Gallo, Pasquale; Romanoff, Jani; Karttunen, Anssi; Frank, Darko; Remes, Heikki

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Synthesis of experimental testing and fatigue behavior of laser stake-welded T-joints on medium-high cycle fatigue range

P. Gallo[a,b,*], J. Romanoff[b], D. Frank[c], A. Karttunen[b], H. Remes[b]

[a]*Kyoto University, Dep. of Mech. Eng. and Science, Kyoto-daigaku-Katsura, Nishikyo-Ku, Kyoto 615-8540, Japan*
[b]*Aalto University, Dep. of Mech. Eng., Puumiehenkuja 5A, Espoo 02150, Finland*
[c]*as2con-Alveus Ltd., Rijeka 51000, Croatia*

Abstract

The paper presents a synthesis of experimental fatigue tests and theoretical studies of laser stake-welded T-joints in steel sandwich panels. The experiments indicate that the slope of the fatigue strength curves varies significantly depending on the type of loading the joint experiences, but also on the geometry. Therefore, the focus is on the influence of crack tip plasticity when the joints are loaded under tension and bending. This is investigated by two different approaches based on square root of J-integral. With this parameter, the experimental fatigue curves meet at the fatigue limit for all of the loading modes and geometries. To investigate the change in slope in the medium-high cycle fatigue range, the suitability of stress gradient and plastic zone size as defined by Irwin are studied. It is shown that the gradient of principal stress correlates well with the variation of slope, but it does not give a practical tool for fatigue assessment of the joints. Instead, based on the plastic zone approach, a new method is proposed that permits the estimation of number of cycles to failure under bending directly from the tension fatigue curve. The method is verified with experiments.

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Keywords: Crack tip plasticity; laser stake-welds; fatigue assessment; slope of fatigue curve;

* Corresponding author. Tel.: +81-70-2803-1673.
E-mail address: pasquale.gallo@aalto.fi

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1. Introduction

Weight reduction is a crucial design challenge not only for the automotive and aerospace industries, but also in shipbuilding. To achieve the weight reduction, one approach has been to replace thick monolithic plates by sandwich panels made from thin plates as shown by Knox et al. (1998); Poirier et al. (2013); Roland and Reinert (2000); Valdevit et al. (2006), (2004); Wiernicki et al. (1991).

Nomenclature

2b	un-cracked ligament
a	crack length
C_T	constant of the tension fatigue curve
E	Young's modulus
F	applied load in experimental tests, joint loaded under tension
F_1	crack driving force
F_R	crack driving force ratio
l_f	length of the face plate
l_w	length of the web plate
m_B	slope of the bending fatigue resistance curve
m_T	slope of the tension fatigue resistance curve
N_f	number of cycles to failure
P	applied load, joint loaded under bending
r_y	first order estimation of the plastic zone size
t_f	thickness of the face plate
t_w	thickness of the web plate
σ_{nom}	applied load, joint loaded under tension
σ_{YS}	yielding stress
σ_{yy}	generic elastic stress distribution
χ	relative stress gradient

This type of lightweight structure introduces an engineering challenge: current methods to estimate fatigue life of welded steel structures are mainly developed for thick plates and are not well suitable to sandwich panels assembled from thin plates. For instance, in the case of the notch stress approach, the actual weld is geometrically modified to assess fatigue effective stresses. In the case on thin plate, this modification may change significantly the load-carrying mechanism of the structure. Although fatigue is often the bottleneck of the design, experimentally verified fatigue design proposals for laser stake-welded T-joints are only few and these are not included in actual design standards. The first fatigue tests of laser stake-welded T-joints were reported by Socha et al. (1998) and later by Boronski and Szala (2006a), (2006b). Fatigue experiments conducted on web-core sandwich panels were performed by the Sandwich Consortium (2002) and Kozak (2007), (2006). The Sandwich Consortium (2002) found that the slope of the fatigue resistance curves for laser-welded T-joints in sandwich panels depends on the loading condition. This result was later found and confirmed by Karttunen et al. (2017) on empty and Divinycell H80-foam-filled beams. In all these experimental works, the slope value of the fatigue resistance curves was larger than the value commonly observed for other steel joints. However, possible reasons for the slope difference were not given and, thus, this was not explicitly consider in given design proposals.

