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PROPOSED DESIGN EQUATION FOR FATIGUE STRENGTH OF DEFORMED BARS

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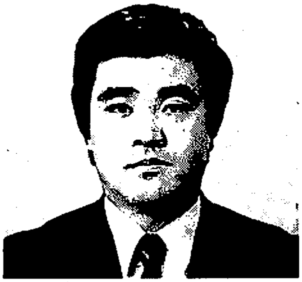

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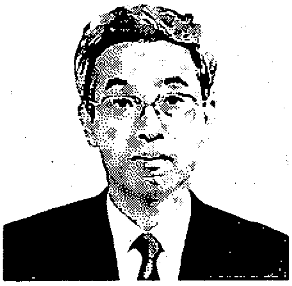

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SYNOPSIS

In this paper, the effect of several important factors affecting fatigue strength of deformed bars, such as, diameter of bar, presence or absence of arc at the base of lug, intersectional angle between direction of lug and longitudinal direction of bar, gas pressure welding joint, were estimated quantitatively. Using these estimations, an equation predicting fatigue strength of deformed bars has been obtained. This equation can predict experimental fatigue strength fairly well. In addition to this equation, considering the application for design, an equation calculating the characteristic value of fatigue strength is presented.

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1. INTRODUCTION

The standard specification of concrete structures of JSCE will be revised to a limit state design method in 1986. In this revision, a fatigue limit state is chosen as one of limit states that should be examined in design procedures. In order to examine a fatigue limit state, it is necessary to estimate fatigue strength properly of members in reinforced concrete structures subjected to repeated loading. Fatigue strength of reinforced concrete members may be normally dependent on that of reinforcing bars. Therefore, fatigue strength of deformed bars has to be predicted quantitatively.

According to previous researches, it is well known that a range of stress, permanent stress, diameter of bar, surface configuration, heat effect due to gas pressure welding are factors affecting fatigue strength of deformed bars. Based on the accumulation of previous experimental data, a design equation for fatigue strength of deformed bars was proposed by JSCE in 1983 [1]. In this equation, the influence of permanent stress on fatigue strength of deformed bars was incorporated.

This equation was derived as follows. An applied range of stress in many previous fatigue tests was converted to a range of stress in perfectly one directional loading using the modified Goodman's diagram. This converted perfectly one directional range of stress and repeated cycles up to failure was plotted on a full-logarithmic graph paper. A regression line was calculated from all of the data. The equation was obtained by parallel removal to a position that contained most of the data conservatively. In the equation, however, the effect of diameter of bar and surface configuration were not considered. At the present time small or middle size bars are generally used in highway slabs and middle or large size bars are used in railway and sea structures. Therefore, if the difference in fatigue strength according to bar size, that has been pointed out previously, is not considered, fatigue strength of small or middle size bars will be relatively underestimated compared with large size bars.

A new equation predicting fatigue strength of deformed bars is necessary as a fundamental design equation. In the equation, at least the following factors have to be incorporated, that is, diameter of bar, presence or absence of arc at the base of lug and intersectional angle between direction of lug and longitudinal direction of bar. In this paper, the extent of the influence of these factors will be estimated quantitatively based on collected data and finally a new equation predicting fatigue strength of deformed bars will be presented.

2. SUMMARY OF COLLECTED DATA

Experimental data were collected from published papers in Japan [2-14]. The sum total of collected data was 280. In these data, an applied minimum stress and a range of stress were kept in an arbitrarily arranged constant value. Loads were applied in one direction. An applied range of stress was from 118 to 332 MPa and an applied minimum stress was from 10 to 87 MPa. In some cases, a deformed bar did not break when repeated cycles reached about 2 millions. For these cases, an applied range of stress was rearranged to be increased and a fatigue test was continued.

All of bars employed in these tests were hot-rolled deformed bars. Nominal diameter of bar was from 10 to 51 mm, yield point was from 294 to 598 MPa and tensile strength was from 483 to 823 MPa. Concerning surface configuration, bars with arc at the base of lug were about 40% in all of collected data. Intersectional angle between direction of lug and longitudinal direction of bar was from 45 to 90 degrees. All of the data were included in the range defined by JIS G 3112 "Steel Bars for Concrete Reinforcement". Besides straight bars, bars with gas pressure welding joint were collected.

