FAILURE ANALYSIS AND FUNDAMENTAL MECHANICAL PROPERTIES OF DUCTILE MATERIALS

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The most unexpected structural failures are usually those connected with instability of compressed parts and with the instability of tensioned parts containing a crack. Under the condition of compression instability small plastic strains take place; on the other hand the high ductility of the material is essential for fractures.

INTRODUCTION

Structural members and machine parts can fail to perform from their intended function mainly in the following ways:

1. Excessive elastic deformation or vibration
2. Excessive plastic deformation
3. Compression instability
4. Tension instability

The safety factors against failures should first of all take into consideration the probability of the overloading and the variability of the actual resistance of structures, taking into account, if necessary, the influence of the time and of different enviroments. The probabilistic concept, however, can be used as a supplement only to the clear deterministic knowledge of the limit states of structures.

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The main intention of this paper is to recommend the international cooperation in the spheres of material science, material testing, structural mechanics and structural engineering with regard to the fundamental mechanical properties of materials; particularly as regards the ductility, which is decisive factor in the safety analysis on tension instability. For example the present draft proposals of international standards for steel and aluminium structures pay too little attention to this problem (ISO/TC 167). The same is true of the mechanical testing of metals with respect to the tension and bending (ISO/TC 167). For further details see my paper "A rational Limit States Design Philosophy for Metal Structures" (1). It is clear that these statements regarding the ductility are valid for all materials used in structures.

LIMIT STATES

The user of structures is not interested to know their stresses and strains but first of all the characteristic monotonous load-displacement relationship (see Figure 1), which involves its most important properties: stiffness, strength and ductility.

The stiffness determines the deflection of the structure under working condition. Its limit is function related.

The word strength has two meanings: 1. The ultimate limit state, which is precisely defined by the peak of the load-displacement curve. It is safety related. 2. The yield strength or damage limit state, which is function and safety related. Therefore it can have quantitatively different definitions; as for example the load at certain percentage of plastic displacement related to the corresponding elastic one. Yet the plastic strain limitation must be always related to the fracture criteria.

The term ductility is more and more frequently used, especially as regards the energy absorption in structures. It represents the ability to deform plastically. For impact and seismically resistant structures the ductility in the post-peak region of load-displacement curve can also be important. When we use yield load and the corresponding elastic displacement as the norms, the maximum load and the corresponding displacement can be expressed with plastic capacity and ductility factors. In this way a simple categorization of structures with regard to these properties is possible.

Tension members

In Figure 2 the load-elongation curve for longer tension member with the constant cross-section, without the notch effect and made of the material which shows local necking under tension test, is indicated with the full line. Various kinds of geometrical and material imperfections (excentricity, residual stresses) have only a limited deformational effect, if there is no possibility for a local fracture. The strength and ductility, however, can be essentially reduced due to the increased influence of the crack. This is indicated with the dashed lines in Figure 2.

Compression members

Local or lateral buckling of compressed member can have a similar effect on the decrease of the strength and ductility as the crack has on the tension member. In Figure 3 the load- shortening diagram is given for a compressed member. This shows the markedly brittle character. Geometrical and material imperfections (residual stresses) can considerably decrease the buckling load as shown with the dashed line in Figure 3.

FUNDAMENTAL MECHANICAL PROPERTIES

The stress-strain relationship for a stress element with the monoaxial stress state indicates fundamental mechanical properties of materials under standard constant temperature and strain rate.The change of these properties under different temperatures and strain rates is also important. The inclusion of the influence of triaxial stresses, up to the fracture, makes possible not only the determination of correlation between results of standard tensile testing and all other mechanical testing, but also the constitutive equations for various materials needed in the computer simulation of the real behaviour of structures (including the influence of details) up to the collapse, using the principles of continuum mechanics.

