International Journal of Mechanics and Solids.
ISSN 0973-1881 Volume 12, Number 1 (2017), pp. 125-138

http://www.ripublication.com/ijms.htm

A Review on Material Selection and Fabrication of Composite Solid Rocket Motor (SRM) Casing

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Abstract

During world wars many innovations are came into existence in the world. These wars has all along provided a sudden movement to scientific research and technology innovations. Rockets and Missiles are used to destroy enemy aircrafts, tankers etc.., At first Solid Rocket Motor (SRM) casings are made of metallic materials, which are more in weight. For decreasing the dead weight of missiles and rockets we can use newer & lighter materials in the construction of the missile system which are composite materials Composite Materials have extensive engineering application where strength to weight ratio, low cost and ease of fabrication are required. A review of technical research on composite materials used in the manufacture of solid propellant missiles has been conducted. This paper presents a review of the current status of composite solid rocket motor casing materials technology, in terms of materials available and properties, fabricating methods of composite casing, loads over cases and non-destructive inspection techniques

Keywords: Rockets, Metallic, Solid Rocket Motor, Motor Casing, Composites, Non-destructive techniques

1. INTRODUCTION:

Solid rocket motors (SRM's), Fig.1., are used in launch vehicles, missiles, and spacecraft. In a solid propellant rocket, the propellant to be burnt is contained within the combustion chamber or in case [1]. The propellant charge or the grain contains the chemical elements for complete burning. Once ignited, it burns at a designed rate till the propellant is completely consumed. Solid rockets are relatively simple as compared to the other systems.

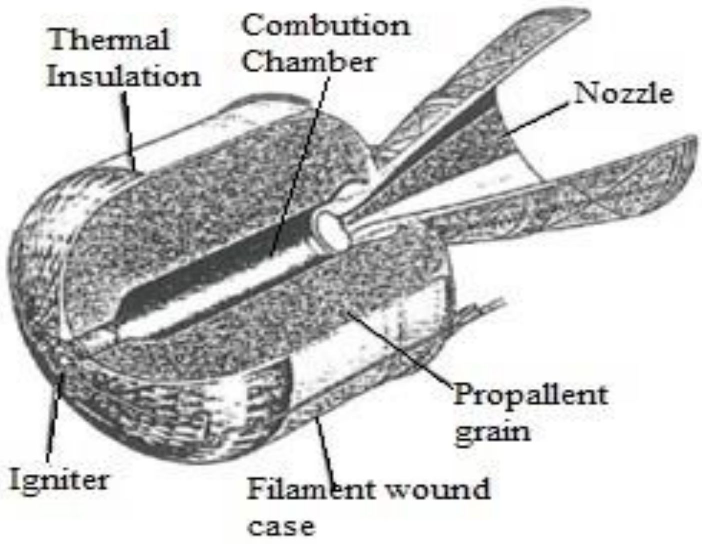

Fig. 1. Solid Rocket Motor

2. PRINCIPLE OF OPEARTION AND COMPONENTS OF SRM

2.1 Principle of operation of SRM

Initially the propellant is ignited and it burns at a rapid rate producing gases. These gases develop pressure inside the combustion chamber and this pressure force the gases to pass through the only exit available, which is the nozzle. Nozzle first reduces the area of exit in order to increase the velocity of exhaust gases and gases reach supersonic velocity at the nozzle throat. Now the area is increased to further increase the velocity, as according to supersonics increase in area produces increase in the velocity.

2.2 Components of SRM casing

Propallant Grain in Fig.2., have fuel and oxidiser mixed together in a suitable proportion. Finished propellant body called grain have rigid shape and form as per design. This shape is obtained by casting or extrusion under pressure. Propellant grains may vary in size depending on application.

