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Excitation Damping of Reinforced Concrete under Cyclic

Capacité d'amortisement du béton armé sous des charges cycliques

Zur Dämpfung von Stahlbeton unter zyklischer Belastung infolge Verbundhysterese

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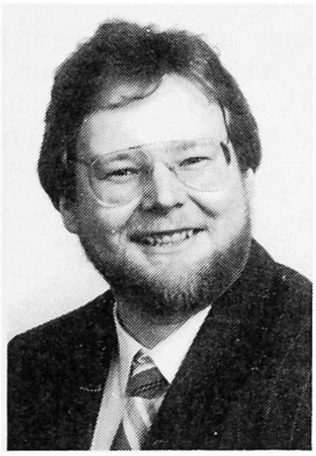

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SUMMARY
The damping behaviour of reinforced concrete significantly influences the deformations of reinforced concrete structures under dynamic loading. The energy dissipation mechanisms due to cyclic bond action are studied experimentally and analytically. Results of theoretical models are compared with experimental data.

RÉSUMÉ
La capacité d'amortisement du béton armé influence de façon considérable les déformations des structures en béton armé sous l'effet de charges dynamiques. Les mécanismes de l'énergie de dissipation résultant de l'action d'adhérence cyclique sont étudiés de façoin expérimentale et analytique. Les résultats des modèles théoriques sont comparés avec les mesures faites.

ZUSAMMENFASSUNG
Die Dämpfungsfähigkeit des Stahlbetons kann die Verformungen von Stahlbetontragwerken unter dynamischer Belastung stark beeinflussen. Die Energiedissipation infolge Verbundhysterese liefert im gerissenen Zustand einen wichtigen Beitrag zur Dämpfung. Hier sollen die Ergebnisse diesbezüglicher experimenteller und analytischer Untersuchungen vorgestellt werden.

1. INTRODUCTION

The dynamic response of structures is influenced to a large extent by the damping behaviour of its structural elements. Especially in the cases of forced steady state-vibration and earthquake action a realistic estimate of damping, which should be regarded as a consequence of energy dissipation, is necessary in order to predict the peak response correctly.

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. This mechanism is one of the main important sources for damping of R/C under service load conditions, where the reinforcing steel remains still elastic.

2. DAMPING AS A CONSEQUENCE OF ENERGY DISSIPATION

A Definition of Damping may be given by the damping ratio d:

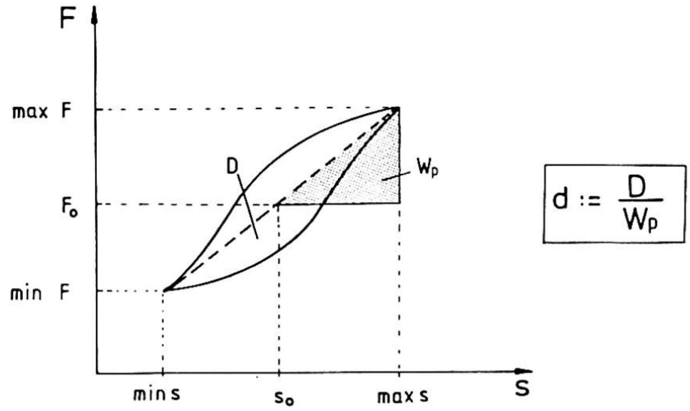
$$d = D / W_p$$

where D denotes the Energy dissipated during one cycle and W_p means the Deformation-Energy (see Fig.1 and [1,2]). It is useful to define the deformational energy using the secant modulus and the Force

$$F_0 = (F_{max} + F_{min})/2,$$

which corresponds to the static equilibrium state as shown in Fig. 1. This definition allows to sum up or integrate D and W_p over different structural parts or volumina and interfaces. So the influence of each possible dissipative mechanism may be considered.

