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Experimental Performance Evaluation of Small Solid Rocket Motor with Composite Case for Environmental Conditions

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ABSTRACT

Polymeric composites are widely used in aerospace. One such important use of polymeric composites is the filament-wound composite case for the Solid Rocket Motor (SRM). Environmental conditions expected during flight and other phases of the SRMs life cycle affect its performance. The performance of SRM, in turn, depends primarily on the composite case and propellant grain. In this study, the performance evaluation of SRM with the composite case is carried out for different environmental conditions. These cases are designed to sustain very high pressure and temperature environments generated due to the combustion of propellant grains and are intended to perform adequately at any time during their service life. The performance evaluation test matrix is formulated considering various expected dynamic and thermal conditions. The small SRM with a composite case is subjected to planned tests as per the matrix, followed by static tests. The pressure versus time data is plotted for all test conditions. The ballistic parameters result of the virgin (without subjecting it to any test) small SRM is considered as a reference for comparative studies with the rest of all other test conditions results. All the ballistic performance test results are also analysed with respect to the pressure-time curve for mission bounds. The analysis of experimental test results reveals that various environmental dynamic conditions like random vibration, acceleration and shock, do not affect the composite case and the ballistic performance of a small SRM. The effect of grain temperature on ballistic performance is also found as expected.

Keywords: Composite case; Filament winding; Solid rocket motor; Environmental condition; Performance evaluation

1. INTRODUCTION

The long-range missile systems are deployed and are kept in storage, subjected to handling and operational trials until they are used. Since these systems are principally strategic and mostly intended to be used once, their safe life post-deployment is always a matter of concern. The present-day state-of-the-art technology uses composites in various structural and thermal applications for missile and space applications[1]. Filament winding is one of the most prominent polymeric composite manufacturing methods, where resin impregnated continuous filaments are wound over a male rotating mandrel in a pre-described manner under tension to yield a surface of revolution with the desired thickness and ply sequences[2]. These products are ideally suited as a composite case for SRMs[2-3]. The in-service performance of the polymeric composite is sensitive to environmental factors[4-5]. Environmental conditions degrade the mechanical properties and effects the structural performance of polymeric composites[6-8]. The primary objective of this study is to qualify the SRM with composite cases for different service and operational conditions of missile systems such as vibration, acceleration, shock and temperature environments. The following are the environmental factors that may affect the performance:

- Chemical and physically induced aging mechanisms due to long-term exposure to temperature and humidity
- Mechanical factors (such as thermally induced stresses, shock loads, acceleration and vibrations)

The above factors, affect the mechanical properties, thermal stability and effective service life of SRM. This SRM was designed to produce a high mass flow rate and high heat flux with an instantaneous pressure rise in the shortest possible time[9-10]. The composite case was designed to withstand very high pressure and temperature environments for a short period of time[1,9-10]. Accordingly, Hizli[4] examined the effect of environmental conditions on the structural performance of composite rocket motor cases using hydrostatic burst methods. However, the burst test does not simulate instantaneous pressure rise and combustion environments. On the contrary, a static test resembles actual operational conditions, as expected during flight. Unfortunately, in the available literature, efforts to understand the behaviour of the SRM exposed to different condition using static firing is extremely rare. Accordingly, the present study has been carried out on a subsystem level resembling the actual flight hardware configuration and the overall effect of environmental conditions on the performance of SRM with the composite case has been experimentally evaluated in an integrated way through static firing.

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2. PRODUCT DESCRIPTION AND DESIGN DETAILS

SRM is an efficient energy release system that contains solid propellant[6-7]. When solid propellants are burnt within a confined chamber, the stored chemical energy within the propellant is converted into pressure in a controlled fashion[9-10] and generates a High Temperature (HT) and pressure environment. The SRM is consisting of four primary elements (i) Head End (HE) metallic flanges with the ignition initiation system (ii) Filament wound glass-epoxy composite case (iii) Thermal protection system and (iv) Hydroxy Terminated Polybutadiene (HTPB) based propellant cast in a Synthetic Resin Bonded Paper Tube (SRBP).

HE flange is a metallic interface with assembly and attachment features. The pyrotechnic-based initiation system actuates the ignition process by converting the mechanical energy into chemical energy, which ignites the propellant grain[9-10]. The thermal protection system consists of an insulator boot, HE insulation, Nozzle End (NE) insulation and carbon phenolic Nozzle Inserts (NI). The carbon phenolic made NI also work as an energy discharge system. A small SRM with composite case is shown in Fig. 1. and its different sub-systems are mentioned in Table 1.

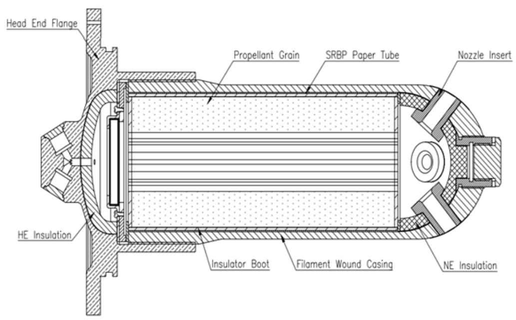


Figure 1. A Small SRM with glass epoxy composite case.

