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Fracture Strength Determination of Maraging Steel Rocket Motor Cases a Comparative Study of Analytical and Experimental Data

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Abstract— Maraging steels are greatly employed for the fabrication of rocket motor cases because of its high strength and fracture toughness. They are low carbon, high nickel, iron base alloys. Maraging steels can be easily machined, formed and welded. It has the composition of 18% Ni, 8% Co, and 5% Mo as a primary alloying element. Based on 0.2% proof stress levels, namely 200, 250, 300 and 350ksi, maraging steel can be classified as M200, M250, M300 and M350. High strength is obtained by ageing at 900 against the heat treatment used for other high strength alloys. Defects like cracks or flaws are developed in this material during fabrication process. Cracks generally have sharp edges and therefore sensitive for initiation of crack growth and fracture. In this paper, a procedure is presented to determine the failure load of a structural component in the presence of crack using an ASTM procedure. Fracture strength plays a vital role in determining critical stress intensity factor for any structural component. Equation for the determination of fracture strength of maraging steel is presented. The relationship between failure strength and critical stress intensity factor is briefly discussed. A limited number of surface cracked tension specimens made of maraging steel material having different width and crack sizes are used to derive fracture strength. The analytical results of fracture strength are determined using fracture parameters of maraging steel. Fracture strength obtained from test data are compared with analytical results and the relative error is presented. Failure assessment diagram in terms of critical stress intensity factor and failure stress is presented. Results are discussed.

Keywords- Maraging steel, Fracture strength, Crack size, Motor cases, Critical stress intensity factor, Surface cracked tension specimen, Failure assessment diagram.

I. INTRODUCTION

Maraging steel is currently being used for construction of space vehicle pressure vessels. It possess superior properties like high strength and toughness due to a combination of two solid state reactions, “MAR + AGING”, meaning martensitic transformation and subsequent ageing. It has the composition of 18% Ni, 8%Co and 5% Mo as a primary alloying element. Resistance of such high strength materials is sensitive to

presence of crack like defects. The specified mechanical properties are:

Plane strain fracture toughness, $K_{IC} \geq 90 \text{MPa}\sqrt{m}$

Yield strength, $\sigma_{ys} \geq 1725 \text{MPa}$

Ultimate tensile strength, $\sigma_{ult} \geq 1765 \text{MPa}$

Weld efficiency $\geq 90\%$

The significant parameters to specify the critical crack size in structure are the applied load levels, the fracture toughness, the location of crack and its orientation. The theoretical determination of failure load and especially the failure process of flawed (in the case notched or initially cracked) structural components is indispensable in the performance of safety analysis. In addition to the generally very complex and expensive FEM, approximate analytical methods have been developed to assess the load bearing capacity of flawed structural components with a relatively low cost and computational time.

II. FRACTURE STRENGTH OF CENTER CRACKED TENSILE SPECIMENS

Several structural analysis method to predict the fracture behavior of cracked structural components were explained in detail by various researchers. Several fracture analysis methods to predict the fracture behavior of flawed structural components used in an experimental and predictive round robin conducted in 1970-'80 by American Society for Testing Materials (ASTM) Task Group E 24.06.02 are : Linear – elastic fracture mechanics (LEFM) corrected for size effects or plastic yielding; Equivalent energy; The Two-parameter criterion (TPFC); The deformation plasticity failure assessment diagram (DPFAD); The theory of ductile fracture; The K_R -curve with the Dugdale model; An effective K_R – curve derived from residual strength data; The effective K_R -curve with a limit load condition; Limit-load analyses; A two-dimensional finite element analysis using a critical crack –tip-opening displacement criterion with stable crack growth; A three-dimensional finite element analysis using a critical crack- front singularity parameter with a stationary crack.

In this paper, equation for fracture strength for a finite width tension plate containing central surface crack is presented.

The stress intensity factor (K_I) for a finite width plate containing a center surface crack of length $2c$ and depth a as shown in fig. 1 is

$$K_I = (\sigma M (\pi a)^{0.5}) / \phi \quad (1)$$

Here σ is the applied stress, ϕ is the flaw shape parameter, M is the magnification factor, W is the width of the plate and 't' is the thickness of the plate.

