Fatigue Strength Prediction Formulae for Steels and Alloys in the Gigacycle Regime

Chaminda S. Bandara, Sudath C. Siriwardane, Udaya I. Dissanayake, and Ranjith Dissanayake

***Abstract*—Most existing fatigue strength prediction models contain parameters related to the critical size of non metallic inclusions or defects. Finding the critical size of the inclusion or defect which causes the fatigue failure is not easy. Further, obtaining experimental stress life curves for gigacycles is expensive and time consuming. Therefore it is important to discover simple but reliable fatigue strength prediction formulae that use easily obtainable material parameters while being independent from the size of inclusions or defects. This paper proposes a new formula for predicting fatigue strengths of steels in the gigacycle regime using the ultimate tensile strength and Vickers hardness as material parameters while introducing a reliable substitute to the critical inclusion size. The formula is verified using published experimental results for forty five steels. Another formula for predicting fatigue strengths of steels and alloys is proposed using more than hundred experimental fatigue strength values at various numbers of failure cycles in the gigacycle regime.**

***Index Terms*—Fatigue strength, gigacycles, inclusion and defect, stress life curve, tensile strength.**

I. Introduction

Fatigue life of components that are subjected to cyclic loading often exceeds the high cycle regime; i.e. 10^7 cycles [1]. Structural parts such as connecting rods, crank shafts and helical springs experience more than 10^{10} cycles in their service lives [2]. Railway and offshore structures generally exceed 10^8 cycles [3]. Most of the fatigue design codes [4] too provide stress life S-N curves up to 10^9 cycles for designing elements in steel structures such as bridges. However, in designs, a fictive fatigue limit is often assumed at the end of the high cycle regime [2], [4].

Since the findings in the 1990s that there is no infinite fatigue life for metals [5], a lot of research has been done to develop experimental S-N curves, theoretical models and empirical relationships to predict fatigue strength (σ_w) of metallic materials beyond the high cycle regime known as the gigacycle regime.

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In the gigacycle regime, developing S-N curves through experiments using material specimens requires sophisticated equipment, precise temperature control techniques and much time [1]. Therefore, it is necessary to develop fatigue strength prediction models (theoretical or empirical) with readily available or easily obtainable material parameters such as the ultimate tensile strength (σ_u) and hardness.

The fatigue cracks in the high cycle regime are caused by surface defects or slip bands [6], [7] whereas the cracks in the gigacycle regime are mainly caused by non metallic inclusions or voids that exist in metals [6], [8]. After extensive research, Murakami and Endo [9] developed fatigue strength prediction models for the high cycle regime based on surface defects and internal voids or inclusions. The main parameters of these models are the size of defect or inclusion ($\sqrt{area}$) and Vickers hardness (Hv) [6], [9]. Liu *et al*. [1], [10], Wang *et al*. [4], Mayor *et al*. [8], [11] and Chapetti *et al*. [12] have all proposed modifications to Murakami's model in order to widen its applicability in the gigacycle regime.

In the existing models mentioned, the term $\sqrt{area}$ is an important parameter. There are many different non metallic inclusions and defects in metals; this makes measuring $\sqrt{area}$ of the inclusion or defect that causes the failure in the future, complex. Further, it has been shown that the formation of a granular bright facet (GBF) also called the optically dark area (ODA) is the initiation of a fatigue crack and that the term $\sqrt{area}$ in Murakami's models should be replaced with the size of GBF or ODA in the gigacycle regime [1], [12], [13]. All these complexities highlight the need for a model which is independent of the term $\sqrt{area}$.

To overcome this problem, this paper first proposes a simple and reasonably accurate alternative relation for $\sqrt{area}$. The proposed relation mainly consists of σ_u. Then it compares four existing fatigue strength prediction models and notes their limitations. Then, a new formula (model) is proposed to predict the fatigue strength of medium and high strength steels in the high and gigacycle regimes. The main feature of this formula is that it consists only of easily obtainable material parameters such as Hv and σ_u. The accuracy of the formula is confirmed and verified by comparing the predictions of the proposed formula with experimental fatigue strength values of steels. As this formula consists of local material parameters of each type of steel and verification is also limited to steel, it is named *"the local gigacycle fatigue formula for steels"* in the present paper. Also, an empirical formula (model) is proposed to predict the fatigue strength in the gigacycle regime by

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studying the experimental fatigue behavior of more than fifty steels and alloys. The main features of this formula are that it consists of only σ_u as the material parameter and represents a significant range of steels and alloys. Therefore in this paper, this empirical formula is named *"the global gigacycle fatigue formula for steels and alloys"*.

