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Qualification of Upper Stage Composite Rocket Motor Casing

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Abstract—*Qualification approach of upper stage Composite Rocket Motor Casing (CRMC) fabricated by Filament winding methodology is presented in this paper.The Qualification and validation of CRMC as a system to a level of flawlessness begins with stringent quality requirements for manufacturing as there are no standard procedures available.This paper also discussesan insight of various stringent quality control requirementsat each and every stepprogressing right from raw materials to in-process checks/inspections during manufacturing and final component acceptance/qualification test, which are important for process improvement leading to reliability enhancement, cost reduction, and schedule optimization. Design validation starts right from the selection of composite raw materials by characterizing their physical andmechanical properties and entire cycle of processing where there is no scope for post corrective action for any major non-conformance condition.The mechanical and physical properties thus obtained from material characterization will define the basic material properties required to be considered for design.The results obtained arealso utilized to understand structural characteristics of filament woundpressure vessels with integrated end domes.Based on our experiences during the development of different configurations of CRMC's and subsequent results of non-destructive testing (NDT), Acceptance & Qualification testing a conclusion is arrived at on the effectiveness to realize consistent quality products.*

Keywords*: Acceptance test, Burst Test, Composite Rocket Motor Casing, Filament Winding, Non-Destructive Testing, Proof Pressure Test, Qualification Test, Static Test and Structural Load Test.*

1. INTRODUCTION

A rocket motor casing is basically a pressure vesselwith two end domes designed to withstand high pressures.A typical rocket motor casing alsoincorporates an integral fore and aft end skirt attachments.

Composite materials withtheir higher specific strength, specific modulus and strength tailoribility characteristics willresult in reduction of weight of the structure. The choice of composite as primary material in design and manufacturing of the casing is dictated by the fact that the performance factor ('n' = *PV/W*) is consistently higher for composite casings as compared to that of metallicones. The casing is insulated internally by nitrile based rubber to protect from hot combustion gases.

The key aspects of Quality Assurance which are involved and of great importance during the entire manufacturing cycle & various mandatory acceptance/ qualification testing are discussed in this paper.As the realization of CRMC is process dominant, a greater focus is placed on understanding and controlling the critical process parameters which affects the overall quality of CRMC [3].

The upper stage CRMCis designedto achieve increase volume of propellant, better specific impulse, weight saving (strength tailoribility, higher specific strength & modulus, versatility of filament winding), higher manufacturing rate, no stress corrosion cracking,lower Factor of Safety (FOS)and higher performance factor. Full scale burst test, structural load test and static tests are done to evaluate design adequacy and to demonstrate fabrication concepts.

The overall qualification approach is divided into three categories - Material characterization, In-process tests and Full-scaleAcceptance Test (AT)&QualificationTest (QT).

2. BRIEF ON CONSTRUCTION DETAIL AND DESIGN ASPECTS

2.1 Construction Details

The general arrangement of casing comprises of

a) **Composite Casing**
It takes primarily the internal pressure load.

b) **The Encapsulated Metallic Polar Boss**
The metallic bosses reinforce the vessel ends whereas, the encapsulating rubber accommodates the differential deformation between metal and composite.

c) **Igniter & Nozzle end Skirt Sub-assembly**
Studs are provided for fastening to respective airframe sections at both ends.To prevent galvanic corrosion on aluminum bulkhead, an in-situ protective layer of E-glass/epoxy is provided. Typically, a combination of shear-plies of nitrile based rubber is laid-up around the skirt at the Y-joint. Skirts are realized and analyzed for axial compression & Bending moment.

d) Y-Joint

Transmission of thrust load between skirt and casing is through the shear ply. The proportion of the load shared by shear ply depends on stiffness of the casing & skirt andshear stiffness of the shear ply.

