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THE DESIGN AND MANUFACTURE OF A MODULAR COMPOSITE (CFRP) WINGBOX

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SUMMARY: The use of carbon fibre epoxy is becoming very popular in modern aerospace design. Superior strength and fatigue life can be obtained, whilst reducing the overall structural weight. In order test performance, and give confidence to the relevant certifying bodies, any new material or structure has to undergo an extensive series of evaluation tests. The first step in the certification process normally involves the testing of standard coupons. Although coupon data is a valuable starting point, other work has shown that the results obtained may not be representative of the final structure. To asses the performance of a new material, so that it can be used in a structure, it is necessary to produce sub-structures in order to verify the material in a given configuration. This is both costly and time consuming. The purpose of this study is to consider these problems when applied to a wingbox structure. The new wingbox uses a modular approach. This consists of three sections: a tip, a root element and a central structural section. The wingbox is mounted in a test frame and loaded by various methods to determine the material and structural performance of the central section. Unlike previous wingboxes, this modular box has been designed so that the central section can be taken to failure and then simply removed whilst leaving the tip and root sections in place. It is proposed that other sections representing different materials, structural features, repair issues or panels, used to investigate damage tolerance, can then be simply fitted to the central section. This paper describes the design methodology coupled with a finite element approach to the universal modular wingbox. The manufacture and evaluation trials of the box are summarised with the focus on correlating between the theoretical design predictions and the experimental results. In conclusion, issues of damage tolerance are investigated, outlining initial findings concerning structural response. Ongoing and future work programmes are also discussed. It has been shown that by adopting the modular approach, the wingbox has all the advantages of a full-scale box at the cost of a sub-element or stringer panel. This facility has lead to a better understanding of composites in full-size structures at a commercially viable cost.

KEYWORDS: CFRP, wingbox, damage tolerance, impact

INTRODUCTION

For a number of years DERA have been investigating the behaviour of large composite structures. This work focuses on one of these structures: a composite wingbox. Over the past five years, work has been published on the impact response, damage formation and failure of such structures, [1-4], which offer a valuable insight into the realistic structural performance and the critical factors affecting new designs. Previous wingbox structures have been produced to investigate different materials, manufacturing methods and impact damage. These studies were very successful although in order to investigate these three variables, three distinct structures have had to be produced.

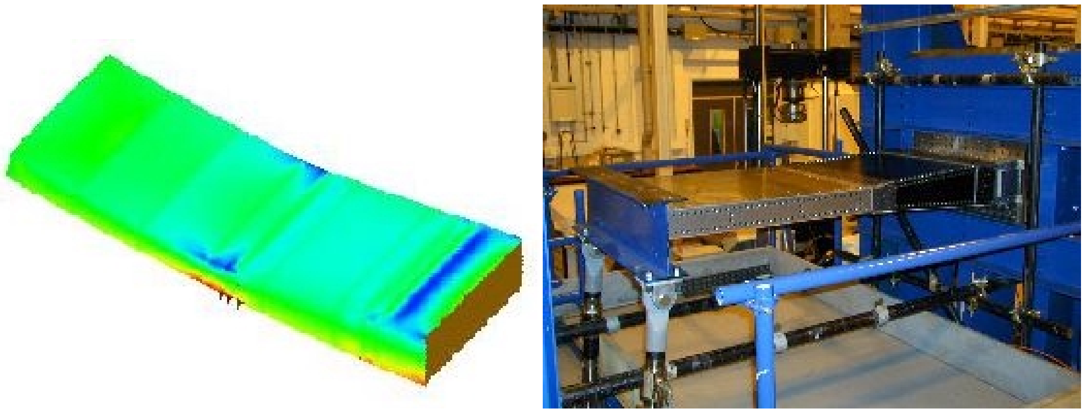
A survey carried out in 1998 identified the major concerns of industry and aircraft operators as the damage tolerance in composite structures. Apart from ballistic damage, the dropping of refuelling hoses onto the structure was identified as the most serious threat. Following this survey, the aim was to develop a new lower cost method to evaluate these potential problems.