Table 1. Different sub-systems of SRM with the composite case

Components	Material
HE Flange	Maraging Steel (M-250)
Filament Wound Composite Case	Glass Epoxy
Thermal Protection System (TPS)	
HE & NE Insulation	Nitrile Rubber
Insulation Boot	Asbestos Phenolic
NI	Carbon Phenolic
SRBP Paper tube	Kraft paper & Synthetic resin
Propellant	HTPB based Composite grain

The SRM produces a sustained combustion environment and needs to perform adequately for the stipulated time interval with required transient characteristics[9-10]. Considering the above inputs and functional requirements, the ballistic performance envelope (Pressure-time profile) for a SRM with upper, nominal and lower bound is worked out considering the variation in the operating temperature range (operating temperature specification: 10-45 °C), propellant burn rate, density, characteristics velocity and throat diameter. In this case, for upper, nominal and lower bounds, the temperature is considered as 10 °C, 27 °C and 45 °C respectively.

The composite case was realised through the filament winding technique, which provides a very high strength to weight ratio[2]. One of the primary objectives is to exploit the properties of the composite materials to the maximum possible extent and to achieve an optimum design[2-3]. The design was worked out based on netting theory with the assumption that the case comprises of a system of fibres alone neglecting the contribution of resin toward strength[2]. The case is primarily designed for internal pressure (MEOP - Maximum Expected Operating Pressure)[2]. For a given MEOP, the allowable total thickness of the case (comprising of the hoop and helical plies) is theoretically calculated and the theoretically calculated ply sequence and thickness were experimentally validated through trial filament winding[4].

3. RAW MATERIAL AND MANUFACTURING PROCESS DETAILS

High-strength E-glass roving and epoxy resin systems were considered in this present study. The E-glass (E stands for electrical insulation application) mechanical properties are better and suit our requirements, the same is considered as a reinforcement for our application. The specifications of the glass roving, epoxy resin system and glass epoxy composites are given in Tables 2, 3, 4 and 5 respectively.

Table 2. Glass roving specifications

Property	Specification
*Tex (gm/km)	1200 ± 20
Tensile strength (MPa)	1000 (Min)
Specific gravity	2.5 to 2.6
Sizing	Epoxy compatibility through Inter Laminar Shear Strength (ILSS)

*Tex is defined as the weight (in gm) of 1 km length of the fibre.

Table 3. Epoxy resin (LY556) specifications

Parameter	Specification
Specific gravity (at Room temperature)	1.10 to 1.20
Viscosity at 25 °C, Pascal-second	8-12
Epoxy content, Equivalent/kg	5.0 to 5.9
Volatile content, by % weight	0.75 % (maximum)

Table 4. Hardener (HY5200) properties

Parameter	Specification
Viscosity at 25 °C, Pascal-second	0.15-0.18
Specific gravity (at Room temperature)	1.0 to 1.1

3.1. Design Properties: Glass Epoxy Composites

Flat laminates were made by the wet filament winding method using a rectangular mandrel[11]. The laminate is cured in an oven to the same cure cycle as that of the composite case. A detailed characterization plan is worked out and different types of laminates were made to cater to the requirement of tensile, compressive and shear properties. The required test samples are prepared from the above laminates and tested in accordance with ASTM standards. The test results are shown in Table 5, and the same was considered for design.

Table 5. Design properties for glass-epoxy composites

Parameter	Specification	ASTM Standard
Longitudinal Modulus	44 GPa	D3039
Transverse Modulus	10 GPa	D3039
Poisson's Ratio	0.24	D3039
Longitudinal Tensile Strength	590 MPa	D3039
Transverse Tensile Strength	18 MPa	D3039
Longitudinal Compressive Strength	400 MPa	D3410
Transverse Compressive Strength	85 MPa	D3410
Shear Modulus	8 GPa	D3518
Shear Strength	44 MPa	D3518
Density	2100 kg/m^3	D792

3.2 SRBP Tube

Filament wound case was thermally protected with SRBP tube which holds the propellant grain as well as acts as an insulator to restrict the interface temperature of composite case within the glass transition temperature of the resin system[9-10]. The paper tube was made of Kraft insulation paper impregnated with polyester resin.

3.3 Glass Epoxy Composite Rocket Motor Case - Manufacturing Process

Glass roving, impregnated with epoxy resin system was wound over a mandrel using a filament winding machine. The helical winding together with hoop winding and doily layup technique was adopted for the realisation of the composite case[2,3]. Detailed process plans including critical parameters such as ply sequence, ply bandwidth, winding angle, the number of spools, resin/hardener mix viscosity, fibre tension, resin bath temperature, etc. were evolved based on experimental trials. The case along with the mandrel was subjected to curing in a calibrated oven as per the cure cycle specified as follows:

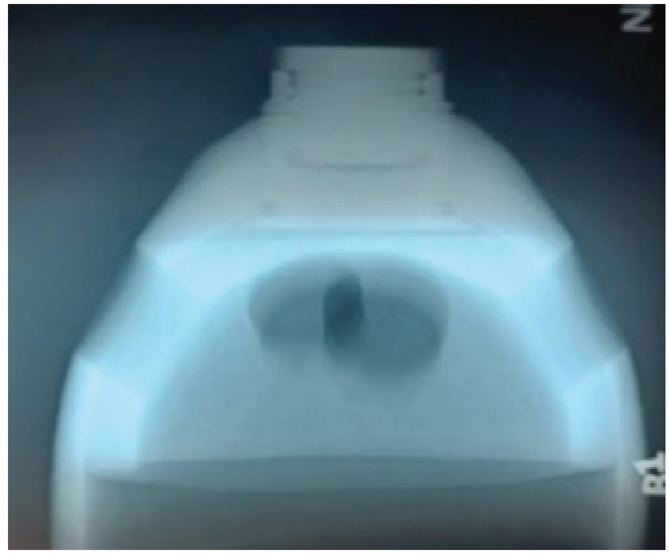
30 °C - 130 °C	- 90 mins
Hold at 130 °C	- 60 mins
130 °C - 150 °C	- 30 mins
Hold at 150 °C	- 240 mins

