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THEORETICAL DETERMINATION OF FATIGUE STRENGTH AT STRESS CONCENTRATION

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FOREWORD

This report was prepared by Professor Dr. Ing, Dr. rer. nat. h. c. H. Neuber, Institut für Technische Mechanik, Technische Hochschule, Munich, Germany, under Project No. 7351, "Metallic Materials," Task No. 735106, "Behavior of Metals," Dr. J. A. Herzog, MAMS, Project Engineer.

The manuscript was released by the author in July 1967 for publication as a Technical Report.

Further results of the theoretical investigations and the comparison with the experimental data are given in AFML-TR-68-19.

The author is indebted to his coworker Dr. H. G. Hahn for assistance in preparing this report. A part II to this report will be published in which the author will amend the herein stated thoughts.

The report has been reviewed and is approved.

C. T. Lynch
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ABSTRACT

The mechanism of stress and strain concentration at fatigue loading is governed by two fundamental effects. Within the yield range of ductile materials the macro-support effect is dominating which in this paper is represented by the results of a nonlinear theory derived by the author. Within the high-cycle fatigue range the micro-support effect is governing which can be described by the author's theory of mean stress value, originally derived in connection with the calculation of sharply curved notches. In this theory a material constant of length dimension is introduced. Taking into account these two effects an approximate precalculation of the fatigue strength of notched construction parts is possible.

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LIST OF SYMBOLS

F	kp	force
A	mm^2	area
σ	kp/mm^2	stress
ε	-	strain
E	kp/mm^2	Young's modulus
α	-	concentration factor
ρ	mm	notch root radius
ρ^*	mm	fictive length of structure
σ_s	kp/mm^2	yield stress
σ_a	kp/mm^2	fatigue strength of unnotched specimen
σ_{an}	kp/mm^2	fatigue strength of notched specimen
$\beta = \frac{\sigma_a}{\sigma_{an}}$	-	fatigue strength reduction factor

All other symbols are explained in the text.

1. General Remarks and Definitions

In order to explain the characteristic mechanism of stress and strain concentration first the homogeneous state of stress may be considered as it is realised in prismatical tension bars, if the resultant external force is passing through the center of gravity of the cross section. In such cases the stress is equal to the ratio of the force F and the cross section area A. In nearly prismatical tension bars with smooth deviations from the prismatical form such a calculation method can serve as a suitable approximation too. But in nonprismatical bars with sudden changes of form and area of the cross section the stress distribution becomes considerably disturbed (notch-effect). Then the effective strength of the material only can be determined by special calculation methods. Especially in the minimum cross section of the bars the stress distribution is non-uniform and at the notch-surface the stresses are considerably higher than the mean value

$$\sigma_N = \frac{F}{A_{min}} \tag{1}$$

which is called nominal stress. The strain corresponding to σ_N with regard to the stress-strain curve of the material (Fig. 1) may be denoted by

$$\varepsilon(\sigma_N) = \varepsilon_N \tag{2}$$

and may be called nominal strain. The ratio

$$\frac{\sigma_{max}}{\sigma_N} = \alpha_\sigma \tag{3}$$

represents the stress concentration factor; consequently the ratio

$$\frac{\varepsilon_{max}}{\varepsilon_N} = \alpha_\varepsilon \tag{4}$$

may be called the strain concentration factor.

At two- and three-axial states of stress, the comparison stress σ_c and the comparison strain ε_c can be defined by suitable strength hypotheses. Their maximal values $\sigma_{c\,max}$ and $\varepsilon_{c\,max}$ are the two most characteristic quantities representing the effective strength of the material. Therefore these quantities must be inserted in (3) and (4) instead of σ_{max} and ε_{max}; with regard to the stress-strain-line (Fig. 1) they shortly will be denoted by σ and ε.

In the linear elastic deformation range, i.e. for HOOKE's law, stress concentration factor and strain concentration factor are identical and equal to the Hookian stress concentration factor α_H which only depends on the geometric form of the notch. In the linear range the Hookian maximum stress (or comparison stress) is

$$\sigma_H = \alpha_H \sigma_N \tag{5}$$

and the Hookian maximum strain (or comparison strain) is

$$\varepsilon_H = \alpha_H \varepsilon_N = \alpha_H \frac{\sigma_N}{E} \tag{6}$$

where E is Young's modulus. The Hookian stress concentration factor can be determined by means of the linear theory of elasticity or by experimental methods.

As an example, in Fig. 2 the Hookian stress concentration factor for a notched flat plate under tension is shown.

2. The Macro-Support-Effect

Now a notched tension bar may be considered which is loaded beyond the elastic limit according to a stress-strain curve as shown in Fig. 1. With increasing load the distribution of the ratio σ_c/σ_N across the minimum section shows a decrease of the peak stress in the nonlinear and plastic range (Fig. 3). At the same time the central part of the cross-section takes more of the load, while the endangered