3. VERIFICATION OF THE PREVIOUSLY PROPOSED EQUATION BY COLLECTED DATA

Before an examination for a new equation predicting fatigue strength, the validity of the previously proposed equation [1] was verified by collected data. The previously proposed equation is represented as eq.(1).

$$\log \sigma_0 = a - k \log N \tag{1}$$

where, σ_0: a range of stress in perfectly one directional loading (MPa)
N : repeated cycles up to failure
a : a constant
$= 3.29$ for $N < 2 \times 10^6$
$= 2.99$ for $N \geq 2 \times 10^6$
k : a factor concerning the gradient of S-N line
$= 0.18$ for $N < 2 \times 10^6$
$= 0.13$ for $N \geq 2 \times 10^6$

If it is assumed that the modified Goodman's theory is valid, a perfectly one directional range of stress can be calculated by eq.(2).

$$\sigma_0 = \frac{\sigma_{max} - \sigma_{min}}{1 - (\sigma_{min}/f_{su})} \tag{2}$$

where, σ_{max} : applied maximum stress
σ_{min} : applied minimum stress
f_{su} : tensile strength of deformed bar

The average and coefficient of variation of a ratio of experimental fatigue strength that is converted to a perfectly one directional range of stress to calculated one by eq.(1) are represented in Table 1. The proposed equation should naturally determine the characteristic value of fatigue strength. Therefore, the ratio of experimental fatigue strength to calculated one is generally more than 1.0. Experimental fatigue strength, however, decreases according to the increase in the diameter of bar independent of the presence or absence of arc. When an arc does not exist, the extent of the decrease of fatigue strength becomes more remarkable. As the proposed equation estimates all sorts of data by only one S-N line, the ratio of experimental fatigue strength

Table 1 Comparison of Experimental Fatigue Strength and Calculated One Using Proposed Equation (Straight Bars)

Diameter (mm)	$\sigma_{o.test}/\sigma_{o.cal}$	
	With Arc	Without Arc
D ≤19	Data 13 Ave. 1.75 C.V. 10.8%	Data 48 Ave. 1.52 C.V. 9.8%
19< D ≤29	Data 26 Ave. 1.61 C.V. 12.7%	Data 72 Ave. 1.38 C.V. 10.9%
29< D ≤38	Data 7 Ave. 1.48 C.V. 3.4%	Data 9 Ave. 1.43 C.V. 7.1%
38< D	Data 36 Ave. 1.39 C.V. 10.9%	Data 2 Ave. 1.20 C.V. 8.4%

to calculated one, that is, the degree of safety may be different depending on the variation of diameter of bar and presence or absence of arc.

4. DETERMINATION OF THE GRADIENT OF S-N LINE

In order to solve serious problems depending on diameter of bar and surface configuration, each individual factor affecting fatigue strength was examined in order. In this approach as well as that of the proposed equation, it was assumed that the decrease of fatigue strength of deformed bars according to the increase of repeated cycles might be dependent on only the quality of material.

Based on this assumption, a factor "k" concerning the gradient of S-N line was determined by a regression line for experimental data that were plotted on a full-logarithmic graph paper. The method of determination of the value of "k" is as follows. The data in which diameter of bar, presence or absence of arc at the base of lug and intersectional angle between direction of lug and longitudinal direction of bar were perfectly identical were extracted from each researcher. It was assumed that the S-N line for the extracted data was determined uniquely and the value of "k" could be calculated from regression analysis for the data.

In order to improve the accuracy of regression analysis, groups in which the number of contained data was less than five were rejected. As a result of this selection, total eleven groups were obtained.

The value of "k" in these eleven groups varied from 0.03 to 0.18. The average of "k" value of groups with arc at the base of lug was 0.13 and that of groups without arc was 0.11. The average of "k" value of groups in which intersectional angle between direction of lug and longitudinal direction of bar was identical varied from 0.03 to 0.13. However, a qualitative tendency, such as, the value of "k" increased according to the increase of intersectional angle, could not be recognized. The average of "k" value of groups in which diameter of bar was identical varied from 0.08 to 0.18. In this case also, a tendency, such as, the value of "k" increased according to the increase in diameter of bar, was not observed.