3.4 Acceptance Testing

Test samples for density, resin content, Differential Scanning Calorimetry (DSC) test, fibre volume fraction, and mechanical properties (ILSS, tensile properties) were drawn from control coupons. The Control coupons are travel coupons manufactured and cured along with the composite case and are used for sample preparation. The required test samples are prepared from the control coupon and tested in accordance with relevant ASTM standards[10].

3.4.1 Proof Pressure Test (PPT)

The composite case was hydro-pressure tested till 11 MPa (1.1×MEOP) with a rubber bladder in a specially designed test fixture. All the Cases sustained the proof pressure without any noticeable pressure loss. Radiography Testing (RT) was carried out on each case before and after PPT, and found to be free from defects. The radiographs of the composite case are shown in Fig. 2.



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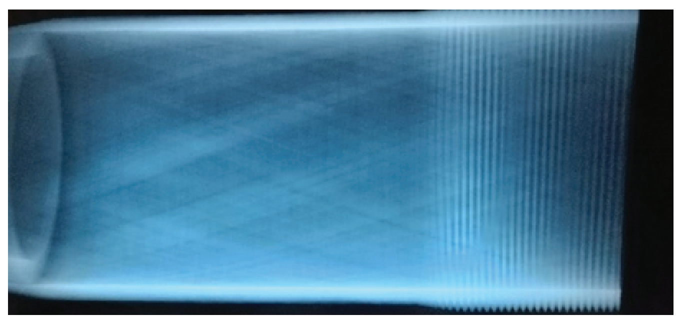


(b)

Figure 2. Radiograph of: (a) NE Region and (b) Cylinder with Threaded Region.

3.5 Burst Test

A burst test was performed on a standalone basis, one case was burst tested for design validation. The insulation-lined composite with a rubber bladder inside is assembled with a dummy test fixture and hydro pressure tested till burst.

3.6 SRM

The HE flange is machined out of M-250 forgings, heat-treated, and aged. It was configured with multiple adaptor ports for pressure transducer and pyro cartridge mounting. The HE flange was insulated with nitrile rubber for thermal protection. NI were realised through the compression molding process using Rayon-based carbon fabric/phenolic resin prepreg and bonded to the composite case. Propellant grain was cast in a SRBP paper tube and was bonded with the composite case.

The pyrotechnic initiation system was assembled with HE flange. Finally, the HE flange sub-assembly was bonded with the composite case bonded propellant grain sub-assembly and SRM was realised.

4. PERFORMANCE EVALUATION

4.1 Test Plan and Methodology

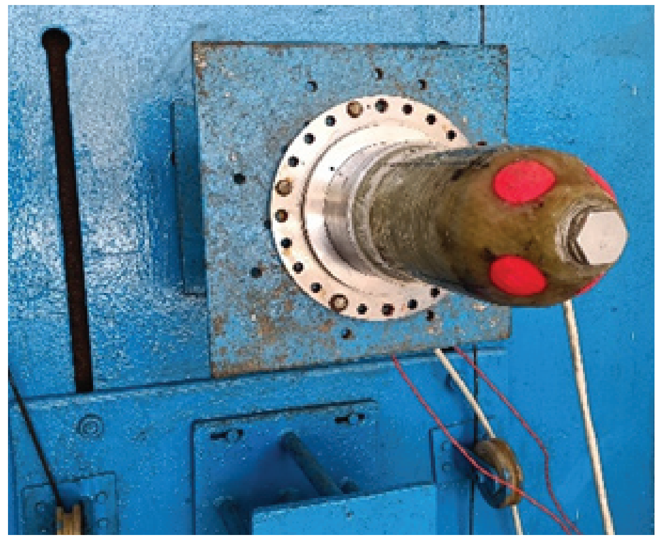
The service and operational environment of the SRM is an important part of its life cycle as the environment in which SRM is preserved, may have a large influence on the structural integrity and functionality during actual flight. The life cycle of SRM includes storage, deployment, and flight environments. A detailed program was designed to verify operational capability throughout the range of service environments expected during its product life cycles[4,10,12]. The number of the tests was derived envisaging the criticality, potential failure risk, load envelope, and availability of hardware. The test levels are arrived at, considering the MIL guidelines as per the operational service requirements for the intended mission. The tests intend to assess the operational capabilities of SRM after subjecting it to an expected thermal and dynamic environment consisting of vibration, acceleration and shock. The overall test matrix is shown in Table 6.

