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Nonlinear Design and an Appropriate Safety Format

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Josef Eibl, born 1936, graduated in Civil Engineering at the University of Munich, doctor's degree at the University of Braunschweig in 1963, several activities in the industry, professor in Braunschweig and Dortmund, since 1982 professor and director of the institute of Concrete Structures and Building Materials at the University of Karlsruhe. Research fields: dynamic loads on RC structures, external prestressing, silos, containments, nonlinear material behaviour.

Summary

Inconsistencies of the nonlinear design concept in EC2 are demonstrated. A safety format based on the comparison of system capacities versus acting loads is proposed. The Probabilistic Finite Element Method (PFEM) is employed to evaluate the safety margin between the mean system capacity and the design load needed for practical engineering applications.

1. Review of the Current ULS-Safety Concept

Prior to the developement of nonlinear analysis techniques in a first step the structural engineer calculated internal section forces and moments applying the fictitious theory of elasticity. Then in a second step the cross-sections were designed for these internal forces and moments using realistic, physically nonlinear constitutive laws for concrete and steel. The safety check was done at the level of cross-sectional characteristics. Consequently two constitutive laws were used simultaneously in one design approach, an elastic one for the first step and a nonlinear, more realistic one for the second step.

The method of nonlinear analysis in Eurocode 2 basically follows the same design format. It demands first a nonlinear evaluation of the internal forces and moments using mean material values and then a cross-sectional design with lower material fractiles. Here two different constitutive laws are also used inconsistently.

This method implies, that at first a rather lengthy and tedious nonlinear computation has to be carried out with estimated values of steel (e.g. over the internal support of a continuous girder) to find the moments and normal forces on the basis of mean material values. At the following cross-sectional design more steel is required for the same cross-section than calculated because of the demand imposed by the lower steel fractile. Thus the former result of the nonlinear analysis is no more than one out of an infinite number of possible equilibrium states. The old inconsistency remains in the new concept.

But there are further reasons why the current concept in EC 2 is not reasonable at all.

- In statically indeterminate structures (hyperstatic beams, plates, shells) failure of a single cross-section usually does not govern the ULS of the system. A local material failure in a

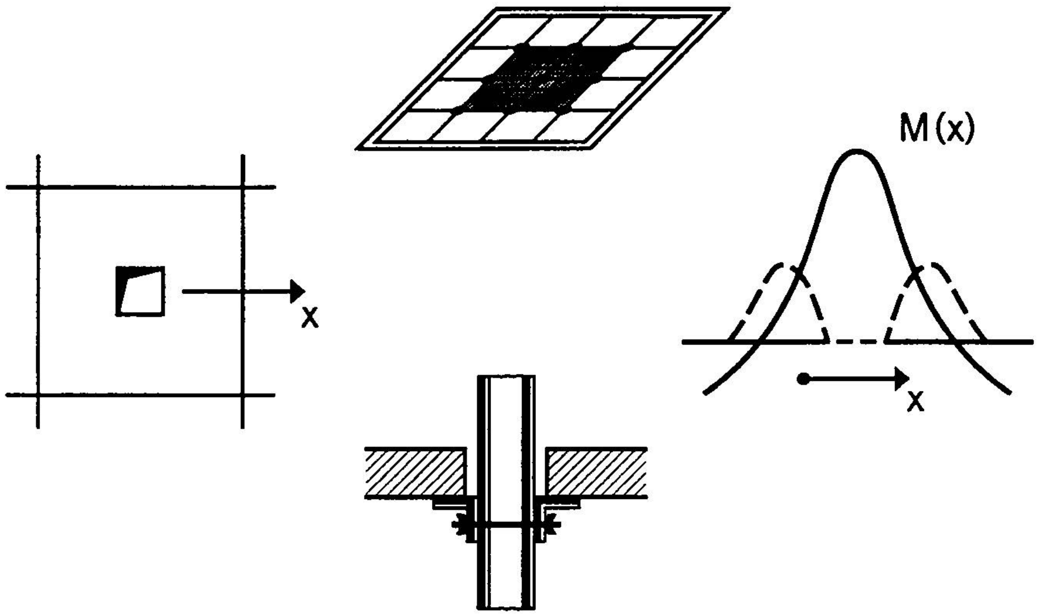

Fig. 1. Flat slab

slab e.g. can easily be absorbed by structural reserves as the example of the liftslab-technique (fig. 1) for the erection of flat slabs demonstrates.

