EXPERIMENTAL STRESS ANALYSIS OF ROCKET MOTOR CASING USING ELASTO-PLASTIC STRAIN THEORY

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ABSTRACT

The purpose of rocket motors is to generate thrust or impulsive force to be passed on an inclined velocity to flight vehicle to transport its payload to its required target. It will be subjected to high pressure loads and temperature during the operating conditions of the motor mechanism. So, while selecting the material for the manufacturing of motor case, utmost care has to be taken, because the material chosen has to withstand all kinds of structural and thermal loads acting on it. 15CDV6 steel is one of the latest trends, used in the design of rocket motors due to its high strength and hardness. The unique quality of 15CDV6 steel is that, it is a hypo-elastic material. This paper intends to analyze and evaluate the performance of 15CDV6 steel in its elasto-plastic range. Three specimens of the material were evaluated with the help of tensile tests and strain gauge data. For calculations, plane stress condition has been considered. From the resulting design parameters, a code was developed on the digital computer using Microsoft Excel, to create data sheets which produce stress data as output, when strain data is given as input. This code is also helpful in quickly analyzing the material behavior by finding the factor of safety for the casing.

KEYWORDS: Motor Casing, Strain Gauges, Elasto- Plastic Range & Microsoft Excel

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1. INTRODUCTION

A rocket engine is a standard energy shift system. High pressure as well as high temperature combustion product gases have been enlarged via converging-diverging nozzle. With the procedure, internal energy of the gas will be transformed to kinetic energy of the fatigue flow; also the thrust was created through gas force over the surfaces subjected to this gas [8]. Solid propellant rocket engine was majorly utilized than the other rocket engines because of its comparatively easy model, higher reliability, simplicity of production also prepared to work with on demand. Since solid-fuel rockets may stay in stock for extended durations, and then reliably initiate on short note, they've been often utilized in military programs like missiles. Nevertheless, it is often utilized together with strap-on boosters to maintain payload potential. An easy solid rocket engine is made up of motor casing, nozzle, inner insulation, propellant grain as well as igniter. The choice of substance for rocket engine parts relies upon high particular power, high particular modulus, fabrication uncomplicated, simple accessibility, crucial needs as well service requirements [6]. Majorly utilized substances for solid rocket engine parts were 15CDV6 steel, M250 Steel, Titanium alloy, Aluminium Alloys. The 15CDV6 steel was high powered steel including fewer concentrations of chromium, molybdenum, and vanadium because alloying components. Due to its great power-ductility integration and also simplicity of fabrication, the substance was broadly utilized in rocket-motor hardware at the Indian space program. This metal locates numerous programs in the aerospace as well as motorsports businesses in these elements

like roll cages, pressure vessels, suspension systems such as desire bones along with sub-frames, rocket motor casings [3]. It's a low-alloy steel, where the ratio by weight of whole alloying components united was lesser than 5% [4]. Its chemical composition is shown in table 1, and mechanical attributes are displayed in table 2.

Table 1: Chemical Composition of 15CDV6 Steel

Composition	C	Cr	Mo	V	Fe	Mn	S	P	Si
Weight %	0.12-0.18	0.25-1.5	0.8-1.0	0.2-0.3	Balance	0.08-1.1	0.015 max	0.02 max	0.2 max

Table 2: Mechanical Properties of 15CDV6 Steel at Room Temperature

Property	Tempering at 650oC and air cooling	Tempering at 625oC and oil cooling
Tensile strength (N/mm2)	105	115
Yield point (N/mm2)	85	100
Elongation %	16	16
Impact strength (N/mm2)	9	13

The rocket motor casing is built up by welding of number of sheets. Firstly, a long rectangular sheet is rolled into a cylinder and then a long seam of weld is done. This welded cylinder is then welded to a similar cylinder by a circular seam. This is continued until the desired size of the rocket motor casing is obtained. Then at the ends of the casing, the thrust skirt and other parts will be welded. After welding the heat treatment for the entire case has to be carried out. Strain gauges are scaled mainly in the cylindrical part, closer the long seam weld joint as the motor case under high internal pressure.

A state of plane pressure exists at each stage on the surface of a member subjected to the given loading. Generally, the condition of plane strain is biaxial along with the parallel deformations are tri-axial. At any provided stage, the direction of principal normal stresses σ_{max} and σ_{min} lie in a plane, where is tangential to that point. In investigational strain experimentation utilizing oil gauges, normally, toils in the surface, i.e., in the tangential plane were discovered in minimum three ways, and from the principal ways 1 and 2, the principal toils ϵ_1 and ϵ_2 may be decided.

