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INELASTIC BEHAVIOUR OF METALS AND METALLIC STRUCTURES

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ABSTRACT: The present possibilities of computer simulations of the inelastic behaviour of metallic structures enable a realistic assessment of their safety and reliability as regards different limit states. The uniaxial stress-strain relationship of metals obtained with the tensile test is fundamental for the material law as the input for the computation. It can be characterized by the Young's modulus, the yield strength, the strain hardening exponent and the fracture ductility. The fracture ductility of metals has a specific role in the case of notch effects and because of its relation to different material constants in fracture mechanics. It therefore has to be adequately defined. The characteristics load-displacement relationship describes the global elastic and inelastic behaviour of structures up to collapse. It can also be expressed with the elastic stiffness, the beginning of global inelasticity and the course of the inelastic curve up to the ultimate load-carrying capacity with the corresponding ductility.

INTRODUCTION

With the use of continuum mechanics the present possibilities of the computational analysis of engineering structures for any configuration of structures, boundary conditions and loading paths enable the determination of stresses, strains and displacements at every point, taking into account geometrical and material nonlinearity, as well as geometrical and material imperfections, up to collapse. The question of what to do with stresses, strains and displacements obtained using such computer simulations is connected with the assessment of the safety and reliability of structures concerning different limit states, considering also the influence of various kinds of damage which can appear in the lifetime of the structure.

Fundamentally important for computational structural analysis are the material parameters, which represent the uniaxial stress-strain curve obtained with the tensile test: the slope at the beginning of the diagram (Young's modulus), the beginning of the inelastic part of the diagram (the yield strength), the course of the whole inelastic part of the diagram (the strain hardening exponent) and the end of the diagram (fracture ductility). For the computational determination of limit states of metallic structures according to the theory of small and medium strains (the beginning of global inelasticity, compression instability, plastic instability in tension), a knowledge of the "engineering" stress-strain diagram is sufficient up to the tensile strength, where necking begins and the curve goes down. But for problems with large strains (fracture problems of ductile metals, particularly due to the notch effect) it is necessary to change the decreasing part of the "engineering" stress-strain diagram into the form of the increasing relationship of the uniaxial "true" stresses and strains up to the real fracture.

Similarly as regards the material alone, the elasto-plastic behaviour of metallic structures can also be expressed by the parameters of the characteristic load-displacement diagram up to collapse: the slope at the beginning of the diagram (elastic stiffness), the beginning of the plastic displacements (the load-carrying capacity at yield), the course of the inelastic part of the diagram, the ultimate load-carrying capacity and the corresponding ductility. The ductility of a structure is particularly important in the case of impact or seismic overloading, where the post-peak course of the load-displacement diagram can have a role, too.

MECHANICAL PROPERTIES OF METALS

The material law, necessary for computer simulations of the inelastic behaviour of metallic structures, has to be based on the results of suitable mechanical tests of the material. The simplest and most common test, as well as the most important one, is the standard tensile test, where the "engineering" stress-strain diagram is exploited. Here usually only the yield strength, the tensile strength and the elongation (as a measure of the ductility) are determined. However, for ductile metals, which show necking at the simple tensile test, the customary elongation is an abortive measure of fracture ductility, because for the computation of large straing problems it represents an non-applicable quantity. The elongation is an average strain, influenced by the variable strains at necking and the uniform strain at tensile strength, and it therefore has different values at different measure lengths. The uniform strain has to be measured separately, because it makes possible the determination of the strain hardening exponent, and also because it represents the fracture ductility of longer tension members with constant cross-section without the notch effect. In order to obtain the material law for the computation of large strain problems up to real fracture (e.g. with the notch effect), the true fracture stress and the true fracture strain have to be determined by tensile tests of smooth specimens, because both make possible the determination of the complete uniaxial true stress-strain relationship up to fracture. The nominal fracture strength of ductile metals is the fracture load divided by the fracture area. However, for the true uniaxial fracture strength a suitable correction has to be made, due to the stress triaxiality and due to the change of the strain rate in this domain under the constant speed of the movement of the cross-head of the testing machine. The true fracture ductility is simply obtainable by making use of the reduction of the area at the fracture, with the assumption of constant volume.

The complete uniaxial true stress-strain diagram of metals can be defined by four parameters: the Young's modulus, the yield strength, the strain hardening exponent and the true fracture ductility. In this way the anisotropy, the non-homogeneity (e.g. at welded joints) and the damage to the material due to the low cycle fatigue or other effects, can be simply expressed by the change in these parameters. These four parameters also appear in the quantitative correlation equations for different fracture toughnesses and other material constants in fracture mechanics. For further research with regard to such correlation equations, the determination of the true fracture ductility and of the uniform strain at each standard tensile test is very desirable. A high value of fracture ductility represents a costly mechanical property, especially for high strength metals, because it depends on the cleanness of the material with regards to non-metallic inclusions and hard particles. Besides the yield strength and the strain hardening exponent, especially the true fracture ductility must appear as an extremely important mechanical property in the rational classification of metals for engineering structures, particularly those exposed to the detrimental effects of stress concentration under different loading and environmental conditions.

