DESIGN, DEVELOPMENT AND CERTIFICATION OF COMPOSITE REAR PRESSURE BULKHEAD FOR A LIGHT TRANSPORT AIRCRAFT

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1 Introduction

Advanced composite technology in the aerospace sector is ever evolving and efficient structures with lower cost and weight are being realized. This is evident from the extensive usage of composites in the programs like A380, Boeing787, A340M and A350. Primary component like rear pressure bulkhead for A380 have been developed through innovative design and manufacturing technologies. Conventionally the rear pressure bulkheads are designed as a flat stiffened plate construction using aluminum alloys, which is not an optimum design for resisting pressure loads. It is well known that a dome shaped shell type construction is more efficient in transferring the pressure loads as membrane stresses [1, 2]. This property of shell makes it more economically viable than a stiffened plate construction. Moreover, the dome shaped shell can be realized easily in composites by exploiting its mouldability.

The concept of integrating the dome with the fuselage frame has not been tried in any other aircraft program as per the information available in open literature. Such an integrated construction is possible using cocuring technology. The principal advantages of this technology are the elimination of stress concentrations due to holes, reduced assembly time and associated costs. CSIR-NAL has played a key role in the development of cocured composite structures for both military and civil aircraft structures.

In the technology developed, the bulkhead ring, which is of I section reinforced with gussets on either side of the web, has been integrated to the dome and the entire structure has been cocured in one single operation. This avoids a mechanical joint at the junction of the dome and the bulkhead ring. The integral construction of the bulkhead has resulted in (a). Lower manufacturing cost (b). Reduced sealing issues (c). No long term corrosion issues. This has resulted in a composite structure having a 50% weight reduction compared to the metallic design. Furthermore 900 fasteners have been reduced to nought!

The integral fabrication of the bulkhead ring, gussets and the dome of the pressure bulkhead structure also posed a great challenge to the tooling methodology. The dimensional stability of the gussets was extremely important as the stringers from the fuselage get attached with each of these gussets during the fuselage assembly. The consolidation, positional accuracy and straightness of the stiffeners were ensured through derivative tooling concepts (DTC). Furthermore, as a part of structural substantiation, the feature level and component level tests were carried out following the industry standard building block approach. This paper discusses details of the design, the fabrication and the certification aspects on the composite pressure bulkhead developed for a light transport aircraft.

2 Geometry and structural features

Fig. 1 shows the geometry of the bulkhead with the ring integrated with the shell (dome). The radius of the dome is 2361mm and the height of the structure is 1.88m. The bulkhead ring is of I-section, having an outer flange, web, gussets and an inner flange. A section of the bulkhead ring is shown in Fig. 2. The bulkhead outer ring is attached to the metallic fuselage skin all around through fasteners. The dome consists of a few cut outs for routing of cables and pipes. At the cut out locations, the dome is flat to facilitate fixing of attachments.

The dome is subjected to mainly in-plane stresses due to pressurization since the thickness of shell is very small compared to the radius. The shell develops meridional and circumferential stresses which are of nearly equal magnitude away from the junction (shoulder area) of the bulkhead ring, close to the junction the meridional stresses dominate. The junction will be subjected to bending due to inplane loads in the dome. The ring transfers the reaction (shear) developed due to the pressure acting on the dome to the fuselage shell. In addition, the bulkhead has to transfer the rear fuselage loads to the center fuselage. Full depth gussets were provided around the ring on either side of bulkhead web to transfer the stringer loads and to stiffen the bulkhead web. The majority of gusset webs provided were in the radial direction so as to match the stringers of the fuselage.

The basic thickness and material directions were decided based on this understanding of the structural behaviour. The fibre orientation and distribution of prepreg layers were finalized such that the ring and the shell (dome area) can be cocured. The dome portion of the shell was provided with 'quasi-isotropic' lay-up sequence to take care of the nearly equal meridional and circumferential stresses. Additional layers with fibres in the meridional directions were provided close to the shoulder area. These layers were continued to bulkhead ring to maintain the continuity of the layers in the shell and the bulkhead ring for the smooth transfer of load from the shell to the ring. The ring was also provided with adequate number of layers in the hoop and longitudinal directions. The major challenge was to arrive at a feasible design from tooling and manufacturing. Care was taken to maintain symmetry and balancing of the laminate at all locations.

