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Safety Considerations for Nonlinear Analysis

Concepts de sécurité dans l'approche non-linéaire du calcul statique

Sicherheitsüberlegungen für nichtlineare Bauwerksberechnungen

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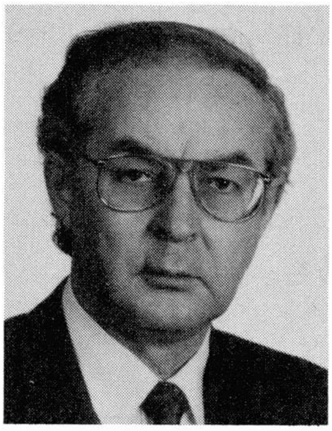

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SUMMARY

It is shown that the recommended safety concepts as proposed in EC 2 and the CEB Model Code are not rational in the case of safety checks for determining the nonlinear bearing capacities of a structure. A new proposal is given.

RÉSUMÉ

On montre que les concepts de sécurité recommandés dans l'Eurocode 2 et dans le Code Modèle du CEB ne sont pas rationnels pour le contrôle de la sécurité dans le cas des charges critiques non-linéaires. On présente une autre proposition.

ZUSAMMENFASSUNG

Es wird gezeigt, dass die im EC 2 und im CEB-Model Code empfohlenen Sicherheitskonzepte für nichtlineare Traglastermittlungen nicht sinnvoll sind. Deshalb wird ein neuer, abweichender Vorschlag unterbreitet.

1. SAFETY FORMAT AND CURRENT DESIGN

The basis of any rationally founded safety concept must be the probability of failure of a structure. The failure may be defined as a collapse situation, or any other limit state as e.g. the loss of serviceability. In more theoretical terms one asks for the probability of succeeding a limit surface in the space of the different design variable's density functions.

A 'Safety Format' is just one selected method out of an infinite number of simplified methods to guarantee a chosen probability of failure. A special choice is merely justified by reasons of practicability and the unavoidable deviation of the target probability for a whole group of structures. There is no principle advantage of a format using a global safety factor over another with e.g. several splitted partial safety coefficients.

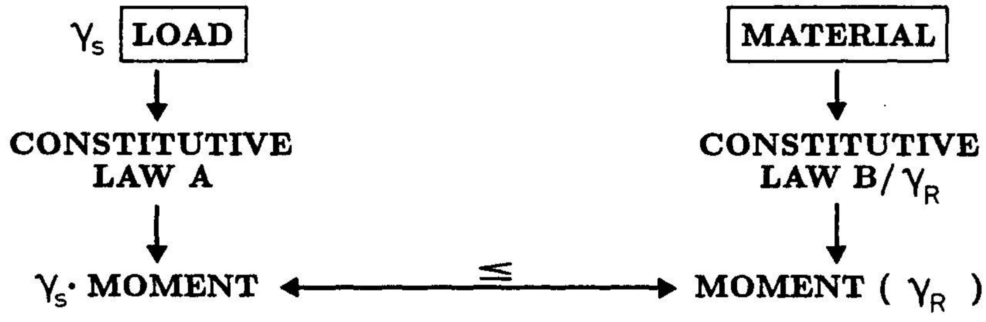

Fig. 1: Linear Analysis / Nonlinear Design

The current design format – called 'Format 1' (Fig.1) – results from the historical development of structural analysis and design. According to this, one first calculates inner forces and moments e.g. by means of the theory of elasticity using a very simple constitutive law A, followed by a so-called cross-section design with a second different set of now nonlinear constitutive laws B for steel and concrete.

Finally on a level of c r o s s - s e c t i o n a l quantities one compares e.g. inner moments increased by a safety factor ≥ 1 to account for the scatter of acting loads with design moments reduced in a n o n l i n e a r manner on the basis of constitutive laws by another safety factor ≥ 1 regarding material defects. Depending on the choice of partial safety coefficients a given minimum probability of failure may be secured.

As due to the different constitutive laws A and B cross-section design is independent of the internal moments and forces, no iteration process including the force distribution is necessary at the design stage.

