IIT, Madras

Innovative tooling concepts for cocured composite structures in aircraft applications

Kotresh M. Gaddikeri · M. N. N. Gowda · Ramesh Sundaram · M. Subba Rao

Abstract Cocuring process is a unique characteristic of composite materials wherein multiple parts like stringers, ribs and spars are simultaneously cured and bonded to a composite skin resulting in an integral structure. It has many benefits like reduction in part count, elimination of stress concentration due to fastener holes in the cocured regions and reduced assembly time and related costs. However, the application of cocuring has been limited on contoured components because of the complexities associated with the tooling. The basic requirements to be fulfilled are (a) consolidation of skins and stiffeners and (b) dimensional tolerance on position and thickness of stiffeners. Proper consolidation can be ensured through the faithful transfer of autoclave pressure by designing tools which are flexible so that they conform to desired shape whereas the positional tolerance can be achieved by using rigid tools. The resolution of such conflicting requirements requires a detailed study of the geometry of the part, design requirements and tolerances achievable on tools. This paper discusses design of tools for two types of cocured structures viz., open and closed cocured structures. The tooling technologies for realising above structures differ considerably. A few tooling concepts have been discussed based on the authors' experience of developing cocured structures over the last two decades.

Keywords Cocured · Stiffened shells · Tooling technology · Silicone · Autoclave moulding · Consolidation

K. M. Gaddikeri (✉) · M. N. N. Gowda · R. Sundaram · M. Subba Rao
Advanced Composites Division (ACD), CSIR-NAL, Bengaluru, India
e-mail: kotresh@nal.res.in

1 Introduction

Polymer matrix composites (PMC) are increasingly being used as structural materials for aircraft structures because of their special and superior properties. Over the years, designers have established that usage of PMC's not only reduces the weight of structure but also the cost by adopting fabrication technologies like cocuring and cobonding. The Industry has realized that the use of composites also reduces the maintenance cost substantially.

Prepregs have been the workhorse of composite industry for manufacturing of aircraft structures for the last three decades. The curing of prepregs is done in an autoclave under high temperature, vacuum and pressure resulting in parts that have excellent consolidation with less than 1 % voids. The major disadvantage with this process is that it requires high capital investment in the form of the autoclave and is energy intensive. Furthermore, the prepregs have limited shelf life/out life and need to be stored at −18 °C. With the industry looking for processes that are economical and less energy intensive, the focus has shifted to liquid composite moulding (LCM) technologies like VARTM and its variants, out-of-autoclave (OOA) prepregs etc. Despite the development of these technologies, autoclave moulding remains the preferred process in aircraft industry. In this paper, authors share their experience of developing cocured structures, using prepregs and autoclave moulding for aircraft applications.

2 Cocuring technologies for aircraft structures

Stiffened shells are commonly used as structural members in airframes. The conventional way of building stiffened shells is to fabricate the shells and stiffeners separately.

These 'separate structures' are integrated either through mechanical fastening or adhesive bonding. In both the techniques, adherends should have proper and intimate contact with each other, which is very difficult to realize in complex shapes. As a result, undesirable assembly stresses will be introduced, which are difficult to account in the design. The assembly stresses will severely affect the life of the structure, particularly, carbon epoxy composites because of their linear elastic behaviour and limited strain capability. These assembly stresses can be eliminated to by building the structures through cocuring. Cocuring is a process in which a large number of smaller parts are integrated to realise a large integral structure. The main benefits are; elimination of holes thereby reducing stress concentration, reduction in assembly time and associated costs, elimination of fuel leaks and the like. However, the success of cocuring technology largely lies in the tooling methodology adopted. Cocuring technology and associated tooling are normally proprietary in nature and details are not available in the open literature. During late 1990s, Japanese developed a cocured wing for XF-2 fighter aircraft wherein spars and ribs were cocured with the bottom skin [1]. This technology was subsequently transferred to a US Industry. US experts believed that the impressive ability of Japanese industry to manufacture high quality large cocured structures resulted primarily from Japanese management techniques, special attention to tooling, and a highly skilled and well-motivated work force [2]. Authors endorse the above opinion based on the experience of developing cocured structures for Indian national aircraft programs for over two decades.