- In case of complex statically indeterminate structures, also in beam systems, an eventual overstrength of the material due to a lower fractile-design in one section may lead to an unsafe result at other sections under different action effects, such as moments, shear and torsion (fig. 2). It is also known from the so called capacity-design in earthquake engineering, that low material values are by no means on the safe side in any case. In complex shell or plate structures it is not even known in advance whether the use of upper or lower fractiles at different locations is on the safe side.

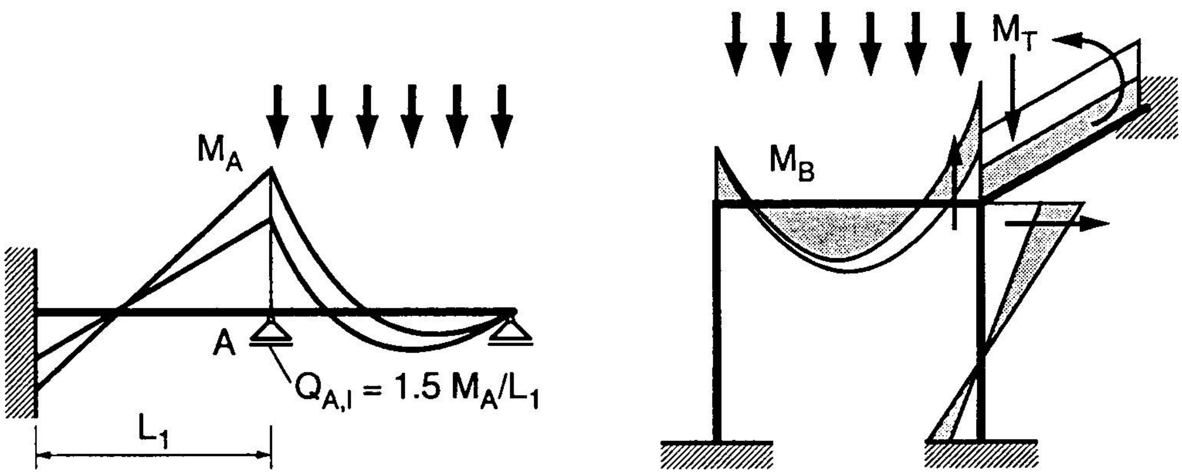

Fig. 2. Shear force and torsion influenced by underestimated flexural strength demonstrated at two systems