The first step in certifying any new material / design normally involves the testing of standard coupons. Although coupon data is a valuable starting point, other work has shown that the results obtained may not be representative of the final structure, [5-7]. This discrepancy is partly due to boundary conditions, but may also be affected by issues such as size, defects and structural features. The modular box was therefore developed as a more efficient approach to composite structural evaluation. For example [8] details the manufacture of a modular box intended to test the behaviour of composite skin panels within a horizontal stabiliser. However, ultimately it is essential to understand how the individual components behave within a structure. That is, it is either the global structural response that becomes important or the material properties. To date, resolution of this situation has been limited to the production of sub-structures, which can give the designer confidence in using new materials by verifying the response of the materials in a given configuration. Typically, this involves the fabrication of a scaled structure, which is both costly and time consuming. In addition, there has been some concern for some time over the scaleability of certain parameters, [5-7]. Previous wingbox structures have been produced to investigate different materials, manufacturing methods and impact damage, [7]. By investigating the load / strain distribution of full size wingboxes it was possible to evaluate a new concept in wingbox testing. Although the role of numerical analysis has become increasingly important in the design of structures in recent years, [9], limitations still exist within the code. This paper demonstrates that by integrating the disciplines of numerical (finite element (FE)) analysis and experimental evaluation, it is possible to enhance the FE modelling further, whilst reducing the number of experimental studies that need to be performed, Figure 1.

The concept of a modular wingbox is based on a similar process that led to the development of modular testing of single structural components, [8]. That is, instead of manufacturing a complete structure, it becomes necessary to manufacture only a smaller central wingbox section. By careful design and finite element analysis it is possible to produce a uniform stress state in the central section. In previous studies [5, 7] this was not of primary importance although if this work is to successfully bridge the gap between coupon testing and composite aircraft structures, then a realistic reproduction of the boundary and loading conditions is required.

By using two independent rams to apply the load, it is possible to subject the structure to the full operational flight envelope in the laboratory; including flap and slat loading. These loads can be simulated through a combination of tensile, compressive and torsional loading. A uniform strain distribution in the skin will also lower the influence and importance of the localisation of individual impact sites, thus eliminating some of the unknown failure variables. Furthermore, this approach enables single component testing to be conducted in situ. That is, whilst it might be a modification to an individual component that is under investigation, it is possible to evaluate its performance in relation to the other components with which it must interact in service.

For comparative purposes, the financial commitment to a single, scaled, composite wingbox might be of the order of £150,000. This includes the costly manufacture and assembly. The long time-scales involved in the design, manufacture and assembly are also a matter for consideration, both in terms of financial outlay and with respect to programme duration. The cost for obtaining the same information, through using a modular approach, is likely to be in the order of £35,000. This clearly illustrates the cost effectiveness of the modular approach and enables greater experimental support to be given to numerical modelling, encouraging a greater cross-fertilisation between the disciplines.



(a) (b)

Figure 1: a) FE contour plot of longitudinal strain showing deformation during loading. b) Modular wingbox mounted in loading frame.

DESIGNING THE MODULAR WINGBOX

The concept, based on previous experience of wing-box testing [4, 5], was to produce a wingbox that comprises three sections. The outer and inner sections were manufactured from an aluminium alloy. These sections are connected by either composite or metallic spars, which can easily be replaced at minimal cost and as a result can be easily modified. The central section of the wingbox is then made up of two skins (600 x 710 mm) and two side ribs. In order to reproduce the load and strain fields typically seen in operational aircraft, a finite element analysis of the wingbox was performed resulting in new optimised wingbox geometry.

A schematic view of the design is shown in Figure 2. This diagram shows the sections of the wingbox as they are referred to in this paper. The wingbox consists of three sections: a tapered section in the middle, and two constant-depth sections at the root and tip of the box. The test section is located on the tapered section. These skins will be referred to as the *upper* and *lower* skins from this point on and can be either flat panels or incorporate stringers or substructures.

The wingbox has been designed so that upper, lower or both skins can be tested. The proposed thickness of these skins range from 2 – 5 mm in either glass or carbon / epoxy panels and can incorporate features such as: novel materials, impact damage, through-ply reinforcement (e.g. Z-pins), open holes, inspection panels and smart sensors. With the added advantage of testing two skins simultaneously i.e. one in tension and one in compression, internal ribs can be fitted to investigate upper and lower skin interaction. The tip is closed off by a rib, to which the actuators are attached. Four booms run the length of the tapered section, one in each corner of the wingbox.

