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DESIGN AND ANALYSIS OF SEALS FOR EXTENDED SERVICE LIFE

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Introduction

Space Station Freedom is being developed for a service life of up to thirty years. As a consequence, the design requirements for the seals to be used are unprecedented. Full scale testing to assure the selected seals can satisfy the design requirements are not feasible. As an alternative, a sub-scale test program[4] has been developed by MSFC to calibrate the analysis tools to be used to certify the proposed design. This research has been conducted in support of the MSFC Integrated Seal Test Program. The ultimate objective of this research is to correlate analysis and test results to qualify the analytical tools, which in turn, are to be used to qualify the flight hardware.

Seals are simple devices that are in widespread use. The most common type of seal is the O-ring. O-rings seals are typically rings of rubber with a circular cross section. The rings are placed between the surfaces to be sealed usually in a grove of some design. The particular designs may differ based on a number of different factors. This research is totally focused on O-rings that are compressed by perpendicular clamping forces. In this type of seal the O-ring is clamped between the sealing surfaces by loads perpendicular to the circular cross section.

In spite of the relative simplicity of the O-ring it does not lend itself to analysis. Which is why O-rings have been so frequently designed based on handbook values, without extensive analysis. O-ring analysis is complicated by the inherent nonlinearities in the problem. The O-ring problem involves nonlinear geometric effects; due to the contact, or moving boundary, problem and the large deformations. It also involves nonlinear material effects; due to the material nonlinearities at large deformations (hyperelasticity) and the viscous behavior of the material (viscoelasticity). Current advancements in computational methods have led to the development of the tools that are capable of handling the O-ring problem.

Specific Problem Addressed

There are four basic design parameters that are to be considered in the development of an O-ring seal: O-ring cross sectional diameter, grove design, O-ring squeeze, and material. In this research a single O-ring diameter was considered. Grove design is typically selected from one of four fundamental grove shapes: rectangular -- no side wall contact, rectangular -- side wall contact, dove tail, and half-dove tail. This research addresses both types of rectangular groves, and the half-dove tail design. The O-ring squeeze levels range from 10% to as much as 50%. In this research three squeeze levels were considered: 15, 25, and 40%. The materials studied were selected from candidate materials for Space Station Freedom: Viton (Parker V747) and Silicone (Parker S383).

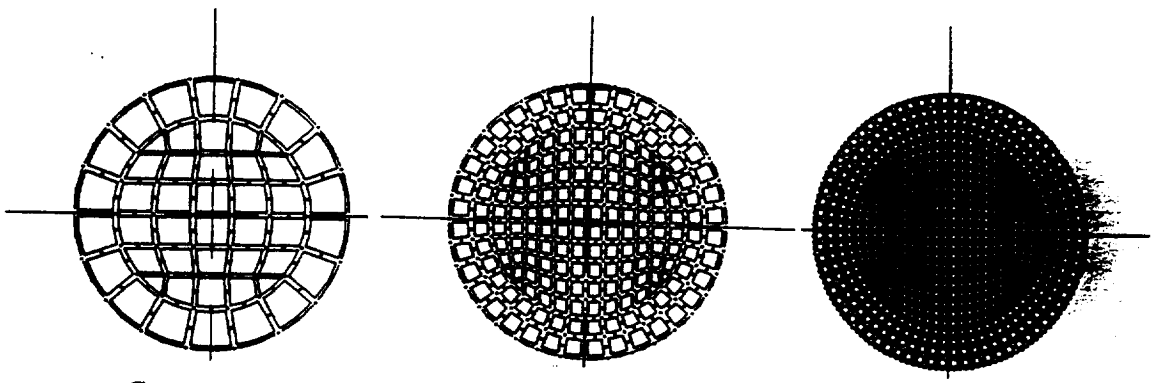
Method of Approach

The designs considered in this research were analyzed using a commercial finite element analysis code: ABAQUS by Hibbitt, Karlsson, and Sorensen, Incorporated. Preliminary model development was accomplished using EMS and IFEM by Intergraph and translation to ABAQUS and post processing using PATRAN by PDA. ABAQUS is a multipurpose finite element program developed without the classical assumptions of small displacements and rotations. It was used in this research because of its ability to analyze contact problems, nonlinear material behavior, and viscoelastic response.

