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Observations on Ductility.

Betrachtungen über die Zähigkeit.

Considérations sur la ductilité.

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In the field of mechanical engineering, endeavours are now being made to construct heavily stressed shafts (such as crankshafts) which are subject to heavy stresses in cast iron instead of in high-ductility special steels, as the former is cheaper in first cost and gives almost equal performance. This analogy with a field of construction adjoining our own serves to illustrate the fact that we now attach a different meaning to the conception of ductility in steels than we formerly did, the crux of the matter being not the *gross* amount of plasticity but the *capacity to resist non-uniform conditions of stress.*

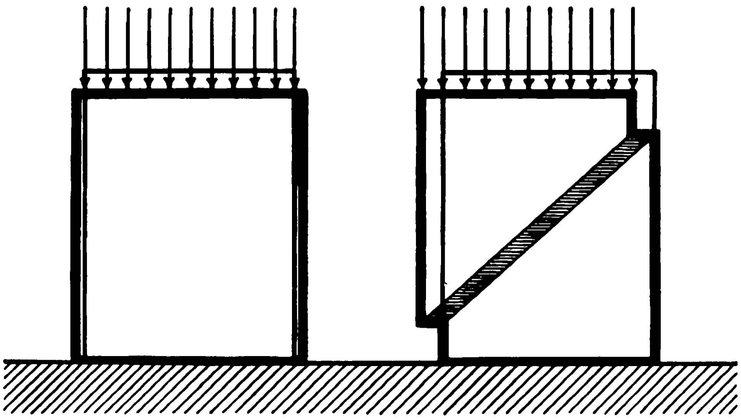

Fig. 1.
Elastic and plastic deformation.

Provided that the structural cohesion is high this capacity is attainable even though the plasticity of structure may be relatively small and only just sufficient. The mechanism of plastic deformation differs from that of elastic deformation as indicated in Fig. 1 through the spontaneous occurrence of layers of yield and rotation. By reason of their kinetic origin these yield layers are fundamentally insensitive, in the statical sense, to variations of stress.[1] They depend for their occurrence on an additive force, which may be determined from the conditions of equilibrium of vectors and is known as the "resisting medium"

[1] *W. Kuntze:* Einfluß ungleichförmig verteilter Spannungen auf die Festigkeit von Werkstoffen. Maschinenelemente-Tagung Aachen. Berlin, V.D.I.-Verlag, 1936.

(Widerstandsmittel).[2] On this basis *Fritsche* has made successful calculations for beams, and has carried the idea further in order to arrive at the carrying capacity of eccentrically loaded columns.[3] [4]

Our structural steels do not, however, actually behave in the ideal way represented in the diagram. It is true that the formation of a slip plane implies a change from purely elastic behaviour, and therefore a danger of brittle fracture, but in our commercial steels it is impossible entirely to eliminate the possibility of *internal microscopical breakdown*. Local microscopic cracks are a phenomenon which, according to the quality of the material, is apt in any case to accompany

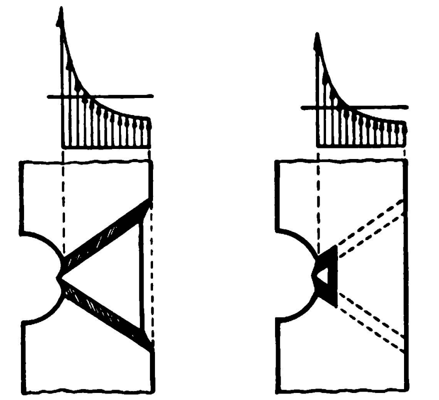

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Fig. 2.
Sensibility against notching action for alternating stresses.

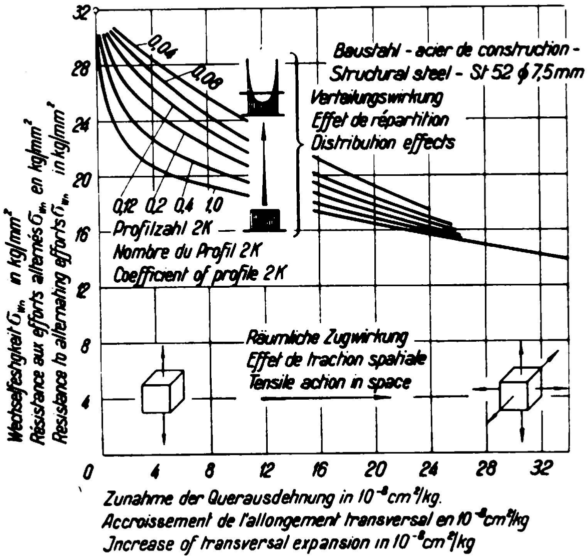

Fig. 3.
Relation between the resistance to alternating stresses and the stress distribution and multidimensional stressing.[5]

plastic deformation and particularly so in the presence of non-uniform stress. Such cracks cause a shortening of the yield paths corresponding to Fig. 2, and this is associated with a lower carrying capacity which is designated in practice as "notch sensitiveness". The ideal condition of insensitivity to notch effect, shown in the left-hand figure, is characterised on the contrary by continuous yield surfaces. Consequently the test results obtained in experiments made under non-uniform conditions of stress usually work out lower than those which would correspond to the carrying capacities calculated on the basis of an ideal resisting medium.

