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The Manufacturing Procedure for Aerospace Secondary Sandwich Structure Panels

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ABSTRACT: This study provides a detailed consideration of five manufacturing options that are used to produce aerospace sandwich panels used in secondary structure. The structural performance of each of the manufacturing options is considered along with a cost analysis. By considering the traditional preimpregnated (prepreg), autoclave-cured process, the sources of cost have been investigated, and it has been shown that by removing a portion of the large labor content and the autoclave cure, in favor of an oven-only cure, it would be possible to make significant savings. Monitoring the time to manufacture representative full-scale sandwich panels using the five manufacturing options has shown that by using a resin film infusion (RFI) oven cure, a 30% reduction in time to production is possible. To make an initial assessment of the comparative structural performance of laminates produced using the five manufacturing options, this article also presents results of material quality, in-plane and out-of-plane loading tests. The results of these tests show that the laminates produced using RFI are comparable in quality and performance to laminates produced using the current aerospace industry standard prepreg/autoclave process.

KEY WORDS: manufacture, aerospace sandwich structure, RFI, cost analysis.

INTRODUCTION

INCREASING ENVIRONMENTAL PRESSURE on the aviation industry to reduce the 'carbon footprint' of aircraft has led to considerable research into the improvement of fuel efficiency. An important factor in improving

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fuel efficiency is reducing the weight of the structure of the airframe. To this end, composite materials are increasingly utilized in airframe manufacture. For example, the Airbus A380 has upward of 22% by weight made from composites [1], and the new Boeing 787 is expected to be made from 50% composite structure [1]. The excellent strength and stiffness to weight ratios of composites in comparison to traditional metallic materials are well known; however, these property improvements come at a cost premium. The aerospace composite structure manufacturing industry is becoming more competitive. Even small reductions in cost can be important in securing a contract for component manufacture, as this reduces the final cost of the aircraft and makes it more attractive to airlines.

There has been extensive research regarding the optimization of production methods for the use of composites in primary aircraft structure; however, few studies have concentrated on the secondary structure. In this article, methods for reducing the cost of manufacturing carbon fiber sandwich panels for use in aircraft secondary structure are investigated, concentrating primarily on ‘gap fillers’ on the wing leading and trailing edges. Such panels are currently manufactured as sandwich panels that use layers of preimpregnated (prepreg) carbon fibers and Nomex honeycomb that are laidup on to a tool by hand before being consolidated and cured in an autoclave. The inherent disadvantages of the hand layup/autoclave process have been discussed in the literature [2,3]. The process is heavily dependent upon labor, and the autoclave introduces large capital and running costs [4]. This article describes how the cost of manufacture can be reduced by removing the autoclave cure from the process and replacing it with oven cure and vacuum bag consolidation.

The aim of this study is to demonstrate that it is possible to change the manufacturing process, and hence material, so that an autoclave cure is not required. In doing this, it is essential that the mechanical performance of the end product is comparable with the autoclave-cured product. In this article, initial work on assessing the manufacturing process and material performance is described. To study the feasibility of and costs savings in the manufacturing process, panels were manufactured from five combinations of processing technique and face sheet materials, which are defined as the manufacturing options. Each manufacturing option (MO) represents an incremental step in taking the component from a fully-autoclave cured product to a fully resin–infused out-of-autoclave-cured product. The design of the five test panels is described, concentrating on each step in the manufacturing process for each panel so that the time saved in each MO can be identified. This article also describes material characterization tests of the face sheet materials; both in-plane and out-of-plane material properties are obtained from specimens manufactured using the five MOs, along with the material volume fraction, thereby enabling a comparison between the quality of the material produced by each of the MOs and the relative cost of each process to manufacture a representative aircraft component.

COST OF MANUFACTURE

Prepreg material is delivered to component manufacture in rolls, which are stored in a freezer until use. To avoid moisture in the layup, it is essential that the material, while still sealed in its packaging, is thoroughly defrosted prior to opening and embarking on the manufacturing process. The freezer storage adds costs both in terms of running and monitoring time out of freezer and the defrosting significantly increased the time for manufacturing, with the average time for defrosting being about 8 hours depending on the size of the roll. Removing or partially removing the freezer storage from the process by using dry fiber materials instead of prepreg would lead to significant cost benefits.

Figure 1 shows each stage of the current manufacturing process for secondary composite sandwich structures after the material has defrosted. The process is subdivided into five key stages: cutting, layup, loading into the autoclave, curing, and unloading. First, the prepreg is cut into kits using

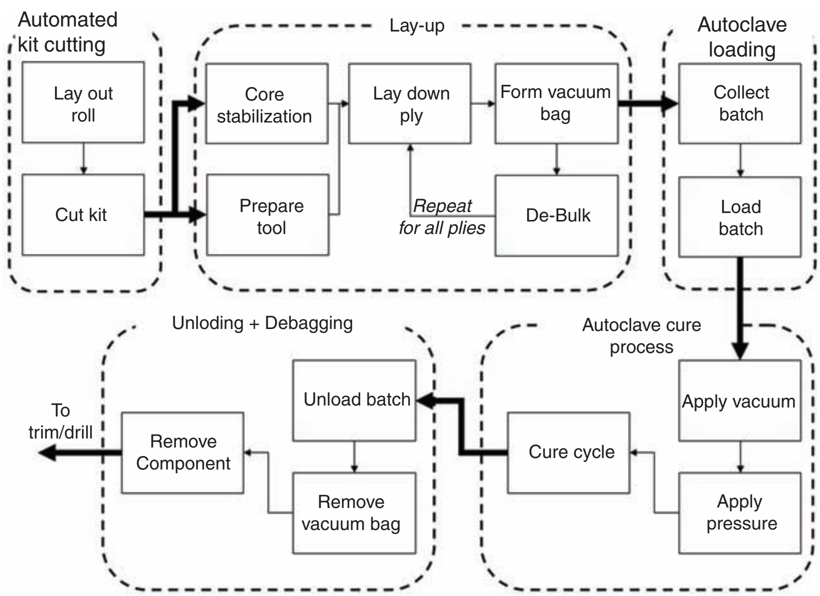

Figure 1. *Flow diagram of the autoclave-based manufacturing process.*

an automated process; a kit is defined as a set of individual plies in a range of geometries that together will form a complete component. The defrosted roll of prepreg is set out on a CNC machine, which is programmed to cut the shapes in a nested fashion, to minimize material wastage. The first process in the layup stage is to prepare the tool by applying a release agent. Concurrently, the core material is stabilized to prevent crushing. This is done by application of adhesive film followed by a curing process. The tool-side face sheet plies are then laidup by hand by placing on a tool. It is necessary to carry out vacuum 'debulks' to remove air from between plies at each stage of the process. The core is added, followed by the bag-side face sheet plies, all with associated vacuum debulks to produce the final component. Then a vacuum bag is formed around the tool and component. The component and vacuum bag are then loaded into an autoclave, where an appropriate cure cycle is applied. The procedure is to collect a batch of components that all require the same curing cycle and then load the batch in the autoclave. After curing, the tool is removed from the vacuum bag and the consolidated component removed from the tool. The component can then be machined, by trimming and drilling, to its final geometry. Following this, the finished component is inspected for defects using ultrasonic nondestructive testing. The final step is assembly, where necessary, to other components to form the final substructure.