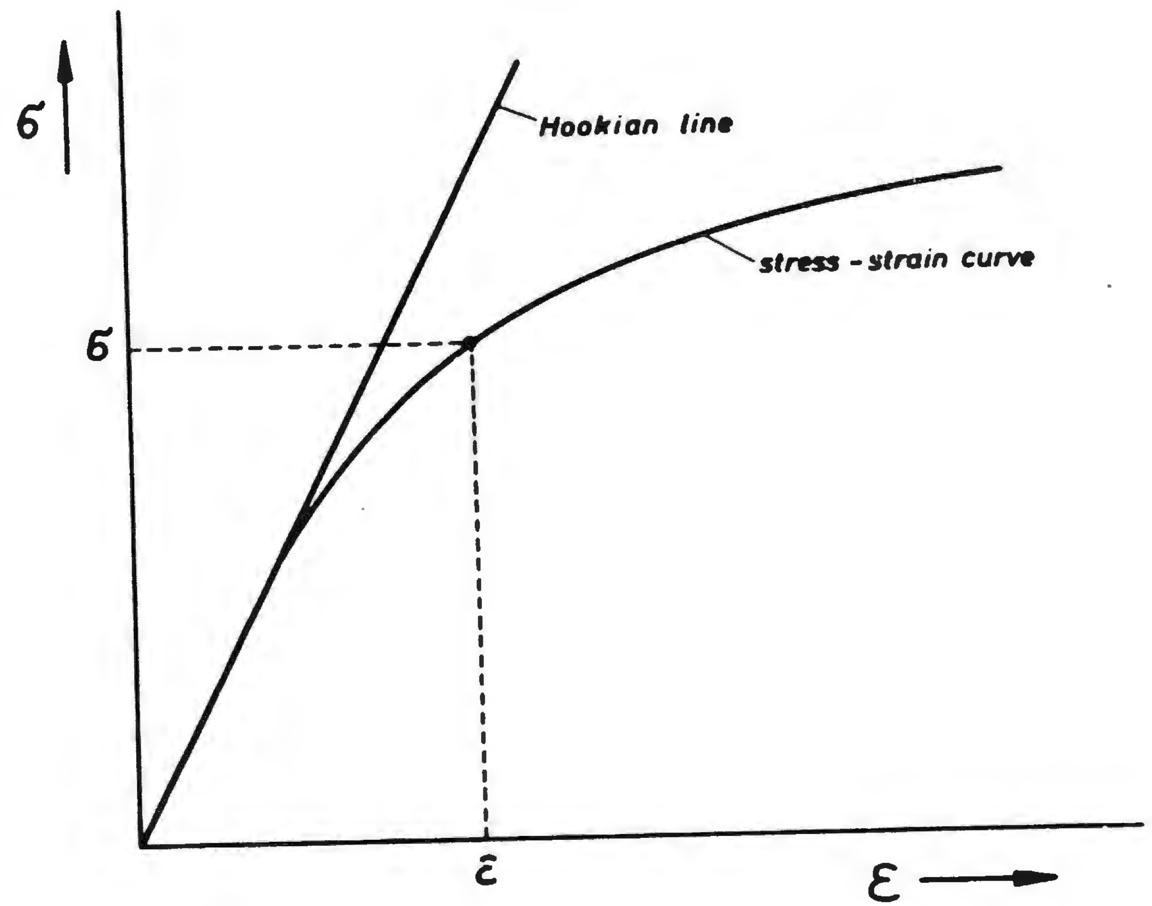


Fig. 1 Stress-strain curve of real materials

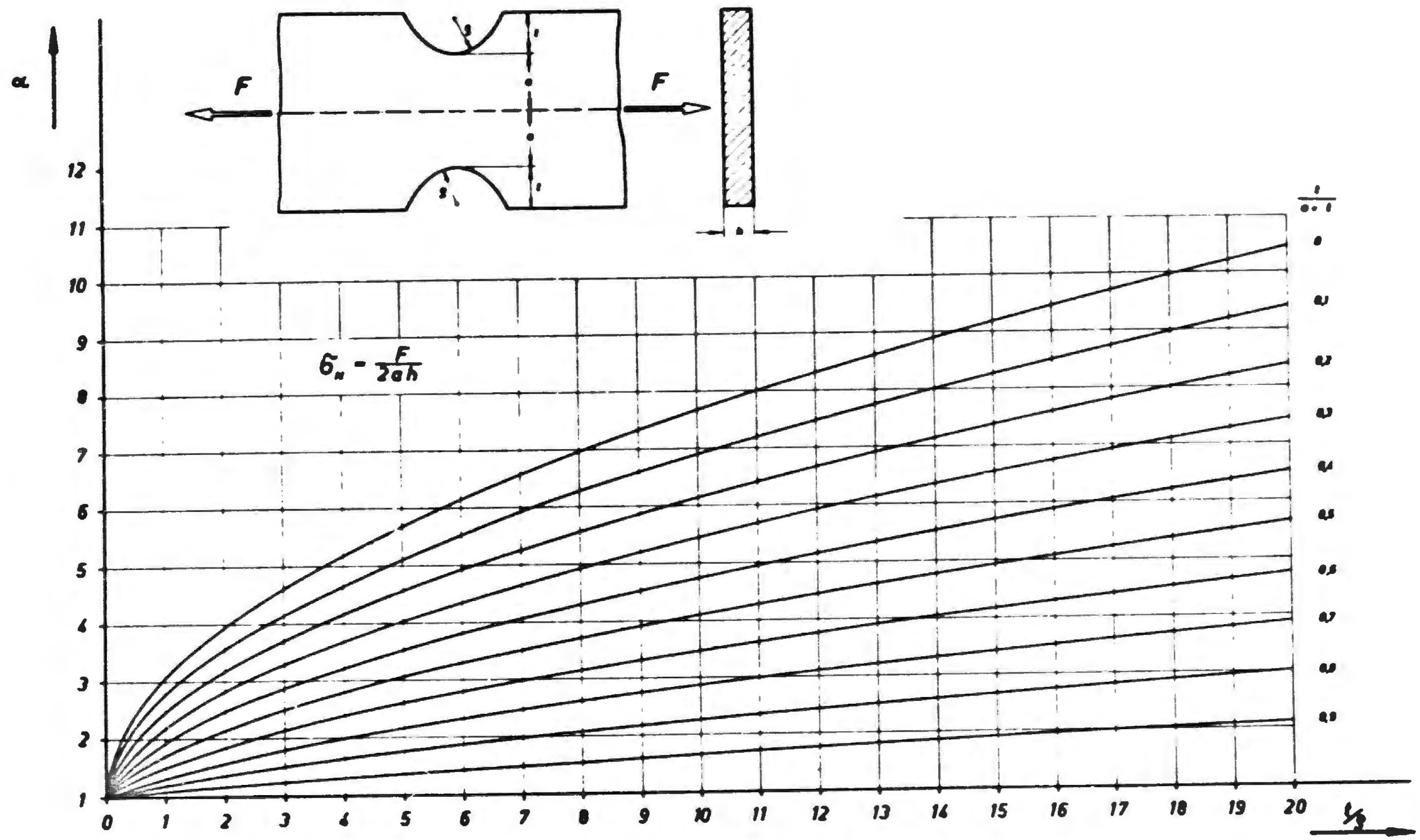


Fig. 2 Hookian stress concentration factor for a notched flat plate under tension