The basic philosophy of 'faithful transfer of autoclave pressure to the prepreg layers and removal of entrapped air' still remain the same as in normal composite structures. Implementation of this philosophy especially on doubly curved surfaces is a challenge. Furthermore, there could be additional requirements imposed from the design wherein tighter tolerance on positions of stiffeners is desired from the view point of structural assembly. The faithful transfer of pressure can be accomplished by designing tools which are flexible so that they conform to any complex shape whereas the positional tolerance can be achieved by using rigid tools. The resolution of such conflicting requirements requires a detailed study of the geometry of part, design requirements and tolerances achievable on tools. The solutions cannot be generalized as there is 'no universal answer'.

2.1 Classification of cocured structures

Composite structures can be divided from the cocuring technology point of view into two categories based on their constructional details viz., open structures and closed

structures. Open structures are those having skin on one side and stiffeners on the other side. Stiffeners can be in both longitudinal and transverse directions. Closed structures are those having two skins which are interconnected with spars and ribs. The technologies for realising open and closed cocured structures differ considerably. The autoclave moulding of composites requires at least one side rigid mould. Techniques like RTM require rigid moulds on both sides (closed moulds). The moulds can be made either in metals or composites. One concern with autoclave molding technology is the poor surface finish on the 'bag side' surface of the part manufactured. This can be improved by using a caul plate which is flexible, made using either rubber or thin composite sheets or even metal sheets.

3 Cocuring of open structures

Integrally stiffened composite shells are manufactured using rigid mould on one side and shaped caul plates on the other side. Design and manufacture of these shaped caul plates is the most important aspect of co-curing technology [3]. Activities involved in manufacturing a cocured structure can be divided into two stages; first stage is the layup and second stage is the curing. The fundamental philosophy is that the layup tools and curing tools are different as one set of tools cannot meet both the requirements. The base tool is used for skin layup and is common for both stages.

Some of the crucial requirements of cocured parts like the spacing of stiffeners (d1, d2), the thickness of stiffener (t1, t2) and the radius (R) are schematically shown in Fig. 1. These requirements will impact the way both layup and curing tools are designed.

3.1 Design considerations for layup tools

Some of the important design considerations are enumerated. Layup tools are rigid so that they maintain the required geometry of stiffener. Provision of assembly of adjacent layup tools after stiffener layup should be provided. The weight of layup tools should be as low as possible for the ease of manual handling. The tool design
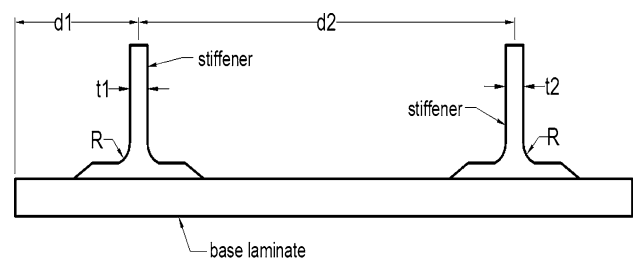
Fig. 1 Schematic representation of stiffened structure

ought to consider the allowances for green-stage thickness of prepreg and release films that are applied to tool surface. The reference for assembly of layup cores with regard to the base skin tool should be provided.

3.2 Manufacturing of stiffener layup tools (cores)

The manufacturing process gets frozen the moment the material selection is made. The selection of particular material for layup tools depends mostly on the accuracy and cost of realisation. Commonly used materials in the industry are (a) NC machined tools in aluminum/mild steel, (b) Room temperature curing cast tools (aluminum powder + epoxy resin) or (c) Composite tools with glass/carbon fibre + epoxy resin.

NC machining of stiffener layup tools using metallic materials is practical when the complexity of contour and ply drops is less. There is a general perception that the NC machined tools would have the desired contour. The major issues in NC machining are as follows viz. (i) twisting of machined core due to the excessive machining of blocks (ii) the availability of raw material for large sized tools. The matching of mating stiffener tool surface to skin tool surface with appropriate skin offsets is of paramount importance. In this pairing, two tools are involved; one is skin tool and other is layup tool. Skin tools are generally large in size and have a larger tolerance on its contour whereas stiffener layup tools are smaller in size with tighter tolerance. Moreover, the magnitude of deviation in contour would have spatial variation on both tools. In this circumstance, it would be difficult to ensure proper contact between both tool surfaces after layup. This mismatch can be minimised for mild contoured parts using NC machining. However for complex and doubly contoured surfaces, a larger mismatch between skin and stiffener tool is likely to occur. This could lead localized higher porosity in the mismatched areas while curing the part. In order to avoid this, the usage of derivative tooling technology [4] is advocated wherein the dummy skin is built on skin tool over which stiffener layup tool is casted/laid up. In this case, variations of skin tool are copied on to stiffener tool and a perfect matching between mating surfaces is ensured. Other two materials/methods except NC machining listed in the previous paragraph require building of dummy component for realising tools.

