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Modelling of Load Carrying Capacity of Plastic Structures

Modélisation de la capacité portante de structures en plastique

Modellierung der Tragfähigkeit von Tragwerken aus Kunststoffen

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Dr. Helen Doubravszky, born 1939, received her architect degree at the Technical University of Budapest. For 18 years she was involved in research concerning load-bearing capacity of plastics, and received her PhD. degree at the Hungarian Academy of Sciences in that field. Now, as senior research associate, she is responsible of the mechanical testing of non-traditional materials and structural connections.

SUMMARY

The verification of the safety of structures and structural elements, the load-bearing capacity of which depends upon mechanical properties of plastics, can not be performed with appropriate confidence on the basis of traditional methods. Their limit states are consequences of loading processes, and can be controlled but through limit strains. This paper shows a design system derived from this statement, and based on the assumptions of linear viscoelasticity.

RÉSUMÉ

La sécurité de structures et d'éléments structuraux, la capacité portante dont dépend les propriétés mécaniques des plastiques, ne peuvent pas être vérifiées avec certitude sur la base de méthodes traditionnelles. Les états de rupture sont la conséquence du processus de charge et ne peuvent être contrôlés que par des déformations limites. La contribution présente un système de calcul et de projet découlant de cette affirmation et basée sur les hypothèses de visco-élasticité linéaire.

ZUSAMMENFASSUNG

Die Sicherheit von Tragwerken und Tragelementen aus Kunststoffen kann mit den traditionellen Methoden nicht genügend zuverlässig ermittelt werden. Die Grenzzustände von Tragwerken aus Kunststoffen sind eine Folge der Belastungsgeschichte und können nur über die Grenzdehnungen erfasst werden. Dieser Beitrag stellt eine Bemessungsmethode vor, die auf dieser Basis beruht, und setzt die Annahmen der linearen Visko-Elastizität voraus.

INTRODUCTION - AN ALTERNATIVE FOR STRUCTURAL ANALYSIS

Structural analysis is based upon models of physical reality. These models provide with patterns for analysis:

- separate phenomena of the first importance from those of secondary importance,
- construct a closed system from phenomena of first importance,
- give approximative methods that take into account phenomena of secondary importance,
- ensure calculation method that optimally conforms to the closed system.

For load-bearing structures and structural elements we use elastic materials. We suppose that they deform under load and recover after the load has been released. If the deformation and the recovery time are short /as with steel and concrete/, we use ideally elastic material model for structural analysis. /Instantaneous elastic deformation is of first importance./ We take a constant design strength as granted, and examine rupture of the structure by comparing design strength to design loading effects /stresses from design loads/. Thus the closed system for verification of the safety of structure /by ISO 2394/ can be summarized by the following relation:

$$\sum_{i=1}^{n} S_{d,i} \leqq R_d \qquad /1/$$

where $S_{d,i}$ is the design loading effect from the i-th design load, and

R_d is the design strength.

Deviation from the ideally elastic behaviour /fatigue, creep, plastic deformation/ of these structural materials is comparatively small /of secondary importance/, and is taken into account by reducing the design strength.

Structural plastics - both thermoplastics and thermosets, homogenous and composites, solids and cellulars - deform and recover long after their state of stress has been changed. The ultimate time-dependable part of their strain is of the same order of magnitude as the instantaneous part. Furthermore, under stress, simultaneously with the increase of strain, their strength decreases. These phenomena are of first importance, and demand viscoelastic model for analysing load-carrying properties of structures as well as structural elements with such materials.

In case of viscoelastic material model, strength is not considered as constant any more, thus a design loading effect can not be related to design strength unless duration and circumstances of loading are known. When examining ultimate limit states, the structural response to the design process of loading effects has to be analysed and compared to a material constant. For this material constant - according to results of the research of last 20 years [1,2], we can take the limit strain. Thus the closed system for verification of the safety of plastic structures can be summarized by the following relation:

$$\sum_{i=1}^{n} \varepsilon_{d,i}(\sigma_i, t_i, T_i, e_i) \leqq \varepsilon_{lim} \qquad /2/$$

where $\varepsilon_{d,i}(\sigma_i, t_i, T_i, e_i)$ is the material response to the i-th design loading effect: strain caused by σ_i stress of t_i duration acting at T_i temperature and e_i environment,

ε_{lim} is the limit strain, beyond which viscoelastic properties of plastics change irreversibely*.

