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Editorial

This collection contains the proceedings of the 21st European Conference on Composite Materials (ECCM21), held in Nantes, France, July 2-5, 2024. ECCM21 is the 21st in a series of conferences organized every two years by the members of the European Society of Composite Materials (ESCM). As some of the papers in this collection show, this conference reaches far beyond the borders of Europe.

The ECCM21 conference was organized by the Nantes Université and the Ecole Centrale de Nantes, with the support of the Research Institute in Civil and Mechanical Engineering (GeM).

Nantes, the birthplace of the novelist Jules Verne, is at the heart of this edition, as are the imagination and vision that accompany the development of composite materials. They are embodied in the work of numerous participants from the academic world, but also of the many industrialists who are making a major contribution to the development of composite materials. Industry is well represented, reflecting the strong presence of composites in many application areas.

With a total of 1,064 oral and poster presentations and over 1,300 participants, the 4-day event enabled fruitful exchanges on all aspects of composites. The topics that traditionally attracted the most contributions were fracture and damage, multiscale modeling, durability, aging, process modeling and simulation and additive manufacturing.

However, the issues of energy and environmental transition, and more generally the sustainability of composite solutions, logically appear in this issue as important contextual elements guiding the work being carried out. This includes bio-sourced composites, material recycling and reuse of parts, the environmental impact of solutions, etc.

We appreciated the high level of research presented at the conference and the quality of the submissions, some of which are included in this collection. We hope that all those interested in the progress of European composites research in 2024 will find in this publication sources of inspiration and answers to their questions.

Each volume gathers contributions on specific topics:

- **Vol 1. Industrial applications**
- **Vol 2. Material science**
- **Vol 3. Material and Structural Behavior – Simulation & Testing**
- **Vol 4. Experimental techniques**
- **Vol 5. Manufacturing**
- **Vol 6. Multifunctional and smart composites**
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- **Vol 8. Special Sessions**

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ARREST OF UNSTABLE COMPRESSIVE CRACKS IN FIBRE REINFORCED POLYMERS USING PLY DISCONTINUITIES

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Keywords: Composite materials, Compression, Unstable failure, Crack arrest, Kink-band

Abstract
The compressive properties of fibre-reinforced composites are significantly inferior to their tensile equivalent. This factor, allied to the 'no-damage growth' design philosophy currently used in aerospace, results in significantly oversized structures. The current work aims to improve the compressive response of composites by compartmentalizing unstable compressive failure in large fibre-reinforced structures. It proposes a ply-discontinuity feature capable of arresting unstable crack propagation in multidirectional Carbon Fibre-Reinforced Polymer (CFRP) laminates subjected to compressive loading. By replacing 0° oriented plies by carefully selected off-axis ones, the feature is capable of dispersing and dissipating compressive kink-band propagation energy as well as modifying the laminate's failure modes. Consequently, the laminate achieves arrest of rapidly growing unstable cracks (propagating at ~1 km/s) and the specimen's ultimate failure strain is increased. To validate the proposed concept, test specimens were designed and manufactured using IM7/8552 carbon-fibre reinforced epoxy. Through compressive tests, the feature's crack-arrest capability was shown, remarkably increasing by nearly a third the strain tolerance upon final failure, when compared to the respective baseline.

1. Introduction

Compressive performance, particularly in the presence of in-service damage, limits composite design. Factors such as a high sensitivity to manufacture defects and complexity in failure modes cause compressive strength of Fibre-Reinforced Polymers (FRPs) to be significantly inferior to their tensile performance [1-3]. Additionally, if compressive failure initiates in a component, there are no means to arrest such fracture. Thus, composites are currently constrained to a 'no-damage growth' design philosophy. Being able to tolerate and manage compression crack growth ('damage growth tolerance' philosophy) would enable the realisation of composites' full structural potential.

