Design and Analysis of End Ring for processing Solid Rocket Motor Segments

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ARTICLE INFO

ABSTRACT

Solid rocket motors are produced in the form of segments which are used as boosters in the launch vehicles. To produce any rocket segment, hardwares are subjected to a series of operations. The rocket hardwares are thin cylindrical shells which are very sensitive to the externally applied loads. During production, a number of handling operations are essential. A suitable interface is to be generated to cater to the production operations. These requirements are met by connecting a circular ring called End Ring to the hardware using the available hardware interfaces. This paper deals with Design and Analysis of HES Dome Side End Ring for Head End Segment.

Introduction

Rocket propulsion [1] is a class of jet propulsion that produces thrust by ejecting stored matter, called the propellant. The energy from a high-pressure combustion reaction of propellant chemicals, usually a fuel and an oxidizing chemical, permits the heating of reaction product gases to very high temperatures(2500 to 4100°C). These gases subsequently are expanded in a nozzle and accelerated to high velocities (1800 to 4300 m/sec). Since these gas temperatures are about twice the melting point of steel, it is necessary to cool or insulate all the surfaces that are exposed to the hot gases. According to the physical state of the propellant, there are several different classes of chemical rocket propulsion devices.

Liquid propellant rocket engines [1] use liquid propellants that are fed under pressure from tanks into a thrust chamber. The liquid bipropellant consists of a liquid oxidizer (e.g., liquid oxygen) and a liquid fuel (e.g., kerosene). In solid propellant rocket motors [1] the propellant to be burned is contained within the combustion chamber or case. The solid propellant charge is called the grain and it contains all the chemical elements for complete burning. Once ignited, it usually burns smoothly at a predetermined rate on all the exposed internal surfaces of the grain. Initial burning takes place at the internal surfaces of the cylinder perforation and the four slots. The internal cavity grows as propellant is burned and consumed. The resulting hot gas flows through the supersonic nozzle to impart thrust. Once ignited, the motor combustion proceeds in an orderly manner until essentially all the propellant has been consumed. There are no feed systems or valves.

For processing solid rocket segments a Harness assembly is being used to meet the process needs, which requires considerable amount of time and human effort for assembly and disassembly.

To meet all the production needs and to reduce the effort & time for assembly a pair of circular rings which are called End Rings are designed for each segment. Figure 1 shows the Head End Segment with HES Dome Side end ring.

The End Ring cross section is a closed hollow box section. The End Ring design of box section extended with internal shell in order to assemble with the interface of Head End Segment.
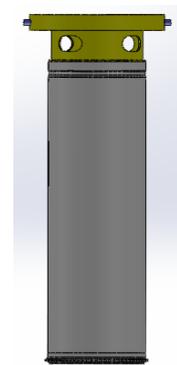

Figure 1. Segment with HES Dome Side End Ring

Nomenclature

W	Total load of segment in kg
a	Distance at which UDL is acting in m
b, b_0	Inner and Outer breadth of ring in m
h, h_0	Inner and Outer height of ring in m
R	Radius at which UDL is acting in m
q	Uniform load in N/m
θ	Angle at which forces are considered in rad
M	Bending moment in N-m
T	Twisting moment in N-m
σ	Bending stress in MPa
τ	Torsional Shear stress in MPa
σ_{equ}	Equivalent stress in MPa
Y	Maximum deflection in mm

Design Methodology

Selection of materials

The following Table 1 and Table 2 shows the properties of material used for End Ring and trunnion support.

Table 1. Material properties of Structural Steel[2]

Material	Property	value
Structural Steel (End Ring)	Young's Modulus (MPa)	210000
	Density (kg/m³)	7850
	Poisons ratio	0.3
	Ultimate Strength (MPa)	410
	Yield stress	240
	Allowable stress (MPa)	120

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Table 2. En24 steel material properties[3]

Material	Property	Value
En24	Young's Modulus (MPa)	210000
	Density (kg/m³)	7850
	Poisons ratio	0.3
	Ultimate Strength (MPa)	850-1000
	Yield stress	680
	Allowable stress (MPa)	340

Design Considerations

The End Ring is a circular elastic ring supported on trunnions and loaded normal to the plane of curvature. The axis of the ring is usually considered to be a plane curve and it is assumed that the ring maintains its circularity under load. Since load is acting normal to the plane of curvature the bending and twisting effects are considered simultaneously [4]. Here the design of End Ring for HES(Head End Segment) considering the ring supported on two trunnion supports with uniformly distributed load of End Ring as shown in Figure 2 is carried.
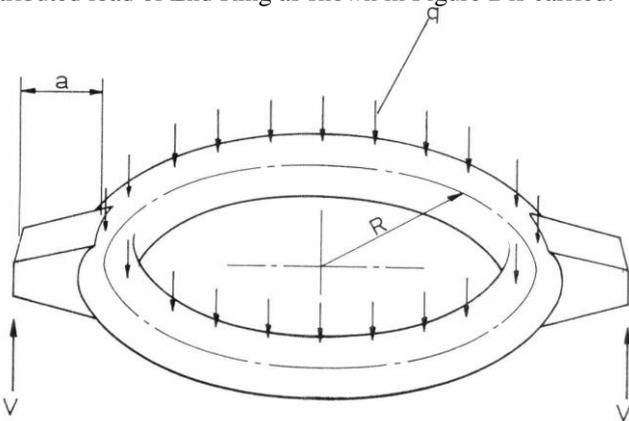