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* Irreversible changes of viscoelastic properties occur when the integrity of the material ceases.

This paper shows how a closed structural analysis system and a calculation method can be constructed on the basis of the viscoelastic material model.

MAKING USE OF THE HYPOTHESIS OF LINEAR VISCOELASTICITY

Definition of linear viscoelasticity given by Ferry[3] sais: "if both strain and rate of strain are infinitesimal ... the ratio of stress to strain is a function of time /or frequences/ alone, and not of stress magnitude", in other words isochroneous strains are proportional to the respective constant stresses.

Plastics remember loading history. Boltzmann superposition principle helps us in analysing this phenomenon. Its simple definiton by Ferry[3] sais, that "the effects of mechanical history of linear viscoelastic body are linearly additive". It means that the sequence of different loads does not influence their summarized material response.

Let us see the degree of the error made when utilizing the assumption of the linear viscoelasticity:

- with composites there is no error, because in most cases their limit strain /0.002...0.005/ is far below their proportional limit;
- with plastic foams there is no error, because their limit of reversible changes coincide with their proportional limit /0.01...0.015/[4];
- with thermoplasts there can be a problem, but it can be solved by allowing a certain error /by ST SEV 5060 - 5 % deviation, by US Plastics Design Manual[5] and by Powell[2] - 15 % deviation from linearity/. In addition, ST SEV 5060 gives for these materials two limit strains: a proportional limit /0.005...0.008/ and a limit of reversible changes /< 0.025/.

Applying the hypothesis of linear viscoelasticity, we get two important facilities for structural analysis:

- stress analysis based on traditional elastic formulae, and
- summing up strains /material response to different loading effects/ on the basis of the Boltzmann superposition principle.

All the engineers agree in the importance of the first assumption, though the importance of the second one does not fall behind it. It merely was not a problem with the instantaneously elastic materials, because loading effects could be summed up without any regard to their succession and duration

A CONSEQUENTLY USED TIME-DEPENDENT LINEAR STRESS-STRAIN RELATIONSHIP

In course of the development of structural analysis, one of the main questions was the overall resistance of the structure, i.e. proving that it had enaugh rigidity to endure the consequences of loading. Obviously, modulus was used for expressing stress-strain relationship: the resistance of the structure was proportional to the material characteristic /modulus/.

With plastic structures, according to eqn. /2/, we are interested both in local and overall deformation of the structure. Moreover, we have to analyse the whole deformation process. This means that first we calculate the state of stress of the structure, after that we calculate the time-dependent deformation caused by this state of stress. Using compliance we do not only describe a property of the structure by a material characteristic proportional to it - this is the only rheologically correct way of engineering calculation:

$$D(t) = \frac{\varepsilon(t)}{\sigma} \qquad /3/$$

where $D(t)$ is the compliance describing retarded deformation, i.e. time-

-dependent strain caused by a given stress*.

Engineers prefere models consisting of simple relationships. It is a convenient method to have an initial compliance /corresponding to some conventional time, e.g. 1 min./, and a time characteristic:

$$D(t) = D_o \times \delta_{ct} \qquad /4/$$

where D_o is the initial standard compliance, and
δ_{ct} is the time characteristic, indicating strain increment after t hours period of loading.

The time characteristic δ_{ct} can be easily determined by a creep experiment as a ratio of the deformation after t hours loading and that of 1 min. loading. The strain in the experiment must not exceed the proportional limit strain /or the limit of reversible changes, if this is the lowest of the two/.