A key component of this design philosophy are crack-arrest methods, which seek to stop unstable failure growth, isolating damage and extending structural life after an initial failure event. Features with these capabilities have already been developed and are widely employed in other fields. In compressed-gas transmission pipelines, ribs are used to contain long tensile cracks in metallic pipes [4,5]. Similarly, in airplane fuselages tear straps are used to stop tear propagation in the composite skin [6]. Nevertheless, little to no study has been done on compression crack-arrest in fibrous composite laminates.

By developing a feature capable of arresting unstable compressive cracks in FRPs, this research aspires to pave the way to successful compartmentalisation of failure in large composite structures. Components designed through this method will remain fit for service after initial failure propagation, enabling safer designs while simultaneously reducing their weight. These developments shall be particularly advantageous in applications where catastrophic failure would lead to loss of lives, as is the case of airplane wings. Figure 1 exemplifies how such a feature would be able to avoid structural collapse in a damaged wing root.

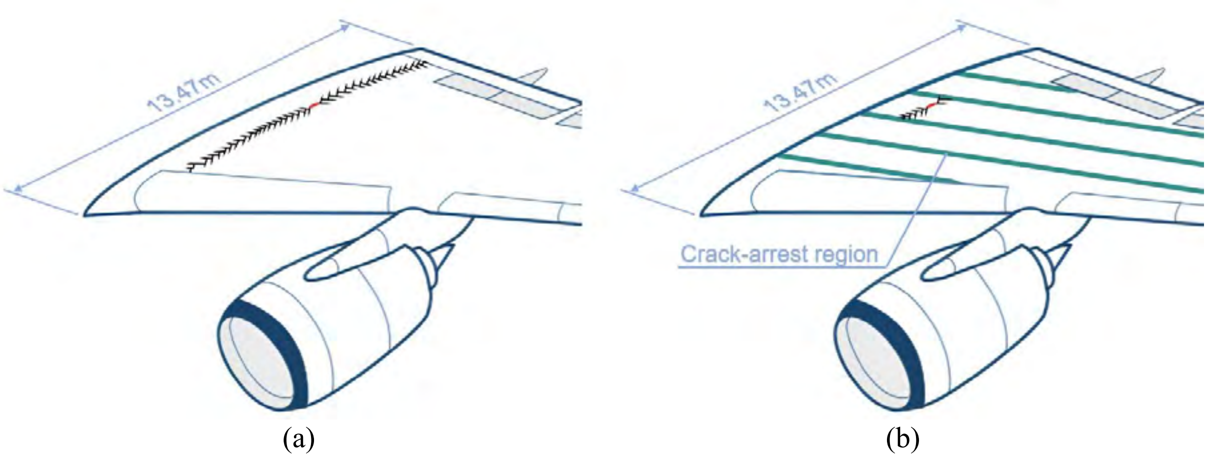

Figure 1. Visualisation of compressive-crack compartmentalisation on a damaged Airbus A350-1000 wing. (a) Crack propagation from the damaged region without crack arrest mechanisms, unrestrictedly expanding across the wing's chord and causing catastrophic failure. (b) Failure compartmentalisation by periodic crack-arrest bands, allowing the wing to remain in service.

2. Feature concept

Unstable compression crack propagation on CFRPs happens at a rate approaching 1 km/s [7]. Therefore, to stop this growth it is important to implement ways of dissipating or deflecting the energy associated to the propagation process. With that aim, a concept based on the idea of ply-discontinuity was developed. It is known that compressive kink-band failure is the main mechanism of crack growth in FRP compression [8]. This fracture mechanism tends to occur in 0° oriented plies, propagating perpendicular to the loading direction. Thus, by implementing regions where 0° plies are replaced by off-axis ones, the feature seeks to force the failure into following new paths, dispersing energy in the process. Moreover, lay-ups where 0° plies are the main loading component (hard lay-ups) have lower translaminar toughness than those where the load is supported only by off-axis plies (soft lay-ups). Therefore, by inserting discontinuities in the lay-up, the feature also implements regions of increased toughness that assist in fracture containment.