In this work, as the strain gauges have been used, the evaluation of stresses depends on the positioning of the gauges on the specimen, as direction is one of the most essential parameters for such setups. A foil type strain gauge was used for this study. From elementary mechanics of materials, the strain at an angle is provided as,

$$\epsilon_{\theta} = \frac{\epsilon_x + \epsilon_y}{2} + \left(\frac{\epsilon_x - \epsilon_y}{2} \right) \cos 2\theta + \frac{1}{2} \gamma_{xy} \sin 2\theta$$

In every scenario, the computations were clarified if the X axis was selected to correspond with $\theta=0$. Afterwards, for both kinds of rosette configurations, then the required equation reduces to $\epsilon_0 = \frac{1}{2}(\epsilon_x + \epsilon_y) + \frac{1}{2}(\epsilon_x - \epsilon_y) = \epsilon_x$

and ϵ_x is directly obtained from the ϵ_0 strain gauge reading. Similarly, for the rectangular rosette ϵ_y is directly obtained from the ϵ_{90° reading [1]. The toil in the x direction in a substance exposed to three mutually perpendicular pressures in the x, y and z directions is provided as $\epsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y - \nu\sigma_z)$

Identical equations put in for ϵ_y and ϵ_z . Consequently, the principal strain at a provided direction could be located in terms of the principal stresses. For two proportional scenario,

$$\sigma_1 = \frac{(\epsilon_1 + \nu\epsilon_2)E}{(1-\nu^2)} \text{ and } \sigma_2 = \frac{(\epsilon_2 + \nu\epsilon_1)E}{(1-\nu^2)} \quad (1)$$

Von mises' theory, commonly, mentioned for the tri-axial strain state using the uni-axial equivalent strain σ_v , was officially with the strain-energy theory. Comparing with similar theories for formulation of equivalent strain (e.g., common strain or shear strain theories), it indicates the better outcomes for isotropic ductile metallic substances. In the above equation, through replacing with the yield strain σ_y , the yield state was acquired. For plane-strain state with $\sigma_3=0$, above equation modifies to $\sigma_v^2 = \sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2$ (2)

Because in the investigational strain examinations utilizing strain gauges, strain is being estimated, it was extremely stable to state a deformation basis than the equivalent strain. Hence, upon above equation, the equivalent strain ϵ_v could be mentioned as

$$\epsilon_v = \frac{\sigma_v}{E} \quad (3)$$

As Hooke's equations states a linear association among pressures as well as deformations, the equivalent strain, ϵ_v could be decided instantly from the principal strains $\epsilon_v^2 = \epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2 - \epsilon_1\epsilon_2 - \epsilon_2\epsilon_3 - \epsilon_3\epsilon_1$

Since, $\nu = (1 + \theta)^2$, The above equation can now be written as

$$\epsilon_v = \frac{1}{(1+\theta)} \sqrt{\epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2 - \epsilon_1\epsilon_2 - \epsilon_2\epsilon_3 - \epsilon_3\epsilon_1} \quad (4)$$

The strain ϵ_3 which cannot be estimated using strain gauges is removed through utilizing the formula =

$$\sqrt{N_q(\epsilon_1^2 + \epsilon_2^2) + N_g(\epsilon_1\epsilon_2)} \quad (5)$$

$$\text{Where, } N_q = \frac{1-\theta(1-\theta)}{(1-\theta^2)^2} \quad (6)$$

$$N_g = \frac{-1+\theta(4-\theta)}{(1-\theta^2)^2} \quad (7)$$

In this, N_q and N_g were expressions of Poisson's ratio. For stable equivalent strain, ϵ_v was stable as well as the equation indicates an ellipse where form was decided using Poisson's ratio. This was very simply identified, while the equation was divided by ϵ_v and squared

$$N_q \left(\frac{\epsilon_1^2}{\epsilon_v^2} + \frac{\epsilon_2^2}{\epsilon_v^2} \right) + N_g \left(\frac{\epsilon_1\epsilon_2}{\epsilon_v^2} \right) = 1 \quad (8)$$

