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ENERGY-DISSIPATION AND STIFFNESS OF REINFORCED CONCRETE MEMBERS UNDER CYCLIC LOADING DUE TO HYSTERETIC BOND ACTION

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SUMMARY

The dynamic response of reinforced concrete structures is influenced not only by the nonlinear stiffness behaviour of reinforced concrete but also to a large extent by its energy-dissipation-characteristics leading to damping. In this paper some results of an experimental and analytical study about the influence of cyclic bond action between concrete and rebars on damping and stiffness of reinforced concrete members are presented. Different methods of modeling are discussed and analytical results are compared with test results for different specimens.

INTRODUCTION

The response of structures subjected to dynamic excitation is influenced to a large extent by the damping behaviour of its structural elements. Especially in the cases of steady state forced vibration and earthquake action a realistic estimate of damping caused by different dissipative mechanisms is needed in order to predict the response behaviour realistically. Whereas for large deformations, when steel and concrete show plastic strains realistic models for steel and concrete under cylic loading are available, for the pre-yield phase it is more difficult to compute realistic values for the damping ratio. Thus, analytical modeling of R/C-structures for rather exact checks of serviceability limit states under dynamic excitation is difficult. In the following some basic considerations are presented which might help to understand and model one of the basic dissipative mechanisms in reinforced concrete: the hysteretic bond action between reinforcement and concrete.

DEFINITION OF A DAMPING RATIO

Damping, which is a consequence of energy dissipation, may be defined by the ratio of dissipated energy D to deformation-energy W_p during a specified time. In many cases it is convenient, to select the duration of a load cycle as reference time (see Fig. 1). The damping ratio defined by this way compares to the equivalent ratio of critical damping divided by four times Pi for the resonance case.
It should be noted, that if additional plastic deformations or strains occur, the energy dissipation due to remaining plastic deformations at the end of the cycle should be treated separately.

EXPERIMENTAL PARAMETRIC STUDY

Energy dissipation in R/C-members may be caused by the following mechanisms:

- hysteresis of stress-strain-relation of concrete,
- hysteresis of stress-strain-relation of reinforcing steel,
- hysteretic action of aggregate interlock in cracks,
- hysteresis of dowel action of rebars,
- friction between aggregates and /or hardened cement paste in cracks, which open and close during cycling,
- flow and transportation of media (e.g. air pumping in opening and closing cracks), and finally
- hysteresis of bond between rebars and concrete, which was the focus of the performed tests.

In order to separate the influence of bond hysteresis, contrary to tests with beams or cantilever elements, as reported e.g. in (Ref.1,2,3) the test specimens used here only represent the region between two adjacent cracks in a R/C structural member (see Fig. 2). The load is applied directly via the rebar. The parameters under investigation are rebar diameter, reinforcement percentage, concrete strength, crack spacing (i.e. length of specimen), loading history (expressed e.g. by the maximum steel stress reached before and the number of cycles), and actual loading, which means maximum and minimum stress of the actual load cyle. Fig. 3 shows a typical plot of the load function block applied to the specimen repeatedly with increased magnitude. Fig. 4 shows the instrumentation of a specimen with strain gages for local measurements and with LVDT's. In order to eliminate transverse bending effects of the slotted rebars transversal and longitudinal strains are measured at each loactiosn of strain gages. The force is recorded by a separate force transducer. 15 series of specimens have been tested. Each sereis consisted of three specimens of which one has been instrumented with strain gages.

EVALUATION OF TEST DATA

On the basis of the measured longitudinal steel strain at the locations of the gages and the deformations recorded by the LVDT's the local steel stress $\sigma_s(x)$, the local bond stress $\tau_s(x)$ and the local slip s(x) can be calculated (low-pass-filtering of raw data, fitting cubic spline functions through the measured values and taking the analytical derivation of the spline functions). The slip is obtained by numerical integration.

Fig. 5 shows a typical force-deformation-plot obtained from the tests. For reasons of clearness only selected cycles are shown. The behaviour of the test specimens may also be illustrated regarding the contribution of concrete to stiffness as tension-stiffening effect. Fig. 6 gives an idea of the stress-strain law of tension-stiffening under cyclic tensile loading.