Finite element analysis (FEA) was employed as a design tool, in order to optimise the geometry of the wingbox and hence ensure that representative strains in the composite skins under test could be obtained. Both 2-D and 3-D, using a mixed plate element and beam element models, were produced in the Master Series IDEAS software. In each case, the root was assumed to be fixed, with the tip being subjected to a ±20kN flexural load. With the addition of extra webs, Poisson's effect was almost eliminated, leading to a uniform strain field across the section with the exception of the interface between the test section and both the metallic root and tip boxes, Figure 3. These hot spots or variations in strain are expected due to the change in modulus, although it is proposed that if the test section incorporated a composite end tab then the load transfer would become more uniform.

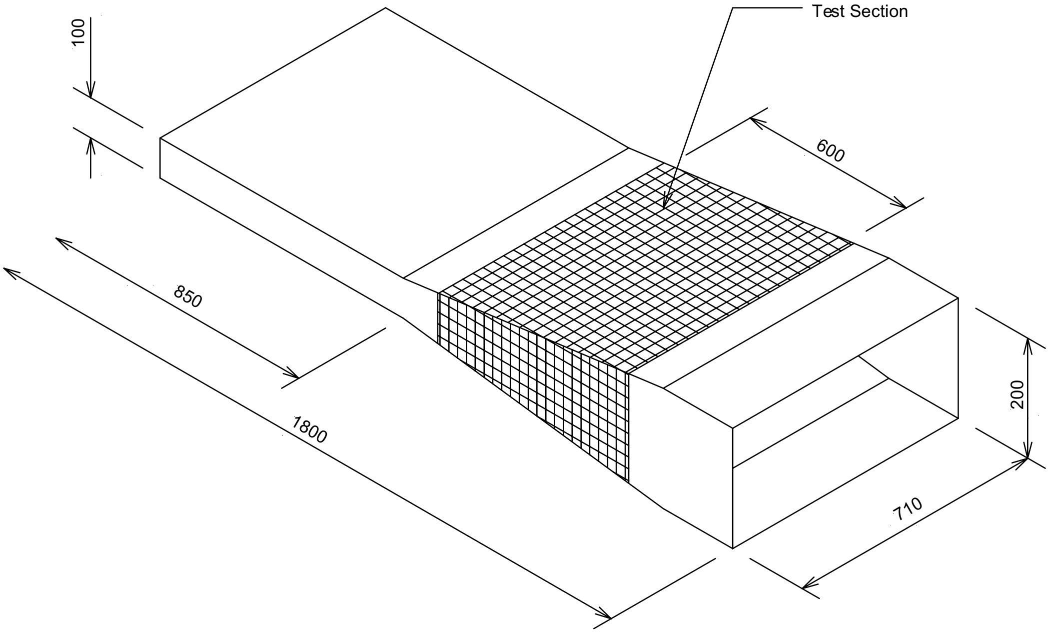


Figure 2: Schematic view of the wingbox. Dimensions in mm. Not to scale.