3 Finite Element Modeling and Analysis

Pre and post-processing of the finite element model was carried out using Hypermesh and solving in MSC/NASATRAN. The structural members like fuselage skin, doublers and stringers were modeled using the CQUAD4 and CTRIA3 with PSHELL property in MSC/NASTRAN. All composite parts were treated as 2D orthotropic layered shell structural elements modeled with PCOMP property in NASTRAN [3]. The fuselage structure was also modeled up to the neighboring bulkhead stations to get the realistic behavior. The FE model of the bulkhead with fuselage is shown in Fig. 3

3.1 Loading and Boundary Conditions

The bulkhead was analyzed for multiple load cases out of which, the pressure case was critical for the bulkhead structure. Therefore, results related to the pressure case alone are discussed in detail in this paper. The analysis for pressure load was carried out by applying ultimate pressure of 0.1 MPa (14psi) normal to the inside surface of the pressure bulkhead and fuselage shell using PLOAD4 option of NASTRAN. All the translational degrees of freedom at the nodes on the forward end of the fuselage skin were constrained in the analysis.

3.2 Material Properties

The unidirectional (UD) carbon prepreg material was used for the fabrication of the pressure bulkhead. The basic properties of the material adopted for analysis are given below.

Composite: E_{11} = 130 GPa, E_{22} = 10 GPa, υ_{12} = 0.35 and G_{12} = 5 GPa

The fuselage skin and stringers were modeled with properties of aluminum alloy.

4 Results and Discussion

From the FE analysis, the deformations and magnitudes of normal stresses (meridional and circumferential) were obtained. The displacement contour is shown in Fig.4. The maximum displacement of 7.51 mm was observed on the dome near the shoulder and cutout region. The stress contours were extracted for the composite parts. In the dome region, the maximum normal stresses in meridional and circumferential direction were nearly equal with a magnitude of 96 MPa, showing a pure membrane action. The failure indices were calculated from the stress output of the analysis based on the Yamada-Sun failure criteria given below.

$$\sqrt{\left[\frac{\sigma_{11}}{S_L}\right]^2 + \left[\frac{\tau_{12}}{S}\right]^2} \leq 1.0$$

where,

σ_{11} = Normal stress in lamina along fibre direction
τ_{12} = Shear stress in lamina
S_L = Allowable stress in lamina along fiber direction
S = Allowable in-plane shear stress in lamina

The maximum failure index observed for the pressure bulkhead was 0.83. The failure index values were less than 1 for the various regions of the bulkhead, thus showing the adequacy of design from the strength point of view. The analysis for other load cases was carried through an integrated analysis with the fuselage of the aircraft. Safety of the composite bulkhead was ensured through these analyses prior to the detailed design and fabrication of the part.

5 Fabrication Methodology

The first step in fabrication was the development of master model using the 'Plaster of Paris'. The advantage of the dome region of the bulkhead being a part of sphere was capitalized. This allowed the development of a single female master segment, from which the required number of splashes for the entire dome were derived using derivative tooling technique. This methodology accelerated the manufacturing process with reduced cycle time. This also ensures a very good accuracy in the tool as only the first female master has to be made very precisely. The female master was casted using hylam templates that were constructed in grid form in order to get the contour accurately. The entire dome surface was created using 9 splashes derived from a single female segment. The challenging task of assembling these segments correctly was achieved through a specially designed base plate with alternate cut outs to position the segments in place.

The fabrication of master model for the ring was complex as its inner contour is a section of a cylinder and outer contour is that of the fuselage. The outer ring had stringent requirements on its contour as this is the mating section of the fuselage. Any deviations in the contour would result in assembly problems. Plaster masters were developed after positioning the templates and the masters were carved manually. Templates were designed in such a way that carving was on one side, thereby optimizing the cost, manpower and the time.

The next task was the assembly of the ring segments with respect to the dome. A base plate for assembly was designed to accurately position and locks the dome segments. Fig.5 shows the segment of dome master and ring masters assembled in base plate kept on the surface table. Subsequently, the tool return flanges were constructed using wooden boards cut into smaller widths to facilitate circular formation. The assembled master model is shown in Fig.6. A composite outer tool was fabricated using the master model.

Cores/pressure intensifiers play an important role in cocuring technology. There are multiple ways of deriving these tools. One of the tooling concepts is to have a rigid tool one side and a flexible tool on the other side. This "Master-Slave concept" provides uniform pressure distribution and consolidation of the layers during curing [4]. The other concept is to achieve consolidation through controlled thermal expansion of the tools. The expansion of the tool itself is sufficient to provide the required pressure during curing. Both concepts were adopted to realize the pressure bulkhead. The master-slave concept was adopted for the forward side of ring and thermal expansion concept was adopted for the aft ring. The master-slave concept was not possible for the aft ring as it was enclosed in the mould cavity, where all sides are surrounded by rigid tools. These tools were realised using the derivative tooling technique by a mixture of aluminum powder and tooling resin in a definite proportion so as to ensure the required expansion at the curing temperature [5].

