ECCM21

02-05 July 2024 | **Nantes - France**

Proceedings of the 21st European Conference on Composite Materials

Vol 8

Special Sessions

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Published by:

The European Society for Composite Materials (ESCM) and the Ecole Centrale de Nantes.

These Proceedings have an ISBN (owned by the Publisher) and a DOI (owned by the Ecole Centrale de Nantes).

ISBN: 978-2-912985-01-9
DOI: 10.60691/yj56-np80

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Editorial

Each volume gathers contributions on specific topics:

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.

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30 YEARS OF DEVELOPMENT OF THE "IMPERIAL COLLEGE LONDON COMPRESSION STANDARD"

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Keywords: Compression standard for fibre reinforced polymer composites. Panel production, sample preparation, and testing guidance. Imperial College of Science, Technology and Medicine, and The Imperial College Method for Testing Composite Materials in Compression.

Abstract

The development of suitable tests for the determination of material properties of fibre-reinforced polymer composites has continued since their inception. Here we discuss how composite production, sample preparation, and compression testing, has developed from those initially carried out on coupon specimens in the late 80s/early 90s at Imperial College London (formally Imperial College of Science, Technology and Medicine, ICTM) and used within the community. The principles of the "Imperial College London Compression Standard" were informative to the production of ASTM International D6641 (Standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture), and closely align with other International Standards (ASTM D3410 Standard test method for compressive properties of polymer matrix composite materials with unsupported gage section by shear loading, and International Organization for Standardization ISO 14126 Fibre-reinforced plastic composites - Determination of compressive properties in the in-plane direction, and others for instance) for the compressive properties of fibre reinforced polymer composites; but with subtle alterations made to improve (i.e. reduce) stress concentrations at the end-tabs and unsupported gauge length region.

1. Introduction

The formalisation of standard tests for the determination of compressive strength of fibre-reinforced composites by the ASTM International, formerly known as American Society for Testing and Materials, and International Organization for Standardization, commonly referred to by ISO, are the primary methods used by academic studies and by industry for material characterisation in coupons. The main issue with determining the compressive properties of fibre-reinforced materials in coupons is their sensitivity, related to their production method and test procedure, and desire to make them applicable across a wide range of thicknesses and material types (predominately polymer based). These standards build upon the research carried out by individuals, multiple organisations and institutes from the 80s, and until current day, in an attempt to produce a reliable test and processing recommendations; for reviews on these initial studies can be found in reports by Bauman [1], and Curtis [2], and best practices summarised by Mathews [3].

The issues can be split into two main areas of concern, (1) producing a coupon specimens and (2) using a test procedure which when combined provides a valid failure mechanism/criteria, and representative results for the material; on the assumption that the material tested is consistent in the properties exhibited i.e. inherently reproducible and repeatable, with low scatter.

1. In compression, the alignment of reinforcing fibres is more critical than in tension, which is often self-aligning with loading conditions, whereas any misalignment in samples compression is exacerbated. This criterion means that compression coupon/sample preparation is critical for representative results of the material tested, and great care and attention should be made with fibre alignment within the specimen, and to the loading direction during the test.
2. Test regimes which are reproducible and repeatable do not guarantee that the properties of the materials are measured to their zenith. Indeed, if the test introduces inherent instabilities or stress concentrations it might reduce the overall expected reported values but produce consistent results. A test regime that allows the material properties to be maximised is likely to better represent the material properties if reproducibility, repeatability, and scatter are comparable between the testing regimes.

Note that there is a reduction in the absolute compressive properties (values) reported for specimens that are greater than 2 mm thickness, when compared to a 2 mm baseline, with no adaptions made other than scaling the specimen (altering length:thickness ratio) and this is discussed elsewhere [4].

Various compression test methods for fibre-reinforced polymer composites are reported, the most common are,

- ASTM D6641, Standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture [5],
- ASTM D3410, Standard test method for compressive properties of polymer matrix composite materials with unsupported gage section by shear loading [6], and
- ISO 14126, Fibre-reinforced plastic composites - Determination of compressive properties in the in-plane direction [7], and others for instance.

These standards contain guidance on the preparation of specimens as previously mentioned, this can affect the outcome as well as criteria to correctly identify a valid failure and how to process collected data. ISO 14126 [7] also provides details on the digital image correlation determination of the strain measured optically, whereas strain gauges are normally favoured due to the small gauge regions - although resolution/fidelity and misalignment, respectively, should be considered in use. It must be stressed that good practices be followed during manufacture to achieve comparable results in any test regime used.

Typically, compression tests require,

- short gauge lengths - to reduce bending effects,
- uniform cross sections - for uniform stress fields, and be
- easily reproduced shapes - to minimise complexity for producing specimens and reduce variability.