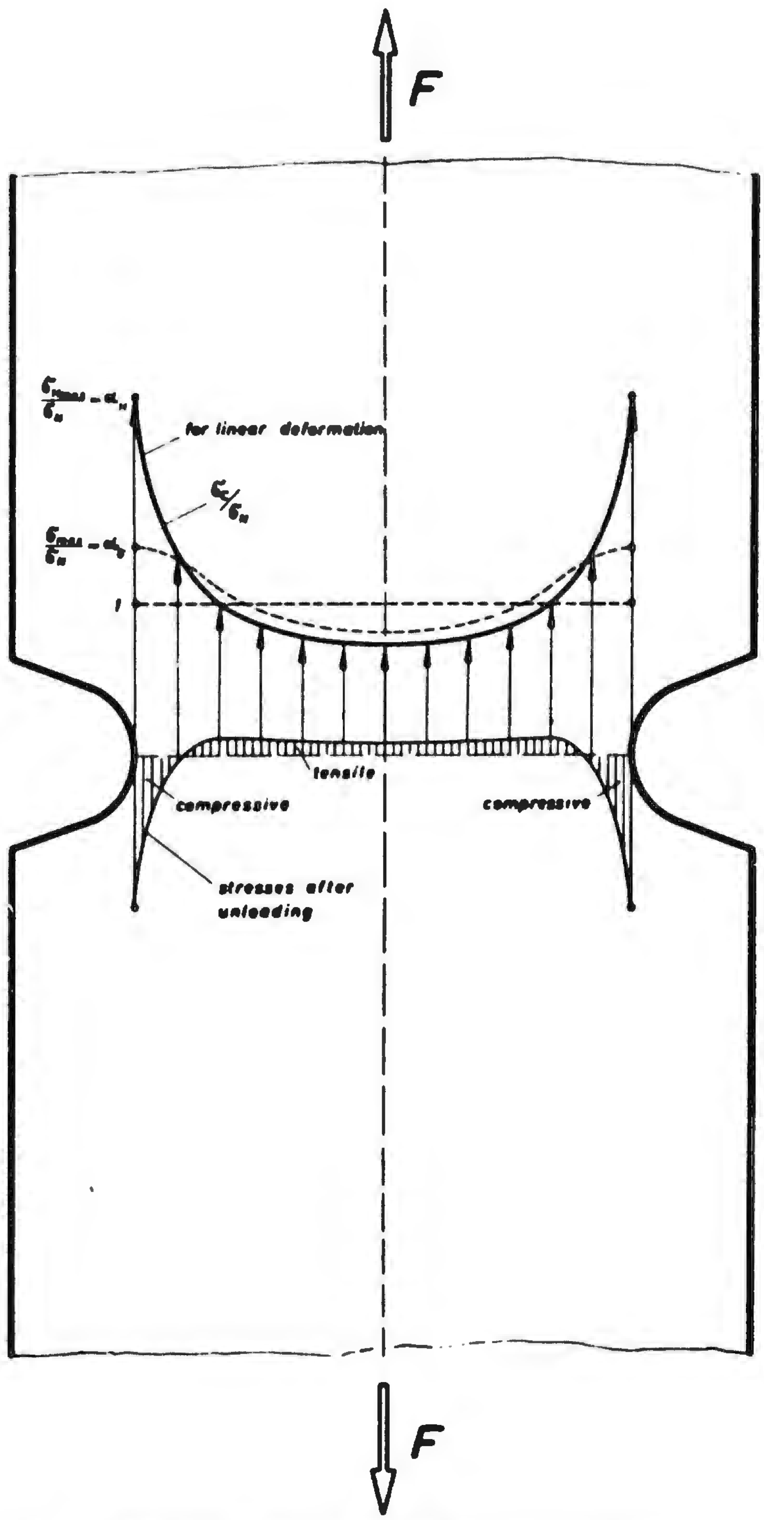


Fig. 3 Stress distribution in a notched flat plate under tension, before and after unloading

edge zones are partially stress-relieved ("macro-support effect"). For the exact mathematical treatment of this effect solutions of nonlinear boundary problems are necessary, but this way leads to considerable difficulties.

On the other hand experimental investigations are not easy to perform and their accuracy is limited too [1].*) Therefore, a theoretical investigation of the nonlinear deformation mechanism is of great advantage. Already in 1950 STOWELL established an approximative formula for stress and strain concentration at a circular hole in the plastic range [2], HARDRATH and OHMAN [3] modified the STOWELL formula into a more general form applicable to other specimen shapes (notched and filleted bars)

$$\alpha_\sigma = 1 + (\alpha_H - 1)\frac{E_s}{E} \tag{7}$$

where

$$E_s = \frac{\sigma}{\varepsilon} \tag{8}$$

is the so-called secant modulus.

This formula, however, is inaccurate in the limit case of very high stress concentration as explained in the following. For $\alpha_H \gg 1$ equations (7) and (8) give

$$\alpha_\sigma = \alpha_H \frac{E_s}{E} = \alpha_H \frac{\sigma}{E\varepsilon}$$

By multiplication with $\dfrac{\sigma_N E\varepsilon}{\sigma}$ we obtain

$$\alpha_\sigma \sigma_N \frac{E\varepsilon}{\sigma} = \alpha_H \sigma_N$$

or with regard to (3) and (5)

*) Numbers in parentheses refer to the Bibliography.

$$(\sigma_H)_{STOWELL} = E\varepsilon$$

instead of the real value $\sigma_H = E\,\varepsilon_H$ (see Fig. 4).

In 1960 the author established a non-linear theory for sharply curved notches under shearing which also can be applied to other types of loading [4] with sufficient accuracy. This theory results in the following relation between the three concentration factors α_σ, α_ε and α_H:

$$\alpha_\sigma\,\alpha_\varepsilon = \alpha_H^2 \qquad (9)$$

By multiplication with $\sigma_N\,\varepsilon_N$ follows with regard to (3) and (4)

$$\sigma\varepsilon = \alpha_H^2\,\sigma_N\,\varepsilon_N \qquad (10)$$

The right-hand side is independent of the stress-strain-line and represents a known value (as α_H and σ_N are given and ε_N can be obtained from the stress-strain curve). We see that all possible σ,ε-values follow a reciprocal hyperbola.

For practical use only some points of the hyperbola are needed lying in the vicinity of the stress-strain curve. The intersection points of the hyperbola with the stress-strain curve give the corresponding values of σ and ε. It is also possible to plot a set of reciprocal hyperbolas in the stress-strain diagram, then stress and strain for arbitrary values of α_H and σ_H can be easily determined. According to Fig. 5 starting from σ_N on the stress-strain curve a hyperbola leads to a fictive nominal stress $\dot{\sigma}_N$ on the Hookian line from which the fictive value of the Hookian stress $\dot{\sigma}_H = \alpha_H\,\dot{\sigma}_N$ can be calculated. From $\dot{\sigma}_H$ another hyperbola leads back to the stress-strain curve and the real value of stress and strain are obtained immediately.

We see that the Hookian stress $\sigma_H = \alpha_H\,\sigma_N$ is somewhat smaller than $\dot{\sigma}_H$; only if σ_N lies in the linear range it is equal to $\dot{\sigma}_N$ and σ_H becomes equal to $\dot{\sigma}_H$.

