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(RESEARCH ARTICLE)

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A critical assessment of fatigue behaviour of ferrous alloys by empirical correlation of multifactor S-N curves

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Abstract

Corrosion and Temperature have a significant deteriorative effect on fatigue life of mechanical structures. The reliability of the fatigue damage assessment techniques depends on the quality of the S-N curve which is derived as a result of corrosion degradation and elevated temperature. In this research paper steel specimens of 9.48 mm diameter were tested under rotating bending conditions at a frequency of 6000 cpm.The influencing factors are stress concentration (K = 2.45) (common for both the cases) corrosion (1 percent NaCl solution as corrodent) and elevated temperature (150 ˚C). The S-N curve so obtained were compared with experimental fatigue test results. Their correlation showed good agreement between the experimental results and the adopted approaches for fatigue life assessment.

Keywords: Fatigue; Corrosion; Stress concentration; Temperature; S-N curve; Correlation

1. Introduction

Fatigue behaviour of metals is influenced by many factors like composition, size, shape, surface treatments, Surface finish, type of stress, corrosion, stress concentration, temperature residual stresses, mean stress, speed of testing, etc. and obviously the stress amplitude [15]. Only small amount of work has been done to estimate fatigue life/strength under the combined influence of two factors because correlations obtained are empirical in nature and cannot be used widely in design. However, the nature of the empirical relation obtained helps in giving better judgement to the designer in the similar applications and laboratory test to be carried out for data collection may be partly avoided. This type of work also helps in understanding the fatigue phenomenon in general and shows proper direction for the future work.

2. Literature review

The fatigue behaviour of iron and steel differs in several ways from most of the other metals. The most important distinguishing feature is that they show a distinct fatigue limit. Their fatigue strength can be appreciably increased by under stressing or coaxing and thirdly the fatigue strength increases with increase in temperature above about 150˚C reaching a maximum value between 200 ˚C to 400 ˚C.These three features are probably interrelated and there is considerable evidence that they may all be attributed to strain ageing [1]. Corrosion is a destructive attack of material by the surrounding corrosive environment. It is regarded as a key factor that dominates the service life of ship structures. Various models were proposed to predict the reduction of thickness due to corrosion. Most of these models are based on regression analysis using gauged thicknesses data collected during the periodical ship surveying events [1],[2],[3],[4]. However, the corrosive environment not only degrades the material thickness, but also deteriorates its

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material mechanical properties and its fatigue life [5] [6]. The fatigue life of structures can be assessed by S-N approach or fracture mechanics approach. However, S-N approach is widely used and it is often the most suitable for fatigue design purposes. Four methodologies can be adopted in fatigue damage calculation of marine structures using S-N curve; deterministic fatigue analysis, simplified fatigue assessment, spectral fatigue analysis and time-domain fatigue analysis [7]. The accuracy of the estimated fatigue life employing those approaches depends mainly on the adopted S-N curve. However, the S-N curve shows a significant scatter in the corrosive environment. Tran Nguyen et al [8] expressed the fatigue life of a tanker deck structural detail based on spectral fatigue approach. They compared the estimated fatigue life using S-N curve in air (thickness deterioration was considered) and in corrosive environment. The fatigue life using S-N curve in corrosive environment was significantly less than using S-N curve in air. However, the S-N curve in corrosive environment is not available for all materials. The numerical investigation of corrosion effect on S-N curve presented in this paper can be useful for predicting S-N curves for corroded structures. Garbatov et al.[6],[13] performed tensile tests on small scale aged specimens which were cut from an initially corroded box girder. The experiments showed that there is a considerable reduction in the mechanical properties (modulus of elasticity E, yield stress σ_y and tensile strength σ_t) due to corrosion and sectional-area loss which has been observed in extensive literatures [9],[10],[11],[12]. Ma et al. [14] investigated the influence of stress concentration on the low-temperature fracture behavior in the A356 alloy, and observed the crack propagation path at 213 and 293 K.

3. Methodology

It was proposed to consider stress concentration, corrosion and elevated temperature as the influencing factor as they are important. The level of each factor was decided to get appreciable loss in fatigue strength. It was also proposed to conduct fatigue tests to get:

- S-N curve of virgin specimens (to be used as basic curve for comparison)
- S-N Curve for corrosion fatigue of plain specimens.
- S-N curve of plain specimens at elevated temperature

In this research paper steel specimens of 9.48 mm diameter were tested under rotating bending conditions at a frequency of 6000 cpm. The influencing factors are stress concentration (K = 2.45) (common for both the cases) corrosion (1 percent NaCl solution as corrodent) and elevated temperature (150˚C).