11 numbers SRMs with the composite case were conditioned for different environmental factors and static fired for performance evaluation[4]. In phase 1, one SRM was static fired (at ambient) for stand-alone performance evaluation and comparison. In phase 2, the balance 10 numbers of SRMs were subjected to temperature environments, and SRM Sl. no. 2 and 3 were static tested. In phase 3, balance SRMs were subjected to a dynamic environment comprised of acceleration, vibration, and shock. Post-exposure, SRM Sl. no. 4 to 7 were static fired after each exposure. In phase 4 evaluation, the balanced 4 SRMs were conditioned at HT and Low Temperature (LT) extremes and 2 numbers were fired for each test-case, immediately after removal from the thermal chamber. This is carried out to assess the performance at both respective temperature extremes.

4.2 Static Testing and Test Results

4.2.1 Phase 1: Standalone Test

The SRM was assembled to a thrust wall frame using the metallic flanges and static fired at ambient conditions (27 °C). The calibrated pressure transducer is assembled to flange adaptor for pressure measurement. The pressure-time curve was in-line with prediction and taken as a reference for comparative studies with the rest of all other test condition results. The test setup and pressure versus time plot are shown in Fig. 3.



(a)

Figure 3(a). Static test setup.

Table 6. Performance evaluation test matrix– SRM with composite case

Environment Test	Test Article No.									
Stand-alone Static Firing at Ambient	1-11		Phase 1							
HT Soak		2-11		Phase 2						
LT Soak			3-11							
Vibration Test- Transportation Vibration				4-11				Phase 3		
Vibration Test- Flight Vibration					5-11					
Acceleration Test						6-11				
Shock Test							7-11			
HT Functional Test								8-11		Phase 4
LT Functional Test									10-11	
Static Firing	1	2	3	4	5	6	7	8-9	10-11	

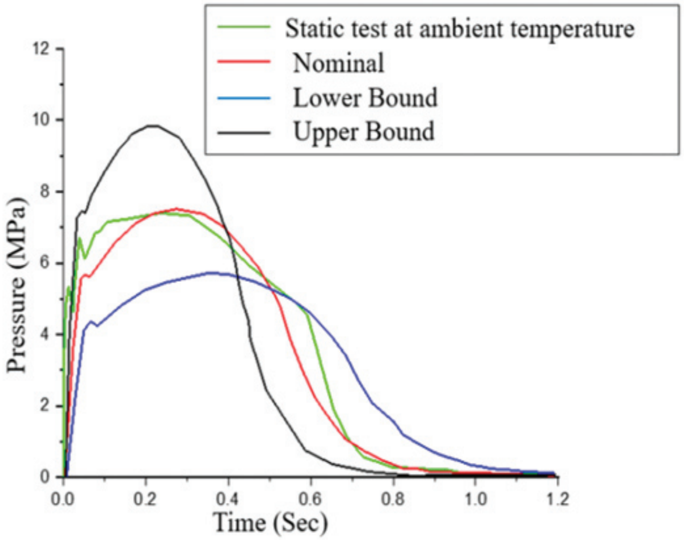


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Figure 3 (b). Static test result at ambient.

4.2.2 Phase 2: Temperature Environments

Both HT and LT exposure tests were carried out, to determine the operational performance against the expected temperature environments. The test was carried out as per MIL-STD 810 G[13] guidelines. The temperature extremes are selected based on the design mission bound. To evaluate the effect of HT and LT on grain performance, conditioning is carried out at 10 °C and 45 °C respectively,

In the HT soak test, SRM was soaked at 45 °, 55 °, and 45 °C for 6, 4, and 6 hours respectively. For, the LT soak test, it was soaked at 10 °, 0 °, and 10 °C for 6, 4, and 6 hours respectively. Considering the propellant web thickness, the temperature is varied by 10 °, to ensure that the grain surface reaches the intended temperature extreme. The static test was carried out at ambient, the results are shown in Fig. 4 reveal that SRM performance is within the predicted performance bound and comparable with the static test result at ambient. The effect of HT and LT soaking on SRM performance is not significant and, in both cases, the peak pressure, burn duration and trend line obtained are almost comparable.

4.2.3 Phase 3: Dynamic Environments

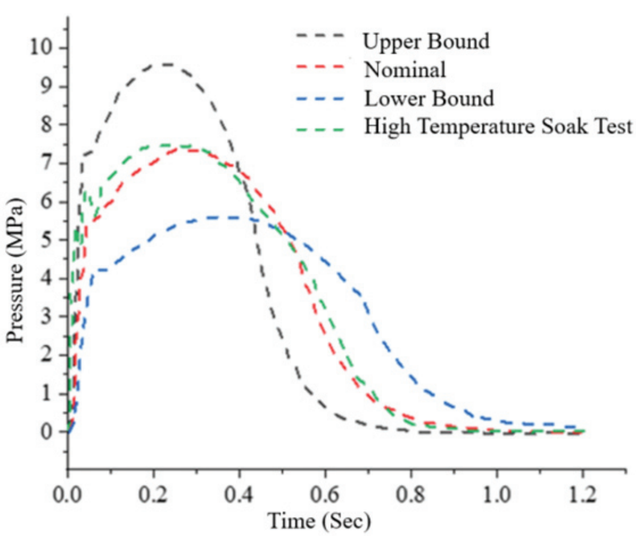
4.2.3.1 Vibration Test

This test was carried out to assess the operational capabilities against vibration severities expected during transportation and flight. The sources of vibration are propulsion and aerodynamic disturbances. Therefore, the test fixture was specially designed to simulate the case to missile interface and test setup. The test fixtures are stiffened suitably to be considered rigid for the expected test frequencies[12]. Experimental trials were carried out before the test to validate fixture design, assembly procedure and to confirm testing requirements[12]. Test levels (Table 7) were chosen based on mission requirements and are arrived at using MIL-STD 1540 D[14] guidelines.