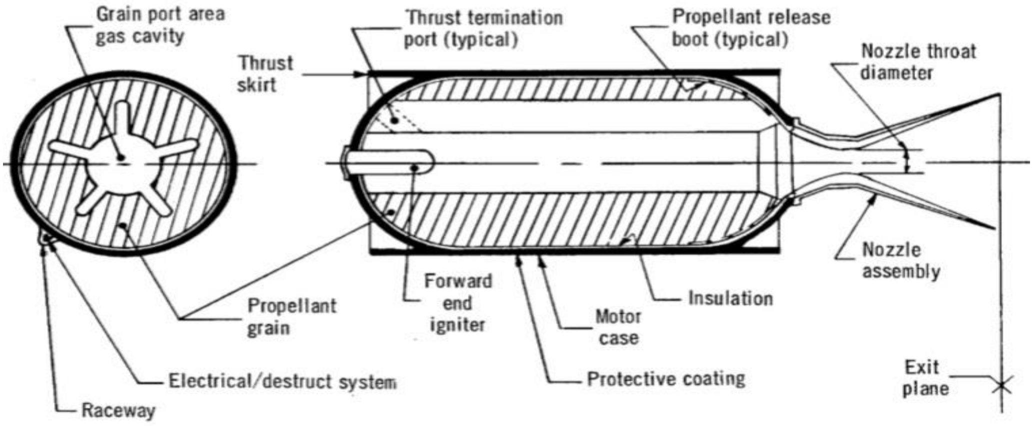

Fig. 2. Components of Solid Rocket Rocket Motor (SRM)

Igniter is the device that helps to start the burning of the main propellant grain of the rocket motor. Its function is for short interval (0.1-2 seconds depending upon size) only but vital. The igniter for small motors will be a few grams of grains while it will be a few hundred kilograms for large boosters. The initiation is done using electrical power by heating a resistance wire and initiating a primary composition.

The nozzle is the component through which the hot gaseous mass in the motor case is expelled out. This has to be designed to withstand high temperatures and flow of gases at high velocities. The dimensions of the nozzle are critical for the performance and efficiency of the rocket motor. Nozzles are also used for producing control force for the missile.

3. SRM CASING

In all solid rocket motors, the casing is a pressure vessel designed and fabricated to withstand up to certain internal pressures [2]. Case design is usually governed by a combination of motor and vehicle requirements. Besides constituting the structural body of the rocket motor with its nozzle, propellant grain, and so on, the case frequently serves also as the primary structure of the missile or launch vehicle. Thus the optimization of a case design frequently entails trade-offs between case design parameters and vehicle design parameters [3].

Generally, Casings are made of metallic alloys. For applications in smaller rockets, titanium alloys and aluminium alloys are used and for bigger rockets nickel alloy steels are used [4]. They are fabricated to give cylindrical shells with ends flared for joints. Complex welding and heat treatment fixtures and processes have been specially evolved for specific casing. The casings are subjected to a number of quality assurance tests for strength, toughness, soundness of weld and hydraulic pressure. The casings are provided with thermal insulation on their inner surface to protect them from hot gases. The casing has provisions for end covers, nozzle and handling, etc.

Casings can also be made of a composite material such as fibre reinforced plastic (FRP). Such a casing has low weight and high strength.

NASA SP-8025 [5] provides that basic motor case design will be based on motor, vehicle and mission design parameters which results in maximum performance and maximum cost effectiveness. The basic case-design parameters include case internal pressure, motor case inertia and flight loads, maximum case limit, length-to-diameter ratio (l/d ratio), propellant mass fraction, internal and external envelope constraints. l/d ratio influences the capability of holding these loads. With l/d ratio b/w 2 to 5 will gives the best case design. The increase in the values of l/d ratio produces a long vehicle violates constraints and result in severe case buckling and bending problems. When the case parameters are not specified the case design selection will be depend on most influencing parameters motor internal pressure, thrust loads and loads resulting from particular motor. Propellant Mass Fraction Parameter is the measure of motor design efficiency and defined as ratio of mass of initial propellant to mass of total motor. For SRM it varies from 0.3 to 0.96 (PMFP).