Fig. 1:
Definition
of Damping Ratio d



3. DISSIPATIVE MECHANISMS IN REINFORCED CONCRETE STRUCTURES

Energy Dissipation in R/C members is mainly caused by the following mechanisms:

- hysteresis of stress-strain-relationship of concrete,
- hysteresis of stress-strain-relationship of reinforcing steel,
- tensile fracture of concrete,
- hysteretic action of aggregate interlock in cracks,
- friction between aggregates and/or hardened cement paste in cracks, which open and close during load cycles,
- hysteresis of bond between reinforcing steel and concrete.

4. EXPERIMENTAL PARAMETRIC STUDY

In order to study the influence of hysteretic bond action upon energy dissipation in R/C-members an experimental program was set up. It was intended to let the experiments reveal the contribution of bond hysteresis to damping only and separate or exclude other dissipation mechanisms. So contrary to tests with beams or cantilever elements reported by [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),
- preloading (i.e. maximum steel stress reached before and number of cycles),
- actual loading (i.e. max. and min. steel stress during actual cycle),
- excitation frequency.

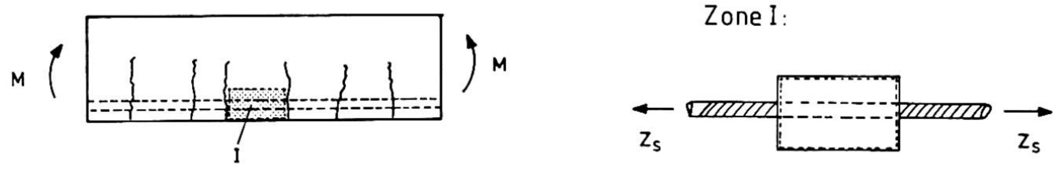


Fig. 2: Choice of specimen

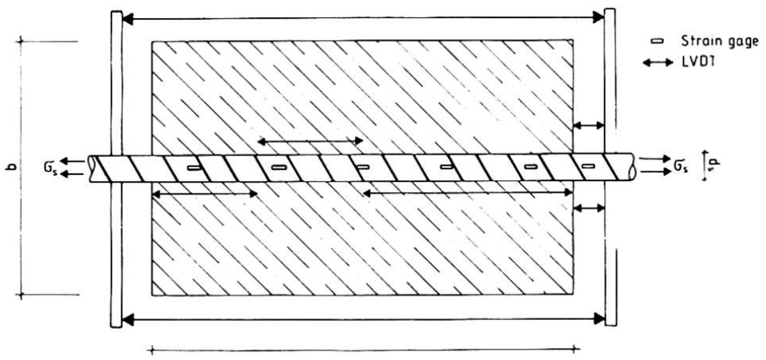


Fig. 3: Instrumentation of specimen

5. EVALUATION OF TEST DATA

On the basis of the measured longitudinal steel strain at the locations of the gages and the deformations measured by the LVDTs (see Fig.3) the
- local steel stresses $\sigma_s(x)$,
- the local bond stresses $\tau_s(x)$ and
- the local slip $s(x)$

can be calculated.

6. PRELIMINARY RESULTS

Whereas in the first cycles a large increase of deformation occurs, the deformation tends to stabilize after a higher number of cycles. Fig. 4 shows an example of the bond stress-slip relation. Whereas for small bond stresses a friction-like-behaviour applies, for larger bond stresses a combination of elastic and plastic effects has to be considered.