CALCULATING RECOVERY

The amount of the recovered deformation depends upon both the creep time and recovery time. Experiments as well as model-calculations carried out according to basic laws of linear viscoelasticity [6] proved that for practical purposes the following is a good approximation:

$$t_{ro} \approx 10 \times t_{ct} \qquad /5/$$

where t_{ro} is the recovery time corresponding to t_{ct} creep time, and
t_{ct} is the creep time /load duration/.

Fig.1 shows its graphical presentation. In practice, the part of the compliance representing retarded deformation $D_o(\delta_{ct}-1)$ has to be multiplied by the recovery ratio δ_r. The last can be approximated - according to Fig.1 - by the following formula**:

$$\delta_r = 1 - \frac{\lg t_r}{\lg(10 \times t_{ct})} \qquad /6/$$

where δ_r is the recovery ratio, indicating fraction of the retarded deformation not yet recovered during t_r time.

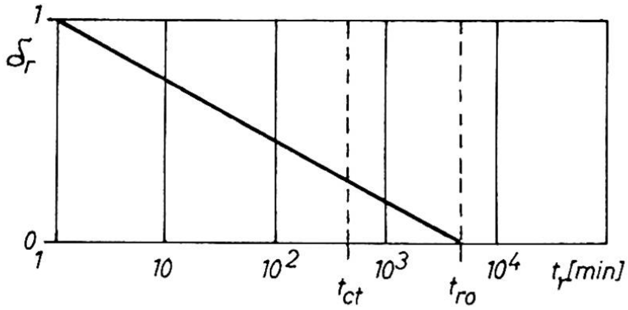

Fig.1

This simple rule was included in ST SEV 5060 and is permitted to apply in cases when max. strain does not exceed neider proportional limit, nor the limit of reversible changes.

CALCULATING STRUCTURAL RESPONSE TO TEMPERATURE AND OTHER ENVIRONMENTAL EFFECTS

Temperature change modifies creep rate of the plastic bodies. This phenomenon can be expressed by shifting "lg compliance - lg time" relationship along the horizontal /and sometimes along the vertical/ axis [3]. This means a simple multiplication:

$$D(T) = D_o \times \delta_T \qquad /7/$$

where δ_T is the temperature characteristic, the ratio of the initial stand-

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* With viscoelastic materials, modulus describes relaxation: $E(t) = \sigma(t)/\varepsilon$, time-dependent stress caused by a given strain

** Formula /6/ is valid between t_o=1 min. and $t_{ro}=10 \times t_{ct}$, with t expressed in minutes ard compliance and that of an other temperature.

According to rules of the shifting, formula /7/ applies to compliance at any load-duration.

Other environmental effects /mainly humidity/, that modifie creep rate /but do not cause degradation/, can be taken into account by the same model[7]:

$$D(e) = D_o \times \delta_e \qquad /8/$$

where δ_e is the environment characteristic, the ratio of the initial standard compliance /corresponding to standard atmosphere/ and the compliance at another humidity.

CONCLUSION - THE STRAIN-BASED DESIGN METHOD IN PRACTICE

The strain-based system for the verification of the safety is advantageous in case of those structures of which at least one of the limit states depends upon the load-bearing capacity of plastics /including polymer concreet and steel reinforced polychloropren bearings/. It provides with method for differentiation between loads of short and long duration, cold and hot periods of service etc.

Fig.2 shows an example for how to sum up consequences of different loads with different loading time. With stress-based system for the verification of the safety, this could not be realized, so the reliability of such design would be much poorer than with the system presented in that paper.

