Multiaxial stress and strain analysis on laminated plates under different flexural loading rates

S Horta Muñoz* and M C Serna Moreno

Universidad de Castilla La-Mancha, Escuela de Ingeniería Industrial y Aeroespacial de Toledo, Departamento de Mecánica Aplicada e Ingeniería de Proyectos, Instituto de Investigación Aplicada a la Industria Aeronáutica, Real Fábrica de Armas, 45004, Toledo, Spain

*E-mail: sergio.horta@uclm.es

Abstract. The occurrence of events associated with Low-Velocity Impacts (LVI) is analysed by drop-weight impact tests on carbon fibre reinforced polymer laminates, comparing the response in these tests with Quasi-Static Indentation (QSI). A laminate sequence of interest, the angle-ply [±45]_4S, is tested in both testing procedures with a simply supported configuration on a circular fixture. Both methodologies show similarities in the critical points for change of behaviour in terms of energy, while the strain rate effect is verified to influence the higher apparent stiffness of the laminate submitted to the LVI test compared with the QSI test. The effect of multiaxiality in loads existing in these tests is addressed in the quasi-static experiment by applying Digital Image Correlation (DIC), comparing the results with numerical simulations using the Finite Element Method (FEM). The orthotropy of the material generates strain and displacement fields which allow understanding the dissimilar response of the laminate in the different radial directions, also giving explanation to the initiation and evolution of different damage mechanisms.

1. Introduction

The widespread application of fibre polymer composites in highly demanding structural applications, such as aerospace or wind energy sectors, is related to their outstanding specific strength and stiffness. Moreover, the mechanical response of some laminates, for instance pseudo-ductile effects in angle-ply sequences, has been proven to enhance large strain response while increasing energy absorption and damage accumulation under quasi-static loading [1,2]. Nevertheless, a major drawback of the applications of these materials is their limited tolerance to out-of-plane loadings, while impact damages are even more concerning. Low energy strikes may produce internal matrix cracking and delamination, difficult to detect but threatening the structural integrity of the component.

Likewise, the experimental characterization of this type of damage produced by impact on a laboratory scale raises certain difficulties due to the dynamic and short-timed nature, with larger dispersion of results during testing campaigns. Therefore, several authors [3–10] have pursued to establish a relationship between the mechanisms of damage and failure under Low Velocity Impact (LVI) with tests applying a lower deformation rate, i.e. Quasi-Static Indentation (QSI). These works contribute conclusions in certain contradictory points, without reaching a clear consensus of the possible extrapolation of the quasi-static tests. The advantage of lower rate tests resides in greater simplicity in their performance and analysis, compared with the dynamic phenomenology observed...
under impact loads. Some authors highlighted certain similarities and differences not only in the failure mechanisms and their visualization, but also in parameters recorded in the test such as the force or energy involved in the stages of damage initiation and evolution.

This study proposes is different than the work already existing in bibliography due to the detailed analysis of the multiaxial stress/strain state in laminates with angle-ply orientations. The orthotropy of the material will be studied in depth from the point of view of the radial strain measured through the application of Digital Image Correlation (DIC), combined with numerical simulations using the Finite Element Method (FEM). In addition, the similarities between the tests at different loading rates will be detailed, highlighting the search for a correlation between the critical points of the behaviour of these laminates, in terms of force-displacement and applied energy. In this way, it will be possible to estimate the initiation and evolution of the main failure mechanisms that appear similarly in QSI and LVI with certain independence of the strain rate, until reaching the final rupture of the laminate.

2. Experimental and numerical procedure

The carbon fibre reinforced polymer (CFRP) laminates tested under QSI and LVI methodologies are manufactured using a commercial prepreg ply by Hexcel, with the specific designation of M21E/34%/UD268/IMA-12K. This lamina is composed by a M21E toughened epoxy matrix at 34 wt.% and reinforced with an IMA-12K intermediate modulus carbon fibre at a 268 g/m² density [11]. Additionally, the average cured ply thickness is equal to 0.25 mm. The manufacturing process consists of hand lay-up of the plies with the proposed stacking sequence, followed by the curing cycle recommended by the manufacturer, which is performed on a LabEcon 300 hot platen press. The fabricated laminates are cut with a circular saw, producing specimens in the form of square plates with 80 mm nominal side dimensions.