The magnification factor (M), finite width correction factor (f_w), flaw shape parameter (ϕ) in terms of the crack depth (a), half the crack length (c), width (W) and thickness (t) are

$$M = M_e f_w; M_e = M_1 + (\phi (c/a)^{0.5} - M_1 (a/t)^q$$

$$M_1 = 1.13 - 0.1 (a/c); \text{ for } a \leq c$$

$$M_1 = (1 + 0.03 (a/c)); \text{ for } a \geq c;$$

$$\Phi^2 = 1 + 1.464 (a/c)^{1.65}; \text{ for } a < c$$

$$\Phi^2 = 1 + 1.464 (c/a)^{1.65}; \text{ for } a \geq c;$$

$$f_w = \sqrt{\sec\left(\frac{\pi c}{W} \frac{\sqrt{a}}{t}\right)}; q = 2 + 8 (a/c)^3$$

When the depth (a) of the crack is equal to the thickness (t), Eq 1 gives the stress intensity factor for finite width tension specimens having a center through crack. Equation 1 holds good for both through and surface crack tension specimens.

Equating the fracture toughness (K_{IC}) of the material to the stress intensity factor (K_I), one can find the fracture strength (σ_f) of a finite width plate containing a surface crack. Fracture strength (σ_f) equation is given as follows:

$$\sigma_f = \sigma_{ult} \left[1 - \left(\frac{2}{3\sqrt{3}} \frac{\sigma_{ult}}{K_{IC}} \frac{M\sqrt{\pi a}}{\phi} \right)^2 \right] \text{ for } \sigma_f \geq \frac{2}{3} \sigma_{ult}$$

$$\sigma_f = K_{IC} \Phi / M \sqrt{(\pi a)}$$

$$\sigma_f = K_{IC} \Phi / M \sqrt{(\pi a)}$$

From this expression fracture strength of M250 and M300 maraging steel rocket motorcase surface cracked tension specimen is evaluated. The results are compared with available test data and presented in the table. Based on the three parameter relationship among critical stress intensity factor (K_{max}), the fracture strength (σ_f) and the ultimate strength (σ_{ult}), failure analysis diagram is presented and one can easily understand the range of K_{max} over σ_f and σ_{ult} . In addition to the determination of fracture strength, an attempt is made to determine the failure load of 30 CT specimens and

the results are compared with the test data. Equation for failure load is as follows:

Failure load,

$$P_{max} = 0.815BW \sigma_{ult} (1 - a_0/W)^2 (2 + a_0/W)^{-1} \{0.3927 + 0.0402 (a_0/W) + 0.6268 (a_0/W)^2\} \quad (2)$$

TABLE 1 FAILURE LOAD P_{MAX} OF THE M250 GRADE MARAGING STEEL CT SPECIMENS

σ_{ult} (MPa)	W	B	a_0	Pmax (test)	Pmax (eqn 2)
1859	14.98	7.62	7.720	9.48	9.31
1761	15.00	7.62	7.377	9.28	9.55
1760	15.02	7.62	7.440	9.04	9.45
1798	14.98	7.62	7.486	9.09	9.49
1791	15.01	7.62	7.520	9.19	9.43
1843	15.64	7.80	8.570	9.21	8.76
1782	15.59	7.80	7.788	10.4	10.0
1782	15.62	7.80	7.833	10.3	9.98
1821	15.54	7.80	7.747	10.7	10.3
1790	15.56	7.79	7.147	11.5	11.4
1766	15.61	7.80	7.903	9.65	9.73
1781	15.55	7.80	7.660	11.0	10.2
1781	15.54	7.80	7.742	10.0	10.0
1815	15.62	7.80	7.740	10.7	10.4
1793	15.60	7.79	7.917	10.3	9.82
1846	15.63	7.81	8.080	10.4	9.83
1763	15.57	7.83	8.045	10.0	9.38
1790	15.57	7.80	8.152	9.90	9.30
1796	15.61	7.79	7.890	11.0	9.91
1817	15.59	7.80	7.223	11.4	11.5
1829	15.61	7.80	7.892	10.5	10.1
1829	15.60	7.80	8.175	9.82	9.47
1780	15.58	7.80	7.620	10.9	10.4
1821	15.67	7.81	7.703	9.88	10.6
1878	15.63	7.80	7.741	10.3	10.8
1847	15.64	7.79	7.713	10.9	10.6
1842	15.64	7.79	7.333	11.9	11.5
1872	15.56	7.78	7.170	11.2	11.9
1822	15.54	7.82	8.123	9.90	9.46
1814	15.59	7.82	7.868	9.90	10.1

III. IMPORTANCE OF K_{MAX} AND Σ_F RELATIONSHIP

Understanding the failure of materials plays an important role in the design and manufacturing process. When dealing with a specific material for a particular application, it is not clearly established whether plain strain fracture toughness (K_{IC}) should be used or plane stress condition. The K_{IC} seems to be important in heavy sections like forging or thick plate. This is the reason why plane strain fracture toughness is used in thick sectional structural member in aerospace applications.