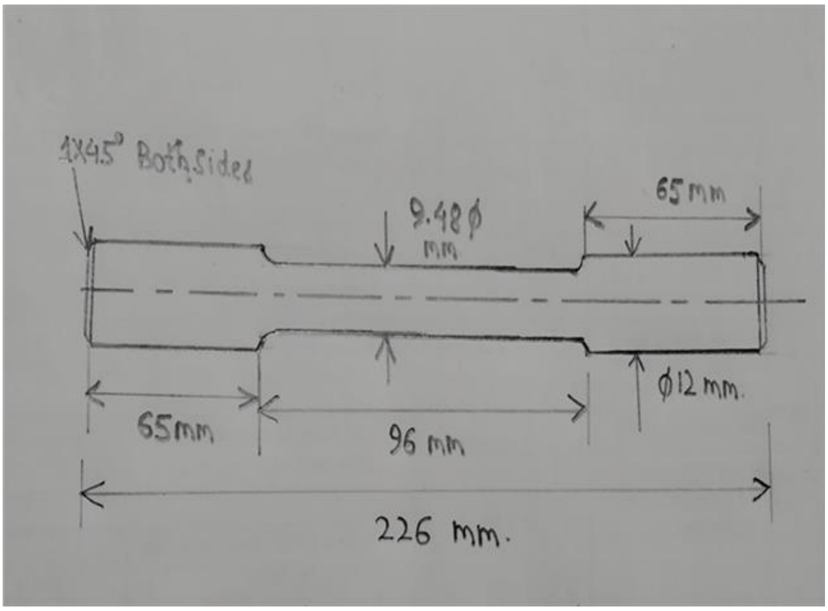

Figure 1 Steel Specimen under testing

It was further proposed to see whether fatigue strength under the combined influence of two factors is obtained by successive multiplication of the fatigue strength of virgin specimen, strength reduction factor fatigue due to first influencing factor and fatigue strength reduction factor due to second influencing factor. In case of invalidity of this relation, it was proposed to modify the same.

3.1. Effect of stress concentration

Stress concentrations due to steps, keyways, oil holes, grooves, etc. reduce the fatigue strength considerably and are responsible for majority of fatigue failures occurring in practice. A measure of the severity of a stress concentration is given by the Stress Concentration factor Kt, which is define d as the ratio of the maximum local stress in the region of the discontinuity to the nominal local stress evaluated by simple theory. Kt depends on

- Reduction in cross sectional area at the discontinuity,
- Shape of discontinuity,
- Type of loading.

Although fatigue strength is considerably reduced by geometrical stress concentrations, the reduction is often less than the stress concentration factor and a fatigue strength reduction factor, Kf has therefore been introduced which is defined as the ratio of the fatigue strength of a specimen with no stress concentration to the fatigue strength with stress concentration K_f depends on material of specimen, type of loading, stress level and size of specimen under testing etc. It is observed that for specimens with stress concentration, the nature of S-N curve does not change

3.1.1. Effect of corrosion

Corrosive action on the surface of a metal may cause a general roughening of the surface and the formation of pits or crevices at certain points and this can result is a considerable loss in fatigue strength if the metal is subsequently subjected to fluctuating stress .Much greater reduction in fatigue strength results, however, from the combined effect of both corrosion and fluctuating stress acting together than from either factor acting separately and the term corrosive fatigue is used to describe this behaviour. The process has been shown to be an electro chemical one. Corrosion fatigue is a process quite distinct from stress corrosion cracking, which results from a steady stress acting in a corrosive environment. Stress corrosion occurs only in certain metals, generally after an incorrect heat treatment, while most, if not all, metals are susceptible to corrosion fatigue.

In corrosion fatigue the crack propagation rate is increased due to chemical action. Ordinary fatigue tests at room temperature are not affected by speed of testing in the range of about 1,000 to 10,000 cycle s/min., but when tests are conducted in corrosive environment, there is a definite influence of the speed of testing on the fatigue behaviour. Since corrosive attack is a time dependent phenomenon, higher the speed of testing, Smaller is the action of materials which show fatigue limit at room temperature without corrosive action, do not show it in corrosion fatigue as the damage corrosion per cycle. Due to Corrosion increases with time. It is obvious that corrosion fatigue strength at any p articular life will depend on the corrosive medium, but it also depends on the method of application of corrosive medium because corrosion depends on the supply of oxygen.