3.3 Building of dummy component

On the base skin layup tool, a 'dummy component' is constructed simulating the exact thickness and ply drops of the part. The dummy component has to be very accurate representing all the features of actual component. The base skin tool should have provision for all references like stiffener center lines, part trim lines etc. The accuracy of dummy component is of paramount importance as the tools derived from this will determine the consolidation of the part. Generally, calibrated wax sheets are used to make the dummy component. The dummy component and uncovered tool surface is coated with proper release agent to aid the removal of cast cores. All around the tool boundaries, a flange construction is done to create cavity using laminated ply wood sheets to contain the casting mixture or layup. The following sections will give an insight of the casting process.

### 3.4 Manufacturing of stiffener layup tools (cores) using casting process

The material used for casting is room temperature curing epoxy resin and aluminum powder. Resin and aluminum powder are mixed thoroughly in an appropriate ratio by weight and until the mixture attains semisolid consistency. Care should be taken not to mix excessive volumes in a given batch as this could lead to exotherms while working/casting. The entrapped air bubbles in resin are removed by degassing under vacuum. Small quantity of aluminium powder is added at a time to the degassed resin while stirring is continuously done. Cores are cast one at a time and are cured under ambient conditions. Cores are demoulded from the tool carefully and postcured in an oven. Subsequently, dimension checks are carried out to determine their fitness for use. The schematic of arrangement for casting of cores is shown in Fig. 2.

3.5 Layup of stiffeners for cocuring

Stiffener layup is done on the 'derived cores' using the prepreg as per design requirements. The layup of stiffeners can be divided into two parts; basic stiffener layup and the corner layup as shown in Fig. 3. One stiffener is derived using layup on two cores that lie on either side of the stiffener as shown in Fig. 3. Once the layup is completed on each core, vacuum is drawn from the vacuum bag and prepreg layers are compacted in green stage. This is called as debulking process. All stiffener cores are assembled as shown in Fig. 2 on
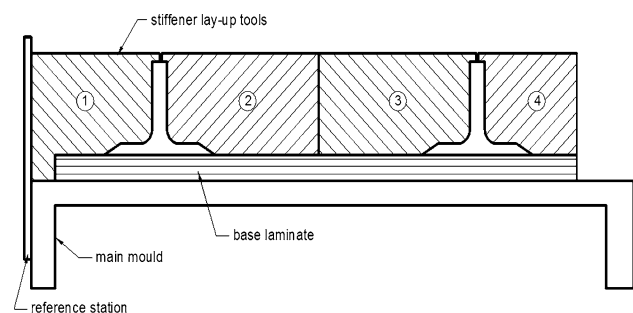
Fig. 2 Schematic representation of tooling for lay-up
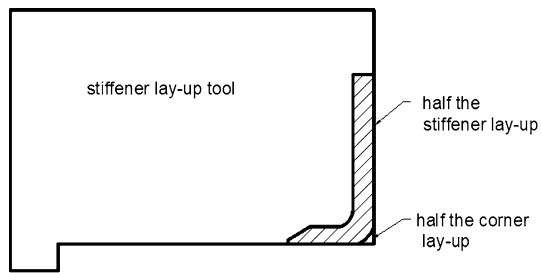
Fig. 3 Typical stiffener lay-up tool

Fig. 4 Scheme for manufacturing caul plates

the skin and the entire assembly is debulked. With this debulk, the stiffener flange gets attached to the skin and both halves of the web bond to each other. Then, the stiffener layup tools (cores) are removed leaving the stiffener layup on the base skin. To facilitate the removal of these cores, the cores have to be initially covered with appropriate release aids like release film.