This is a very simple 'Safety Format' with however strong inconsistencies e.g. that the strains calculated at the first process using material behavior A have nothing to do with the ones which result from the second material law B used for design.

2. BEARING CAPACITY DESIGN

It is however well known that in general local strength values do not control the safety of a structure at least not in case of indeterminate structures (Fig. 2). So e.g. the governing scatter of resistance within the length L of a yield line drops with L

(Fig. 2a), the local value being not decisive. The same is of course known from continuous girders, where yielding of one cross-section does not cause failure of the structure.

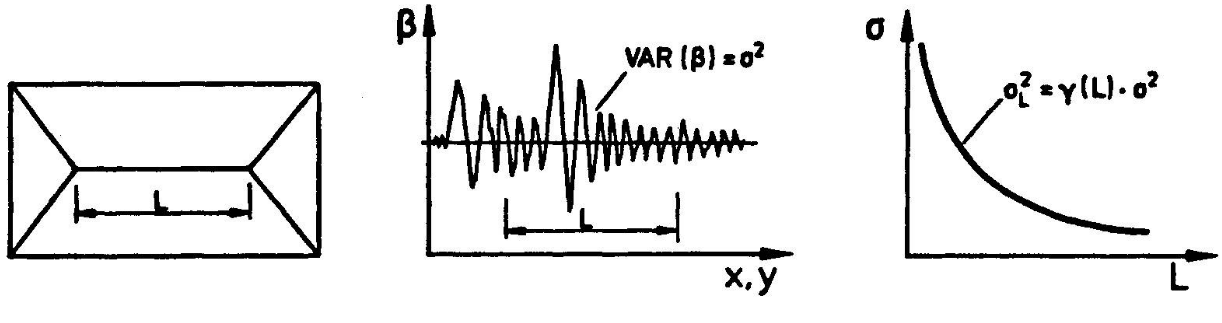

Fig. 2a: Plate as Example

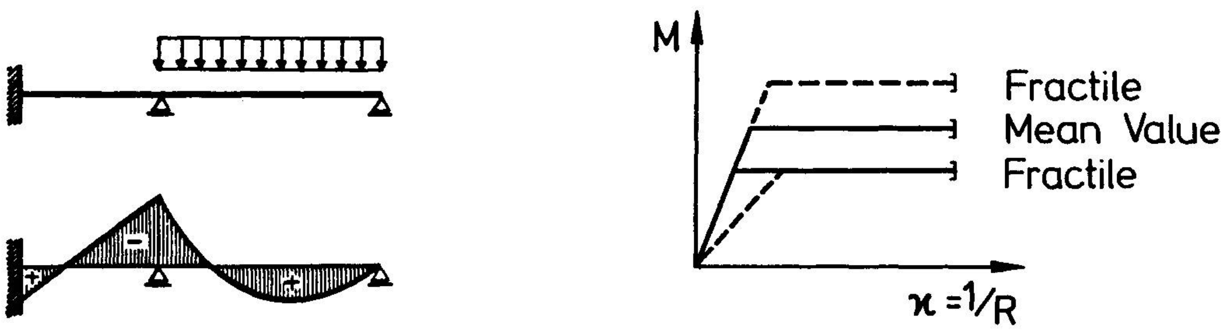

Fig. 2b: Continuous Beam as Example

Now nonlinear analysis allows to calculate the bearing capacity of a structure including local yield without overemphasizing it. This is done on the basis of only o n e physical correct set of constitutive laws A (Fig. 3) and allows a safety cheque comparing bearing l o a d s that can be endured and acting outer loads.