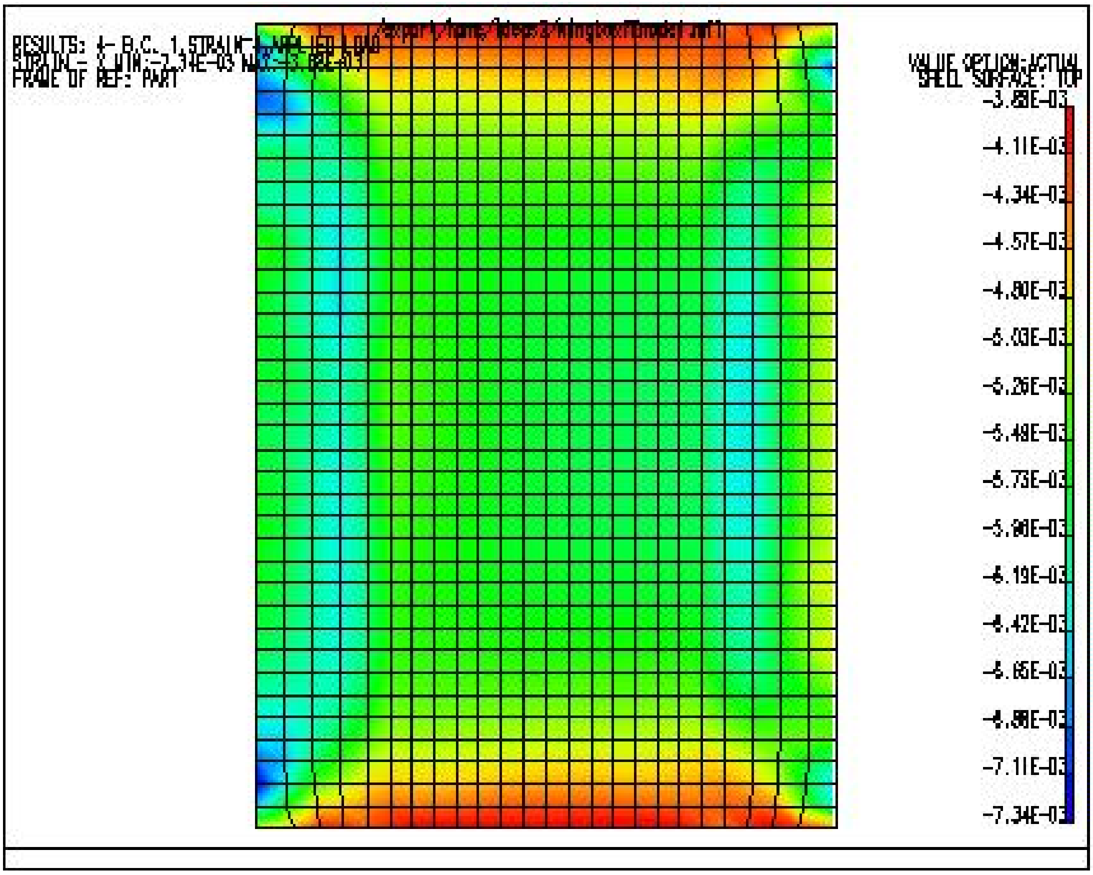


Figure 3: Contour strain plot looking down on upper skin test section of FE model, deformations not shown

MANUFACTURE OF THE MODULAR WINGBOX

The wingbox comprises a root box, tip box, four spars and upper lower and side skins. The tip box is manufactured from aluminium alloy. This section is connected to the two main loading rams. The tip section is reinforced with two internal ribs to prevent warping through bending. The test section end of the tip box has been designed to accommodate four spars that connect the tip to the root box. In order to reduce stress concentrations between the tip box and test section, the geometry of the tip box reduces in depth just prior to the test section.

The root box is a similar construction to the tip box consisting of a parallel section, which bolts to the hard mounting points of the load frame. Due to the large bending moment of the root box the section is reinforced with metallic spigots. The cross section of the root box then tapers in a similar way to the tip box, such that the change in section does not occur at the interface between the root box and the test section.

Four booms, that comprise the test section, connect both the root and tip sections. These booms can be manufactured from various materials depending on the type of test. Adjacent to the booms, located just within the tip and root sections, is a removable web. These webs have been specially designed so that a test panel containing stringers can be connected, through the stringers, to the tip and root sections, thereby transferring a realistic load through the stringers as well as the skins. The central test section varies according to the material or structure being tested. However, for evaluation purposes, a 4mm quasi-isotropic lay-up was selected for the skins and side webs. Four sacrificial aluminium alloy booms were manufactured. Two additional aluminium supports were manufactured to support the booms within the test section.

The advantage that this type of wingbox has over previous structures is that by having removable skins, the response of damage through localised impact threats can also be investigated. This might be an appropriate representation of damage resulting from debris during landing or take off, for example.

From previous work, [10], it has been shown that a stress field, applied prior to the impact loading, can result in a different response in the test structure, for example a skin-stringer panel, [10]. In these tests it was possible to apply the compressive pre-load using a standard vertical frame test machine by impacting the pre-loaded panel horizontally. This preliminary research has highlighted the differences associated with the way in which damage occurs in the skin-stringer panel when the impact is conducted under load in comparison to the occurrence of a simple impact; that is, where no stress field is present prior to the impact event. As a result of this work, a number of concerns have been raised relating to the propagation of damage through structures that have been subjected to impact under load.