Tension test

We take the Ramberg-Osgood material as the simplest case. It has the following normalised true stress-logarithmic strain equation

$$\bar{\varepsilon} = \bar{\sigma}\ (1 + \bar{\sigma}^{N'})$$

where the yield strength is defined with the total strain, equal to the double of the corresponding elasting strain, therefore the symbol Re2. Here is $\bar{\sigma}=\sigma$:Re2 and $\bar{\varepsilon}=\varepsilon$:Ae with Ae=Re2:E, N'=N-1 with N=1/n, n being the Ludwig's strain hardening exponent. The value in the bracket represents the reciprocal value of the normalised secant modulus. We know that n=ln(1+Am) where Am is the uniform linear strain at the beginning of the necking under the maximum load. In our opinion four numbers 4, 10, 30 and ∞ can be internationally accepted for the exponent N' as representatives to be used in the generalised computer simulation of the normalised elato-plastic behaviour of typical strength examples. Afterwords the true values for displacements, strains and stresses can be determined on the basis of the actual elastic modulus and yield strength.

As seen in Figure 2 the uniform strain Am also determines the ultimate elongation, and the tensile strength Rm determines the ultimate load of longer tensile members with constant cross-section. True stress corresponding to Rm is simply Tm=Rm(1+Am).

The Ramberg-Osgood curve ends in the true stress and logarithmic rupture strain. The approximate value of the true rupture stress is Tu=Fu:Su, where Fu stands for fracture load and Su for cross-section area at the place of fracture. Due to volume constancy the approximate linear rupture strain is simply Au=Zu:(1-Zu) with rupture reduction of area Zu=(So-Su):So, So being the original cross-section area. These approximations do not take into consideration the nonuniform stress and strain distribution, triaxiality of stresses, higher strain rate, and higher temperature in the fracture cross-section.

It is important to empasize that the classical average rupture strain A5 or A10 as measures of ductility must be replaced by the uniform strain Am and by the true rupture strain Au. Mechanical metallurgy uses three quantities for the rupture ductility: logarithmic strain, reduction of area and linear strain. The linear rupture strain Au gives a clear geometric presentation and therefore it deserves the priority.

For the sake of the unified classification of materials regarding the ductility under different strength classes, only elastic modulus and yield strength need to be dimensional quantities in statistical analyses.

The normalised values $\bar{R}m$=Rm:Re and $\bar{A}m$=Am:Ae generally decrease with higher Re, the same is true for the normalised values $\bar{T}u$=Tu:Re and $\bar{A}u$=Au:Ae, but they also depend essentially, as we know, on impurities, hard particles and voids.

In connection with fracture analyses the true rupture properties Tu and Au are crucial. Therefore the "engineering" stress-strain diagram in textbooks and manuals should always end with Rm and Am, since the post-peak part of the curve is of no benefit. In place of it the additional true stress-linear strain curve should describe the real behaviour of the small stress element up to the fracture, as shown in Figure 4. It is important to teach that in the tension test the ordinates of the falling part of the curve have a meaning only as far as they represent the decreasing load, while the abscisas represent only the prolongation of the measure length Lo. As evident in Figure 5 different Lo's in comparison to the local necking have until now caused a lot of confusion as regard the term ductility.

It is interesting that the statistical study of the correlation between the ratio Fu:Fm and the true rupture strain Au may offer the simplest method to determine Au on the basis of this ratio only.

For small plastic strain problems the knowledge of proportional limit strength is necessary. It can be defined with the total strain which is 5% greater than the corresponding elastic strain, therefore the suitable symbol is Rpl,05.

Thus E, Rp, Re, Rm, Am, Tu, Au or better E, Re and $\bar{R}p$, $\bar{R}m$, $\bar{A}m$, $\bar{T}u$, $\bar{A}u$ are the fundamental mechanical characteristics obtained by way of simple tensile test of ductile materials.

In the case of materials which exhibit the plastic plateau in tensile testing, its length has also to be measured.

The area under the true stress-linear strain curve represents the specific work to fracture. Therefore it has to be correlated with toughness parameters in fracture mechanics.

Naturally, the influence of the initial anisotropy, nonhomogeneity, mechanical and thermal treatment, the changes and damages with the time, etc, should be primarily expressed with the change of above parameters in the tension test.

Influence of temperature and strain rate. The influence of the temperature on strength parameters of monoaxial stress-strain relation at standard strain rate tensile testing is shown in Figure 6. The transition in the area of cleavage strength Rc is determined with the critical temperatures Tc, Tm and Tu. Besides the change of strength parameters Re, Rm and Tu we must also know the change of strain parameters Am and Au with the temperature. The influence of different strain rates on Re, Rm, Tu, Am and Au can be represented on the similar diagram.