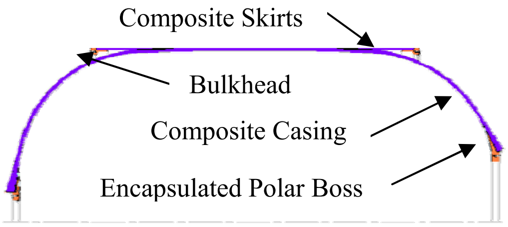


Fig. 1: Schematic View of CRMC

2.2. Design

Helical winding together with hoop winding& doily, is the processing technique adopted for realization of the casing and the skirts at two ends are made by filament winding and fabric lay-up process. Doily are made either from a unidirectional fabric or through drum wound hoop layers. Different types of loads acting on the casing are internal pressure, structural loads and thermal loads. Further two basic requirements are to be satisfied by the casing i.e. pressure containment and shape containment of the end grains.Pressure containment is taken care by the inside rubber lining & polar bosses (PB)and shape containment of the end grains is taken care by providing loose flaps in the rubber lining. The preliminary design is performed using netting analysis method to address the inner pressure loading.

2.3. Modes of Failure

a) Composite Casing: Hoop & Helical fiber failure, Compressive strength failure and Buckling.
b) Composite skirts : Compressive strength failure and Buckling.
c) Polar Boss Joint : Boss Blow-out & Excessive stress in metal/rubber.
d) Y- Joint : Strength failure of composite and Bond failure.
e) Bulkhead joint: Composite bearing failure & Fastener failure.

3. RAW MATERIAL

Development of composite casing use a host of different raw materials including high performance advanced composites and conventional metal materials viz. aluminum alloy.

3.1. Composite Raw Material

Higher grade of carbon fiber and toughened epoxy resin with suitable hardener having longer gel time, suitable for multiple cure cycles and better mechanical properties are selected for this casing. This cured resin system has a glass transition temperature of 165°C.

Naval Ordnance Laboratory (NOL)ring samples are fabricated to simulate the effect of winding parameters on mechanical properties during raw material testing and it is also made as travel coupon during realization of CRMC as a tool for quality control. Each lot of reinforcement& resin system are tested as per the specified sampling plan for below mentioned properties for acceptance and further usage.The following tables (Table 1 & 2) show the technical specifications of compositeraw materials used in realization of CRMC.

Table 1: Technical Specifications of Carbon Fiber

Sl. No.	Property	Specified Value/ASTM Standard
1.	Impregnated tow tensile strength,GPa	3.0 (min)/ ASTM D 4018
2.	NOL ring tensile strength (MPa)	2000 (min)/ ASTM D 2290
3.	Inter laminar shear strength (MPa)	70 (min)/ ASTM D 2344

Table 2: Technical Specifications of Epoxy Resin

Sl. No.	Property	Specified Value/ASTM Standard
1.	Epoxy resin Viscosity, CPs	14000-18000 ASTM D 2393
2.	Sp. gravity	1.1-1.2 ASTM D 891
3.	Hardener Viscosity, CPs	140-200 ASTM D 2393
4.	Sp. gravity	1.0-1.1 ASTM D 891
5.	Gel time at 100°C	120 (min) for an established mix ratio ASTM D 2471

3.2. Conventional Metals

Igniter End (IE)& Nozzle End (NE)Polar bosses are made of AA2014 aluminum alloy with 15-5 PH steel (H-1025 condition)inserts. This CRMC also has two end metallic rings connected to skirts called bulkheads(BH)(AA2014Aluminum alloy) which give way to attach the subsequent stages.

Table 3: Technical Specifications of AA2014 Aluminum Alloy

Sl. No.	Parameter	Specified Value
1.	Young's Modulus	70000
2.	Poisson's ratio	0.3
3.	UTS (MPa)	470

Table 4: Technical Specifications of 15-5PH Inserts

Sl. No.	Parameter	Specified Value
1.	UTS (MPa)	1069 (min)
2.	0.2% PS (MPa)	1000 (min)
3.	Elongation (%)	12 (min)

3.3. Material Characterization

The design of composite structures unlike that of metals goes hand in hand with design of material system. The selection of the materials and process option for various parts of CRMC is done simultaneously [3].The composite materials selected shall be evaluated with respect to materialprocessing, fabrication methods,operating environments and other pertinent factors that affects the resulting strength & stiffnessproperties in fabricated configuration.

Flat plate laminates are madefor material characterization and to determine physical properties like resin content and fiber volume fraction (V_f).For minimum characterization of a unidirectional composite, four independent elastic constants are determined namely elastic moduli in longitudinal and transverse directions, in-plane shear modulus, major Poisson's ratioand five independent strengths namely tensile and compressive strength in longitudinal & transverse directions and in-plane shear strength [3].Following elastic constantsand strengthsas determined experimentally are considered for design.