For this reason, a horizontal impactor has been designed and developed at DERA. It was intended to use this equipment to present impact threats at angles other than the vertical to the modular wingbox. The horizontal impactor comprised a spring-loaded ‘gun’ and a carriage, upon which is mounted the impact tup and attached mass. This assembly was mounted in a portable frame, enabling it to deliver a localised impact at a wide range of positions on the wingbox. The tup contains an instrumented load washer that enables the load-time history to be recorded. Two optical gates ensure that the impact velocity can be determined.

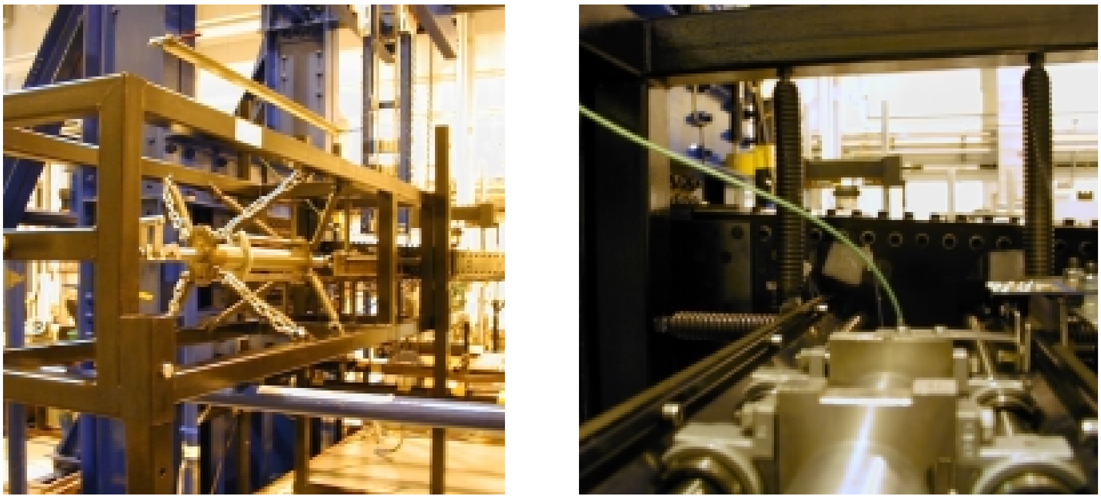

(a) (b)

Figure 4: Photographs depicting the horizontal impactor (a) and the instrumented carriage (b)

EXPERIMENTAL WORK

A series of flat panels were manufactured and instrumented to verify the FE model. These panels constituted the upper and lower skins and the rear and front webs. Two materials were tested; the upper skin and rear web were manufactured from T800/924 whilst the lower skin and front web consisted of AS4/8552. A typical quasi-isotropic lay-up was selected.