Following are main considerations to be done in casing design. The case end closure shall be the minimum size and optimum shape required to satisfy propellant grain design and clearances for auxiliary equipment. The minimum mechanical properties of the case material shall not be less than needed for structural loading at the critical operating temperature, as imposed by fracture mechanics theory and design safety factors. The material strength to density ratio shall result in a case with in the weight limit defined by the required propellant mass fraction for the motor. Case materials shall not experience brittle and ductile failure at a case loading less than the design load. Case-material mechanical and physical properties shall be within established design limits after exposure to the intended fabrication process. The case material shall withstand any harmful environment encountered during fabrication, processing, storage and service and also withstand the thermal, moisture, corrosive effects etc., The case material shall with stand both low and high-cycle fatigue induced either by the predicted thermal cycling, by the predicted pressure cycling or by the worst combination.

The case loading profile includes all individual design loads or the combination of design loads such as Attachment loads (Motor Igniter, Single or Multiple Nozzles, Thrust-vector-control System, Motor Thrust Skirt, Clustering Structure, Motor Staging, Thrust-Termination or Thrust-Reversal Hardware, Aerodynamic Control Surfaces, Instrumentation, Electrical and Destruct-System hardware), Internal Loads (Internal Pressure, Axial Thrust, Thrust Misalignment, Thermal Stress) and External Loadings (Ground Handling, Launch Pad Loads, Flight Loads). The case design Stress shall not exceed the allowable stress, whether yield or ultimate: and the maximum deflections shall not exceed allowed deflections. The case fabrication shall be most reliable, least time consuming and cost effective. The fabrication shall not produce undesirable effects. Destructive Testing and Non Destructive testing (Inspection Plan, Inspection Process, Hydrostatic Proof Test).

4. MATERIALS IN SRM CASING

The selection of materials for SRM components is done on the basis of high specific strength, high specific modulus, fabrication easiness, easy availability, critical requirements and service conditions [6] shown in Fig.3. The classification of materials of rocketry are shown in Fig.4., as follows structural metallic materials, composite materials, thermo-structural materials, thermal protection materials, special materials and chemicals. Table 1 depicts different materials and their applications in SRM casing.