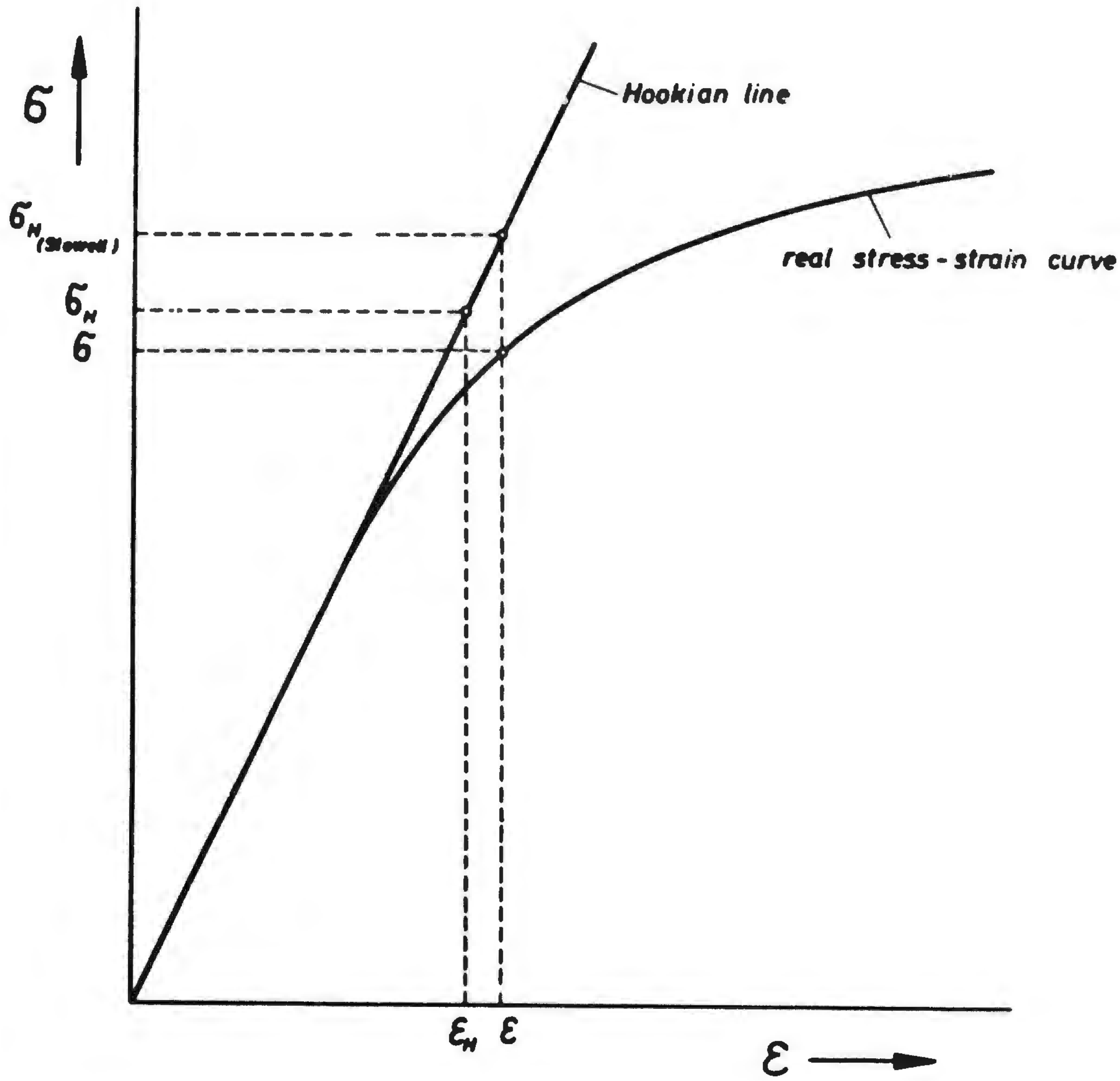


Fig. 4 Comparison with the Stowell formula for high stress concentration

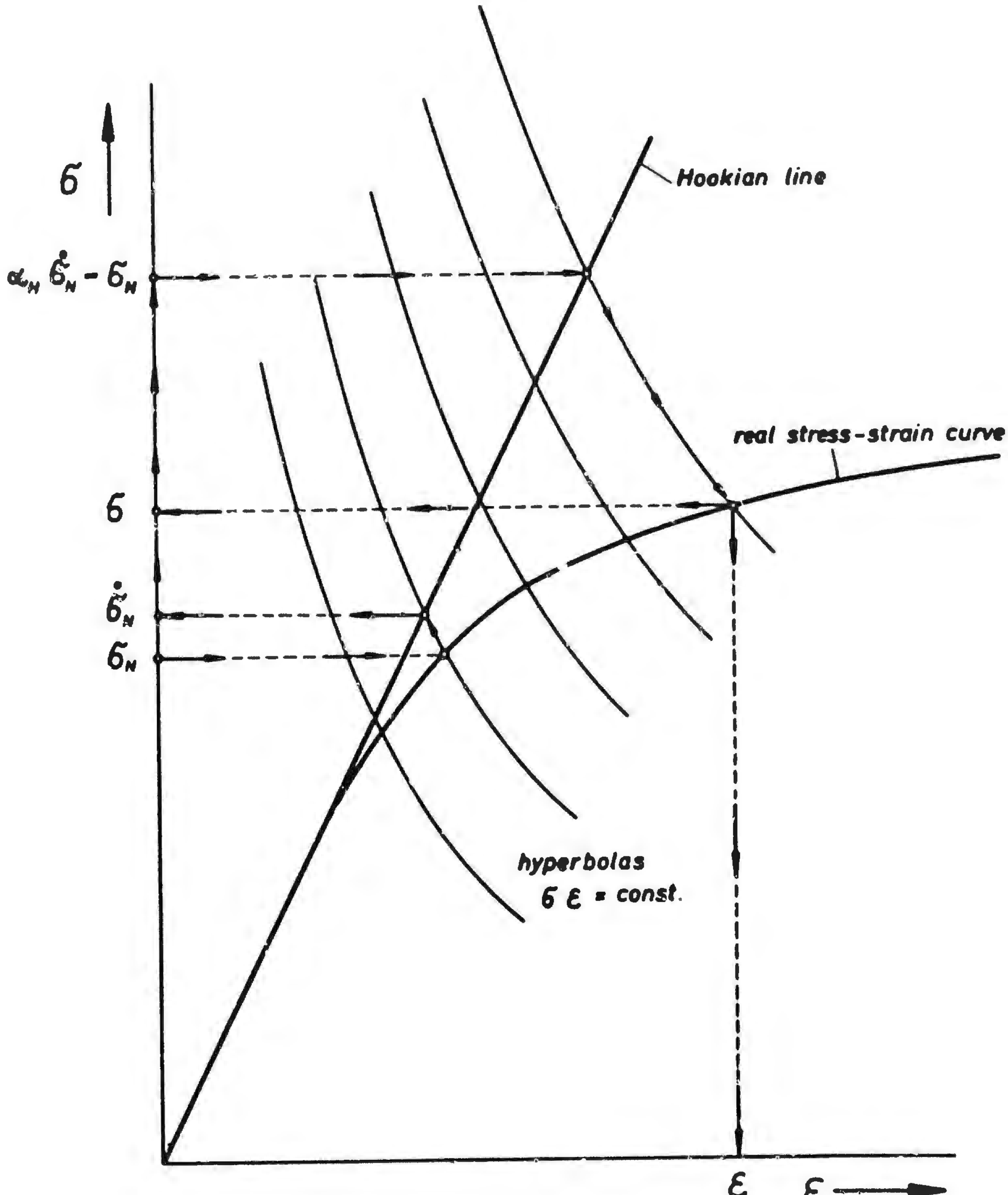


Fig. 5 Procedure for determination of the real values of stress and strain for stress concentration in the non-linear range

Furthermore ε is very much larger than ε_H also for high stress concentration in contradiction to STOWELL's assumption.

In the case of unloading stress and strain follow a straight line; therefore, the procedure of unloading can be described by HOOKE's law too, but with a displaced zero point. For a notched flat bar at unloading after tension the peak stress at both notches is not only relieved but reversed into a small compressive stress. From the stress value σ, which is smaller than σ_H, the value σ_H is to be subtracted. Therefore the compressive stress after unloading is represented by $-(\sigma_H - \sigma)$. The residual state of stress consists of compressive stresses near the notches and of tensile stresses in the central part of the cross sectic (see Fig. 3). The mean value of the residual principal stress parallel to the axis of the bar must be zero as no external force acts after unloading. We have internal stresses which are self-equilibrating within a larger domain (macro domain) of the material and therefore may be called "macro-internal stresses" (in contrast to the "micro-internal stresses" which are self-equilibrating within micro domains).