II. Proposed Substitute for Inclusion Size

Microscopic examinations of fracture surfaces of test samples show both external and internal failures at high and gigacycle regimes; for example, Mayor *et al*. [11] observed that, for Bainitic 100Cr6 steel, 42% failure was caused by internal Al_2O_3 inclusions while 28% failure was caused by surface defects within the range of 2×10^6 to 10^{10} cycles. Further, Bayraktar *et al*. [13] developed formulae considering the effect of the position of inclusions or defects between the center and the surface of a specimen. As such, the position of an inclusion or defect is a major factor that affects σ_w.

The maximum stress intensity factor $K_{I\ max}$ for fatigue cracks of the major failure mode (mode I) at an internal inclusion and an external defect are given by $0.5\sigma_a(\pi\sqrt{area})^{1/2}$ and $0.65\sigma_a(\pi\sqrt{area})^{1/2}$ respectively [6], [9] where σ_a is the applied stress. The critical inclusion or defect could be anywhere in or between the center and the surface. Therefore, we propose that the most appropriate value for the stress intensity factor K_I in a simple model that captures the effect of the location of an inclusion or defect as the average of the two above values which is given by

$$K_I = 0.575\sigma_a(\pi\sqrt{area})^{1/2} \tag{1}$$

where K_I is given in MPa $\sqrt{m}$, σ_a is given in MPa, and $\sqrt{area}$ is given in m.

Experiments conducted at the stress ratio R = -1 for non propagating crack lengths versus $K_{I\,max}$ show that the cracks are propagating for $K_{I\,max}$ in the range of 1.8 MPa $\sqrt{m}$ and 2.0 MPa $\sqrt{m}$ and that the threshold value of $K_{I\,max}$ under which no cracks could initiate is approximately 1.8 MPa $\sqrt{m}$ regardless of the size of the crack [6], [9]. Therefore, we propose that, for a propagating crack, the mean value for K_I in the range 1.8 MPa $\sqrt{m}$ to 2.0 MPa $\sqrt{m}$, (i.e. 1.9 MPa $\sqrt{m}$) should be a reasonably accurate prediction. Substituting 1.9 MPa $\sqrt{m}$ for K_I in (1), the effective minimum value for $\sqrt{area}$ can be simplified as

$$\sqrt{area} = 1.92/\{(0.575\sigma_a)^2\pi\} \tag{2}$$

where, the units of the terms in (2) are the same as that in (1). Equations (1) and (2) are based on Murakami's research [6], [9], conducted in the high cycle regime at 10^7 cycles [1], [10].

Therefore, replacing σ_a with σ_w at 10^7 cycles in (2) should give a value for $\sqrt{area}$ that causes the fatigue failure at 10^7 cycles.

TABLE I: Comparison of Experimental Value and Predicted Value Using (3) for $(\sqrt{area})^{1/6}$

Steel	Reference	σ_u (MPa)	Experimental $\sqrt{area}$ (μm)	Experimental $(\sqrt{area})^{1/6}$ ($\mu m^{1/6}$)	Calculated from (3) $(\sqrt{area})^{1/6}$ ($\mu m^{1/6}$)
AZ91hp	[8]	190	520	2.84	2.70
AM60hp	[8]	178	480	2.80	2.76
AE42hp	[8]	184	447	2.77	2.73
AS21hp	[8]	131	510	2.83	3.06
AlSi9Cu3	[8]	216	781	3.03	2.59
42CrMo4	[4]	1,530	20	1.65	1.35
42CrMo4	[4]	1,530	13	1.53	1.35
CrV	[4]	1,800	25	1.71	1.28
54SC6	[4]	1,692	22	1.67	1.30
54SC6	[4]	1,692	30	1.76	1.30
54SC7	[4]	1,800	25	1.71	1.28
54SC7	[4]	1,800	22	1.67	1.28
SUP10M3	[4]	1,828	14	1.55	1.27
SUP10M6	[4]	1,841	29	1.75	1.27
SUP9TM1	[4]	1,482	260	2.53	1.36