Table 5: Properties Evaluation of Composite Raw Material

Sl. No	Carbon/ Epoxy Composites	
1.	UD Laminate Properties	Tensile Strength & Modulus (E11) for various Vf (50-60%) were evaluated and found to be in the order of 2000 MPa & 110-130 GPa.
2.	Compressive Strength	In the order of 800 (MPa)
3.	Poisson's Ratio µ12	In the order of 0.28-0.29
4.	Shear Strength σ12	In the order of 50 (MPa)
5.	Shear Modulus G12	In the order of3-5 (GPa)

In view of the critical nature of this system it is imperative that a detailed Quality Assurance Plan (QAP) is essential for raw material to ensure consistent performance.

4. TOOLS, FIXTURES &EQUIPMENT'S

The composite fabrication requires simultaneous consideration of various parameters such as component geometry, production volume, reinforcement & matrix types, tooling requirements, and process. Tool shall facilitate manufacturing of accurate repeatable part within the confines of process parameters and detail performance characteristics meeting the end requirements. The following are such tools/fixtures used in realization of CRMC.

a) Mandrel Assembly for main casing.
b) IE & NE polar boss sub-assembly Encapsulationmoulds.
c) Mandrel for IE & NE skirt sub-assemblies.

Mandrel consists of a steel shaft which provides features for holding both end metallic polar bosses and skirt winding fixture accurately. The selection and design of mandrel should facilitate forproduction reusability, tolerance required, thermal expansion control, weight saving, deflections like sagging, part removal from mandrel [3].Rigid polyurethane foam discs are assembled on the shaft over which Plaster of Paris is laid.

The machinery/equipment's required for realizing different parts and sub-assemblies/assembly are filament winding machine, oven & related instrumentsand Computer Numerical Control (CNC) lathe. All the tools/fixtures are inspected for critical dimensions, geometrical tolerances and profiles along with the review of calibration status, test reports for material and critical process in order to accept the tools/fixtures.

5. MANUFACTURING OF COMPOSITE ROCKET MOTOR CASING

The upper stage CRMC consists of following sub-assemblies.

a) Igniter & Nozzle end Encapsulated Polar Boss sub-assembly.
b) Igniter & Nozzle end Skirt sub-assemblies.
c) Casing sub-assembly.

5.1. Development Cycle

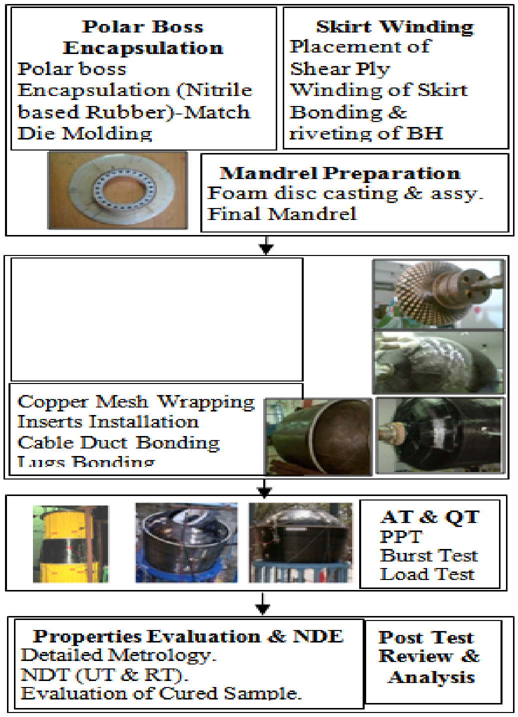


Fig. 2: Development Cycle of CRMC

5.2. Quality Methodology

Close review, meticulous monitoring and stringent quality control is carried out during the transformation of motor casing from design phase to realization phase. The various quality requirementswere documented emphasizing various critical stages during manufacturing.Raw material traceability, its clearances, antecedents and Shelf life are ensured at the time of usage.