During the part manufacturing, the cores have to be assembled along with the basic skin after the lay-up, The most difficult task was to synchronize the web location of forward and aft gussets as they get attached with fuselage stringers on either side. When the aft cores were placed in position, the gussets could not be seen as the cores were already enclosed in the mould cavity. This problem was solved by a specially designed template that precisely aligned the forward cores with respect to the aft cores. Fig.7 shows the component in bagged condition before curing in the autoclave. Using these tools, the component was fabricated. The cured composite pressure bulkhead is shown in Fig.8. The part was subjected to dimensional inspection and non destructive inspection (NDI). The part met all the dimensional requirements and was found to be defect free.

6 Certification

The structural strength substantiation was planned as per industry standard building block approach in two levels [6]. In the first level, the segments at the joint between bulkhead ring and the dome were tested. The objective of the test was to prove the structural integrity of the joint between dome and bulkhead ring. Test segment was conceptualized as shown in Fig.1. The geometry details of the segment are shown in Fig. 9. The segment width was kept equal to the spacing of the gussets in the ring. The joint was designed by simulating the layup sequence and the thickness as in the bulk head. The angle between the dome and the inner flange was maintained as in the structure. The curvature in the ring was not considered in the segment for the sake of simplicity. This does not however, affect the behavior of the joint greatly. The forward and rear ends of the gussets were provided with attachments which were similar to stringers in the fuselage. In order to simulate the continuity of the web of I section, either ends of the web were provided with hinge type of attachments.

The joint segments were tested for three critical load cases experienced by the fuselage. They are 1. Cabin pressure load 2. Cabin pressure load plus critical fuselage bending load and 3. Fuselage bending load. The first load case is simulated by applying a tensile load on the dome end which will generate equivalent membrane stresses at the joint due to the cabin pressure. The forward stringer end and web ends were fixed in this case. The rear stringer end was free. The specimen was loaded to failure. In the second load case, the cabin pressure load was applied at the dome end and the fuselage bending load was applied at the rear stringer end. This specimen was loaded to failure during the test. Figure 10 shows the photograph of the test setup. In the third load case, the fuselage bending load was applied at the rear stringer end. The forward stringer end was fixed and the dome end and web ends were kept free for this case.

The segments withstood the design ultimate loads (DUL) in all the tests proving the integrity of the joint. Fig.11 shows the failure mode of the segment for the second load case. The segment withstood up to 370% of the design limit load. Currently, the preparations for the full scale test are in progress, wherein, the part would be subjected to the critical case i.e. cabin pressure load up to DUL by pressurizing a fuselage segment. Strains and deflections would be monitored during the test at relevant locations and correlated with FE predictions. Successful completion of the test would qualify the pressure bulkhead for assembling to the fuselage for flight trials of the aircraft.

7 Concluding Remarks

The design of an integrally made composite pressure bulkhead was discussed. The advantages of such construction in terms of reduction in number of parts, joints, assembly process and reduced weight were demonstrated. The design posed a challenge to bring continuity of layers across the shell and the bulkhead ring. A novel way of lay-up scheme was used in the shell, ring and the gussets to cater for the main load path. The stress analysis carried out using FEM showed that the structure met the strength and stiffness requirements. A substantially 50% lower weight is achieved compared to a conventional stiffened metallic pressure bulkhead.

The efficacy of tooling and manufacturing methodology adopted were demonstrated through realisation of part which met dimensional and NDI requirements.

The structural strength substantiation was through tests at feature level for the joints supported by FE analysis. The first level of structural tests was successfully completed on segments with adequate margins to ensure the capability of the part to transfer load at the joints. The full scale test is planned on the rear pressure bulkhead which is in progress.

