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Prof. Christophe BINETRUY
ECCM21 Conference Chair
Institute of Civil Engineering and Mechanics (GeM)
Centrale Nantes
Nantes Université

Prof. Frédéric JACQUEMIN
ECCM21 Conference Co-Chair
Institute of Civil Engineering and Mechanics (GeM)
Nantes Université

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CONTENTS

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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Table of Contents

COMPRESSIVE FAILURE OF CARBON FIBRE COMPOSITES DUE TO INSTABILITY AT STRUCTURAL, MATERIAL AND CONSTITUENT LEVEL

Michael R. Wisnom

Bristol Composites Institute, University of Bristol, Bristol BS8 1TR, UK
Email: m.wisnom@bristol.ac.uk Web Page: http://www.bristol.ac.uk/composites

Keywords: compression, failure, instability, microbuckling

Abstract

Compressive failure is controlled by instability at three different levels. Firstly, there is overall stability at the structural level. Secondly there is shear instability at the material level, and thirdly at the constituent level there can be instability within the fibres themselves. This paper considers these three mechanisms and the way they may interact to control compressive behaviour of carbon fibre composites.

1. Introduction

Compressive strength of carbon-fibre composites is often less than tensile strength. Notched compressive strength and compression after impact are major design drivers for many structures, and are strongly affected by the basic compressive strength of the material. Failure in compression is fundamentally about stability, and so it is important to consider the different ways in which instability may occur rather than treating failure as being controlled by a fixed material strength. Macroscopic instability at structural level can affect failure of small test coupons as well as full sized components and structures. Mesoscopic instability at the material level controls compressive failure of many carbon fibre composites. Because failure depends on stability, the stresses and strains at which it occurs are not constant, but can vary with other factors. Microscopic instability of the graphitic structures within the fibres is critical for the non-linear response and failure of the fibres themselves. These three mechanisms will be discussed first, and then interactions between instabilities at different levels will be considered. Examples will be taken from classical carbon fibre compression tests and from hybrid composites where the significant differences in failure modes can help to highlight the underlying mechanisms.

2. Structural Instability

Structural stability affects all materials, but is particularly important in carbon fibre composites because the elastic modulus decreases with strain. Fitting stress-strain data for a typical high strength carbon/epoxy, XAS/914, shows a reduction in tangent modulus of 50% or more at high strains, Fig. 1.

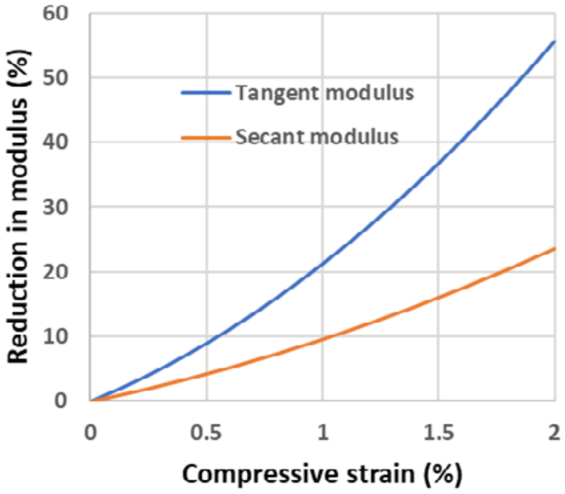

Figure 1. Reduction in compressive modulus with strain for carbon/epoxy [1]

This non-linearity can cause a big reduction in buckling stresses at high strains. For example, simple Euler buckling calculations for rectangular specimens 2 mm thick and 20 mm long built in at both ends gave a buckling stress of 1556 MPa when fibre-direction non-linearity was taken into account, compared with 2101 MPa when response was assumed to be linear elastic [1]. If shear deformation was ignored, the predicted buckling stress was 4297 MPa. Finite element analysis modelling of the test end support conditions gave even lower values, but again showed similar trends, with a 25% reduction in predicted buckling stress due to non-linear fibre-direction and shear response. The full non-linear FE analysis correlated well with the experimental results.

Table 1. FE predictions of buckling of UD struts [1]

Full non-linear	1236
Linear shear modulus	1312
Linear shear and longitudinal modulus	1655
Experimental	1188

Great care is necessary in designing tests. Buckling stresses tend to show lower variability than compressive strengths since they are controlled by stiffness, and failures are more likely to occur in the gauge section, which may be mistakenly taken as indications of a successful test. In the above example, the failure at 1188 MPa with a low coefficient of variation of about 3%, well below the analytical buckling stress, might be interpreted as a reliable strength measurement, rather than premature failure.

