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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**
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Cobotic manufacture of hierarchically architectured composite materials

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Abstract

A novel generation of manufactured composite materials is under development which takes inspiration from the hierarchical architectures which characterise natural composite materials such as bone, wood, and shell. This report describes results from ongoing research within a wider programme of enquiry aimed at significantly improving the compressive performance of components formed from fibre reinforced composite materials through employment of such biomimetic systems.

Automated lay-up techniques, and particularly the collaborative human / robotic potential offered by cobotic systems, have been identified as offering the potential benefits of highly efficient material deposition within a safe manufacturing environment. The novel processing method and tooling developed to manufacture a simple hierarchically structured composite laminate is outlined, along with current work aimed at developing processes for the creation of more complex hierarchical systems in the future.

The last section of the report presents results attained from the compressive testing of a sample laminate manufactured using the processing methods described. The samples tested displayed an initial linear response to loading, however the ultimate compressive failure mode could not be determined due to movement of the samples. Potential refinements of the method are considered based on images generated during testing.

1. Introduction

The engineering science of advanced composite materials is defined by the desire to generate stronger, lighter, and more resilient materials for use in increasingly demanding technical applications. A principal design paradigm for the field has been the reinforcement of lightweight polymer matrices with higher strength and stiffness fibres, such as carbon (CFRP). Progress in the field has seen continual advances in the development of mechanical properties in such materials, particularly regarding tensile and toughness values. However, at the component level compressive properties for fibre-reinforced composites can be significantly lower than equivalent tensile values. In large part it is the microbuckling of inherently wavy fibres and shearing at the fibre-matrix interface within laminates which reduces load carrying potential [1, 2]. In consequence, to obviate such failure modes components are often manufactured with superfluous material, increasing costs, and reducing the possible benefits of this class of materials.

NextCOMP is an EPSRC funded research programme currently being undertaken jointly by Imperial College London and the University of Bristol, aimed at significantly improving compressive properties in fibre-based composites. This is being achieved through investigation of the fundamental determinants of compressive load carrying characteristics, and the development of novel materials to better resist such loads. Of particular interest is the integration of discrete structural elements into the hierarchical systems architectures seen in natural composite systems. Despite usually being formed of intrinsically weak constituent materials, composites such as bone, wood, and shell can exhibit high relative load carrying capacities. A key determinant of such behaviour is understood to be the complementary interaction of discrete and dissimilar systems of reinforcement at different length scales, acting to functionally distribute imposed loads through the whole of the structure [3–5]

As highlighted by Fratzl, natural composites differ fundamentally from manufactured materials in two important ways [6]. Firstly, they develop as a functional cellular response to the environmental loading conditions present as they are grown, whilst the material engineer must anticipate applied structural loads in advance. This necessarily imparts graded interfacial material between genetically determined structural design elements, which are fundamental to the distribution of loads through the various distinct structural systems. It is this characteristic which allows the combination of intrinsically weak structural elements to form highly load resilient bulk materials. The second key difference is that due to the weak nature of the constituent materials, natural composite systems can accrete material with extremely low levels of energy expenditure. This is in stark contrast to manufactured materials, where the engineer has access to elements of much higher intrinsic strengths but with correspondingly higher embedded energy costs. Such fine molecular tuning of manufactured structures is usually not cost effective at commercial scales. However, for the biomimetic hierarchical composites under development, it highlights the necessity of ensuring accuracy and consistency in the deposition of the various structural elements to be integrated, to enhance as much as practical the effective load distribution through the component structure.

Previous experience in the hand lay-up of hierarchical composites has highlighted the difficulty in ensuring such accuracy, so the use of automated lay-up techniques has become a focus of attention. Cobotics is a growing area of research within the field of automated manufacture of advanced composites. Historically the processing of materials such as fibre reinforced polymers has relied heavily on the knowledge, experience, and creativity of skilled technicians to hand lay-up laminates of the required geometries and material properties. The highly accurate and repeatable dynamic control offered by industrial robotics, which has allowed increased efficiency and production rates in a diverse variety of manufacturing settings, can often struggle with the fine dexterous motor skills and functional adaptability required in composite material manufacture [7]. It is hypothesised that given the increased adoption of composite materials within high-volume consumer products, processing methodologies which allow safe and effective, direct human & robot collaboration offer the potential to increase production accuracy and efficiency whilst simultaneously reducing the negative effects of repetitive motion and suboptimal manual handling often experienced by technicians.