The tendency of materials to internal fracture must, therefore, limit the accuracy of calculations made by reference to the "resisting medium". What,

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[2] *W. Kuntze:* Ermittlung des Einflusses ungleichförmiger Spannungen und Querschnitte auf die Streckgrenze. „Der Stahlbau", Vol. 6 (1933), pp. 49/52.

[3] *J. Fritsche:* Grundsätzliches zur Plastizitätstheorie. „Der Stahlbau", Vol. 9 (1936), pp. 65/68.

[4] *J. Fritsche:* Der Einfluß der Querschnittsform auf die Tragfähigkeit außermittig gedrückter Stahlstützen. „Der Stahlbau", Vol. 9 (1936), pp. 90/96.

[5] *W. Kuntze:* Einfluß des durch die Gestalt erzeugten Spannungszustandes auf die Biegewechselfestigkeit. Arch. Eisenhüttenwesen 10 (1936/37) S. 369/73; Ber. Nr. 367 Werkstoffaussch. Ver. dtsch. Eisenhüttenl.

from this point of view, are the special cases liable to arise, and what is the nature of the forces tending to promote premature brittleness?

On relating the results of changes in the notch effects to the three-dimensional conditions of tensile stress, and to those of the distribution of stress as in Fig. 3,

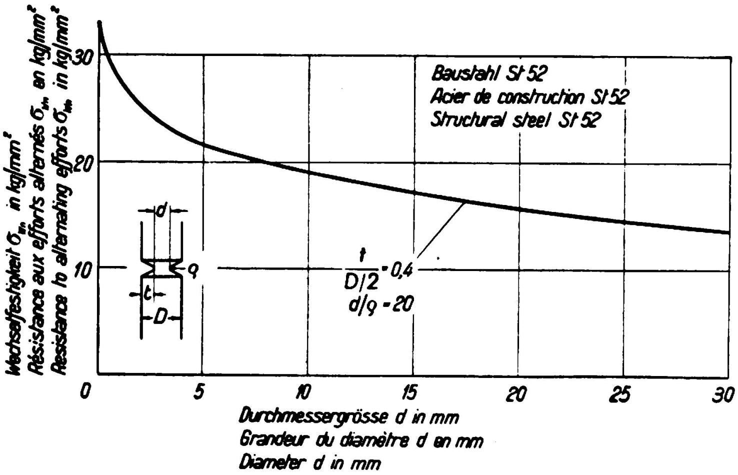

Fig. 4.
Resistance to alternating stresses in relation to size (diameter).

it will be seen that *it is not primarily the concentrations of stress but the multi-dimensional condition of stress which causes a reduction in the alternating fatigue strengths.* Indeed in the present series of experiments those samples which showed high concentrations of stress gave a higher notch fatigue resistance than the specimens under the same average three-dimensional conditions in which the

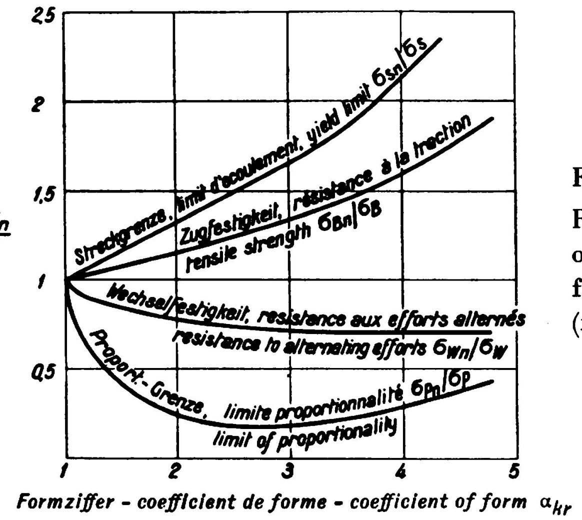

Fig. 5.
Relative increase or decrease of different limits of strength for increasing peak stress (form coefficient α_{kr}).

distribution was more uniform. These are actual experimental results, which cannot be set aside.