For technical strength calculations we have to distinguish between materials without and those with a distinct yield stress σ_s. For the first group we have a stress-strain-curve as in Fig. 1, for the second group in most cases a simplified diagram consisting of the Hookian line $\sigma = E\varepsilon$, and the straight line $\sigma = \sigma_s$ is sufficient (see Fig. 6).

3. The Micro-Support Effect and the Theory of Mean Stress Value

The solid body model for the classical theory of elasticity is a material with linear elastic properties, without structure and without memory. By means of this conception the stress vector can be defined as the ratio of force element to area element and the stress tensor also can be introduced.

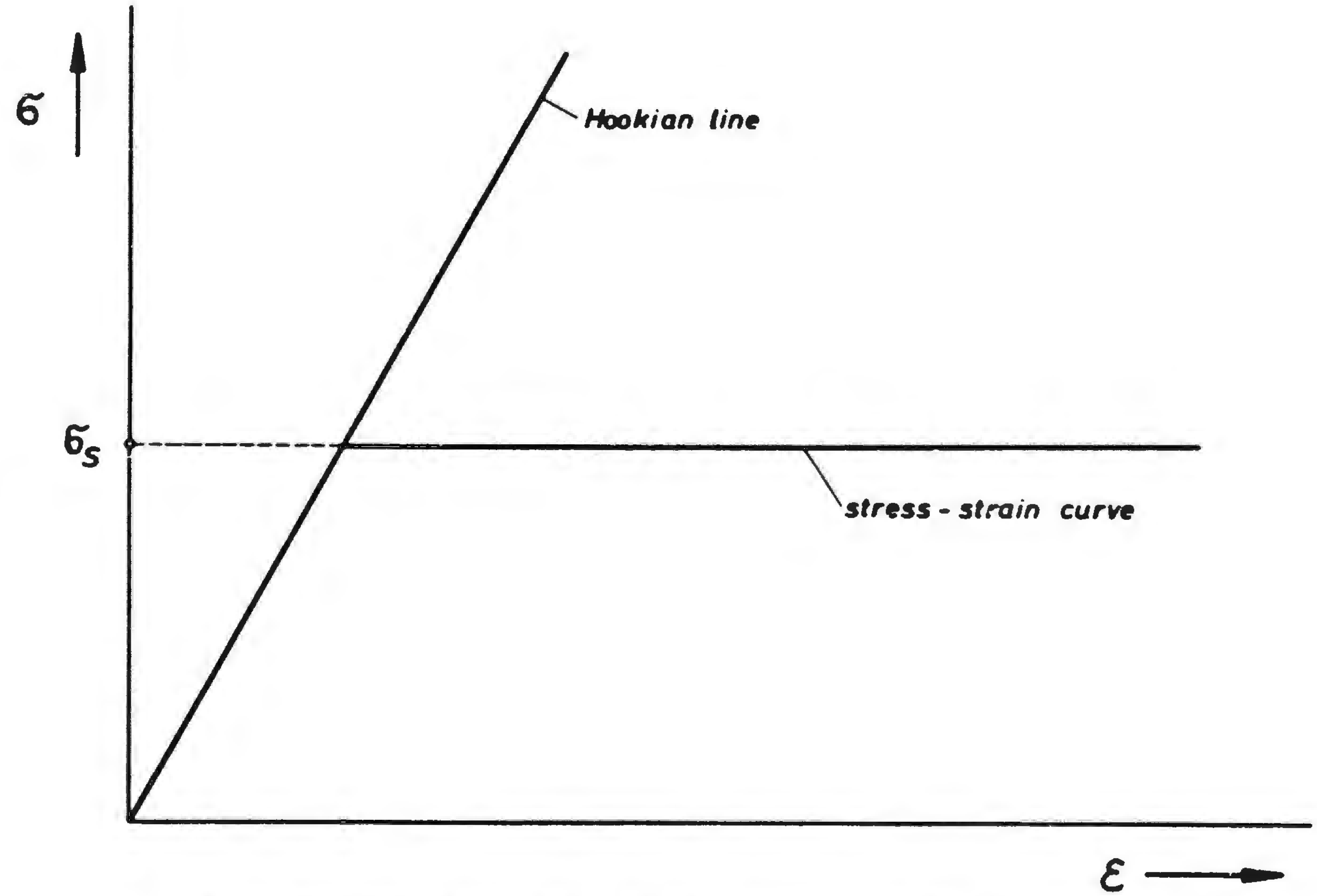


Fig. 6 Simplified stress-strain curve for materials with distinct yield point

But real materials always have a certain structure (crystalline, molecular). Within certain domains of the material there may exist stronger bonds between the single particles. Therefore these material domains are supported quasi-rigidly by their environment. This so called "micro-support effect" results in a deviation from the state of stress in the ideal material. The exact theory of the mechanism in the real discontinous material leads to immense physical and mathematical complications so that a successful application seems to be impossible.

