Structural analysis and experimental strain measurement of T700/epoxy composite solid rocket motor casings

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ABSTRACT

Filament-wound composite casings are widely used in solid rocket motors because of their high specific strength and superior pressure resistance. This study presents a casing design method based on the geodesic winding technique and applies it to a solid rocket motor casing made of T700 carbon fiber/epoxy composite, designed to operate at a maximum pressure of 12 MPa. The mechanical properties of the composite material were experimentally determined and used as the basis for the design calculations. Strain responses under internal pressure loading were measured using strain gauges aligned with the fiber reinforcement directions. Experimental results showed good agreement with analytical predictions for stress and strain distributions, and the critical load-bearing regions of the structure were accurately identified. Based on the validated design methodology, a motor casing employing the propellant grain as the winding mandrel was manufactured and successfully tested in a static firing experiment. The results demonstrate the feasibility and effectiveness of filament-winding technology for the design and manufacture of composite solid rocket motors in Vietnam.

Keywords: Measuring stress and strain of composite motor casings; Critical locations of the casing.

1. INTRODUCTION

Solid rocket motors (SRM) are widely used in launch vehicles and missiles due to their high thrust-to-weight ratio and simple structure. Fiber-reinforced polymer composites are preferred for motor casings because of their lightweight and high specific strength. Burst pressure is a key parameter for evaluating the load-bearing capacity of filament-wound composite structures. Accurate prediction of burst pressure requires stress analysis to identify critical failure regions. Differences between predicted and experimental burst pressures may result from factors such as stacking sequence, winding layers, mandrel material, curing process, and winding path. Therefore, validating analytical or numerical predictions against experimental results is essential to ensure the reliability and safety of SRM.

Current research on the burst pressure and mechanical behavior of filament-wound composite structures has mainly focused on composite pressure vessels for hydrogen storage [1]. However, significant differences exist between composite pressure vessels and rocket motor casings in terms of manufacturing conditions. Pressure vessels are typically fabricated with aluminum alloy liners possessing high stiffness, whereas rocket motor casings are wound on thermal protection layers or resin-sand mandrels with much lower stiffness. This difference leads to variations in stress and strain distributions, making it difficult to directly apply the results obtained for pressure vessels to rocket motor casings. For composite motor casings, existing studies have mainly focused on numerical simulations of stress and strain [2, 3], as well as investigating the effects of the number of winding layers and fiber tension on burst pressure [4]. However, given the stringent safety and reliability requirements for rocket motors, experimental measurement of the casing stress and strain, together with comparison between theoretical predictions and experimental results, is essential for validating the analytical model and accurately assessing the load-bearing capability

of the structure.

This study presents a method for determining the structural parameters and predicting the stress–strain behavior of filament-wound composite casings along geodesic winding trajectories. A propellant-free casing was fabricated and experimentally tested for stress, strain, and burst pressure, and the results were compared with analytical predictions to validate the model and identify critical regions. Finally, a firing test was conducted to assess the casing's structural integrity and operational performance.

2. STRESS-STRAIN MODEL OF THE SRM CASING

2.1. Assumptions and forces acting on SRM casing

During operation, the SRM case is subjected to both mechanical and thermal loads. In the present study, the following assumptions are adopted for the dome design:

- The internal pressure (p) is uniformly distributed over the inner surface.

- The glass transition temperature of aerospace-grade composite matrices typically ranges from T_g = 200–260 °C [5]. For short-duration thermal exposure below $T \le 0,5T_g$, the mechanical properties in the fiber direction are only marginally affected [6]. In composite SRM casing, a thermal protection layer is usually designed to maintain the casing temperature below the matrix glass transition temperature $T \le 0,5T_g$ [7] throughout motor operation. Consequently, thermal effects are generally considered secondary to those induced by internal pressure. Therefore, SRM casing design is commonly based on an increased design pressure rather than an explicit thermo-mechanical analysis. The design pressure is expressed as $p = kp_{max}$, where $k = 2 - 3$ is safety factor [7] and p_{max} is the maximum internal pressure within the motor.