3.2. Effect of temperature

The results of fatigue tests show similar stress endurance relation at all temperature, although at high temperatures, there is seldom a fatigue limit and the downward slope of the curve is usually steeper than at room temperature. Almost without exception, fatigue strengths of both plain and notched pieces are increased with the reduction in temperature, but the increase in the fatigue strength of notched specimen is lesser than that of plain specimens.

In other words, metals are usually more notch sensitive at low temperature fatigue strength with decrease in temperature is usually greater for soft materials than for hard ones and particularly marked for mild steel. The tensile strength also increases with decrease in temperature but not usually to the same extent as the fatigue strength. It is found that the materials having fine grain size show greater fatigue strength at lower temperatures as compared to the same material with coarse grain size. As the temperature is raised, this difference in strength gets reduced and finally in higher temperature region where the creep predominates the coarse-grained materials show higher fatigue strength, because grain boundaries become weaker than the grains.

3.2.1. Influence of elevated temperature

From the plot, it could be seen that the fatigue strength of plain specimen at elevated temperature is less than that of virgin specimen in the range of fatigue life considered. From S-N curves of virgin and plain specimens at elevated temperature, the values of 't' were calculated at various fatigue values and plotted in Figure 2. From that it could be concluded that the percentage reduction in fatigue strength than virgin specimen due to elevated temperature is increasing with increasing fatigue life. This may be explained by the increasing damage due to creep and oxidation with respect to time. Even though mean stress is zero, creep due to half cycles in tension side may not be counter balanced by creep due to half cycle in compression sides.

3.3. Calculations

3.3.1. Nomenclature

In the following research paper, following nomenclature for technical terms and parameters was used:

- c = fatigue strength reduction factor due to corrosion (S_c/S_v)
- i_{nc}= fatigue strength reduction factor due to interaction between stress concentration and corrosion
- i_{nt} = fatigue strength reduction factor due to interaction between stress concentration and elevated temp.
- K_t = theoretical stress concentration factor
- i = suffix indicating concerned fatigue life in million cycles
- N = fatigue cycles
- n = fatigue strength reduction factor to stress concentration
- n_c = fatigue strength reduction factor due to the combined influence of stress concentration and corrosion (S_n/S_v)
- n_t = fatigue strength reduction factor due to the combined influence of stress concentration and elevated temperature
- (S_{nt}/S_v)
- S_c = corrosion fatigue strength of plain specimen, kg/mm2
- S_{nt} = fatigue strength of notched specimen at elevated temperature, kg/mm2
- S_t = fatigue strength of plain specimen at elevated temperature, kg/mm2
- S_v = fatigue strength of virgin specimen, kg/mm2
- t = fatigue strength reduction factor due to elevated temperature, kg/mm2
- α = Correlation coefficient

3.3.2. Correlation for stress concentration and corrosion

Values of calculated fatigue strength reduction factors due to the combined influence of stress concentration and corrosion (n.c), assuming no interaction effect, were tabulated and plotted. It was observed that 'nc' < n.c at any fatigue life. The variation was accounted for interaction effect. Hence i_{nc} was introduced. The experimental values of i_{nc} were calculated at various fatigue lives using the following equation:

$$i_{nc}\,(\text{Expt}) = n_c/n.c$$

Table 1 Various values of fatigue strength reduction factor of steel specimen in corrosion

Fatigue life (10^6 cycles)	**n_c**	**n**	**c**	**n.c**
0.3	0.47	0.61	0.88	0.53
0.4	0.45	0.59	0.84	0.48
0.5	0.42	0.57	0.81	0.45
0.6	0.39	0.56	0.76	0.43
0.7	0.37	0.55	0.74	0.42

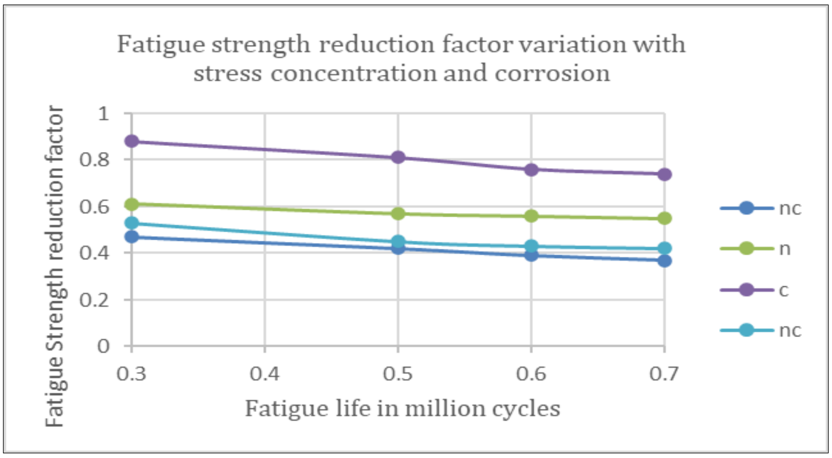

Figure 2 Variation of fatigue strength reduction factor with combined effect of stress concentration and corrosion