Articles no. 4 – 11 (Table 6) were subjected to transport vibration conditions on a 2-ton dynamic shaker in both longitudinal and transverse directions respectively followed

Table 7. Vibration spectrum

Type of test	Test specification	No of axes
Transport Vibration	Frequency 5 Hz-20 Hz, PSD 6 dB Octave Frequency 20 Hz-50 Hz, PSD 0.02g^2/Hz Rolling down to 0.001g^2/Hz at 500 Hz Total Duration – 2 Hrs	Two
Random Vibration (Flight)	Frequency 20-2000 Hz, PSD 0.07g^2/Hz, Total Duration- 100 Seconds	



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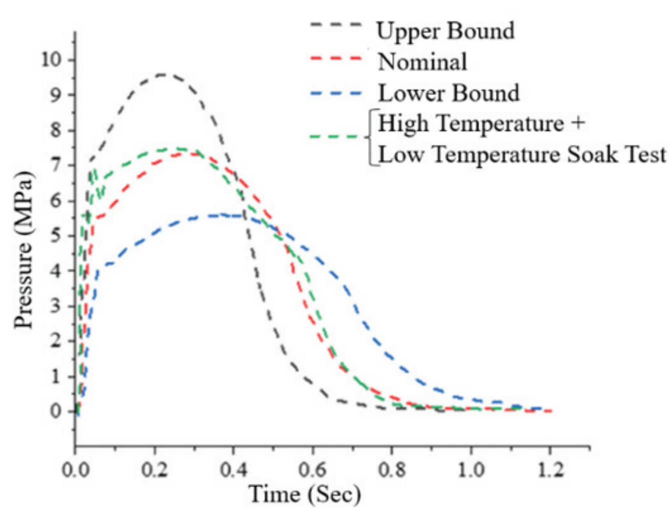
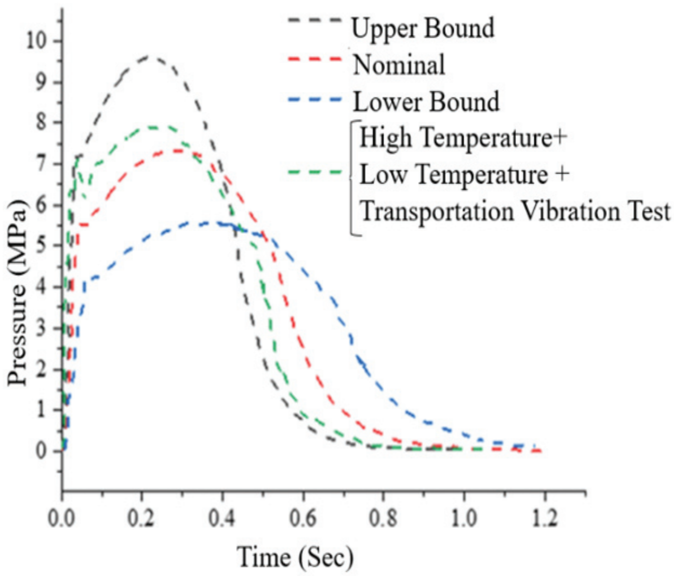


(b)

Figure 4. Static test results after: (a) HT and (b) LT soak test.

by a static test of Sl. no. 4. Further, articles Sl. no. 5-11 were subjected to a flight vibration environment, followed by a static test of Sl. no. 5. The static test performance is satisfactory and comparable, the result of both the tests are given in Fig. 5.



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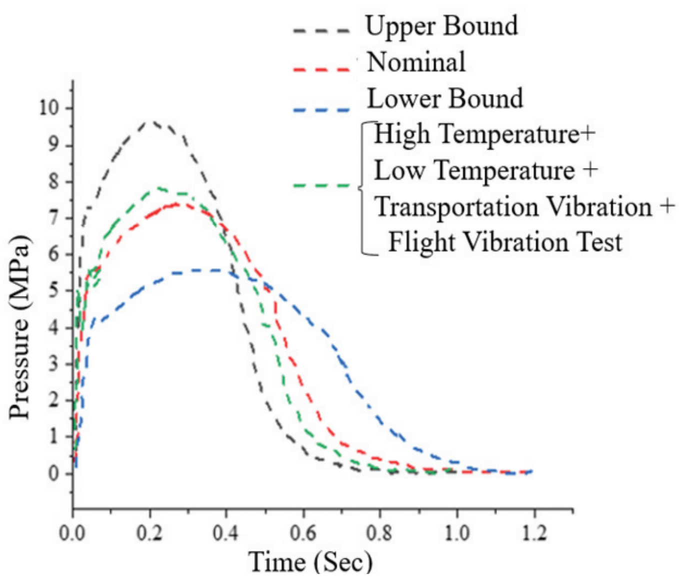
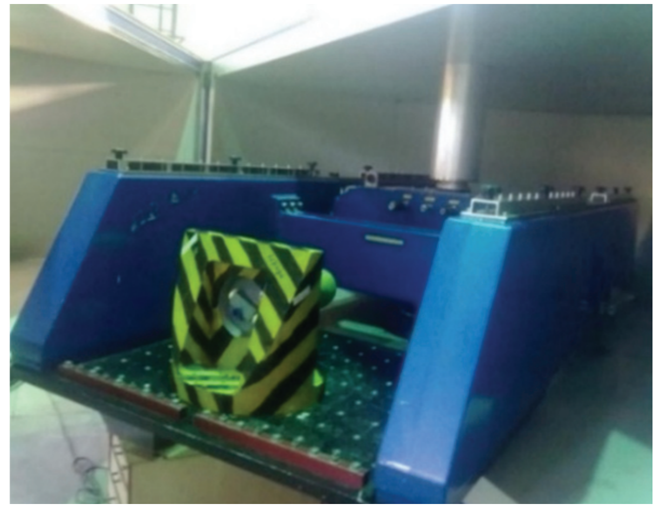