This study focuses on the costs incurred in converting the raw material to a cured component, i.e., 'automated kit cutting' through to 'unloading from the autoclave,' as described in Figure 1. Each of the stages in the manufacturing process have been observed, and by monitoring the time taken, labor, materials, and power usage, an estimation of the relative cost of each of the activities shown in Figure 1 has been made. Table 1 lists the activities identified in Figure 1 and provides an indication of the overall contribution to costs by showing the relative cost in terms of capital investment and operation costs. Table 1 highlights that both the large labor content in hand layup of the face sheets and the capital and running costs of the autoclave incur the largest portion of the cost of producing aircraft sandwich structures. This justifies a thorough investigation into how the process can be changed to reduce the labor costs in the face sheet layup procedure and to remove the autoclave from the process.

By studying the entire manufacturing process, from receipt of material to full assembly of components, it has also been identified that the autoclave-curing process introduces a significant 'bottleneck' in production, as shown in Figure 2. The bottleneck is caused, primarily, by the need to resort to batch processing of components in the autoclave. This is because the number of autoclaves that a company can purchase and install is restricted by high capital and running costs. To avoid backlogs of components, and

Table 1. Breakdown of cost contributors in autoclave-based prepreg tape manufacturing process.

			Running costs	
Manufacture area		**Capital costs**	**Labor**	**Material and power usage**
Automated kit cutting		Medium		
	Layout roll	–	Low	–
	Cut kit	–	Low	–
Layup		Low		
	Core stabilization	–	Medium	Medium
	Prepare tool	–	Low	Low
	Layup and debulks	–	High	Medium
	Form vacuum bag	–	Medium	Medium
Loading		Low		
	Collect batch	–	Low	–
	Load batch	–	Low	–
Cure process				
	Autoclave	High	Low	Medium
Unload and debag		Low		
	Unload	–	Low	–
	Debag	–	Low	–
	Component removal	–	Low	–

increase efficiency, batches are created that require the same curing cycle. Therefore, components often wait in the production line until there are sufficient to fully occupy an autoclave. Another consideration is that the loading and unloading of the autoclave can only be carried out at one end, which also slows the process. Furthermore, the tooling is such that it must withstand high pressures and is therefore heavy and difficult to maneuver. Introducing an oven cure would mean that components could be loaded from one side and removed from the other, creating better production flow, the cost of tooling would be reduced, and batch sizes could be smaller or larger as appropriate because ovens are much less costly to purchase and run than are autoclaves. In replacing the autoclave with an oven cure, the production bottleneck would be changed, as shown by the dotted lines in Figure 2, with layup being the main cause of a new, but less severe bottleneck.

The main cost contributors in the manufacture of composite components have been shown to be the large labor content in manually laying up the laminate and the capital and running costs of the autoclave. Therefore, in this study, it is proposed that a process is used that both reduces the high labor content and removes the autoclave cure in favor of an oven- and

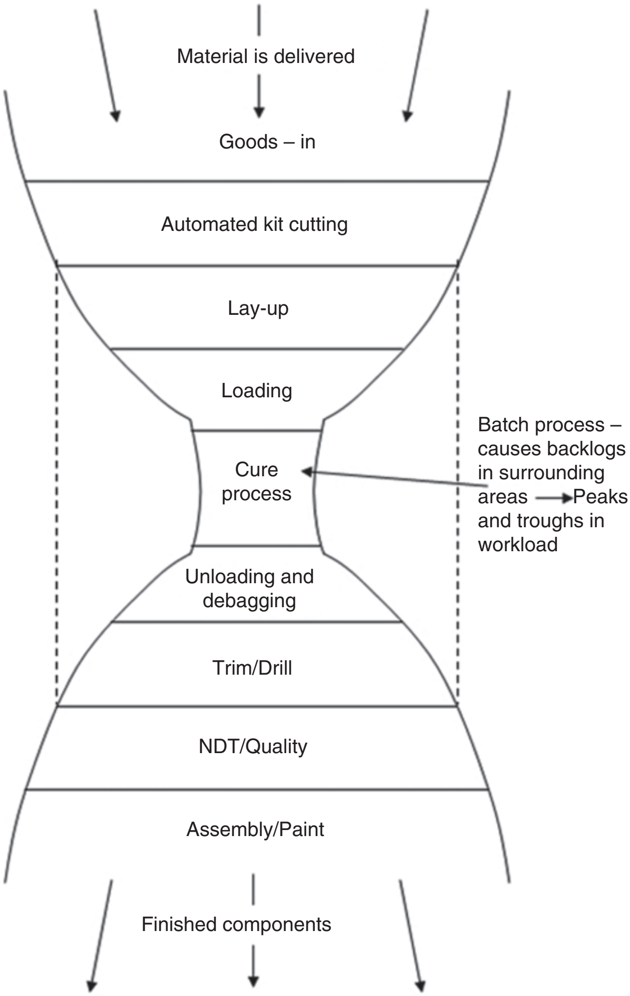

Figure 2. *Bottleneck caused by the curing in the autoclave.*

vacuum-only cure. This will have the added advantage of improving the flow of manufacture and remove the bottleneck caused by batch processing used in the autoclave.

MANUFACTURE AND PERFORMANCE

In this study, the cost of manufacture is the main driver; however, it is essential to assess the mechanical performance of components produced if the manufacturing process is changed. Therefore, for any cost reducing process it must also be demonstrated that the end product has adequate structural performance. In this study, the structural performance of five different MOs was tested by producing representative panels, monitoring the manufacture time, labor, and material usage to produce these panels, and then, testing on a specifically designed test rig. Figure 3 shows a schematic of the procedure, in the form of a flow chart, of how the manufacturing process is linked with the design and the assessment of the structural performance. The outcome of the scheme is a component that is optimized for manufacturing cost, while retaining the necessary structural performance. The preliminary stages in the process are indicated in Figure 3 by the grey boxes, the work described in this article, that focuses on manufacturing, is indicated by the white boxes, and future work is indicated by the black boxes.

The first stage in the procedure was to review existing designs of aircraft secondary sandwich structure; this informed the definition of the geometry of the representative large panel, known as the generic panel, that is described in detail in 'Generic Panel Design' Section. To produce the evaluation given in Table 1, it was necessary to investigate the current manufacturing process and to establish the relative costs. This allowed the five MOs, for the generic panels, to be defined and these are described in 'Manufacturing Options' Section of this article, along with the results from the monitoring of the manufacturing process for each MO. The effectiveness of the consolidation of each face sheet material is provided in 'Material Quality' Section by deriving of the volume fraction for each MO from thickness measurements and micrographs. During the production of the generic panels, characterization specimens were obtained for each of the face sheet materials to enable an initial material performance assessment based on tensile, flexural, and through-thickness properties of the face sheet material; this is described in 'In-plane Loading' and 'Out-of-plane Loading' Sections. This work allows a relationship to be defined between the material performance and the manufacturing process, which fulfils the objective of this article.