This paper reports on the ongoing investigation into the development of the manufacturing techniques and tooling required to generate a novel composite material featuring a hierarchical system of reinforcement. It then reports on the results generated testing the sample material to determine its compressive properties.

2. Method

2.1. Materials and design

Initial investigations have focused on developing simple systems architectures integrating two pre-manufactured CFRP structural elements with known material properties, Figure 1. illustrates the desired architecture. Cured CFRP pultruded rods are arranged in planar rows with a defined rod separation and two facing laminates of uncured fibre / epoxy prepreg are adhered to them. The fibre direction in the rods defines the system 0° direction. Initial consolidation is achieved through action of the cobot during deposition, full system consolidation occurs during curing within an autoclave at a pressure of 7 bar.

The pultruded rods selected were supplied by Hyperflight.co.uk and consist of cured continuous carbon fibre reinforced epoxy resin with diameter 0.8 mm. The fibre system is noted as Toray T300, but the specific epoxy matrix is unknown, so a prepreg system was chosen based on the resin glass transition temperature. The prepreg is a unidirectional thin ply material supplied by SK Chemicals, featuring Tairyfil TC33 fibres and a standard grade epoxy, K51. Each facing laminate consists of nine sheets of prepreg giving a total cured ply thickness of 0.27 mm per face. Experimentation identified this material allowed easier adhesion and forming to the underlying cured rods than thicker prepregs such as IM7 / 8552. Table 1. lists the material properties for the prepreg, previously collated by Tamas Rev [8]. Table 2. lists the available material properties for the pultruded rod component [9].

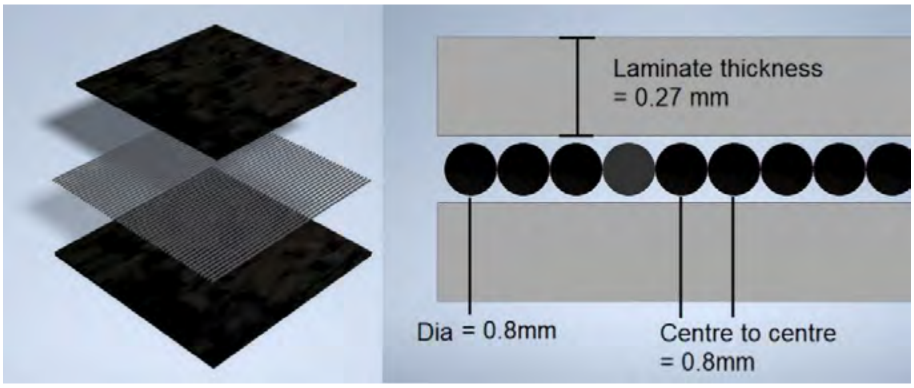

Figure 1. a) Rod / UD prepreg laminate, b) Rod spacing & face laminate thickness

Table 1. TC33 / K51 Material Properties (adapted from Rev [8])

Fibre tensile modulus	230	GPa
Fibre tensile strength	3.45	GPa
Fibre failure strain	1.5	%
Fibre density	1.8	g/cm^3
Filament diameter	7	μm
Fibre areal weight	20	g/m^2
Resin density	1.2	g/cm^3
Resin weight fraction	43	%
Fibre weight content	43	g/m^2
Fibre volume fraction	39	%

Table 2. Pultruded rod properties (adapted from supplier data [9])

0.8 mm Pultruded Rod Specification		
Weight	0.72	g/m
Structural Material	T300	
Matrix	Epoxy Resin	
Fibre volume fraction	60	%
Young's modulus	230	GPa
Ultimate Tensile Strength	1600 – 2300	MPa
Fibre Density	1.4 – 1.8	g/cm^3
Resin glass transition	170	°C

2.2 Cobotic equipment & tooling

The cobotic equipment used is the Dobot-CR5 system, Figure 2. This is a six-axis light commercial unit specifically designed for cooperative use with human operators due to its integrated collision detection capability. The system has a tool carrying capacity of 5 kg, with a 360° operational area of 1 metre radius. Tool movement can be programmed using the simple Blockly graphical user interface which allows the robot to be taught a series of process steps as the operator moves the tool head in 3D space, saving positional coordinates and defining the translational motion required. Repeatability of tool movement is stated by the manufacturer as 0.03 mm.

