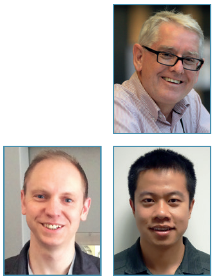
Destructive and non-destructive testing of composites for design and manufacture

Early in the design cycle, the modelling and simulation of composite components for use in demanding structural applications requires a detailed knowledge of the properties of these anisotropic and inhomogeneous materials. The determination of these properties requires a wide range of mechanical tests, possibly over a range of temperatures, on materials conditioned in a variety of different environments. Later in the design cycle, mechanical tests on composite components are often employed to validate models by comparing model predictions to measurements on prototypes.



By

Ian McEnteggart,
Composites Marketing Manager, Instron
Guy Tolley, Business Development Manager,
Sheng Yue, ISG Applications Manager,
North Star Imaging

During manufacturing, various non-destructive inspection methods are employed to ensure that parts conform to specifications and are free from significant defects. One of the most exciting recent developments in non-destructive testing is the use of computerised tomography (CT) – a technique that uses X-rays to produce a 3D representation of the internal structure of an object. This 3D representation makes it possible to quantify defects within a composite, allowing measurement of the size and location of voids, the density and total volume of voids, and the local/global fibre orientation and concentration.

Figure 1 shows two views of a 3D CT reconstruction of a composite plate with a wrinkle defect. In the first image, the intensity is proportional to the density and in the second image, the density is colour coded. The CT model can be manipulated in real-time 3D and it is also possible to slice through in any direction for internal inspection.

Determining material properties for modelling and simulation – static properties

Determining the static bulk properties of a composite laminate requires a range of mechanical tests (tension, compression, shear and flexure). In most cases, the properties of interest are in-plane properties (in the same plane as the lamination), but in some cases the through-thickness properties (in a direction normal to the plane of the laminate) are also required.

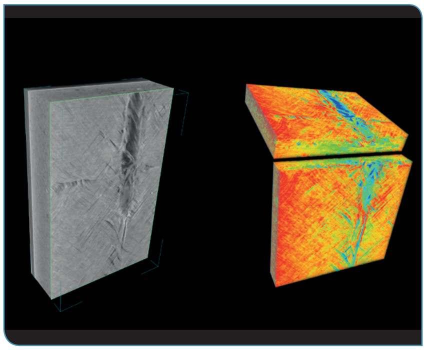
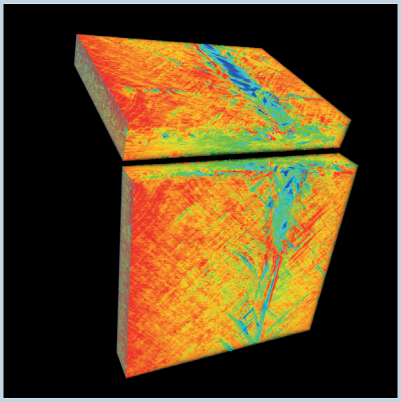


Fig. 1: 3D reconstruction of a composite plate



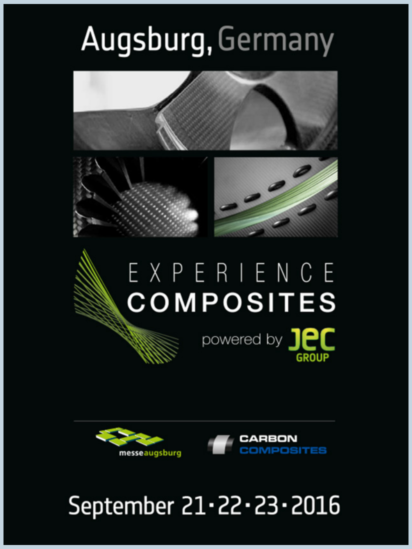


Fig. 2: Instron 5985 composites testing system

Fig. 3: Instron drop tower for impact testing

Fig. 4: Instron high-rate servohydraulic testing system

In-plane tension testing of composite laminates is similar, in principle, to a traditional metals or plastics tension test. The test specimen is usually a rectangular coupon cut from a laminate panel in a specific direction relative to the fibre directions. Glass fibre composite tabs are usually bonded to the gripped ends of the specimens to help prevent the grip jaw faces from damaging the laminate and causing premature failure. When required, through-thickness properties of thick laminates can be obtained from direct tension tests on cylindrical specimens cut from the laminate. Through-thickness tension testing on thin laminates can also be performed, indirectly, by subjecting a curved laminate beam to a four-point bending test to generate a through-thickness tensile stress in the curved section.