Common compression tests issues reported,

- misalignment of fibres to loading direction - reducing expected properties,
- failure in end-tabs/jaws because of uneven/corner loading – invalid failures, and
- specimens bending significantly during tests. For a discussion on the effects of bending on the compressive performance please refer to the work by Wegner and Adams, page 88 [8].

2. Stress concentrations in unsupported gauge regions

The unsupported gauge region, adjacent to the end-tabs, is the most likely region to lead to a stress concentration and premature failure. Whilst the failure will often be in the gauge region, providing a gradient to reduce this stress concentration effect was of a greater concern for early investigations [9]. Indeed, multiple variations in end-tabbing procedures/modification are proposed to reduce this effect (Figure 1), and focus predominately at the critical section of end-tabbed samples at the junction of the unsupported gauged region. End-tab materials were also varied in early studies, for instance the use of metal end-tabs improving overall measured compressive strengths, and epoxy reinforced composites using differing fibres (carbon/glass for instance), but there is now a consensus that glass-fibre woven epoxy end-tabbing materials has the right balance of support and ease of processing, and are now common. Studies within Imperial's Department of Aeronautics and later and separately by the National Physics Laboratory (NPL) investigated modifications through the addition of a unbonded end-tab region through polytetrafluoroethylene (PTFE) film inserts, (Figure 1 (c)) [3, 10-14], or reversed chamfered/epoxy fillets, Figure 1 (d) [15-17], respectively. Internally, at Imperial, the reversed chamfered/epoxy fillets approach was adopted into the test regime, superseding the unbonded end-tab region method. The effect of the end-tab modifications were investigated by Dogra in a PhD Thesis [18] and reported in a conference paper [19], and thicker variations of specimens though MSc projects [20]. These studies showed that the reversed chamfered/epoxy fillets were an effective method of reducing stress concentrations in a short gauge length test. These tests when ranked/benchmarked against other standards often produces data which has increased strain-to-failure (for similar gauge length tests, and thicknesses), and higher compression strengths as a result, with comparable reproducibility, repeatability, and scatters reported [18]. The Imperial College London Compression Standard has been used for unidirectional and woven reinforced specimens, pre-pregs and resin infused panels, and using an array of reinforcing fibres (carbon, glass, and natural, for example flax) and in thicker coupon geometries with further modifications. It is noted that the ISO and ASTM tests do not suggest any modifications to this end-tab/gauge region through geometry or additional end-tab modification. ASTM D6641 provides a rational behind this recommendation "While tapered tabs would be potentially beneficial in reducing stress concentrations in the specimen at the tab ends, they increase the effective unsupported length (gage length) of the specimen, increasing the possibility of inducing specimen buckling. Thus, untapered (square-ended) tabs are recommended" Section 8 Sampling and Test Specimens, 8.2 Geometry, page 5 [5].

Since the adoption of the reversed end-tab chamfered/epoxy fillet regions at Imperial College London, a process to improve the end-tabbing process has been developed by the Aeronautics Department Technicians (Gary Senior and Jon Cole), at the Composite Centre. They have been instrumental to improving the production of samples, introducing alignment jigs, and ensuring high quality of samples are produced. More recently, equipment developments in cutting pre-preg through computer aided automation processes allows for greater refinement of the lay-up procedure (using location pins for instance), which improves fibre alignment in the resultant panels, and produces more uniform panels to prepare specimens from.