3. Composite Material Instability

Failure of many carbon fibre composites occurs due to shear instability at the material level caused by fibre misalignment and the non-linear shear response of the composite. This is quite well understood, and there are many experimental and modelling studies explaining how the instability develops and leads to kink bands, e.g. [2,3].

However, since failure is controlled by stability rather than strength, the stress and strain at which it occurs may vary with other factors rather than being fixed values. For example, where there is a strain gradient, the less highly loaded fibres support the others, delaying failure. This is illustrated by fully scaled compression tests on pin-ended buckling specimens, which gave a substantial increase in failure strain with decreasing thickness, as shown in Fig. 2.

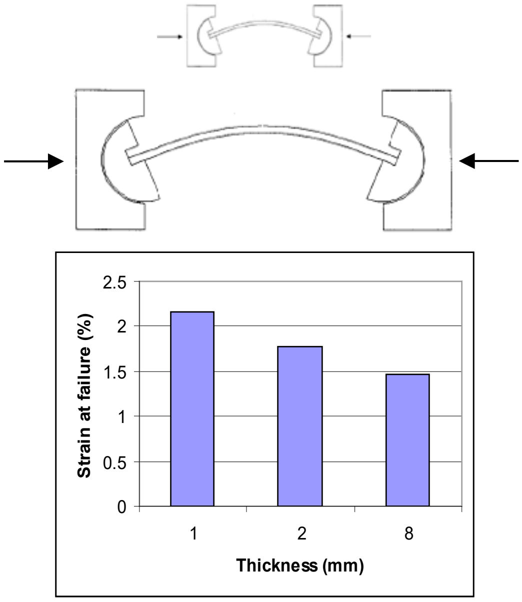

Figure 2. Increase in compressive failure strain due to strain gradient in fully scaled UD T800/924 specimens [4]

Another illustration is the effect of hybridisation. Tests on TC33 carbon/epoxy hybridised with S-glass/epoxy failed at a compressive strain of 2.61%, around double the strain of the pure carbon/epoxy [5].

4. Fibre Instability

There is also potentially instability of the graphite planes within the fibres themselves. This mechanism is the origin of the fibre non-linearity, and may also lead to failure with a kink band such as shown in Fig. 3. Failure of high modulus carbon composites in particular may occur in this way rather than by composite shear instability. Failures propagate at an angle of about 45° and look like shear fractures, but are actually controlled by instability at the local level. They can be treated in a similar way to composite material instability e.g. using the Budiansky and Fleck model based on kinking, with a misalignment angle and elastic-plastic shear properties, applied at the micro scale [6].

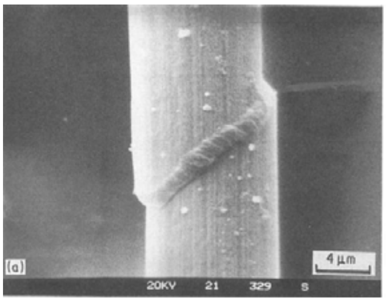

Figure 3. Kink band in high modulus pitch fibre [7]

This mechanism of fibre failure is illustrated by tests on M55J high modulus PAN composites with 0.03 mm ply thickness hybridised with 0.155 mm S-glass/epoxy plies. The stress-strain response shows a knee-point at around 0.5% strain due to failure and fragmentation of the carbon fibres, Fig. 4. These look like shear fractures, Fig. 5, but occur at a much lower strain compared with the 0.85% failure strain in tension [8]. Stress transformation equations show that the maximum value of shear stress occurs on a

CONTENTS

plane at 45° to the loading direction, and is the same irrespective of whether the fibre is loaded in tension or compression. So, the lower strain measured in compression than tension is not consistent with a shear fracture, supporting the argument that it is due to fibre instability. Final failure happens much later, due to delamination from the fragmented plies.