The damping ratio is computed for each group of cycles as given by the load-time-function. Primary cycles (cyles with higher steel stress than reached ever before) and secondary cyles are treated separately. Due to plastic bond deformation primary cycles reveal higher energy dissipation than secondary cycles. However, also secondary cycles can have high damping ratios. The Figures 7 and 8. illustrate the influence of maximum preloading and the ratio of minimum to maximum stress in the actual cycle considered on the damping ratio. In general the influence of the parameters under investigation is illustrated by Fig. 9.

MODELING

For modeling of the damping and stiffness behaviour of reinforced concrete elements under cylic tensile load, three steps have to be performed:

- calculate crack spacings under consideration of all cross sectional forces,
- compute cyclic bond action between adjacent cracks of given spacing,
- superposition of dissipated energies due to different dissipative mechanisms.

For the calculation of crack spacings the basic principles are reported in (Ref.4). By a nonlinear fracture mechanics method the bond force necessary to open a new crack in between two already existing cracks is computed as function of the initial crack spacing, the value of the concrete compressive force and the height of the compression zone. The maximum possible crack spacing for a given loading is reached, when the existing reinforcement is able to transmit a bond force equal to the critical value into the concrete (see Fig. 10). A parametric study showed, that for practical purposes as a simple rule the tensile zone of the section may be represented by a r/c-tie with an effective height equal to three times the distance from the outmost tensile concrete fibre to the centroid of the reinforcement.

For treatment of cyclic bond action it is possible to use numerical methods (e.g. FE-method or shooting techniques for solving the differential equation of bond under cyclic loading) or to use an analytical method, which implies, that several simplifications have to be made.

For numerical calculations a bond rule has been developed on the basis of the proposal presented in (Ref.5). This rule has been implemented as constitutive relationship for contact elements simulating the bonding interface into a nonlinear finite-element-program (Ref.6). Those elements are used together with 2D-membrane elements for the concrete, truss- or beam-elements for reinforcing steel and contact elements simulating the stress-crack-opening relationship of concrete, as can be seen in Fig. 11 which shows a mesh simulating one of the test specimens. Fig. 12 shows the force-deformation behaviour, expressed as tension stiffening effect for cyclic loading computed with this model. Modeling of more complex structures with this method is possible, but computation time and possible bad conditioning of the stiffness matrix, which may be composed of very different stiffness coefficients due to largely differing contact stiffnesses at various points, limits the application.

So for fast calculations and application to more complex structures an analytical method has been developed, which starts by assuming typical bond stress-distributions over the length according to a simplified bond law (Fig. 13). At those points, where the bond stresses change, which is a consequence of the fact, that another branch of the bond law begins to govern, and at the crack face equilibrium and compatibility conditions are formulated, whereas for the other points along the bar equilibrium and compatibility is satisfied approximately (see Fig. 14). Fig. 15 shows the variation of the damping ratio in secondary cycles with the value of the frictional bond resistance τ_F and compares it to the experimental results. τ_F - values between 0.2 MPa and 0.3 MPa provide for good agreement between theoretical and experimental results.

With this method the behaviour of a R/C-cantilever column under earthquake loading conditions has been simulated and compared with test results (Ref.3). Fig. 16 shows the computed damping ratio for a secondary cycle calculated for different values of τ_F. Agreement with the tests can be found also for similar values of τ_F. The mesh used to model the test column has been composed of 6 beam elements with three nodes and ten concrete fibres each and furthermore two steel fibres, which used the analytical method discussed above, formulated as tension stiffening model.

CONCLUSIONS

Energy dissipation due to hysteretic bond action plays an important role in respect to damping of R/C-structures under dynamic loading, especially when serviceability has to be maintained during or after the extreme loading. The experiments have shown the large influence of actual loading and loading history on stiffness and damping behaviour. All parameters influencing the crack spacing will influence the damping ratio also. For modeling purposes analytical and numerical procedures have been discussed.