Provided that σ_w at 10^7 cycles is not known, the approximate upper bound fatigue limit (fictive) of a material in the high cycle fatigue regime is known and equal to $0.5\sigma_u$ [6]. Therefore the value of $(\sqrt{area})^{1/6}$ in (2) can be simplified by substituting $0.5\sigma_u$ for σ_a in (2) and expressed as

$$(\sqrt{area})^{1/6} = (14/\sigma_u{}^2)^{1/6} \tag{3}$$

where, the units of the terms in (3) are the same as that in (1).

The comparison of experimental and predicted values for $(\sqrt{area})^{1/6}$ given in Table I shows that (3) provides a reasonably accurate theoretical value for $(\sqrt{area})^{1/6}$. Further, the value of $\sqrt{area}$ varies with the applied stress that affects the failure life [9], [12]. The effect of this variation is adopted in Section IV when developing the fatigue strength prediction formula.

III. Existing Fatigue Strength Prediction Models and Their Limitations

In order to develop a simplified fatigue strength prediction model, four existing models were first studied. The Murakami model [6], [9] which is given (for R = -1) by

$$\sigma_w = \beta\cdot(Hv+120)/(\sqrt{area})^{1/6} \tag{4}$$

where, the value of the parameter β is 1.43 for surface defects or inclusions, 1.41 for defects or inclusions in contact with the surface, and 1.56 for internal defects or inclusions. In (4), σ_w is in MPa, Hv is in kgf/mm^2, and $\sqrt{area}$ is in μm. The main limitation of this model is that it is valid only for the high cycle regime for 10^7 cycles [10]. The main difficulty of using this model is that it requires a prior prediction of the location of the inclusion or defect that causes the damage in the future.

Wang *et al*. [3] proposed modifications to (4) for predicting σ_w at any number of cycles to failure (N_f) defining β in the form

$$\beta = \beta_1 - \beta_2 Log N_f \quad (5)$$

where, the material and location related constants β_1 and β_2 are 3.09 and 0.12 respectively for internal inclusions and 2.79 and 0.108 respectively for surface defects. The Difficulty of using this model is that it also requires a prior prediction of the location of the inclusion or defect that causes the damage in the future.

The modified Murakami model by Liu *et al*. [1] for gigacycle regime for R=-1 and for 10^9 failure cycles is given by

$$\sigma_w = 2.7(Hv + 120)^{15/16} / (\sqrt{area})^{3/16} \quad (6)$$

where, the units are as same as those in (4). The limitations of (6) are that it is valid only for failures due to internal inclusions or defects and for 10^9 cycles.

The fatigue life prediction model of Chapetti *et al*. [12] is a relation between σ_w, N_f , the radius of the optically dark area (R_{ODA}), the inclusion radius (R_i), the maximum inclusion radius ($R_{i\,max}$), and the threshold stress intensity factor range (ΔK_{th}). For R = -1, the relation is given by

$$\sigma_w = 256 \cdot \Delta K_{th} / \sqrt{R_{i \cdot \max}} \quad (7)$$

$$\Delta K_{th} = 0.004(Hv + 120) \cdot (3R_{i.\max})^{1/3} \quad (8)$$

$$R_{ODA} / R_i = 0.25 N_f^{0.125} \quad (9)$$

where σ_w is in MPa, Hv is in kgf/mm^2, R_{ODA}, R_i, and R_i^{max} are in µm, and ΔK_{th} is in MPa √m. The maximum value of ΔK_{th} in the expression is 10 MPa √m and R_{ODA} is approximated to $3R_i^{max}$ [12]. The limitation of this model is that it is valid only for failures due to internal inclusions or defects.

