Defence Science Journal, Vol 51, No 2, April 2001, pp. 201-210

SHORT COMMUNICATION

High Cycle Fatigue, Crack Propagation Resistance and Fracture Toughness in Ship Steels

R.S. Tripathi, R.V. Rama Rao and S.P. Pattanaik

Naval Dockyard, Visakhapatnam – 530 014

ABSTRACT

In this paper, two grades of steel, viz., plain carbon steel and low alloy steel used in naval ships have been selected for studies on high cycle fatigue, crack propagation, stress intensity and crack opening displacement (COD). Specimen for high cycle fatigue was prepared as per IS: 1608. High cycle fatigue was carried out up to 50,000 cycles at 1000 kgf to 2000 kgf loads. Up to 2000 kgf loads, both the materials were observed within elastic zones. A number of parameters, including stress, strain and strain range, which indicate elastic behaviour of steels, have been considered. Low alloy steel specimen was prepared as per ASTM standard: E-399 and subjected to 5,00,000 cycles. Crack propagation, COD, stress intensity, load-cycle variations, load-COD relation, and other related parameters have been studied using a modern universal testing machine with state-of-the-art technology.

Keywords: Crack propagation, fracture toughness, high cycle fatigue, crack opening displacement

1. INTRODUCTION

Strength of materials deals with the relation between internal forces, deformation and external loads. The internal resisting forces are usually expressed by the stress acting over a certain area. The distribution of stress is calculated by measuring the strain distribution in the area. In principle, all solid materials can be deformed when subjected to external load. Up to a certain limiting load, a solid will recover its original dimensions when the load is removed. This is the elastic behaviour of a solid material and the limiting load beyond which the material no longer behaves elastically is the elastic limit of the material. Under this condition, stress experienced during external load is proportional to strain.

Similarly, toughness is the capacity of a material to absorb energy by deforming plastically before fracture. As such, toughness is assessed by the strength and ductility in a material. Important assumption in strength of materials is that the body is continuous, homogeneous and isotropic. In general, it has been seen that structural members and machine elements fail to perform intended functions due to excessive elastic or excessive plastic deformations or fracture. Fracture in a metal may be due to a sudden brittle fracture or fatigue/ progressive fracture or delayed fracture[1].

The process of fracture is due to crack initiation and propagation. Failure occurring under conditions of dynamic loading is called fatigue failure. Progress of fracture is indicated by a series of rings or beach marks progressing inwards from the point of initiation of failure. Basic factors causing fatigue failure could be due to maximum

Revised 19 December 2000

tensile stress of high value, large enough variation or fluctuation in applied stress, large number of cycles of applied stress[2,3], etc.

Fatigue strength is one of the most important factors for the strength of ships. Fatigue cracks have been observed in all types of ships and also at various discontinuous parts of the ship structure. These cracks have the possibility for the intiation of catastrophic failure. Therefore, fatigue cracks found in structural members of ships after a certain service period require the actual working stress to repair the failed parts and to predict the service life[4,5,6].

In the present study, two grades of steel, viz., plain carbon steel and low alloy steel have been used. Unnotched specimens of the steels as per IS:1608 have been prepared for high cycle fatigue tests limiting the total cyclic loads to 5×10^4 cycles at 1000 kgf, 1500 kgf and 2000 kgf loads. Important parameters relevant to the elastic behaviour of steels have been obtained. Likewise, standard specimen as per ASTM standard:E-399 has been prepared to study crack propagation, stress intensity at the crack tip, crack opening displacement (COD), crack length versus number of cycles, load versus displacement and displacement versus time.