A few studies have tried to explain why the slope of the fatigue resistance curve changes with the loading conditions. Some fundamental contributions on the topic are from Frank (2015); Frank et al. (2013a), (2011). In particular, Frank et al. (2013a) presented a study on the influence of loading mode on the slope of the fatigue resistance curve. The test results were presented using a J-integral approach and showed that the slope of the fatigue curve depends on the gradient of the elastic stresses at notch tip of the laser-stake weld. This gradient was found to be affected by plate thicknesses and T-joint loading mode, causing an higher gradient of elastic stresses in bending than in tension and in thin than thick plates. Similar effects have been observed earlier by Lazzarin and Berto (2008) for tensile and shear loaded welded joints. This raised a question of differences in small-scale yielding at different loading modes. Recently, a contribution by Gallo et al. (2017) theoretically showed that the reason for the slope difference in the case of laser-stake welded T-joints is indeed on the small-scale yielding and that in bending the plasticity at the weld notch develops faster than in tension. Based on those findings, a method to compute bending fatigue resistance curve from the corresponding one for tension was given.

This study gives a synthesis of recent experimental fatigue tests and theoretical studies of laser stake-welded T-joints in steel sandwich panels. Experimental tests are analysed by means of principal stress gradient and plastic zone size, as introduced by Frank et al. (2013a); Gallo et al. (2017).

2. Short review of the fatigue tests

The fatigue test results from sandwich panel to welded joint under tension or bending are summarized in Fig. 1. The tension fatigue tests performed on laser stake-welded T-joints were conducted by Socha et al. (1998) and Frank et al. (2013b) while the bending test by Sandwich Consortium (2002) and Karttunen et al. (2017). The materials in testing were DIN S235JR and S355MC structural steel in the web and face plates, respectively. The plate thicknesses varied in webs from 4mm to 8mm and in the faces from 1mm to 8mm. The weld thickness is typically between 1-1.5mm as shown by Romanoff et al. (2007a). The experimental campaign on steel sandwich panels was started by Sandwich Consortium (2002) which considered 1000mm long and 480mm wide panels supported by rollers along longer edges, and loaded by rigid indenter at the middle stiffener. The face plate thicknesses varied from 1-3mm and the panels were empty or filled with polyurethane foam or balsa. The results indicated significant improvement in load-carrying capacity of the panels with filling material, but also change in the slope of the force-cycles to failure curves.

In sandwich panels, the unidirectional core plates carry significant amount of shear load and it has significant influence on load-carrying mechanism and stake-weld bending deformation as shown in Fig. 1. Since the bending deformation of a stake weld can affect the actual fatigue strength of the joint, further investigations were carried out on panel response by Frank et al. (2013a), (2013c), Romanoff et al. (2007a), (2007b), and on the joint strength by Frank et al. (2013c). Then, fatigue strength assessment on tension specimens was considered first, varying the plate thicknesses; see Socha et al. (1998), Frank et al. (2013c). It was observed that when plate thicknesses are decreased, the slope value m of the fatigue resistance curve increases. Detailed FE-analyses on the measured geometry and comparison to fatigue strength revealed that the traction free boundaries at the T-joint start to interact strongly in case of thin plates which, in turn, could affect the fatigue strength (Frank et al. 2013a).

Later, further analysis have been carried out on panel bending. The experiments from Sandwich Consortium (2002) were reanalyzed by Frank et al. (2013a), and it was observed that in bending there is another effect due to stress gradient at the T-joint. This gradient of first principal stress changes as the loading mode does from tension to bending, and it is also affected by possible contact inside the stake weld at very high loads. The influence of contact was further narrowed down to have major impact on panel level load-carrying mechanism rather than the fatigue effective stresses. To confirm these findings, Karttunen et al. (2017) performed beam experiments using the same set-up as in Sandwich Consortium (2002), but attention was paid in the measurement of T-joint bending. These experiments confirmed the results from above and showed that the slope indeed is affected by T-joint bending. This is visible in the strain histories shown in Fig. 1. This difference in T-joint bending results in higher slope of the fatigue resistance curve.