The principal axes of the ellipse were prepared at 45° to the ϵ_1 - ϵ_2 co-ordinate system along with their lengths were $2a = \frac{2}{\sqrt{N_q+0.5N_g}}$; and $2b = \frac{2}{\sqrt{N_q-0.5N_g}}$ respectively. Thus by including variable features, irrespective of the stable modulus of elasticity E and Poisson's ratio θ , the elasto-plastic substance reaction could be officially explained in the similar format like linear-elastic behavior as

$$\epsilon_v = \frac{\sigma_v}{S} \quad (9)$$

Where, S is the secant modulus. The total equivalent strain ϵ_v in accordance with equation is made of elastic as well

as a plastic element. Consistently, an integrated Poisson's ratio ϑ_g for the entire deformation lies among Poisson's ratio ϑ also 0.5. ϑ_g relies upon the magnitude of deformation then reaches 0.5 for larger plastic-strain elements, $\vartheta \leq \vartheta_g(\epsilon_v) \leq 0.5$. The secant modulus describes only a point on the stress-strain curve, hence itself an expression of the equivalent strain ϵ_v . for a known value of equivalent strain, the values of Secant modulus could be read off from the stress-strain curve. With the Secant modulus as well as integrated Poisson's ratio, Hooke's stress-strain associations are reasonable for plane-stress states. Thus for the elasto-plastic range, the principal pressures will be

$$\sigma_1 = \frac{S}{1-\vartheta_g^2}(\epsilon_1 + \vartheta_g \epsilon_2) \quad (10)$$

$$\sigma_2 = \frac{S}{1-\vartheta_g^2}(\epsilon_2 + \vartheta_g \epsilon_1) \quad (11)$$

$$\text{Where, the combined Poisson's ratio is given by } \vartheta_g = 0.5 - (0.5 - \vartheta) \frac{S}{E} \quad (12)$$

To be valid, the above two equations pre-suppose isotropy; hence the co-axiality was assured. Thus the principal pressures as well as principal strains have similar ways.

2. METHODOLOGY AND EXPERIMENTATION

The heat treated specimen, as shown in figure 2 is tested on BiSS Universal testing machine shown in figure 4, with the load on the specimen is increased continuously, until the fracture load is obtained. The strain of the material versus the stress induced curve is simultaneously obtained on the monitor, and the stress-strain data is plotted accordingly and is shown in figure 3. From the tensile test data, curve fitting was done and the factor of safety (n) value was evaluated. All specimen tensile test data was taken for the evaluation of factor of safety, and n value will be finalized based on method of least squares for error approximation. Strain gauges have been installed at different locations on the Rocket motor as shown in figure 1, and pressure was applied. The pressure was first increased and then decreased in steps. The variation of strains with respect to the pressure has been recorded and shown in table 5 and 6. In this work, a code is developed based on the theoretical equations [2] with Microsoft Excel, with the flow chart mentioned to run on the digital computer. Once the strain gauge readings are substituted into the code, the final results of stresses will be displayed as shown in table 7 and 8.

Figure 1: strain gauges attached at different locations of rocket motor casing

Figure 2: specimens tested under UTM

3. RESULTS AND DISCUSSIONS

The final stage of analysis consists of the evaluation of the factor of safety, and checking for it being in the permissible

limits. The permissible limits of the factor of safety have been found from theoretical equations and checked the value from experimentation. The leastsquares procedure is a form of mathematical regression examinations that locates out the line of best suits for a set of information, giving a visual presentation of the association among the data points. Every stage of informationis indicative of this association among a famous individual factor as well as an unknown dependent factor. It offers the general reason for the position of the line of best match, one of the data points being analyzed. The major typical use of this least squares procedure, that can be known as linear or ordinary, intends to make a direct line which reduces the amount ofthe squares of the mistakes created through the outcomes of the related equations,like the squared residuals caused by distinctions from the noticed value,and the value expected depending on the design. The technique of regression examinationsstarts with a pair of data points to be drawn in an x- and y-axis graph. Anevaluation with the least squares procedure will find a line of best fit, which clarifies the possible connection among an independent factor as well as adependent factor.

In regression examinations, dependent factors werelected on the vertical Y-axis and independent variables were selected on the horizontal X-axis. These selections will form the equation for the line of best match. The equation for the line $y = mx + b$, m = slope or gradient, b = y-intercept (where the line crosses the y-axis).