The elastic properties of the lamina in material principal directions, characterized in previous studies [1,12–15], is summarized in Table 1, where elastic moduli (\(E\)), shear moduli (\(G\)) and Poisson’s ratios (\(\nu\)) are included.

| \(E_1\) (GPa) | \(E_2\) (GPa) | \(E_3\) (GPa) | \(G_{12}\) (GPa) | \(G_{13}\) (GPa) | \(G_{23}\) (GPa) | \(\nu_{12}\) | \(\nu_{13}\) | \(\nu_{23}\) |
|---------------|---------------|---------------|----------------|----------------|----------------|---------|---------|---------|
| 177.56        | 11.84         | 11.84         | 5.42           | 5.42           | 3.10           | 0.39    | 0.39    | 0.36    |

For both testing procedures, i.e. QSI and LVI, the same specimen dimensions and boundary conditions are applied (see Figures 1 and 2). A non-standardized procedure is developed, in order to perform a test in which a squared plate is simply supported in a 74 mm diameter span fixture, while a semi-spherical indenter with 10 mm radius applies the load at the centre of the specimen. In the case of the QSI testing, displacement is applied at a fixed rate of 0.8 mm/s by means of a MICROTEST MAEFH electromechanical machine (Figure 1a). During this test, strain values are acquired at different gauge zones, that is, the displacement fields at the upper compressive face are recorded by means of a 3D DIC system (namely LaVision StrainMaster). Simultaneously, strains at the centre of the bottom surface are acquired by means of a foil strain gauge rosette. Specifically, KYOWA KFGS triaxial rosette with 0º, 45º and 90º stacked gauges are utilised, with 5x1.4 mm gauge length and width, respectively.
Figure 1. Experimental set-up for QSI testing: (a) Testing facility showing DIC installation. (b) Detail of loading application over simply supported specimen.

Regarding the impact testing, an instrumentalized drop-weight tester INSTRON CEAST 9340 is utilised (Figure 2a). The LVI tests are performed with an impact velocity of 2.0 m/s to avoid total penetration of the specimen and the kinetic energy applied was 89.9 J. The utilised indenter is the same than in QSI testing (Figure 1b), fitted to an impact hammer with the mass adapted to deliver the required impact velocity and energy. Regarding the supporting fixture (Figure 2b), this is specifically designed to be fitted in both the electromechanical and impact testing machines.

Figure 2. Experimental set-up for LVI testing: (a) Drop-weight tower. (b) Novel fixture with 74 mm diameter circular window.
3. Results and discussion
This section describes the experimental results obtained in the QSI and LVI tests, analysing the similarities in the recorded data and detailing the failure modes observed in the fractographies for the tested specimens. Furthermore, the analysis of the multidirectional strain state is completed with the comparison of the normal strain contours obtained by DIC and FEM.

3.1. Experimental results
The results obtained for two groups of [±45]_{AS} specimens respectively tested under QSI and LVI are detailed below. The force-displacement and energy-displacement curves obtained for two representative tests are shown in Figure 3, although note that this study collects the numerical data from a campaign of repetitive tests. Figure 3a depicts a significant difference in the apparent stiffness of the laminate, leading to an average rigidity that is 36.3% higher in the case of LVI. This change can be explained by the strain rate effects observable in polymer matrix composites, as is extensively reported in literature [16,17]. Due to this, similarities between both testing methods are not found in terms of force or displacement.

However, neglecting the dynamic component of the LVI test, both curves have a significant qualitative similarity. It is verified how there are similar points of change in behaviour in both evolutions, so it is possible to foresee the appearance of similar damage mechanisms. If the events highlighted in Figure 3a are compared in terms of instantaneous internal energy, it is possible to find a relevant correlation between both tests at different velocities. The internal energy values (Figure 3b), calculated as the integral of the force-displacement curve, differs only 6.5%, 3.0% and 1.8% between both tests (in average values), for the three marked events, respectively. These correlated values of energy allow us to indicate a relationship between the appearance and evolution of damage phenomena, mainly macrocracks, independently of the applied load rate.

This idea is supported by the optical observations of the tested specimens, which helps to estimate the evolution of the typically expected failure mechanisms in CFRP laminates. Figure 4 depicts the photographs of both sides, upper and lower faces, of a specimen subjected to LVI, and the inspection of a plate subjected to QSI is very similar when observed under similar internal energy levels. Taking into account that the plate is subjected to bending in all radial directions, it is expected that, for instance, the bottom-side will develop tensile stresses and strains in all radial directions, these being
the maximum through-thickness values. The absolute maxima are located in the mid-span, where bending moment is also the highest. Out-of-plane shear stresses and strains are also expected, which are maximum in the neutral fibre of the specimen, i.e. the midplane in case of similar tensile and compressive behaviour of the laminate. In addition, stress/strain concentrations appear in the vicinity of the indenter, so the first failures at the upper layer are observed in this region. In Figure 4b it is possible to observe the indentation produced in the central area of the plate.