Therefore, it was considered that it was insufficient to point out a qualitative tendency, such as, the value of "k" increased according to the increase in diameter of bar. In this research, the average of "k" value calculated from all of groups was used as a common "k" value for total analysis. The influence of diameter of bar, intersectional angle and presence or absence of arc would be considered apart from the value of "k".

On the process of calculation to determine S-N line, a range of stress in each experiment was converted to that in perfectly one directional loading assuming that the modified Goodman's theory was applicable.

As it was considered that the quality of material of bars was influenced by the heat effect due to gas pressure welding, the value of "k" for gas pressure welded bars was determined apart from straight bars.

Finally the value of "k" for straight bars became 0.12 and that for gas pressure welded bars became 0.21.

5. INFLUENCE OF DIAMETER OF BAR

In order to estimate only the influence of diameter of bar on fatigue strength, at first experimental data with arc were examined. For data without arc, it was considered that the decrease of fatigue strength would occur due to stress concentration at the base of lug besides the influence of the increase in the diameter of bar and it might be difficult to separate only the effect of stress concentration from the decrease of fatigue strength. For data with arc, the relation of fatigue strength and diameter of bar was examined by eq.(3). Eq.(3) was rewritten from eq.(1) assuming that the value of "k" was 0.12.

Table 2 Spacing and Height of Lugs

Diameter (mm)	Spacing/Dia.			Height(mm)		
	Maker			Maker		
	A	B	C	A	B	C
D 25	0.54	—	0.67	1.8	—	2.1
D 29	0.51	0.66	0.65	2.0	1.8	2.3
D 32	0.51	0.62	0.65	2.2	2.0	2.6
D 35	0.49	0.63	0.65	2.4	2.3	2.8
D 38	0.48	0.65	0.67	2.7	2.4	3.0
D 41	0.46	0.68	0.67	2.9	3.5	3.5

$$a = \log \sigma_0 + 0.12 \log N \qquad (3)$$

The value of "a" generally increases according to the increase of fatigue strength. As a result of calculation, it was confirmed that the value of "a" would decrease steadily according to the increase in the diameter of bar. This phenomenon has been pointed out in the previous research [3] and can be explained by several reasons. For example, it is considered that a total number of latent defects that are contained in a deformed bar and will cause failure of the bar may increase according to the increase in the diameter of bar. Besides this reason, spacing of lugs that are provided to improve the bond characteristics of bar will relatively decrease and height of lug itself will increase according to the increase in the diameter of bar.

A ratio of the spacing of lugs to the diameter of bar and the height of lug itself should be related to stress concentration at the base of lug. The effect of stress concentration has been completely clarified by an elastic finite element analysis carried out by Yamazaki et al.[15]. Considering this result, the standard spacing and height of lug is recommended. Table 2 shows an example of details of deformed bars that are provided in Japan. In most of the bars the ratio is around 0.6, in some of them, however, the ratio decreases according to the increase in the diameter of bar. In addition to the effect of diameter of bar itself, the effect of the ratio of the spacing of lugs to the diameter of bar and that of the height of lug should coexist. Therefore, fatigue strength of deformed bars decreases significantly according to the increase in the diameter of bar.

As a result of regression analysis, the influence of diameter of bar on fatigue strength was estimated as eq.(4) and a new equation predicting fatigue strength could be represented as eq.(5) using eq.(4).

$$a = 3.23 - 0.0031 D \qquad (4)$$

$$\log \sigma_0 = 3.23 - 0.0031 D - 0.12 \log N \qquad (5)$$

where, σ_0: fatigue strength presented by a perfectly one directional range of stress (MPa)
D : nominal diameter of a deformed bar (mm)

Eq.(5) was derived from the data of which repeated cycles were less than 2 millions. For the data of which repeated cycles were more than 2 millions, the extent of the decrease of fatigue strength according to the increase of repeated cycles seemed to be more gradual. For this region, however, only very few experimental data was available and it was very difficult to determine the S-N line. It was presumed that the value of "k" generally had a tendency to become about a half of that for less than 2 millions.

Eq.(5) can predict experimental fatigue strength with reasonable accuracy. The coefficient of variation of the ratio of experimental fatigue strength to calculated one for 82 data is 10.1 % (Fig.1).

