IMPACT TESTING OF STEEL FIBRE REINFORCED CONCRETE SLABS WITH LINER

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SUMMARY

In the reactor building of THTR nuclear power plant Schmelhausen, reinforced concrete slabs with liner will be built in. Their two main functions are: leak tightness and protection against internal impacts. Several types of slabs were considered for comparison: Concrete with reinforcing steel bars and steel liners of different thicknesses, a liner on one side as well as on both sides, steel fibre reinforcement instead of steel bars.

The results of the dynamic tests performed by a drop hammer facility were that steel fibre reinforced concrete is an excellent material for impact resistant structures because the steel fibres effect
- more ductility, i.e. more energy absorption capacity
- that the maximum and residual deformations are diminished (this was necessary, in this case, for functional reasons)
- that the local penetration and spalling damages are considerably restricted etc.

One liner only on the scabbing side (opposite to the load application side) turned out to be sufficient for the requirements of leak tightness.

The advantages of steel fibre reinforcement are verified by measurements, high speed movie records and photos.
1. Introduction

For the reactor building of THTR Nuclear Power Plant Schmelhausen in Germany, reinforced concrete slabs with steel liner are planned as structural components. Because of special functional requirements under exceptional internal accident conditions - e.g. impact of fragments, pipe rupture, pipe whip effects etc. - steel fibre reinforced concrete was taken into consideration as an alternative to improve the dynamic behaviour of the slabs.

The requirements are: a sufficient structural resistance against impacts and other extreme internal dynamic loads as well as a sufficient leak tightness - that is why the liner, which must stay uncracked, is used. Furthermore a limitation of the deformations because of functional reasons was necessary for these slabs.

At first, a rough dynamic analysis was done, which led to a highly conservative design of the slabs. Because of lack of knowledge, it was very difficult to reduce or to quantify conservatism by analytical means, as in engineering practice an analysis must be on the safe side, the more if uncertainties in the assumptions remain and a fairly realistic approach is not possible. From experimental experiences with similar cases /1/ could be guessed that a realistic design would be much more economical than estimated analytically. A reasonable solution seemed to be attainable. In order to prove this, it was decided to perform tests at full size scale. This decision was favoured by the fact that an impact test device working by a falling weight (fig. 1) already existed /1, 2/.

2. Prediction of the test results

It was necessary to estimate approximately the magnitude of what the tests would bring forth. The dynamic problem to be solved is to find an economic slab type resisting to an impact energy of some 150 kNm (here simulated by a 1.3 tons mass, as a rigid body without any contribution to deformation or dissipation energy, falling from some 10 m height). Further conditions were that the liner has to remain leak tight, i.e. uncracked, and that the maximum slab deformations are limited to some 20 cm.

For economic reasons, this limit was intended to be reached as close as possible.

The service loads for these slabs are of subordinate magnitude. Therefore the design is defined by the extreme exceptional impact load conditions.

A simple method was used for a rough estimation of the necessary design. This method, the results of which were verified on the whole by the tests, in principle is based on the impulse and energy conservation laws and briefly is described as follows:

\[ v_1 = \sqrt{2gh} \]

\( m_1 = 1.3 \text{ tons; } h = 10 \text{ m} \)

dynamically effective mass fraction of the impacted slab:

\[ m_2 \]

velocity of masses \( m_1 + m_2 \) after ideally plastic impact:

\[ v_2 = \frac{m_1 \cdot v_1}{m_1 + m_2} \]

energy after plastic impact:

\[ E = \frac{1}{2} (m_1 + m_2) \cdot v_2^2 \]
(Energy difference $\Delta E = m_1 \cdot g \cdot h - E$ is absorbed by penetration and other local material destruction effects.)

energy balance: 

$$\frac{1}{2} (m_1 \times v_2) \cdot v_2^2 = E_1 + E_2$$

where $E_1 = \int \int \int \int dS dV$, elastic and plastic deformation energy due to bending, shear and membrane effects ($G =$ stress, $\varepsilon =$ strain, $V =$ volume), for maximum deformation state (fig. 2)

$E_2 =$ internal friction energy (dissipation)

These energies must be supplied by the slab for a sufficient design. Of course, this is a rough estimation method, especially because impulse and energy conservation laws are applied successively, although both phenomena described by these laws overlap in reality. Nevertheless reasonable results were obtained.

