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SUMMARY OF DISCUSSION - SESSION 2

1. Limit State Design

With ambitious hopes for the future of plastic analysis as a means of structural design, B. Thürlimannn had opened his introductory lecture on "Plastic Analysis of Reinforced Concrete Beams" with a picture of the free cantilever construction method being applied to a major prestressed box girder bridge.

J. Blaauwendraad profited from this example to question rhetorically the value of plastic analysis in treating the major design problems encountered in the actual design of such structures. As pointed out, the cross section may be multicellular with cantilever flanges and not the academic rectangular boxes which form the basis for the theory. Also the multitude of prestressing cables needed in such a structure leads to considerable organisational problems in reaching a satisfactory positioning of the cables within the geometric restraints of the cross sections.

Further a major problem in designing such structures is the control of the horizontal alignment and of the short- and long term deflections, in order to ensure the required form of the finished structure. B. Thürlimann replied that of course plastic analysis could not treat serviceability requirements.

In this way B. Thürlimann focused on the important fact that plastic analysis is a rational means of treating the ultimate limit state conditions only. To achieve a fully operational design basis, plastic analysis should be supplemented by other analytical methods able to treat the requirements within the serviceability limit states.

When developing a complete design basis, this dualism, reflecting modern design principles, should not be forgotten.

2. Basics of Plastic Design

The further discussion focused on some of the basic problems still to be dealt with in some detail before a broad acceptance of the modern rational theory of plasticity can be achieved.

B. Thürlimann drew attention to the multitude of different effects covered by the effectiveness factor ν. Effects such as stress concentrations at the intersection between stirrups and longitudinal reinforcement, effective wall thickness in box- or solid cross sections subjected to torsion, distorsion of the side walls of such box sections, and bond slip are just a few examples of the role of ν. B. Thürlimann therefore recommended that much care should be exerted in defining what was covered by ν, so as possibly to separate the different effects caused by ν. In this way a rational explanation of the origin of the ν - values could answer for the different values of ν presented for each type of test. The criticism that ν is often just an empirical calibration factor introduced to improve the relation between theoretical and experimental results, could be dealt with in a more satisfactory manner.

Contrary to this opinion, M.W. Braestrup felt that the problem was more to make a choice of the values for ν than to make a calculation of ν. The code could specify the values to be used in the different types of load effects, as this is already done in several cases - just using another terminology than "effectiveness factor", e.g. maximum concrete compression design strength being different in bending, shear and torsion.

J. Witteveen discussed the deformability of concrete fundamentally necessary for the application of lower and upper bounds in plastic theory. Extensive research on plates has shown that in the yield lines considerable rotation can take place under a constant or even slightly increasing moment. According to Witteveen, the contributions on reinforced concrete shear walls and beams presented so far at this Colloquium have given no proof that concrete in compression has adequate deformation capacity for these structural elements to indeed reach the plastic collapse load. After a certain deformation, concrete in compression "softens", while it is well known from the plastic theory of steel structures that "hardening" in Witteveen's terms is essential for the formation of plastic zones. This strain softening of concrete in compression is taken into account by introducing the effectiveness factor ν. Also J. Witteveen therefore found that the fundamental weakness of the approach was the fact that ν depends on many factors such as the type of structure, type of loading, type of statically admissible stress field chosen, and the type of failure mechanism.

The freedom achieved with plastic analysis to choose the statically admissible stress field and design accordingly has of course its price, but as pointed out by B. Thürlimann the answer to this question depends on the case considered. When, for example, applying the plastic hinge approach to design a frame, the necessary rotation capacity of the hinges, and thus the necessary deformation capacity of the concrete, depends completely on whether all hinges form at the same time or whether there is a substantial difference in load level between the formation of the first hinge and the last hinge. The experience, as expressed by Thürlimann, is that concrete has a formidable ability to redistribute stresses, and if the effective concrete compression strength is applied sensibly, the design proves to be satisfactory.

The discussion on the origin and role of the ν-factor was concluded by referring to the paper by H. Exner, "On the Effectiveness Factor in Plastic Analysis of Concrete" presented in Session 1, this theme being a central subject within the theory of plastic analysis of concrete and a field in which further research should be encouraged.

3. Shear

A. Losberg discussed the possible influence of prestressed reinforcement on the shear capacity of beams in plastic design. The preliminary results of ongoing shear tests on simply supported beams with one cantilever, representing the support region of continuous beams, was reported. The parameters varied were the level of prestress and the existence or non-existence of stirrups in the shear failure region behind the support near the cantilever. Furthermore the prestressed reinforcement was in some of the test beams brought to yield by external stressing just prior to shear failure in order to study the possible decreased or vanishing effect of prestress upon the shear carrying capacity when the prestressed main reinforcement yields prior to a shear failure.

According to Losberg, the test results show that the level of prestress has a considerable influence on the shear carrying capacity, and that this effect could be fully represented by an influence term of the traditional type.

Furthermore there was no significant difference between the shear capacity of beams with yielding support reinforcement and with non-yielding support reinforcement.

Based on the contribution on "Shear in Beams with Bent-Up Bars" by C.M. Pedersen, A. Losberg noted that the effect of bent-up bars now seemed to be better considered than previously. To Losberg's question on whether separate methods were required to treat the effect of stirrups and of bent-up bars, Pedersen reported that all the tests he had studied verified the theoretically predicted result that there is no basic difference in the ability of stirrups and of bent-up bars to carry shear, and that a distinction is thus unwarranted.

B.C. Jensen pointed out that the model applied by J.F. Jensen to treat the lower bound shear strength of non-shear reinforced beams required that either the longitudinal support reinforcement be situated half-way up the support zone under two-dimensional hydrostatic pressure to ensure equilibrium, or a longer support region would be needed to ensure adequate stress transfer between the longitudinal reinforcement and the inclined uniaxial stress zone. J.F. Jensen found that an additional moment transfer system at the support zone could easily be achieved either by the concrete itself or supplemented by a few additional stirrups behind the support region.

Another possibility, shown by P. Marti, was to introduce a stress field for the part of the beam behind the support, which may for example be constructed starting from a simple truss model. In this case a certain stirrup reinforcement behind the support as well as a longitudinal reinforcement in the upper part - or at the top of the beam - will be needed. In any case, a simple bending failure mechanism may possibly be associated with an inclined collapse crack beneath the centre of rotation.

4. Statically Admissible Stress Field

P. Marti also reminded the gathering that the problems of simply supported rectangular beams under concentrated and uniformly distributed loads have already been treated by D.C. Drucker in his 1961 IABSE article "On Structural Concrete and the Theorems of Limit Analysis". In this article Drucker showed that in these cases a compatible bending failure mechanism may always be associated with the statically admissible stress field. According to Marti, the same remark also applies to the class of complete solutions given by M.P. Nielsen in his dissertation "On the Strength of Reinforced Concrete Discs".

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