But the author had shown in 1936 [5, 6] that the micro-support effect can be taken into account in a simplified manner: By determination of the mean stress value taken along a fictive length of structure.

Applying this procedure to the ideal comparison stress of the linear theory of elasticity we obtain

$$\bar{\sigma} = \frac{1}{\rho^*} \int_{y=y_0}^{y_0+\rho^*} \sigma_c \, dy \qquad (11)$$

Here ρ^* means the fictive length of structure, σ_c the ideal comparison stress and y the coordinate normal to the surface into the material (see Fig. 7). The boundary lies at $y = y_0$.
As results from this theory the stress $\bar{\sigma}$ at the root of a notch also depends on the fictive length of structure which represents a material constant.

For large stress gradients - as in the case of stress concentration - the domains in the vicinity of the highly stressed zone participate in the transmission of force more intensively than according to the linear theory of elasticity; at the same time the endangered zone is somewhat relieved. By this theory the described micro-support effect can be taken into account without contradictions and can be reduced to simple rules.

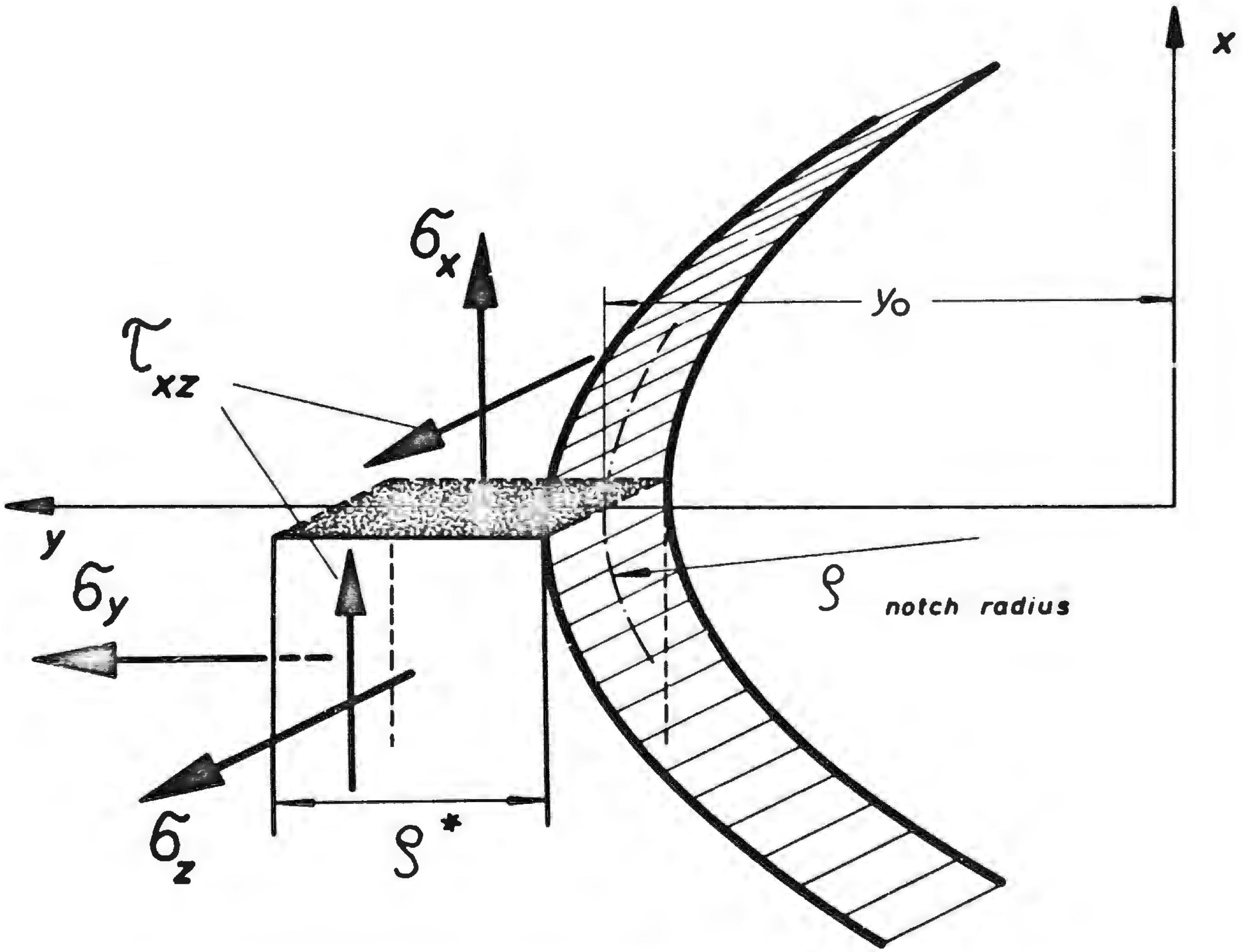


Fig. 7 Model mechanism in connection with the theory of mean stress value

We consider the case that the surface of the design part in the vicinity of the highly stressed zone can be approximated by a parabolic cylindrical surface $u = u_0$ (see Fig. 7). With the Cartesian coordinates

$$x = -2\,uv \qquad y = u^2 - v^2 \tag{12}$$

the radius of curvature becomes

$$\rho = 2\,u_0^2 = 2\,y_0 \tag{13}$$

The AIRY stress function [5] with K as an arbitrary constant

$$F = 4\,K\left(\frac{u^3}{3} - u_0^2 u\right) \tag{14}$$

satisfies the condition of compatibility $\Delta\Delta F = 0$ and the boundary conditions $\left(\frac{\partial F}{\partial u}\right)_{u=u_0} = 0$ and $\left(\frac{\partial F}{\partial v}\right)_{u=u_0} = 0$. Along the y-axis we get the stresses

$$\sigma_x = K\left(\frac{1}{\sqrt{y}} + \frac{\rho}{2\,y\sqrt{y}}\right) \qquad \sigma_y = K\left(\frac{1}{\sqrt{y}} - \frac{\rho}{2\,y\sqrt{y}}\right) \tag{15}$$