2. EXPERIMENTAL PROCEDURE

Universal testing machine (model MTS-810), USA, is a 25 ton system with microconsole, close-loop control for hydraulic system, actuator, transducer, hydraulic power supply, etc. Machine is provided with extensometer for static and dynamic testing applications, including tension/compression testing, low and high cycle fatigue, strain rate, creep/stress relaxation testing. Extensometer uses precision, resistant type foil strain gauges bonded a metallic element to form a wheat stone bridg Two-knife edges of the extensometer arms cont

Table 1. Composition of carbon steel and low alloy steel

Composition	Carbon steel (%)	Low alloy stee (%)
Carbon	0.20	0.12
Manganese	0.65	0.62
Silicon	0.35	0.25
Sulphur	0.30	0.30
Phosphorous	0.02	0.02
Chromium	–	0.95
Nickel	–	3.00
Copper	–	0.20

Table 2. Mechanical properties of carbon steel and low al steel

Properties	Carbon steel	Low alloy steel
UTS (kgf/mm^2)	40.0	70.0
YS (kgf/mm^2)	35.0	55.0
E (%)	26.0	22.0
Hardness (VPN)	180.0	210.0

the specimen. Changes in the specimen caus movement of the extensometer arm. This moveme bends the metallic element changing the resistan of the strain gauges. The change in the balance the wheat stone bridge produces an electrical outp proportinal to the displacement of the extensomet arms. Plain carbon steel and low alloy steel with tl following compositions and mechanical properti were selected for various types of observatioı (Tables 1 and 2).

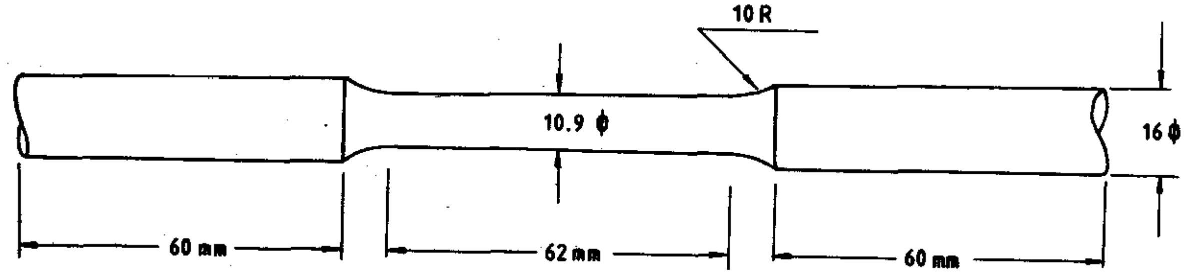

Figure 1. Round sample for fatigue test

Table 3. Fatigue test for low alloy steel

Cycle (N)	Max load (kgf)	Stress intensity (kgf/mm 1.5)	Crack length (mm)	Pre-crack (%)
1000	817.77	72.178	13.318	11
50.000	816.19	72.153	13.336	12
1.00,000	807.26	72.055	13.447	16
1,50.000	795.72	72.074	13.616	22
2,00.000	780.63	72.168	13.848	31
2,50,000	764.64	72.248	14.093	40
3,00,000	745.62	72.310	14.382	51
3,50,000	719.12	71.991	14.729	64
4,00,000	697.14	73.330	15.110	78
4,50,000	564.77	60.301	15.412	89
5,00,000	521.59	57.238	15.694	99

Round unnotched specimen of plain carbon steel as per IS:1608 (Fig. 1) was prepared and tested to cyclic loads of 1000 kgf, 1500 kgf and 2000 kgf. 1 Hz cyclic frequency was maintained throughout the experiment. Similarly, another round, unnotched specimen of low alloy steel was prepared and tested at 1000 kgf and 2000 kgf loads at 1Hz cyclic frequency. In both the specimens, total number of cycles were limited to 5×10^4, considering that such a large number of cycles will indicate the actual behaviour of steels in elastic region. One specimen from low alloy steel was prepared as per ASTM standard: E-399 (Fig. 2) to have detailed information on stress intensity factor, crack propagation, COD and other related parameters. The test was carried out by applying 817.7 kgf load (as recorded by machine) up to 5×10^5 cycles (Tables 3 and 4).

