# The Design of Impact Endangered Concrete Structures

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Abstract

For the design of reinforced concrete structures such as plates and shells against impact not many reliable procedures [2], [3], [4] are available. Therefore a FE-code with special material models for concrete and reinforcement is presented. With the knowledge gained from computational examinations and own experiments a simple design model has been developed. Good conformation between the results from both mechanical models and experiments can be stated.

## 1. The Problem

If one distinguishes between hard and soft impact, the latter being characterized by the definition that the whole kinetic energy of the missile deforms the striking body, while the struck body remains undeformed, air plane crashs on thick reinforced concrete slabs may be treated as soft impact.

Until now for the design of plates and shells against such an impact as e.g. in nuclear power plants mostly empirically gained methods are used. As the first mentioned author from his practical experience as a check engineer knows, these rules are very sensitive with regard to the necessary amount of stirrups at the impact zone, do not rationally include the influence of support conditions and estimate the effectiveness of the bending reinforcement for punching quite differently. The same poor knowledge has to be stated for the evaluation of the crack width, which may be important to judge the possibility of Kerosin entry.

Therefore efforts were made also by the authors to develope a simple design model [1] covering especially the already mentioned aspects of

- demand of stirrups respectively bending reinforcement
- influence of support conditions
- deformation and crack width.

The model, in spite of being simple, should be based on the relevant physical facts and should be controlled by a more detailed computer analysis as well as by experiments.

In the following a short report will be given on the results gained in the meantime at our institute. Hereby special emphasis is laid on the punching problem although the bending problem is included.

## 2. Numerical Investigation

As already mentioned we developed a finite element code for a nonlinear dynamic analysis, where with regard to a comparison with our own experiments we made every effort to describe the material behaviour realistically [8].

### 2.1 Computational Models

In most practical cases it is sufficient to use an axisymmetric model for the examination of the local impact response [3]. This has the advantage of reducing a three-dimensional problem to a plane one and therefore computational effort can be saved. However three-dimensional stress and strain states are to be considered.

We carry out a finite element analysis as follows:

- incremental solution strategy with BFGS-equilibrium iterations
- Newmark time integration scheme
- discretisation of a circular plate in a radial cross-section with 4-, 5- or 6-node isoparametric axisymmetric elements describing the concrete as well as the reinforcement (Fig. 1 and 4).

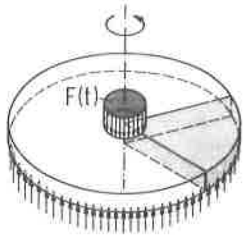



Fig. 1 Circular Plate under Impact Load

### 2.2 Constitutive Assumptions

The stress-strain formulation of a concrete element according to the constitutive model for short time loading of OTTOSEN [5] served as a starting basis. It was augmented by the failure criterion of the same author [6]. The model is valid for all stress states. Characteristics as dilatation under compressive stresses close to failure and softening behaviour in the postfailure region are included (Fig. 2).

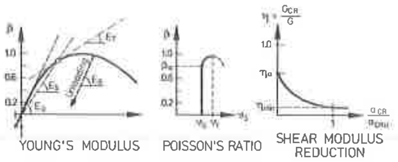



Fig. 2 Constitutive Assumptions for Concrete

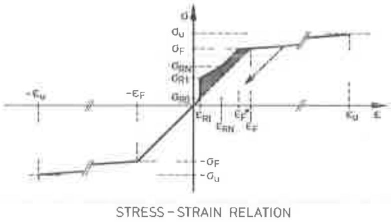



Fig. 3 Constitutive Assumptions for Reinforcement Including an Alternative to "Tension Stiffening"

Cracks in a concrete element are considered as smeared cracks. Tensile stresses perpendicular to a crack cannot occur, whereas shear stresses can be transmitted depending on the crack width.

The main effects of high strain rates - increasing of tensile and compressive strength, decreasing of nonlinearity of stress-strain curve [7] - additionally was included. The failure envelope is "blown up" with a factor depending on the effective strain rate. This means that the material strength increases and the "nonlinearity index" of the Ottosen formulation decreases.

For the reinforcement an elastic-plastic behaviour is assumed (Fig. 3). As an alternative to the so called "tension stiffening" which can not be used for the problem under consideration the concrete locally surrounding the reinforcement and stiffening it was taken into account.

### 2.3 Results

The finite element analysis enables us to trace the time history of deformations, stresses, strains and crack states of an impacted concrete structure. As an illustrative example an analysis of the test II/4 of the Meppen test series [9] is performed.

