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Evaluation of the Rotation Capacity of «D» Regions

Capacité de rotation des zones «D»

Schätzung der Rotationsfähigkeit von «D»-Zonen

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SUMMARY
The main objective of this paper is to discuss the effectiveness of some currently applied models in predicting the real rotation capacity of concrete slabs reinforced with welded wire meshes, as a functional of steel properties, reinforcement percentage and load condition. Comparisons are made with the experimental results obtained from 36 tests performed at the University of Pavia. Attention is given to the implications of the results for design codes and practical detailing.

RÉSUMÉ
L'objectif principal de cet article est de discuter l'efficacité de quelques modèles appliqués actuellement pour prévoir la capacité de rotation des dalles en béton armées de treillis, en fonction des propriétés de l'acier, du pourcentage d'armature et des conditions de mise en charge. Des comparaissons sont faites avec les résultats expérimentaux obtenus à partir de 36 essais effectués à l'université de Pavie. On portera son attention sur les conséquences de ces résultats sur les normes de dimensionnement, ainsi que sur les détails constructifs.

ZUSAMMENFASSUNG
Hauptgegenstand dieser Arbeit ist, die Effektivität einiger allgemein angewandter Modelle zu diskutieren, die die tatsächliche Rotationsfähigkeit von mit geschweissten Betonstahlbalken bewehrten Betonplatten als Funktion der Materialeigenschaften des Stahles, des Bewehrungsgehaltes und der Belastung ausdrücken. Es werden Vergleiche mit Ergebnissen aus 36 Versuchen, die an der Universität von Pavia durchgeführt wurden, angestellt. Die Einbindung dieser Ergebnisse in Normen und in die Praxis wird betrachtet.

1. PRELIMINARY REMARKS

The CEB Model Code 78 [1] allowed the redistribution of the bending moments calculated from a linear analysis if some ductility requirements were met by the critical sections.
The available plastic rotation was computed as a function of the neutral axis position according to the experimental results obtained from about 350 tests performed in the sixties [2,3].
Most of these tests had been performed on specimens reinforced with mild steel bars, with very good elongation capacity and large overstrength after yielding.
More recently it has become more and more common in Europe to produce steel with lower elongation capacity and lower overstrength, due to different production processes (cold worked steel) and weldability requirements (welded wire meshes). The applicability of the older results has been therefore questioned and discussed on the base of numerical analyses [4,5].
The plastic rotation capacity available for redistribution purposes has been consequently reviewed in the most recent codes [6,7], adding a second parameter to be considered: the elongation capacity of the steel.

The main objective of this paper is to discuss the ability of current numerical models to predict the real rotation capacity of plastic hinge regions and to examine the implications on codes of practice. Particular attention will be paid to the case of welded wire meshes, for a number of reasons: the steel is usually cold worked and has a lower elongation capacity; the steel percentages are often small; the bond between steel and concrete and the crack pattern can be strongly affected by the presence of the transversal bars.

2. FACTORS AFFECTING THE PLASTIC ROTATION CAPACITY

The basic parameter used in design codes to determine the available rotation capacity of a D region is the neutral axis depth (x/d) [1,6,7]. It has to be noted that the CEB MC 90 recognizes a decreasing rotation capacity if the neutral axis is too high, which means that the steel mechanical percentage is too low. The neutral axis depth is a very comprehensive parameter because it summarizes the effect of the section geometry and of some mechanical properties of the material.

Nevertheless the most recent codes are assuming a second parameter, i.e. the steel elongation capacity. The reason for which the influence of steel elongation was not considered in the past is simply due to the good uniform quality of the steel used up to the seventies.

A third parameter which is implicitly recognized as important is the ratio of the ultimate strength (f_{su}) to the yielding strength (f_{sy}) of the steel: a higher ratio allowes a larger region in which the yielding moment is attained, and the theoretical plastic rotation is consequently higher. Actually only a minimum for this ratio is given by the codes, but a tendency to the production of steel with less and less f_{su}/f_{sy} does exist, particularly for what concerns welded wire meshes.