IV. Proposed Local Gigacycle Fatigue Formula for Steels

A. The Proposed Model

The requirements of the proposed model are that it should be simple and a single formula that addresses the limitations and difficulties of the existing models. For this purpose, in this paper, we propose modifications to the Murakami model following the modifications introduced by Wang *et al*, described in Section III.

In order to avoid location related limitations and difficulties, we propose location independent values for β_1 and β_2 that are estimated as 2.41 and 0.109 respectively. (These values were obtained by using optimization techniques for minimizing the error between the experimental fatigue strengths with model predicted fatigue strengths for forty five steels). It is to be noted that β_1 includes the effect of the variation of $\sqrt{area}$ with the number of cycles for $N_f > 10^7$. Combining (4) and (5) and substituting β1 and β_1 with 2.41 and 0.109 respectively, σ_w can be expressed as

$$\sigma_w = (2.41 - 0.109 Log N_f) \cdot (Hv + 120) / (\sqrt{area})^{1/6} \quad (10)$$

Substituting $(\sqrt{area})^{1/6}$ in (10) with $(14/\sigma_u^2)^{1/6}$ from (3) with the relevant units, σ_w at any $N_f > 10^7$ cycle can be expressed as

$$\sigma_w = 0.001(Hv + 120) \cdot (155 - 7 Log N_f) \cdot \sigma_u^{1/3} \quad (11)$$

where σ_w and σ_u are in MPa, and Hv is in kgf/mm^2.

If one of the two parameters σ_u or Hv is not available, the approximate relationship of σ_u and Hv [6], [9] modified and given by; σ_u = 3.33Hv may be used to evaluate the unavailable parameter. The constant 3.33 in this expression is obtained by plotting σ_u versus Hv for forty steels in this study (Fig.1).

B. Verification of the Model

The verification of the predictions of the proposed model was done by comparing the experimental fatigue strengths at known N_f (from published research work for forty five steels by others [1],[3],[10],[12],[14]-[25]) with calculated fatigue strengths at the same N_f by using (11) as shown in Fig. 2 for the range $10^6 < N_f < 10^{10}$. The tensile strengths of steels used are in the range 800 MPa to 2025 MPa. The experimental stress ratio R = -1, loading frequencies; in the high cycle regime in the range 20 Hz to 165 Hz and that in the gigacycle regime in the range 20 kHz to 30 kHz. Carbon equivalency values of selected steels are less than 1%.

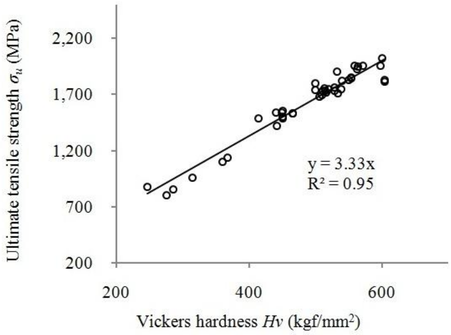

Fig. 1. Relationship between σ_u and Hv for steels.

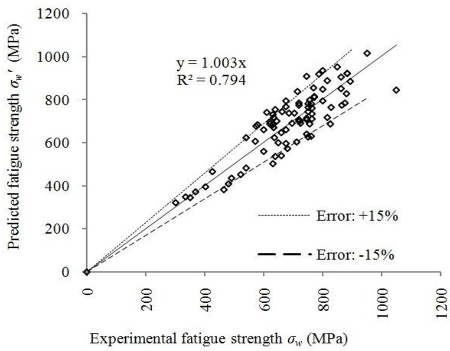

Fig. 2. Experimental fatigue strength versus calculated fatigue strength by using (11).

The comparison exhibits that the model predicts σ_w fairly accurately. The fatigue strength predictions at a given number of cycles for 95% of the heats of steels used in the study are within 20% error margin while 76% are within 15% error margin (Fig. 2).