Figure 2: Ring on trunnion support with UDL

HES Dome Side End Ring on trunnion supports

Total load given, W = 27000 kg
Distance of Trunnion support from the ring, a = 0.308m
Radius at which UDL is acting, R = 0.571m
The cross section of the End Ring is hallow section.
Dimensions of the section , b = 0.238m
$$b_0 = 0.202m$$
$$h = 0.2m$$
$$h_0 = 0.168m$$
Uniform load, $q = \dfrac{W}{2\pi R}$ = 73827.26756 N/m

Bending moment at $\theta = 0$,
$$M = \frac{\pi q R \cos\theta}{2}(a + R) - qR^2$$
$$= 34134.47 \text{ N-m}$$
Bending stress in the section, $\sigma = \dfrac{M}{Z}$
$$= 51.52 \text{ MPa}$$
Twisting moment,
$$T = \frac{\pi q R \cos\theta}{2}(\alpha + R) + qR^2\left(\theta - \frac{\pi}{2}\right)$$
$$= 20394.99 \text{ N-m}$$
Torsional Shear stress, $\tau = \dfrac{T}{2[A]t}$
$$= 18.78 \text{ MPa}$$
Equivalent stress, $\sigma_{eqe} = \left(\sigma^2 + 3\tau^2\right)^{1/2}$
$$= 60.93 \text{ MPa}$$
Vertical Deflection,

$$y = \frac{qR^3}{8EI}\left[\pi(a+R)(1+\lambda)(2\theta\cos\theta - 2\sin\theta - \pi\cos\theta + \pi) + 4\lambda R(\pi\theta - \theta^2 - \pi\sin\theta)\right]$$
Maximum deflection at $\theta = 90°$
$$Y = 0.3 \text{ mm}$$

As the induced stress is less than the allowable stress, design is safe. The design can be safe up to 120MPa.

Design of trunnion pin for End Ring

Design of trunnion pin for End Ring
Diameter of the pin, d = 70mmTotal load on the end ring, W = 27000 kg = 264870 N
Load on end ring is distributed equally by two trunnions,
Length of the pin from end ring, L = 70 mm
Bending moment because of cantilever,
$$M = wl = 10872400 \text{ N-mm}$$
Pin material selected is En24
Cross sectional area of the pin, $A = \dfrac{\pi d^2}{4}$
$$= 3848.45 \text{ mm}^2$$
Moment of Inertia of the pin, $I = \dfrac{\pi d^4}{64}$
$$= 1178588.119 \text{ mm}^4$$
Section modulus of the pin, $Z = \dfrac{I}{y}$ = 33673.9 mm³

Bending stress induced in the pin, $\sigma = \dfrac{M}{Z}$ = 275.3 MPa

Shear stress, $\tau = \dfrac{w}{A}$ = 34.4 MPa

Equivalent stress, $\sigma_{equ} = \dfrac{\sigma}{2} + \dfrac{1}{2}\sqrt{\sigma^2 + 4\tau^2}$ = 279.5 MPa

Since all stresses are within allowable limits, the design is safe.

Modeling and Finite Element Analysis

Modeling

The considered designed values of End Ring is taken with the interfaces of Head End Segment is modeled using SolidWorks as shown in Figure 3 and further analysis is carried out.
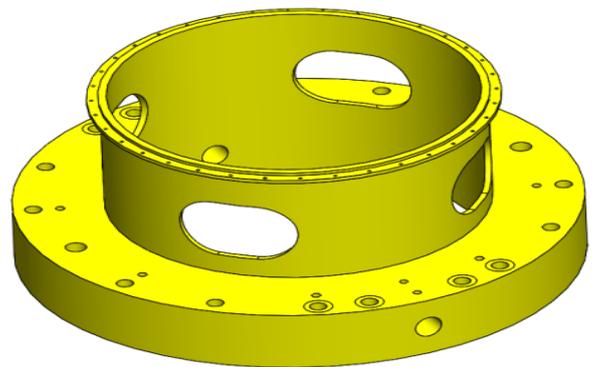

Figure 3. 3D modeling of HES dome side end ring

Finite Element Analysis

The results of structural analysis for a critical load case of 27tonns.

