracture of the CFRP composite. The DIC result, along with the experimental data of the CFRP composite structure subjected to tensile load, are used to explain the complex behavior of the structure and illustrate the mechanism of composite deformation before the fracture state, which is later used for the measurement of fracture energy and failure parameters of 0° CFRP lamina. Using the proposed experimental-numerical approach, validated FE models of the experimental cases are employed to examine the accuracy of the mechanical properties, including the fracture energy parameter, which led to full characterization of the 0°-FRP lamina. In addition, this innovative approach and results provided an insight into the mechanics of deformation and the mechanism of damage of 0°-CFRP composite. It is concluded that the method can be applicable to characterize other fibrous composites where the mechanical behavior of the structure is dependent on reinforcement constituents and their arrangement in the composite system.

2. Continuum damage mechanics of 0°-lamina failure

The 0°-lamina is treated as an equivalent orthotropic ply with greater mechanical properties in the fiber direction. The constitutive model response of the composite material at the local point is represented by a bilinear softening law for fiber fracture damage mode, as depicted in Fig. 1. In this model, the elastic properties and strength could be obtained using a standard test [28], while the fiber fracture energy (G_{CF}), deformation and fracture, and the damage softening form could potentially be determined using the DIC method.

Considering lamina behavior on fiber direction, the stress-strain behavior within the elastic regime could be determined using orthotropic Hooke s law [29], while damage initiation is predicted using a quadratic relation [14]:

$$\left(\frac{_{11}}{X^T}\right)^2 \quad \left(\frac{_{12}}{S^L}\right)^2 \quad {d_f^t}^2 \tag{1}$$

where $_{11}$ and $_{12}$ are the effective normal and shear stresses within the elastic regime, generated in the lamina under tension, and X^T & S^L are the constant values corresponding normal and shear strength of the lamina, while the parameter d_f^t Indicate the fiber damage initiation in the lamina in tensile conditions. The displacement at fracture of the lamina in the fiber direction is computed using [13]:

$$^{f}_{eq} \quad \frac{2 \quad {^{o}_{11}}^2 \quad {^{o}_{12}}^2}{^{o}_{11}\,^{o}_{11} \quad ^{o}_{12}\,^{o}_{12}} G_C^{XT} \tag{2}$$

where $^{f}_{eq}$ is the equivalent displacement computed at failure, while the variables $^{o}_{ij}$, $^{o}_{ij}$, *and* $^{o}_{ij}$ are the effective stress and strain values in the lamina at the onset of damage, used to compute the maximum displacement before failure or cracking. The stress and strain data are generated at the unit volume of the material subject to deformation. The value of energy, G_C^{XT} determining critical deformation at fracture plays an important role in the estimation of the lamina fracture, which is difficult to obtain correctly for fiber direction. The fracture energy value

speckle. The two cameras were placed at a 40 cm distance from the test coupon and with a stereo angle of 15° The camera s resolution was 2456 × 2058 Pixels (having 8-bit digitization for grey levels), while a 0.00345 mm/pixel length-pixel ratio was considered for the imaging system. For this test, the CCD cameras were set vertically to the plane (field of interest) of the sample while taking images at a speed of 2 frames/second. The specimen surface was kept in the same plane parallel to the CCD camera during deformation and loading [38]. The system setup was calibrated to transform the image position on the CCDs of two cameras of a specimen surface point to the corresponding coordinates of that point. The calibration procedure aims to set the intrinsic parameters for both cameras of the imaging system, as well as adjust the external position and orientation of the cameras concerning a global coordinate system. In this work, *CorelliSTC software (Holo3, France)* was employed to compute local deformations and strains by using the images collected in the testing program.

4. Material and methods

4.1. Material and experiment

Five samples with single edge-notch configurations made of UD CFRP composite with $[0]_6$ lay-up are made and used for the experiment. The average sample dimension is listed in Table 1. The samples are fabricated according to ASTM standards [7] with a 5 mm edge-notch length. The test was controlled by a 0.5 mm/Min displacement rate until full failure. The structural response is recorded as a load-displacement curve and used to obtain the properties of the composite. A 3D DIC system is used for full-field measurement of displacement and strain of the CFRP composite surface. The result is used to measure the strain field around the notch tip and estimate the unit deformation of fibers at the final fracture. The fiber fracture energy is then calculated using the deformation at fracture based on the damage mechanics concept.