V. Proposed Global Gigacycle Fatigue Formula for Steels and Alloys

A relationship between σ_w and $\sigma_u^{1/3}$ is observed in (11). Therefore, an empirical analysis was performed by plotting experimental observations of $\sigma_w \mathrm{Log}N_f/\sigma_u^{1/3}$ versus $\sigma_w \mathrm{Log}N_f$ for the steels used in Section IV with nine aluminium and magnesium alloys obtained from published research work [2],[8],[25]. The tensile strengths of alloys used are in the range 131 MPa to 641 MPa and R = -1.

The variation shown in Fig. 3 reveals a simplified formula for fatigue strength of steels and alloys in the gagacycle regime as

$$\sigma_w = \gamma \sigma_u^{\eta} / LogN_f \tag{12}$$

where γ and η are calculated as 0.707 and 1.214. The units of both σ_w and σ_u are in MPa and N_f is in the range 10^6 to 10^{10} cycles.

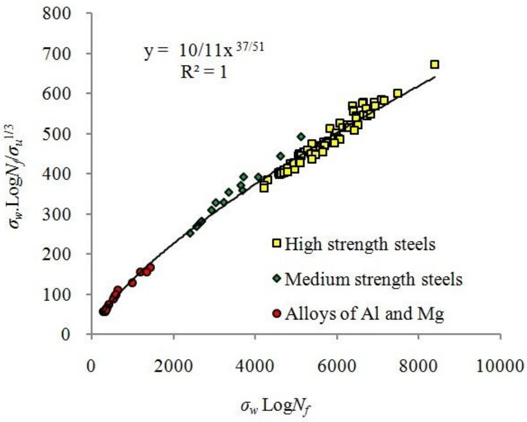

Fig. 3. Relationship between σ_w, $\sigma_u^{1/3}$ and N_f for steels and alloys.

VI. Discussion

The applicability of the two proposed gigacycle fatigue formulae in this study is wide ranging. These formulae can be applied for general engineering designs such as steel elements in bridges, offshore structures, mechanical structures and components where the design S-N curves are prepared using probability based approaches with safety factors. As the formulae are simple, they could be easily used in computer based programming and design applications. The relative ease of obtaining the material parameters required for these models and the fact that they can be presented in a single formula are their main advantages.

While the term $\sqrt{area}$ is not used in the proposed models, it should not be assumed that there is no effect from this term for the fatigue strength: here, $\sqrt{area}$ is simply substituted by a reasonably approximate term related to σ_u. Such approximation is possible due to the fact that σ_u has a good relationship with the properties, shapes, sizes and population densities of inclusions or defects in a metallic material [6].

Hardness, especially Vickers hardness, has a close relationship with the inclusions or defects in metals [6], [9]. However, depending on various material properties (carbon and alloy contents, treatment process and production process etc.) the correlation of σ_w, $\sqrt{area}$, Hv and σ_u varies. Therefore, a model that combines all these and any other related parameters should provide better strength predictions. This phenomenon explains the efficiency of the local model (which is developed using both σ_u and Hv) that provides better predictions than the global model (which is based only on σ_u).

Although there are no limitations for the proposed models except the material and range of cycles, it was observed that the steels with σ_u > 2,000 MPa, σ_w > 900 MPa and carbon equivalency > 1% show a slight deviation from the expected predictions. Therefore, further studies and modifications are required for these areas. The method proposed in this paper could be applied to other metals in a future study through which material related parameters (β_1, β_2, γ, η) could be discovered and the material limitations of the proposed models could be eliminated.

VII. Conclusions

In this paper, a reliable approach for estimating the term $(\sqrt{area})^{1/6}$ was proposed. Then, two simplified formulae were proposed to overcome the limitations and difficulties of existing experimental and theoretical approaches for predicting the fatigue strength of steels and alloys in the gigacycle regime.

The first formula is a local formula for steels. The distinctive feature of this formula is that it is independent of the term $\sqrt{area}$ and only consists of σ_u, Hv and N_f. The formula is verified for forty five steels.

The second is an empirical global formula introduced for steels and alloys. The formula was developed using fatigue strengths of forty five steels and nine alloys. This formula is proposed as the most simplified fatigue strength prediction formula for a given N_f as it only requires σ_u.

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