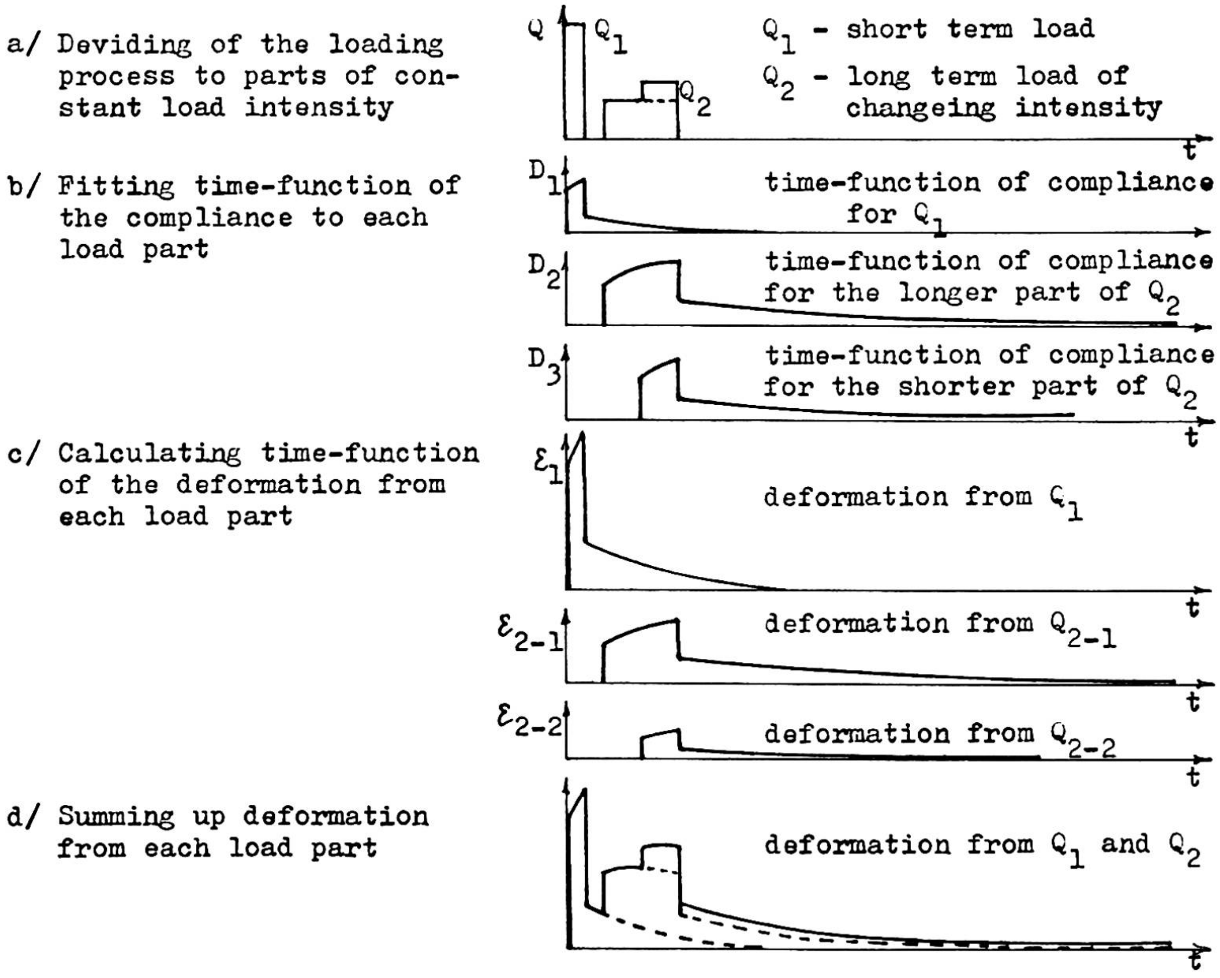

Fig.2

The basic differences between the principles of the strain-based and those of the stress-based design methods, as well as the great variety in the field of application of plastics in structures and structural elements make considerable obstacles in the way of putting this method in practice. It would be preferable to issue a series of documents beginning with the vocabulary and with the principles of structural design of plastic structures, followed by rules for constructing the design loading process, by rules for determination of design characteristics of structural plastics, by analysis methods for various kinds of plastic structures, and by rules of performing experiments with full-size elements for the verification of their safety.

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REFERRED INTERNATIONAL STANDARDS

ISO 2394-1973 General principles for the verification of the safety of structures

/ST SEV 5060/ СТ СЭВ 5060-85 Надежность строительных конструкций и оснований КОНСТРУКЦИИ ПЛАСТМАССОВЫЕ Основные положения по расчету