At this stage a relation between n.c and i_{nc} (Expt), which is valid at any fatigue life is necessary to predict interaction effect. Estimated values of i_{nc} were found out from above equation. Difference between experimental and estimated i_{nc} values was found to be less than 5 per cent in the range of fatigue life considered. It could be seen that interaction effect decreases as fatigue life increases. For finding empirical relation between fatigue strength and stress concentration factors corresponding to corrosion and elevated temperature, fixed value of N= 0.5 x 10 ^{6} cycles per second was taken for calculations, corresponding to this fixed value of N following values have been taken from standard data book

Table 2 Values of fatigue parameters due to corrosion taken from standard design data book at N= 0.5 x 10^6 cps.

Sn	Sv	Sc	Snc
18.35	33.05	25.71	12.89

Accordingly, the values of other parameters have been calculated

$n = [S_n / S_v]$

= 18.35/33.05 = 0.55

$c = [S_c / S_v]$

=25.71/33.05 = 0.78

$n_c = [S_{nc} / S_v]$

= 12.89/ 33.05 = 0.39

nc = n x c

= 0.55 x 0.78 = 0.429

Now $i_{nc} = n_c / n \times c$

= 0.39/0.429

= 0.91

Now empirical relation becomes

$$\mathbf{i_{x_1y_1} = 1- (x_1y_1)^{\alpha}}$$

$0.91 = 1- (0.55 \times 0.78)^{\alpha}$

$(0.429)^{\alpha} = 0.09$

Taking log both sides

$\alpha \log (0.43) = \log (0.09)$

α (-0.365) = -1.1

α = - 1.1/-0.365 =3.014 = 3 approx.

value of correlation coefficient α = 3

After calculations following empirical relation was found

$$\mathbf{i_{nc}\ (Estimated) = 1 - (n.c)^3}$$

3.3.3. Correlation for stress concentration and elevated temperature

Values of calculated fatigue strength reduction factors due to the combined influence of stress concentration and elevated temperature (n.t), assuming no interaction effect, were calculated and plotted as in table 3.

It was observed that ‘nt' < n.t at any fatigue life.

The variation was accounted for interaction effect. Hence i_{nt} was introduced. The experimental values of i_{nt} were tabulated at various fatigue lives and plotted using the equation

$$\mathbf{i_{nt}\ (Expt) = nt/n.t}$$

Table 3 Various values of fatigue strength reduction factor of steel specimen at elevated temperature

Fatigue life (10^6 cycles)	**n_t**	**n**	**t**	**n.t**
0.3	0.44	0.61	0.98	0.57
0.4	0.42	0.59	0.95	0.54
0.5	0.38	0.55	0.93	0.52
0.6	0.37	0.53	0.91	0.51
0.7	0.36	0.52	0.89	0.49