(b)

Figure 5. Static test results after: (a) transport and (b) flight vibration test.

4.2.3.2 Acceleration Test

This test was performed for a steady acceleration environment of 17 g for 60 seconds according to mission specifications. The test setup was designed with a suitable fixture to facilitate the required level of acceleration in the desired direction simulating the flight interfaces. Articles Sl. no. 6-11 was subjected to an acceleration test, followed by a static test of Sl. no. 6. The test result is in line with the predicted performance bounds and comparable with the static test result at ambient. Test setup and test results are given in Fig .6



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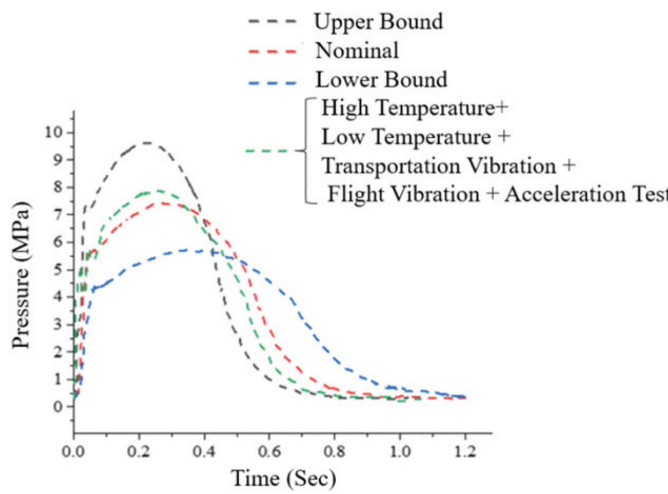


(b)

Figure 6. (a) Test set-up for acceleration test and (b) Static test result after acceleration test.

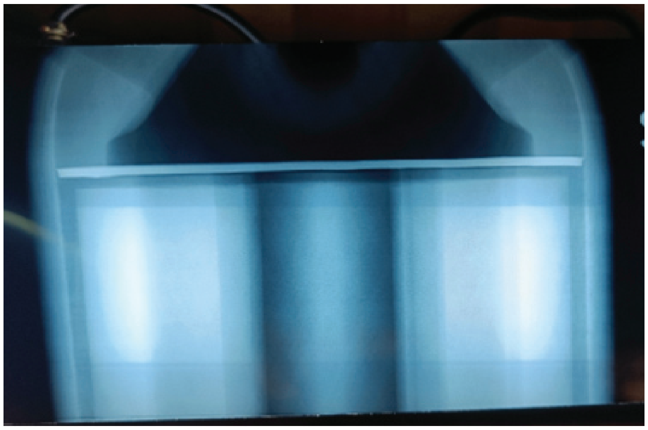
4.2.3.3 Shock Test

The Shock test was carried out to verify the resistance of the SRM to mechanical shocks (expected in flight due to stage separation and explosive firing) by applying simple low duration reproducible impulsive acceleration. The test fixture for the shock test is designed and qualified to simulate the flight interfaces and subjected to the required test levels in a suitable setup. Articles Sl. no. 7-11 were subjected to a shock test as per the specifications given in Table 8.

Table 8. Shock test specification

Type of test	Test specification	No of axes
Shock test	45g for 11 msec, half-sine wave	Two shocks in 2 longitudinal and 1 in radial axes

The RT of SRM Sl. no. 7, conducted after completing all the dynamic environment exposures does not show any defects and demonstrates overall structural integrity as shown in Fig. 7.



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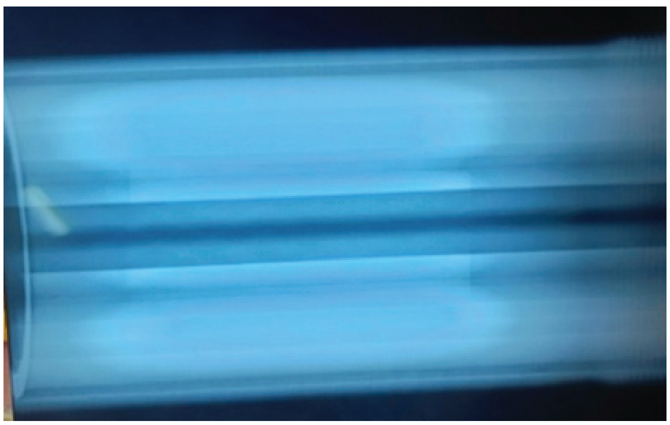