Thus, the experiments showed that the fatigue strength is affected by the plate thickness, the loading mode and the load-carrying mechanism of the panels. While plate thickness effect may be explained employing FE elastic solutions at the T-joint including interacting traction free boundaries, the loading mode affects mainly the gradient of elastic stresses at the crack-like notch tip. Load-carrying mechanism of the panels is affected by the contact at the T-joint, which increases local panel shear stiffness. If these effects are properly taken into account, the fatigue strength at fatigue limit is the same for all of the considered geometries, but also for different load-ratios of R=0 and R=-1; see Frank (2015). However, the slope of the fatigue strength curve is an open topic from the theoretical point of view and further investigations on the subject have been carried out.

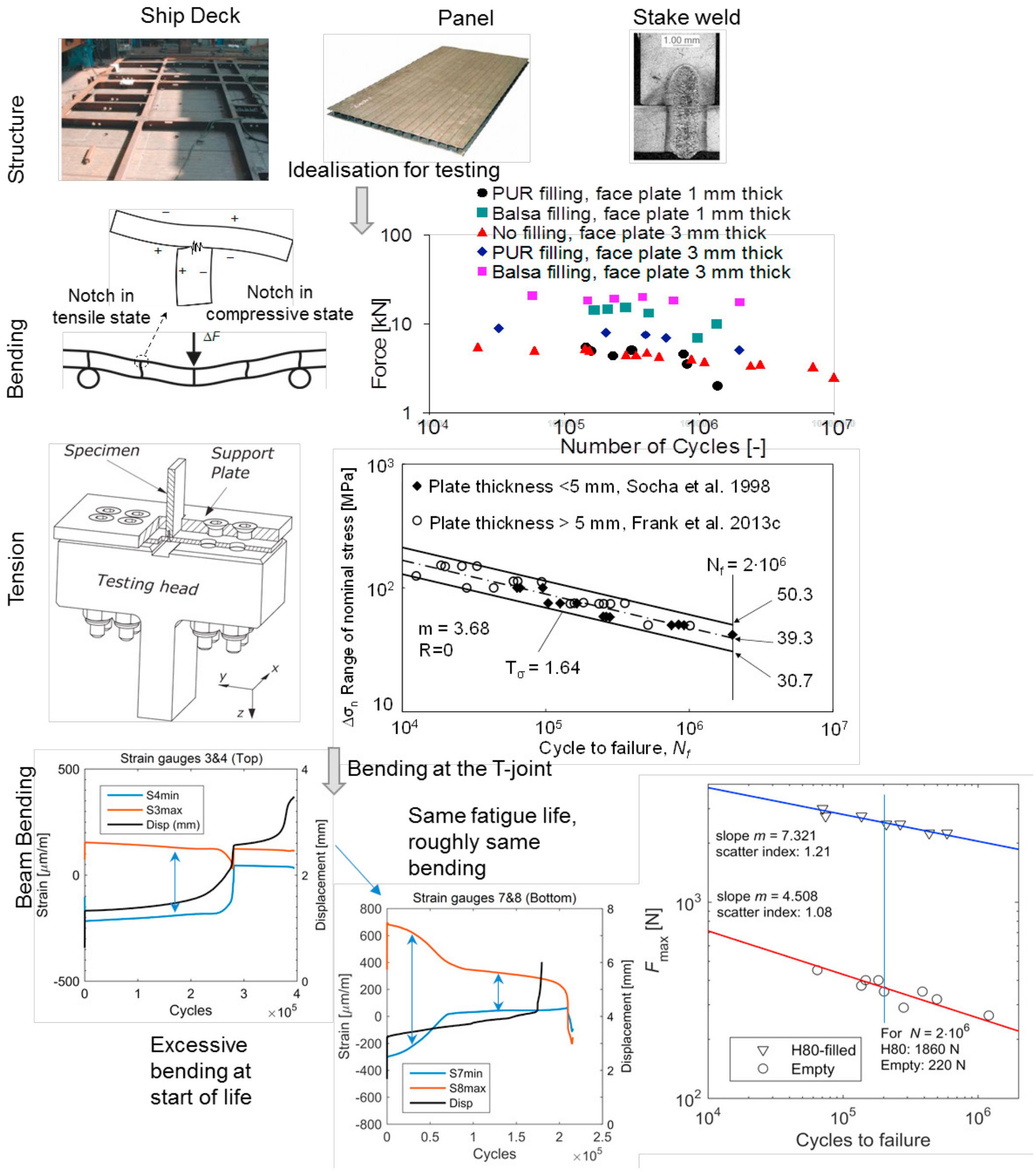

Fig. 1. Review on the fatigue strength test results on laser stake-welded T-joints by Socha et al. (1998), Sandwich Consortium (2002), Frank et al. (2013a), (2013c), Karttunen et al. (2017).