The slope can be calculated as, $m = \frac{N \sum(xy) + \sum x \sum y}{N \sum x^2 + (\sum x)^2}$

N is the number of points. The Intercept b can be calculated as $b = \frac{\sum y - m \sum x}{N}$. The slope of the graph for the specimen 1 is calculated within the elastic range, using a scatter diagram from figure 3. The line equation of elastic range is $y = 209091x - 17.455$. Hence, Young's modulus = 209.091 Mpa. The factor of safety $n = \frac{\ln(2)}{\ln(\frac{E\epsilon_0}{\sigma_0})}$, the values of σ and ϵ are obtained from a point on the curve, intersecting at 0.2% offset yield stress. From the above data we get $n = 2.114143537$. Similarly we can calculate the young's modulus and factor of safety for specimen 2 and 3, and shown in table 3.

Table 3: The Young's Modulus and n Values

	Specimen 1	Specimen 2	Specimen 3
Modulus of Elasticity(MPa)	209.091	219.623	226.455
Factor of safety(n)	2.1141	2.1581	2.1543

It is observed that the n value is slightly different for different specimens because, this error is vanished by finding the best fitting straight line, through the set of data points obtained. Hence from least square curve fitting, we finalize the best value of n suiting the specimens considered. The final values of Modulus of elasticity (E) are 220 Mpa and the factor of safety (n) is 2.145. The following is a clarified method that was designed on a digital computer, for the pressure examinations in the elasto - plastic range, with the help of foil gauges. Depending on the biaxial strain area, an equivalent foil ϵ_v was ascertained through replacing an estimated principal foils ϵ_1 along with ϵ_2 into the equation. The values of ϵ_1 and ϵ_2 are obtained from the strain gauge data. Considering at location 3 from table 5, for a pressure of 30 ksc, the values of ϵ_a , ϵ_b and ϵ_c are 1818, 1152 and 478, respectively. Then, from equation (4),

$$\epsilon_{1,2} = \frac{\epsilon_a + \epsilon_c}{2} \pm \frac{1}{\sqrt{2}} \sqrt{(\epsilon_a - \epsilon_b)^2 + (\epsilon_b - \epsilon_c)^2}$$

$$\epsilon_1 = 0.001818 \text{ and } \epsilon_2 = 0.000477$$

Assuming $\vartheta = 0.3$, Equation (5) can be written as,

$$\epsilon_v = \sqrt{N_q(\epsilon_1^2 + \epsilon_2^2) + N_g(\epsilon_1\epsilon_2)} = 0.00186$$

$$\text{Where, } N_q = \frac{1-\vartheta(1-\vartheta)}{(1-\vartheta^2)^2} = 0.95399$$

$$N_g = \frac{-1+\vartheta(4-\vartheta)}{(1-\vartheta^2)^2} = 0.13283$$

In this, N_q and N_g are functions of positions ratio, which is originated from the distortion energy theory. The pressure σ_y correlating to ϵ_v has acquired from the uniaxial stress-strain curves of the substance. In the plastic area, Secant modulus of elasticity S has considered equal to σ_y/ϵ_v . Accordingly, the combined Poisson's ratio for the entire deformation rest among Poisson's ratio ϑ and the 'plastic' Poisson's ratio 0.5[2].

$$\text{From equation (12), } \vartheta_g = 0.5 - (0.5 - \vartheta) \frac{S}{E} = 0.3095$$

The three unknowns, ϵ_v , σ_v and S have been decided from the above equations and the uniaxial stress-strain curve. A constitutive relationship, which offers the pressure as an explicit expression of the foil was very helpful in the

investigation. This association was $\sigma = E\epsilon(1 + (\frac{\epsilon}{\epsilon_0})^n)^{-\frac{1}{n}} = 38.815$

Where σ was the pressure, E is the Young's modulus, ϵ was the toil, ϵ_0 is the plastic toil as well as n was a parameter describing the form of the nonlinear stress-strain association. However, in this equation, the stress reaches the plastic stress asymptotically with raising toil. The consistent n and ϵ_0 can be determined approximately by curve fitting by the method of least squares. $n = \frac{\ln(2)}{\ln(\frac{E\epsilon_0}{\sigma_0})} = 2.145$