As mentioned above, Figure 3 also includes future work. To provide a link between the performance of the generic panels, which cannot be assessed through specimen coupon testing, it is necessary to carry out mechanical testing of the panels. To make this full-scale assessment of the generic panels, the review of existing designs provided information on the service loading. This has enabled the design and commissioning of a test rig for full-scale testing [5] that replicates the in-service loads. In service, the panels are subjected to a pressure load across the mould-side face sheet, which is constrained by bolts on three sides. To experimentally model the pressure load, a water-filled cushion is used to impart the load into the panel in a uniform fashion. This approach has been used successfully in the past [6]. The design differs from those used previously as it is intended to use full-field measurement techniques to assess the stresses in the generic panels and identify regions of weakness resulting from the manufacture. Therefore, it is necessary to have optical access to the surface of the bag-side face sheet; a full description of the test rig is given in the study by Crump et al. [5] and preliminary work on the full-field experimental analysis is given in the study

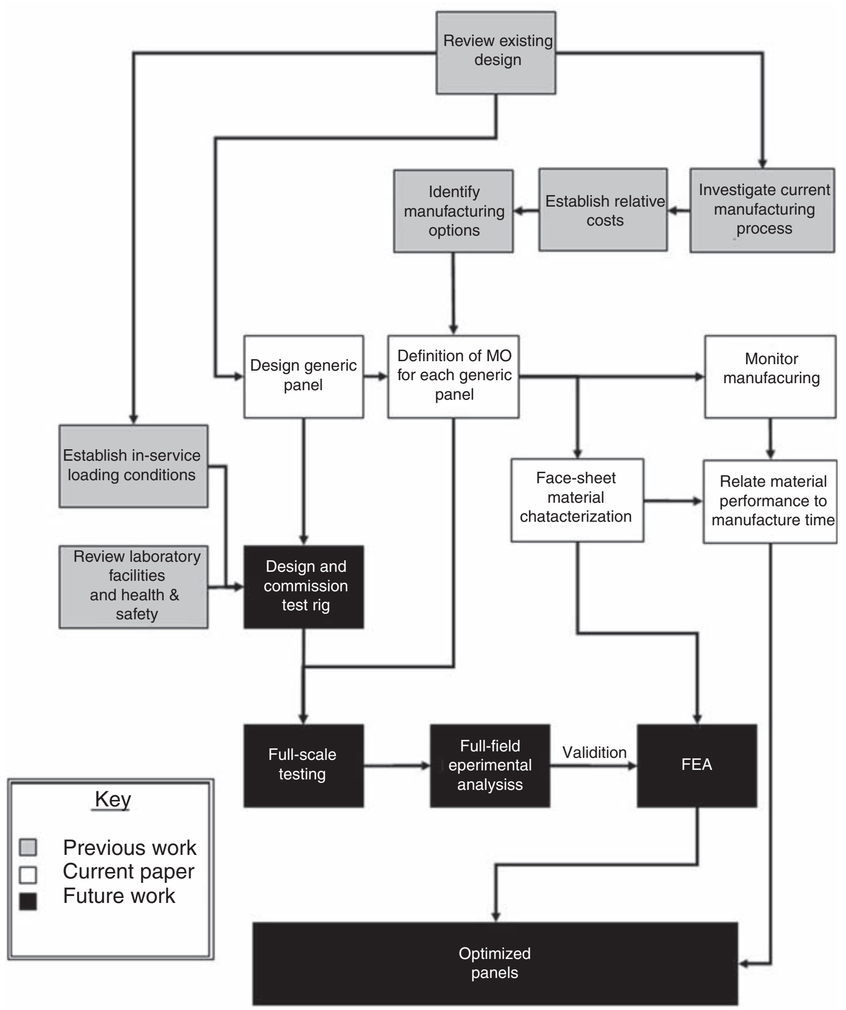

Figure 3. *Work flow diagram to link manufacturing cost with material and structural performance.*

by Crump et al. [7]. This full-field experimental data will be used to validate FEA models of the generic panel. It is envisaged that in the future, full-scale testing will be unnecessary and validation of the FEA of the generic panel will be sufficient to have confidence in the structural performance data that it provides.

GENERIC PANEL DESIGN

The review of existing designs identified trailing edge access panels, classified as wing secondary structure on a commercial passenger aircraft, as a suitable basis for the design of the generic panel. The trailing edge access panels are bolted to the main wing beam and 'A-frames' along three sides, allowing one of the longer edges to be free to deflect under service load. The panels are subjected to aerodynamic out-of-plane loads across their surface. The review of previous designs identified a number of 'common' features as follows:

- Face sheets are of quasiisotropic layup with 12 plies at 0.125 mm per ply
- Panels are long and narrow—between 700 and 1500 mm long by 300 wide
- Cutouts and notches are used to account for neighboring structure
- Inserts and solid pucks are used for attachments
- Simplistic blocklike core geometry

Features such as inserts, attachments, cutouts, and notches have been set aside in this study as these would lead to stress concentrations that are dependent on the ply layup and orientation and would detract from a straightforward evaluation of the manufacturing processes. Taking into account the above considerations, a generic panel was defined, as shown in Figure 4. The generic panel is flat and has a plan area of $0.9\,\text{m} \times 0.3\,\text{m}$. The Nomex honeycomb core is $0.6\,\text{m} \times 0.2\,\text{m}$ and 12.5 mm thick. A noncore

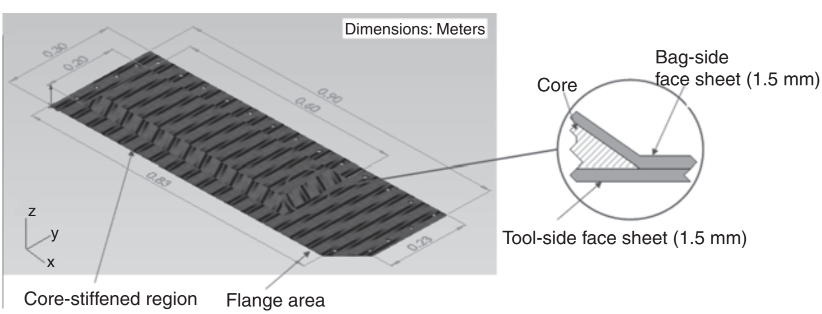

Figure 4. *Generic panel geometry.*

stiffened flange is included as this is a key feature in such panels and is essential for attachment purposes. The flange has a total cured thickness of approximately 3 mm, half formed by the tool-side face sheet and half by the bag-side face sheet. The flange contains 19 holes on three of its sides of 7 mm. This models the attachment to the airframe and facilitates attachment to the rig in the full-scale tests. Figure 5 shows a photograph of a generic panel made using prepreg tape and autoclave curing (MO1, see next section) mounted in the test rig.

In this work, the face sheet core bond is not studied; however, this will be important in the subsequent stress and damage analysis work carried on the panels indicated in Figure 3. Therefore, each panel was inspected using C-scan after manufacturing was complete. The C-scans showed that the initial face sheet core bond was complete. In fact there was no indication from the C-scan of any voids in the structure.