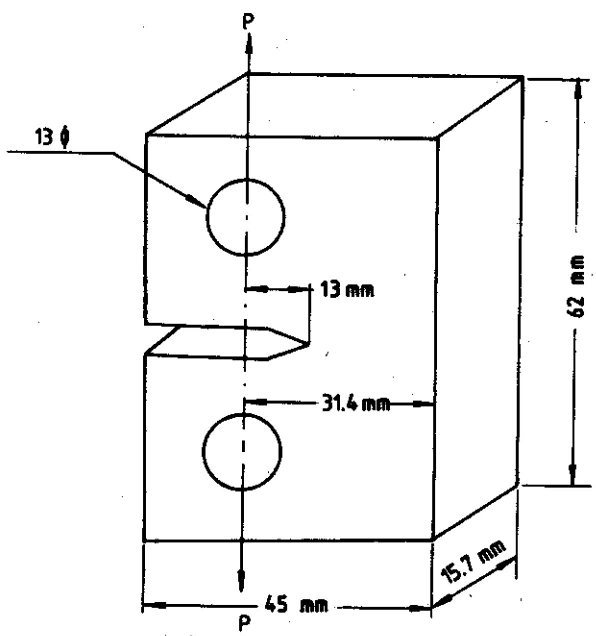

Figure 2. Compact tension specimen for K1c test

3. RESULTS & DISCUSSION

3.1 High Cycle Fatigue Test

Round unnotched plain specimens (Fig. 1) of carbon steel and low alloy steel were prepared and tested for high cycle fatigue test. Cyclic loads of 1000 kgf, 1500 kgf and 2000 kgf at 1Hz cyclic frequency were applied to the mild steel specimen. Stress-strain in tension and compression modes, stress-strain range, elastic-inelastic strain range were measured. Stress-strain in tension and compression modes were proportional and increased as load increased. Likewise, specimen of low alloy steel was subjected to cyclic loads of 1000 kgf and 2000 kgf. Stress-strain in tension/compression modes, stress-strain range, elastic-inelastic strain range were measured. Observations for carbon steel and low alloy steel are shown in Tables 5 and 6, respectively.

Detailed information about elastic behaviour of carbon steel and low alloy steel is very important since within elastic region, the structural and machinery components remain safe. Ships encounter constant zerks/stresses during sailing,

Table 4. Fatigue test for low alloy steel

Time (s)	Load (kgf)	COD (mm)	Displacement (mm)
7.14	249.5	0.02344	– 0.16780
14.61	375.4	0.04413	– 0.10680
22.19	500.5	0.06519	– 0.09918
29.77	626.4	0.08597	– 0.09155
37.29	752.3	0.10710	– 0.03815
44.87	877.4	0.12880	0.00000
52.40	1003.0	0.15040	0.03052
59.87	1128.0	0.17250	0.09155
67.50	1255.0	0.19510	0.10680
74.97	1380.0	0.21800	0.18310
82.55	1506.0	0.24110	0.22890
90.13	1633.0	0.26470	0.24410
97.77	1758.0	0.28910	0.27470
105.20	1883.0	0.31380	0.34330
112.70	2008.0	0.33950	0.38150
120.30	2135.0	0.36640	0.41200
127.90	2260.0	0.39380	0.45780
135.40	2385.0	0.42290	0.52640
142.90	2511.0	0.45360	0.55690
150.30	2637.0	0.48610	0.59510
158.00	2763.0	0.52210	0.63310
165.80	2888.0	0.56270	0.62560
173.20	3014.0	0.60770	0.72480
181.00	3139.0	0.66090	0.79350
188.40	3264.0	0.72560	0.86210
196.20	3391.0	0.81490	0.92320
203.80	3516.0	0.94380	1.06000
211.50	3641.0	1.17800	1.25100

hence the elastic behaviour of steels provides complete information for safety and security of ships and their crews. Performance of both the steels was found satisfactory at the above-stated loads.

3.2 Crack Propagation & Fracture Toughness

Fracture mechanics can be utilised by designing and predicting service life of engineering structures in which sub-critical crack growth or time-dependent fractures are important. Fracture of structural components as a result of cyclic loading has long been a major design problem and has resulted in numerous investigations into the growth of cracks by fatigue. Although, a considerable amount of fatigue data are available, the majority are concerned with the nominal stress required to produce fracture in a given number of cycles, namely S-N curves. Such data are usually obtained through a laboratory endurance tests on smooth specimens. Such data provides the necessary guidelines for material selection, these do not indicate the effects of stress raisers on over-all fracture resistance.