Here, the values of σ_0 and ϵ_0 were acquired from the point on the curve at the place where the curve intersects the line of 0.2% Offset yield stress. The precision of illustration of the stress-strain curve explained in the stress equation above can be enhanced further through alternating the values of ϵ_0 as well as n by least-square curve fit. The value of Secant modulus S for indicated values of E, ϵ_0 can be directly obtained as $S = E(1 + (\frac{\epsilon}{\epsilon_0})^n)^{-\frac{1}{n}} = 20868.7$

Using the above equations, one might obtain the Secant Poisson's ratio ν_g in terms of ϵ_v as

$$\nu_g = 0.5 - (0.5 - \nu)(1 + (\frac{\epsilon}{\epsilon_0})^n)^{-\frac{1}{n}} \text{ (From equation (12))}$$

$$\text{Also, from equation (5), } \epsilon_v = \sqrt{N_q(\epsilon_1^2 + \epsilon_2^2) + N_g(\epsilon_1\epsilon_2)}$$

Since in the above two equations, ν_g and ϵ_0 are inter-dependent, an iteration procedure was required to assess the correct values of ϵ_0 and ν_g that can fulfill both the equations. Once the value of ϵ_0 was accepted, the Secant modulus of elasticity S could be calculated. The iteration process for the evaluation of ν_g and ϵ_0 was as mentioned. Originally, the integrated Poisson's ratio was presumed as ν as well as replaced with the equation (2) to get ϵ_0 for the indicated values of ϵ_1 and ϵ_2 . The value of ϵ_0 was replaced with equation (1) to get ν_g . Utilizing the value of ν_g , substituting in equation (2), ϵ_0 is obtained. This iteration procedure was to be carried on till the un-known ν_g and ϵ_0 fulfill both the equations with the determined level of perfection. Three to four iterations might be needed to acquire correct values of ν_g along with ϵ_0 . Obtaining values are,

$$\nu_g = 0.3095, S = 20868.7 \text{ and } \epsilon_0 = 0.005$$

With the Secant modulus as well as integrated Poisson's proportion, the principal pressures σ_1 as well as σ_2 could be computed with the Hooke's equations from the biaxial pressure states were

$$\sigma_1 = \frac{S}{1-\nu_g^2}(\epsilon_1 + \nu_g\epsilon_2) = 45.365 \text{ Ksi and } \sigma_2 = \frac{S}{1-\nu_g^2}(\epsilon_2 + \nu_g\epsilon_1) = 23.995 \text{ Ksi}$$

Because the formulation of the fact was common, the evaluation of principal pressures and estimated principal toils in elastic and elasto-plastic ranges could be decided. The iteration process defined here was programmed on a digital computer using Microsoft Excel. From the code, the evaluation of stresses from strains has been done and the results have shown in table 7 and 8. An element of protective reveals how much powerful a structure was, than it requires to be for a considered load. For the given material, the 0.2% Proof Stress is found to be 1014 MPa and Ultimate Tensile Strength is 1150 MPa. By referring table 7, The Factor of safety at location 1, at a pressure value of 51 ksc is :

$$\text{Factor of safety (n) at 0.2\% proof stress} = \frac{0.2\% \text{ proof stress}}{\text{actual stress}} = \frac{1014}{80.7 \times 9.81} = 1.28, \text{ and the Factor of safety (n) at 0.2\% UTS is}$$

calculated as $\frac{\sigma_{\text{max}}}{\sigma_{\text{allow}}} = \frac{1150}{80.7 \times 9.81} = 1.45$. In the similar manner, the factor of safety is calculated at different locations of casing and shown in table 4.

Table 4: Factor of Safety evaluated at distinct Places

Location	1	2	3	4	5	6	7	Minimum FOS
0.2% PS	1.28	3.61	1.62	1.61	1.86	1.49	2.14	1.28
UTS	1.45	3.57	9.07	4.10	1.60	2.95	1.84	1.45

4. CONCLUSIONS

- Investigational pressure examinations were conducted on the rocket motor casing created of 15CDV6 steel, from which it is found that, the principal stresses and Factor of safety are in the permissible limits at various locations
- The Factor of Safety obtained is much lower than that can be obtained from the analysis in the linear region. Thus, the design that is a result of such an analysis is safer
- It is also observed that the stresses calculated are found to be more concentrated at critical sections like bolts and welded areas of the rocket motor casing.
- Factor of Safety for 0.2% proof stress was found to be 1.28, while the Factor of Safety for Ultimate Tensile Strength was found to be 1.45
- This code can be here on used for the stress-strain analysis conveniently, and also consumes less time, manually calculating the parameters.