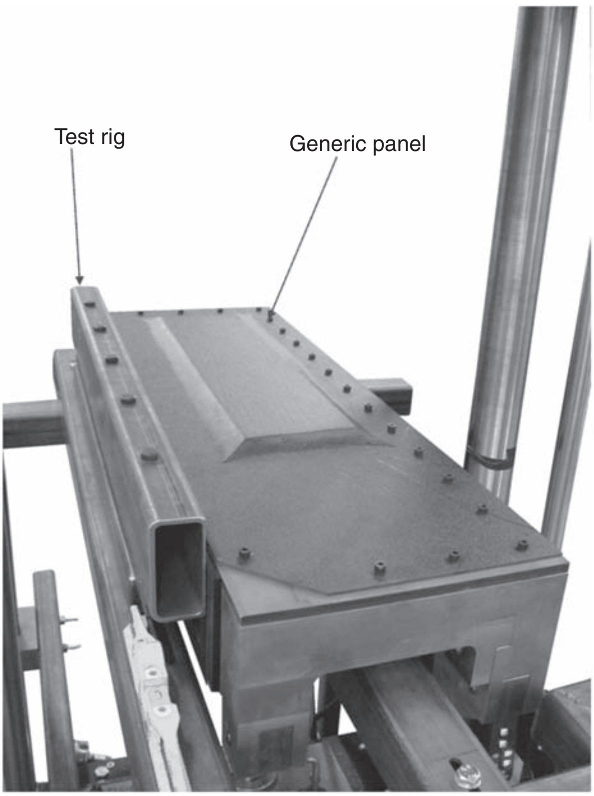

Figure 5. *Photograph of a generic panel attached to the loading rig.*

MANUFACTURING OPTIONS

Five material and processing combinations (known as MOs) were selected for the mechanical performance comparison. The five MOs are listed below:

1. Unidirectional prepreg tape cured in an autoclave.
2. Woven prepreg cured in an autoclave.
3. Noncrimped fabric with separate resin film cured in an autoclave.
4. Woven sidepreg and oven cured.
5. Noncrimped fabric with separate resin film using resin film infusion (RFI) process.

The following sections discuss the production of generic panels, to the design presented in 'Generic Panel Design' section of this article, by the five MOs. This discussion includes an analysis of the time taken for manufacture by each MO and thereby an estimation of the relative cost of each panel.

Prepreg Tape Autoclave Cured (MO1)

MO1 is based on the traditional approach for manufacturing aerospace components, which makes use of unidirectional prepreg tape. The process involves hand layup of individual plies that are spliced together from the tape, which provides a cured ply thickness of 0.125 mm. Therefore, to make the generic component shown in Figure 4, 12 plies are required to make the 1.5-mm face sheets. A layup was defined that would produce quasiisotropic face sheets. This choice was based on current design guidance outlined in the study by Niu [8]. Therefore, a (0°, 45°, −45°, 90°, 0°, 45°, −45°, 90°, 0°, 45°, −45°, 90°) layup was used for each face sheet. These were constructed in a symmetrical configuration about a Nomex honeycomb core.

Prior to the laying up process, the Nomex core must undergo a stabilization process so that it does not deform or crush when the curing/vacuum pressure is applied. The stabilization process was identical to that used in production and used a foam adhesive to strengthen the chamfered edges of the core and a film adhesive is applied to the flat faces to provide some rigidity. The stabilization requires that the core undergoes a separate cure before it can be introduced into the sandwich panel layup. Table 2 lists the operations to stabilize the core before panel layup and the breakdown of the times.

Hexcel's 914C-TS-5-34% prepreg tape was used to produce the face sheets. The individual plies were laidup by hand on a flat mould tool comprising a sheet of steel. As the stack was constructed it was vacuum 'debulked' after each ply was introduced in an identical fashion to the process used in production. The debulk process is essential in production as

Table 2. Operations in the core stabilization procedure and their duration.

Operation	Time (min)	Operation	Time (min)
Layer of lightweight (0.030) glue film	10	Remove bag	5
Peel ply	5	Layer of heavyweight (0.060) glue film	15
Layer of heavyweight (0.060) glue film	10	Replace bag	5
Make consolidation bag	30	Consolidation for 20 min (reduced vac)	20
Consolidation for 20 min	20	Remove bag	5
Remove bag	5	Peel ply	10
Core down	10	Replace bag	5
Replace bag	5	Consolidation for 20 min (reduced vac)	20
Consolidation for 20 min (reduced vac)	20	Remove bag	5
Remove bag	5	Layer of lightweight (0.030) glue film	10
Perimeter of foaming adhesive	20	Layup cure bag	30
Replace bag	5	Consolidation for 20 min (reduced vac)	20
Consolidation for 20 min (reduced vac)	20		
Total			305

it removes trapped air from the stack that could cause porosity during the curing process. To perform the debulk, a vacuum bag was constructed on the mould tool that enclosed the stack and a vacuum applied for approximately 20 min. When the tool-side face sheet had been laidup, the Nomex honeycomb core was positioned on the face sheet. The bag-side face sheet plies were then laidup over the core material. A debulk was carried out as each of the 12 plies were added to the stack. The unidirectional tape was difficult to form over the shaped core and therefore the 12 bag-side face sheet plies took longer to layup than did the 12 tool-side plies. Once the component was fully laid up on to the tool, a final vacuum bag was then formed around the component that was used during the curing process. The bagged tool and stack was then placed into an autoclave for curing.

When the component was placed into the autoclave, a full vacuum was applied. Then the autoclave curing pressure was applied. When the autoclave pressure reached approximately 1 bar, the vacuum was reduced to a value of 0.2 bar to prevent void formation within the component due to disparity in the vapor pressure. When the curing pressure of 3 bar gauge was achieved, the temperature was increased. The component was heated to 120°C at a rate of 2°C/min. The ramp rate controls the viscosity of the resin so that the resin can flow and 'wet out' occured throughout the component before the resin started to cure. Initially the temperature in autoclave was held at 120°C for 60 min. The temperature was then ramped at 2°C/min to the final curing temperature of 175°C. The cure temperature was held for 120 min. Once the cure cycle had been completed, the autoclave was allowed to cool at 3°C/min, with the pressure held at 3 bar until the temperature was 60°C or below, ensuring the component was held in position as it cooled to below the gel temperature.

During the layup procedure, the time spent on each step in the process was noted to allow an estimation of the number of labor hours spent to produce such a panel (Table 3). It was estimated that this component took approximately 14.6 h to layup, with a further 5 h to perform the core stabilization (Table 2). These times do not include the length of the two cures. The autoclave cure, including time for pressurization and depressurization, took approximately 5.7 h and the core stabilization cure, 3.5 h. Therefore, an estimate of the total time to layup and cure for a component using MO1 is 28.8 h. This process is time consuming due to the large number of individual plies and therefore the large number (23) of debulks that must be manually set up. The nature of the material also means it is not easily draped over shaped objects, such as the core, and this also adds to the time it takes an operator to layup an individual ply. The number of plies required to achieve the thickness leads to a large labor input in the manufacturing process, with the cost of the component reflecting this input. On the positive side, the large number of plies required to build the panel face sheets leads to significant flexibility in defining the ply orientations. This has allowed designers to tailor the material properties for the final laminate but the time taken for lay-up and debulk is excessive, indicating that a material with fewer plies is more desirable.

Woven Prepreg Autoclave Cured (MO2)

MO2 uses a woven prepreg that incorporates a predefined amount of fibers in both the longitudinal and transverse directions in the same ply. Each ply is equivalent to two plies of the UD tape, laid in a crossply (0°, 90°) configuration, and has a cured ply thickness of 0.25 mm. This method reduces the number of plies required in MO1 and hence layup and debulk time, with the 1.5-mm-thick face sheets of the generic panel requiring six plies of this material. The crossply nature of the woven prepreg leads to an alteration in the layup of the panels. A (0°, 45, 0°, 45°, 0°, 45°) layup was used for each face sheet, orientated symmetrically about the core material and was assumed to be comparable to the layup in MO1.