Table 5. Mild steel test results at different loads

Test		1000 kgf	1500 kgf	2000 kgf
Final cycle (N)		50000	50000	50000
Cal modulus (kgf/mm^2)		21226	21729	21275
Max stress (kgf/mm^2)		11.0200000	16.0700000	21.2300000
Min stress (kgf/mm^2)		−10.7200000	− 16.1200000	− 21.5100000
Stress range (kgf/mm^2)		21.7400000	32.1900000	42.7400000
Max strain (mm/mm)		0.0004030	0.0006410	0.0009570
Min strain (mm/mm)		− 0.0006090	− 0.0008930	− 0.0011300
Measured strain range	(mm/mm)	0.0010100	0.0015300	0.0020900
Max calc inelastic strain	(mm/mm)	− 0.0001160	− 0.0000985	− 0.0000413
Min calc inelastic strain	(mm/mm)	− 0.0001040	− 0.0001510	− 0.0001200
Calc inelastic strain range	(mm/mm)	− 0.0000126	− 0.0000521	− 0.0000782
Calc elastic strain range	(mm/mm)	0.0010200	0.0014800	0.0020100
Max meas inelastic strain	(mm/mm	− 0.0000988	− 0.0001100	− 0.0000804
Min meas inelastic strain	(mm/mm)	− 0.0001010	− 0.0001160	− 0.0000858
Meas inelastic strain range	(mm/mm)	1.91 E-060	6.58 E-060	3.4 E-0600
Inelastic strain range	(mm/mm)	0.0010100	0.0015300	0.0020800
Pseudo stress alt	(kgf/mm^2)	10.7400000	16.6200000	22.2000000

The fatigue life of a structure can be thought of comprising three distinct stages (Table 6), namely (i) crack initiation, (ii) crack propagation, and (iii) fast fracture. The presence of a pre-existing crack will reduce or eliminate the initiation stage. For many design considerations, the second stage, fatigue crack growth, is of utmost importance. As fatigue crack grows under cyclic load of constant amplitude, stress intensity at the crack tip increases as a result of increase in crack size. Eventually, the crack may grow to a length sufficient for the stress intensity factor to reach the critical value at which fast fracture occurs.

Local stresses near a crack depend on the product of the nominal stress (σ) and square root of the half flaw length (a). This relationship is denoted as

$$K = \sigma \sqrt{\pi a} \quad (1)$$

where K is the stress intensity factor, which is a convenient way of describing the stress distribution around a crack. It is further defined as

$$K = \alpha \sigma \sqrt{\pi a} \quad (2)$$

where α is a parameter that depends on the specimen and crack geometry.

The dependence of fatigue crack growth rate on the stress intensity factor has been verified and a formula evolved as

$$da / d_N = C (\Delta K)^n \quad (3)$$

where da/d_N is the fatigue crack growth rate; C and N are constants that depend on material, load and frequency of loading. ΔK is the range of the stress intensity factor during one loading cycle.

The advantage of the fracture mechanics approach to crack growth studies is that the variables, i.e. applied load and crack length can be incorporated into the parameter ΔK, which describes the stress intensity conditions corresponding to a given crack growth rate under cyclic loading.

3.3 Crack Opening Displacement

The crack tip displacement concept considers that the material ahead of the crack contains a series

Table 6. Low alloy steel test results at different loads

Test		Load	
		1000 kgf	2000 kgf
Final cycle (N)		50000	50000
Calc modulus	(kgf/mm^2)	20288	21358
Maxi stress	(kgf/mm^2)	13.2700000	26.2400000
Min stress	(kgf/mm^2)	– 13.2700000	- 26.1300000
Stress range	(kgf/mm^2)	26.5300000	52.3700000
Max strain	(mm/mm)	0.0005080	0.0011400
Min strain	(mm/mm)	– 0.0007830	– 0.0014700
Meas strain range	(mm/mm)	0.0012900	0.0026100
Max calc inelastic strain	(mm/mm)	– 0.0001460	– 0.0009350
Min calc inelastic strain	(mm/mm)	– 0.0001290	– 0-.0002510
Calc inelastic strain range	(mm/mm)	– 0.0000168	– 0.0001570
Calc elastic strain range	(mm/mm)	0.0013100	0.0024500
Max meas inelastic strain	(mm/mm)	– 0.0001150	– 0.0001610
Min meas inelastic strain	(mm/mm)	– 0.0001280	– 0.0001720
Meas inelastic strain range	(mm/mm)	0.0000136	0.0000114
Meas elastic strain range	(mm/mm)	0.0012880	0.0026000
Pseudo stress alt	(kgf/mm^2)	13.0900000	27.8600000