It is also well known that the bond between steel and concrete plays an important role for the determination of the available rotation capacity, but there has not been in the past any transposition of this fact in the codes of practice. If this may be acceptable for deformed bars (but the bond is in this case proportional to the bar diameter), in the case of smooth bars the spreading of the yielded region of the bar can significantly affect the rotation capacity. In this case the distance between transversal bars may become the fundamental parameter.

Finally it has to be reminded that the beam slenderness (length over depth, l/d) governs the relation between fiber deformation, section curvature and overall rotation, therefore if the maximum fiber deformation is given (i. e. the steel elongation capacity and the bond relations) the available rotation is proportional to the beam slenderness. Also if the depth of a beam is kept constant the theoretical length of the plastic hinge (distance between the points at which the yielding moment is attained) increases with increasing span. The beam slenderness is usually taken into account in the codes by means of some limit value of slenderness for which the given relations are applicable.

3. MODELS TO PREDICT THE AVAILABLE ROTATION CAPACITY

The most commonly used models able to predict the plastic rotation capacity of D regions are based on a few common hypotheses and follow some common steps:

- plane sections are supposed to remain plane;
- the sections are divided into layers, each of them being characterized by the appropriate stress - strain relation;
- the sectional moment - curvature relations are then constructed by imposing increasing curvatures, getting strains and stresses and computing the corresponding bending moments;
- for a given bending moment diagram is then possible to compute the total rotation integrating the section curvatures on the desired length.

The key issue of such models is a refined consideration of the tension stiffening effect of the concrete around the bars from crack to crack. For this purpose some bond stress-slip relation is needed [8], together with some model to predict the position of the cracks.
If the tension stiffening effect is not considered a rotation for the case of so called "naked" bars is obtained, which is generally always greater than the real rotation. The difference in the curvature for the two cases are qualitatively shown in fig. 1.

Some possible plastic penetration beyond the limit of the yielding moment should also be considered.

A fundamental problem which is far from being solved is to decide if, in which cases, and for what amount a translation of the bending moment diagram has to be considered, as required by the well known "truss analogy". In [4] it is suggested to consider a translation if some shear cracking is expected.

If only one crack is present in the yielded region and if the reinforcement percentage is low (i. e. the neutral axis depth is very small), a simplified model could be used to estimate the maximum available plastic rotation.
The beam could be considered as a combination of two rigid bodies, connected by a hinge in the compressed zone of the critical section and by a deformable steel element at the level of the tensile reinforcement. The length of the steel element should be defined on the base of the distance at which a perfect bond is believed to have been reached.

4. EXPERIMENTAL RESULTS

Tests on thirty six slabs reinforced with welded wire mesh have been recently completed at the Laboratory of the Department of Structural Mechanics of the University of Pavia. The specimens had the same rectangular section (440 mm x 160 mm), slenderness of about 14 and were casted with the same concrete. The spacing of the transversal bars was normally set at 150 mm. All the details on materials, geometry and results are presented in [9]. The variable parameters were as follows.

Steel properties

Three types of steel were used, with different stress-strain relations and different bond characteristics. The main differences can be identified in the mean ultimate elongation capacity (ε_u equal to 3.45, 4.36 and 7.99 %) and in the surface of the wires (smooth or deformed).

Reinforcement percentage

The geometrical percentages of the tensile steel were 0.23, 0.38 and 0.64 %, corresponding to neutral axis depth approximately equal to 0.09 d, 0.12 d and 0.17 d. The steel at the compressed edge was kept constant (geometrical percentage 0.23 %).

Applied load

The load was either concentrated at midspan or divided into four equal loads.

The main results in term of available plastic rotation are given in fig. 2: the experimentally measured rotations are systematically higher than the corresponding values accepted in the CEB MC 90, but the ratio between available and accepted plastic rotation does not seem to be uniform.
The trends given by the CEB are roughly confirmed, but the steel with higher elongation capacity seems to be much more sensitive to a decrease of the reinforcement percentage and of the bar diameters.
The smooth wire meshes deserve a special mention because of the good uniform behaviour.