Hexcel's 8552S/37%/AGP280C five harness satin weave prepreg was used to produce the face sheets. The process for layup and cure described in

Table 3. Operations in the MO1 manufacturing process and their duration.

Operation	Time (min)	Operation	Time (min)
1st ply down	5	Consolidate for 20 min	20
Apply consolidation bag	30	Remove bag	5
Consolidate for 20 min	20	Layer of 319 film	10
Remove bag	10	Replace bag	5
2nd + 3rd plies down	25	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	13th ply down	10
Remove bag	5	Replace bag	5
4th + 5th plies down	20	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	14th ply down	10
Remove bag	5	Replace bag	5
6th + 7th plies down	25	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	15th + 16th plies down	30
Remove bag	5	Replace bag	5
8th + 9th plies down	15	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	17th + 18th plies down	30
Remove bag	5	Replace bag	5
10th and 11th plies down	15	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	19th + 20th plies down	30
Remove bag	5	Replace bag	5
12th ply down	10	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	21st + 22nd plies down	30
Remove bag	5	Replace bag	5
Layer of 319 film	10	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	23rd + 24th plies down	30
Remove bag	5	Layup cure bag	30
Stabilized core down	10	Consolidate for 20 min	20
Replace bag	5		
Total			875

'Prepreg Tape Autoclave Cured (MO1)' section was again used for panel manufacture. As in MO1, the Nomex honeycomb core had to undergo the core stabilization process prior to its inclusion in the generic panel. The time spent on each step in the process was, again, recorded to allow estimation of the labor hours to produce the panel using MO2 (Table 4). It was estimated that components manufactured in this way took 8.9 h, not including the

Table 4. Operations in the MO2 and MO4 manufacturing processes and their duration.

Operation	Time (min)	Operation	Time (min)
1st ply down	5	Consolidate for 20 min	20
Apply consolidation bag	30	Remove bag	5
Consolidate for 20 min	20	Layer of 319 film	10
Remove bag	10	Replace bag	5
2nd + 3rd plies down	25	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	7th ply down	10
Remove bag	5	Replace bag	5
4th + 5th plies down	20	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	8th and 9th plies down	15
Remove bag	5	Replace bag	5
6th ply down	25	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	10th and 11th plies down	15
Remove bag	5	Replace bag	5
Layer of 319 film	10	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	12th ply down	10
Remove bag	5	Layup cure bag	30
Stabilized core down	10	Consolidate for 20 min	20
Replace bag	5		
Total			535

5 h for the core stabilization (Table 2). These figures do not include the time for cure but this is identical to MO1. Therefore, an estimate of the total time for layup and cure of a component manufactured using MO2 is 23.1 h. The layup time represents a 19.8% reduction in the number of labor hours, largely attributed to the reduction in plies and debulks. However, the woven prepreg was also easier to drape over the shape of the core, so the time to form the bag-side face sheet was also reduced.

Noncrimp Dry Fabric with Resin Film Autoclave Cured (MO3)

MO3 combines dry noncrimp fabric and resin film materials proposed for the resin infusion with a traditional autoclave cure. Hexcel's NC2 dry fabric was used, which consists of four individual layers of UD material that are loosely stitched together to hold its form. Each ply of the NC2 has a layup of (0°, 45°, −45°, 90°], with a total fiber weight of 560 gsm. The resin is introduced as a layer of resin film between each ply. The resin is Hexcel's

DLS1726 (320 gsm). Because each ply of the NC2 consists of four layers of UD material, each 1.5-mm-thick face sheet requires only three plies of the NC2 fabric. These were laidup as follows (0°, 0°, 0°), i.e., equivalent to MO1.

The layer of resin film was adhered to the underside of the NC2 fabric before they were both laid up, resin side down, onto a flat mould tool. After each layer was laidup, a vacuum debulk was required. When the three plies that formed the tool-side face sheet had been laidup, the Nomex honeycomb core was positioned. The bag-side plies could then be laidup over the core material, with a debulk after each layer. Once the component was fully laidup on the tool, a final vacuum bag was then formed around the component that was used during the cure process. The bagged tool and component were placed into the autoclave. A similar cure process as MO1 was used except that the initial dwell temperature was increased from 120 to 130°C and the final postcure temperature was increased from 175 to 180°C, as defined by the resin manufacturers.

It was estimated that this process took approximately 6.7 h to layup (Table 5), with a further 5 h for the core stabilization (Table 2). The time for cure was identical to MO1. Therefore, an estimation of the total time to layup and cure a component using MO3 is 20.9 h. This represents a further 9.5% reduction in manufacturing time from MO2. The reduction in labor time is

Table 5. Operations in the MO3 and MO5 manufacturing processes and their duration.

Operation	Time (min)	Operation	Time (min)
1st ply resin and fibers down	10	Consolidate for 20 min	20
Apply consolidation bag	30	Remove bag	5
Consolidate for 20 min	20	Layer of 319 film	10
Remove bag	5	Replace bag	5
2nd ply resin and fibers down	10	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	4th ply resin and fibers down	10
Remove bag	5	Replace bag	5
3rd ply resin and fibers down	10	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	5th ply resin and fibers down	10
Remove bag	5	Replace bag	5
Layer of 319 film	10	Consolidate for 20 min	20
Replace bag	5	Remove bag	5
Consolidate for 20 min	20	6th ply resin and fibers down	10
Remove bag	5	Layup cure bag	30
Stabilized core down	5	Consolidate for 20 min	20
Replace bag	5		
Total			400

attributed to the reduction in the number of plies and debulks, as well as the material being easy to drape over the shaped core and because each ply was laid in the same direction, there were no need for multidirectional alignment.

Woven Sidepreg Oven Cured (MO4)

MO4 removes the costly autoclave cure by combining a woven sidepreg with an oven cure. Hexcel's DLS1726/40%/285T2/AS4C-6K, a sidepreg 2×2 twill woven fabric, uses a similar fiber mat to that described in MO2 and the same resin system as that in MO3. This resin system has been specifically formulated for use in vacuum-only cure. The lay-up for this component is identical to that in MO2, so six plies are required for each face sheet. The layup procedure was identical to the method described in 'Woven Prepreg Autoclave Cured (MO2)' section for MO2. When the final vacuum bag had been made, the bagged tool and component were placed in an oven. In the oven, a full vacuum was applied to the component, then the component was heated to 130°C at the rate of 2°C/min. The oven was held at 130°C for 60 min before a second ramp at 2°C/min up to 180°C was initiated. The oven was held at 180°C for 120 min before the component was allowed to cool at 3°C per min.

Estimations of the time to layup showed it took approximately the same amount of time as MO2, i.e., 8.9 h to layup (Table 4) and 5 h to core stabilize (Table 2). The component cure time has, however, been reduced from 5.7 to 5 h by replacing the autoclave with an oven cure and removing the pressurization and depressurization stages. An estimation of the total time to layup and cure a component through MO4 is 22.4 h, which represents a 3% reduction in manufacturing time from MO2.

Noncrimp Dry Fabric with Resin Film Oven Cured (MO5)

MO5 uses Hexcel's NC2 dry fabric with DLS1726 resin film, i.e., as used in MO3. These are laidup in an identical approach to that described for MO3. Once the component had been placed in the final vacuum bag, the bagged tool and component were put in the oven for cure. The oven cure was identical to that for MO4.