5.2.1. QA Requirements for Sub-assembly/ assemblies.

a) Casing

- At first mandrel dimensional & profile inspection are carried out with certified templates.
- Calibration status of all the instruments areverified.
- Validated & verified winding program is used and efforts are made to reduce the total winding duration.
- Resin bath is heated to 50±5°C& viscosity is measured at regular intervals to control the resin pick up.
- Fiber placement, fiber tension, fiber damage and fuzzing aremonitored and regulated.
- Excess resin is squeezed out manually after each layer without disturbing the fiber pattern.

b) In-Situ Skirts

- Validated&verified ply sequence is followed.
- During machining of sacrificial layers sufficient care is taken to not cut any helical layer.
- Shear ply dimensionsareensured at the time of assembly.
- Riveting iscarried out as per established procedure.

a) Polar Boss & Bulkhead

- Metallic hardware'sare machined as per approved QA plan.
- Dye penetrant test and annodizationare carried out onall componentsas per approved plan
- Detailed dimensional &geometrical tolerances are measured, if any deviations found due to process variations,are analyzed functionally for its end implication from system point of view.
- Self-locking helical thread inserts are provided on end bosses.

b) Polar Boss Encapsulation

- Verified encapsulation moulds&cleared template is used for rubber cutting.
- Validated & verified vulcanization cycle,ply sequence & properties of the rubber used.
- Dimensional & Ultrasonic Test (UT)are carried out and Hardness achieved on cured rubber is measured.

5.3. Component Level Inspection & Acceptance Testing (Proof Pressure Test-PPT)

5.3.1. Component Level Inspection.

a) AverageTensile strength observed is in the order of 2100Mpa.

b) Samples cut from the travel coupon are evaluated for the following properties which are shown below.

Table 6: Properties Evaluation of NOL Ring

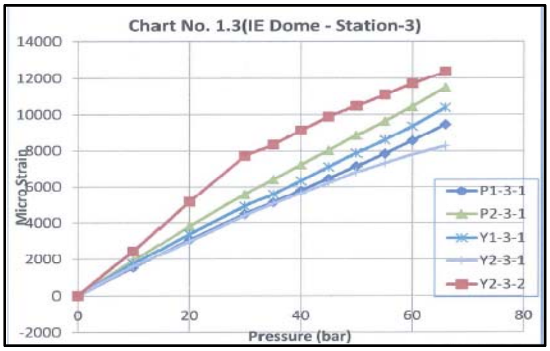
Sl. No.	Parameter	Average Tested Value
1.	Density g/cc	1.52
2.	Resin content (% by weight)	30
3.	Fiber content (% by weight)	70
4.	Fiber volume fraction (%)	60
5.	Glass transition temperature (oC)	165
6.	Degree of cure	No exotherm peak

c) V_f is affected by process parameters such as fiber tension, viscosity of resin system, winding time, number of starts and number of spools. The above parameters are established to achieve desirable V_f. These parameters becomesthe basis for laying down the process quality requirements [3].

d) Detailed metrology inspection is carried out on the casing to measure all the dimensions & specified geometrical parameters before and after PPT [3].

e) Through transmission UT and X- Ray Radiography (RT) are carried out as part of NDT on the casing & critical Y-joint to identify de-bonds, delamination's, resin rich & resin starve areas and results are plotted [3]. Both UT & RT are complimentary to each other and shall be done as a part of Acceptance Test Procedure (ATP) on every casing before and after PPT to ensure its health.If any deviations found, additional gauges shall be provided & monitored during PPT and observe for any changes with previous values.

5.3.2. Proof Pressure Test. PPT is done for each casing up to Established FOS X Maximum Expected Operating Pressure (MEOP)as a part of acceptance planto validate the quality of workmanship [1] and to prove the structural integrity, as safety margin is very low. All the motor casing interfaces & primarily seals shall be leak proof. PPT is carried out with instrumentation viz. Strain gauge and Linear Variable Differential Transducer (LVDT) at specified locations as per approved test procedure to measure the strains, deformations/dilations at various locations up to proof pressure.Torque relaxation check iscarried out to evaluate the joint adequacy.The test results are shown below.