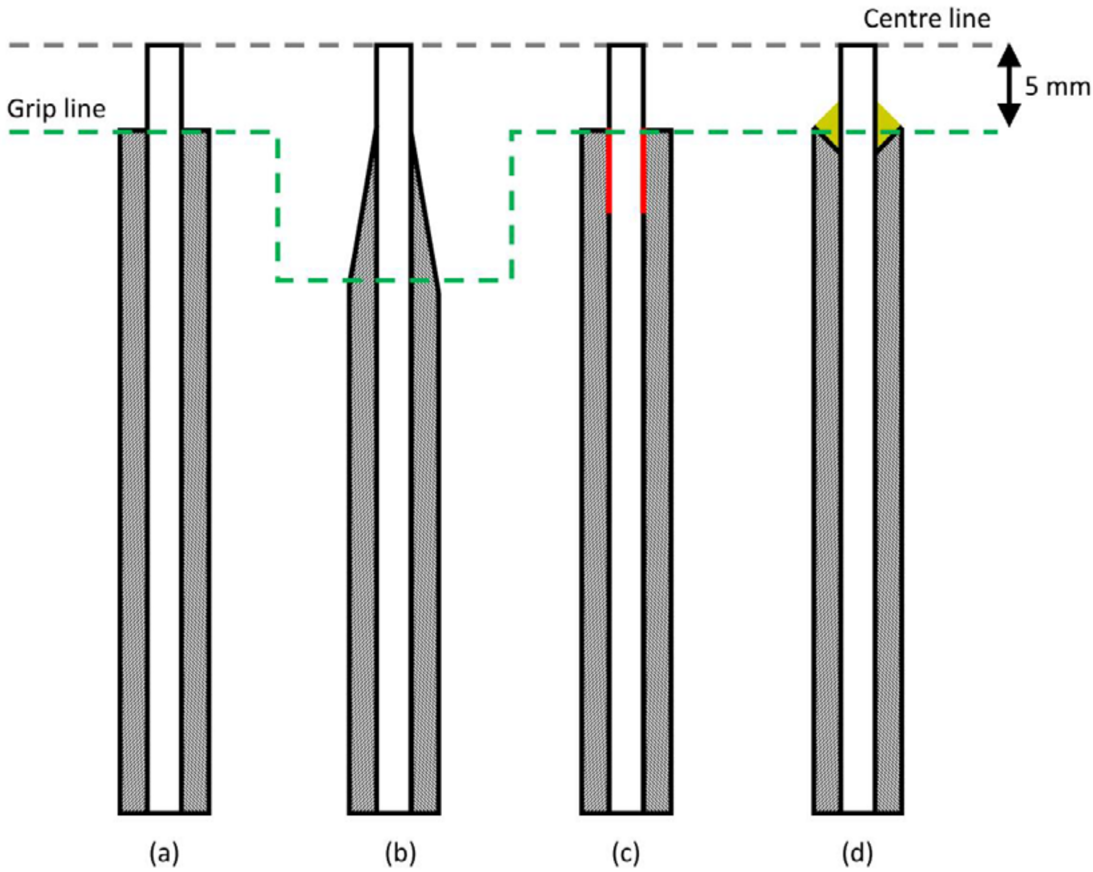

Figure 1. Side view cartoons of end-tab variations indicating gripping conditions (green line) and centre line (grey) shown relative to the unsupported gauge region (half shown, 5 mm) for a typical specimen of thickness ca. 2 mm, (a) untapered fully gripped as found in ASTM [5, 6] and ISO standards [7], then end-tabs proposed to reduce stress-concentrations in unsupported gauge region, (b) tapered fully gripped (note: if gripped region kept constant this would increase overall specimen length), (c) untapered fully gripped with PTFE film insert (film coloured red, ~5-7 mm in length) reduced effective transfer load from inserted film section [13], and (d) reversed chamfered/epoxy fillet modification to end-tab region (epoxy fillet coloured olive-green, spanning ~2 mm in total, reducing the uncoated gauge region to 8 mm total (or 4 mm shown here). Adapted from [9], not shown to scale.

3. Comparison of nominal sample geometries for common fibre reinforced composite compression standards

Table 1. Nominal coupon dimension according to associated standards with a fixed thickness of approximately 2 mm for end-tabbed and unsupported gauge sections for unidirectional fibre reinforced composite samples.

Test method	Nominal thickness [mm]	Overall length [mm]	Overall width [mm]	Gauge length [mm]	End-tabs Length [mm]	End-tab thickness [mm]
ASTM D6641 (Procedure B) [5]	2.5 ± 0.03 †	140 ± 0.3	13 ± 0.06	13	63	1.6
ASTM D3410 [6]	1.54 ± 2 % minimum*	140 to 155	10 ± 1 %	10	65	1.5
ISO 14126 (Type A) [7]	2 ± 0.2	110 minimum	10 ± 0.5	10	50	1.0 ± 2 %
Imperial College Compression [13]	2 ± 0.2	90 ± 0.5	9.5 ± 0.5	10 ◊	40	1.6
Imperial College Compression [18]	2 ± 0.2	90 ± 0.5	9.5 ± 0.5	10 ‡	40	1.6

† for specimens with thickness on the order of 2.5 mm, links to ASTM D3410 for thickness determination
* with longitudinal modulus 200 GPa and expected compressive strength 1800 MPa
◊ PTFE film inserts used
‡ bare surface ~8 mm with reverse chamfered tapered fillet of epoxy between end-tab and adjacent to gauge region

For the user there are benefits and limitations to all these tests that are mentioned in detail elsewhere, Dogra [18], but a consideration of materials required and loading conditions produced by the suggested fixtures are important concerns.