As regards the cleavage strenght Rc it is useful to know how it changes with temperetures and strain rates, and how it is correlated to the true rupture stress Tu under the standard tensile testing.

Influence of triaxiality on stress element. Figure 7 shows the influence of the triaxiality with different maximum principal stress-strain curves for proportional loading. Here the change of the Poisson's ratio in the elasto-plastic region also has to be considered. It is useful to reach the international consensus regarding the unified manner how to express the degree of the triaxiality of stresses.

With the use of circumferential notched tensile specimens it is possible to find out how the cleavage strength depend on the triaxiality of stresses (2).

Bend test

Bend test offers the simplest method for the approximate determination of the bending rupture strain, but only up to about 0.8. Unfortunately, present standardized bend test of the parent materials and of weldments require until now only yes or no answers. A better exploatation of the bend test is possible with the suitable measurement of the local strain at the appearance of the visible crack. This has particularly value for bend tests of welded joints.

In order to obtain bending rupture strain under the plane strain condition, which gives essentially lower result than for plane stress, the corresponding width to thickness ratio for bent plate has to be applied. The bend test, with local rupture strain measurements, also offers the simplest method for the approximate determination of the ductility in the weakest direction of materials which exhibit lamelar tearing. It can also be used for the determination of the bending ductility curve,in addition to the hardness curve in Jominy testing. This can be achieved simply by the bending of thin circular plates cuted after the hardness measurement.

Correlation with fracture mechanics parameters

The change of the inelastic stress-strain field at the root of the notch, particularly in the process zone of the crack, is possible to know only with the simulation on computer. The main problem is the treatment of the damage due to the cavitation as a smeared property in the continuum mechanics stress element. It has a close connection with the micro and macro structure of the material. It is not surprising that the Cray supercomputer must also be employed. Of course, the permanent comparison of the results of computer simulations, fracture mechanic tests and large scale tests is extremely important. But the input for the computation requires constitutive equations of the material, which are based on fundamental mechanical properties of the material, including the effect of temperature, straining rate, triaxiality and their changes with time, under repeated loading and/or enviromental effects.

It is evident that for stable crack growth the rupture stress-strain characteristics, as well as the loading and geometry, are the most important factors, and that for unstable crack growth the characteristics in terms of energy are decisive. Because the toughness is also a function of fundamental mechanical properties, the results of all fracture mechanics tests should always be accompanied by the fundamental mechanical properties of material, including the fracture stress Tu and fracture strain Au. Correlation studies which include Tu and Au would have much higher value. For example in connection with the Dugdale crack model, in the expression for the average plastic strength the replacement of the tensile strength Rm with the rupture stress Tu should be more justified. For shearing of materials it is also likely that the rupture stress Tu, rather the tensile strength Rm, is a more decisive material property.

The known fatigue strain-life curves and corresponding equations clearly indicate the importance of the rupture strain Au obtained in the tension test. Therefore, no low- and high-cycle fatigue test data should omit the information concerning Au and Tu besides the usual mechanical characteristics of the material.

This will contribute considerably to the new knowledge of criteria relating to plastic strain limitations, which are so necessary in many codes for structures, relating the static and cycling loading, with and without notch effects.

CONCLUSION

Because the definition of standardization in the newest ISO/IEC Guide implies knowledge also for potentional and not only for actual repeated use, the following may be the most important conclusion of this paper.

> For the interdiscipliiary sphere of mechanics of materials and structures a new technical committee, with a suitable number of subcommittees, is urgently needed at ISO in order to standardize precompetitive knowledge regardless of the kind of materials and the use of structures. In addition to the national standard bodies, the various international organizations dealing with the problems of materials in structures should support this proposal, and collaborate in consultations, discussions of problems and the organization of international research.

Hope has been awakened with statement by H. Blumenauer that results of a round robin program may lead to a standard, possibly an ISO standard (EGF Newsletter nr.1, Winter 1986/87, p.9).