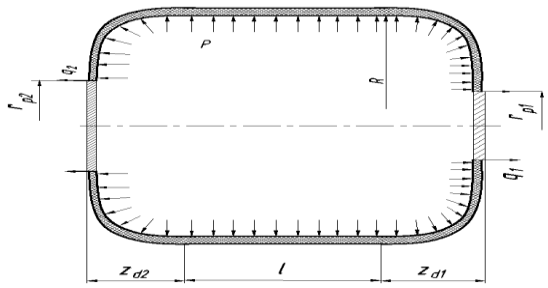


Figure 1. *Forces acting on the SRM casing.*

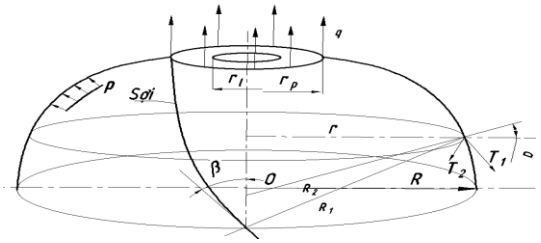


Figure 2. *The geometry of a dome profile of the SRM casing.*

Consider the motor casing with inner radii r_{p1} and r_{p2} as shown in Figure 1, in which one dome is connected to the nozzle section, while the other dome is sealed by the igniter. Consider the end connected to the nozzle as shown in Figure 2. Some geometric and physical characteristics of the first dome in Figure 1 are as follows:

- R the radius of the cylindrical section; r_1 is the radius of the nozzle throat section, $r_1 = 0$ - for the remaining dome, h- SRM casing' thickness.

- β is the winding angle, which is the angle formed by the tangent of the fiber trajectory with the tangent of the shell meridian.

- T_1 and T_2 are the internal forces in the meridional and parallel directions; R_1 and R_2 are respectively the radii of curvature in the meridional and parallel directions [8].

$$R_1 = -\frac{\sqrt{(1+r'^2)^3}}{r''} \qquad (1) \qquad\qquad R_2 = r.\sqrt{1+r'^2} \qquad (2)$$

where r', r'' are respectively the first and second derivatives of r with respect to z.

- p is the calculated pressure in the engine, and q is the force distribution at the polar hole.

Under pressure p, internal force components appear as the meridional force T_1 and the parallel force T_2 [8]:

$$T_1 = \frac{pR_2}{2}(1 - \frac{r_l^2}{r^2}) \tag{3}$$

$$T_2 = \frac{pR_2}{2}\left(2 - \frac{R_2}{R_1}(1 - \frac{r_l^2}{r^2})\right) \tag{4}$$

2.2. Stress-strain model of the SRM casing

- *Determine the dome profile of the SRM casings*: To determine the deformation of the SRM casing, it is first necessary to determine the dome profile that satisfies the condition of uniform stress distribution. According to [8], the system of equations describing the dome profile of the SRM connected to the nozzle, following a geodesic winding roving trajectory:

$$\begin{cases} r'' = \left(\tan^2\beta - \dfrac{2.r^2}{r^2 - C_p.r_{p1}^2}\right)\dfrac{1+r'^2}{r} \\ r\sin\beta = r_p = const \end{cases} \tag{5}$$

where $C_p = \left(r_l / r_p\right)^2$ - Coefficient nozzle radius.

For the dome closed by the igniter case ($r_l = 0$), the system of equations describing the dome profile becomes [8]:

$$\begin{cases} r'' = \left(\tan^2\beta - 2\right)\dfrac{1+r'^2}{r} \\ r\sin\beta = r_p = const \end{cases} \tag{6}$$

The boundary conditions for solving the system of equations describing the dome profile are: $z(0) = 0, r(0) = R, r'(0) = 0, \beta(0) = \beta_{xd}$, where β_{xd} - The winding angle at the equator.

- *Determine the thickness of casings:* Based on netting theory, the structural integrity of the pressure is assessed using the maximum fiber tensile stress criterion, whereby the structure is deemed safe when the tensile stress in the reinforcing fibers remains below the material's allowable tensile strength:

$$\sigma_d \le [\sigma_d]$$

where $[\sigma_d]$ - Longitudinal tensile strength composite materials.