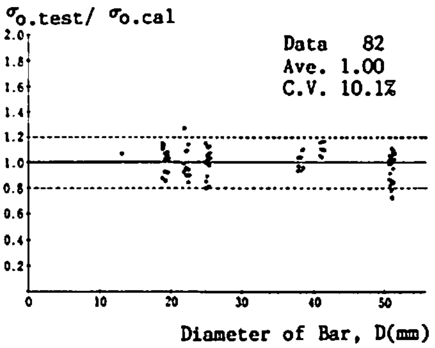

Fig.1 Prediction of Fatigue Strength of Deformed Bars with Arc (a=3.23-0.0031D)

6. INFLUENCE OF PRESENCE OR ABSENCE OF ARC AT THE BASE OF LUG

It was considered that presence or absence of arc at the base of lug was also a factor having an important effect on fatigue strength. If an arc does not exist, fatigue strength will decrease remarkably due to stress concentration at the base of lug [3]. The effect of stress concentration will be promoted moreover when the intersectional angle between direction of lug and longitudinal direction of bar approaches to a right angle. On the other hand, if the intersectional angle becomes small, the influence of stress concentration is softened even if the arc is not provided.

This is due to the decrease of the ratio of change of the cross sectional area of a deformed bar along longitudinal direction. Therefore, in order to estimate the influence of absence of arc quantitatively, the effect of the intersectional angle has to be considered at the same time. For deformed bars without arc, experimental fatigue strength was compared with calculated one using eq.(5). Consequently, it was admitted that fatigue strength of a deformed bar without arc generally decreased compared with that of a deformed bar with arc and the ratio of fatigue strength of a deformed bar without arc to that of a bar with arc decreased gradually according to the increase of the intersectional angle. These results are coincident to experimental facts pointed out previously.

As a result of various examinations, fatigue strength of a deformed bar without arc could be represented by eq.(6). In eq.(6), "b" is a factor concerning the extent of the decrease of fatigue strength due to absence of arc. The value of "b" is calculated by eq.(7)

$$\log \sigma_0 = b\,(\,3.23 - 0.0031\,D\,) - 0.12 \log N \qquad (6)$$

$$b = 1 - 0.0002\,\theta \qquad (7)$$

where, θ: intersectional angle between direction of lug and longitudinal direction of bar (degree)

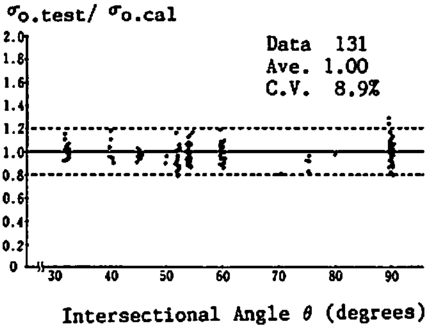

Fig.2 Prediction of Fatigue Strength of Deformed Bars without Arc ($b=1-0.0002\theta$)

Table 3 Comparison of Experimental Fatigue Strength and Calculated One Using Proposed Equation (Gas Pressure Welded Bars)

Diameter (mm)	$\sigma_{o.test}/\sigma_{o.cal}$	
	With Arc	Without Arc
$D \leq 29$	Data 4 Ave. 1.65 C.V. 9.9%	Data 13 Ave. 1.52 C.V. 13.1%
$29 < D \leq 38$	Data 34 Ave. 1.51 C.V. 11.4%	Data 8 Ave. 1.38 C.V. 7.0%
$38 < D$	Data 7 Ave. 1.46 C.V. 8.8%	Data 0

Fig.2 shows the ratio of experimental fatigue strength to calculated one using eq.(6). From Fig.2, it is admitted that eq.(6) can predict experimental fatigue strength fairly well. The coefficient of variation for 131 data is 8.9 %.

7. FATIGUE STRENGTH OF GAS PRESSURE WELDED BARS

It was recognized that fatigue strength of gas pressure welded bars was naturally less than that of straight bars. This fact could be explained by the following reasons, that is, the increase of latent defects in the heat affected zone, the expansion of diameter of bar and the stress concentration according to the decrease of spacing of lugs. These reasons have been pointed out previously [2]. According to observation on a fatigue failure mode, however, it was noticed that the fatal crack originated from the base of lug adjacent to the heat affected zone. Therefore, it was presumed that for gas pressure welded bars the influence of diameter of bar, intersectional angle and presence or absence of arc at the base of lug also existed as well as for straight bars.