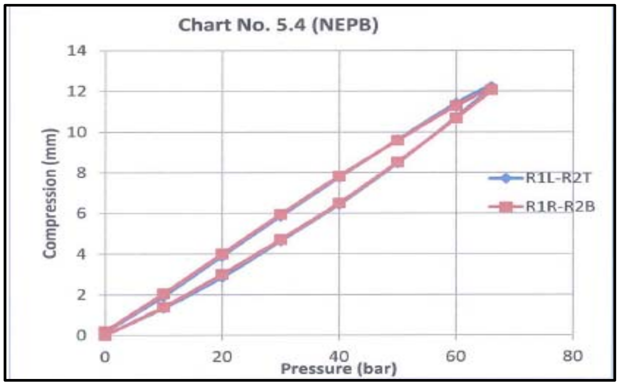


Fig. 3: Proof Pressure Test Results

The hoop strain @ proof pressure is observed to be in the order of **12000 µstrains** in IE Dome portion and a maximum deformation of **11 mm** on NEPB. The strains observed are within the limits and FOS is calculated.

6. QUALIFICATION TESTING

Launching any strategic vehicle is a single shot operation and every component that goes into this system is required to have a very high order of reliability to achieve a successful mission. Hence, it is highly imperative to test & qualify motor casings on the ground simulating various load conditions that are encountered during their flight. CRMC's are subjected to elaborate qualification tests as their reliability requirements due to low FOS are higher than booster stagesto take the advantage of higher performance factor and more gain in term of range & payload capability [1].

The tests to be conducted under qualification tests are as follows.

a) **Structural test -** axial compression plus bending moment up to design level; Established FOS X MEOP.
b) **Burst test -** internal pressurization up to burst level; up to Burst.

6.1. Structural Load Test

DESIGN LOADS

Casing is qualified for various structural loads encountered during flight/handling/transportation. The critical load casesconsidered for design qualification aregiven below.

a) **Design axial force, F = Established FOS X Axial Force**
b) **Design bending moment, M = Established FOS X Bending Moment**
Load test for axial force & bending moment for casing subject the skirts to severe compressive stress & buckling environment and same is considered as qualification test for the skirts [2]. During the test casing is placed in a vertical test rig and a compressive load is applied with actuators. For uniform distribution of the concentrated loads on to the casing steel shells are used at the ends. During load test strains, dilations are monitored at different critical locations and compared with predicted values. The following are the different load cases.

Table 7: Load Cases for Structural Load Test

Sl. No.	Possible Load Cases	
1.	Case I	Pure bending moment
2.	Case II	Combined bending moment
		Axial Force (compressive)
3.	Case III	Axial Force (compressive)
4.	Case IV	Axial Force (tensile)

6.2. Burst Test

The casing shall be pressurized to the design burst pressure level and subsequently till it bursts.The casing shall not burst or prior to the end of the hold time (min. 5 sec). Upon successful completion of the hold period, the pressure is increased at a controlled rate until casing got burst and the strains & pressure values are recorded. The maximum hoop strain observed isin the order of **19000µstrains** in NE Dome region. Failure is observed near NE composite.After burst test, samples were cut from various loactions of the casing and analyzed for properties like $V_f$andbond strength between lining & casing.Analysis is re-done based on the test results achieved & subsequently matched with the design and found to have a strong correlation.

6.3. Static Test

During static testvarious ballistic parameters are measured along withstrains and dilations at different critical locations as per static test plan.

After successful completion of all Qualification tests, same configuration was successfully used in flight test and strains/dilations were recorded and comparable with prediction.

Fig. 4: Static Test Set-up

7. CONCLUSION

The upper stage CRMC being critical in its shape and size requires special attention during its transformation from design phase to its realization. Quality Implementation plays a crucial role to achieve consistent quality as composites are highly process dominant.The new design callsfor detailed qualification tests to prove the casing design adequacy. Any changes implemented during the manufacturing of the casing in its developmental phase shall be well documented and same shall be laid down in the quality plan.The optimized parameters shall become the basis for laying down quality requirements and same shall be stringently monitored to obtain a healthy casing.After repeated and satisfactory completion of all the QT, both design & process are frozen and henceforth each casing shall be subjected to pressure test only.Experience gained during manufacturing have shown that casings can be realized with consistent quality using high strength composite material which leads to higher performance factor. Such a caseallows to save up to 30 to 40 % of the inert mass while increasing the MEOP marginally, thus allowing to attain a better specific impulse.

8. ACKNOWLEDGMENT

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