Therefore, the thickness at the equator of the dome is determined by the following formula:

$$h_{xd} = \frac{p.R.(1 - r_l^2)}{2.[\sigma_d].\cos^2(\beta_{xd})} \tag{7}$$

In determining the composite thickness at the dome, we assume a constant fiber count across any section; thus, the thickness of the dome is determined by:

$$2.\pi.R.h_{xd}.\cos\beta_{xd} = 2\pi r.h.\cos\beta \tag{8}$$

From equation (8), we obtain the thickness of the helical winding layer:

$$h = h_{xd}.\frac{R.\cos\beta_{xd}}{r.\cos\beta} \tag{9}$$

To ensure the structural integrity of the casing, a hoop winding layer with a thickness of h_n is added to the cylindrical section. In this case, the forces in the parallel directions are defined as follows:

$$T_2 = \sigma_d.\left(h_{xd}.\sin^2\beta_{xd} + h_n.\cos^2\beta_{xd}\right) \tag{10}$$

By combining equations (9) and (10), we obtain the thickness of the hoop winding layer:

$$h_n = \frac{pR - [\sigma_d].h_{xd}.\sin^2\beta_{xd}}{[\sigma_d]} \tag{11}$$

Longitudinal tensile strength is determined by the following formula:

$$\sigma_d = \frac{T_1}{h.\cos^2\beta} \tag{12}$$

According to the mechanics of composite materials [8], the stress–strain relationship in the casing can be expressed as follows:

$$\varepsilon_d = \sigma_d / E_d \tag{13}$$

where σ_d, ε_d are the stress and strain in the direction longitudinal to the fiber axis; E_d is the elastic modulus of the composite material in the longitudinal direction.

3. STRESS–STRAIN MEASUREMENT TEST OF THE ROCKET MOTOR CASING

3.1. Determination of the mechanical properties of the composite material for SRM casing.

Composite materials are multiphase systems composed of two or more insoluble constituents, with their mechanical properties depending strongly on constituent type and ratio. Therefore, accurate determination of these properties is essential for designing solid-propellant SRM casings. For filament-wound fiber-reinforced composites, ring specimens are commonly used to evaluate properties along the fiber direction in axisymmetric structures [9]. According to GOST 25603-82, these specimens are fabricated using a steel mold consisting of two semicircular disks with a diameter of 150.5 ± 0.1 mm and a thickness of 20 ± 0.1 mm. Tensile testing determines the composite's tensile strength, elastic modulus, and relative elongation.



Figure 3. *Testing to determine the mechanical properties of composite materials.*



Figure 4. *Ring specimen before and after failure.*

The materials used for manufacturing the SRM casing and the test ring are presented in the following table.

Table 1. *Materials for manufacturing the composite SRM casing.*

No	Name and function	Material code	Origin	Physical form
1	Resin (Epoxy)	ED20	Russia	Liquid
2		EDG-1	Russia	Liquid
3	Polyester	P9-14	Viet Nam	Liquid

4	Curing agent	m-Phenylenediamine	China	Flakes
5	Carbon fiber T700	T700 12K	China	Solid

After testing, the mechanical properties of the composite material T700 carbon fiber/epoxy used for casing fabrication are presented in Table 2.

Table 2. *The mechanical properties of the T700 carbon fiber/epoxy composite.*

No.	Material	Material sample	Tensile strength, MPa	Elastic modulus, GPa	Relative elongation, %
1	T700 carbon fiber/epoxy composite	No. 1	1994	132,4	2,5
2		No. 2	1991	132,3	2,5
3		No. 3	1996	132,1	2,5
Average value			1993,7	132,2	2,5

3.2. Design and fabrication of SRM casing

The authors selected a design burst pressure of $p = 3p_{max} = 36$ MPa corresponding to a safety factor of $n = 3$. The resulting motor casing geometry and thickness distribution are shown in Figure 5. In addition, the winding angle distribution in the dome section was determined, as illustrated in Figure 6.