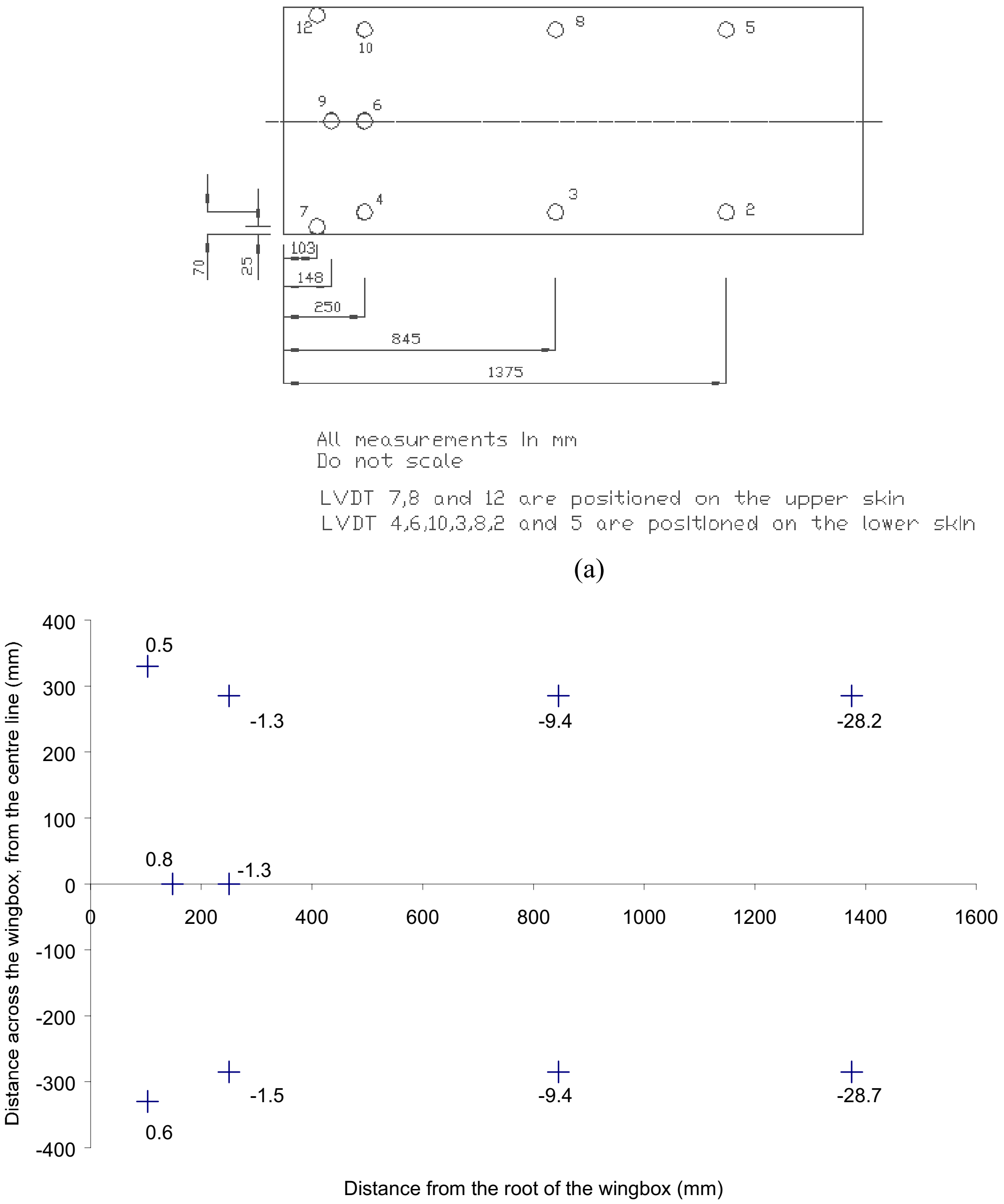
In the first test, the two actuators were loaded in tension up to 10kN each, i.e. the total load was 20kN. In the second test, the two actuators were loaded to –10kN each, i.e. a compressive force of 20kN was applied in total. These formed the flexural tests. Finally, applying 10kN on one actuator and –10kN on the other resulted in the performance of a torsional test. In each case, strain distribution maps were plotted, obtained from gauges mounted on the surface, and strain-time and displacement-time histories were examined in order to determine the structural response of the composite parts. In addition, the global response of the modular wingbox was considered; it was shown that even loading of the structure could be obtained for each of the loading types. For example, Figure 5 shows the positions of the LVDTs and the distribution of maximum displacement across the wingbox. It is clear from this that the structure is being loaded evenly and is responding as expected to the applied tensile load.

DISCUSSION

The design of the modular wingbox has been based on the evolution of composite structural testing. An integration of both numerical (FE) and experimental disciplines have been used during this research. This has enabled augmentation of the numerical work, whilst minimising the amount of experimental work required. The design and manufacture of the resultant wingbox has produced a facility that will enable economical testing of large panels / structures and thus lead to a better understanding in the certification of future composite structures, through a closely co-ordinated approach of numerical and experimental work.

The initial commissioning tests suggest that the structure is behaving well when subjected to both flexural and torsional loading. Figure 6 illustrates a global strain distribution in the x-direction. This demonstrated similar trends to the preliminary FE results presented in Figure 3. That is, other than the definite and quantifiable edge effects in the longitudinal (ε_x)

direction, the bulk of the test plate demonstrates a reasonably uniform strain field; the numerical results have been confirmed qualitatively in practical application.