For the normal stress hypothesis we have $\sigma_c = \sigma_x$. Equation (11) gives with regard to (15)

$$\bar{\sigma} = \frac{2\,K\sqrt{2}}{\sqrt{\rho + 2\rho^*}} \tag{16}$$

The comparison with $\sigma_{c\,max} = 2\,K\sqrt{\frac{2}{\rho}}$ shows that ρ is to be replaced by

$$\rho_F = \rho + 2\,\rho^* \tag{17}$$

Similar relations can be derived for the other strength hypotheses. Within the range $\rho^* \ll \rho$ only the factor of ρ^* is different; therefore, the fictive radius of curvature ρ_F approximately can be calculated by the formula

$$\rho_F = \rho + c\,\rho^* \tag{18}$$

The fictive length of structure ρ^* depends on the properties of the material, the methods of machining, the kind of loading and its variation with time as well as on other influences. The dimensionless factor c only depends on the type of loading and the applied strength hypothesis (see the table).

Strength Hypothesis	Factor c of Micro-Support Effect for $\rho^* \ll \rho$		
	Tension and Bending		Torsion and Shear
	Flat Plates with Notches, Holes and Fillets	Round specimens with Circumferential Notches	
Normal Stress Hypothesis	2	2	1
Shear Hypothesis	2	$\frac{2-\nu}{1-\nu}$	1
Strain Energy Hypothesis	2.5	$\frac{5-2\nu+2\nu^2}{2-2\nu+2\nu^2}$	1

For flat bars with holes or notches under tension or bending the two-axial state of stress is valid and c has a value between 2.0 and 2.5. For round specimens with circumferential notches under tension or bending the state of stress becomes tri -axial; the circumferential strain, however, usually can be neglected and we have plane strain and c takes values between 2.0 and 3.0.

With the new radius ρ_F instead of ρ the new stress concentration factor $\overline{\alpha}$ is obtained, which replaces the ideal (Hookian) stress concentration factor α_H.

The fictive length of structure can be considerably larger than the real lengths of structure as for instance the dimension of grains in crystalline materials.

The reason for this probably lies in the fact that by the theory of mean stress value according to the explained procedure the error of the linear theory of elasticity is corrected within the highly stressed zone, but due to the simplicity of the method no further corrections are included with regard to the other domains of the material.

Theoretical homogeneous states of stress as in prismatical tension bars correspond in reality also to a nonuniform stress distribution produced by structural influences. In those cases however, the structure effect must be neglected with regard to technical strength calculations because all experimentally determined values of strength and strain are defined as average values over the cross section of the specimen. The theory accounts for this fact too, as for σ_c = const σ equals σ_c and is independent of ρ^* . Therefore by the theory of mean stress value the real mechanism of micro-support-effect is represented by a very suitable model mechanism which works just in all cases where the linear theory of elasticity is not satisfactory for strength calculations. It may be mentioned that by the theory of mean stress value the linear dependence of the stresses from the external forces remains valid.

The theory of mean stress value which already has been approved by many experiments in the author's laboratory, has a wide range of applicability: Stress concentration problems at notches and holes of arbitrary curvature, static as well as alternating loading. It is also possible to explain the effect of the size of specimen on bending and torsion fatigue strength inasmuch as it is not caused by inhomogeneities of the material.

4. Stress Concentration at Fatigue Loading*)

For materials with linear-elastic deformation behavior, no macro-support effect occurs, but the micro-support effect is of considerable significance, e.g. for brittle materials which exhibit linear-elastic behavior until fracture.

*) All considerations in the following are restricted to the case of completely reversed stress.

For ductile materials because of their nonlinear stress strain curve the macro support effect plays an important rôle in the yield range. In the high-cycle fatigue range the fatigue strength in most cases lies below the yield point of the material and a linear deformation behavior can be assumed for such kind of loading with sufficient accuracy. Therefore the high-cycle fatigue strength of ductile as well as of brittle materials is influenced primarily by the micro-support effect.

The high-cycle fatigue strength at push-pull fatigue loading of unnotched specimens may be denoted by σ_a and that of notched specimens by σ_{an} (these are nominal stresses). In order to eliminate effects of inhomogeneity the accurate experimental determination of these quantities requires that the nominal cross sections (i.e. minimum cross sections) of all notched specimens and the cross sections of all unnotched specimens are the same; furthermore equal kind of machining, surface finishing and so on should be required.

Since σ_{an} is defined as nominal stress we get

$$\frac{\sigma_a}{\sigma_{an}} = \beta \qquad (19)$$

where β is called the <u>fatigue strength reduction factor</u>. The high-cycle push-pull fatigue test takes place in the linear elastic deformation range. Therefore the comparison stress at the highly stressed zone of the specimen causing the fatigue fracture is $\bar{\alpha}_a \sigma_{an}$ (the index a in $\bar{\alpha}_a$ points out that the micro-support effect at <u>alternating</u> load is considered). Because of the linear-elastic behavior of the real material with micro-support effect we can assume that the initiation of rupture at the highly stressed zone in the notched specimen is similar to that in the unnotched specimen. This leads to the basic equation of the author's theory of fatigue strength at stress concentration

$$\bar{\alpha}_a \sigma_{an} = \sigma_a \qquad (20)$$

or with (19)

$$\bar{\alpha}_a = \beta \tag{21}$$

where $\bar{\alpha}_a$ is to be determined in the same way as α_H but with the fictive radius of curvature

$$\rho_F = \rho + c\,\rho_a^* \tag{22}$$

instead of the real radius of curvature ρ.

If we have sufficient test data for the determination of σ_{an} and σ_a, the value of $\bar{\alpha}_a$ can be calculated. By comparison with the theory of notch stresses (which furnishes formulas or diagrams for α_H) finally the value of ρ_a^* for the material is obtained.

With the known values of σ_a and ρ_a^* for a certain material the fatigue strength of arbitrary specimens with notches or holes, and of any other design elements can be determined with satisfactory accuracy.

Because of the great technical importance of this problem a considerable number of approximate methods of precalculation of the fatigue strength have become known in the last decades. The formulae of KUHN [7], KUHN and HARDRATH [8] and HEYWOOD [9] resulting from modifications of a previous formula of the author [5,6] may be mentioned.