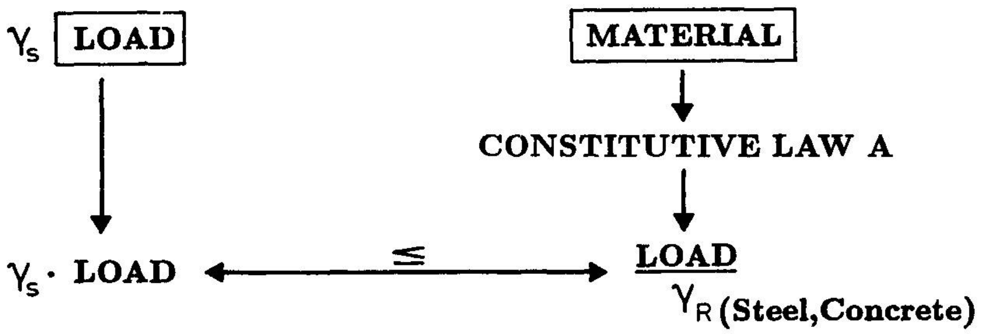

Fig. 3: Nonlinear Analysis and Design

In a 'Safety Format 2' then the bearing capacity is usually calculated by means of material mean values, which will be divided by a partial safety factor to account for materials scatter only at the final level of comparison. Similarly the acting load is increased by another partial load factor.

However instead of dividing the final bearing capacity at the stage of comparison and increasing the acting load both in a linear manner, one may also multiply both safety coefficients together and so end up with a global safety factor.

Proposals made in EC 2 in the CEB-Model Code for a safety concept in nonlinear analysis are not consistent with 'Format 2' and also not very rational.

It is proposed to compute in a nonlinear manner the inner forces of the structure by m e a n values of constitutive laws A and to do afterwards a cross-section design using now different constitutive laws B based on f r a c t i l e values. The consequence is that the inner forces and moments result from strain states that have nothing to do with the strain state of cross-section design and that the inner forces characterize just one arbitrary state of equilibrium as in 'Format 1'. This approach gives up the the advantage of nonlinear analysis to calculate system bearing capacity and does not justify the much higher amount of work necessary.

The opinion, it would be possible by iteration, to adjust the amount of reinforcement chosen first for the determination of inner forces and the one necessary for cross-section design is wrong of course. It is impossible to be in every cross-section (Fig. 2b) at the horizontal m e a n value branch and at the 5 % f r a c t i l e branch simultaneously.

When this was acknowledged it was then proposed to do the nonlinear analysis by only fractile laws to be on the 'safe side'. In general this is also not favorable as may be shown e. g. with Fig. 2b where too small support moments may lead to too small shear force at the inner supports. This proposal demands that one always has to decide what the 'safe side' is.

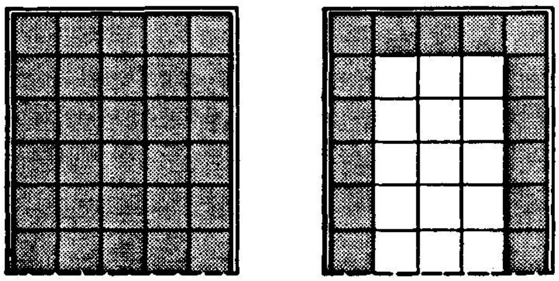

Fig. 4: Plate as Example

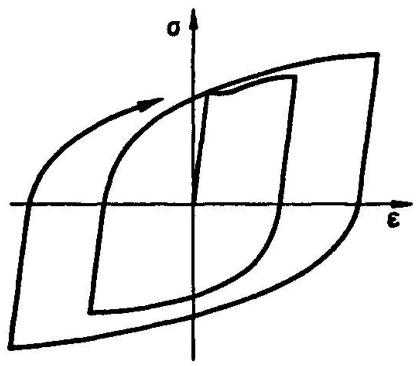

Fig. 5: Cyclic Constitutive Law

To save the concept of two partial safety coefficients, further proposals have been made to manipulate the constitutive laws in such a way as e.g. to take mean values for the first part of a bilinear stress – strain law to define stiffness and combine it with a reduced horiontal fractile branch.

It is obvious that such arbitrary manipulations cannot be a general answer to the problem. How should one manipulate a constitutive law in case of a nonlinear Finite Element computation for a plate (Fig. 4) e.g. to find a 'safe solution' ? If one reduces the whole stress strain law equally in all elements or alternatively only within the boundary elements, one finds quite different moments in the midst of the plate.