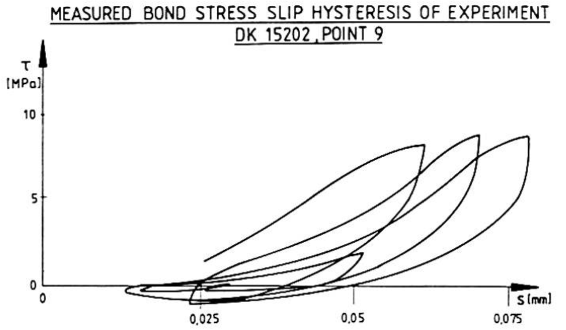


Fig. 4: Example of bond-stress-slip relation

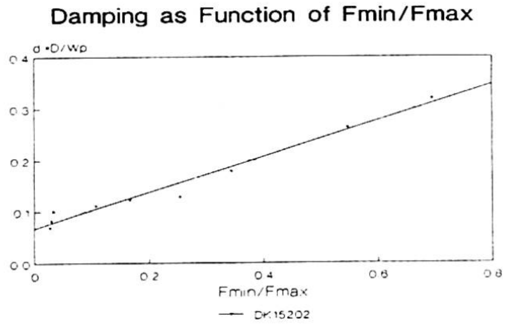


Fig. 5: Damping ratio d as function of F_{min}/F_{max} for max σ_s = 200 MPa

Fig. 5 shows the damping ratio d as a function of the ratio of minimum to maximum Force. For a large ratio F_{min}/F_{max}, this means, that for small oscillation amplitudes compared to the average Force F_0 the damping ratio d is higher than for small values of F_{min}/F_{max}. The damping ratio increases with crack spacing. This is a consequence of the large percentage of deformational energy of bond compared to the deformational energy in the steel. Vice versa this means that e.g. for high reinforcement percentages low damping values can be expected.

7. MODELING

In order to model the damping and stiffness behaviour of cracked R/C subjected to cyclic (tensile) load two steps are necessary:
- calculate the crack spacing,
- simulate bond action under cyclic loading for given crack pattern.

For the calculation of crack spacings the basic principles are reported in [5]. In order to simulate the bond action under cyclic loading the relation between bond stress and slip is needed as constitutive relation. Because of the fact that the bond law is influenced by many parameters which are not easy to estimate (e.g. self induced stress, dependancy from local discontinuities) simple bond models should be used.

For fully numerical calculations the model described in [6] may be used in the modified formulation [7] (Fig.6). It has been implemented into a nonlinear Finite-Element-Program as constitutive relation for contact elements [7] enabling a discrete crack approach.

MODELING OF BOND-STRESS-SLIP-RELATION

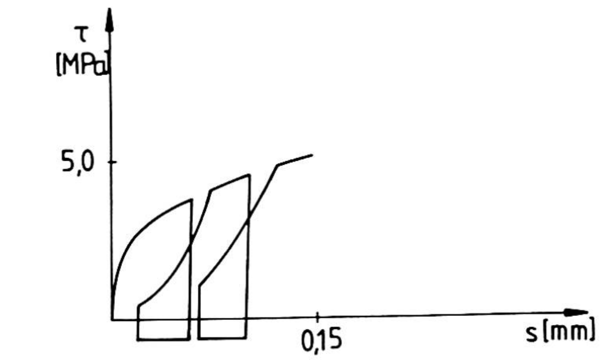


Fig. 6: Modified Bond Model after [6,7]

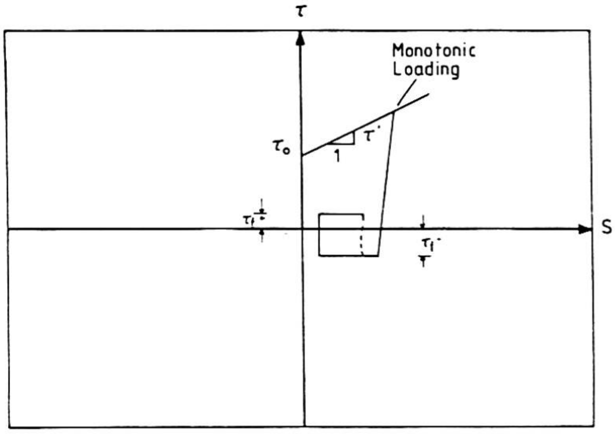


Fig. 7: Simplified Bond Law

For analytical treatment a simplified bond model can be adopted (Fig. 7). This enables a direct calculation of $\tau_s(x)$ and $\sigma_s(x)$, as Fig. 8 illustrates. Also the mean strain ε_{sm}, the crack width w and the deformational energy as well as the dissipated energy can be calculated directly. Fig. 10 gives the damping ratio calculated on the basis of a bond law as shown in Fig. 7. Also the tension stiffening effect for cyclic loading can be computed on this basis. Fig. 9 shows calculated deformations for axial tension.