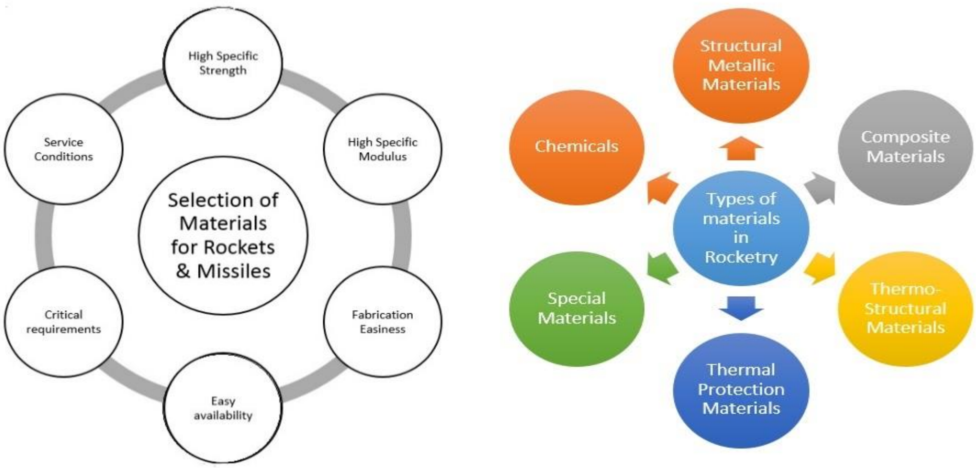

Fig. 3. Selection of Materials and Types of materials used in Rocketry

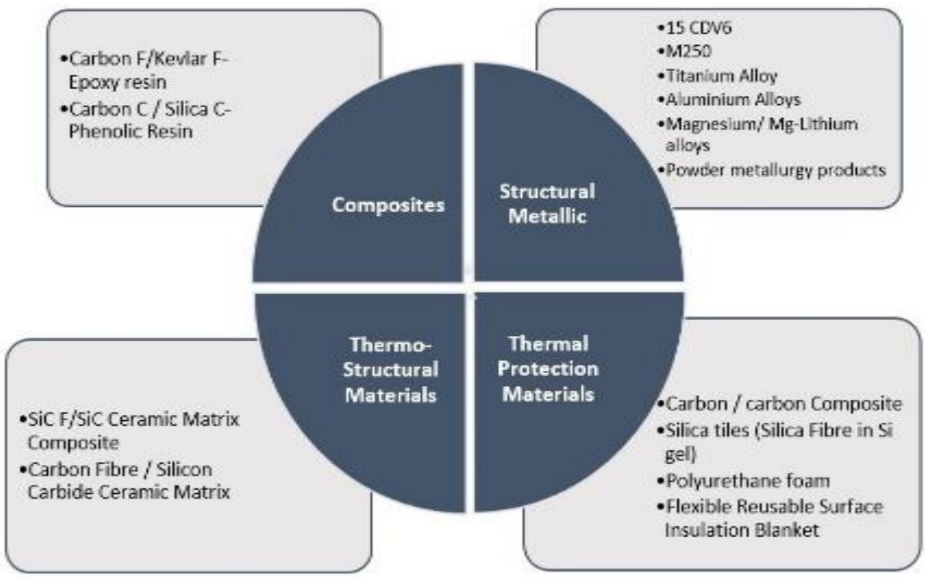

Fig. 4. Classification materials in SRM casing

Table 1- Different materials and their applications in casings

S.No	**Material(s)**	**Application**
1.	Low case Carbon Steel (15 CDV6)	Used in solid rocket motor case
2.	Maraging Steel (M250) with high strength and high toughness	Used in booster solid rocket motor case
3.	Titanium Alloy (Ti-6Al-4V)	Used in high pressure gas bottles
4.	Aluminium Alloys (AA 2219, AA2014, AA6061)	Used in liquid propellant tanks, engine Components, airframe in reusable Launch vehicles.
5.	Magnesium/ Mg-Lithium alloys	Used in upper stage structure like payload adopter, avionic decks, equipment bay structure.
6.	Carbon F/Kevlar F- Epoxy resin	Used in solid motor case, pressure vessel, inter stages, payload adopter.
7.	Carbon Fibre / Silicon Carbide Ceramic Matrix	Used in nose-cap of heat-shield, leading edge and control surface of Rocket Launching Vehicle (RLV)
8.	SiC F/SiC Ceramic Matrix Composite	Used in high temperatures / hot structures
9.	Silica tiles: (Silica Fibre in Si gel)	used in space shuttle and SRE (capsule) mission
10.	Different coating materials	Used for protection and imparting certain characteristics to surfaces, potting of connectors

George P. Sutton et.al. [7] mentioned that certain metallic casings have stress-corrosion cracking problem which can result in spontaneous failure without any visual evidence of impending catastrophe. Importance given to lightweight thin metal cases aggravates stress corrosion and crack propagation, often starting from a flaw in the metal, with failure occurring at a stress level below the yield strength of the metal. Composites are used for the cases and their principal advantage is their lower weight

S.T. Peters et al. [8] compared different motor case materials with composites shown in Table 2.

Table 2 - Different Materials and their applications in Casing

	D6AC Steel	Maraging steel	Glass-filament composite (s-2)	Organic-filament Composite (Kevlar)	Intermediate-modulus polyacrylonr carbon fiber
Tensile strength, (MPa)	230 (1586)	250 (1724)	170 (1172)	120 (827.4)	225 (1551)
Density, g/cm3	489 (7.883)	499 (8.00)	124 (1.993)	85 (1.356)	97 (1.550)
Strength/ density	202.5	215.5	588.1	610.2	1000.6
Modulus, 10^6 Gsa	29(199.5)	27 (189.1)	5 (31.72)	11 (75.84)	25(172.4)

5. COMPOSITE MOTOR CASING

Composite materials are widely used in SRM's because of their intrinsic material characteristics, such as high strength-to weight-ratio, high thermal resistance, and ability to be tailored for a specific application [9]. They are primarily used for structural components such as solid rocket motor casings, inter stages, nose cones, nozzle support structures and nozzle insulators. While these materials exhibit better performance than metals, they often require advanced analytical methods to characterize their behaviour under complex mechanical and thermal loading environments. They are also susceptible to developing defects or damage during manufacturing, storage, handling and transportation.