of miniature tensile specimens having a gauge length and width. It is felt that crack growth occurs when the specimen adjacent to the crack is fractured. The failure of the first specimen adjacent to the crack tip immediately causes the next specimen to fail, and so on. The overall fracture process is unstable and crack propagation occurs under decreasing stress. Widespread plasticity at the crack tip enables the crack surfaces to move apart at the crack tip without an increase in crack length. This relative movement of the two crack faces at a distance removed from the crack tip is called the COD. COD is precisely measured with a clip gauge.

4. PLANE STRAIN FRACTURE TOUGHNESS TEST

ASTM standard: E-399 defines K1c as the material toughness property measured in terms of

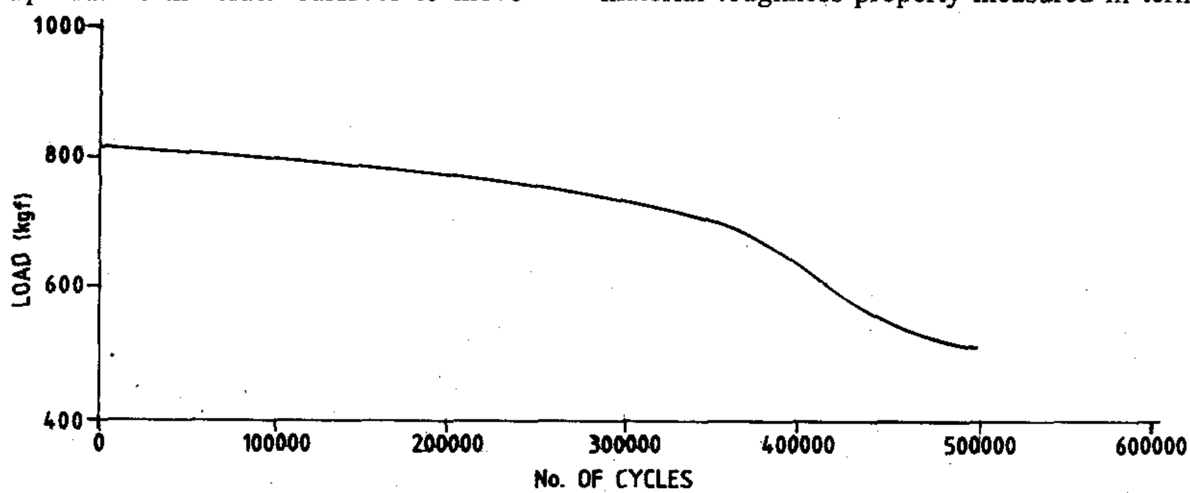

Figure 3. Load versus number of cycles

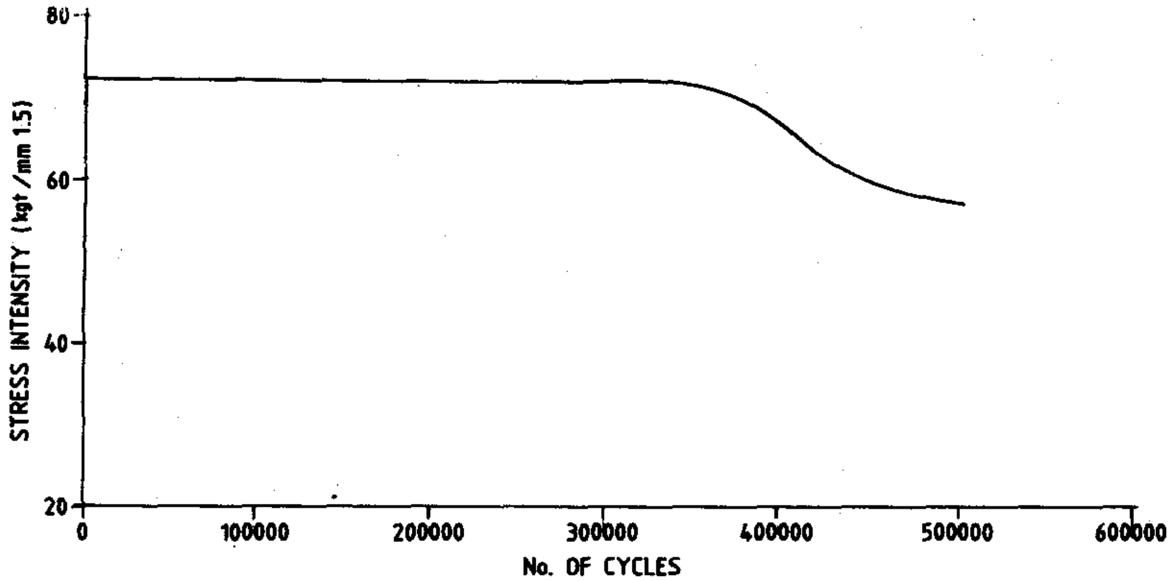

Figure 4. Stress intensity factor versus number of cycles

the stress intensity factor, K1 by a specified procedure. The procedure is designed to determine the stress intensity at which unstable crack propagation begins. According to this, ASTM standard, K1 is a measure of the stress field intensity near the tip of an ideal crack in a linear elastic medium when deformed so that the crack faces are displaced apart, normal to the crack plane (mode 1 deformation). For K1c measurement, specimen as shown in Fig. 2 is prepared. The crack tip plastic region is small compared to crack length and to specimen dimensions in the constraint direction. From a record of load versus crack opening and crack configuration to stress intensity, plane strain fracture toughness can be measured accurately. Maximum cyclic load of 817.77 kgf was applied on the low alloy steel