Three finite element models were developed. Although O-rings present natural symmetries that may be used advantageously to reduce model size, symmetry was not used in any of the models developed. This was motivated by the desire to include axisymmetric behavior and pressure loads on internal surfaces. In the model development care was exercised to limit the number of triangular elements in the models. Further care was exercised to limit the skewness of the elements, maintain uniform element size, and maintain element aspect ratios near one. The models developed are shown in Figure 1 and the significant model characteristics listed in Table 1.

Table 1. Finite Element Model Characteristics.

Model	Number of Nodes	Total Number of Elements	Number of Triangular Elements
Coarse	202	86	4
Intermediate	633	244	8
Fine	1295	840	16



Coarse Model   Intermediate Model   Fine Model

Figure 1. O-Ring Finite Element Models.

The contact problem was analyzed through use of special purpose elements within ABAQUS. These elements require definition of the rigid surfaces in the model. The side wall contact – rectangular grove and the half dove-tail grove are shown in Figure 2. Note in the figure that the grove dimension change based on the squeeze used. The rigid surfaces are defined through use of line and arc segments. The letters in the figure designate ends of the segments and the numbers indicate the centers of the arcs. The coordinates of these points are listed in Tables 2 and 3.

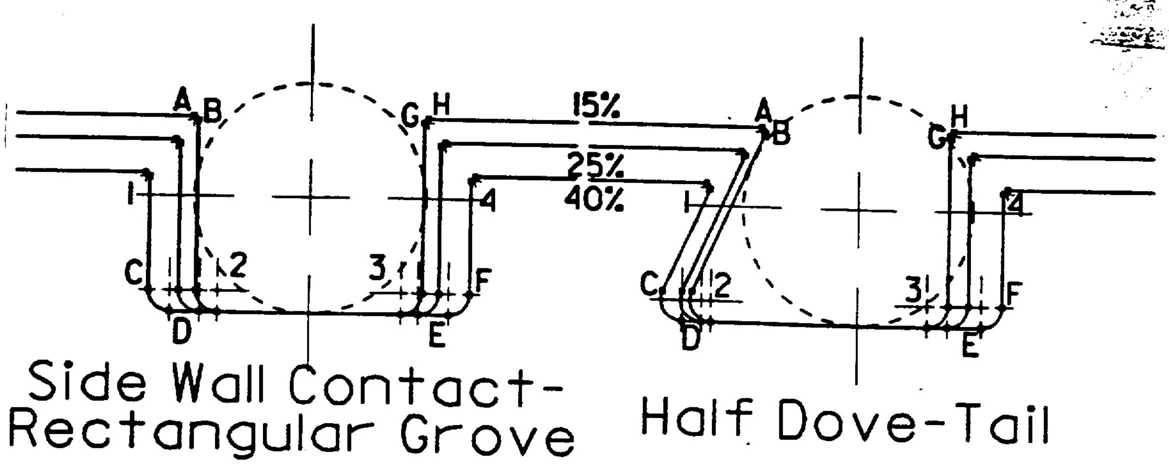


Figure 2. Candidate Grove Designs as Investigated.

Results

PATRAN and a special purpose program were used to analyze the results generated by ABAQUS. A separate translator was used to translate the results into PATRAN. This translator at this time does not support the contact element or apparently the axisymmetric elements in ABAQUS. PATRAN was used to produce plots of the deformed geometries, as shown in Figure 3, and contour plots of the stresses in the O-ring. Figure 3 shows three typical deformed geometries, 15% squeeze with no side wall contact, 15% squeeze with side wall contact, and 25% squeeze with side wall contact. Note the smaller contact areas on the horizontal surfaces for the higher squeeze. This is due to the different grove dimensions between the models.