In Germany another method was developed by SIEBEL [10,11], SIEBEL and PFENDER [12], SCHWAIGERER [13] and others, given in the VDI-standards 2226 [14].

The significant value of this method is the relative stress gradient normal to the surface

$$\chi = \left(\frac{1}{\sigma}\,\frac{d\sigma}{dy}\right)_{y=y_0} \qquad (23)$$

calculated by means of the linear theory of elasticity. In all publications known (as mentioned above) the calculation of χ is not consequently carried out using the comparison stress with regard to the different strength hypotheses. If the values of χ are determined exactly for the different strength hypotheses a connection to the theory of mean stress value can be derived. It results approximately

$$\chi \approx \frac{c}{\rho} \qquad (24)$$

(c has the above mentioned values) and (18) can be written

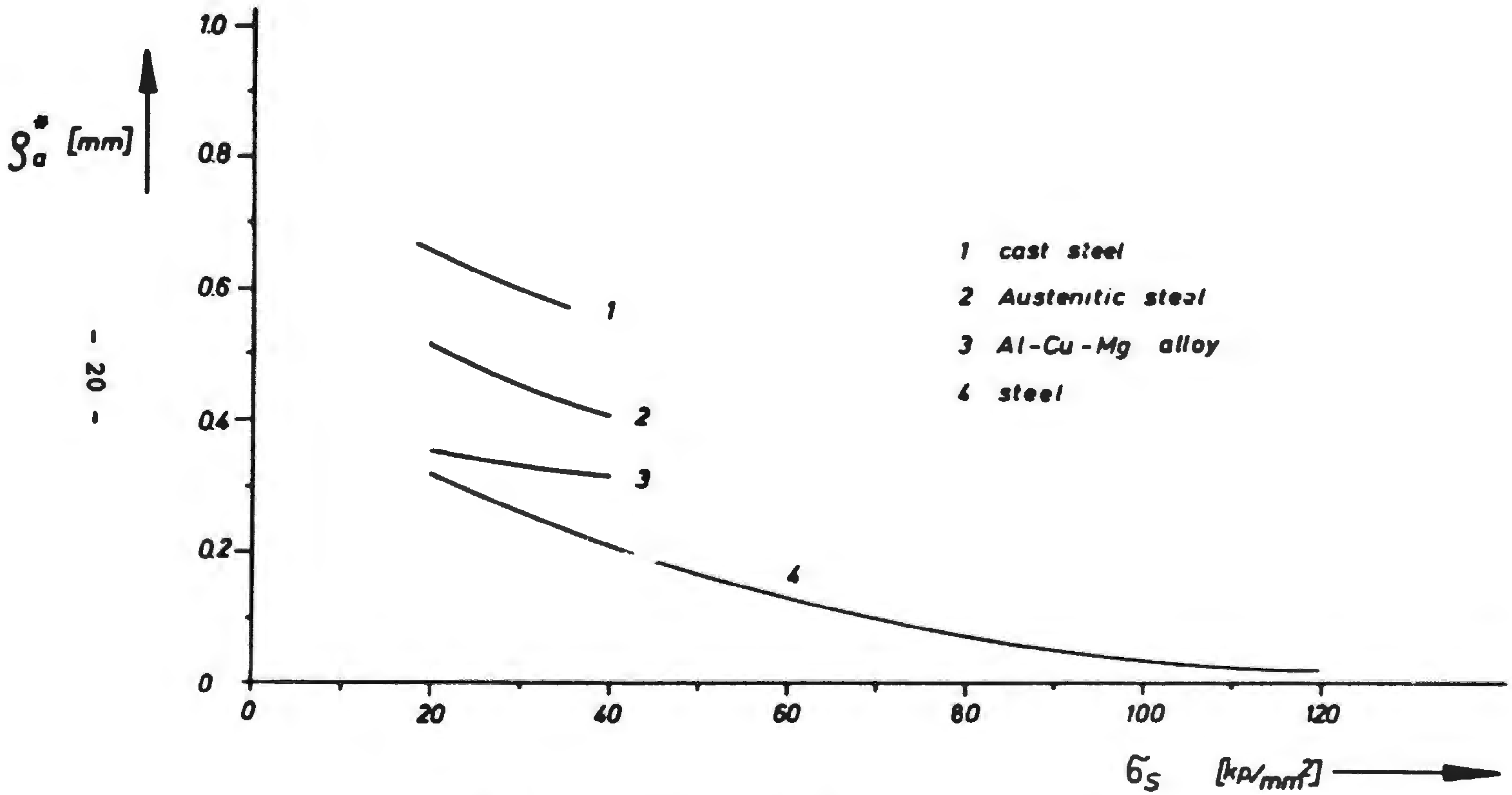
$$\rho_F = \rho\,(1 + \chi\,\rho^*) \qquad (25)$$

The method according to the VDI-standards, however, is based on the non-theoretical assumption that the ratio of alternating stresses

$$\delta_a = \frac{\alpha_H}{\beta} \qquad (26)$$

i.e. the quantity $\frac{\alpha_H}{\bar{\alpha}_a}$ in our theory, for various materials is a function of χ. Within this assumption values of δ_a larger than α_H are possible, leading to the impossible values $\beta < 1$.
But the VDI-method is applicable within a certain range of α_H and χ values where it is in agreement with numerous experimental results.

The derived theory was compared with our own and other test results and the fictive length of structure could be determined for a number of materials in dependence of the yield stress (see Fig. 8). As it was expected, the value of ρ_a^* decreases with increasing strength. A further discussion will be given in the forthcoming Final Report of Contract AF 61(052)-671.



<u>Fig. 8</u> Dependence of ρ_a^* on the strength for various materials

The explained theories of the two support effects can be applied to bending and torsion problems too, but then additional calculations become necessary.

The introduction of the fictive length of structure leads to similar consequences for engineering design as the application of crack propagation theories, for instance the procedure established by IRWIN [15].

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13. ABSTRACT

The mechanism of stress and strain concentration at fatigue loading is governed by two fundamental effects. Within the yield range of ductile materials the macro-support effect is dominating which in this paper is represented by the results of a non-linear theory derived by the author. Within the high-cycle fatigue range the micro-support effect is governing which can be described by the autors s theory of mean stress value, originally derived in connection with the calculation of sharply curved notches. In this theory a material constant of length dimension is introduced. Taking into account these two effects an approximate precalculation of the fatigue strength of notched construction parts is possible.

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