3.6 Design considerations for curing tools

Curing tools are also referred to as caul plates. The design of caul plates depends on many factors viz., geometry of the part, configuration of stiffener, tolerances for stiffener spacing and thickness, edge tapering, surface finish, cure temperature, manufacturing tolerances on tools, thickness of prepreg stack in green stage especially for thicker sections, variations in prepreg thickness and the like. Doubly curved contours mandate flexible caul plates to accommodate tolerances in tools and prepreg whereas tolerances on stiffener spacing and close control on thickness require a rigid tool held accurately in position. The edge tapering of stiffener web demands a dam at the end of stiffener. A good design will have curing tools with spatially tailored stiffness depending on region-wise requirements of the cocured structure. The proper consolidation of cocured part depends on the accuracy of the tools used. The selection of proper material is important to meet both consolidation and geometrical requirements. Moreover, the life of caul plate for repeated use is mostly determined by the material and the procedure adopted to manufacture the caul plate.

In this article, two ways of making these shaped caul plates are discussed. The technology also differs the way these caul plates are used to produce the cocured structure subsequently.

3.7 Manufacturing of composite caul plates using wet layup

There are many ways of realizing caul plates for curing. One popular method of making caul plates is using carbon epoxy composites. Using dummy component as the master, caul plates are made through wet layup and vacuum bag
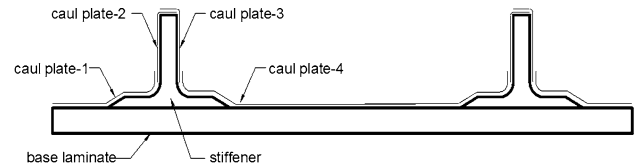
technique. These caul plates are initially cured at room temperature and post cured in free standing at high temperature. Caul plates are split into multiple pieces as shown schematically in Fig. 4, especially for highly contoured parts so that conforming to the shape during curing becomes easy.

The main problem with such caul plates are: (i) prone to damages as they are thin and (ii) higher tool count as they are made in pieces. Maintenance and storage are also issues that need to be addressed. Otherwise, these caul plates give satisfactory results.

3.8 Manufacturing of silicone rubber caul plates

A hybrid solution using silicon rubber and carbon epoxy laminates can also be used for making curing caul plates. This is essentially an integrated tool having a stiff composite retainer plate which is either encapsulated or embedded in silicone rubber on one side of the stiffener and the other side with silicone rubber alone as shown in Fig. 5. Each stiffener will have a separate caul plate overlapping with the other caul plate in the middle of panel.

Fabrication of carbon epoxy retainer plate is important as it is the backbone of the integrated silicone rubber caul plate. It is of inverted L shape with 6–8 mm thickness and rigid so that prepreg layers during curing are forced to take its shape. The flange edge near the fillet area is tapered so that the stiffness variation is gradual. The manufacturing of retainer plate can be done in one or two stages depending on the complexity of geometry. The important aspect is to have the length of flange of inverted L on top side equal to the stiffener web thickness. Furthermore, the twisting of retainer plates after post curing is to be checked and removed before encapsulating/embedding in silicone rubber. Using the silicone rubber spray technique, thinner caul plates (about 2 mm thick) on opposite face of retainer plates can be made. The silicone rubber material selected should withstand the cure temperature of the part repeatedly with minimum shrinkage.

Suitable fixtures have to be developed for clamping retainer plate to skin layup so that it acts like a rigid surface to maintain the required dimensions [4]. The main advantage of this method is that it ensures rigid tool on one side and flexible tool on other side. The experience of the authors is that the consolidation of parts made with this
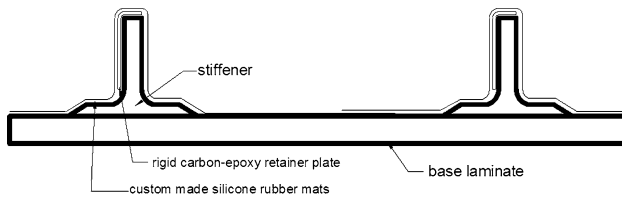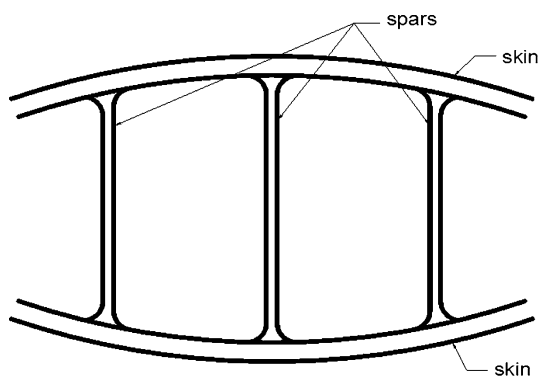
Fig. 5 Scheme to make silicone rubber caul plates