All measurements in mm
Do not scale
LVDT 7,8 and 12 are positioned on the upper skin
LVDT 4,6,10,3,8,2 and 5 are positioned on the lower skin

(a)

(b)

Figure 5: Schematic indicating the LVDT positions, (a), and a maximum displacement (mm) map obtained from the LVDT results for 20kN load applied in tension to the wingbox tip, (b)

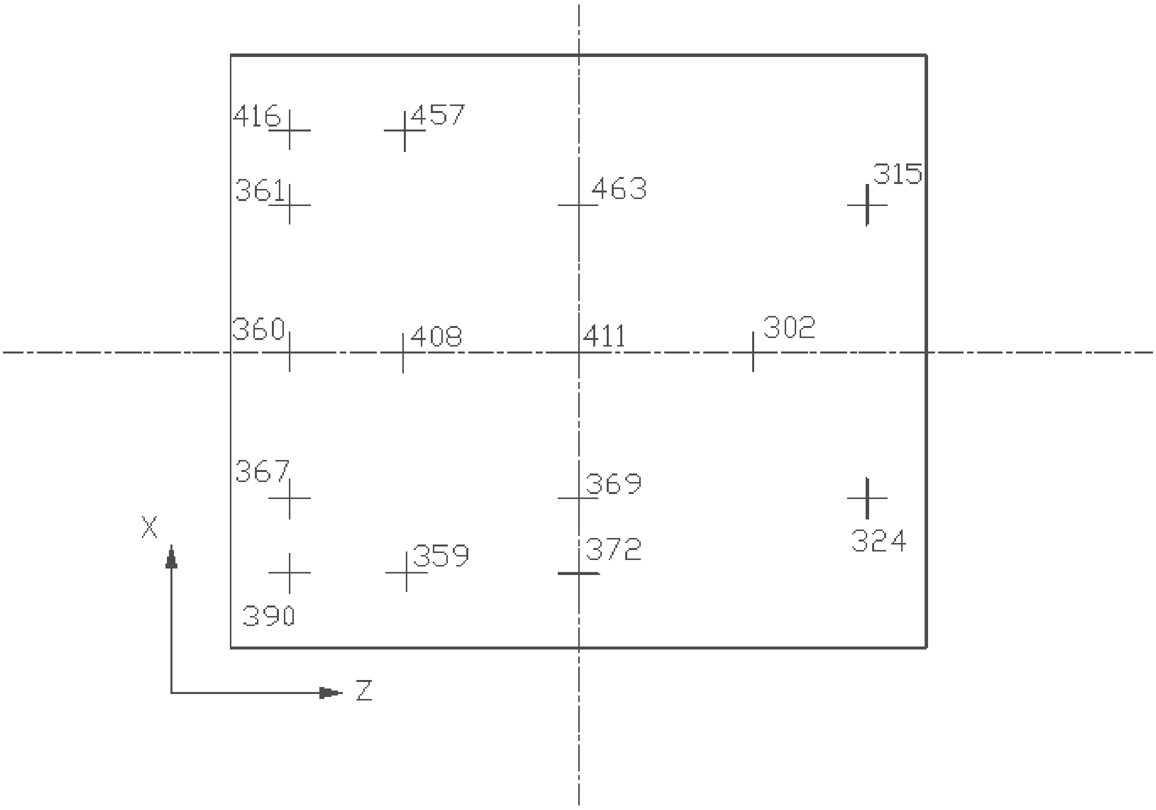


Figure 6: Strain field in the x direction (ε_x) in the top plate when the structure is subjected to a tensile load of 10kN.

It is clear from these preliminary tests that edge effects are present and that some concentration of stress may be evident in the material immediately surrounding the fasteners. In order to reduce this effect and to improve load transfer to the test panels, it is proposed to incorporate end tabs to subsequent test panels.

It is possible to use the equipment not only to determine the global structural response, but also to identify any localised buckling within the test panels. This data could be used in order to provide support and validate future numerical analyses conducted in this area, through the construction of a responsive strain field. The incorporation of these localised buckling modes within the current FE program would permit a more accurate representation of the real structure to be produced.

During the evaluation trials, strain gauge data is captured on a high-speed data logger and is used in conjunction with the information acquired from the instrumented impactor, the effects of applied localised impact energy on the composite panels can then be evaluated. On going investigative work includes the analysis of localized buckling modes within wingbox structures, investigations into the response of the webs due to localised impact (whilst being subjected to a biaxial shear field) and comparative studies between different fibre-resin systems. It is anticipated that the results from these investigations, which will be supplemented with fractographic evaluation, will be published in due course.

FUTURE WORK

The modular approach will be used as a vehicle to validate predictive models and continue to investigate new materials and through thickness reinforcement. It is proposed that a series of stringer panels will be manufactured to investigate the use of novel materials and impact response of the structure.

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