This rough estimation yields a necessary structural resistance resulting in concrete thickness of 20 cm, a reinforcement of some 20 cm$^2$/m BST 420/500X (each direction, both sides together), and in a steel liner thickness of 5 mm (fig. 3) where the restriction of deformability due to geometric boundary conditions (deformation limit: some 20 cm) is taken into account. Alternatively, steel fibres (6% of weight) instead of reinforcing bars were to be tested. It was assumed that steel fibres would improve the behaviour of the slabs, under the given circumstances.

A few small studs only are used in order to keep the concrete structure and the steel liner close-lying under normal service conditions. A shear interaction under extreme impact load conditions is not intended nor necessary. Thus, the energy absorbing contribution of the membrane effects is emphasized (figs. 4, 7), and the bending and shear effects are suppressed. This design solution is more economic /1/.

3. Description of test specimens

For the tests, slab design, cross section, distance of supports, supporting columns etc. are in original conformity with the slab types proposed for being carried out. However, the reality of a continuous slab on multiple supports could not be realized in the original way. A rectangular slab section on four supports is chosen for the tests. The continuous effect is simulated by a cantilever slab border beyond the supports. Thus, the dynamic behaviour of the test specimens due to impacts, centric or eccentric, within the supports is the one of an infinite continuous slab on multiple supports. This was verified by the test results, which showed that the impact load influence is closely localized and that the cantilever slab border, because of its mass inertia and its two-dimensional stiffness, is not recognizably affected (fig. 5).

Different types of specimens were used.

4. Instrumentation

The time histories of the vertical response forces at the supports were measured by dynamometers. These reaction results (example see fig. 6) can be used for controlling the overall behaviour, e.g. symmetry conditions, and for explaining differences in measured and analytically predicted results and thus can contribute to improve the analytical
methods and their basic assumptions.

Moreover, high speed film records (some 300 exposures per second) were taken, in order to study the motions, deformations, velocities, and accelerations in detail. These films were evaluated. They provided lots of useful informations to explain the test phenomena and to improve analytical verifications.

5. Results

The film records, dynamometer records, registrations of residual deformations and damages, as well as registrations of the internal structural constitution after rests gave interesting results.

The main knowledge derived from the test evaluations are:
- all test specimens resisted to the impact load, the ultimate dynamic structural resistance was not reached
- structural damages due to extreme impact loads are closely localized
- the degree of local damage (e.g. concrete surface damage, fig. 9) is considerably reduced, if steel fibre reinforced concrete is used
- the membrane effects are predominant compared with bending and shear effects, and the liner contributes highly to the resistance even without shear connection between liner and concrete structure
- the maximum deformation is less than the admissible deformation of some 20 cm
- the liner remains uncracked, i.e. leak tight according to the given definition
- scabbing effects do not occur, even a dust protection is given
- steel fibres instead of reinforcing bars in the concrete turned out to be an excellent reinforcement for the special requirements of this sandwich structure; the steel fibres guarantee a sufficient energy absorption capacity, not only due to their contribution to the structural resistance, but also due to an increased energy dissipation capacity.

6. Conclusions

The test described above verified, by experimental means instead of analytical means, that the planned structural NPP components designed for extreme internal impact loads fully meet the requirements. Moreover, a certain conservatism of the design is included.

By analytical methods, a more conservative design would have been obtained due to lack of knowledge concerning the dynamic material behaviour, which obviously is more positive than generally assumed. Further experimental research is necessary to reduce conservativeness and to increase the reliability of progressive impact response analysis methods.

7. References

/1/ F. STANGENBERG, W. ZERMA: Extreme Load Resistant Design of Nuclear Power Plant Structures, paper J 8/5 of 4th SMIRF-Conference, San Francisco USA, August 1977

/2/ S. STANGENBERG: Dynamic Analysis in Nuclear Structural Engineering, paper 33 of the Conference on Structural Analysis, Design and Construction in Nuclear Power Plants, Porto Alegre, Brazil, April 1978
Fig. 1  Impact test conditions

Fig. 2  Resistance function
**Fig. 3** Nets of reinforcing steel bars (slab type with additional bars)

**Fig. 4** Principle of membrane effects
Fig. 5  Residual deformation shape after impact test

Fig. 6  Measured time history of response supporting force
Fig. 7  Photograph of residual deformation shape

Fig. 8  Photograph of impact crater on the upper concrete surface