tooling technology has been good. Maintaining the spacing of stiffeners can be achieved with more certainty as the retainer plates are held in a unique location. Another advantage of this process is that it leads to 'integrated tooling'.
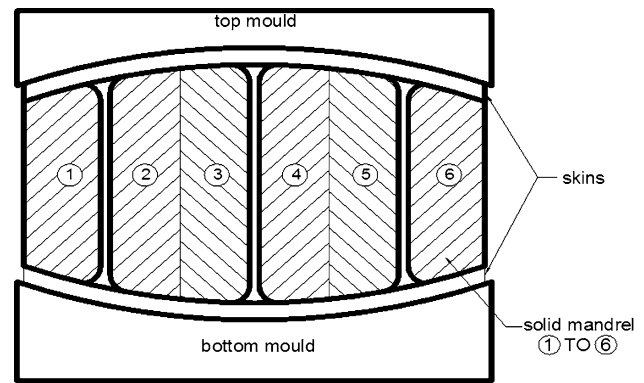
4 Closed structures

Closed structures possess two skins interconnected with either spars and/or ribs. The fabrication requires two moulds; one for each skin. Typical Schematic is shown in Fig. 6.

One simple method of making these structures is described below. The skin layup is done on the top and bottom metallic moulds. The spar layup is done on the CNC machined metal mandrel. The mandrel with spar layup is assembled on the bottom skin layup. Subsequently, the top mould along with the skin layup is assembled on the previously assembled mandrels as shown schematically in Fig. 7. Entire mould assembly is vacuum bagged and cured in the autoclave. The mandrels are ejected after the completion of cure pull out and the part is demoulded.

The main issues with this method are as follows. As top and bottom moulds and mandrels are rigid, the tooling cannot accommodate any variations in the prepreg thickness even though they are within acceptable tolerance limits. This also implies that any variation in tool, prepreg thickness and improper assembly etc. will lead to non-uniform application of pressure leading to pockets of poor
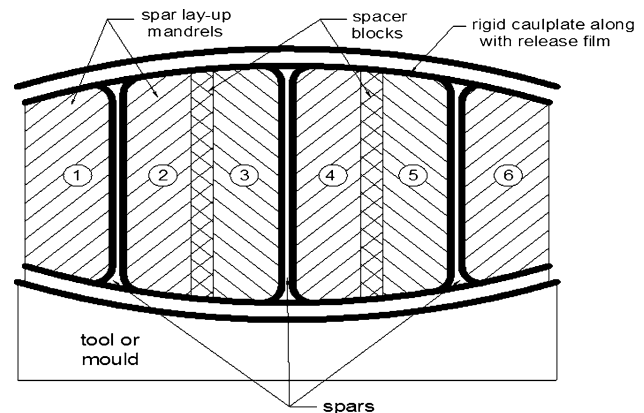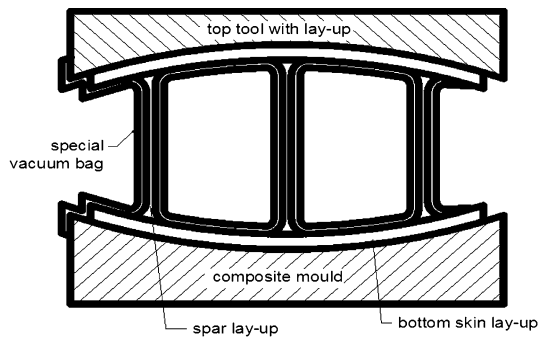

Fig. 7 Scheme for co-curing of closed structure

consolidation. This is the major cause of rejection of parts adopting this technology. Moreover, handling of assembly of such bulky tools might require special handling equipment. Chances of damaging part while demoulding are also high.