The initial processing method developed requires the operator to deposit precut rods (length = 300 mm) on to a tooling board. The face of the board has channels machined into its top face, of a depth equal to the radius of the rods, and covering an area of 300 mm x 300 mm. The spacing between the channels is set at twice the required final rod spacing within the laminate. The cobot is programmed to move a silicone rolling wheel repeatedly across the tool face at a distance sufficient to impart a translational force on the rods whilst also compressing located rods into channels. The wheel is contained within a housing manufactured using 3D printing technology in polylactic acid (PLA).

During operation, the operator is free to rectify misaligned rods as they occur whilst also preparing further materials. Once all the channels have been filled by rods, the operator can pause the roller movement and place the required number of precut prepreg sheets (300 mm x 300 mm) over the rod area. A second program is then initiated which moves the roller over the laminate promoting adhesion between the rods and prepreg, creating one half of the final laminate. Two such half laminates are then carefully laid one on top of the other with the rod sides facing each other. A third program is then used to consolidate both sides to create the final laminate. The release film covering the tool plate in Figure 2.b, is to reduce unwanted adhesion between the tool and the laminate once the prepreg plys are introduced. The samples described in the testing section below were processed using this method.

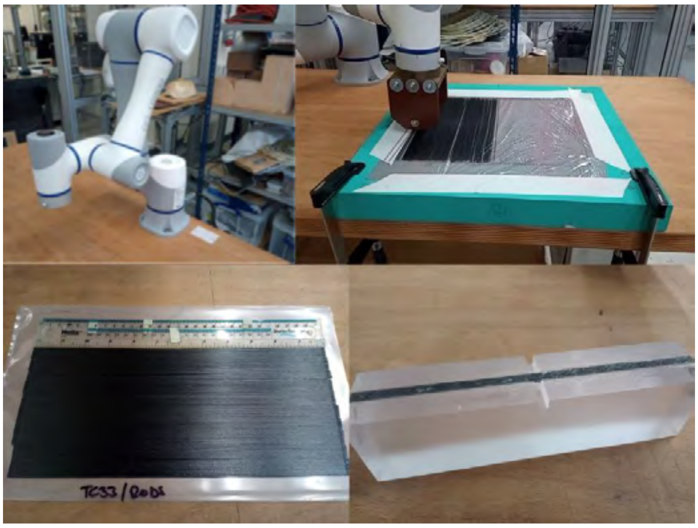

Figure 2. a) Dobot CR5 unit, b) Silicone roller in PLA housing, moving rods across tooling, c) Finished laminate section, d) Laminate sample adhered to four-point bending test cradle

During the manufacture of the sample laminates described above a qualitative assessment of the manufacturing process highlighted the potential for damage to occur to the rods during the rolling phase. Consequently, alternative methods for accurate and repeatable deposition of rods on to the tool surface are in development. A rod placement system has been designed which combines a rod carrying unit and optically controlled dispensing mechanism. A prototype hopper was designed in Autodesk and printed in PLA, Figures 3a & b. The optical control system makes use of an ITR-9608 phototransistor reflective interrupter sensor controlled by an Arduino R3 board. The optical sensor is affixed to the hopper and a digital on/off signal is triggered as the reflected IR beam is interrupted by a PLA comb, with teeth printed at spacings matching the tool channel spacings, Figures 3c & d. The comb is to be fixed to the tool surface and will activate the sensor as the hopper moves. The signal is used to control an electromagnetic push-pull solenoid, which moves a plate with a hole sufficient to allow one rod at a time to be deposited. The digital signal can also be used to control the progress of the cobotic programme and thus tune the hopper's movement across the tool in step with the rod deposition speed, minimising further potential rod misalignment and increasing process efficiency.