specimen. Stress intensity, crack length and progression of crack length were recorded. As the number of cycles increased, load and stress intensity decreased and crack length increased. At 5,00,000 cycles, load was reduced to 521.59 kgf; stress intensity was reduced to 57.238 kgf/mm 1.5; crack length increased from 13.318 mm to 15.694 mm. At this stage, sample did not show further strength and crack propagation was supposed to be complete. Specimen and control parameters were essentially included to have complete information about the test specimen and procedure adopted. After obtaining of pre-crack length, static load was applied on the specimen. Table 6 shows the complete information about load variation, enhancement in COD and progression in the crack length. Final figure indicates that at 211.5 s and at 3641 kgf load, the COD attained 1.178 mm from initial value of 0.02344 mm. Similarly, crack displacement from 0.1678 mm to final value of 1.251 mm was attained.

There is always evidence of slow crack propagation that preceded unstable crack growth. This slow propagation, known as stable crack growth, is the ductile characteristic of the material. It is regarded as the first stage of fatigue failure.

Figure 3 shows a graph of load versus number of cycles. Load was steadily declining with

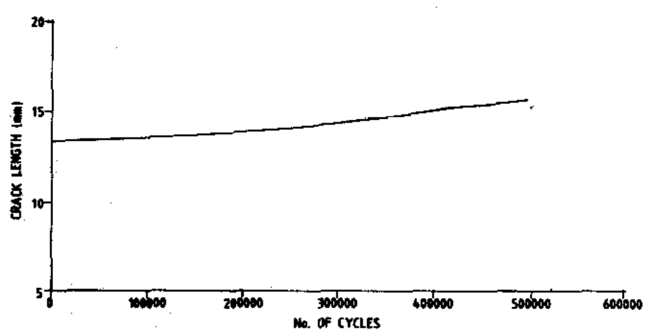

Figure 5. Crack length versus number of cycles

progression of cycles. After completion of 4,00,000 cycles, load dropped to below 700 kgf until crack propagation achieved 85 per cent of its intial length. At that stage, stress intensity continued reducing from 72 kgf /1.5 mm to 57 kgf /1.5 mm until the desired crack length was achieved. Applied load was reduced from 817 kgf to 521 kgf in stages (Table 3).