In-plane composite compression test methods provide a means of introducing a compressive load into the specimen while preventing buckling of the specimen. In practice, there are several different compression test methods and associated fixtures in widespread use employing different methods of load introduction and anti-buckling. All composite compression fixtures are required to have excellent alignment and high lateral stiffness in order to prevent specimen bending and premature failure. Most compression test methods require specimen bending to be monitored by independently measuring the strain on both sides of the specimen using bonded strain gauges and set a limit for the maximum allowable bending strain during a test. Through-thickness compression testing is also performed.

Variations on in-plane tensile and compression tests for laminates include tests on specimens with both open and filled holes. These tests provide information on the strength reductions associated with such common features.

Shear properties for design databases are generally determined using a V-notch specimen subjected to shear loading using either ASTM D5379 (Iosipescu) or ASTM D7078 test fixtures. The shear strain is measured using strain gauges bonded to the specimen. Specimen preparation and testing for V-notch shear tests are complex. Simpler shear tests that are suitable for comparative testing, screening, and quality control (QC) are available. The in-plane shear (IPS) test is a tension test on a specimen cut from a 0/90 laminate panel so that the fibre directions are +/-45° to the specimen axis. This test enables shear modulus and shear strength to be determined. The inter-laminar shear strength (ILSS) test is in widespread use for QC testing and screening. It uses a small specimen subject to three-point bending. This configuration results in large shear stresses along the mid-plane of the specimen, resulting in a shear failure.

Flexure testing can also be used to determine a number of composite material properties. Compared to other test methods, flex testing has the advantage of requiring simple rectangular specimens without tabs or complex machining.

In addition to tests designed to determine the bulk properties of composites, a number of tests have been developed to evaluate the fracture toughness properties of composite laminates. Examples of such tests include Mode I fracture testing using a double cantilever beam (DCB) specimen and Mode II fracture testing using an end notched flexure (ENF).

Figure 2 shows a typical electromechanical testing system capable of performing most of the mechanical tests on composite materials over a range of temperatures.

Determining material properties for modelling and simulation – fatigue and high-rate properties

In addition to static properties, designers need to be able to assess the service life of structures subject to the time-varying loads and environmental factors that will be encountered in use, and possibly to assess the behaviour of a structure under extreme conditions such as an impact or crash.

Fatigue testing of composite materials is most commonly performed using tension-tension cyclic loading of rectangular specimens. Typically, a number of specimens are subjected to cyclic loading at various stress amplitudes in order to produce an S-N curve that relates the varying stress conditions to the number of cycles to failure. Fatigue testing of composites is time consuming because the test frequency must be limited to prevent the specimen from overheating. Fatigue loading cycles, which include compression loading, are not yet common due to the difficulty of preventing specimen buckling, but there is increasing demand to test and analyse under such loading conditions.

High-rate testing of composite materials is required to predict their behaviour in the event of a crash. Common examples of high-rate testing of composite materials include impact testing and high-rate tension/compression testing. In a high-rate impact test, a composite panel or part is subject to an impact from a drop weight or a hydraulically-driven indenter. After impact, damage is evaluated by either visual or ultrasonic inspection and/or the determination of residual strength in a compression after impact (CAI) test. In a CAI test, an impact-damaged composite panel is mounted in a support to prevent buckling and loaded in compression until it fails, giving a measurement of the strength reduction due to the impact damage. High-rate tension or compression testing can be performed using either a drop tower (figure 3) or with a high-rate servohydraulic testing machine (figure 4). The servohydraulic machine provides a more flexible platform for this type of work. For example, it can test over a wider speed range and can maintain a constant speed during the test.