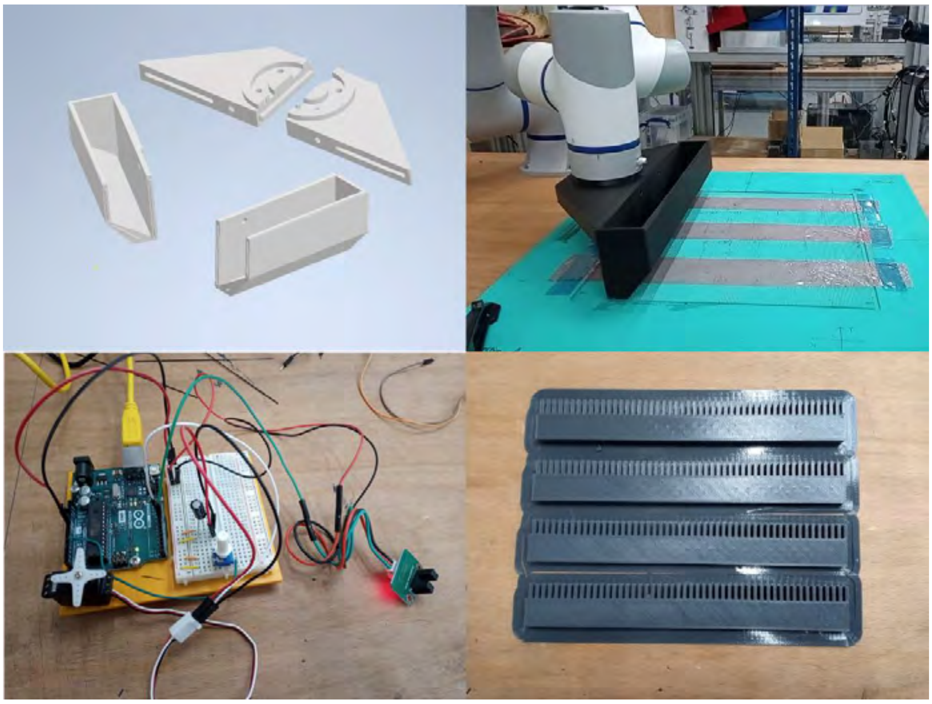

Figure 3. a) Prototype pultruded rod hopper & b) Optical sensing system

A supplementary refinement of the initial method is utilising 3D polymer printing to generate the tooling surface itself. The channels in the tool are required to have a diametric tolerance that allows rod location without unwanted movement during further consolidation steps. The machined channels in the tooling block pictured are suitable only for rods of around 0.8 mm. A next step in creating more complex hierarchical systems is to integrate further component elements such as fibre over-braiding covering the rods and more formable materials such as discontinuous fibre prepreg to enhance component interfacial adhesion and load distribution. The introduction of such elements will require tooling with channels of different diameters and spacings, and prototypes can be more quickly and cheaply designed and manufactured using polymeric materials.

2.3 Testing method

A novel four-point bending test developed within the NextCOMP group was used to characterise the sample laminate created using the initial processing method [10, 11]. This test has a proven advantage over comparable compressive protocols in that it requires minimal material to be generated per sample. The test apparatus consists of a cradle manufactured from polymethylmethacrylate (PMMA) in the form of a beam. Samples are adhered within channels machined on the top surface using the epoxy adhesive Araldite A-2021. The cradle is then subjected to compressive loading within a universal test unit utilising a 25 kN load cell with displacement of 0.5mm / min. Strain data are captured through use of Digital Image Correlation (DIC) imaging of the sample within the central gauge section, Figure 4.

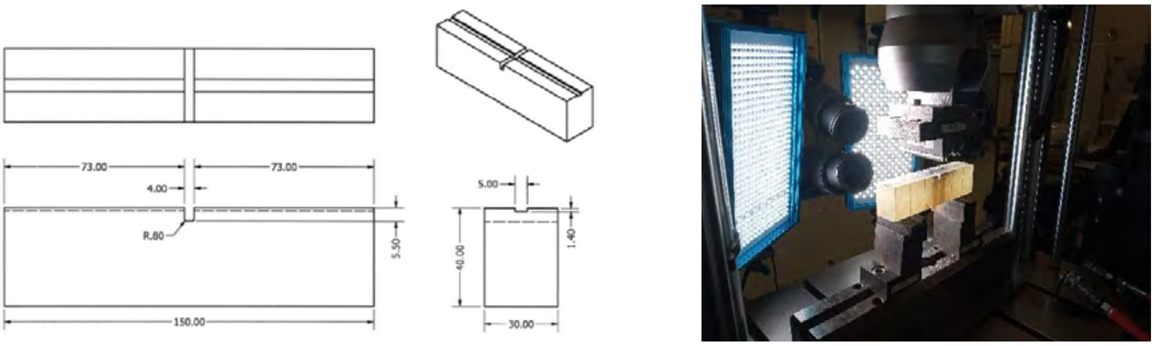

Figure 4. a) PMMA cradle dimensions, b) Testing and DIC set up

Samples were cut from the cured laminate, Figure 2c. Sample length was 150 mm and average thickness was 0.85 mm. The channel machined in the top surface of the cradle has a width of 5 mm, so samples were cut to contain 5 rods resulting in nominal widths just below 5 mm, this was to allow the adhesive to penetrate between the sample edges and cradle, Figure 2d.

