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Testing of Composites: A Review

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ABSTRACT

Manufacturers from various industries always strive to produce structures that are lighter, stronger, offer greater corrosion resistance and exhibit other required properties; than those of the traditionally available materials. Composite materials offer a solution to all the needs of these manufacturer(s). Composites are complex structures made of a variety of different polymers, metals, and ceramic materials. Composite materials are being used increasingly in a wide variety of products and applications. Ever-increasing performance demands in the industries viz. the aerospace, automotive, and environmentally sustainable-energy systems requires a wider range of physical and mechanical testing. Testing of composites for physical and mechanical properties is required to characterize and understand the performance of these materials. Testing of composite materials includes high force tension and compression, impact, flexure, shear, rheology, and fatigue tests under a range of environmental and/or experimental conditions. Mechanical testing is an important step in the "building block" approach to design of composite aircraft structures. Mechanical testing instruments are configured using a range of fixtures that have been developed to provide various ways to test composite materials depending on the type of material and its intended end use. In this paper various methods of testing composite materials has been discussed in details. The paper also provides a source of information about the current testing methods through which the advanced composites can be evaluated to yield satisfactory results.

Introduction

Composite materials are extending the horizons of designers in all branches of engineering, and yet the degree to which this is happening can easily pass unperceived. The eye, after all, does not see beyond the glossy exterior or the race performance of a glass-fibre-reinforced plastics yacht, nor does it sense the complexity of the structure of a composite helicopter rotor blade or of a modern carbon-fibre-reinforced plastic tennis racket. Nevertheless, this family of synthesized materials offers the possibility of exciting new solutions to difficult engineering problems.

In composites, materials are combined in such a way as to enable us to make better use of their virtues while minimizing to some extent the effects of their deficiencies. This process of optimization can release a designer from the constraints associated with the selection and manufacture of conventional materials. He can make use of tougher and lighter materials, with properties that can be tailored to suit particular design requirements. And because of the ease with which complex shapes can be manufactured, the complete rethinking of an established design [1] in terms of composites can often lead to both cheaper and better solutions.

The simple term 'composites' gives little indication of the vast range of individual combinations that are included in this class of materials. Figure 1 gives a clearer idea of the scope for ingenuity which is available to the Materials Scientist and his customer, the Design Engineer. First, within each group of materials — metallic, ceramic and polymeric — there are already certain familiar materials which can be described as composites. Many members of the commonest and largest group of engineering materials, the family of steels, consist of combinations of particles of hard ceramic compounds in a softer metallic matrix. These particles are sometimes plate-like, sometimes needle-shaped, and sometimes spherical or polygonal. Polymers, too, are often two-phased, consisting of a matrix of one polymer with distributions of harder or softer particles contained within it; wood is a perfect example of this, as we have seen. And concrete is a classic example of a ceramic composite, with particles of sand and aggregate of graded sizes in a matrix of hydrated Portland cement. These materials have been well known for many years, and Materials Scientists have learned to control their properties by controlling their microstructures; that is to say, the quantity, the form, and the distribution of what we

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might refer to as the 'reinforcing phase'. The idea of mixing components across the materials class boundaries is a natural extension of this idea.

The properties of engineering materials should be reproducible and accurately known for them to be used as a building block for the composite. And since satisfactory exploitation of the composite principle depends on the design flexibility that results from tailoring the properties of a combination of materials to suit a particular requirement, we also need to be able to predict those properties successfully. At the present time some of the more important engineering properties of composites can be well predicted on the basis of mathematical models, but many cannot.

In application, it is important to evaluate mechanical properties of these new materials. Properties[2] to be evaluated include tensile, compressive, shear and bending modulus, and strength.

A thorough understanding of composites properties, are paramount to determining whether a material is suitable for a specific application, or not. Changes in the polymeric chemistry, due to the effects of external environment will change physical properties and thus these must be characterized and understood well; to determine how a selected material will behave during manufacture, usage and service.

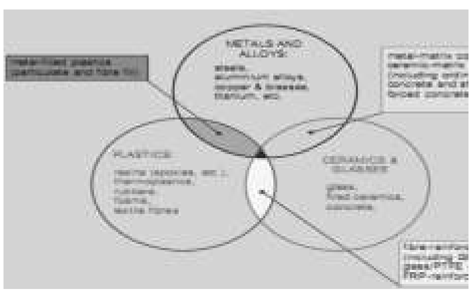

Fig 1: Relationships between classes of engineering materials, showing the evolution of composites

Why & How to Test Composites?