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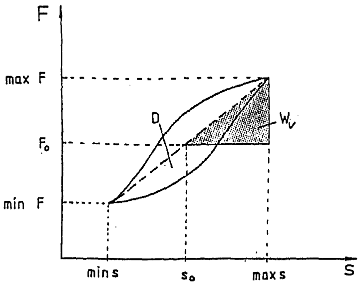


$$\boxed{\bar{\xi} := \frac{D}{W_P}}$$

Fig. 1

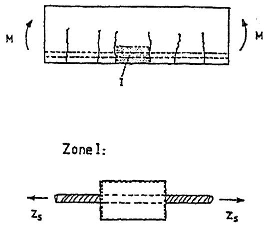
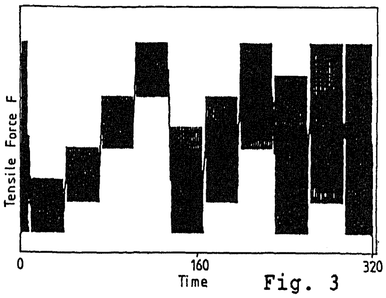


Fig. 2



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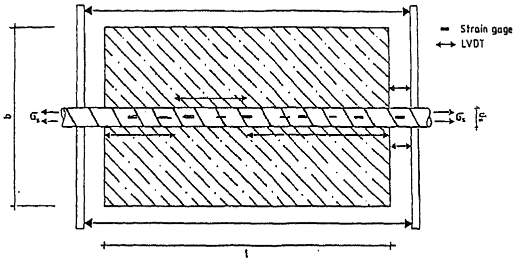
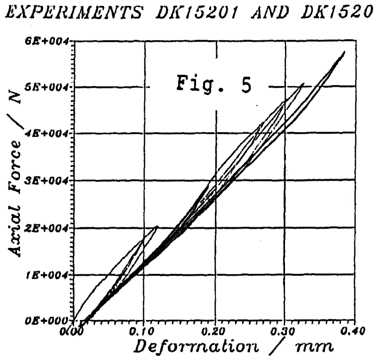
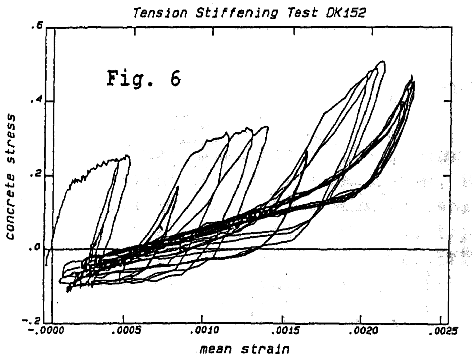
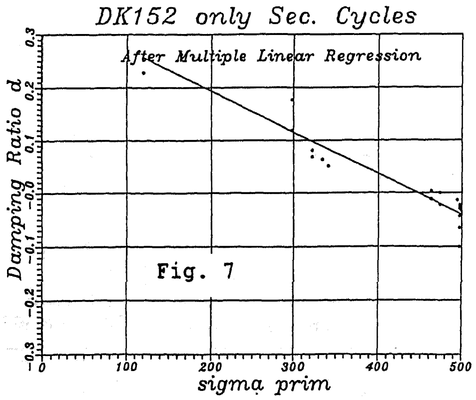
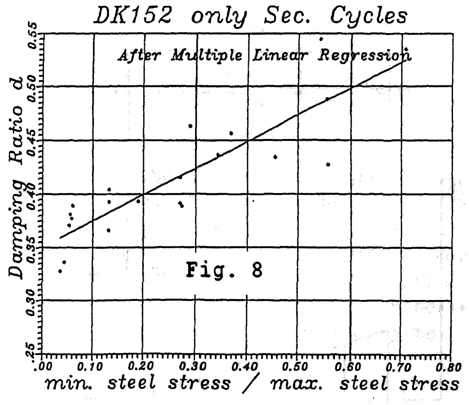


Fig. 4









EXPERIMENTAL RESULTS SUMMARY

Parameter	Damping
- High $\frac{\min \sigma_s}{\max \sigma_s}$ - Large Crack Spacing - Primary Cycles	↑
- Secondary Cycles - High Reinforcement Ratio - High previous load	↓