3. Results

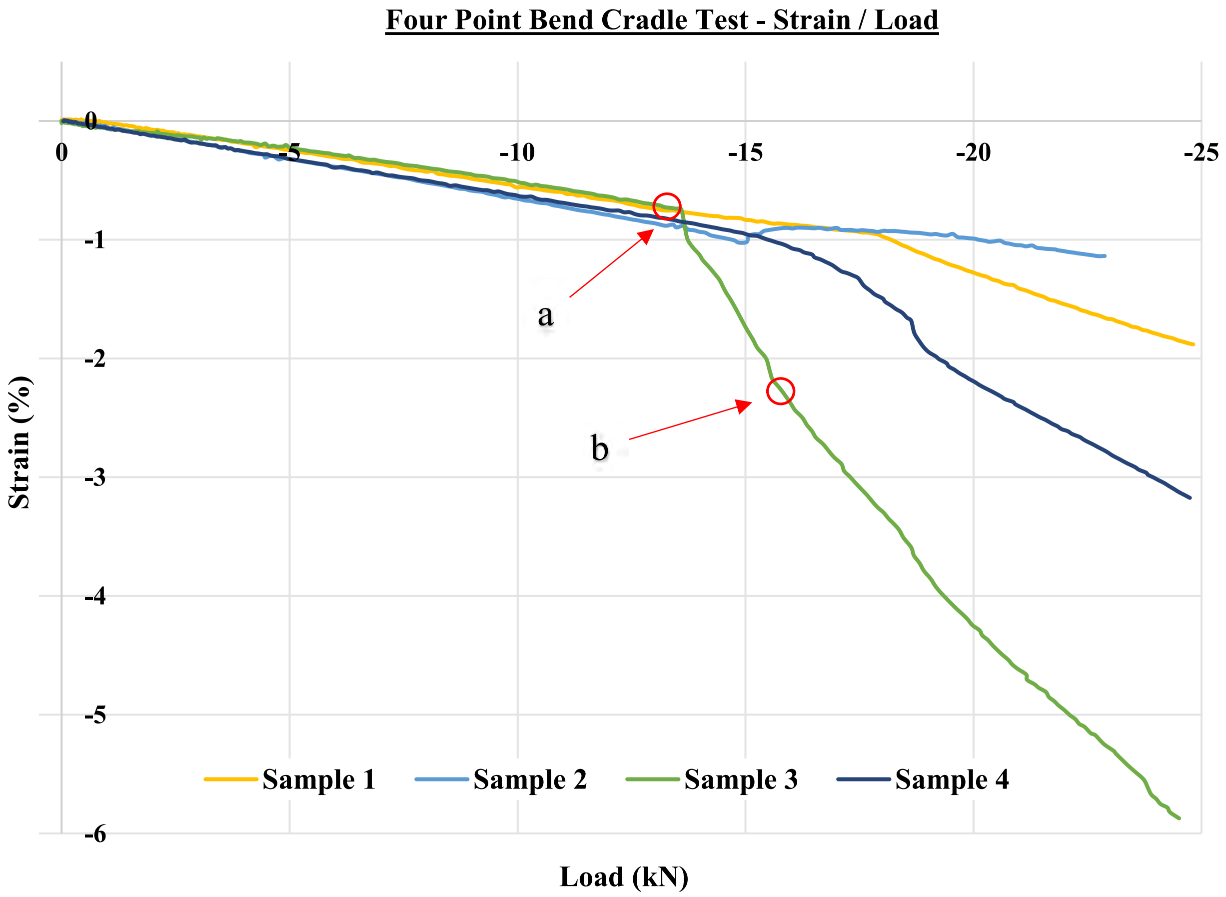

Figure 5. Chart of strain vs load for samples evaluated by four-point bending.