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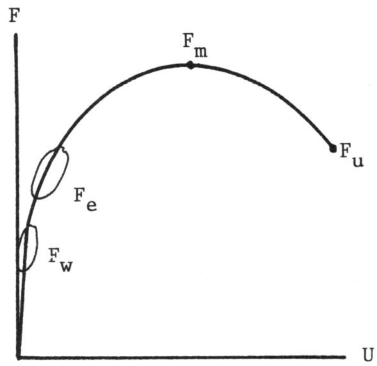


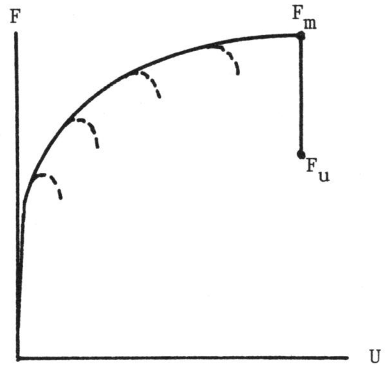
F_w working load

F_e yield (damage) load

F_m maximum load

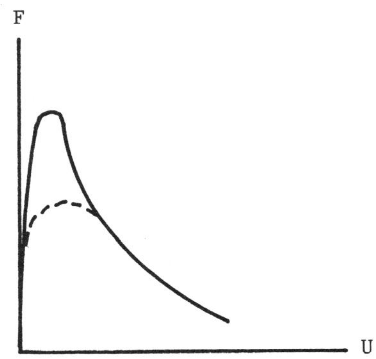
F_u fracture load

Figure 1 Load-displacement diagram of a structure



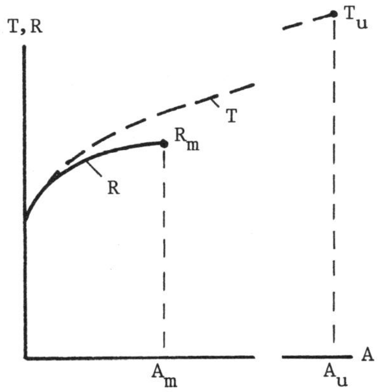
– – – lower ductility due to the notch effect

Figure 2 Load-displacement diagram for tension member



– – – effect of residual stresses

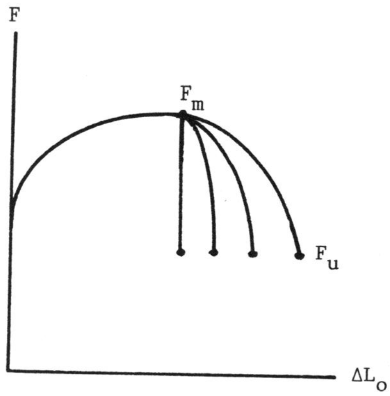
Figure 3 Load-shortening diagram with buckling



T true stresses

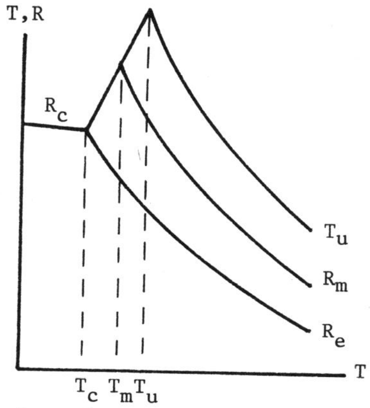
R "engineering" stresses

Figure 4 Stress-strain curves for tension



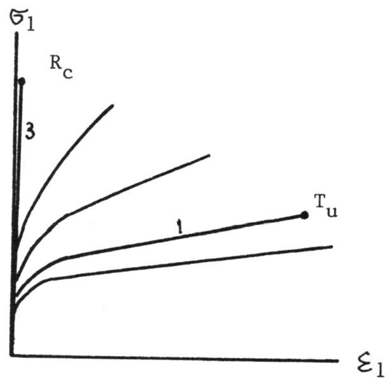
post-peak curves
for different
measure lenghts L_o

Figure 5 Load-elongation diagram in tension test



R_c cleavage strength
T_u true rupture strength
R_m tensile strength
R_e yield strength

Figure 6 Influence of temperature in tension test



1 monoaxial stress state
3 hydrostatic tension

Figure 7 Influence of stress triaxiality