Parameters of the true stress-strain relationships are temperature dependent. With lower temperatures the material becomes harder. Certain types of metals exhibit brittle fracture under the simple tensile test at low temperatures. Here the fracture ductility approaches zero and smooth specimens break at cleavage strength. A higher strain rate has a similar effect on tensile test results. However, the material becomes harder and also brittle due to the unfavourable triaxiality of the stress state (e.g. in the vicinity of the crack tip under tension). It could be interesting to know if the cleavage strength, as an other fundamental material property, is basically independent of temperature, strain rate and the stress triaxiality outside the ductile fracture region. It is important to know for the computer simulation of the inelastic and fractural behaviour of metal bodies, how different stress triaxialities alone change the parameters of the complete uniaxial true stress-strain relationship up to fracture, taking subsequently into account the effect of different temperatures and strain rates.

For the computational treatment of small strain problems the details in the initial part of the uniaxial stress-strain relationship are important. For metals with a continuous stress-strain diagram the yield strength is usually defined by the stress at 0.2% plastic strain. In order to control the strain hardening exponent near the yield strength, the proportional limit stress, suitably defined, has also to be determined. However, with the usage of the equality of elastic and plastic strains for the definition of the yield strength of the continuous stress-strain diagram, a very simple dimensionless continuous stress-strain diagram can be made, with the strain hardening exponent as the parameter for the shape of the curve (the dimensionless Ramberg - Osgood diagram). Useful parametric studies with computer simulations with generalized dimensionless results for typical metallic structural components or details can be made with such diagrams.

For metals which demonstrate a plastic plateau, the Lüder's strain (the yield point elongation) has also to be measured, which can reach 6%. It is important to know that Lüder's bands produce macroscopically extremely non-homogeneous straining of the material, which can cause difficulties for the interpretation of the local strain or stress results when computing with the assumption on an ideal elastic - ideal plastic material. Furthermore, the upper yeald point is not a material property used in computer simulations of structures. Instead of the upper yield point the lower yield point, which represents the level of the plastic plateau, is used. The upper yield point is a very unstable quantity. It can reach a 60% higher value than the lower yield point, but it can also completely disappear during tensile testing, as a consequence of eccentricity or non-homogeneity. As regards the lower yield point, it is not generally known that it can be reduced by up to 20% under an entirely static loading.

Material science and micromechanics can help us understand the micromechanisms of different macroscopic phenomena in connection with the inelastic and fractural behaviour of metals and to improve the material laws for computer simulations in those cases of structural behaviour where this is needed (e.g. process zone).

LIMIT STATES OF METALLIC STRUCTURES

Metallic structures, their members, or machine parts can fail to perform in their intended functions mainly in the following ways:

1. Excessive elastic deformations or vibrations (serviceability limit states);
2. Beginning of the global plastic deformations (the load-carrying capacity at yield);
3. Compression or tension instability (ultimate load-carrying capacity, with the corresponding ductility).

The safety factors as regards the above limit states are related to the probability of the occurrence of service loads, of accidental overloadings and the variability of the resistance of the structure, taking into account, too, the influence of time and different possible environments. Probabilistic treatment, however, must be based on a clear deterministic knowledge about the limit states.

Today the use of computers for the structural analysis of metallic structures as regards serviceability limit states is routine work. However, for a thorough determination of the yield carrying capacity and the ultimate load-carrying capacity with the related ductility suitable materially nonlinear computer programs have to be used in order to determine the characteristic load-displacement diagram. While the knowledge of elastic stresses is relevant for the assessment of high cycle fatigue, the determination of inelastic strains is necessary in connection with the plastic strain limitation criteria related to low cycle fatigue. Inelastic computer simulations also enable the determination of the gradual reduction of the ultimate load-carrying capacity and of the corresponding ductility due to fatigue or other crack propagations. It also enables an assessment of the effect of different residual stresses, non-homogeneities and geometrical imperfections on limit states. It is useful to investigate how different strain hardening exponents and different fracture ductilities of metals have an influence on the yield and ultimate load-carrying capacity with the corresponding ductility of structures. Such studies enable the creation of standardized rules for the design of metallic structures.

CONCLUSION

The most important conclusion is that the usual elongation, obtained with the standard tensile test of ductile metals, has to be abandoned as a measure for ductility. In the place of elongation, the uniform strain and the true fracture strain should be determined. In such a manner the establishment of the parameters needed for the complete uniaxial true stress-strain relationship up to the real fracture is possible. This relationship is a fundamental material law for the computer simulation of the inelastic behaviour of metallic structures even in the case of very large strain problems (e.g. notch effects). These material parameters enable a rational classification of engineering metals according to yield strength, the strain hardening exponent and fracture ductility. They also appear in the correlation equations for different fracture toughnesses and other material constants used in fracture mechanics. A necessary pre-standardization work is needed in order to complete suitably the present national and international standards for the tensile testing of metals.