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APPENDIX

Figure 3: Stress vs Strain plot for Specimen 1

Figure 4: BiSS Universal Testing Machine

Table 5: Experimental values ϵ_a , ϵ_b and ϵ_c obtained from the strain gauge rosettes at locations 1,2 and 3

Pressure in ksc	location 1			location 2			location 3		
	1'00	1'45	1'90	2'00	2'45	2'90	3'00	3'45	3'90
0	2	2	2	0	-1	0	1	0	1
10	357	675	1064	28	149	254	556	351	127
0	7	16	25	1	4	5	5	2	-2
10	357	673	1065	28	150	253	555	350	126
0	5	11	19	0	2	4	4	1	-2
35	1155	2116	3330	94	533	914	2181	1347	561
0	1	1	1	1	1	1	1	1	1
10	357	667	953	29	150	251	553	355	130
20	692	1273	1898	55	301	510	1185	757	304
30	1010	1830	2757	81	455	775	1818	1152	478
48	1516	2760	4278	129	735	1263	3032	1866	781
51	1591	2909	4547	137	782	1346	3255	1993	834
56	1722	3162	4993	150	862	1487	3651	2225	930
56	1713	3172	5052	151	862	1488	3711	2254	939
51	1574	2929	4660	138	784	1348	3364	2044	848
48	1485	2782	4441	129	736	1265	3175	1927	796
40	1251	2391	3856	108	612	1048	2688	1620	660
30	947	1876	3070	82	457	778	2068	1233	488
20	631	1323	2222	56	303	511	1444	841	316
10	301	733	1298	29	152	252	825	449	145
0	-50	80	258	0	2	-3	280	103	20

Table 6: Experimental values ϵ_a , ϵ_b and ϵ_c at locations 4, 5, 6 and 7

Pressure in ksc	location 4			location 5			location 6			location 7		
	4'00	4'45	4'90	5'00	5'45	5'90	6'00	6'45	6'90	6'00	6'45	6'90
0	3	2	1	1	1	1	2	2	0	6	4	2
10	634	379	110	431	182	-21	846	507	203	326	262	180
0	12	8	1	1	-4	-7	18	10	4	-6	1	-1
10	634	379	108	432	181	-21	846	507	203	324	261	179
0	9	6	2	2	-3	-6	14	8	4	-5	-1	-2
35	2283	1360	446	1862	991	232	2669	1558	630	1432	1032	683
0	1	1	1	1	1	1	1	1	1	1	1	1
10	634	379	108	438	191	-16	843	503	202	338	266	184
20	1285	766	243	999	502	73	1598	942	382	782	577	381
30	1927	1148	375	1566	829	179	2299	1348	548	1234	884	569
48	3131	1867	626	2627	1445	394	3503	1995	834	1979	1388	961
51	3343	1996	665	2815	1553	433	3681	2078	882	2088	1462	1038
56	3739	2240	737	3163	1753	501	3976	2224	967	2281	1593	1164
56	3790	2272	750	3199	1766	503	3979	2209	969	2262	1577	1184
51	3443	2059	675	2887	1581	439	3676	2040	890	2038	1430	1079
48	3255	1948	634	2712	1478	401	3487	1930	843	1895	1335	1023
40	2765	1654	527	2259	1211	306	2991	1641	721	1523	1090	880
30	2144	1283	393	1688	876	189	2351	1266	563	1060	782	698
20	1517	908	261	1119	549	81	1684	877	398	604	475	510
10	884	530	129	561	239	-8	976	464	223	161	172	318
0	248	154	27	110	48	12	195	-3	27	-162	-78	140