3. Estimation model for the number of cycles to failure of bending load

In high-cycle fatigue range, the explanation of the fatigue curve slope changes can be based on the assumption that small-scale yielding condition is satisfied. This means that the load-carrying mechanism of the T-joint is only slightly modified from fatigue limit towards medium-high cycle range.

In Frank et al. (2013a), a stress gradient at the notch tip was employed to explain the changes of the slope; see Figure 2. The square root of J-integral, as originally proposed by Lazzarin et al. (2013); Lazzarin and Berto (2008) for the strain energy density, was used as a fatigue strength parameter. The dimensionless stress gradient of maximum principal stresses of the T-joint was evaluated using extremely fine FE discretization and the initial geometry of the laser-stake weld. A semi-empirical linear relation between dimensionless stress gradient, χ, and the slope of the fatigue strength curve, *m*, was derived and proposed.

However, the dimensionless stress gradient is not able to explain the actual plasticity of the joint or to generalize the solution for wide variety of T-joint parameters (e.g. geometry, materials and loading). Moreover, even if it gives important explanation on T-joint fatigue curve slopes, it does not provide a practical tool for fatigue assessment. Therefore, simple linear-elastic perfectly-plastic model has been used to investigate the differences between tension and bending. The same first-order plastic zone size r_y (see Fig. 3a-b) as defined by Irwin (1968), (1960) and thus the same effective plastic zone is assumed as a comparison condition between tension and bending loads. Simplified diagram of the procedure is proposed in Fig. 3c, while detailed explanation of the method is proposed by Gallo et al. (2017).