The test data generated for four samples indicated a linear strain response to loading until -14 kN. The mean compressive strain value at -12.5 kN is 0.75 %, with a standard deviation of 0.07. Samples 3 and 4 highlight most clearly the non-linear increase and divergence in measured strain values for the samples once beyond -13 kN. Samples 2 and 3 display increasing noise in the data as the loading of the system increased to the load cell limit. An inspection of the DIC images for sample 3 highlights the cause of the breakdown in linear response for the measured strain rate of the samples at a load of -13.5 kN. Images a) and b) in Figure 6 relate to the points a & b indicated on Figure 5.

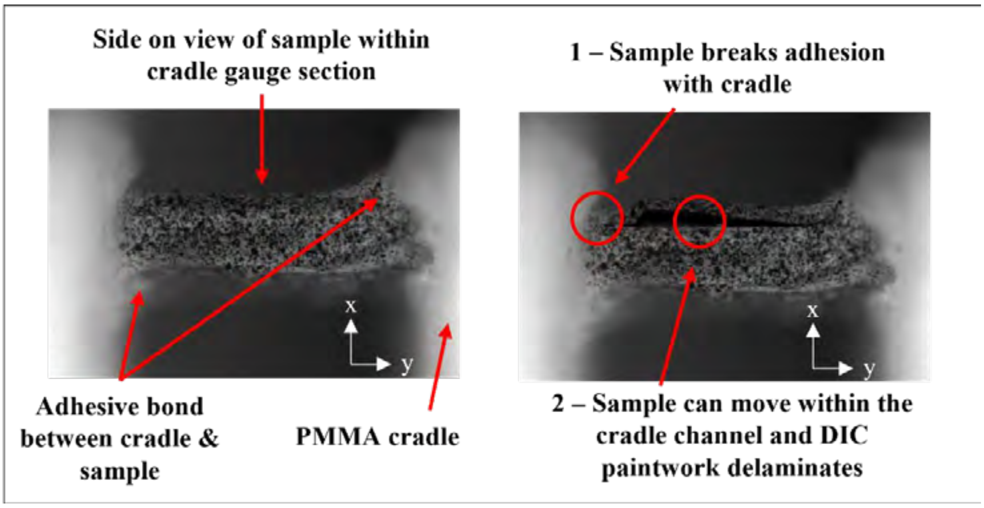

Figure 6. a) Sample 3 at -13.5 kN (188 secs), b) sample 3 at -15.7 kN (207 secs)

Image b) indicates that the adhesive bond between the sample and the PMMA cradle has begun to fail, allowing the sample to begin moving within its channel on the top surface of the cradle. The adhesive layer on the sample top surface, outside the gauge section, remains intact and functions as a sleeve around the sample inhibiting out of plane bending but allowing lateral movement within the channel, the y-direction in the above image. System loading past this point is not increasing the compressive strain within the sample and none of the samples tested reached the point where damage of the sample was visible. The high strain values noted as the loading increased past the point of debonding are a function of the DIC data capture method and are a measure of the intact paintworks' response to the applied compressive force. Consequently, whilst the samples tested indicate that this composite system can withstand at least -13 kN compressive load, full characterisation of the failure mode is still required. The failure of sample adhesion for this material mirrors previous issues encountered by the authors when testing highly aligned discontinuous fibre composite samples of the same geometry and resin epoxy system [11]. Future testing will focus on samples manufactured from alternative epoxy systems to attempt to control for this variable. Likewise, a further refinement under development is the control of sample movement by means of sample tabbing and the use of a clamping mechanism attached to the cradle.

4. Conclusions

Cobotic technology has been utilised for the manufacture of a two-component hierarchical composite with the aim of increasing accuracy, repeatability and efficiency in material deposition when compared with hand lay-up methods. Given the anticipated importance of such accuracy in determining load distribution within biomimetic hierarchical materials, cobotic methods promise to be a preferable manufacturing method as the complexity of the composite systems being developed increases. Potential refinements of the initial manufacturing method have been identified in which 3D polymer prototyping and digital sensing control are utilised to increase further the process efficiency whilst minimising unwanted component deterioration. A simple hierarchical composite laminate has been manufactured using cobotic methods and tested to generate compressive property characteristics. Samples of the material were seen to display an average compressive strain value of 0.75 % at –12.5 kN. Further refinement of the testing method is in development to allow a more complete characterisation.

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