Estimations of time for this component are, 6.7 h for lay-up (Table 5), 5 h for core stabilization (Table 2), 5 h for component cure, and 3.5 h for core stabilization cure. A total manufacture time for this component of 20.2 h, which represents a 12.6% reduction in manufacturing time from MO2. MO5 benefits from significantly reduced layup and cure times over the other MOs. However, the performance of the material needs to be assessed prior to making any claims that this approach is better than MO1 or MO2.

Relative Cost of Each MO

Table 6 presents the time to manufacture of each MO in hours. The baseline, MO1, is estimated to require 28.8 h to manufacture. A large proportion of this time is taken on the layup the individual plies of the UD material, which provides the majority of the labor costs. By using the heavier woven fabric in MO2, this time is reduced to 23.1 h and by using the even heavier noncrimp fabric in MO3, this is further reduced to 20.9 h. A total reduction in time of approximately 27% is achieved by using of heavier material and hence reducing the large labor content of the layup stage of the manufacturing process.

By removing the autoclave cure in favor of an oven (vacuum only) cure, in MO5, the total time to manufacture is 20.2 h. This represents a further reduction of approximately 3% of the total manufacture time. However, this does not take into account the reduction in cost provided by removing of the autoclave from the process or the manufacture flow process advantage discussed in 'Cost of Manufacture.' Furthermore MO3 and MO5 do not require freezer storage of the dry mat and therefore further reducing the running cost of the processes and the production time by removing the need to defrost.

Table 6 contains an assessment of the relative labor, running, and capital cost involved in each MO in the form of a value between 1 and 5 for each. MO1 is considered to score 5 for all three cost indicators due to the labor-intensive layup and expensive autoclave cure. MO2 and MO4 show a reduction in labor to score 3, while MO3 and MO5 show a further reduction to score 2. The removal of some of the need for freezer storage in MO3 reduces its running and capital cost scores to 4, while the total out-of-autoclave processes (MO 4 and MO5) reduce the running and capital costs further. It is thought that a reduction in the labor could offer an 'easier' reduction in cost for these processes in many cases, where autoclaves are

Table 6. Time to manufacture panels for each MO and the relative cost of each process.

MO	Time Layup (h)	Cure time (h)	Total time to manufacture (h)	Relative labor costs	Relative running costs	Relative capital costs
1	19.6	9.2	28.8	5	5	5
2	13.9	9.2	23.1	3	5	5
3	11.7	9.2	20.9	2	4	4
4	13.9	8.5	22.4	3	3	2
5	11.7	8.5	20.2	2	3	2

already installed and in use. Therefore, any reduction in capital costs is only relevant when considering investment in new plant. The cost evaluation has clearly shown it is beneficial to manufacture secondary aircraft sandwich structure face sheets using MO5. The next step is to show that changing the manufacturing process does not result in a reduction in quality or performance of the face sheet materials. Hence the following sections describe the material characterization of the face sheet materials.

MATERIAL QUALITY

This section of the article describes the work undertaken to analyze the quality of the face sheet material produced by the five MOs by assessing the consolidation. The material for this part of the investigation was obtained by producing single skin laminate panels identical to those used in the face sheets for each MO; these were then cured inside the bag used to produce the generic panels. The material quality was assessed by estimating the fiber volume fraction (V_f) using thickness measurements and through visual analysis of microscopy images. V_f was chosen as the quality indicator as it provides a measure of the effectiveness of the curing process. The micrographs will provide an indication of the void content and hence wet out. Furthermore, the V_f also indicates how much resin has been lost during the curing process. For aerospace laminates, V_fs >50% are required [4,9]; in the case of the five MOs, it is expected that the V_f would be in the range 50–60%. The quality assessment is essential as out-of-autoclave processes traditionally provide laminates that are less well wetted and consolidated than a full-autoclave cure.

A common means of estimating V_f of laminates is to measure the average thickness of the laminate using the following equation:

$$V_f = \frac{nA_w}{\rho_f t} \qquad (1)$$

where V_f is fiber volume fraction, n is number of plies, A_w is areal fiber weight, ρ_f is fiber density, and t is thickness.

The thickness of each laminate was obtained in 10 positions using Vernier callipers; the average thickness, t, is provided in Table 7 along with the V_f value calculated from Equation (1). The values of n and A_w, used in the calculation are also listed in Table 7, ρ_f was assumed to be 1.77 g/cm^3 for all. This is known to be accurate for MO1 and MO2 and it is therefore reasonable to use this for the other MOs as the density of carbon fiber can be assumed to be constant for each of the MOs. The laminates manufactured by MO1 and MO2 (autoclaved prepreg) have identical V_f values of 55%. The laminates manufactured by MO3 and MO5 (new material, one autoclaved, one oven

Table 7. Volume fraction of the face sheets produced by each MO obtained from thickness measurements and image analysis.

MO	n	A_w (g/cm^2)	t_{avg} (mm)	V_f % (thickness)	V_f % (image analysis)
1	24	131.8	3.21	56	56
2	12	280	3.41	56	57
3	6	560	3.57	53	54
4	12	285	3.74	52	53
5	6	560	3.56	53	56

cured) also have identical V_f, 53%. However, the V_f of MO3 and MO5 are approximately 4% lower than that of MO1 and MO2. The similarity of the V_f of MO3 and MO5 indicated that removing the autoclave cure has little effect on the quality of the consolidation. MO4 has a V_f, of 52%, this is approximately a 7% reduction from MO1 and MO2 and may be due to the open weave structure of the 2×2 twill used in this MO. The important outcome from this work is that in all cases the volume fraction of the material is greater than 50%. However, the measure of V_f derived from Equation (1) provides no indication of the void content or distribution of the resin with the laminate; this assessment must be made by visual inspection using micrographs of each MO. Image analysis of microscopy images was also used to estimate the V_f of the laminate.

The single skin panels produced by each MO were cut transversely and divided into small sections. These were potted into resin and polished so that they could be viewed in an optical microscope. Sixteen sections were taken from each material. The polished sections were assessed first at five times magnification to investigate the overall quality. Then each section was assessed to estimate the V_f, by applying a grayscale threshold in an image analysis process and counting the number of pixels above this threshold. Figure 6 shows two images from each MO at five times magnification. Figure 6(a) and (b) show microscopy images of laminates produced by MO1. As expected from prepreg tape manufactured in an autoclave, the laminate is well consolidated with resin and fibers evenly distributed. Images from MO2 (Figure 6(c) and (d)) show pockets of resin in between the tows of the woven structure; however, the fibers are closer packed in the tows than in MO1. Figure 6(e) and (f) are images from laminates manufactured by MO3. The laminate is well consolidated as in MO1 but there are some resin pockets around the discontinuity caused by the polyester stitching that loosely binds the dry NC2 fabric prior to layup. Although MO3 is cured in an autoclave, there is also some evidence of small voids across the laminate; these areas are darker than the resin. Figure 6(g) and (h) show images of