Figure 4 shows a graft indicating relation between stress intensity factor and number of cycles. Stress intensity was steady up to 4,00,000 cycles but at 4,50,000 cycles, it recorded 60.301 kgf /mm 1.5 and finally at 5,00,000 cycles, it was 57.238 kgf /mm 1.5.

Figure 5 shows a graph of crack length versus number of cycles. Crack length steadily increased from inital value of 13.318 mm to 15.694 mm.

Figure 6 shows a graph of load versus COD. The trend of the graph is linear and shows that crack opening is uniform and increases with load.

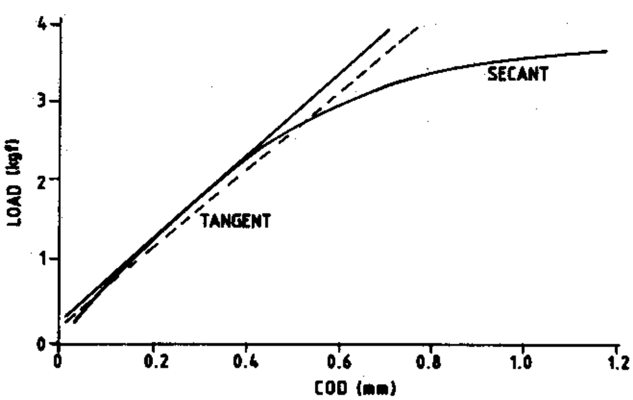

Figure 6. Load versus crack opening displacement

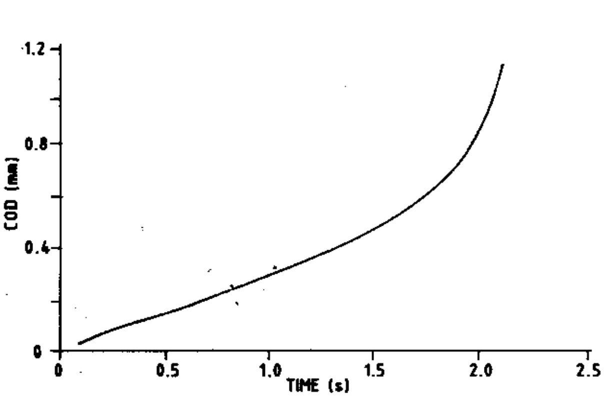

Figure 7. Crack opening displacement versus time

Figure 7 shows a graph of COD versus time. Crack opening shows resisting trend up to certain time, although stress is increasing. After critical time, there is sudden enhancement in the crack opening. This is a critical stage at which the specimen stress intensity factor shows downward trend.

Figure 8 shows a graph of load versus time. The graph has linear trend and shows that load/stress increases as time progresses.

Figure 9 shows a graph of load versus displacement. The trend is linear but not uniform. Crack propagation or crack displacement increases as the load increases but due to changes in stress intensity factor, the specimen resists the load and it may be correlated to stress resistance factor.

Figure 10 shows a graph of displacement versus time. Up to a certain period, displacement/ propagation of crack is very slow but beyond that displacement suddenly increases.

All the curves shown in Figs 3 to 10 are very informative, indicating the total behaviour of the