The discretisation of the axisymmetric model is shown in Fig. 4. The load is brought up uniformly on a fictitious load-distribution-plate which is modeled with linear-elastic matérial just above the impact zone. Contact elements which only transfer compressive forces connect this plate with the concrete structure.

Selected results of the analysis are ploted in Fig. 5 and 6. The fat lines in Fig. 6 indicate open cracks with relativ large crack widths. In the struck region of the plate nearly every element is subjected to cracks because tensile stress waves move through the whole structure. During some time steps a zone can be observed where the crack width is

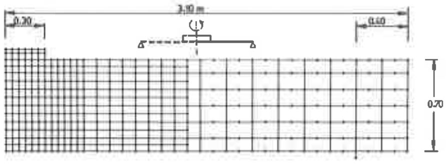


Fig. 4 Discretisation of the Plate from Meppen Test II/4

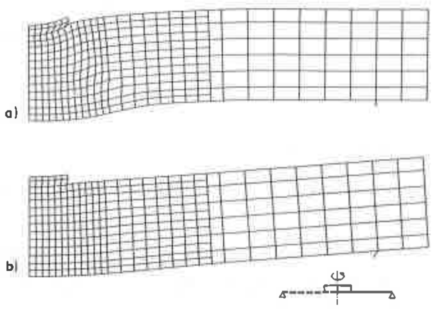



Fig. 5 Deformed Mesh of Meppen Test II/4
a) t = 0.001 s b) t = 0.005 s

considerably larger than in the remaining elements. This zone determinates the shape of a possible punching cone.

If during this time the internal forces in the cracks, namely the shear forces and the stirrup-forces, can not withstand the external forces, a cone will be punched out. Bending reinforcement is first activated at a later time.

During the analysis of different problems the following phenomenia were statet:

- Stirrups are activated soon after contact. They increase the resistance to punching considerably.
- Bending reinforcement has no significant influence to the punching problem, because it is activated only after large deformations of the punching cone.
- The stiffness of the striking body resp. the distribution of the load at the impact area determinates the fracture mechanism of punching - contact problem.
- Loading close to the supports requires a larger amount of stirrups, because the kinetic energy of the missile must nearly exclusivly be absorbed by the stirrups.

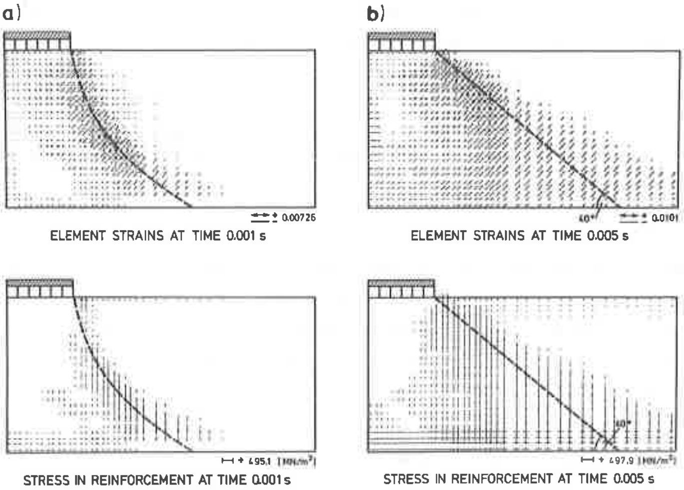



Fig. 6 Strains in Concrete Elements and Stresses
in Reinforcement of Meppen Test II/4
a) t = 0.001 s     b) t = 0.005 s

3. <u>A Design Model</u>

Since the computational analysis as described above requires an enormeous effort a more simple design procedure is desirable. It is the intention of the authors to develope a mechanical model which can easily be handled by engineers. Such a first model, covering the mean physical facts, may be as follows:

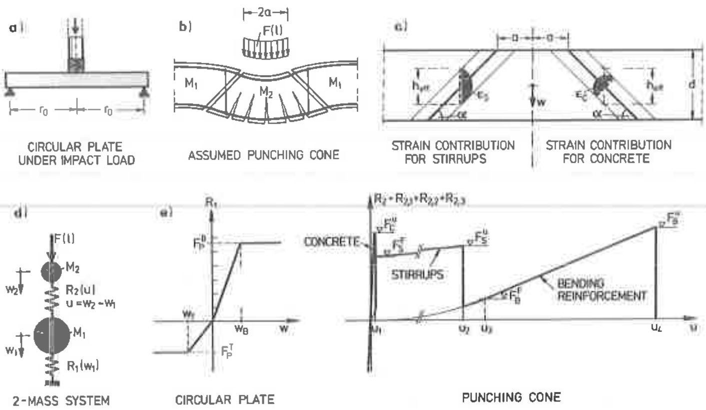



Fig. 7 Simple Design Model

a) Original System
b) Section of the Impacted Zone
c) Details of Punching Cone
d) Simulation Model
e) Spring Characteristics
(Compare Table I)