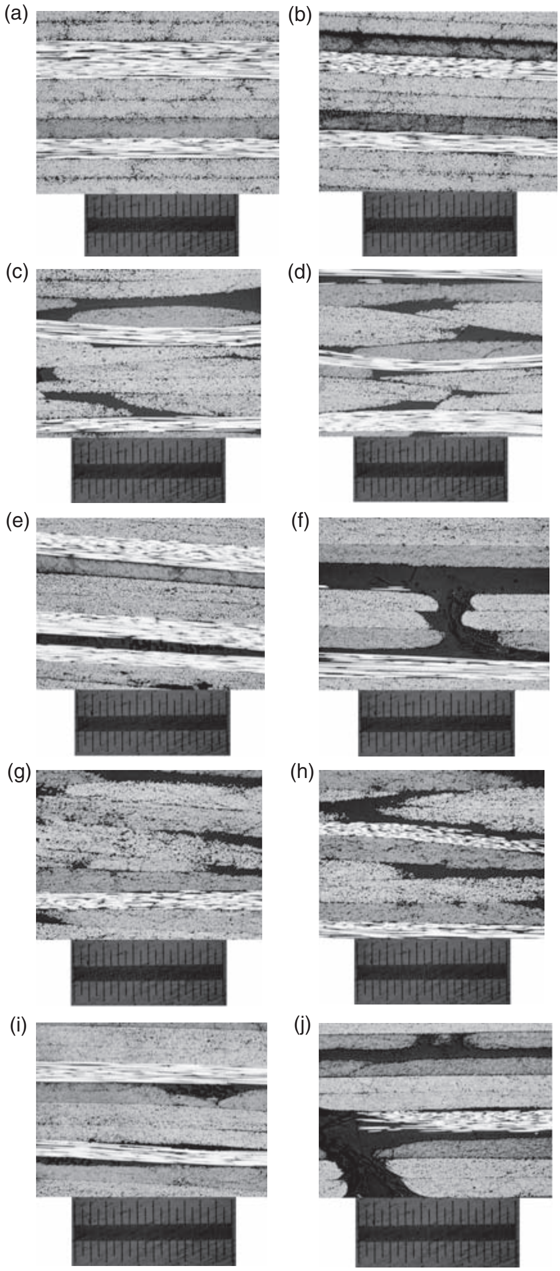

Figure 6. *Microscopy images of consolidated laminates (each division represents 0.5 mm); (a, b) MO 1, (c, d) MO 2, (e, f) MO 3, (g, h) MO 4, (i, j) MO 5.*

MO4, a woven fabric cured in the oven. These images have a similar structure to that for MO2 but the fibers are less closely packed and there is some evidence of very small voids. The other oven-cured laminate MO5 is shown in Figure 6(i) and (j) and has a structure similar to that of MO3. The out-of-autoclave cure appears to have had no apparent negative impact on the consolidation of the laminate. In fact there appears to be smaller resin pockets and less voids.

Table 7 contains V_f values estimated from analysis of microscopy images. These values compare favorably with those estimated through the thickness method for MO1–3 and confirm the accuracy of Equation (1) for autoclave cure. However, there is a significant difference in the V_f obtained from the micrographs and that from Equation (1) for MO4 and MO5. The V_f of MO5 (at 56%) through this method compares is identical with V_f given for MO1. The only explanation for this is that as the NCF produces a thicker laminate in the oven consolidation, the resin is infused through the stack and some drawn to the surface but in the autoclave consolidation (MO3) the resin is forced to remain within the stack.

In general the micrograph analysis has produced results that confirm that in all cases the MOs produce aerospace quality laminate face sheet. It is shown that the actual volume fraction of the MO5 is identical to that produced in the autoclave and in this sense the quality of the face sheet material is not changed by the new less-expensive process. However, the micrographs show voids and localized large resin pockets that occur as a result of stitching. The effect of these on mechanical performance must be assessed to confirm that the MO5 can be used with confidence instead of MO1.

IN-PLANE LOADING

The in-plane properties were measured using tensile tests on specimens manufactured from laminates with the plies all aligned in the longitudinal direction. These will provide material properties for individual lamina that can be use in the FEA models (E_1, E_2, ν_{12}, ν_{21}). Tensile test were also carried out on laminates with the plies in the same configuration as the face sheets in the generic panel to assess the global performance of each face sheet material (σ_{FL1}, σ_{FT}) and obtain global material properties (E_L, E_T, ν_{LT}, ν_{TL}). The test specimens were manufactured to the geometry specified in ASTM D3039 and loaded according to the standard in an Instron 5569 servo-mechanical test machine; the strains were obtained using a 50-mm gauge length extensometer. Five specimens of each orientation and MO were tested. The specimens were orientated so that the longitudinal direction was on the x-direction shown in Figure 4 and the transverse was on the y-direction.

Table 8 provides the tensile properties and their standard deviations for the lamina used in MO1, MO2, and MO4; it was not possible produce these kinds of specimen for the stitched NCF dry mat used in MO3 and MO5. It is clear from these results that as expected the MO1 produces highly orthotropic lamina and the woven material of MO2 and MO4 produces a quasiisotropic lamina. There is some scatter in the derived Young's modulus values of less than 10% (with the exception of E_1 for MO4). The scatter in the Poisson's ratio values is large in both cases but this is more indicative of the accuracy of the extensometer rather than the material quality.

Table 9 provides the global tensile properties and their standard deviations for each MO. For the longitudinal modulus, E_L, there is practically no difference between the two autoclaved, prepreg products. The scatter for MO2 to MO5 is less than 5%. The scatter in MO1 data is greater but similar to that reported in Table 8. Using MO5 results in a 7% reduction in E_L with an 8% reduction for MO3 and 13% loss for MO4 compared to MO1. There is practically no difference between the autoclave-cured material in MO3 and the oven-cured material in MO5. The resin system used for MO3 and MO5 is identical and has been formulated for out-of-autoclave cure and will therefore wetout the fibers better during an oven cure; this can explain the slight improvement in modulus. The reduction in properties for MO4 can be attributed to the woven form of the material in MO4. A similar pattern is observed for the transverse modulus. It is interesting to note that the Poisson's ratio values vary enormously, with MO1 being significantly different from MO3 and MO5, which are all made

Table 8. Elastic properties of the face sheet lamina material for MO1, MO2, and MO4.

MO	E_1 (GPa)	E_2 (GPa)	ν_{12}	ν_{21}
1	134.3 ± 9.3	9.0 ± 0.4	0.32 ± 0.02	0.05 ± 0.01
2	80.9 ± 5.6	75.6 ± 1.4	0.06 ± 0.02	0.04 ± 0.02
4	64.4 ± 10.5	66.1 ± 3.1	0.10 ± 0.05	0.09 ± 0.05

Table 9. Tensile properties of the face sheet materials produced from each MO.