Composites testing is performed to determine material properties, reliability, and damage tolerance. Other testing is done to study the effects of variables on the materials. Material properties: Structural variables such as fiber orientation, fiber volume fraction, laminate thickness, and core density; and processing variables such as layup accuracy, curing temperature and pressure, can have a dramatic affect on the mechanical properties of composite materials. Mechanical and process testing is necessary to understand the effect these variables have on finished material or component.

Reliability and repeatability of component properties must be proven through testing to ensure optimal service in high-performance applications in aerospace, automotive, and motorsport applications.

Testing is necessary to simulate real-life conditions such as impact on components from dropped tools, minor accidents, and manufacturing imperfections. Testing is performed to investigate variables that can affect mechanical properties and damage tolerance, and to provide data for use in finite element analysis.

Selecting the Right Test

Composites [3] are complex structures made of a variety of different polymer, metal, and ceramic materials. The mechanical and chemical integrity of composite materials are affected by many variables, making property prediction and analysis challenging. Thus, testing is a vital addition to chemical analysis, as well as being essential for quality control. Brief descriptions of some of the tests used to characterize composites are given below.

A New Method for Testing Composites at Very High Strain Rates [4] was proposed and developed by I.M. Daniel, R.H. LaBedz and T. Liber, 1980, for testing and characterizing unidirectional and angle-ply composite laminates at strain rates in the 100 to 500 s^{-1} regime.

This method utilizes a thin ring specimen, 10.16 cm (4 in.) in diameter, 2.54 cm (1 in.) wide and 6-8 plies thick[5]. This specimen was loaded by an internal pressure pulse applied explosively through a liquid as shown in Fig 2. Pressure was measured by means of a calibrated steel ring instrumented with strain gages.

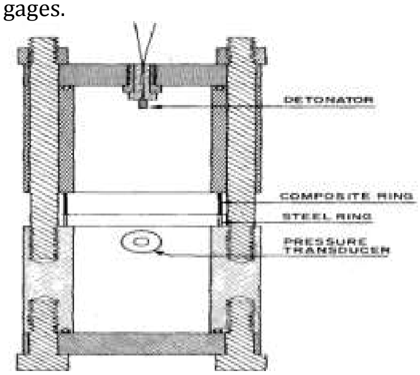

Fig 2: Fixture for dynamic loading of composite-ring specimens [4]

Strains in the composite specimen were measured with strain gages [6]. Strains in the calibration and specimen rings were recorded with a digital processing oscilloscope. The equation of motion was solved numerically and the data processed by the mini-computer attached to the oscilloscope. Results were obtained, and plotted by an X-Y plotter in the form of a dynamic stress-strain curve.

A computer program was written involving smoothing and approximations of the strain data, strain rate and strain acceleration. Dynamic stress- strain curves were obtained and plotted for 0-deg, 90-deg and 10-deg off-axis graphite/epoxy specimens. In the case of 0-deg specimens, the dynamic modulus exceeds the static by approximately 20 percent, whereas, the dynamic strength[7] and dynamic ultimate strain were very close to the corresponding static values. In the transverse to the fiber direction, the dynamic modulus and strength were two to four times the corresponding static values, whereas the dynamic ultimate strain was close to the static one. The in-plane dynamic shear modulus and shear strength are approximately 30 percent higher than the static values. However, the dynamic ultimate shear strain is lower than the static one, because the nonlinearity of the shear stress-strain curve is less pronounced under dynamic conditions.

A conventional Charpy tester, Tinius Olsen Model 64, was modified and instrumented by **V.S. Gopalaratnam, S.P. Shah and R. John**, 1984,[8] to facilitate tests on concrete[9] specimens at different impact[10] velocities. Among the three primary modifications were: (a) instrumentation of the striker and the two supporting anvils, (b) seating arrangement to accommodate large-sized specimens, and (c) low-blow fixture to enable tests at different impact velocities.

This model is capable of providing suitable guidelines for the a priori selection of the basic test parameters with a view to minimize parasitic effects of inertial loading. The general features of the instrumented impact test used in this study are presented in Fig. 3.

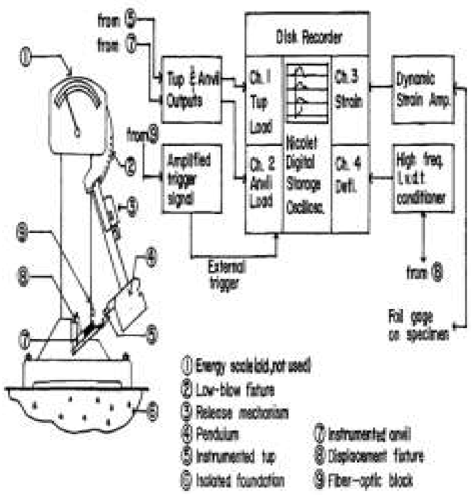

Fig 3: A schematic showing the general features of the modified instrumented Charpy test [8]