To simplify the model and to reduce the computational time truncated model is considered for FE analysis as shown in Figure 4. Since, the area of interest is on end ring the HES hardware is truncated to a height of around 500mm from the end ring skirt flange. The total load is applied as equivalent density to the truncated HES hardware based on its volume without changing the elastic properties of the material.
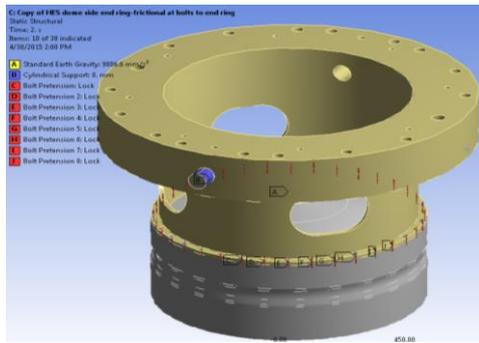
Figure 4. HES dome side end ring Loads & boundary conditions

Design Load : 27t

Volume of the HES hardware modeled: $1.293 \times 10^7 \text{mm}^3$

Equivalent density, $d_e = 2.08 \times 10^6 \text{kg/m}^3$

Number of Handling points: 2

Bolt Size: M8

No. of bolts: 36

Boundary Conditions : Cylindrical support at 2 trunnions (Axial: free, Radial: fixed, tangential: fixed)

Contacts:

● M8 socket head screw to HES is bonded contact.

● M8 socket head screw to End ring is frictional contact with 0.2 as coefficient of friction.

● HES Dome side end ring to HES and Trunnion to end ring are frictional contacts with 0.2 as coefficient of friction.
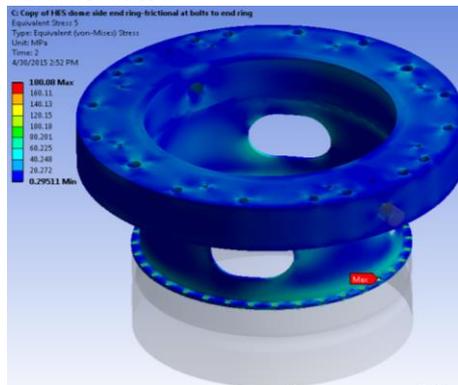
Equivalent stress: 100MPa

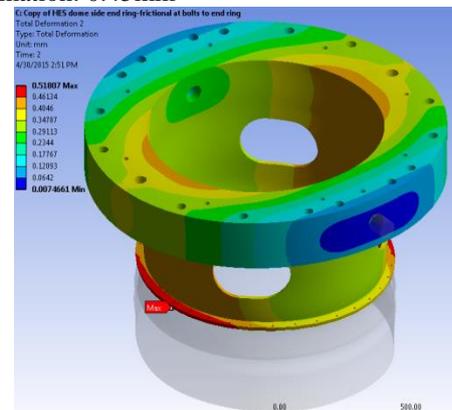**Figure 5: Equivalent (von mises) stress for End Ring**

Max deformation: 0.45mm

Figure 6: Total Deformation
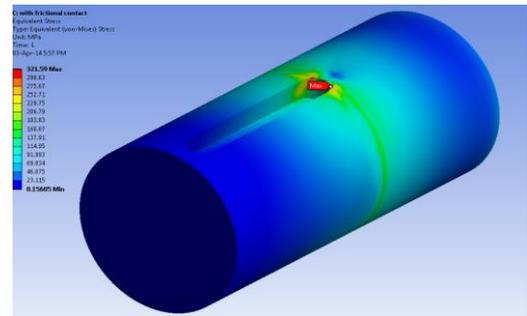
Equivalent stress: 212MPa

Figure 7: Equivalent (von mises) stress for Trunnion

Figure 3 and Figure 4 shows the equivalent stress and deformation is maximum at the internal shell with 100MPa and 0.45mm respectively. Figure 7 shows equivalent stress is maximum at the trunnion joint with 212MPa.

Conclusion

Following are the conclusions from the above results:

● End Rings for solid rocket motor segments are configured to meet all the process requirements.

● End Rings are designed theoretically using the classic methods derived from curved beam bending theory.

● Table 3 shows the theoretical, analytical and allowable stress and deflection values for HES Dome Side End Ring and Trunnion pin.

Table 3: Results from Static Analysis

Component	HES Dome Side End Ring		Trunnion pin
Parameter	Eq. stress (MPa)	Deflection (mm)	Eq. stress (MPa)
Theoretical value	60.93	0.3	279.5
Analytical value	100	0.45	212
Allowable value	120	1	340

● Static analysis of End Rings is carried out for vertical lifting condition which is the worst loading condition governing the design of end ring. From the results of theoretical and finite element results considerable variation is found between theoretical and FE results, this is because of the inherent assumptions in the theoretical model and idealization of the present problem in the form of existing theoretical model. Hence, from the above discussion it is concluded that the available theoretical model can be used for arriving the initial design parameters of the end ring.

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