The reducing effect, on the alternating fatigue strength, exerted by the multi-dimensional condition of stress depends also on the absolute dimensions of the constructional member in question. Fig. 4 shows how if the depth of notch $\frac{t}{D/2}$ and its sharpness $\frac{d}{\rho}$ are maintained proportional then *the fatigue strength drops off steadily as the diameter of the specimen is increased.*

The *limit of proportionality* is another factor which greatly influences the structural cohesion,[1] its effect in the case of non-uniform stress being similar to that exerted by the alternating fatigue strength. But as regards the *yield point* (resistance to slipping) the existence of multi-dimensional stress has the opposite effect, this causing an increase whereas a concentration of stress results in a decrease, especially if the dimensions are large. Fig. 5.

A clue to these partly contradictory effects may be sought in the fact that frequently contradictory measurements are reported.

Multi-dimensional stresses occur in the construction (1) as the result of its external arrangement, and (2) through shrinkage in welded connections. Under what conditions do these two factors operate detrimentally?

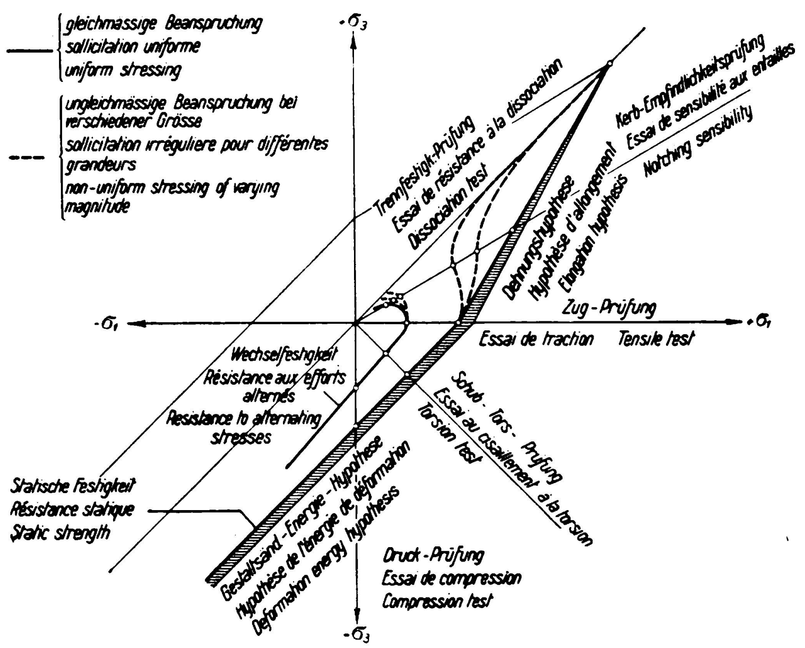

Fig. 6.

Arrangement for multi-axial resistance test.

If, for instance, at some point a multi-dimensional condition of stress is present as the result of shrinkage, compressive stresses will be present in the immediate neighbourhood since within the constructional member equilibrium must exist. By applying the law of the "resisting medium", which implies an average effect, it must be anticipated that in such a case the yield point will not be appreciably affected. *But if the dimensions are large the statical strength will be somewhat reduced as a result of the concentration of stress, and the alternating fatigue strength will be considerably reduced in consequence of the multi-dimensional condition of tensile stress.*

The effect represented here varies in magnitude according to the material, and this is due to the *mode of development of the testing of materials.* The classical tests for compressive, shear and tensile strength under statical and alternating stress are represented in the four quadrants of Fig. 6 showing the maximum tensile principal stress and the maximum compressive principal stress.

The new tests for "splitting strength" *(Trennfestigkeit)* and notch sensitivity, under statical or alternating loads, appear in the purely tensile quadrants,[6] and with the aid of these the material in question may be assessed as regards its behaviour under multi-dimensional tensile stresses in different sizes of member. The results of the test, then, provide an approximate measure as to how far, in the case of any given material, the calculated values will fail to be attained on account of the operation of the "resisting medium". In this way it becomes possible to introduce the factor of proportionality, suggested by *Klöppel*[7] as a means of correction.

These results of recent research may serve as directives for calculation and design, but they do not touch upon the question of how far in bridge work — especially in the case of statically indeterminate systems — the changes in the loads imposed operate as true alternating fatigue stresses in the sense that the term is used in the testing of materials. This remains a special problem of bridge engineering which must always be borne in mind.

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[6] *W. Kuntze:* Kohäsionsfestigkeit. Berlin 1932, J. Springer. Also Spezial N°. XX of Mitt. deutscher Materialprüfungsanstalten. (Methods of testing cohesion have meanwhile been further developed.)

[7] *K. Klöppel:* Gemeinschaftsversuche zur Bestimmung der Schwellfestigkeit voller, gelochter und genieteter Stäbe aus St. 37 und St. 52. „Der Stahlbau", Vol. 9 (1936), pp. 97/119.