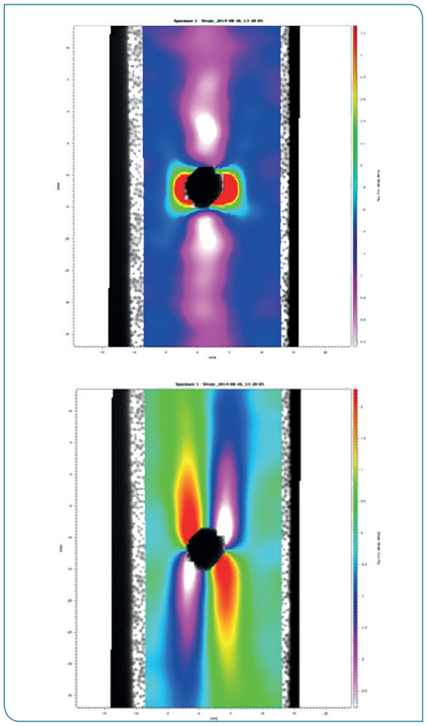


Fig. 5: DIC axial and shear strain maps for an open-hole composite specimen

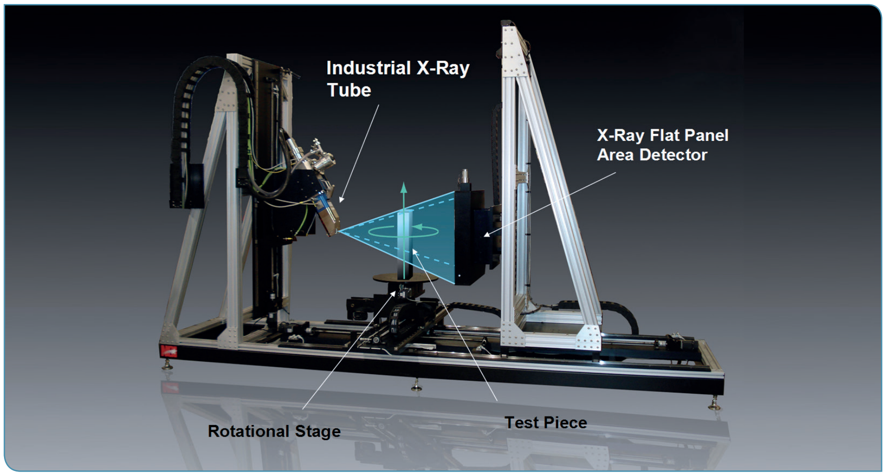


Fig. 6: General principle of a modern industrial CT scanner

Full-field strain measurement for model validation

Mechanical testing of prototypes is a long established practice, but recent developments in full-field strain measurement have revolutionised this process.

The most widely used approach to full-field strain measurement is digital image correlation (DIC). This technique works by applying a random pattern to the surface of the component under test, capturing a series of images of a specimen during a test, and then analysing the images with an algorithm that determines first the displacement field and then the strain field for each image. The first image – also known as the reference image – is captured when there is no load on the sample. The image is then split into small subsets, the patterns within each subset of subsequent images are compared to the reference image and displacements are calculated. From these displacements, a strain map is calculated. The strain maps of all the strain components (axial, transverse and shear strain), along with maximum and minimum normal strains, can be determined. Example strain maps for an open-hole composite tensile test coupon are shown in figure 5. The magnitude of the strain is represented by different colours. The first image shows the axial strain distribution in the vertical direction and the second image shows the shear strain distribution.

Even the most efficient DIC algorithms require a large amount of computing power and it is generally not possible to perform the analysis in real time, i.e. during the test. The usual approach is to acquire and store the images during the test and then perform the analysis afterwards. One challenge when using DIC systems with testing machines that incorporate other measurement systems (force, displacement and temperature) is how to synchronize and record all of the test data. A recent, integrated DIC system for use with material testing machines has solved this problem by synchronizing the recording of the images and the other test data digitally.

Compared to traditional methods measuring local strains (e.g. strain gauges), full-field strain measurement yields an enormous amount of additional information that can help engineers and scientists better understand material behaviour and validate complex models.

Computerised tomography for the non-destructive inspection of composites

Industrial CT (figure 6) uses a series of two-dimensional images taken at specific intervals around the entire sample. An industrial CT system uses three principal components: an X-ray tube, an X-ray detector and a rotational stage. Everything is enclosed in a radiation shielding steel/lead/steel cabinet. In addition to the cabinet, a computer workstation, consisting of a 2D X-ray console for acquisition, and a 3D CT workstation for volume reconstruction are required.