A nonlinear 2-mass system is used to simulate the behaviour of an impacted plate (Fig. 7). The first mass $M_1$ characterises the circular plate, the second mass $M_2$ an assumed punching cone, specified by the angle $\alpha$ and the radius of the load a. Whereas $M_2$ can directly be determined, the mass $M_1$ is evaluated under the assumption, that the original plate in the cracked state and the 1-mass system ($M_1$ + $M_2$), $F_p^B/w_B$ have the same lowest natural frequency.

The spring $R_1$ describes the bending behaviour of a circular plate by application of the "yield-line theory" including support conditions.The spring $R_2$ is composed by three additional parts: resistance $R_{2,1}$ of the concrete, resistance $R_{2,2}$ of the stirrups and resistance $R_{2,3}$ of the bending reinforcement (Fig. 7e).

## 4. Comparison of Results including Experiments

The capability of the FE-program, resp. the validity of the material model has been checked by comparison with experimental results. Thereby the Meppen test series [9] as well as own test series with nearly 40 plates of 2,50 x 2,50 x 0,40 m under hard impact [10], [11] were considered. The experimental and computational results show satisfactory conformation in deformation behaviour, in the stressing of concrete and reinforcement and in the kind and degree of damage.

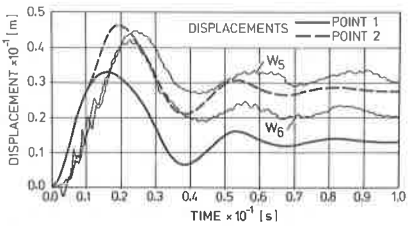
Out of this many comparisons done, on which a special report will be given, Fig. 8 shows two results from Meppen test II/4 and calculated results by using the two-mass design model. As observed in the FE-analysis as well as in the experiment an angle of $\alpha$ = 40° was assumed for the punching cone.

The calculation is carried out using the characteristic values given in Table I and a damping coefficient of 5 % of the critical one.

The dashed line (POINT 2) represents the calculated deformation of the punching cone and must be compared with the measured lines $w_5$, $w_6$. A good conformation can be statet,

Table I Characteristic Values of 2-Mass System for Meppen Test II/4

| | |
|---|---|
| $M_1$ = 0.005454 $MNs^2/m$ | $M_2$ = 0.002905 $MNs^2/m$ |
| $w_T$ = - 0.0172 m | $F_p^t$ = - 5.70 MN |
| $w_B$ = 0.0194 m | $F_p^t$ = 11.23 MN |
| $u_1$ = 0.000023 m | $F_c^u$ = 11.10 MN |
| $u_1$ = 0.000023 m | $F_S^F$ = 9.16 MN |
| $u_2$ = 0.04 m | $F_S^u$ = 11.60 MN |
| $u_3$ = 0.067 m | $F_B^F$ = 1.75 MN |
| $u_4$ = 0.35 m | $F_B^u$ = 13.00 MN |




NONLINEAR 2-MASS SYSTEM

Fig. 8 Time Hisotry of Displacements Meppen Test II/4: Calculates Values (POINT 1 = $M_1$, POINT 2 = $M_2$) - Measured Values $w_5$, $w_6$

taking into account the scattering of $w_5$ and $w_6$, which should be identical. The difference between the displacements of $M_1$ and $M_2$ are a measure for the crack widths. The analysis of many other impact problems with the 2-mass system gives similar good results.

In some experimental tests the targets show no significant damage, whereas in other tests under only little changed conditions a completely failure can be observed. This phenomenia occurs at "underreinforced" plates and can be explained with the tensile strength of the concrete. In one case it withstands the external forces, in the other one it does not and then the reinforcement is overstressed.

## 5. Conclusion

By a computer program thoroughly developed with regard to the constitutive relations the impact resistance of R.C.-plates can be treated in detail and a simple design model my be derived hereof. A cheque by own and reported experiments confirms this statement.

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