It was felt that recording of anvil and striker loads[11] simultaneously was essential both to a proper interpretation of inertial loads, and to assess the influence of parameters like test-system compliance, specimen size and impact velocity on the test results. The anvil and the striker were designed to serve as compression load cells capable of recording dynamic loads[12] transmitted through them during an impact event. They were made from hardened tool steel (oil hardened, SAE 01, Rockwell C55) to ensure elastic behavior even under high loads. They were sufficiently rounded at the specimen contact points so as to avoid local compressive damage to the specimen on impact, and at the same time facilitate smooth specimen rotation during bending.

In these years advanced composite materials are widely used. New fibers [13] with very high performance are also being developed. For example, TS00 carbon fiber of Toray Company has a tensile strength of 5 GPa, which was already available commercially. Further, TI000 fiber with a strength higher than T800 has been developed. In application, it is important to evaluate mechanical properties of these new materials. Properties to be evaluated include tensile, compressive, shear and bending modulus and strength.

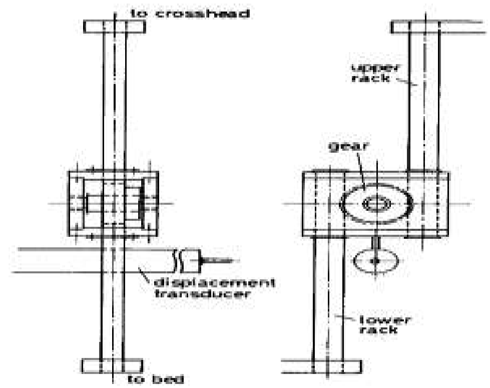

Fig 4: A device to measure maximum deflection [15]

Fig 5: Setup of devices [15]

Many of the current testing methods for advanced composites [14] are duplicates of the testing methods for conventional metals or plastics. Hiroshi Fukuda, 1989, [15] proposed a new bending test method for the advanced composited. A newly proposed method was based on a bending by means of axial compression and this method overcomes the disadvantages by the conventional three-or four-point bending method to obtain a bending strength for the advanced composites. This method was based on bending by means of axial compression. Since no loading device was attached at the failure region of a specimen, this method overcomes the undesirable effects of loading nose which were common for conventional three- or four-point bending. Based on this idea, a device was designed and machined. Using this device, a compression bending test was tried for various kinds of composites. It was proved by the results that this method is superior to the conventional method especially for super-high strength composites like T800 composites.

L.R. Deobald and A.S. Kobayashi, 1991, [16] developed a bar impact test to study the dynamic fracture responses of precracked ceramic bars [17], AI208 and 15/29-percent volume SiCw/AI208 [18]. Crack-opening displacement was measured with a laser-interferometric displacement gage and was used to determine the crack velocity and the dynamic stress-intensity factor [19]. The crack velocity increased with increasing impact velocity while the dynamic-initiation fracture toughness, Kx.,, did not vary consistently with increasing impact velocities.

The bar-impact experiment consists of a 50.8-mm long, rectangular bar specimen which is impacted on its end by a 25.4 mm long bar impactor of the same material. Ideally the reflected tension wave from the free end of the specimen bar interacts with the incoming compressive wave and generates a tensile stress pulse of 5.2 μs duration in the middle of the bar specimen with the transit of approximately 3/4 of the compressive pulse as shown by the Lagrangian diagram of Fig. 6. In practice, the impact typically produces a compressive stress wave of 1.6 μs rise time propagating in both the impactor and the specimen. The superposition of the incoming ramping portion of the compressive stress waves causes a tension pulse, which rises in about 0.8 μs and is sustained for another 3.6 μs, at the crack plane.

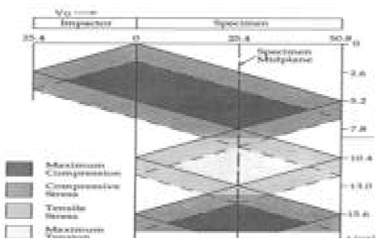

Fig 6: Lagrangian diagram for impact experiment, C_b = 9.8 mm/μs [16]

The schematic of the experimental apparatus is shown in Fig. 5. The specimen and impactor bars are held by molded urethane holders which are mounted in two carriages. Both the specimen and the impactor carriage run on guide rails. An air gun propels the impactor carriage down the guide rails towards the stationary specimen carriage. The ceramic bars impact well before the collision of the urethane holders. The resultant compressive stress is proportional to the impact velocity which is determined by a laser-velocity measurement system.