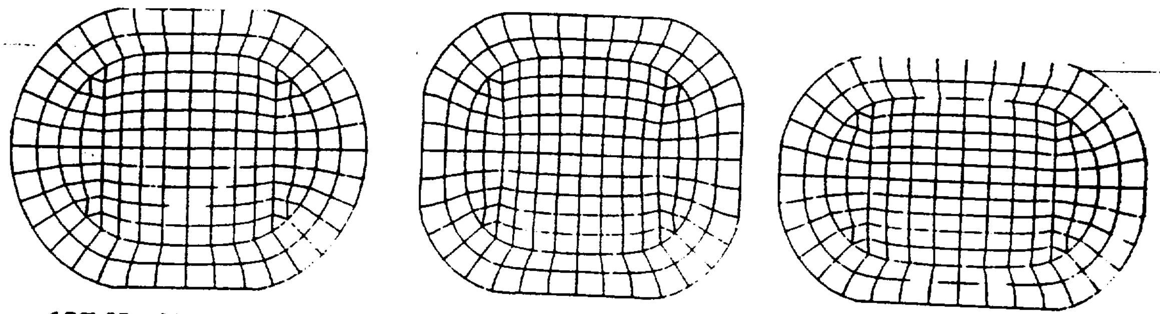
The translator files were used to calculate a von Mises stress and the strain energy at each node. These values were also plotted using PATRAN.

Table 2. Side Wall Contact - Rectangular Grove Coordinates Relative to O-Ring Center.
All units are in inches.

Position	15% Squeeze		25% Squeeze		40% Squeeze	
	x	y	x	y	x	y
A	-0.1395	0.0965	-0.1600	0.0685	-0.1960	0.0275
Center - 1	-0.1395	0.0915	-0.1600	0.0635	-0.1960	0.0225
B	-0.1345	0.0915	-0.1550	0.0635	-0.1910	0.0225
C	-0.1345	-0.1125	-0.1550	-0.1125	-0.1910	-0.1125
Center - 2	-0.1095	-0.1125	-0.1300	-0.1125	-0.1660	-0.1125
D	-0.1095	-0.1375	-0.1300	-0.1375	-0.1660	-0.1375
E	0.1095	-0.1375	0.1300	-0.1375	0.1660	-0.1375
Center - 3	0.1095	-0.1125	0.1300	-0.1125	0.1660	-0.1125
F	0.1345	-0.1125	0.1550	-0.1125	0.1910	-0.1125
G	0.1345	0.0915	0.1550	0.0635	0.1910	0.0225
Center - 4	0.1395	0.0915	0.1600	0.0635	0.1960	0.0225
H	0.1395	0.0965	0.1600	0.0685	0.1960	0.0275

Table 3. Half Dove-Tail Grove Coordinates Relative to O-Ring Center.
All units are in inches.

Position	15% Squeeze		25% Squeeze		40% Squeeze	
	x	y	x	y	x	y
A	-0.1162	0.0965	-0.1402	0.0685	-0.1810	0.0275
Center - 1	-0.1162	0.0915	-0.1402	0.0635	-0.1810	0.0225
B	-0.1116	0.0895	-0.1356	0.0615	-0.1764	0.0205
C	-0.1970	-0.1023	-0.2086	-0.1023	-0.2311	-0.1023
Center - 2	-0.1742	-0.1125	-0.1857	-0.1125	-0.2082	-0.1125
D	-0.1742	-0.1375	-0.1857	-0.1375	-0.2082	-0.1375
E	0.0835	-0.1375	0.1075	-0.1375	0.1475	-0.1375
Center - 3	0.0835	-0.1125	0.1075	-0.1125	0.1475	-0.1125
F	0.1085	-0.1125	0.1325	-0.1125	0.1725	-0.1125
G	0.1085	0.0915	0.1325	0.0635	0.1725	0.0225
Center - 4	0.1135	0.0915	0.1375	0.0635	0.1775	0.0225
H	0.1135	0.0965	0.1375	0.0685	0.1775	0.0275



15% No side wall Contact **15% Side Wall Contact** **25% Side Wall Contact**

Figure 3. Typical Deformed Geometries.

Conclusions

ABAQUS is an excellent tool for addressing seal performance. However, at this time the program is not capable of performing hyperelastic-viscoelastic analyses. For viscoelastic analyses the program is limited to elastic-viscoelastic analyses. This addresses the nonlinear aspect of the contact problem and the associated large deformations, but does not include the nonlinear material behavior associated with the large deformations.

A second, potentially less troublesome, limitation of the code is the limitation to a single time dependent material property. In the code the shear stress relaxation modulus and the bulk stress relaxation modulus differ only by a scale factor (which can be zero). This may not be an accurate description of the material behavior.

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