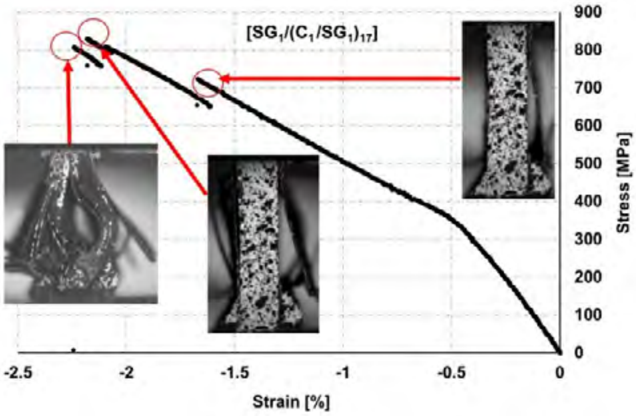

Figure 4. Knee point in compressive stress-strain curve due to fragmentation [9]

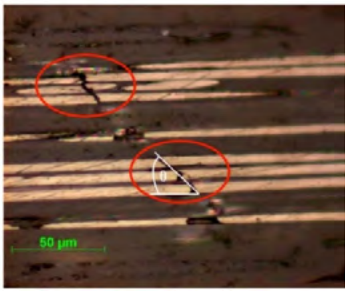

Figure 5. Compressive fracture of high modulus M55J ply in glass/carbon hybrid

Standard and intermediate modulus fibres may also fail at much higher strains than typically observed in composites. For example, Jeong and Ueda measured a failure strain of 2.5% for a single T800 fibre in a block of epoxy, much higher than the 1.1% observed in a composite [10]. Failures were at an angle of about 45°. Careful micromechanical tests on increasing numbers of fibres showed a single fracture and no kink band when there were few fibres, with a transition to a kink band failure at lower strain when there were a larger number of fibres.

5. Interaction of Instabilities

The strut buckling example discussed in section 2 is actually more complex than it initially seems. Euler buckling theory suggests that strut buckling under displacement control should be a stable and reversible process, and that is what has been observed for slender carbon/epoxy struts [1]. However, the 20 mm long specimens failed by a sudden and catastrophic instability. There is an interaction between the classical buckling geometric non-linearity and the material non-linearity of the carbon fibre. As bending increases following the initiation of buckling, the load reduces due to the reduction in effective bending stiffness caused by the non-linear material behaviour. The drop in load produces an increase in specimen length. In a displacement controlled test, this can only be accommodated by increased bending, leading to a further drop in load. At a certain point this process can become unstable, and the specimen snaps through from its initial state of high compression with some bending, to a new state of high bending with small compression, but the same overall length. This is shown schematically in Fig. 6. It is a different type of instability that is neither classical buckling, nor composite shear instability. Shortly after this point, the overloaded strut breaks, forming a kink band in the usual way, but this is not what actually precipitates the failure.

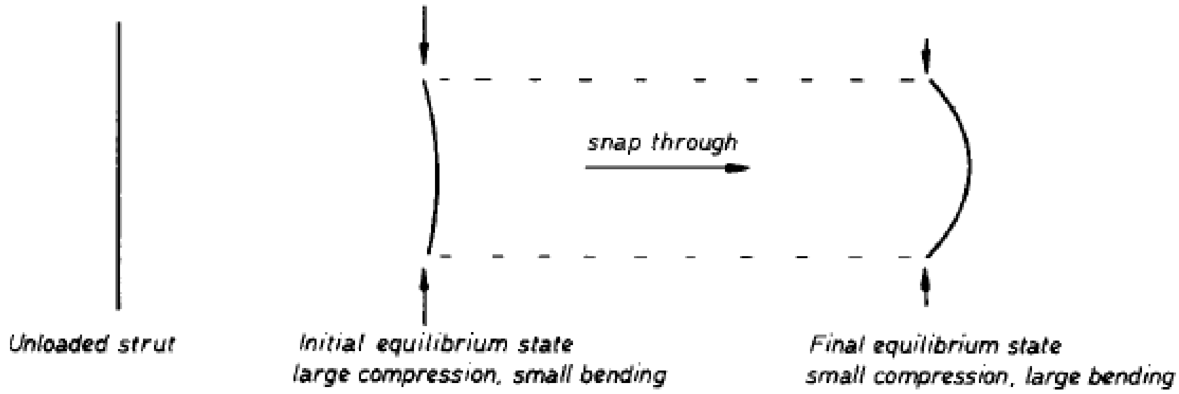

Figure 6. Interaction between geometric and material non-linearity [1]

Another example of interaction is between fibre and composite level instabilities. High modulus HR40 PAN fibre composites fail at low compressive strains, believed to be controlled by instability within the fibres themselves. However, failures show in-plane kink bands at a characteristic angle across the specimen width that look very similar to shear instability failures in standard modulus carbon fibre composites, rather than the fibre failures observed with M55J [11]. It is hypothesised that the reason for this is that the instability initiates at the level of the fibres, but since the stress is relatively high, it starts to interact with shear instability of the composite. The final failure therefore looks like a classical kink band even though it probably initiated in the fibres themselves. This contrasts with the M55J/S-glass composite shown in section 4, where there was no such interaction. Because of the low failure strain of the M55J, and the big difference between its modulus (540 GPa) and that of S-glass fibres (88 GPa), the composite stress at the point of M55J failure was relatively low, much below the point at which a composite shear instability would be expected.