By this method the energy dissipation due to bond can be calculated for R/C-members rather fast. Furthermore the proposed method is well suited to be used as subroutine in nonlinear Finite Element codes in order to model the hysteretic behaviour of reinforcement embedded in concrete by a smeared crack approach.

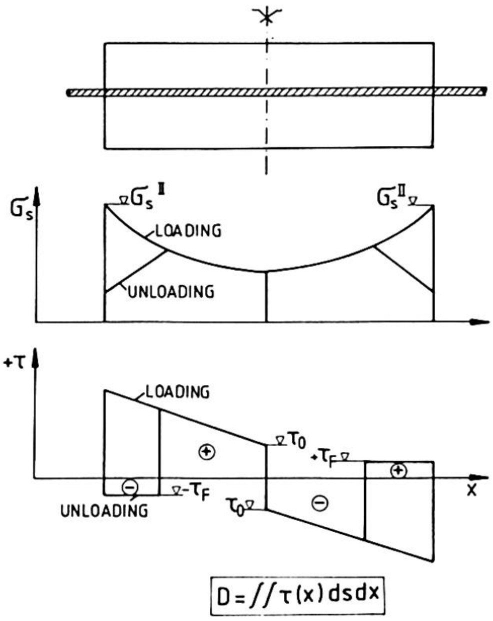


Fig. 8: Direct Calculation of $\sigma_s(x)$ and $\tau_s(x)$ for repeated loading

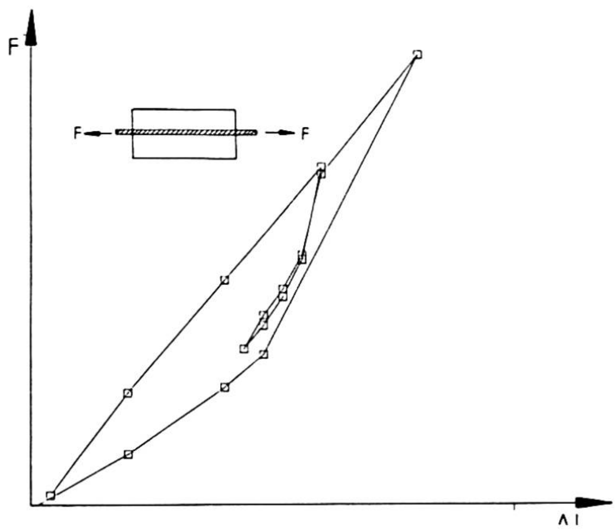
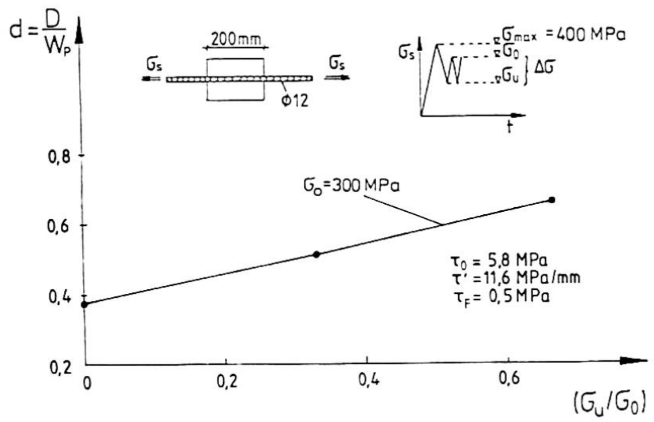


Fig. 9: Computed Force - Elongation - Relationship

Fig. 10: Computed Damping Ratio



8. CONCLUSIONS

Energy dissipation due to hysteretic bond action plays an important role in respect to damping of R/C - structures under service load conditions. The experiments have shown the large influence of actual and previous loading on stiffness and damping behaviour. All parameters influencing the crack spacings will influence the damping ratio also. For modeling a numerical and an analytical procedure are discussed. Whereas both of them can be used with Finite Element Codes, the analytical approach also enables quick estimates of damping values with only few computational effort.

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