MO	E_L (GPa)	E_T (GPa)	ν_{LT}	ν_{TL}	σ_{FL} (MPa)	σ_{FT} (MPa)
1	48.7 ± 3.5	50.4 ± 4.0	0.09 ± 0.02	0.15 ± 0.03	565 ± 5.5	597 ± 22.3
2	47.1 ± 1.1	49.3 ± 0.6	0.26 ± 0.03	0.25 ± 0.02	534 ± 8.4	568 ± 15.8
3	44.5 ± 2.1	44.3 ± 1.1	0.32 ± 0.04	0.27 ± 0.01	595 ± 21.5	579 ± 42.4
4	42.2 ± 0.6	41 ± 0.5	0.24 ± 0.03	0.25 ± 0.04	532 ± 10.5	549 ± 17.5
5	45.2 ± 0.6	46.7 ± 1.1	0.32 ± 0.02	0.26 ± 0.02	640 ± 24.5	667 ± 37.1

from NCF materials; the scatter in these reading are identical to those shown in Table 8, further confirming that the scatter is an indication of the precision of the extensometer. The material manufactured using MO1 has a longitudinal failure stress of 565 MPa and transverse failure stress of 597 MPa, while the material manufactured using MO5 shows an improved longitudinal failure stress of 640 MPa and a transverse failure stress of 667 MPa. This represents an increase in strength of approximately 12% by using the out-of-autoclave MO. This is an unexpected result as it is generally accepted that the autoclave will produce a higher quality product. The increase in strength may be attributed to the resin used and possible improved wetout, although the indication from the micrographs is that there are significant resin pockets around the stitching in MO5 and therefore a much less uniform distribution of the resin. Figure 7 shows typical strain to failure curves for the two materials. These data were taken without an extensometer, using only the cross-head displacement, the compliance of the test machine causes a false reading and hence an increase in the strain reading; therefore these should be used for comparison only. The extensometer data for both tests are also shown to demonstrate the level of inaccuracy. However, it can be seen that for both MO1 and MO5, the failure is immediate and progressive failure is not the reason for the increased strength values. In all cases, strength values had a scatter of much less than 10%, so the simple explanation is that the NCF oven-cured approach produces a stronger material. From these results it can be

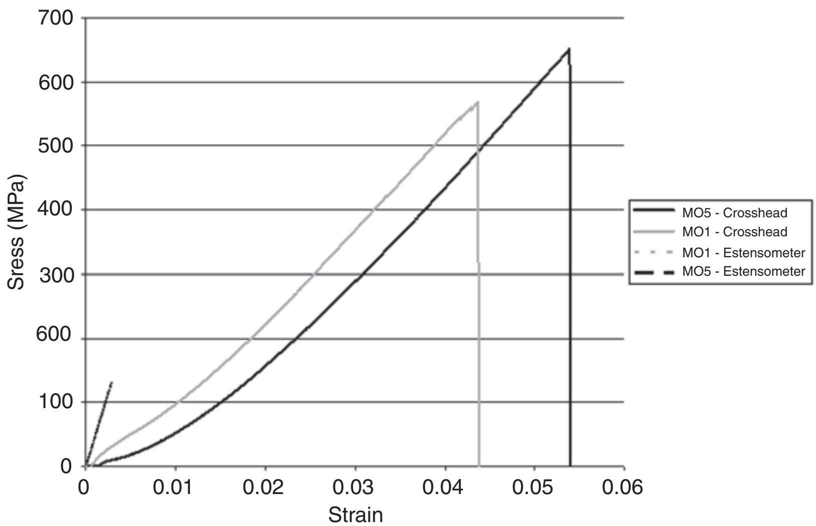

Figure 7. *Typical stress–strain curves of specimens manufactured from MO1 and MO5.*

concluded that the out-of-autoclave product shows no significant changes in mechanical properties, although the differences in Poisson's ratios will have an effect on the behavior of the generic panels when loaded in bending.

OUT-OF-PLANE LOADING

The out-of-plane properties of a laminate may be greater affected by poor quality material or process than in-plane properties. Therefore, the interlaminar shear strength (ILSS) and flexural properties (flexural stiffness, E_f and flexural strength, σ_{Ff}) of laminates of the five MOs are also investigated. The test specimens were manufactured and tested as specified in ASTM D2344 for interlaminar shear strength and ASTM D4762 for the flexural properties. These tests were conducted using an Instron 8872 servo-hydraulic test machine. At least five specimens of each MO were tested for each out-of-plane property. Table 10 lists the out-of-plane properties of QI laminates produced by the five MOs, namely ILSS, flexural strength, and flexural modulus.

The laminate produced by MO1 has an ILSS of 56.75 MPa, the laminate produced using MO3 (new material, autoclaved cure) has an ILSS of 43.25 MPa. This represents a reduction of 24%. However, the laminate produced by MO5 has an ILSS of 52.8 MPa, a reduction of only 7% compared with MO1. It is believed that because the resin system has been formulated for out-of-autoclave cure, the best consolidation results are provided by a vacuum-only cure. It is known from literature that per 1% void content, the ILSS reduces by 7–10% [10]. The micrographs in Figure 5 show that there are more voids in MO5 than in MO1 and furthermore there are many more voids in MO3 than in MO5. The flexural properties of the laminate produced by the out-of-autoclave procedure (MO5) compare favorably with the original method (MO1). The MO1 laminate has flexural strength of 827.69 MPa and flexural modulus of 47.37 GPa, while the MO5 laminate has a flexural strength and modulus of 795.12 MPa and 46.39 GPa, respectively. This represents a reduction of 4 and 2% in the flexural properties by curing out-of-autoclave.

Table 10. Out-of-plane properties of the face sheet material produced from each MO.

MO	ILSS (MPa)	σ_{Ff} (MPa)	E_f (GPa)
1	56.8 ± 0.5	827.7 ± 26.7	47.4 ± 1.4
2	59.6 ± 3.0	760.9 ± 38.7	48.1 ± 0.9
3	43.3 ± 2.6	763.9 ± 52.7	45.0 ± 2.1
4	52.0 ± 1.9	689.7 ± 5.9	40.0 ± 0.8
5	52.8 ± 2.6	795.1 ± 35.4	46.4 ± 2.4

CONCLUSIONS

This article has presented an investigation into reducing the manufacturing costs of carbon fiber/Nomex honeycomb sandwich aircraft secondary structure. An analysis of the current manufacturing procedure, hand layup of prepreg cured in an autoclave, has confirmed that in particular the capital and running costs of the autoclave and the labor costs of layup are the largest cost contributors. Therefore, a major conclusion of the work described in this article is that removing the autoclave and replacing with a vacuum-only oven cure would improve the cost efficiency of the process. A further benefit of removing the autoclave from the process would be the elimination of batching components for cure, improving the flow of work and therefore total manufacturing costs.

An analysis of the time taken to produce panels from five MOs has been conducted that shows that by removing autoclave cure and using RFI, the number of labor hours required for layup can be reduced by approximately 30%. However, because the fiber mats are much thicker than the prepreg, sufficient resin infiltration from film through the thick mats was in question. Therefore, a program of material characterizations and mechanical tests has been conducted to measure material consolidation, in-plane properties, and out-of-plane properties of laminates produced by the five MOs.

Material consolidation was tested by estimating the fiber volume fraction by measuring the thickness of the consolidated material and analysis of microscopy images of material sections. These showed that the volume fraction of the laminates produced by the new process is of similar quality to the current process. A visual check of the microscopy images also revealed features in the NCF that may cause detrimental effects on the mechanical performance. In general, the mechanical testing showed that the new material performed equally well as the autoclaved material in tension, with only a 7% reduction in stiffness and a 12% increase in failure strength. Similarly, the out-of-plane properties, namely interlaminar shear strength and flexural stiffness and strength, were reduced by only between 2 and 7%.

In summary, it has been shown that the most cost-effective manufacturing process MO5 produces face sheet materials that can perform to aircraft specification. A scheme has been devised that links manufacturing costs with mechanical performance. The work in this article has shown that the scheme is effective for linking the performance and cost of the face sheet materials in simple material characterizations. The next step is to take the generic panels and link the cost of manufacture to the performance of the entire sandwich structure.

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