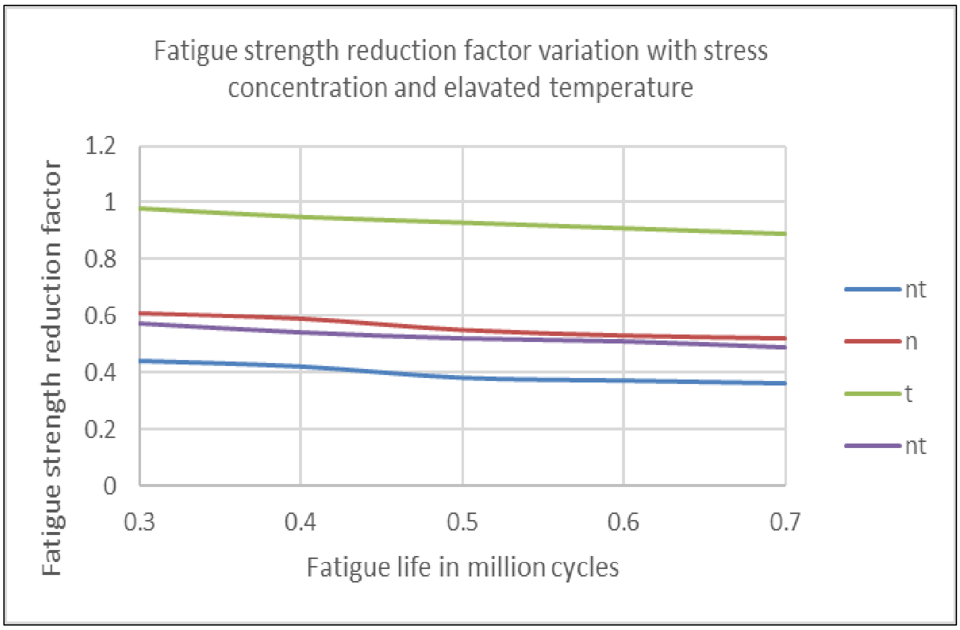

Figure 3 Variation of fatigue strength reduction factor with combined effect of stress concentration and elevated temperature

At this stage a relation between n.t and i_{nt} (Expt), which is valid at any fatigue life is necessary to predict interaction effect. After some smoothening calculations following empirical relation was found

$$i_{nt} \text{ (Estimated)} = 1 - (n_1.t_1)^2$$

Estimated values of int were found out from above equation and plotted in Figure 2. Difference between experimental and estimated i_{nt} values was found to be less than 5 per cent in the range of fatigue life considered. It could be seen that interaction effect decreases as fatigue life increases. Reduction in fatigue strength due to interaction effect can be related with the data obtained from single factor S-N curves in the following form.

$$i_{x1y1} = 1 - (x_1 y_1)^{\alpha}$$

where x_1 and y_1 are strength reduction factors due to any two factors effecting fatigue strength depending upon values of level of factors and fatigue life. Values of α may depend upon level and combinations of the factors. In this research fixed value of N= 0.5 x 10 ^{6} cycles per second assumed for calculations, for fixed value of N following values have been taken from standard data book

Table 4 Values of fatigue parameters due to elevated temperature taken from standard design data book at fixed value of N= 0.5 x 10^6 cps.

S_n	S_v	S_t	S_{nt}
18.35	33.05	30.60	13.30

Accordingly, the values of other parameters have been calculated

$n = [S_n / S_v]$

= 18.35/33.05 = 0.55

$t = [S_t / S_v]$

=30.60/33.05 = 0.93

$n_t = [S_{nt} / S_v]$

= 13.30/ 33.05 = 0.402

nt = n x t

= 0.55 x 0.93 = 0.511

Now $i_{nt} = n_t / n . t$

= 0.402/0.511

= 0.79

Now empirical relation becomes

$$i_{x1y1} = 1 - (x_1 y_1)^{\alpha}$$

$0.79 = 1 - (0.55 \times 0.93)^{\alpha}$

$(0.51)^{\alpha} = 0.21$

Taking log both sides

αlog (0.51) = log (0.21)

α (-0.29) = -0.6

α = - 0.6/-0.29 =2.06 = 2 approx.

Therefore, value of correlation coefficient α = 2

After calculations following empirical relation was found

$$i_{nc}\ \textbf{(Estimated)} = 1 - (n.c)^2$$

4. Conclusion

In this paper fatigue behaviour of virgin steel specimen is calculated and compared with standard permissible values. From the Figure so obtained, it can be deduced that:

- Considerable interaction effect is present when two factors influencing fatigue act together.
- Interaction effect decreases with increasing fatigue life.
- Percentage of fatigue strength of virgin specimen increases with increasing fatigue life.
- Fatigue strength of specimen in corrosive condition is less than that of virgin specimen.
- Fatigue strength of plain specimen is less than virgin specimen.
- Reduction in fatigue strength due to stress concentration, corrosion an elevated temperature increases with increasing fatigue life.

Benefit to Society

This research work focus on estimation of fatigue behaviour of alloys especially steel working in unfavorable environmental conditions mainly corrosion and elevated temperature. Accordingly, values of safe fatigue limits can be estimated by correlation equations deduced after calculations. This can aid in safe designing of submersible vessels working under corrosive conditions and boilers in industries.it can help in reducing failures occurring due to fatigue occurring through corrosions and high temperatures.

Compliance with ethical standards

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Disclosure of conflict of interest

Author declares that there are no conflicts of interest in any form.

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