As the quality of material of bars was affected by the heat effect due to gas pressure welding, the value of "k" for gas pressure welded bars might be different from that for straight bars. Table 3 represents the average and coefficient of variation of a ratio of experimental fatigue strength of gas pressure welded bars to calculated one by the proposed equation [1]. Experimental fatigue strength of gas pressure welded bars steadily decreases according to the increase in the diameter of bar and the absence of arc at the base of lug as well as that of straight bars.

The value of "k" for gas pressure welded bars could be obtained from the same method for straight bars. The "k" value became 0.21 as was stated previously. Using this "k" value, the value of "a" could be estimated by eq.(8).

$$a = 3.66 - 0.0031\,D \qquad (8)$$

Fig. 3 shows the ratio of experimental fatigue strength of gas pressure welded bars with arc at the base of lug to calculated one using the value of "a" represented by eq.(8). From Fig.3, it is admitted that experimental fatigue

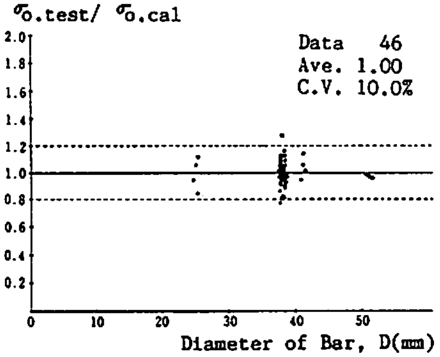

Fig.3 Prediction of Fatigue Strength of Gas Pressure Welded Bars With Arc ($a=3.66-0.0031D$)

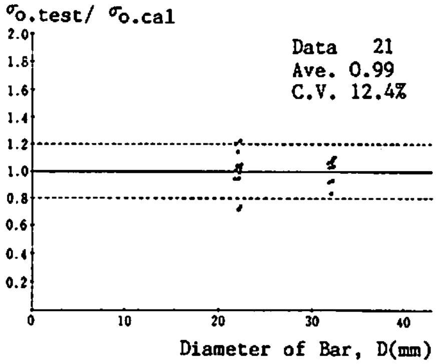

Fig.4 Prediction of Fatigue Strength of Gas Pressure Welded Bars Without Arc ($b=1-0.0002\theta$)

strength of gas pressure welded bars can be predicted fairly well as well as that for straight bars. The coefficient of variation for 46 data is 10.0%.

As the number of data without arc at the base of lug was quite few in collected data, the influence of absence of arc could not be examined precisely. Fig.4 shows the ratio of experimental fatigue strength of gas pressure welded bars without arc to calculated one using the "b" value represented by eq.(7). The average and coefficient of variation for these sort of data was 0.99 and 12.4%, respectively and the accuracy of calculation did not decrease significantly. Therefore, it was presumed that the influence of the presence or absence of arc at the base of lug for gas pressure welded bars would exist nearly to the same extent for straight bars.

In the case of automatic gas pressure welding method, that has been researched and developed vigorously, the accuracy of welding can be ensured easily and static strength of bars can be obtained sufficiently. In result, the expansion of diameter of bar that should decrease fatigue strength of gas pressure welded bars can be controlled within a certain limit [16]. Therefore, when automatic gas welding method is employed, it is reasonable to consider the increase of fatigue strength. However, as the number of the data concerning automatic gas welded bars were quite few in collected data, fatigue strength of automatic gas pressure welded bars could not be estimated clearly.

8. NEW EQUATION PREDICTING FATIGUE STRENGTH AND THE CHARACTERISTIC VALUE

A new equation predicting fatigue strength could be obtained considering the influence of the diameter of bar, the presence or absence of arc at the base of lug and the intersectional angle between direction of lug and longitudinal direction of bar. The equation could predict an average value of fatigue strength keeping the coefficient of variation to be within 10 %. Therefore, using this equation and assuming that the reliability is 95 %, an equation calculating the characteristic value of fatigue strength can be derived.

