Damping and stiffness behaviour of reinforced concrete under cyclic excitation – Experimental and analytical studies

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1 INTRODUCTION

The quality of dynamic structural analysis depends to a large extent on the assumptions for the stiffness- and damping behaviour of the structural elements. For reinforced concrete it is often difficult to get realistic values for the actual stiffness and damping. One of the causes, even under service conditions, is the influence of cracking on the hysteretic behaviour of R/C-members. In the cracked state cyclic bond action is one of the main dissipative mechanisms leading to damping. In this paper some considerations for modeling cracked R/C-elements are presented. Special attention will be payed for the calculation of crack spacings under bending and normal force and for simplified numerical treatment of bond under cyclic loading.

2 CRACK SPACINGS FOR REINFORCED CONCRETE MEMBERS UNDER BENDING AND NORMAL FORCE

The formation of a new crack between two adjacent existing cracks is enabled by the bond force, which the reinforcement introduces into the concrete portion between two existing cracks. Further the effect of the concrete compression force in the compression zone has to be considered. In order to calculate the crack spacings for a given state of loading the relation between maximum crack spacing s_{cmax} and ultimate bond force T_u must be known. While for axial tension the ultimate bond force equals the cracking load of the concrete it is more difficult to compute the ultimate bond force T_u for the case of bending or bending with normal force. It can be done, if the mechanical model in Fig. 1 is transformed to a FEM-model taking into account the behaviour of the crack to be opened between the existing cracks by a discrete crack approach. For this purpose the capacity of concrete in tension is decribed by its stress-crack-opening-relation /1,2,3,4/. In a parametric study using this nonlinear Fracture-Mechanics-

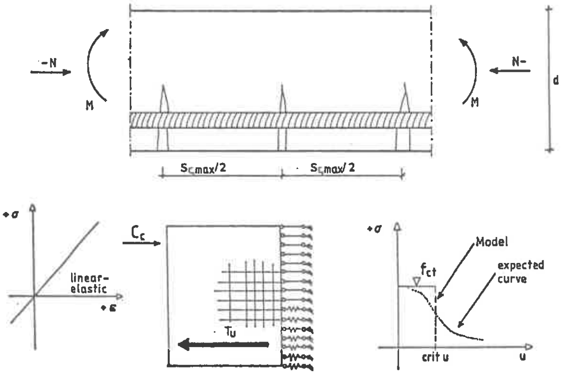

Fig. 1.
Mechanical and FE-model for calculation of maximum crack spacings in R/C members with bending and normal force

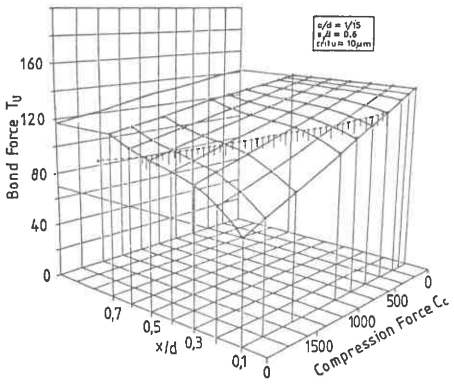

Fig. 2.
Ultimate Bond Force T_u as function of Compression Force Cc and relative depth of compression zone x/d

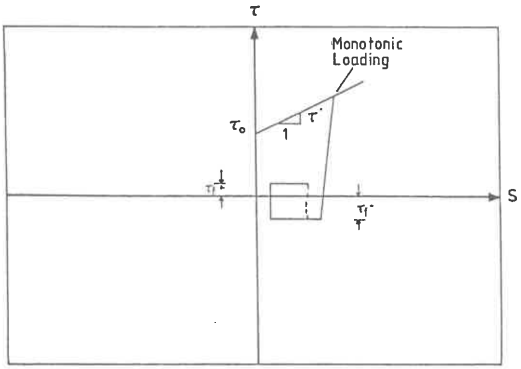

Fig. 3.
Simplified Bond-Slip-Law for analytical model

Model with the simplified σ_c-u-relation after /5/ a catalogue has been derived, in which the ultimate bond force T_u is given as a function of the maximum (initial) crack spacing, the compression force and the depth of the compression zone. Some of the results are shown in Fig. 2.

By correlating the ultimate bond force $T_u(s_{cmax})$ and that one calculated as a function of crack spacing s_{cmax}, the bond-slip-law and the steel strain the actual maximum crack spacing can be obtained. Then the minimum crack spacing results to

$s_{cmin} = s_{cmax} /3$

whereas the average crack spacing comes out to

$s_{cm} = s_{cmax} / 1.7$

as shown in /6/, if a hyperbolic distribution function for the crack spacings is assumed. On the basis of the known crack spacings the treatment of bond action under cyclic loading becomes possible.

3 DISSIPATIVE MECHANISMS

As shown in /7,8/ the energy dissipation and thus, damping of reinforced concrete members is caused by material damping of the components concrete and steel and by structural damping, e.g. due to cyclic bond action. The most important mechanisms are :

- hysteretic behaviour of concrete (especially in the compression zone),
- hysteretic behaviour of reinforcing steel (plasticity),
- hysteretic behaviour of bond,
- friction (aggregate interlock) in cracks.

Whereas the hysteretic behaviour of steel is important for large strains in the plastic range, the other mechanisms contribute significantly to the total energy dissipation also under service load conditions. Because of its importance for members subjected to bending or bending with normal force the energy dissipation due to cyclic bond is the focus of the presented research work.