6. Conclusions

Carbon fibre composites may fail in compression due to instability at the structural, material or fibre levels. Structural instability is strongly affected by the non-linear stress-strain response of the fibres, and can occur at much lower stresses than predicted from simple buckling equations. Care is needed in designing compression tests to ensure they do not fail prematurely due to buckling.

Many carbon fibre composites fail in compression due to shear instability. The stresses and strains at which this occurs are not necessarily constant, but can depend on factors such as strain gradients and hybridisation.

Carbon fibres themselves fail in compression by an instability within the structure of the fibre. This can lead to composite failure that is not controlled by classical material shear instability, especially with high modulus fibres. For example, M55J/S-glass hybrids fail by carbon fibre fragmentation followed by delamination.

There can be interaction between material and geometrical non-linearity that produces catastrophic failure before reaching the point of composite shear instability.

Fibre and composite level instabilities can interact to produce what appear to be classical shear instability failures with kink bands, but may actually initiate at the fibre level. Such interaction does not happen when there is a significant separation between the strains for the two mechanisms.

Acknowledgments

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References

[1] M. R. Wisnom and J. G. Haeberle JG. Prediction of buckling and failure of unidirectional carbon fibre-epoxy struts. *Composite Structures,* 28:229-239, 1994. https://doi.org/10.1016/0263-8223(94)90011-6

[2] B. Budiansky and N. A. Fleck. Compressive failure of fiber composites. *Journal of the Mechanics and Physics of Solids*, *41*(1):183-211, 1993. https://doi.org/10.1016/0022-5096(93)90068-q

[3] R. Gutkin, S. T. Pinho, P. Robinson and P. T. Curtis. On the transition from shear-driven fibre compressive failure to fibre kinking in notched CFRP laminates under longitudinal compression. *Composites Science and Technology*, *70*(8):1223-1231, 2010. https://doi.org/10.1016/j.compscitech.2010.03.010

[4] M. R. Wisnom, J. A. Atkinson and M. I. Jones. Reduction in compressive strain to failure with increasing specimen size in pin-ended buckling tests. *Composites Science and Technology*, 57: 1303-1308,1997. http://dx.doi.org/10.1016/S0266-3538(97)00057-2

[5] A. Tongloet, X. Wu and M. R. Wisnom. Compressive failure behaviour of hybrid composite with different low-strain carbon fibre. *21st European Conference on Composite Materials, ECCM21*, Nantes, 2024.

[6] F. Tanaka, T. Okabe, H. Okuda, I. A. Kinloch and R. J. Young. The effect of nanostructure upon the compressive strength of carbon fibres. *Journal of Materials Science*, *48*(5):2104-2110, 2013. https://doi.org/10.1007/s10853-012-6984-z

[7] M. G. Dobb, D. J. Johnson and C. R. Park. Compressional behavior of carbon-fibers. *Journal of Materials Science*, *25*(2A):829-834, 1990.

[8] G. Czél, M. Jalalvand and M. R. Wisnom. Design and characterization of advanced pseudo-ductile unidirectional thin-ply carbon/epoxy-glass/ epoxy hybrid composites. *Composite Structures*, 143: 362-370, 2016. http://dx.doi.org/10.1016/j.compstruct.2016.02.010

[9] P. Suwarta, G. Czél, M. Fotouhi, J. Rycerz and M. R. Wisnom. Pseudo-ductility of Unidirectional Thin Ply Hybrid Composites in Longitudinal Compression. *ASC 33rd Annu. Tech. Conf.,* Seattle, Sept. 2018.

[10] T. K. Jeong and M. Ueda. Longitudinal compressive failure of multiple-fiber model composites for a unidirectional carbon fiber reinforced plastic. *Open Journal of Composite Materials*, *6*(01):8, 2016.

[11] A. Tongloet. PhD thesis, University of Bristol, 2024.

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