A comparison of numerical and experimental results is presented in fig. 3.
The numerical model was not refined and did not consider the tension stiffening effect; the complete stress-strain curve of the steel was used.
The numerical simulations should have therefore sistematically overestimated the available rotation. This is not the case for some specimens with smooth bars (LiB) and with the more ductile deformed bars (NeA). For these cases the introduction of a tension stiffening effect in the model would have further underestimated the available plastic rotation. While the substantial approximation of the same values for the experimental and numerical results could have been predicted in the case of smooth bars (i.e. in this case the bond could be neglected), the results obtained from NeA type steel still deserve some explanation.

The tension stiffening effect is experimentally very clear, as shown in fig. 4, where the moment-curvature diagrams for different regions of a beam are shown. It is also clear that only in one crack the steel has been able to reach yielding: the yielded length depends therefore on the bond stress-slip relation rather than on the distance between the points at which the yielding moment is attained. This consideration explains why the numerical predictions are generally too high in the case of smaller deformed bars: in this case the bond is much higher.

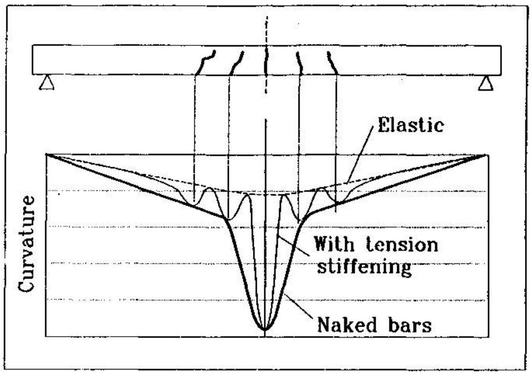

Fig.1 - Comparison of typical curvatures with and without considering the tension stiffening effect