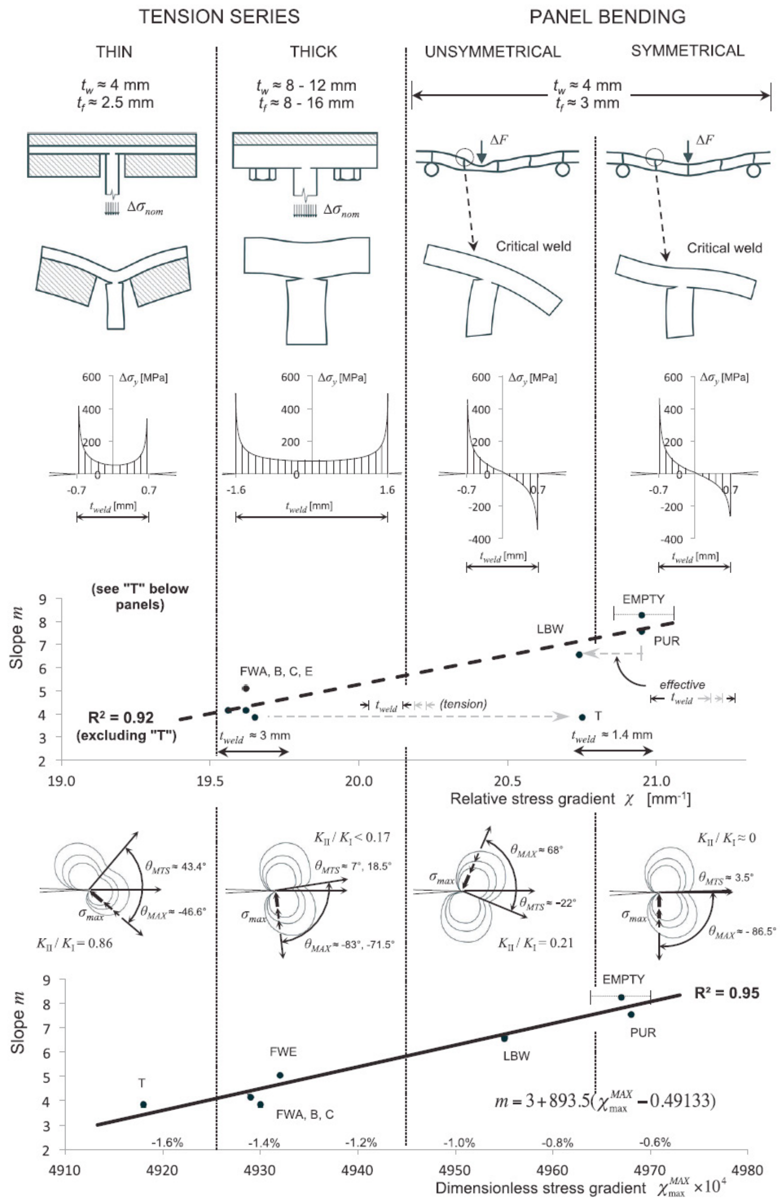

Fig. 2. The slope of fatigue resistance curve as a function of stress gradient, from Frank et al. (2013a).

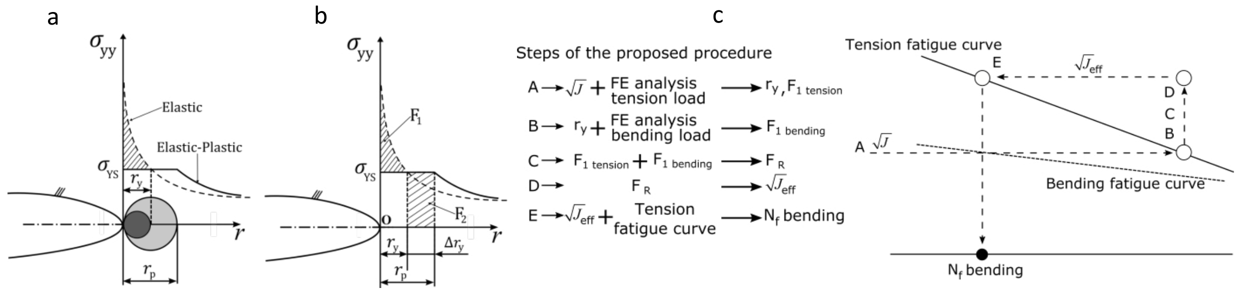

Fig. 3. Qualitative representation of the first-order r_y and second-order r_p plastic zone size (a), and (b) load redistribution and force equilibrium; (c) simplified diagram of the proposed procedure for the evaluation of the number of cycles to failure of laser stake-welded T-joints under bending load.

The force F_1, depicted in Fig. 3 is considered to be the *crack driving force* acting on the plastic (fatigue) zone, and can be used to quantify the difference between the tension and bending. The crack driving force is theoretically defined by the following integral both for tension and bending (Gallo et al., 2017):

$$F_1 = \int_0^{r_y} \sigma_{yy} \mathrm{dr} - \sigma_{YS} \cdot r_y \tag{1}$$

The ratio within the force F_1 of the bending and the tension, assuming the same r_y, is defined as the *representative crack driving force ratio* F_R:

$$F_R = \frac{F_{1\text{ bending}}}{F_{1\text{ tension}}} \tag{2}$$

This was derived numerically with the aid of Finite Element analysis. Based on the crack driving force ratio, an effective J-integral is defined as follows:

$$\sqrt{J}_{eff} = \sqrt{J} \cdot F_R \tag{3}$$

It is now assumed that the bending number of cycle to failure can be derived from the tension fatigue curve if the effective J-integral defined in Eq. (3) is employed. On the basis of these assumptions, the bending fatigue curve, in terms of the square root of the J-Integral, is defined by the following equation according to Wöhler form:

$$\left(\sqrt{J}_{eff}\right)^{m_T} \cdot N_{f,B} = C_T \tag{4}$$

The following procedure for the fatigue assessment of laser stake-welded T-joints under a bending load is proposed (see Fig. 3c):

- once the desired $\sqrt{J}$ is selected, evaluation through finite element analysis of the corresponding force $F_{1\text{ tension}}$ and first-order plastic zone size r_y; Step A;
- evaluation of the equivalent force $F_{1\text{ bending}}$ for the bending case, assuming the same first-order plastic zone size evaluated in the previous step, through finite element analysis; Step B;
- evaluation of F_R as defined by Eq. (2); Step C;

- evaluation of the effective $\sqrt{J}$ according to Eq. (3); Step D;
- the new effective J-Integral is then used as the input parameter in the fatigue curve equation of the tension load and the number of cycles to failure of the bending is obtained (according to Eq. (4)); Step E.