The choice of composite materials for rocket motor case is done by using higher performance factor, N which is defined as **N = P V/ W** where P = internal pressure, V = internal volume W= weight of the motor case. By comparing performance factors of different isotropic and composite materials the composite materials have the good value of performance factor.

Table 3- Comparision of Performance factors of Isotropic and Composite Materials

Parameter	Isotropic Materials			Composite Materials (Epoxy resin)			
	7075-T6 Aluminum	**D6AC Steel**	**6 Al, 4V Titanium**	**E-Glass**	**K-49 Kevlar**	**T-300 Carbon**	**T-1000 Carbon**
Performance factor (km)	7.0	9.5	9.0	4.0	12.0	11.0	25.0
Mass per unit length(Kg/m)	360	290	295	650	220	250	100
Wall Thickness(mm)	22	6	11	44	26	21	11

Devon K. Cowles [10] designed a ground launched rocket booster to meet specific mission requirements viz., minimum speed and maximum flight altitude. The motor parameters such as nozzle size, expansion ratio, propellant size and shape are determined through an iterative process. The initial motor casing design made of a light weight casted aluminum later compared to a design made of a fiber and resin composite material. Composite casing has more flight performance than Aluminum casing shown in Fig.5.

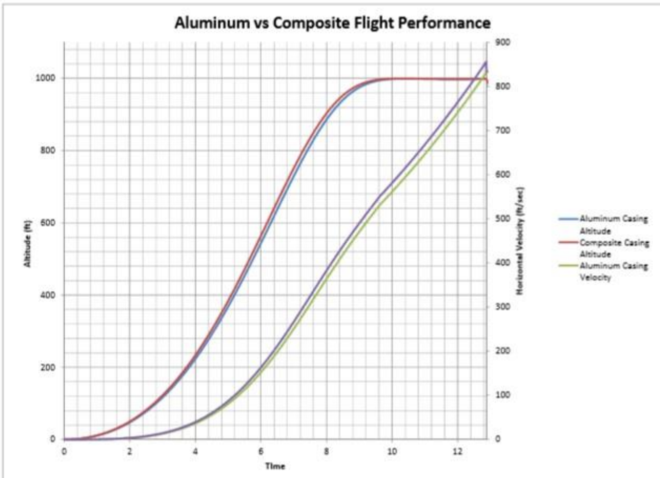

Fig. 5. Aluminum vs composite casing flight performance

G.Avinash et al. [11] deals with the design of composite rocket motor casing and compared results with metallic casing to quantify the improvement of performance factor. A systematic approach is adopted for modelling of various components (composite casing shell, igniter end, nozzle end, igniter skirt end and nozzle skirt end) of composite rocket motor casing. The maximum expected operating pressure (MEOP) is considered for the design of the rocket motor casing and axial load as well as pressure is used for design of the igniter and nozzle end skirts.

Vinay K. Goyal et al. [12] described Structural analysis of components in solid rocket motors (SRM's). Modelling simplifications are required to make the analysis of SRM's practical. These simplifications are illustrated using the main components of an SRM: the composite motor case membrane, the joint regions, the nozzles and the propellant. These simplifications enable the practical use of progressive failure analysis (PFA) and discussed with examples when PFA is necessary to effectively account for the load redistribution that occurs as a component is damaged.