Fig. 9

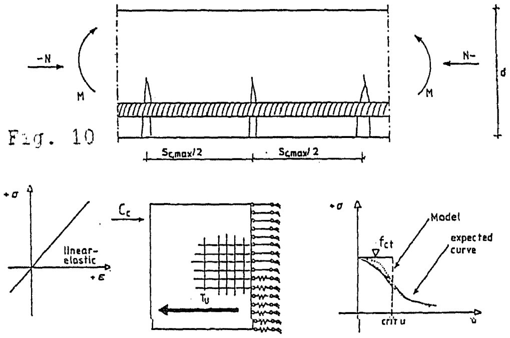


Fig. 10

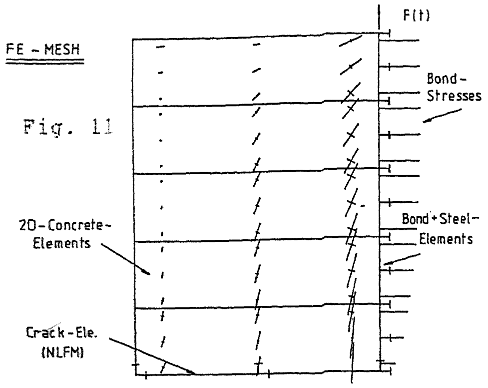


Fig. 11

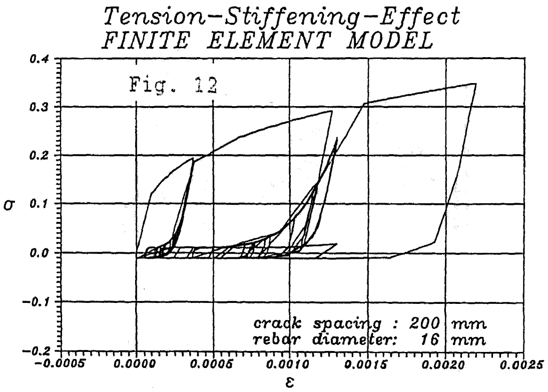


Fig. 12

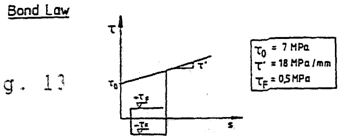
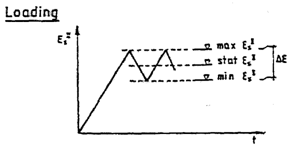


Fig. 13



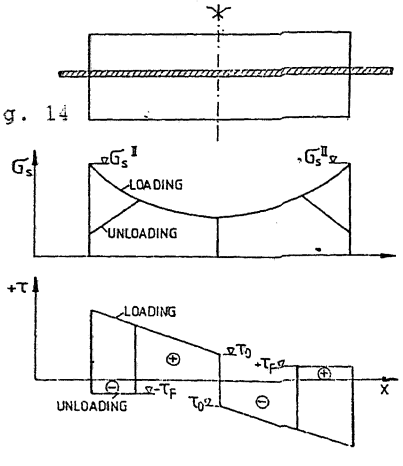


Fig. 14

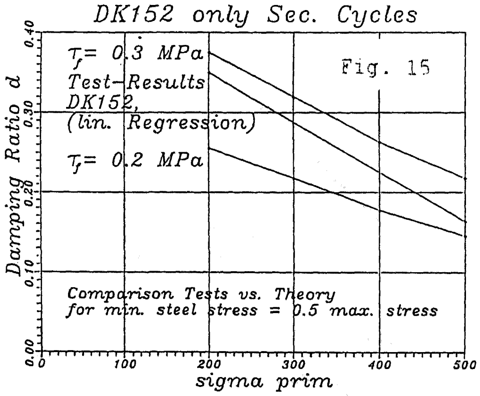


Fig. 15

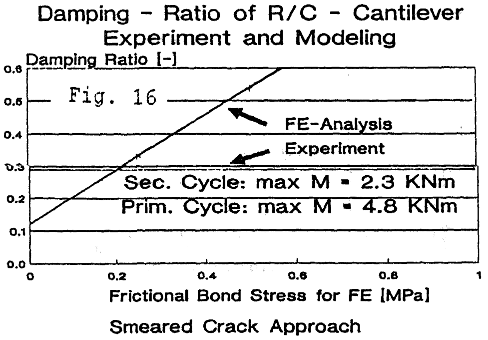


Fig. 16