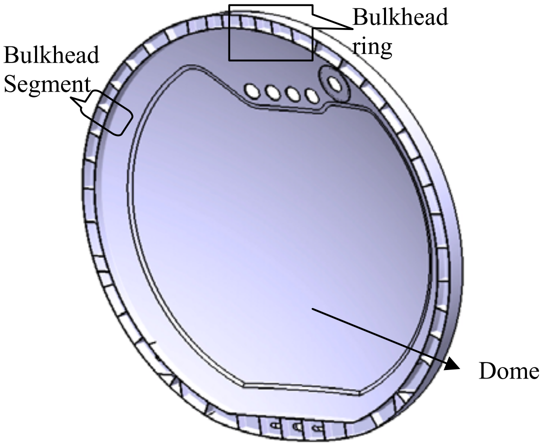

Fig.1. Geometry of the pressure bulkhead

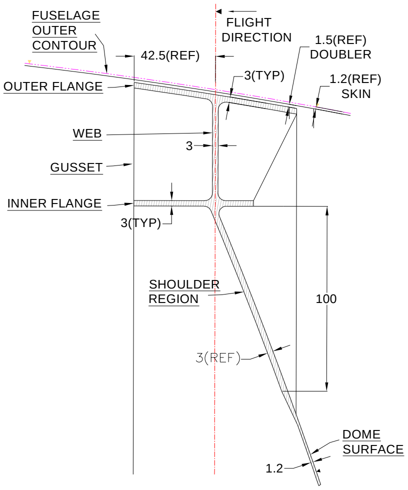

Fig.2. Sectional View of the Bulkhead Ring

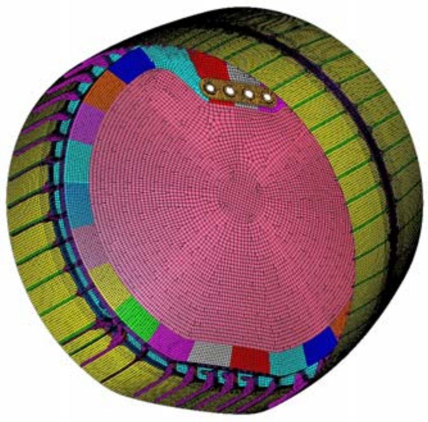

Fig.3. FE model with Fuselage Skin

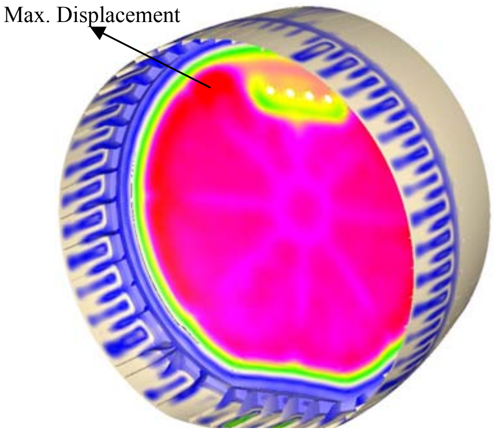

Fig.4. Displacement Contour

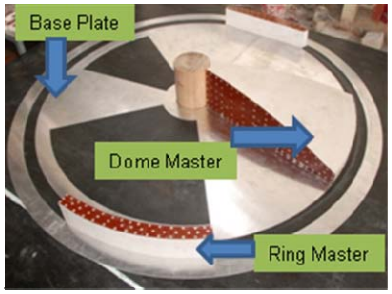

Fig.5. Assembly of master model on base plate

Fig.6. Assembled view of master model before tool layup

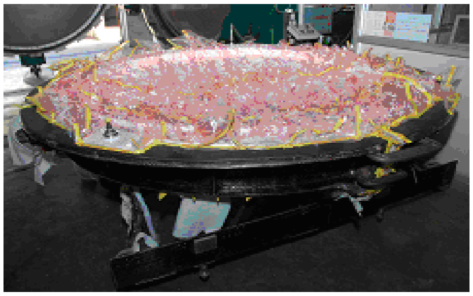

Fig.7. Component before curing

Fig.8. Cured Component

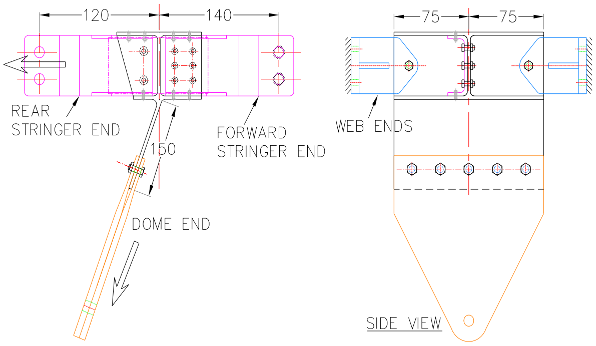

Fig.9. Geometry of the test segment

Fig.10. Photography of the test

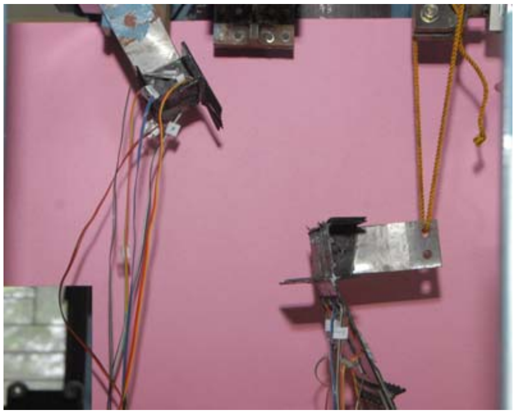

Fig.11. Failure mode of the pressure bulkhead segment

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