### 4.1 Novel solutions for realizing closed structures

Some flexibility can be built into the assembly by removing the metallic top mould and replacing it with a semi-rigid caul plate. This has been found to give better results. As in the case of open structures, the layup tools need to be different from curing tools. Spacers are added besides layup tools for fine tuning while assembling spars with skin. The composite moulds can also be used to fabricate the skin layup tools using carbon-epoxy prepreg. The spar layup tools in this application are accurately fabricated mostly using composite materials. Each spar will have two mandrels. This scheme is shown in Fig. 8. For curing, vacuum bag is directly used in the cavity between two spars. The main challenge will be to avoid the bridging at fillets and corners which are inaccessible from outside.

Fig. 6 Typical closed structure

Fig. 8 Scheme for positioning the spars on the skin lay-up

Fig. 9 Scheme for positioning the vacuum bag for cure
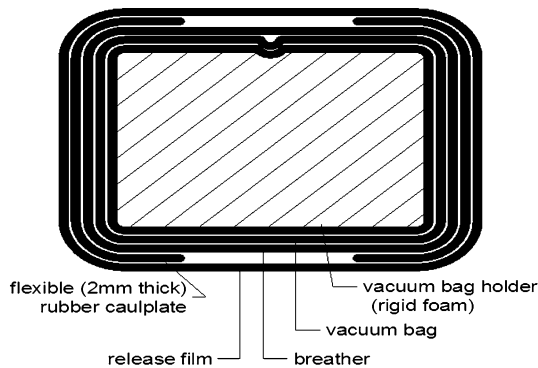
Fig. 10 Special vacuum bag with bag holder

The methodology for manufacturing a closed structure is as follows. The skin and spar layup is done on corresponding moulds and mandrels respectively. Initially, mandrels are assembled on bottom skin and the assembly is debulked. Before placing the top skin, the internal vacuum bag is positioned in cavities formed by spars and skins to avoid bridging in inaccessible areas using special techniques [5, 6]. Custom sized vacuum bags as shown in Figs. 9 and 10 are inserted with the help of bag holders. These bag holders are made using soft materials like EPS foam. Special vacuum bag holders help in making the bag very close to the cavity size. Subsequently, top skin is positioned and entire assembly is vacuum bagged. As the bag presses against the spar and skin layup, the bag holders will become loose. These holders can be removed easily. Subsequently, the part is cured.

Skins are well consolidated and bag directly applies pressure on the skin layup towards the mould giving good quality skins. Moreover, the bag is directly pressing the spar flange towards skins resulting in good bonding between sub-structure and skin.

5 Conclusions

Polymer matrix composites have found wide acceptance in the industry as structural material for primary aircraft structures. The motivation for use of composites is to reduce the weight and cost of the structure by selecting advanced fabrication methods like cocuring technology. There are several options for cocuring which depend upon the type of structure. The selection of appropriate technology to achieve consistent quality requires a thorough understanding of achievable tolerances on tools, process parameters and design requirements. Caul plates made using silicone rubber will reduce the number of caul plates required and improve the quality of laminate. The crux of composite technology lies in the tooling and as the popular cliché goes, 'the component is as good as the tooling'.

References

1. Kageyama, M., Yoshida, S.: Development of XF-2 fighter composite structures (cocured composite wings).In: Proceedings of the 41st structures, structural dynamics, and materials conference and exhibit, AIAA, 2000
2. Lorell, M.: Troubled partnership: A history of U.S.-Japan collaboration on the FS-X Fighter. Project Airforce-RAND, 1995
3. Kotresh M. Gaddikeri., SubbaRao, M.: Cocuring technique for integrally stiffened shells. INCCOM-1, May 2002
4. Kutty, MG., Saravanakumar, N., Radhakrishnan, G., Dinesh, BL., Subbarao, M.: Development of composite tools for cocured and cobonded stiffened composite structure for aircraft using derivative tooling technology. INCCOM-7, December 2008
5. SubbaRao, M., Gowda, M.N.N.: Development of fin for LCA using advanced composites. J. Aeronaut. Soc. India **54**(2), 106–108 (2002)
6. Gowda, MNN., Pitchai, P., Ravi, S., Pavithran, S., SubbaRao, M.: Issues in combining different fabrication techniques to produce cocured structures. National seminar on composites product development, NASCOMP 96, April 1996