![Figure 4. Failure modes of the angle-ply laminate under LVI. (a) Bottom/tensile face view. (b) Upper/compressed face. The fibre orientation at the outer ply is symbolised with the material principal directions.](image)

If the most-tensioned surface is observed in detail (Figure 4a), the previous explanation indicates that the central zone is the region of maximum normal tensile stress. The highest local elastic modulus (ply-level) is found on the fibre direction, i.e. at 45° in Figure 4, and fibre-matrix debonding is expected to be the initial failure mode, as this weak interface is subjected to higher stresses. This microcracks propagate originating a larger matrix crack that advances through the diagonal, but with less intensity than in the central zone (see detail in Figure 4a). The apparition of large matrix cracking is reflected in Figure 3 with the first highlighted event. This failure mode extends also to internal plies, but alternating the orientation with the fibre direction, and decreasing in length due to the lower bending moment when moving towards the neutral fibre. This damage mechanism is combined with the delamination of the plies, producing larger surfaces which are reflected in the loss of rigidity, associated to an internal energy liberation.

When observing the compressed surface (Figure 4b), the failure modes are not only matrix dominated, but also certain fibre kinking could be observed (green magnification in Figure 4b). Nevertheless, the initial failure mechanism continues to be the matrix-dominated, due to the lower strength of the matrix, giving rise to large cracks that propagate again on the diagonal at 45°, associated with the fibre-matrix debonding described above. The larger cracks propagate up to reaching the proximities of the boundary conditions, which has been related to the second event in Figure 3 [10]. Finally, out-of-plane shear stresses are relevant in the propagation of the final failure (third event in Figure 3), producing the greatest drop in stiffness of the plate. This results in an abrupt opening near to the laminate mid-surface.

Finally, post-mortem photographs for the QSI test are shown in Figure 5, in a similar manner to Figure 4. Comparable failure modes are observed, with a significant difference in the severity of the matrix splitting (Figure 5a) and the depth of the indentation mark (Figure 5b), due to the higher deflection reached in the quasi-static test.
Figure 5. Failure modes of the angle-ply laminate under QSI. (a) Bottom/tensile face view. (b) Upper/compressed face. The fibre orientation at the outer ply is symbolised with the material principal directions.

3.2. Comparison of numerical and experimental strain fields
Numerical simulations performed using Abaqus/Standard FEM software lead to a better understanding of the results from the quasi-static bending test. The model carried out is based on a mesh consisting of solid linear elements with 8 nodes and reduced integration (S8R), in which the symmetry at 45º is used to generate only half of the actual geometry (Figure 6a). A static non-linear analysis is carried out, applying an orthotropic material model, and defining the elastic properties of the ply and its orientations.

Figure 6. (a) Detail of the mesh applied in numerical simulations of QSI testing. (b) Schematic drawing of the fixture, laminate and indenter (dimensions in mm, not to scale)

The testing facility is represented in Figure 6b. The indenter is modelled as a rigid solid, on which a 1 mm displacement is applied perpendicular to the laminated plate. The indenter-laminate interaction is defined as frictionless surface-to-surface contact [10]. The boundary conditions imposed by the support tool are reproduced preventing perpendicular displacements in a circumference of diameter 74 mm. The results of this analysis are compared (Figure 7) with the experimental strain contours obtained by DIC at the same level of applied displacement, before damage initiates and the response changes. Due to limitations of the image acquisition with the DIC cameras, i.e. range of view...
constrained by indenter, supports and load application system, only half of the top surface can be measured.

![Figure 7](image)

**Figure 7.** Comparison of experimental (top) and numerical (bottom) strain fields at uppermost compressed ply: (a) $\varepsilon_{xx}$ and (b) $\varepsilon_{yy}$. Local coordinate system for the observed ply is included.

The similarities between both approaches are noticeable, in terms of numerical values and shape of the strain fields. It can be noted the lack of symmetry regarding the $x$ and $y$ directions, due to the flexural orthotropy of the laminate. In other words, the $[\pm45]_4$s laminate experiments a non-negligible orthotropy in the flexural stiffness when observed at the material principal directions, developing the maximum apparent flexural stiffness at the direction aligned with the fibre of the outermost ply. Therefore, the strain gradients, with reference to the centre of the plate, moves forward with an angle close to the 0º and 90º, but slightly deviated to the maximum stiffness direction (corresponding to the 4 principal direction in Figure 7). Additionally, the effect of the circular boundary conditions is reflected on the maximum tensile strains appearing at the edges of the plate.