ASTM-E561 suggests generation of a R-curve from through crack test coupons like CT specimens. It should be noted K_{IC} is geometry dependent whereas R-curve is considered to be a material property independent of geometry. Therefore R-curve of material will be useful for the accurate determination of critical load of the through cracked specimen. For part through cracked configurations, fracture strength estimations are not possible directly from the R-curve of the material because the part through crack has 2 dimensions, namely crack length and its depth. In such situations, development of a relationship between the failure stress and the stress intensity factor at failure will be useful for fracture strength evaluation of cracked configurations.

Rao et al derived a relation between the stress intensity factor and corresponding stress at failure for cracked configurations using crack-growth resistance curve (R-curve) of the material from CT specimens. The failure stress decreases with the increase of crack size. When the crack size is negligibly small, failure stress tends to the ultimate strength of the material. Since the stress intensity factor (K_I) is a function of load, geometry and crack size, it is more appropriate to have a relationship between stress intensity factor at failure K_{max} and the failure stress from the fracture data of cracked specimens and this is useful for fracture strength evaluation of flawed configuration.

The relationship between K_{max} and σ_f can be of the form

$$K_{max} = K_F \{ 1 - m (\sigma_f / \sigma_{ult}) - (1 - m) (\sigma_f / \sigma_{ult})^p \}$$

Where, σ_f is the failure stress normal to the direction of the crack in a body and σ_u is the normal stress required to produce a plastic hinge on the net section. For centre crack tension specimen, failure stress is equal to ultimate stress of the material. For the pressurized cylinders, failure stress is the hoop stress at the failure pressure of the flawed cylinder and ultimate stress is the hoop stress at failure pressure of an unflawed cylinder. In the above equation, K_F , m and p are fracture parameters derived from fracture test data. The above equation is known as 3 parameter fracture criterion which was derived from the conventional 2 parameter criteria. It is a well known fact that the tensile strength of a specimen decreases with increasing crack size. If the failure stress is less than the yield stress, then there exists a linear relationship between σ_f and K_{max} . For small sizes of cracks where $\sigma_{ys} < \sigma_f < \sigma_u$, the relationship between σ_f and K_{max} is expected to be non linear. σ_f is the 0.2% proof stress or yield stress of the material.

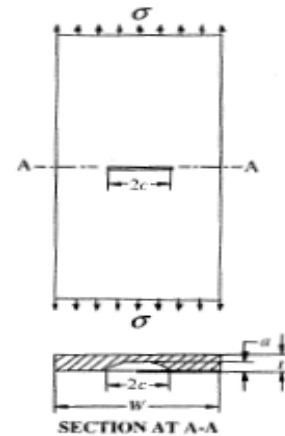


Fig.1. Finite width tension plate containing a center surface crack

Understanding the failure of materials plays an important role in the design and manufacturing process. When dealing with a specific material for a particular application, it is not clearly established whether plane strain fracture toughness (K_{IC}) should be used for plane stress condition. The K_{IC} seems to be important in heavy sections like forging of thick plate. This is the reason why plane strain fracture toughness is used in thick sectional structural member in aerospace applications.

TABLE 2 COMPARISON OF ANALYTICAL AND EXPERIMENTAL FRACTURE STRENGTH OF M300 GRADE MARAGING STEEL SCT SPECIMENS
($t=3\text{mm}$, $\sigma_{ult}=2255\text{MPa}$, $K_F=151.7\text{MPa}\sqrt{\text{m}}$, $m=0.4$, $p=15.8$)

Width (mm)	Crack Dimensions (mm)		Fracture strength σ_f (MPa)		
	A	2c	Test	Analysis	Relative Error (%)
15.2	0.8	4.0	2008.0	1879.8	6.4
15.2	1.1	5.0	1668.5	1705.7	-2.2
15.1	1.1	5.8	1566.8	1646.4	-5.1
19.6	1.4	7.5	1426.9	1446.8	-1.4
18.4	1.4	7.2	1367.9	1458.8	-6.7
19.1	1.7	9.0	1349.1	1259.7	6.6
18.5	1.7	7.5	1220.0	1349.1	-10.6

Standard error obtained is 0.063

TABLE 3 COMPARISON OF ANALYTICAL AND EXPERIMENTAL FRACTURE STRENGTH OF M300 GRADE MARAGING STEEL CYLINDRICAL VESSELS HAVING SURFACE CRACKS.