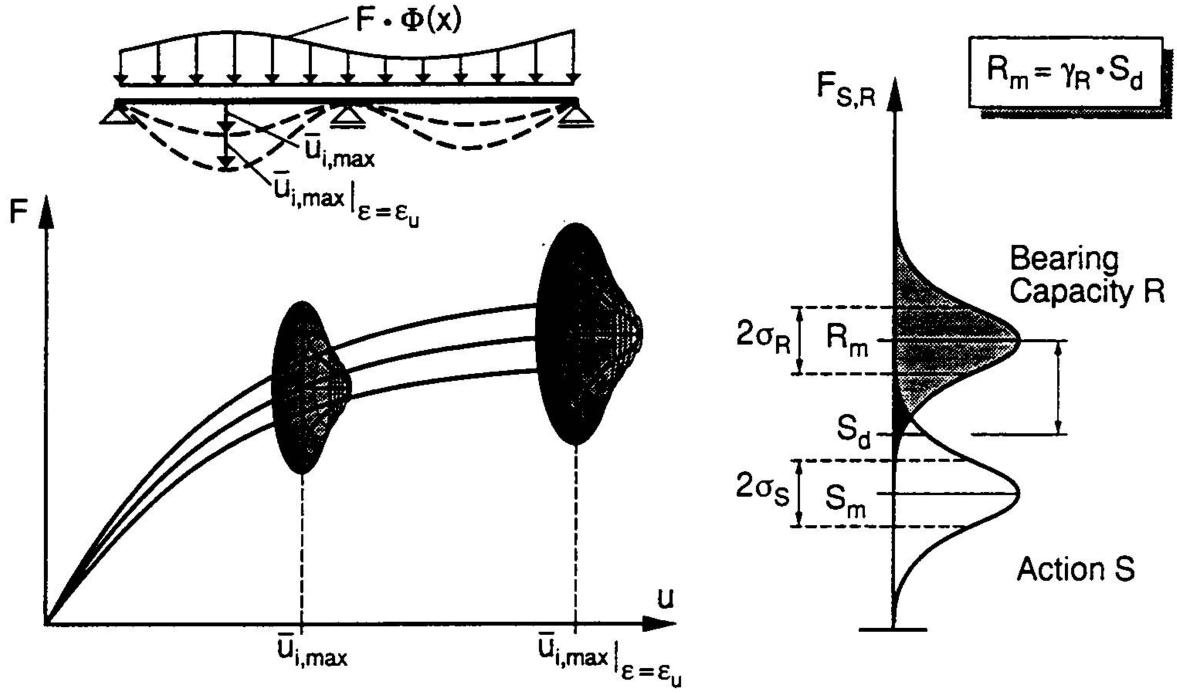

Fig. 3. Stochastic comparison of structural limit force and action force

- Global overstrength can also lead to an unsafe design e.g. in cases of differential settlement, temperature effects or composite structures.

These deficiencies of the safety format in EC2 have been addressed by the author in greater detail in several papers [1], [3], [4].

2. A New Safety Format

What the engineer finally needs at the ULS (Ultimate Limit State) is the realistic load-bearing capacity of the structure and, with regard to a rational safety format, its scatter resp. the density function of the system capacity. Then the probability of failure can be determined using also the density function of the acting loads, both distributions in terms of forces (fig. 3). To this end the system capacity and its scatter have to be calculated using a nonlinear constitutive model that corres-ponds to the real behavior of the structure. Such an analysis automatically includes the redistribution of sectional forces if reserves resp. redundancies are available in the system.

For such a safety check at the level of acting forces and resisting system capacities expressed in terms of forces one single γ-value is enough to guarantee an intended probability of failure, as will be shown. Whether different γ-values are used for different failure modes – steel or concrete failure – or whether different partial safety factors are introduced for the material and the action side is open to discussion. In the latter case both partial safety factors can always be multiplied to give again one global safety factor regarding the source of failure.

Such an approach is possible in detail – with simplifications for daily work – applying the

Probabilistic Finite Element Method ([6], [8]) combined with a special variational approach developed by the author and his coworkers. Details of this method cannot be given here. The reader is referred to [1].

For a better understanding of the available outcome an example is given in the following.

3. Example

The stochastic method addressed in section 2 was implemented into an existing finite element program for beams. The latter had been developed at our institute taking into account the physical nonlinearity of steel and concrete as well as the geometrical nonlinearity on the basis of small displacement theory. For further information it is referred to [2].

The following two-span girder was selected out of several other examples (Concrete C25/30 and Steel S500), its reinforcement chosen so that yielding of the steel governs failure. Therefore only the randomness of the yield stress of steel was considered. The coefficient of variation was assumed to be 10% in a perfectly correlated random field.

Fig. 4 shows the resulting system capacity and its scatter characterized by the mean value of the