4.2. Finite element modelling

In the computational work, a systematic approach is taken to develop three different finite element (FE) models and to highlight the study s aim in determining the fracture energy and features of the fiber bundle in the form of FRP lamina. In this regard, FE models with three different configurations were systematically generated in the commercial software ABAQUS/Implicit, as shown in Fig. 3a-c. Model-1 was developed as a plain FRP lamina with gripping, in which the dimensions were similar to the experimental sample (refer to Table 1), and the notch was not considered. Model 2 was generated similarly to the experiment. Model-3 was created based on a single edge-notch composite, however, the material part along the notch was removed. The length and thickness of each model were the same as the experimental test according to ASTM standards [5,6]. The deformable 3D shell element (SC8R: 8-node quadrilateral in-plane continuum shell) was used to model the lamina, and a rigid 3D element (R3D8 element) was assigned to the gripping area.

Fig. 4a shows the mesh configuration of the samples, indicating higher mesh density in the sample gripping area (tab region) as well as the notch area, enabling accurate mechanical variables in stress concentration zones. To ensure the accuracy of FE model results, independent of the mesh density with minimized element size error, a mesh convergence study was performed on the model with elastic-damage definition. Two parameters, including measured von Mises stress at the material point, as well as strain energy of the whole structure, are computed in the model with different mesh densities, as shown in Fig. 4b This enables minimizing the element size error at the material level as well as the global structural response. Computed results signify that a mesh density (element number) of 10,000 provides accurate results with minimized error of <0.5 %; however, this study utilized the FE models with mesh density over 22,000, enabling greater resolution for localized phenomena, as recommended elsewhere [29]. To apply the boundary condition, one end side was fixed vertically and two plane rotational degrees of freedom (free to move in the width direction), and the other side was under displacement rate until fully ruptured following the load and boundary condition during the experiment. The applied loading rate was equal to the experiment (0.5 mm/min). To avoid matrix damage and grip indentation in the gripping area, which was observed in experimental tests, a GFRP tab was used in those regions. An orthotropic model was considered to model elastic behavior and for the prediction of failure mode and material degradation. Hashin s continuum damage mechanism was applied to the lamina specimens.

4.3. Hybrid experimental-computational approach

The flowchart of the methodology is illustrated in Fig. 4. The research methodology is developed based on a hybrid approach that links the experimental data and computational findings to explore the internal behavior of the composite specimens obtained through 3D FE simulation.

A 3D DIC equipment eliminating the mesoscale roughness of the CFRP composite to measure accurate data of fiber damage evolution in the form of linear-nonlinear strain variation was used along with the mechanical testing to provide insight for mechanical characterization and explain the damage behaviour of 0°-CFRP composite lamina. Three different FE models were developed to predict the internal mechanical behavior of the test sample, as well as to assist in the accurate estimation of the carbon fiber properties in the form of CFRP lamina. The approach is used to validate the model and simulation process and confirm the validity of the elastic and damage properties of the composite obtained in the study. Two verification steps are defined; first, elastic properties are validated through a comparison of experiment and simulation results, and then the damage properties are verified by experimental data, in which significant help from DIC data to ensure the accuracy of the data is highlighted.

5. Results and discussion

5.1. Mechanical behavior of single edge-notch FRP lamina structure

To understand the mechanisms of deformation and damage process, the results of the experiment in terms of the load-displacement curve are illustrated in Figs. 5 and 6, which indicate three distinct stages with different structural behaviours. Fig. 5 shows a schematic representation of the *load-displacement signature* of the single edge-notch composite sample under tensile loading conditions, while Fig. 6 presents the data obtained during the experiment. Two distinct magnitudes of stiffness are observed, including an elastic stiffness up to 6 % structural deformation, where no matrix crack occurred (Structure stiffness; k_S), and the second is when the matrix crack occurs at the notch tip and propagates

Table 1
The geometry of the single edge-notch specimens.

Specimen Dimension, mm			U-Notch Dimension, mm			Tab, mm	
Thickness	Width	Length	Length	Width	Tip Radius	Thickness	Length
0.89	15.05	235.79	5	1.11	1.05	1.03	55.32

Validation, Methodology, Formal analysis, Data curation. **N. Yidris:** Writing review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **S.M. Sapuan:** Writing review & editing, Visualization, Validation, Supervision, Resources, Project administration, Formal analysis, Conceptualization. **M.R. Abdullah:** Writing review & editing, Visualization, Validation, Resources, Project administration, Funding acquisition, Formal analysis. **M.N. Tamin:** Writing review & editing, Visualization, Validation, Supervision, Resources, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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