In addition to static loads, many concrete structures are often subjected to short-duration dynamic loads. These loads originate from sources such as impact from missiles and projectiles, wind gusts, earthquakes and machine vibrations. The need to accurately predict the structural response and reserve capacity under such loading has led researchers to investigate the mechanical properties of the component materials at such high rates of strain.

One method to improve the resistance of concrete when subjected to impact and/or impulsive loading is by the incorporation of randomly distributed short fibers. Concrete so reinforced is called fiber-reinforced concrete. Many investigators have shown that addition of fibers greatly increases the energy-absorption and cracking [20] resistance characteristics of concrete. Despite this, there are no standard methods for determining the impact resistance of such composites.

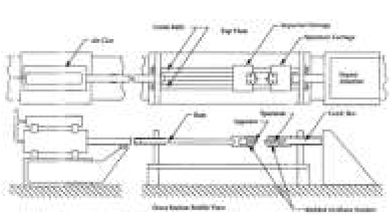

Fig 7: Impact apparatus and air gun [16]

Woven fabric [21] composites have received considerable attention in recent years due to their increased damage tolerance as compared to unidirectional composites and because of the ability to reduce fabrication cost. For example, in making complex curved parts the improved drapability that is achievable with fabrics[22] provides considerable cost advantage as compared to unidirectional prepreg. Although several analytical models for predicting the elastic response of woven fabric composites have been developed, the available experimental data are sparse. Furthermore, the available data exhibit considerable variability which suggests the response mechanisms and test methods are not well understood.

In 1994, H. Ho, M.Y. Tsai, J. Morton and G.L. Farle [23]proposed a method to experimentally investigate the in-plane shear response of uniweave, plain weave and satin weave composites using the Iosipescu specimen 3-8 in the modified Wyoming test fixture. All woven materials are either Celion or AS4 carbon fibers. The matrix is 3501-6 epoxy. Whole field moir6 interferometric [24] and conventional strain gage were used to quantify the response and develop an understanding of how the woven architecture influences the response. Whole field strain contours were obtained by a full-node localized hybrid analysis. The uniformity, purity of the shear fields and the repeating unit cells of the strain contours for the different woven fabric architectures were investigated. The effectiveness of using conventional strain gages to determine shear modulus [25] was also assessed.

In order to judge the textile quality of Non Crimp Fabrics (NCF) (e.g. homogeneity and orientation of the reinforcement fibers, gaps between the fibers, etc.) a discontinuous laboratory testing method was developed by Markus Schneider, Klaus Edelmann and Uwe Tiltmann, 2004, [26] based on a digital image processing system. A flat bed PC scanner with an additional transmitted light device was used for the digital image acquisition of flat fabric reinforcement. In principle, the pixels of a digital image are similar to a map of numbers, which in this case range from 0 (i.e. black pixel) to 255 (i.e. white pixel). In this map all pixels within user-defined ranges can be detected by the software. Finally, the user selects geometrical dimensions (e.g. distance, size of an area) to be measured and the software analyses all pixels according to the selection. All data is automatically displayed in tabular form and can be immediately converted into diagrams or histograms.

The development of this quality inspection system started with standard biaxial NCF. According to Airbus Industry Material Specifications (AIMS) standard testing routines were developed in order to quantify the following parameters: regularity of knitting structure (distance between all adjacent knitting points), fish eye measurement in the layers, gap quantification, reinforcement fiber [27] orientation and abrasion particles.

Moreover, the system could be expanded to include other reinforcement types such as woven fabrics and UD-prepregs. The aim was to get an automatic general system suitable for quality control of different reinforcements for carbon fiber reinforced plastics (CFRP).

Conclusion

One of the principal difficulties at the present time is that no one composite test method is generally favored by the composite materials testing community. It has not been clearly established whether the various competing methods can produce similar test averages and standard deviations, and how relatively reproducible and forgiving each method is. It is not known, for example, whether there is any advantage of shear-loaded specimens over end-loaded specimens, or vice versa. It is generally agreed, however, that none of the available test methods is without faults. Thus, an in-depth experimental comparison of the most promising of the available composites test methods needs to be performed. Limited attempts to do this to date, as identified in this report, have suggested that if performed properly, and resulting in proper failure modes, any of the commonly used test methods will provide similar results. Even if this is true, some methods are obviously easier to use, easier to prepare specimens for, and are more tolerant of fixture, specimen, and procedural errors. In performing such a comparative study, extreme care should be taken to obtain the best possible results, to provide a fair comparison. Thus, this comparison study should all be performed by one or a very few of the more experienced testing laboratories, rather than as a broad round robin as is typically conducted by ASTM.

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