Notably, the feature does not introduce any new material types into the design. The sole presence of materials that have been previously certified and are already in use in the aerospace industry constitutes a remarkable advantage in the mechanism's incorporation into service. Furthermore, the usage of a single type of composite facilitates recycling and disposal processes.

3. Materials and methods

A compression specimen was designed to test the developed crack-arrest feature. The angle of the off-axis plies responsible for replacing 0° in the soft lay-up was defined as ±30°. A sandwich configuration with aluminium honeycomb core and IM7/8552 CFRP skins was chosen to prevent the composite laminate from global buckling during test. A notch was designed to induce initial failure in the gauge

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region at an applied strain close to -3100με. This value was chosen for being slightly above the -2500με design limit load typically used in aerospace industry [9]. Figure 2 illustrates the specimen's geometry.

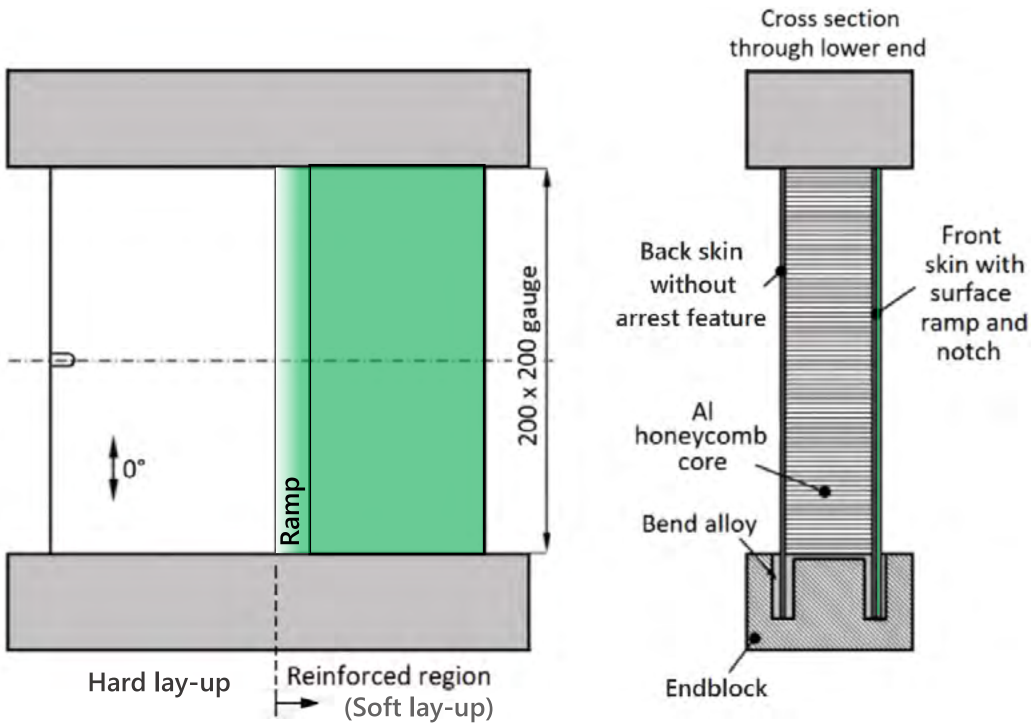

Figure 2. Compression test specimen geometry (crack-arrest region is presented in green).

While defining the skins' lay-up, a series of restrictions was defined to control test variables. Since the hard lay-up is multidirectional, while 0° layers were replaced by ±30°, the remaining plies were maintained continuous to conserve specimen integrity. Moreover, both hard and soft lay-ups were designed to be symmetrical to avoid compression-bending coupling effects. Finally, as a consistent stiffness was desirable throughout the specimen width, additional layers were added to the soft lay-up to compensate for the difference in stiffness induced by changing ply-orientation. To reduce stress concentration, the lay-up transition was designed to happen gradually, assuming the shape of a 'ramp'. Since the front skin of the of the crack-arrest specimen was defined as surface of interest, only this face possessed the arrest feature.