4 ANALYTICAL MODELING OF CYCLIC BOND ACTION

Several numerical approaches are suitable in order to compute the behaviour of bond in reinforced concrete subjected to dynamic loading. Theese are: Finite-Element Methods, numerical solution methods for differential equations in connection with any iterative shooting technique or finite difference methods. For all methods a significant amount of computational efforts is necessary. In order to avoid large computation time a simplified analytical approach seems to be appropriate. Using a schematized bond law (see Fig. 3) on the basis of a cyclic bond law presented in /9/ it is possible to work with

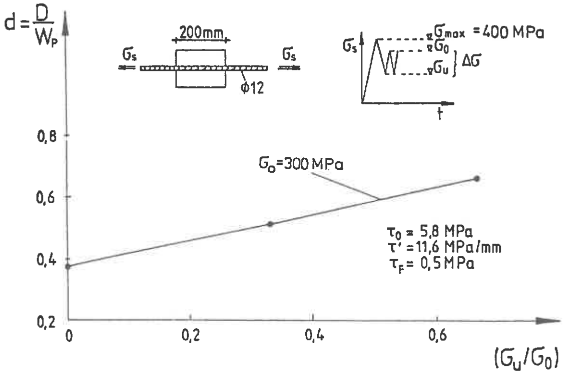

Fig. 4.
Dissipation ratio d as function of stress-amplitude and maximum stress according to theoretical model.

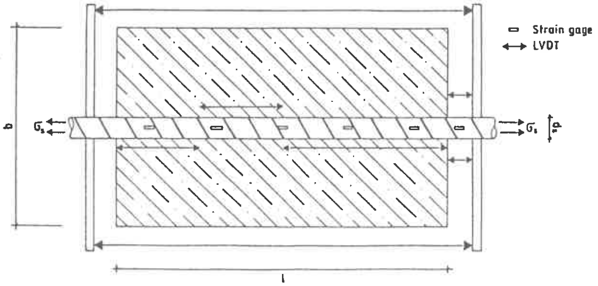

Fig. 5.
Test specimen with intrumentation

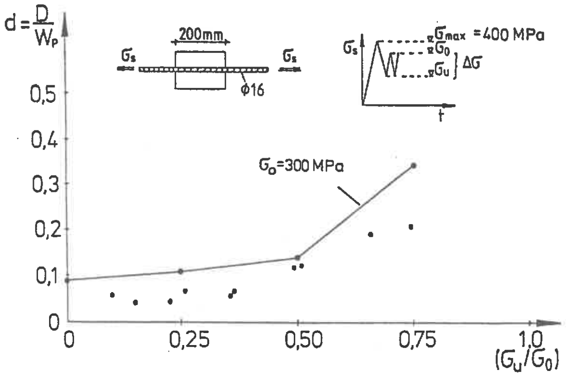

Fig. 6.
Dissipation ratio d as function of stress-amplitude and maximum stress (from experiment).

simple shape functions for the distribution of bond stresses along the reinforcing bar.
Doing this it can be shown, that the maximum theoretical dissipation ratio, defined as the quotient of the energy dissipated during one cycle W_{diss} and the potential energy W_{pot}

$$d = W_{diss} / W_{pot}$$

for frictional bond behaviour is d = 2.67. This value corresponds to a critical damping ratio of approx. 21%. For large stress amplitudes this value cannot be reached. Fig. 4 shows the calculated dissipation ratio for a concrete specimen with a length of 200 mm and a 12 mm rebar for an assumed bond-slip law.

A comparison between the proposed simplified method and numerical calculations showed little differences in the range of larger stress amplitudes and significant differences, where the assumption of the rigid-plastic bond behaviour in the simple model decides about the distribution of bond stresses.
The procedure is capable of computing force and deformation of a reinforced tensile loaded member for any time step as far as the reinforcing steel remains in the linear elastic range. So the actual stiffness as well as the energy dissipation can be determined.

5 EXPERIMENTAL PROGRAM

In parallel to the theoretical calculations an experimental program was set up in order to measure the energy dissipation and the stress and deformation states of R/C-members under cyclic loading. A typical test specimen with its instrumentation is shown in Fig. 5. Besides integral measurements of deformations the strain distribution in the rebar is recorded for each time step of 10 ms, while the period of one loading cycle is 2 seconds. The loading history for one 'loading step' consists of a block of 3 primary cycles with maximum force and then 10 blocks of 15 secondary cycles with different amplitudes and different values of upper stresses. A parametric study is performed in order to investigate the influence of the following parameters:

- rebar diameter,
- crack spacing,
- concrete strength (i.e. specimen length),
- concrete area (or reinforcement percentage respectively),
- load history and actual load (steel stress).

Although the evaluation of test results has not yet been completed, one result of the tests is shown in Fig. 6. It shows the influence of stress amplitude on the dissipation ratio.

6 SUMMARY AND CONCLUSIONS

The stiffness and damping behaviour of reinforced concrete can be modeled, if the crack pattern corresponding to a given load is known. For this purpose a method is presented, which predicts the maximum, minimum and mean crack spacings using NLFM. On this basis it is possible to get estimates for the energy dissipation ratio. A series of experiments has been performed in order to study the real behaviour and find the most influencing factors for the stiffness and damping behaviour of reinforced concrete members.

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