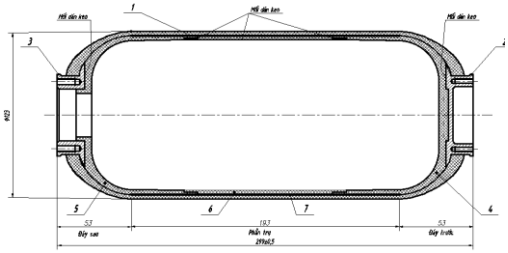


Figure 5. *Drawing of the SRM casing.*

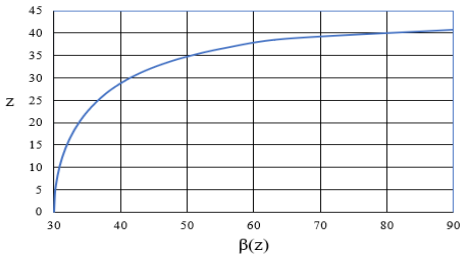


Figure 6. *Winding angle of the casing dome along the height z.*



Figure 7. *SRM casing.*

3.3. Stress–strain test of the composite material used for the SRM casing

To validate the reliability of the mathematical model, strain measurements of the composite rocket motor case were conducted using electrical resistance strain gauges. A total of eight strain gauges were installed on the motor case surface along the fiber direction, including six gauges located on the two dome sections and two gauges positioned on the cylindrical section. Measurements were performed under internal pressures of 12 MPa, 18 MPa, and 36 MPa. The arrangement of the strain gauges is shown in Figure 8.

The stress and strain distributions obtained from the calculation and experimental measurements are presented in Figures 10, 11. The results show good agreement between the predicted and measured values, confirming the reliability of the calculation in predicting the stress–strain behavior of the composite motor case under internal pressure. At the nominal operating pressure of 12 MPa, the maximum strain of the motor case was approximately 30×10^{-6} (%), corresponding to a maximum stress of 483 MPa, which is significantly lower than the allowable

strength of the composite material. When the internal pressure increased to 36 MPa, the maximum stress reached approximately 1450 MPa, while still remaining below the structural strength limit.

The analysis results indicate that both stress and strain gradually increase from the polar opening toward the dome equator, where the maximum values are observed. This behavior can be attributed to the smaller radius and, consequently, greater wall thickness near the polar opening, resulting in lower stress and strain levels compared with those in the equatorial region. The cylindrical section, reinforced with three hoop-winding layers, exhibits lower stress and strain levels than the transition regions. The most critical location of the structure was identified at the equatorial region of the aft dome, where the dome is connected to the nozzle assembly. Among all measurement locations, the maximum discrepancy between the calculation and experimental results was 5.6%, observed at the equator of the front dome under an internal pressure of 36 MPa. This discrepancy remained within the acceptable error range.



Figure 8. *The location of strain gages attached.*

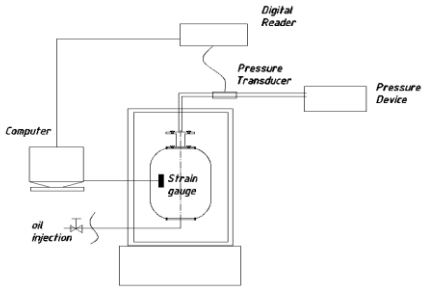


Figure 9. *Schematic diagram of the experimental setup.*

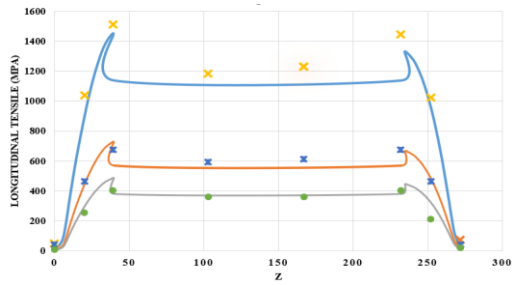


Figure 10. *Comparison of longitudinal tensile between calculated and experimental results. ×××●- experimental tensile in 36 MPa, 18 MPa, 12 Mpa. ▬▬▬- calculated tensile in 36 MPa, 18 MPa, 12 MPa.*

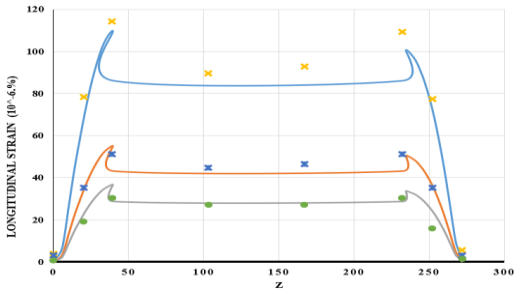


Figure 11. *Comparison of longitudinal strain between calculated and experimental results. ×××●- experimental strain in 36 MPa, 18 MPa, 12 MPa, ▬▬▬- calculated strain in 36 MPa, 18 MPa, 12 MPa.*