4. Compression fixture designs

There are several different methods used in fixture-grip designs, they are typically designated as introducing the load in the specimen through either shear-loading, end-loading, or combined shear-end-loading. In ASTM D46641 [5] and ISO 14126 [7] the combined shear-end-loading fixture is preferred, however the ASTM D3410 [6] uses shear-loading only. The general availability of fixtures from commercial manufacturers has reduced the prominence of standards used outside of those reported by ASTM and ISO. However, the Imperial College Compression Standard uses a simple in-house made fixture and grips (Figure 2); which comprises of a steel block, with clamping screws and a clamping block used to secure the specimen and provide shear-loading in conjunction with a hardened steel plate surface which provides end-loading - to produce a combined loading grips for the upper and lower portions of the specimen. The design is a subtle variant of the Birmingham fixture [21], but in practice operates in the same manner with torque wrenches used for tightening the clamping screws to provide the shear loading. The upper fixture is mounted directly to a commercially bought high precision die-set with the lower grip fixture floating to reduce undesired bending/torsional and misalignment effects. The lower section of the die-set is also attached to an additional alignment ball jointed socket (not shown), this rests on a hardened steel block and is included to minimise misalignments in the universal testing equipment. The Imperial College Compression fixture can be easily produced without specialist equipment and has the benefit that it may be adapted for larger/thicker specimens if desired. Although care must be made to changes in thickness and overall specimen geometries and design, especially when comparing results with thinner coupons.

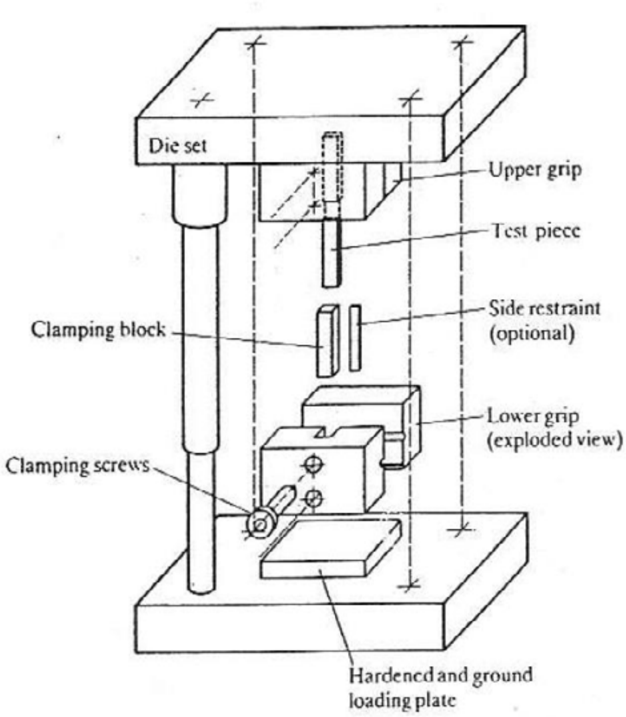

Figure 2. Imperial College Compression Standard fixture/test rig and specimen [14].

5. Conclusions

Compression tests of fibre-reinforced polymer composite materials remain a challenge and current standards attempt to reduce variability and improve reproducible and repeatable results. The most commonly used compression standards do not address the stress concentrations that are inevitable in the unsupported gauge regions adjacent to the end-tabs. Solutions to reduce these stress-concentration effects have been on-going within the community [17]. The use of the Imperial College London Compression Standard also attempts to address these stress-concentration concerns, but only initial publications are available externally, with primarily in-house knowledge transfer prevailing. Subsequently, improvements in the production of compression specimens and best practices associated with these changes, including the use of more modern methods of cutting pre-pregs, and the adoption NPL's reversed chamfered/epoxy fillets design, and the investigation of its use in the Imperial Compression Standard fixture (with short gauge region samples) have not been widely reported. We suggest that reduce chamfered/epoxy fillets design is a reasonable and practical method to reduce the stress concentration gradients at the critical end-tab and unsupported short gauge regions. We understand that there are additional processes required to produce reverse chamfered specimens, however we deem this effort worthwhile. For readers who are interested in the breadth of other fixture designs which have been used in determining compressive performance of fibre-reinforced composites and not possible to discuss in this article they are directed to Mathews [3].

Acknowledgments

The authors kindly acknowledge the funding for this research provided by UK Engineering and Physical Sciences Research Council (EPSRC) programme Grant EP/T011653/1, Next Generation Fibre-Reinforced Composites: a Full Scale Redesign for Compression (NextCOMP) a collaboration between Imperial College London and University of Bristol. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY-NC 4.0) license to any author accepted manuscript version arising.

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02-05 July 2024 | **Nantes - France**

Volume 8

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ISBN: 978-2-912985-01-9
DOI: 10.60691/yj56-np80