How does one have to manipulate the cyclic constitutive law (Fig. 5) to find a safe solution for what? These questions show clearly that in general a new approach, that means a new 'Safety Format' is necessary when calculating nonlinear and more realistic bearing capacities.

3. AN ADEQUATE SAFETY CONCEPT FOR NONLINEAR ANALYSIS

In the following a new adequate safety concept is derived by means of the nowadays possible stochastic Finite Element method – not to use it for practical design – for nonlinear analysis and design.

Beginning with the Equilibrium equations:

$$\Big[[\overline{\mathbf{K}}] + [\delta\mathbf{K}]\Big] \cdot \Big\{\{\overline{\mathbf{u}}\} + \{\delta\mathbf{u}\}\Big\} = \{\overline{\mathbf{R}}\}$$

where

K = stiffness matrix
u = deformation
$\overline{(\ )}$ = mean value
R = bearing capacity

one finds after some manipulations (See [6], [7] e.g.):

$$[\mathbf{C_u}] = [\overline{\mathbf{K}}]^{-1} \cdot \left[\frac{\partial \mathbf{K}}{\partial \alpha}\right] \cdot \{\overline{\mathbf{u}}\} \cdot [\mathbf{C}_\alpha] \cdot \left[\frac{\partial \mathbf{K}}{\partial \alpha}\right]^{\mathrm{T}} \cdot \{\overline{\mathbf{u}}\}^{\mathrm{T}} \cdot [\overline{\mathbf{K}}]^{-\mathrm{T}}$$

with

$[\mathbf{C}_\alpha] = \delta\alpha \cdot \delta\alpha^{\mathrm{T}}$ [ ] = Matrix
$[\mathbf{C_u}] = \delta\mathbf{u} \cdot \delta\mathbf{u}^{\mathrm{T}}$ {} = Vektor

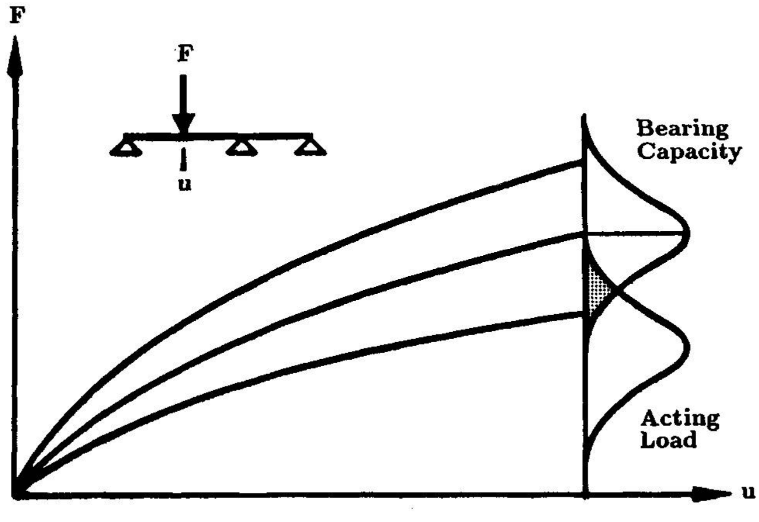

Fig. 6: Nonlinear Analysis including Probabilistic Approach

saying that from the given covariance matrix $\mathbf{C}_\alpha$ of the scattering basic variables α one can easily compute the covariance matrix $\mathbf{C_u}$ of the deformations $\mathbf{u}$ and by means of $\delta\mathbf{u}$

finally the values $\overline{\mathbf{R}}$ and the scatter of $\mathbf{R}$. So even in nonlinear analysis the scatter of the bearing capacity may be given in a $\mathbf{R} - \mathbf{u}$ plot (Fig. 6).

From these argumentations the following conclusions may be drawn :

What is necessary to achieve a desired probability of failure is just one **global** safety factor to determine the distance of the acting load density function to the density function of the bearing capacity computed by mean material values. This may be a different factor in cases of steel or concrete failure of course. Even the different safety behavior of structural determinate and indeterminate structures is then inherently covered.

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