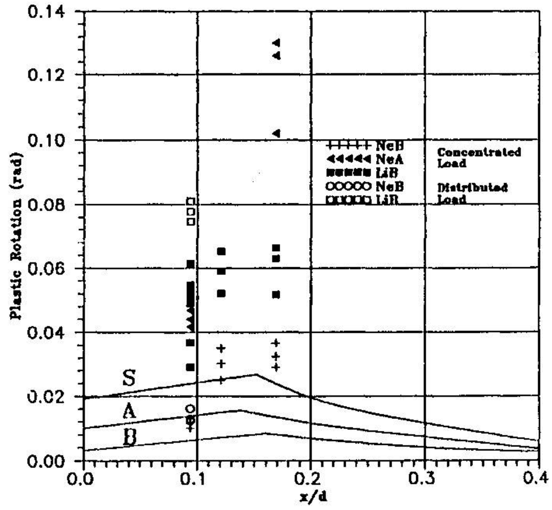

Fig.2 - Experimental plastic rotation vs. the CEB MC 90 design curves

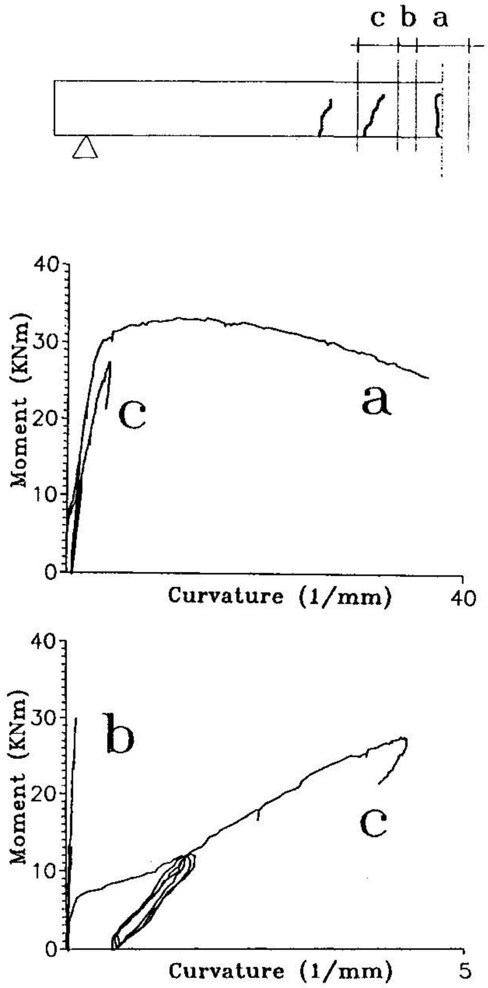

Fig.4 - Evidence of the tension stiffening effect from the experimental results

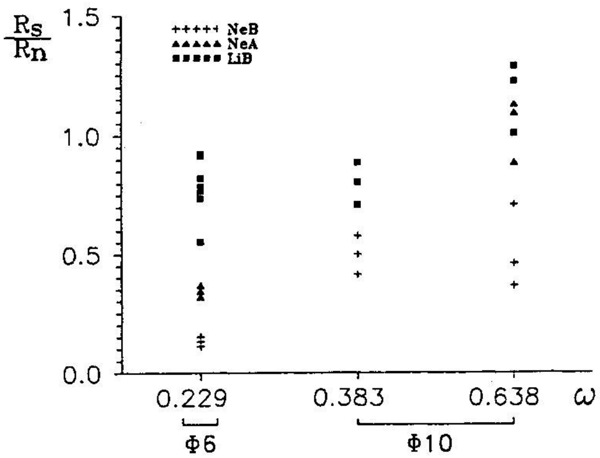

Fig.3 - Ratio between experimental and numerical ("naked bars" with bending moment diagram traslation) rotations as a function of steel percentage (bar diam.) and quality

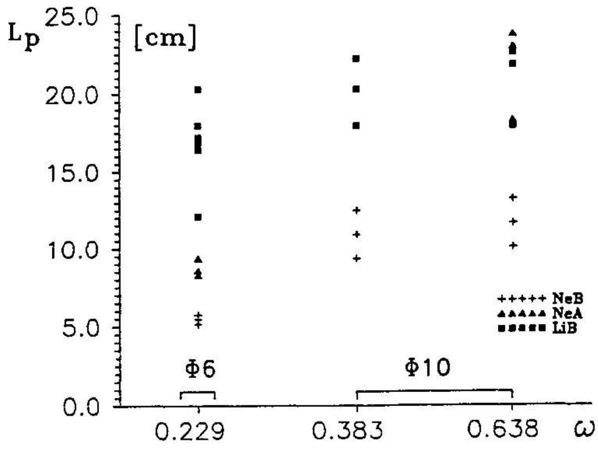

Fig.5 - Yielded lenghts required by the "rigid bodies model" as a function of steel percentage (bar diam.) and quality

The simplified model previously mentioned has been also applied to check the implications of the experimental results. In fig. 5 the lengths of the bars that should have fully yielded to match the experimental results are shown.
In the case of deformed bars, the bond is clearly playing the fundamental role, with required plastic length approximately proportional to the bar diameter.
In the case of smooth bars the required plastic length is about constant, confirming the negligibility of bond stress-slip relations with respect to the mechanical restraints offered by the transversal bars.

5. IMPLICATIONS FOR DESIGN CODES AND CONCLUSIONS

The importance of bond relations in the evaluation of the available rotation capacity in D regions has been generally neglected by codes and this is particularly dangerous in the case of small diameter bars, for which also the mechanical properties of the steel are usually worse.
On the opposite, from experimental results it appears that the use of smooth bars could assure a series of advantages if a mechanical bond is anyway guaranteed by the presence of transversal welded wires.
The definition of minimum values of reinforcement and minimum bar diameters seems to be particularly important in the case of deformed bars, when some plastic rotation is required, even if a good elongation capacity of the steel is provided.

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