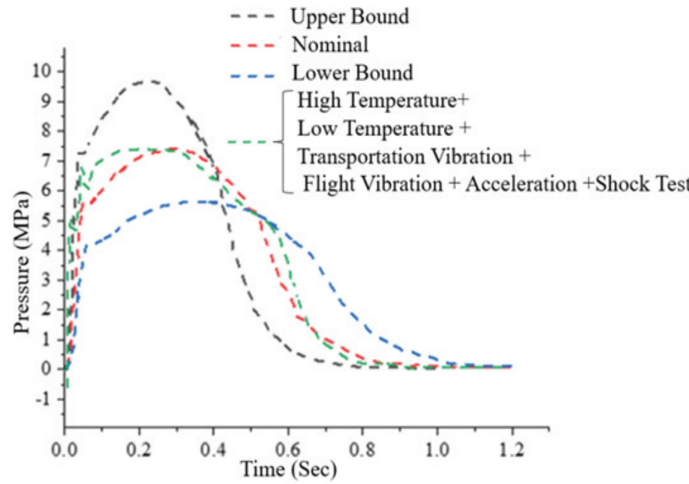
(b)

Figure 7. Radiograph after shock test: (a) HE region and (b) Cylinder region.

Post RT, article Sl. no. 7 was test-fired. The test result is comparable with the predicted performance bound. The test setup and static test results are shown in Fig. 8.

(a)

Figure 8(a). Test setup for shock test.



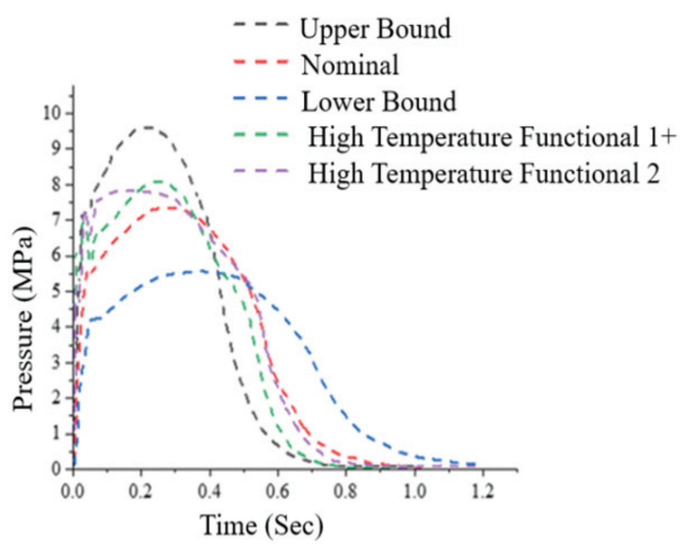
(b)

Figure 8(b). Static test result after shock test.

4.2.4 Phase 4: HT and LT Functional Test

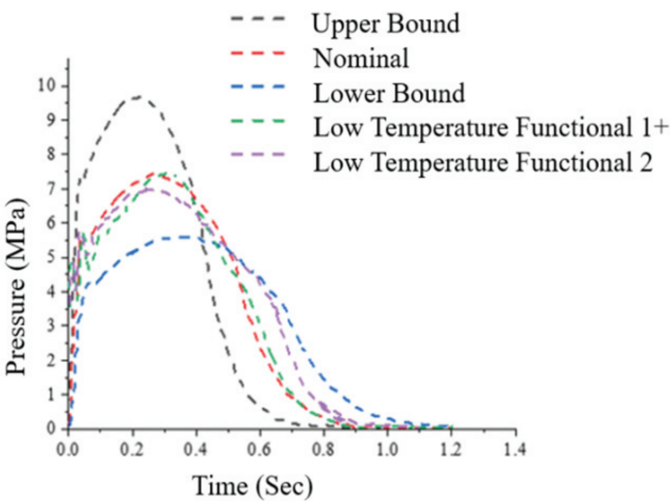
To evaluate the functional performance of SRM at temperature extremes, both the HT and LT functional tests were carried out. Articles Sl. no. 8-11 was conditioned at high (55 °C) for 12 hrs (10 °C higher than the specified upper bound temperature) followed by a static test of articles Sl. no. 8 and 9.

Balance articles Sl. no. 10 and 11 were conditioned at 0 °C for 12 hours (10 °C lower than the lower bound temperature) and test fired. In both cases, the static test was carried out within 30 minutes of thermal conditioning to evaluate the effect of grain temperature on functional performance. As articles Sl.no. 8-11 underwent, the cumulative effect of all the environmental factors, for better comparison and repeatability, 2 no. of SRM were tested for each condition. The static test results are well within the bound and comparable with the standalone test. The results of the static tests are given in Fig. 9.



(a)

Figure 9(a). Static test result: HT functional test.



(b)

Figure 9(b). Static test result: LT functional test.

5. DISCUSSIONS

The performance of SRM under the combined effects of all the environmental factors was as expected, repetitive and in line with the prediction. In all the above test cases, the SRM with composite case withstood static firing for the required burn duration. To, evaluate the effect of grain temperature on the ballistic performance of SRM, two test-cases are identified. In the first test-case, SRM is conditioned at HT and LT respectively and then static tested. For the second test-case, SRM is soaked at HT and LT respectively for 12 hours and static tested within 30 minutes of removal from the thermal chamber.