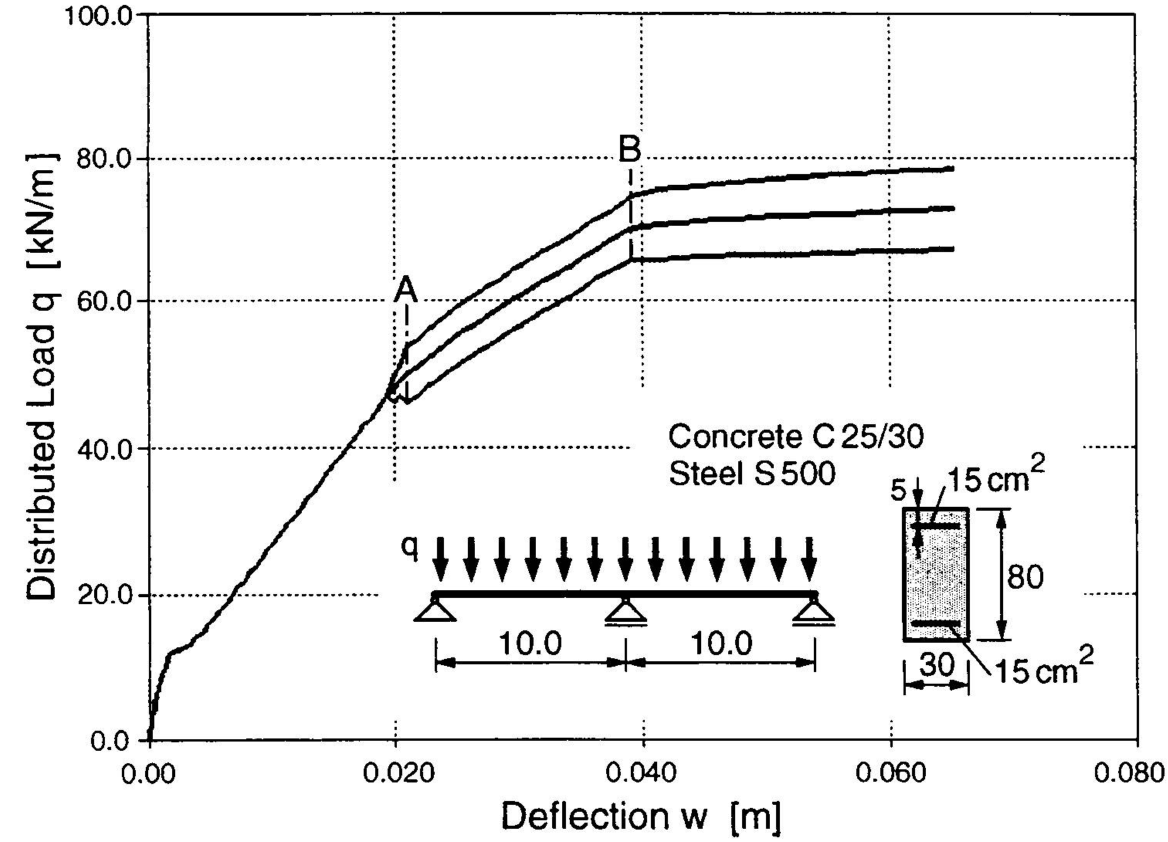

Fig. 4. Scatter of load-bearing capacity at a two-span girder

yield stress and its coefficient of variation $V_R \approx 8\%$.

The redistribution capacity of section forces amounts to about 40% after the first yielding of steel at the internal support between points A and B in fig. 4. The girder fails after reaching the ultimate strain in the compressive zone over the support. Nevertheless failure is initiated by ductile yielding of the reinforcement. Reaching the ultimate compressive strain of concrete is just a secondary effect of the large support rotation.

In table 1 the reliability index β [7] is given for different global safety factors γ_R according to fig. 3 between the mean value of the system capacity and the 99.98%-fractile of the acting load S_d. The latter together with the coefficients of variation for the load $V_S = 0.1$ and $V_S = 0.2$ characterize its distribution function. Both gaussian as well as lognormal distributions for system capacity and load have been studied. A safety factor of $\gamma_R = 1.3$ between design load and the mean ultimate load capacity ensures the required safety level with a reliability index of $\beta = 4.7$ or a probability of failure of $p_f \approx 10^{-6}$ according to [5].

Table 1: Reliability index β: two-span girder

γ_R	β (R, S gaussian)		β (R, S lognormal)	
	$V_S = 0.10$	$V_S = 0.20$	$V_S = 0.10$	$V_S = 0.20$
1.0	2.41	2.92	2.71	3.13
1.3	4.45	4.58	4.78	4.36
1.7	6.31	6.27	6.90	5.61

Summing up, a consistent safety format for non-linear analysis is proposed by further developing the existing EC 2. Major deficiencies of the existing concept are eliminated.

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