Two specimens were manufactured: a crack-arrest (CA) specimen, with the arrest feature lay-up presented, and a baseline (plain) specimen. The baseline consisted in a sandwich coupon with two hard lay-up skins and no ply-discontinuity, possessing an equivalent stifness to that of the CA specimen.

The specimens were tested in a 250 tonne screw-driven compression test machine under displacement control. Digital Image Correlation and strain gauges remote from the crack region were used to monitor mechanical behaviour and compute applied strain. C-scans and X-ray images of the fractured specimens were taken to achieve deeper understanding of the processes through which failure initiates and is subsequently arrested.

4. Results and discussion

As expected, the baseline specimen suffered an abrupt failure that propagated across the notched face's width, leading to almost complete loss of load-bearing capability. The failure of the CA specimen, however, was successfully stopped upon reaching the beginning of the arrest region. Following this

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initial failure, additional strain was endured by the specimen, progressively causing smaller failure steps. Ultimate failure was achieved when the crack front reached the opposite end of the skin's width. Figure 3 represents both specimens after they had reached ultimate failure.

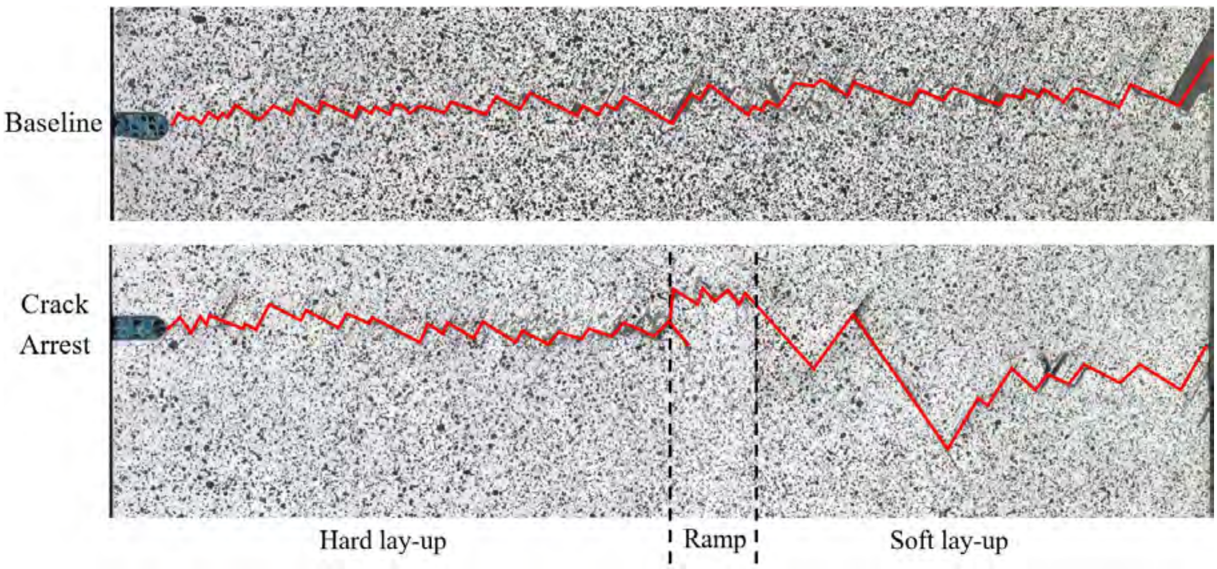

Figure 3. Fractured region of the test specimens, portraying the change in failure path caused by ply-discontinuity. Main visible failure paths are highlighted in red.

It was notable that, as seen in the baseline, initial fracture in the CA specimen grew perpendicular to load application direction. Similar fracture morphology was also observed between these failures, consistent with the baseline's suitability as comparison. Nevertheless, following the initial arrest, the subsequent failure in the CA specimen presented significant changes in both growth direction and fracture morphology. These behavioural changes hint as to the effects of the of ply replacement in obstructing the kink-band propagation.