The effect of grain temperature on ballistic performance is as expected. In the HT functional test, the pressure-time curve is close to upper bound prediction whereas, in the case of LT functional tests, the pressure-time curve is between nominal and lower bound. Out of all the test cases, burn duration is found to be maximum (Table 9) in the case of a LT functional test as predicted. The pressure versus burn time obtained across all test cases is given in Table 9 and performance is repetitive.

Table 9. Pressure versus time data observed during performance evaluation tests

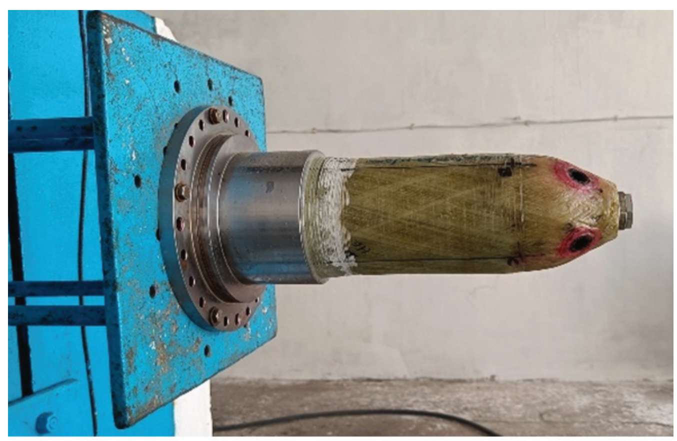
Type of test	Maximum pressure (MPa)	Burn time (sec)
HT soak test	7.6	0.550
LT soak test	7.6	0.580
Transport vibration test	8.1	0.490
Flight vibration test	8	0.500
Acceleration test	7.9	0.520
Shock test	7.7	0.580
HT functional test	8.3	0.480
HT functional test	8	0.530
LT functional test	7.6	0.580
LT functional test	7	0.600

To evaluate the effect of the expected dynamic environment of flight, a load envelope is evolved as per MIL guidelines and expected mission bounds. The SRM is subjected to low-frequency transport vibration, worst-case flight vibration, acceleration and shock test. The test setup and fixtures simulate the flight environment and the test is carried out as per the plan. The peak pressure and burn duration obtained in all the tests are shown in Table 9. The performance of SRM with the composite case against all the dynamic environments mentioned above is found to be satisfactory and comparable with the performance of virgin SRM.

The pressure versus time plots of all the phase 3 dynamic tests reveal that vibration, acceleration and shock do not affect the ballistics and structural performance of SRM. The pressure, burn duration and profile is following a similar trend in all cases (Table 9).

All the SRMs are subjected to RT before and after the environmental exposures. The grain, composite case and all the interfaces were found to be intact and structurally integral. RT of article Sl. no. 7 (Fig.7), having undergone the cumulative effect of all the four dynamic environments and before static firing, reveals no effect on the overall structural integrity.

The radiograph of static tested SRM reveals that the composite case is free from defects and all the interfaces are intact. The test article after the LT functional test and post-static test radiograph of the article is shown in Fig.10.



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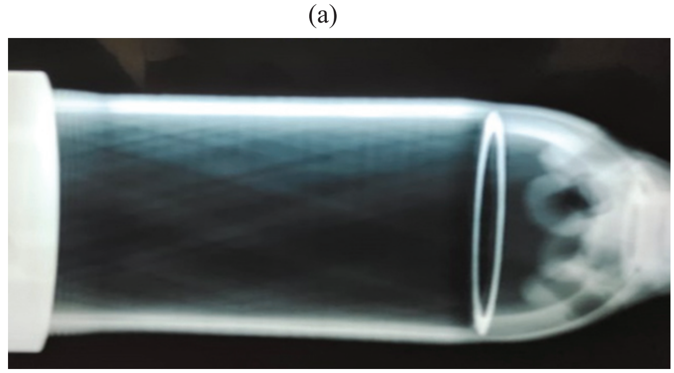

(b)

Figure 10. (a) SRM after static test and (b) Radiograph after static firing.

6. CONCLUSIONS

SRMs are exposed to a rigorous performance evaluation program in this experimental investigation encompassing various missile system service situations. The SRM was subjected to RT for structural integrity evaluation before and after each exposure. The static firing was carried out in a phased manner after every exposure. All the SRM with composite cases were found to sustain all the environmental conditions, including acceleration, shocks, vibration and temperature extremes. The following are the salient findings and inferences of this research study:

- All of the composite cases worked admirably and exhibited their capacity to endure pressure and temperature loads throughout the combustion process
- The temperature extremes and the dynamic environments consisting of transport vibration, flight vibration, acceleration and shock do not affect the structural integrity of grain, interfaces and composite case
- There is a good agreement observed between predicted and evaluated ballistic performance. The effect of HT and LT soak tests on ballistic performance is not that predominant, however, the effects of HT and LT functional tests are as predicted.
- The low dispersion behaviour during all the static firing displayed the repeatability and reliability of the SRM performance along with the composite case
- The above study demonstrates the safe life of SRM for the said operational environments

The results of the above tests reveal that the SRM with the composite case performed well under all expected operating conditions and the results are closely comparable with the results of virgin SRM (without any exposures).

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