As the internal pressure increased to 38 MPa, a pressure drop and oil leakage occurred near the equatorial region of the aft dome at the nozzle connection, corresponding to the maximum stress and strain predicted by calculation. This indicated the initiation of localized composite damage, followed by rapid propagation due to stress concentrations and fiber breakage, ultimately causing loss of load-carrying capacity. The measured burst pressure was 5.2% higher than the design pressure because the calculated helical winding thickness did not correspond to an integer number of layers. Consequently, two helical layers were applied during manufacturing, resulting in a greater actual wall thickness and, therefore, a higher burst pressure.

3.4. Firing test SRM

Following the experimental evaluation of the stress-strain behavior of the SRM casing, five rocket motors were fabricated using the propellant grain as a winding mandrel. Static firing test

results demonstrated that the two composite motor casings operated stably for a duration of 20 s. Visual inspection of the external surface post-testing revealed that the structural integrity was maintained, with no evidence of cracking, blistering, or thermal deformation. Based on these findings, it can be concluded that the SRM casings fabricated from composite materials fully satisfy the design requirements, structural strength, sealing integrity, and operational conditions.



Figure 12. *Composite SRM casing before and after the firing test.*

4. CONCLUSIONS

This study developed and validated a methodology for designing composite solid rocket motor (SRM) casings using geodesic filament winding. Based on calculated results and experimental testing, the main conclusions are:

- The calculated results and experimental stress–strain distributions showed consistent trends, with maximum values concentrated in the equatorial region, identifying it as the critical region of the casing.

- At 38 MPa, pressure loss and oil leakage occurred near the equatorial region of the aft dome at the nozzle connection, coinciding with the predicted maximum stress and strain and confirming the model's ability to identify the critical failure location.

- Firing tests of five propellant-loaded motors confirmed adequate structural strength, pressure tightness, stability, and operational safety, with no critical damage or failure observed.

Overall, the results demonstrate the reliability of the proposed design and analysis methodology and provide a scientific and technological basis for the further development and application of composite SRM casing manufacturing technology in Vietnam.

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TÓM TẮT

Phân tích kết cấu và đo ứng suất -biến dạng của vỏ động cơ nhiên liệu rắn làm từ vật liệu composite sợi carbon T700/epoxy.

Thân vỏ động cơ nhiên liệu rắn bằng vật liệu composite chế tạo theo công nghệ quấn sợi được ứng dụng rộng rãi trong lĩnh vực hàng không vũ trụ nhờ khối lượng nhẹ, độ bền riêng cao và khả năng chịu áp suất lớn. Nghiên cứu này trình bày phương pháp thiết kế thân vỏ theo kỹ thuật quấn trắc địa và áp dụng cho thân vỏ động cơ sử dụng composite sợi carbon T700 trên nền epoxy làm việc ở áp suất cực đại 12 MPa. Các đặc trưng cơ học của vật liệu được xác định bằng thực nghiệm và sử dụng làm cơ sở tính toán thiết kế. Độ tin cậy của mô hình được đánh giá thông qua so sánh biến dạng đo bằng cảm biến biến dạng bố trí theo phương dọc trục sợi với kết quả tính toán dưới tác dụng của áp suất trong. Kết quả cho thấy sự tương đồng cao giữa thực nghiệm và tính toán về phân bố ứng suất, biến dạng cũng như vị trí chịu tải tới hạn của kết cấu. Trên cơ sở mô hình đã được kiểm chứng, thân vỏ động cơ sử dụng khối thuốc phóng làm lõi quấn được chế tạo và thử nghiệm đốt thành công. Kết quả nghiên cứu khẳng định tính khả thi của phương pháp thiết kế và tiềm năng ứng dụng công nghệ quấn sợi trong chế tạo thân vỏ động cơ nhiên liệu rắn bằng vật liệu composite tại Việt Nam.

Từ khoá: Đo ứng suất biến dạng thân vỏ động cơ từ vật liệu composite; Vị trí nguy hiểm thân vỏ.