Example and verification of the approach is presented next considering a laser stake welded T-joint.

4. Case study and evaluation of the model

Geometric features of the case study are shown and listed in Fig. 4 and Table 1. The gap between face and web has been considered and modelled as a crack being the notch-gap radius $\rho << a$. The details of the FE-modeling are given in Gallo et al. (2017). The load levels are classified as *low* and *high* as a function of the r_y/b ratio, and are listed in Table 2. To cover the fatigue strength variation results from the thicknesses for the same loading condition, simplified unified fatigue curves are assumed for tension and bending that better represent the considered geometry: an average value of the slope m=4.2 is assumed for tension load, while m=7 for the bending case. The results are summarized in Table 2, and show a good agreement with the experimental results.

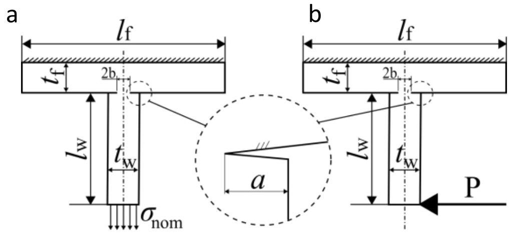

Fig. 4. Case study: laser stake-welded T-joint geometry under a) tension and b) bending load.

Table 1. Case study mechanical properties and geometry parameters

σ_{YS}	σ_{UTS}	E	t_w	l_w	t_f	l_f	a	2b
(MPa)	*(MPa)*	*(GPa)*	*(mm)*	*(mm)*	*(mm)*	*(mm)*	*(mm)*	*(mm)*
235	400	206	8	60	8	100	2.5	3

Table 2. Comparison between the estimated and expected number of cycles to failure for bending load. *simplified curve: m =4.2, fatigue strength at two million cycles=0.37 $kJ^{0.5}/m$. ** simplified curve: m =7, fatigue strength at two million cycles=0.37 $kJ^{0.5}/m$, Frank et al. (2013a).

Load Level	r_y/b	P	σ_{nom}	F_R ratio	$\sqrt{J}$	$\sqrt{J_{eff}}$	$N_{f\,bending}$	$N_{f\,bending}$	Δ%
		(N/mm)	*(MPa)*	(bend./tens.)	*($kJ^{0.5}/m$)*	*($kJ^{0.5}/m$)*	Estimated*	Experimental**	
1	0.007	1.65	16.875	1	0.1263	0.1263	>2.00E+06	>2.00E+06	-
2	0.050	4.60	45	1.07≈1	0.3365	0.3365	>2.00E+06	>2.00E+06	-
3	0.101	6.75	61.875	1.17	0.4627	0.5417	4.04E+05	4.18E+05	-3%
4	0.154	8.75	75	1.28	0.5609	0.7179	1.24E+05	1.09E+05	14%
5	0.204	10.80	85.125	1.39	0.6366	0.8827	5.19E+04	4.48E+04	16%

5. Conclusion

The paper presented an overview of the fatigue strength assessment of the laser-stake welded T-joints based on both experimental and theoretical investigations carried out over several years. The main findings are as follows:

1. Experiments show variation in fatigue strength curves as a function of different parameters, i.e. thickness, loading mode, load-carrying mechanism of the panels;
2. When $\sqrt{J}$ is used as fatigue strength parameter, all experimental results share the same fatigue strength at fatigue limit;
3. When the dimensionless stress gradient, χ, is assessed, a semi-empirical relation has been obtained that explains the change in the slope of fatigue strength curve, m, based on $\sqrt{J}$;

4. When small scale yielding is modelled using simple linear-elastic perfectly-plastic material model and first order plastic zone size as proposed by Irwin, the change in the slope can be explained theoretically for the medium to high cycle range;
5. Based on Irwin's first order plastic zone size, a method that permits the number of cycles to failure under bending to be derived from the tension fatigue resistance curve is given, and a good agreement with the experimental results is obtained.

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