Considering the convenience of the application for design, eq.(5) and eq.(6) were rewritten in the form containing an applied range of stress, an applied minimum stress and tensile strength of a deformed bar directly. A new constant "k_0" was incorporated in the equation. The value of "k_0" was changed as described as follows according to the value of the intersectional angle and the presence or absence of arc. Finally the following equation was obtained.

$$f_{sr} = (1 - \sigma_{min} / f_{su}) \frac{10^{a}}{N^{k}} \tag{9}$$

where, f_{sr}: fatigue strength represented by a range of stress (MPa)
k : a factor concerning the gradient of the S-N line
$= 0.12$ for $N < 2 \times 10^{6}$ cycles
$a = k_o (3.17 - 0.003 D)$
k_o:a constant concerning the intersectional angle and the presence or absence of arc
$= 1.00$ for the case of absence of arc and the intersectional angle of more than or equal to 60 degrees
$= 1.01$ for the case of absence of arc and the intersectional angle of less than 60 degrees
$= 1.02$ for the case of presence of arc

The value of "k_o" was intentionally arranged to be equal to 1.00 for the most severe case, that is, the case in which an arc was not provided and the intersectional angle was more than or equal to 60 degrees. Using eq.(9), experimental fatigue strength is predicted fairly well. The coefficient of variation for total 213 data is 9.6% (Fig.5). Therefore, if the safety factor is estimated as 1.20, the equation calculating the characteristic value of fatigue strength can be presented as eq.(10).

$$f_{srk} = (1 - \sigma_{min} / f_{su}) \frac{10^{a}}{N^{k}} / 1.20 \tag{10}$$

where, f_{srk} : the characteristic value of fatigue strength of deformed bars

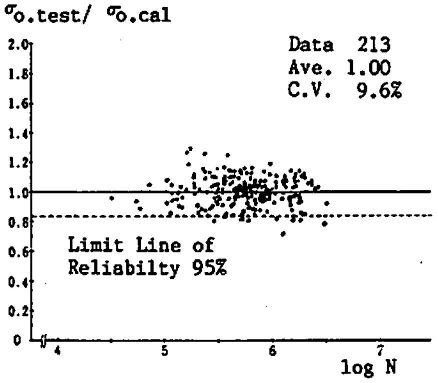

Fig.5 Prediction of Fatigue Strength of Deformed Bars Using Eq.(9)

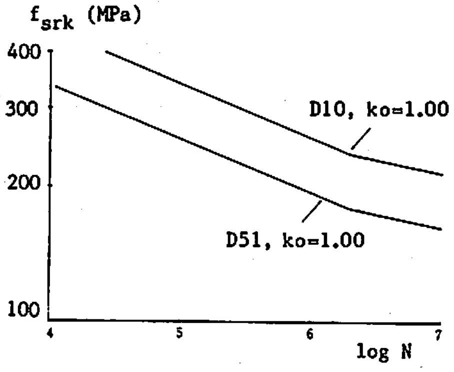

Fig.6 The Characteristic Value of Fatigue Strength

In design procedures, it is thought that an engineer can generally select the type of deformed bars and the diameter of bar but can not order the intersectional angle and the presence of arc. Therefore, a design equation in which only the diameter of bar is a parameter is desirable. When eq.(10) is used, it had better assume that the value of "k_o" is equal to 1.00. When a repeated loading condition is remarkable severe, it is recommended to employ resistive deformed bars for fatigue. In that case, the value of "k_o" may be determined considering the presence or absence of arc and the intersectional angle.

It is determined that eq.(10) is adopted in the standard specification of concrete structures of JSCE revised in 1986. Fig.6 shows the characteristic value of fatigue strength for D10 and D51 (nominal diameter is 10 and 51 mm, respectively) assuming that the value of "k_o" is 1.00.

9. CONCLUSION

Factors affecting fatigue characteristics of deformed bars including the diameter of bar, the presence or absence of arc at the base of lug, the intersectional angle between direction of lug and longitudinal direction of bar and the heat effect due to gas pressure welding joint were considered and the extent of each individual influence was estimated quantitatively. Based on these estimations, the equation predicting fatigue strength of deformed bars could finally be obtained. This new equation predicts the experimental fatigue strength fairly well. Considering the application for design, an equation calculating the characteristic value of fatigue strength is presented.

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