Figure 4 presents the applied strain versus load of both specimens during test. It's important to note that the specimens' 200x200mm gauge area represents only a very small fraction of the dimensions of the structures they seek to represent. Therefore, even the loss of the entire 200mm section would not represent a significant reduction in the complete structure's load capacity. As of consequence, the most reliable way of analysing the specimens' performance is not through their load capacity but through their strain tolerance. This tolerance represents the structure's capability of being deformed before collapsing.

In Figure 4, it is possible to observe that both specimens showed similar elastic behaviour before initial failure. The baseline's failure happened at $\varepsilon_b^{ult} = -3070\mu\varepsilon$, while that of the CA specimen started at $\varepsilon^{ini} = -3600\mu\varepsilon$. The chart still portrays its subsequent growth steps, up to the ultimate failure at $\varepsilon^{ult} = -4065\mu\varepsilon$. It is notable that, although possessing the same stiffness as the baseline, the CA specimen presented an ultimate strain to failure nearly a third higher than it.

X-rays and C-scans were used to visualise subsurface damage in both specimens. The analyses showed that CA specimen's soft lay-up region presented considerably more extensive delamination than both the hard lay-up region and the baseline. Together with the more tortuous failure path caused by crack deflection, the increase in secondary damage surfaces contributed to energy dissipation, leading to the feature's success.

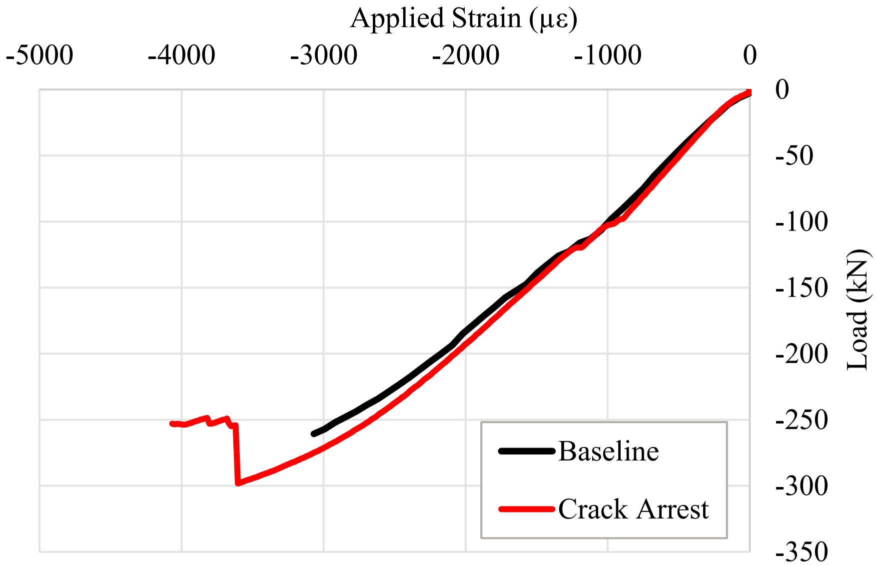

Figure 4. Evolution of applied strain in both specimen tests, evidencing feature-induced crack arrest and increase in strain tolerance.

5. Conclusions

A concept of crack-arresting feature for FRPs under compression was developed and tested. The concept was proven to successfully stop unstable compressive kink-band propagation, considerably delaying the specimen's ultimate failure and improving its strain tolerance. When compared to an equivalent baseline, the crack-arrest specimen showed a one third higher ultimate failure strain.

It was perceived that, by using discontinuity in fibre orientation, the feature can deflect the crack, forcing it to generate longer failure paths. Moreover, the soft lay-up suffered higher levels of secondary failure, contributing to energy dispersion. Therefore, by generating additional failure surfaces and imposing difficulties to crack propagation perpendicular to loading direction, the feature is able of dispersing enough energy to stop kink-band propagation.

Next research steps include fractographic analysis, to deduce the detailed failure mechanisms, followed by optimisation of the ply angles and stacking sequence. Through this process, crack-arrest effects will be maximised, whilst maintaining the same panel stiffness.

Acknowledgments

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