($D_0=77.2\text{mm}$, $t=3\text{mm}$, $\sigma_{ys}=2120\text{MPa}$, $\sigma_{ult}=2255\text{MPa}$, $K_F=148.6\text{MPa}\sqrt{\text{m}}$, $m=0.4$, $p=15.8$)

Crack Dimensions (mm)		Failure pressure P_{bf} (MPa)		
a	2c	Test	Analysis	Relative error (%)
0.4	2.5	193.8	174.6	9.9
0.9	4.0	157.7	157.2	0.3
1.0	5.5	158.6	145.9	8.0
1.4	5.2	144.0	139.8	3.0
1.6	10.0	105.7	105.5	0.2
1.7	12.0	99.0	96.6	2.5
1.7	8.0	117.7	112.7	4.3
1.8	14.0	94.3	85.3	9.5

Standard error obtained is 0.06

TABLE 4 COMPARISON OF ANALYTICAL AND EXPERIMENTAL FRACTURE STRENGTH OF M250 GRADE MARAGING STEEL PARENT METAL SCT SPECIMENS

($W=15\text{mm}$, $t=7.5\text{mm}$, $\sigma_{ult}=1860\text{MPa}$, $K_F=235.7\text{MPa}$, $m=0.6$, $p=20.4$)

Crack dimensions(mm)		Fracture strength, σ_f (MPa)		
a	2c	Test	Analysis	Relative error (%)
1.3	2.7	1850	1746.4	5.6
1.4	3.0	1850	1737.0	6.1
1.5	3.4	1840	1719.3	6.6
1.7	3.8	1831	1702.1	7.0
1.7	4.1	1820	1689.5	7.2
1.7	4.3	1830	1681.3	8.1
1.8	4.0	1822	1692.9	7.1
2.0	4.0	1830	1691.9	7.5
1.9	4.8	1798	1656.1	7.9
2.0	4.9	1800	1651.8	8.2
2.0	4.5	1786	1668.3	6.6
2.0	4.4	1802	1673.0	7.2
2.2	4.8	1783	1651.1	7.4
2.0	5.0	1788	1644.8	8.0
2.2	5.3	1771	1625.5	8.2
2.2	5.7	1760	1605.2	8.8
2.3	5.9	1760	1591.5	9.6
2.5	5.8	1754	1590.7	9.3
2.5	6.3	1711	1562.5	8.7
2.5	6.5	1730	1551.5	10.3
1.6	3.9	1796	1698.8	5.4
1.7	4.2	1825	1685.4	7.7
2.0	4.7	1817	1658.9	8.7
2.1	5.1	1753	1637.8	6.6
2.1	5.2	1772	1632.9	7.9
2.5	6.3	1732	1562.5	9.8
2.5	6.8	1713	1535.1	10.4

Standard error obtained is 0.079

TABLE 5: COMPARISON OF ANALYTICAL AND EXPERIMENTAL FRACTURE STRENGTH OF M250 GRADE MARAGING STEEL PARENT METAL SCT SPECIMENS

($W=15\text{mm}$, $t=7.5\text{mm}$, $\sigma_{ult}=1720\text{MPa}$, $K_F=235.7\text{MPa}$, $m=0.6$, $p=20.4$)

Crack dimensions(mm)		Fracture strength (MPa) σ_f		
a	2c	Test	Analysis	Relative error (%)
1.3	2.7	1735	1627.0	6.2
1.5	2.7	1713	1620.0	5.4
1.0	2.8	1700	1625.4	4.4
1.1	2.8	1752	1624.5	7.3
1.7	3.8	1711	1592.9	6.9
1.5	3.9	1706	1591.5	6.7
1.4	3.9	1700	1592.9	6.3
1.5	4.0	1736	1588.7	8.5
1.6	4.8	1711	1564.6	8.6
2.2	5.0	1666	1546.8	7.2
2.0	5.0	1682	1549.8	7.9
2.0	5.3	1621	1539.3	5.0
2.2	5.4	1654	1531.4	7.4
1.9	5.7	1616	1528.8	5.4
2.3	6.0	1581	1506.5	4.7
2.7	6.2	1590	1485.6	6.6
2.2	6.6	1590	1485.5	6.6
2.2	6.8	1553	1478.0	4.8

Standard error obtained is 0.066

TABLE 6: COMPARISON OF ANALYTICAL AND EXPERIMENTAL FRACTURE STRENGTH OF M250 GRADE MARAGING STEEL PARENT METAL SCT SPECIMENS

($W=15\text{mm}$, $t=7.5\text{mm}$, $\sigma_{ult}=1720\text{MPa}$, $K_F=235.7\text{MPa}$, $m=0.6$, $p=20.4$)