4. Conclusions
The thorough analysis of the QSI and LVI tests instrumented for the acquisition of the strain states, applied forces and accumulated strain energy in each stage of the test has allowed us to find similar situations under both methodologies. That is, the events where the behaviour changes are most notable occur at similar levels of internal energy regardless of the strain rate applied, despite the notable apparent stiffness difference under different velocities. Damage initiation and evolution stages are correlated, and the more progressive quasi-static methodology helps to describe the failure mechanisms.

5. Acknowledgements
This work was financially supported by the Ministry of Economy and Competitiveness of Spain and the European Regional Development Fund under the grant DPI2016-77715-R. In addition, the Government of Castilla-La Mancha and the European Social Fund have funded S. Horta Muñoz through the predoctoral grant SBPLY/16/180501/000263.

References

[1] Serna Moreno M C, Horta Muñoz S, Romero Gutiérrez A, Rappold C, Martínez Vicente J L, Morales-Rodríguez P A and López Cela J J 2018 Pseudo-ductility in flexural testing of symmetric $\pm45^\circ$ angle-ply CFRP laminates *Compos. Sci. Technol.* **156** 8–18

[2] Horta Muñoz S and Serna Moreno M C 2020 Numerical modelling of the pseudo-ductility
effect in ±45° angle-ply laminates under biaxial loading ECCM 2018 - 18th European Conference on Composite Materials (Applied Mechanics Laboratory)

[3] Lee S M and Zahuta P 1991 Instrumented Impact and Static Indentation of Composites J. Compos. Mater. 25 204–22

[4] Kwon Y S and Sankar B V. 1993 Indentation-flexure and low-velocity impact damage in graphite epoxy laminates J. Compos. Technol. Res. 15 101–11

[5] Spronk S W F, Kersemans M, De Baerdemaeker J C A, Gilibert F A, Sevenois R D B, Garoz D, Kassapoglou C and Van Paepegem W 2018 Comparing damage from low-velocity impact and quasi-static indentation in automotive carbon/epoxy and glass/polyamide-6 laminates Polym. Test. 65 231–41

[6] Nunes S G, Reichwald L G G, Júnior W F A, Manes A and Amico S C 2018 Quasi-Static Indentation and Low-Velocity im pact response of aramid/epoxy Composites 323–9

[7] Wagih A, Maimí P, Blanco N and Costa J 2016 A quasi-static indentation test to elucidate the sequence of damage events in low velocity impacts on composite laminates Compos. Part A Appl. Sci. Manuf. 82 180–9

[8] Sun X C, Wisnom M R and Hallett S R 2016 Interaction of inter- and intralaminar damage in scaled quasi-static indentation tests: Part 2 - Numerical simulation Compos. Struct. 136 727–42

[9] García-Rodríguez S M, Costa J, Bardera A, Singery V and Trias D 2018 A 3D tomographic investigation to elucidate the low-velocity impact resistance, tolerance and damage sequence of thin non-crimp fabric laminates: effect of ply-thickness Compos. Part A Appl. Sci. Manuf. 113 53–65

[10] Serna Moreno M C and Horta Muñoz S 2020 Mechanical response of ±45° angle-ply CFRP plates under low-velocity impact and quasi-static indentation: Influence of the multidirectional strain state Compos. Sci. Technol. 194 108145

[11] Hexcel 2015 HexPly® M21 - Product Data Sheet - EU Version Hexcel 1–6

[12] Serna Moreno M C, Romero Gutiérrez A and Martínez Vicente J L 2016 Different response under tension and compression of unidirectional carbon fibre laminae in a three-point bending test Compos. Struct. 136 706–11

[13] Serna Moreno M C, Romero Gutiérrez A and Martínez Vicente J L 2016 First flexural and interlaminar shear failure in symmetric cross-ply carbon-fibre laminates with different response under tension and compression Compos. Struct. 146 62–8

[14] Serna Moreno M C, Romero Gutiérrez A and Martínez Vicente J L 2016 Flexural testing on carbon fibre laminates taking into account their different behaviour under tension and compression IOP Conf. Ser. Mater. Sci. Eng. 139 012047

[15] Serna Moreno M C and Horta Muñoz S 2020 Elastic stability in biaxial testing with cruciform specimens subjected to compressive loading Compos. Struct. 234 17–8

[16] Cui H, Thomson D, Pellegrino A, Wiegand J and Petrinic N 2016 Effect of strain rate and fibre rotation on the in-plane shear response of ±45° laminates in tension and compression tests Compos. Sci. Technol. 135 106–15

[17] Fotouhi M, Fuller J D, Longana M, Jalalvand M and Wisnom M R 2019 The high strain rate tension behaviour of pseudo-ductile high performance thin ply composites Compos. Struct. 215 365–76