Sidhant Singh [13] had proposed an Experimental Sounding rockets for research in the field of aerospace engineering. The paper is focused on design and construction of a solid rocket motor that can be utilized as the main propulsion unit in experimental sounding rockets by researchers. Initially, basic designs were evaluated and the different concepts of propellant configuration were observed. The availability, ease of manufacturing and casting of propellants was a major factor in determining the suitable propellant.

STRAND Company`s [14] Proposal provided the values of different SRMs for launching vehicles. They also stated that Composite filament cases, successfully employed in applications for more than 40 years, have created a small revolution in SRM design e.g. the case's performance criterion. Pressure and internal volume/solid propellant case mass for a composite case is 5 times a metallic one's.

M. Madhavi et al. [15] involves material characterization of FRP of carbon T300/Epoxy for various configurations experimentally determined using filament winding and matched die mould technique. Mechanical and physical properties are obtained in the design of the composite shell. Netting analysis is used for the calculation of hoop and helical thickness of the shell. Methodology of composite pressure vessel design, calculation of necessary hoop and helical thicknesses of the shell. Progressive failure analysis over geodesic domes is carried out.

Nagesh [16] initiated with different types of composite failures and gave a full-fledged information about Progressive Degradation. A degradation model (S44) incorporated into the finite-element analysis of the pressure vessel based on a progressive failure criterion is discussed.

Alexis A. Krikanov [17] encompasses a new method to design laminated composite pressure vessels under strain and strength constraints. Graphical analysis is presented to find optimum layer thicknesses for given fiber orientations. Minimum pressure vessel mass is determined from active execution of two constraints. By replacing circumferential layer by second helical layer is suggested as a new way of strain suppressing among the commonly used ways for strain suppressing such as (1) addition of extra plies and (2) use of composite material with a higher stiffness which are supported with numerical results and graphs.

Shaik Shaheen et al. [18], Rao et al. [19], Mahesh Babu et al. [20], Rajesh et.al [21], Sheikh Naunehal Ahamed et.al [22] did design and analysis of composite motor casing using different composite materials. Composites rocket cases are pressure vessels, which are axis-symmetry in nature. Problems involving three-dimensional axisymmetric solids or solids of revolution, subjected to axis-symmetric loading, reduce to simple two-dimensional problems. Thus the problem is needs to be looked at as a two-dimensional problem

6. FILAMENT WOUND FABRICATION OF CASES

Filament-wound composite pressure vessels, which utilize a fabrication technique of filament winding to form high strength and lightweight reinforced plastic parts, are a major type of high pressure vessel and are widely used in the commercial and aerospace industries such as fuel tanks, portable oxygen storage, rocket motor cases and so on. These kinds of vessels consist of a cylindrical drum and dome parts, just like typical pressure vessels [23]. Design of filament wound composite pressure vessel comprises of, design of composite material, design of metallic polar boss and rubber lining design [24].

Motor cases are realized by the filament winding process. A combination of hoop and helical winding is employed. The layer sequence and angle of winding are arrived at based on design and analysis. The shell portion and ends have different layer sequence and thicknesses. Composite motor cases will have metallic end fittings and attachments to facilitate integration/interfacing with other systems .These end fittings are embedded / attached to the composite part at the different stages of manufacturing. Carbon fiber with epoxy resin system is mostly used as material.

The major steps involved in the processing of Composite Motor case are represented in a flowchart. Composite Nozzles are also manufactures in this process.