Crack dimensions(mm)		Fracture strength, σ_f (MPa)		
a	2c	Test	Analysis	Relative error (%)
1.0	2.7	1703	1628.6	4.4
1.2	2.9	1732	1621.8	6.4
1.9	4.0	1724	1587.5	7.9
1.9	4.2	1689	1581.0	6.4
1.9	4.2	1726	1581.0	8.4
1.8	4.3	1721	1578.5	8.3
2.1	4.9	1703	1556.4	8.6
2.2	5.0	1690	1551.9	8.2
2.2	5.2	1662	1544.9	7.0
2.2	5.2	1713	1544.9	9.8
2.5	5.6	1668	1526.4	8.5
2.3	5.9	1693	1518.9	10.3
2.8	6.0	1647	1506.1	8.6

Standard error obtained is 0.080

IV. FAILURE ASSESSMENT DIAGRAM (FAD)

Failure assessment diagram is widely employed to ensure the safety of defected engineering or structural components. FAD helps to address the acceptable and unacceptable range of a material. FAD for Table 2 and 4 are given below.

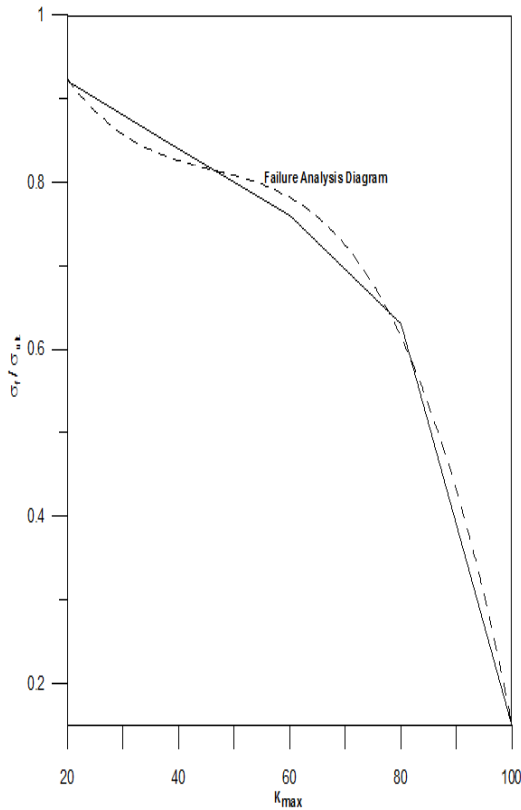


Fig.2. FAD for Table 1

For both figures K_{max} is plotted along horizontal axis and σ_f/σ_{ult} ratio along vertical axis. Dark line represents curve for specimens given in tables. Dotted line represents the smoothed fitted curve. The area within the curve is the acceptable region and the area outside the curve is the unacceptable region for the concerned material. For figure 1, σ_f/σ_{ult} is maximum when K_{max} is 20%. The maximum value of σ_f/σ_{ult} is 0.920. Similarly in the case of figure 2, the maximum value of σ_f/σ_{ult} is 0.880. For both the cases σ_f/σ_{ult} is minimum when K_{max} is 100%.

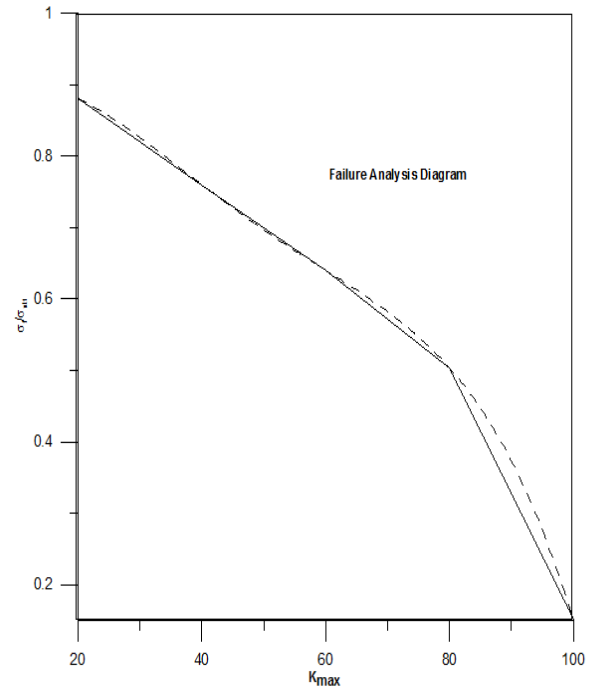


Fig.3. FAD for Table 3

V. CONCLUSION

Fracture strength of M250 and M300 grade maraging steel parent SCT specimens has been evaluated analytically using MATLAB coding and compared with the available test datas and computed relative error for each specimen considered. Failure assessment diagram for one specimen of M250 and M300 grade maraging steel has been drawn and determined the area of acceptance.

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