Table 7: Principal stresses and equivalent stress at locations 1, 2 and 3

Pressure in ksc	location 1			location 2			location 3		
	σ_1	σ_2	σ_v	σ_1	σ_2	σ_v	σ_1	σ_2	σ_v
0	225.79	240.39	110	219.56	219.56	110	168.42	194.15	110
10	27.92	16.15	24.28	6.34	2.51	5.53	14.32	7.09	12.4
0	0.66	0.35	0.57	0.14	0.06	0.11	0.1	-0.01	0.11
10	27.95	16.15	24.3	6.32	2.5	5.51	14.28	7.05	12.37
0	0.5	0.26	0.43	0.1	0.03	0.09	0.08	-0.02	0.09
35	76.06	46.31	66.4	22.57	8.85	19.7	53.25	28.18	46.14
0	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
10	25.32	15.4	22.1	6.29	2.51	5.48	14.27	7.13	12.36
20	48.36	29.38	42.2	12.7	5.01	11.08	30.3	15.76	26.25
30	66.3	40.94	57.95	19.21	7.54	16.76	45.35	24.05	39.3
48	89.23	55.94	78.1	30.87	12.15	26.94	69.71	37.63	60.43
51	92.2	57.79	80.7	32.8	12.92	28.62	73.47	39.79	63.7
56	96.55	60.66	84.53	36.04	14.21	31.44	79.59	43.43	69.02
56	97.04	60.6	84.9	36.07	14.24	31.47	80.43	43.85	69.75
51	93.28	57.74	81.54	32.86	12.96	28.67	75.16	40.57	65.16
48	90.9	55.79	79.4	30.92	12.16	26.98	72.06	38.63	62.46
40	83.57	50.04	72.84	25.8	10.13	22.51	63.27	33.27	54.82
30	71.21	41.06	61.91	19.29	7.58	16.83	50.56	25.84	43.79
20	54.55	29.87	47.31	12.74	5.04	11.11	36.23	17.8	31.38
10	32.91	16.4	28.5	6.31	2.52	5.5	20.86	9.41	18.09
0	5.9	0.63	5.61	0.02	-0.11	0.12	7.05	2.37	6.21

Table 8: Principal stresses and equivalent stress at locations 4, 5, 6 and 7

Pressure in ksc	location 4			location 5			location 6			location 7		
	σ_1	σ_2	σ_v	σ_1	σ_2	σ_v	σ_1	σ_2	σ_v	σ_1	σ_2	σ_v
0	600.73	542.55	110	139.63	179.75	110	150.64	219.29	110	485.64	424.87	110
10	16.05	7.24	13.92	10.27	2.6	9.25	21.74	10.98	18.83	9.19	6.7	8.23
0	0.3	0.11	0.26	-0.02	-0.16	0.15	0.46	0.23	0.4	-0.02	-0.2	0.19
10	16.03	7.19	13.91	10.29	2.6	9.27	21.74	10.98	18.83	9.13	6.66	8.18
0	0.23	0.11	0.2	0.01	-0.14	0.14	0.37	0.2	0.32	-0.06	-0.16	0.14
35	54.52	26.26	47.23	44.68	18.67	38.87	62.8	32.48	54.4	38.38	26.24	33.98
0	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
10	16.03	7.19	13.91	10.46	2.77	9.39	21.66	10.93	18.76	9.5	6.89	8.5
20	32.15	15.02	27.86	24.41	8.95	21.39	40.05	20.36	34.69	21.48	14.78	19.04
30	46.95	22.4	40.67	37.98	15.43	33.08	55.5	28.56	48.07	33.22	22.31	29.33
48	70.49	34.97	61.05	60.65	27.18	52.62	77.21	40.79	66.9	51.68	35.71	45.83
51	73.96	36.84	64.05	64.21	29.13	55.69	79.91	42.45	69.25	54.31	37.93	48.25
56	79.92	40.14	69.21	70.36	32.52	60.99	84.09	45.17	72.89	58.73	41.54	52.3
56	80.64	40.62	69.84	70.92	32.75	61.48	84.16	45.18	72.95	58.54	41.8	52.22
51	75.48	37.54	65.37	65.48	29.67	56.79	79.93	42.49	69.27	53.65	38.42	47.89
48	72.47	35.77	62.76	62.23	27.83	53.99	77.11	40.75	66.82	50.49	36.41	45.13
40	63.86	30.88	55.31	53.21	22.94	46.23	68.95	35.88	59.73	41.89	31.01	37.65
30	51.47	24.2	44.6	40.71	16.48	35.47	56.8	28.93	49.19	30.51	23.76	27.76
20	37.44	17.03	32.47	27.26	9.97	23.89	42.3	21	36.63	18.98	15.81	17.61
10	22.11	9.47	19.21	13.5	3.83	12.05	25.3	11.99	21.92	9.27	5.77	8.1
0	6.21	2.43	5.42	2.78	1.06	2.43	5.88	1.09	5.42	2.45	-3.14	4.85

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