A high-end CT scan consists in taking several 2D X-ray images around the object, preferably covering 360° (complete rotation). CT systems typically acquire between 360 and 3600 images depending on the final desired resolution. Each image is between 3-10 megapixels and is also averaged and filtered to reduce noise.

Once the acquisition process of the CT scan is completed, calibration and reconstruction algorithms are used to reconstruct the 3D CT volume. Visualization software allows the 3D volume to be manipulated in real time, enabling the viewer to slice through anywhere inside the object, inspect and look for defects, and take accurate measurements. The 3D CT volume non-destructively reveals a complete model with both external and internal surfaces. Moreover, CT works with any surface, shape, colour or material (up to a certain density and/or thickness penetrable with X-rays). A modern start-to-finish CT scan can be as fast as a few seconds or take longer than an hour, depending on the resolution requirements and size and/or density of the object.

Combining mechanical testing with computerised tomography

Combining mechanical testing with DIC provides much more information on the behaviour of materials and structures than is obtained from a traditional test. However, the full-field strain data is confined to the surface and the spatial resolution of DIC is limited (typically 1 mm). CT makes it possible to look inside the part with a much higher spatial resolution (typical resolution 20 µm) and offers the exciting possibility of helping us develop a much deeper understanding of the mechanisms behind the failure of composite parts.

As an example of the use of CT alongside mechanical testing, an open-hole woven composite coupon was tested in an Instron® 5985 250 kN testing machine. The coupon was scanned before, during and after the test in a North Start Imaging X5000 series CT scanner (figure 7).

The scans during the test were conducted at the points where there were small drops in the load (accompanied by audible pings) indicating partial failure of the coupon.

The sectioned 3D images from the scans are shown in figure 8. Figure 8a is an image of the coupon before the test; the woven structure can be clearly seen. Figure 8b is from a scan taken after the first drop in load and the zoomed-in view shows both axial and transverse cracking in the vicinity of the hole. The final image (8c) shows the coupon immediately after failure.

The results of this test show the ability of X-ray CT to produce high-quality 3D images of composite materials with sufficient resolution to resolve cracks and provide valuable information on the failure mechanisms of composite materials.

Fig. 7: North Start Imaging X5000 series CT scanner

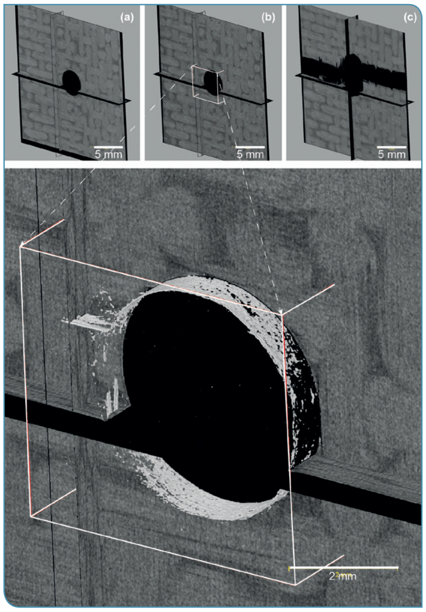


Fig. 8: CT images from open-hole test

Conclusion

Conventional mechanical tests to determine the static properties of composite materials continue to play an essential role in providing data on materials for use in models. In addition to static material properties, fatigue and high-strain rate data is important for many applications. Combining mechanical tests on structures with full-field strain measurement techniques enhances the understanding of the behaviour of composite materials and models.

3D CT is now more accessible than ever for the composites industry. User-friendly interfaces, increased scan speeds and decreasing prices have all contributed to the rapid growth of this technology. Having very accurate internal dimensions without destroying the item, along with the ability to compare to a reference model, is entirely unique to CT. There are no shaded zones, it works with all kinds of shapes and surfaces, there is no post-processing work needed, and the resolution is excellent. Above all, the greatest benefit is the ability to non-destructively obtain the 3D internal structure of the object, and CT is the only technology capable of achieving such performance. ■

References

[1] Mechanical testing of advanced fibre composites, Woodhead Publishing, ISBN: 1 85573 312 9

[2] Handbook of Experimental Solid Mechanics, Springer, ISBN: 978-0-387-26883-5

More information:
www.instron.us