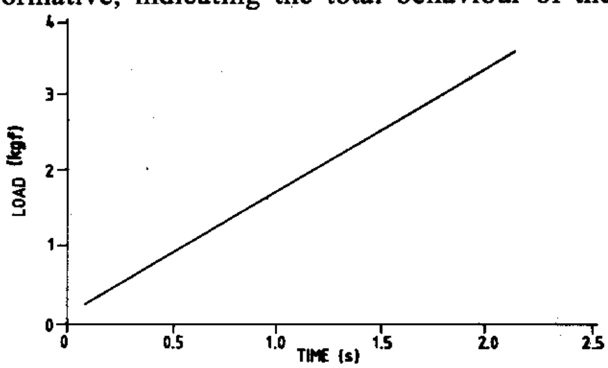

Figure 8. Load versus time

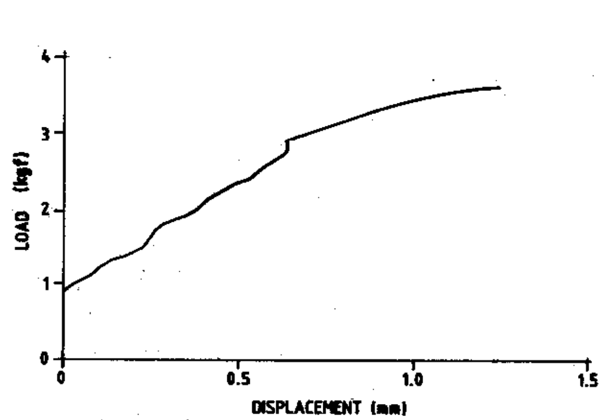

Figure 9. Load versus displacement

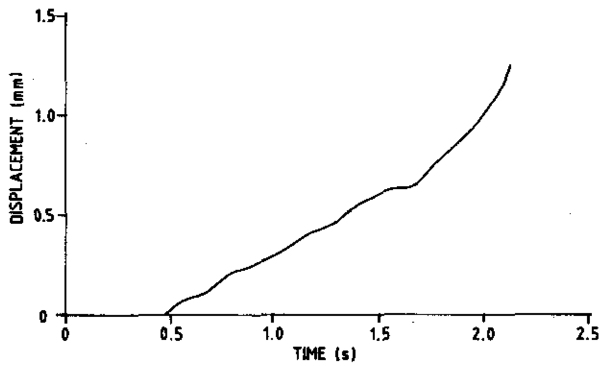

Figure 10. Displacement versus time

materials. Relationship of crack propagation with stress intensity factor K1c/COD, is not completely linear. As crack propagates, COD increases and stress intensity factor K1c decreases as crack advances. Similarly, load decreases as crack increases. All these curves clearly indicate that low alloy steel has excellent elastic and plastic behaviour and is a durable steel which can bear normal stresses and strains without any damage to the structure. Such a steel has been used in pressure hull of submarines for quite some time without any untoward incident. Low alloy steel of this grade is a quenched and tempered steel with relevant specified properties and is found a seaworthy material.

5. CONCLUSION

Round unnotched specimens of plain carbon steel were subjected to different dynamic loads of 1000 kgf, 1500 kgf and 2000 kgf at 1Hz. Behaviour of specimens for basic properties, viz., stress, strain, elastic, plastic deformation under tension and compression modes are important factors and help in assessing the performance of such steels for structural applications. Up to 2000 kgf load plain carbon steel has been found behaving purely elastically in compression as well as in tension modes. This implies that such steels should be preferred in structures where load fluctuations occur.

Low alloy steel is a quenched and tempered steel and free from flaws. Specimens made out of this steel were subjected to normal dynamic loads at 1000 kgf and 2000 kgf and the specimens behaved in elastic zone. Thereafter, specimen as per ASTM standard: E-399 was prepared and subjected to dynamic loading up to 5,00,000 cycles under varying loads. Pre-crack length was induced. Various parameters like stress intensity factor at the tip of the crack, COD, crack propagation, time versus load and relationship of such materials constants with each other were studied. This analysis reveals that basic materials properties are interdependent, therefore, every possible parameter related to fracture mechanics and behaviour of material should be taken into account for detailed performance of the material. Low alloy steel of the grade stated above is a standard steel quite suitable for pressure hull structure. Environmental conditions have entirely different effects and need to be discussed separately.

REFERENCES

1. ASM Handbook Committee. Failure analysis and prevention. *In* Metals handbook, Vol **10**, 1986. pp. 30-44.
2. Dieter, G.E. & Bacon, David. Mechanical mettallurgy. McGraw-Hill Book Company, 1988, pp. 375-31.
3. Srivastava, Y.P. & Garg, S.B.L. Crack propagation law using crack tip opening displacements. ASM Publications, 1986, pp. 181-92.
4. Tomita, Y. & Fujimoto, Y. Prediction of fatigue life on ships structural members from developed crack length. ASM Publications, 1986, pp. 37-46.
5. Urashima, S.N.C. & Yamada, R.E.Y. Low cycle fatigue properties under rotating bending and push-pull structural steels. ASM Publications, 1986, pp. 127-33.
6. Jankowski, D.M. Fatigue and fracture properties of a medium carbon high strength low alloy steel. ASM Publications, 1986. pp. 203-11.