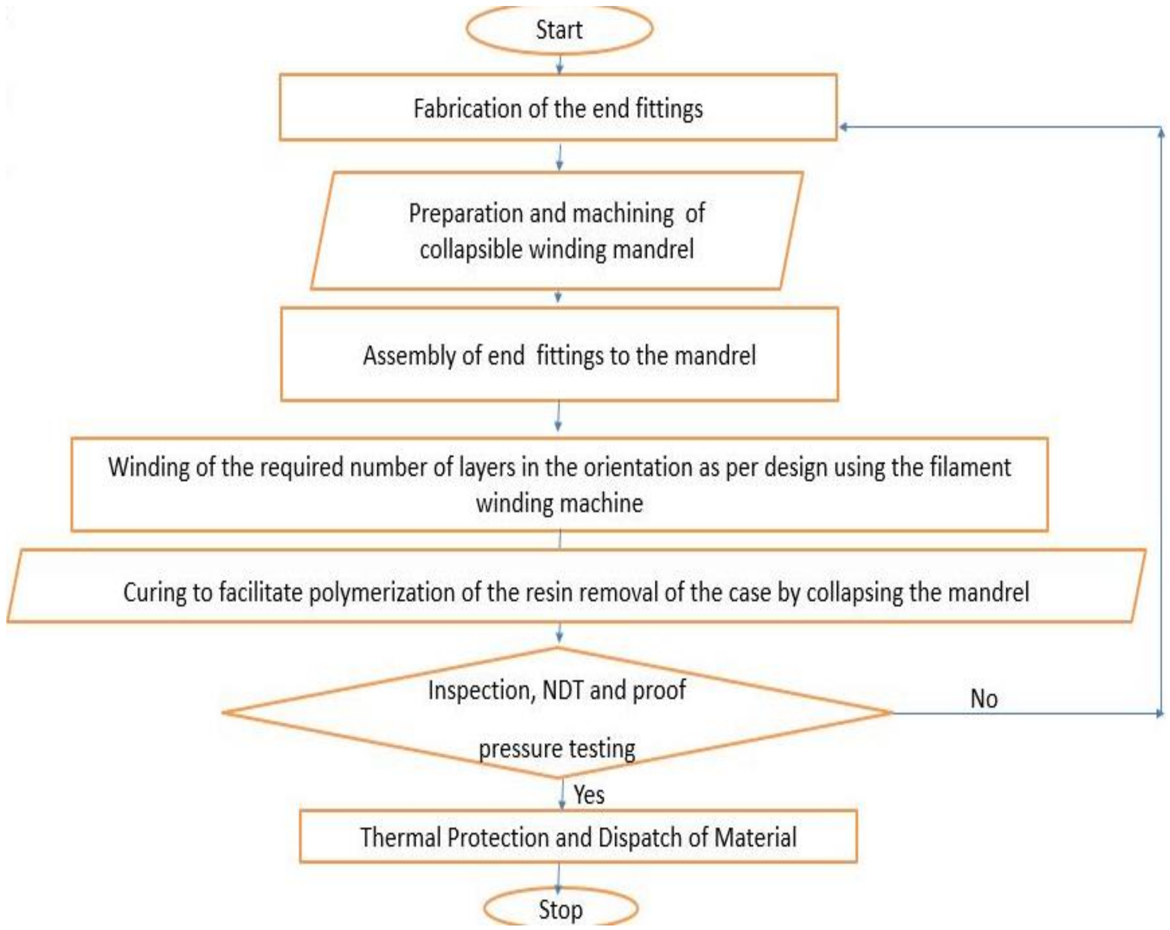

Fig. 6. Flow chart showing the steps in fabrication of composite casing

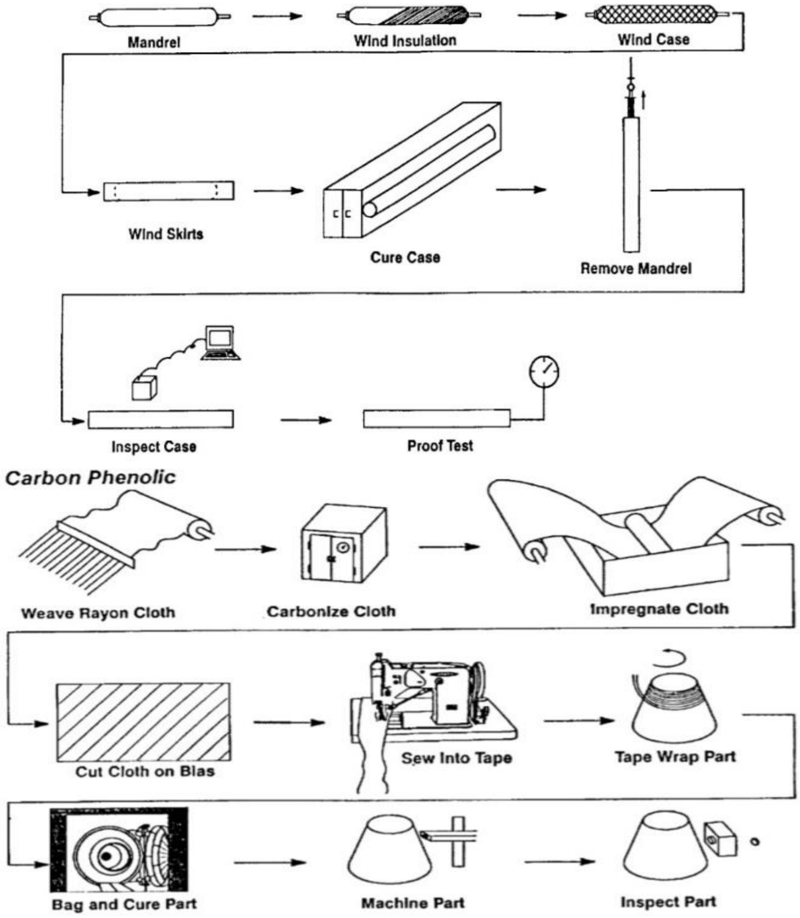

Fig. 7. Filament wound case and Nozzle manufacturing process steps

Fig. 8. Filament case manufacturing over drum and mandrel

V.V.Vasiliv et al. [25] presented over composite pressure vessels made by continuous winding of fibrous tapes reinforced in longitudinal and transverse directions and proposed winding of unidirectional fibrous band instead of instead of isotensoid vessels for minimum mass.

7. TESTING AND INSPECTION METHODS

The solid rocket motor cases, considered as pressure vessels, are designed with very small safety margins. The cracks in solid rocket cases are very small, on the order of 0.025 mm, and difficult to detect. Different types of defects in composite cases are voids, propellant wound with tails, cluster of voids, propellant entrapment, loose flap filled resin and separation between propellant & insulation may result in a catastrophic failure of the flight [26]. Different NDT methods used in crack detection of composite rocket cases are (i) Ultrasonic, (ii) Radiography and (iii) Thermography [27-28].

The detection of cracks in small and narrow diameter cylindrical structures is a big problem. Pipelines, rocket cases, boilers, pressure vessels, chimney etc... are hollow cylindrical in nature. Cracks in these will results in the loss of strength, which could lead to failure of component and its function. In generally, Non-destructive testing methods in Fig.9., are widely available for quality assurance and fault diagnostics [29]. Various inspection and testing are Dimensional inspection, NDT of the casing – UT and Radiography, Proof pressure testing, Post PPT NDT, Load testing and Burst test for validation of design margins.

Fig. 9. NDT Inspection of casings

8. CONCLUSION

In the paper for the design of Solid Rocket Motor casing, a comparision of different properties of carbon composites with Metal casings (D6AC Steel alloy, Maraging Steel, Titanium etc.) shows that carbon fiber composites are best to use as materials in fabrication of SRM Casing. On the other hand Carbon - Epoxy composite materials with their higher specific strength, moduli and tailoribility characteristics will result in reduction of weight of the structure. Filament winding is best manufacturing method for fabricating conposite casings and are inspected through different NDT Techniques. In this we discussed design considerations of the composite shell is described in detail. Finally, if motor case must be stiff, able to tolerate high pressures and light in weight we should choose composites.

ACKNOWLEDGEMENT

First author thankfully acknowledges the support provided by M.Tech students; faculty of Mechanical Engineering Department, Vignan University, Guntur and M/S Resin & Allied Products Ltd., Nidamanuru, Vijayawada, Andhra Pradesh.

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