Selected Results of Meppen Slab Tests — State of Interpretation, Comparison with Computational Investigations

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Abstract

In the scope of the experimental program performed at Meppen test site, reinforced concrete slabs are investigated, extremely stressed under the impact of highly deformable projectiles.

A main objective of these tests consists in an approvement of theoretically founded methods, which are applied to the treatment of aircraft impact load.

Comparative computational investigations are carried out for the analysis of experimental results, using a dynamic, physically nonlinear method.

Most of the parameter variations examined at Meppen concern with the design of structural parts, with regard to the relations between bending and shear bearing capacity.

By varying the bending and the shear reinforcement, the portions between bending and transverse shear deformations are distinctly influenced, and thus the amount of the total displacements, too. This corresponds with different degrees of damage and crack formation in the experiments. An accentuation of bending was only obtained for a relatively low bending reinforcement, combined with a relatively high amount of effectively working stirrups.

Including the investigation of ultimate limit state of slabs within the analysis, the results generally show a high sensibility with respect to the load conditions. These are strongly influenced by the impact velocity as well as by the deformation behaviour of the projectiles.

In the experiments, the structural behaviour of the test slabs demonstrates a much greater sensitivity to altering thicknesses than to variations of the equivalent amount of reinforcement.

1. Introduction

The impact experiments on reinforced concrete structures, performed at Meppen test site, are integrated in an extensive program on the safety of nuclear plants; the tests relate to investigations of aircraft impact load.

A main objective of Meppen tests consists in an approvement of theoretically founded computational methods, which are applied in practice to the treatment of aircraft impact mentioned above. Comparisons are made between the experimental results and the results of appropriate analyses.

According to the design level "full protection" considered in Germany, the stress level of test slabs extends to the limit state of the bearing capacity, when scabbing from the rear face of structural parts just begins (scabbing limit state).

The tubular projectiles used in Meppen show a high deformability. In comparison with this crushing projectiles, the deformations altogether arising at the structural parts are very small. Only a small "penetration" is caused at the concrete members by destroying the front cover of reinforcement. This also turns out for such extremely stressed slabs, when scabbing limit is even slightly exceeded. Hence, the conditions of soft missile impact are satisfied by Meppen tests.

The parameter range realized in Meppen distinctly differs from that one of many other test series (among others experiments e.g. in a smaller scale, using hard missiles, investigating perforation limit state).

2. Tests performed

In the scope of the research program, sponsored by the German Federal Ministry of Research and Technology (BMFT), two test series took place at Meppen.

Series I: Impact of highly deformable projectiles against rigid targets, for an investigation of the generated load time curves; this series enclosing 9 tests was mainly accomplished by HOCHTIEF (JONAS/et al., /1/).

Series II: The same projectiles impinging reinforced concrete slabs. The following statements of this contribution only relate on this second test series, consisting of two test groups with altogether 21 tests. The first group of 10 experiments had been carried out till 1979; the remaining 11 tests have been completed until the end of 1982.

16 of 21 test slabs had a thickness of 70 cm (table I). Only in one test the structure of the generally used projectile (type 11) was changed. The actually realized impact velocities lie between about 220 and 250 m/s. Most of the parameter variations examined at Meppen concern with the structural design of test slabs, with regard to the relations between bending and shear bearing capacity.

3. Theoretical basis of the computational method

For the selection of test parameters and, as already mentioned, especially for the analysis of experimental results, extensive comparative computational investigations are carried out (e.g. NACHTSHEIM/STANGENBERG, /2/).

Herein, we use a dynamic, physically nonlinear theory for plane structures. Stresses are summarized to resultants across the structural thickness. The system of dynamic equations is solved by direct numerical time integration, using finite time as well as spatial differences (STANGENBERG, /3/).

Applying realistic stress-strain curves for the components of reinforced concrete, a nonlinear correlation follows in the fundamental constitutive relations between stress resultants and distortions. Fig. 1 shows appropriate curves from the analyses presented in the following. The determination of the trilinear shear force relation is based on the treatment of DILGER (/4/).

This integral procedure significantly reduces the computational effort and enables an effective study of parameter dependencies. On the other hand, the slab bearing behaviour can be described sufficiently exact, as long as local effects in the immediate impact region play minor parts, applicable to soft missile impact below the limit state of bearing capacity.

In our calculations carried out up to now, the bearing system of test slabs has been approximated by a rotationally symmetrical circular slab with an outer cantilever ring beyond the supports (fig. 2); post-calculations for tests II/1-12 are presented in /5/, /6/, e.g. (NACHTSHEIM/et al.).

The impact load-time curves, from which the calculations have to start, are based on investigations performed by HOCHTIEF. Herein the respective impact velocities and the actual deformations of projectiles arising in the experiments are taken into account.

4. Comparison of results

4.1 Reinforcement relations

Within Meppen tests an extensive variation of the ratio between bending and shear reinforcement has been performed, for a constant slab thickness of 70 cm and an unchanged structure of projectile (type 11). In the first section of tests, the shear reinforcement has been enlarged (tests II/5-7-8-4), starting from the very small amount of stirrups of test 5. The bending reinforcement remained unchanged on a sufficient, relatively high level. Thereby, the ratio μ , between the geometrical reinforcement percentages μ_2/μ_τ , diminishes from about 6.0 to about 1.5 (table I).

Afterwards, in the second section of tests, the bending reinforcement has been reduced for sufficiently high, constant shear reinforcement. In this way, the reinforcement ratio μ further decreases to finally about 0.9 (tests II/4-12-14,16 resp. II/8-11).

A direct comparison of the experimental results of all 8 mentioned tests is less informative with respect to a quantitative analysis, among others because of the different impact velocities of projectiles.

To establish directly comparable values, the computational investigation, presented in the following, was performed in the sense of a parameter study. Herein, only one load function has been taken into account (ref. to curve L1 in fig. 3a), according to an impact velocity of about 240 m/s. All other geometrical and mechanical parameters remain unchanged, too. The yield strength of the bending reinforcement was assumed to 470 MPa, the average from static tensile tests investigating Meppen reinforcing steel.

The contrast of displacement curves (fig. 4b) indicates distinct shear deformations for low amounts of stirrups; the sharp step in the curves corresponds with a concentrated shear distortion and marks the location of a forming punching cone in the calculation. With increasing stirrup reinforcement (μ = 6.0 - 1.5), a distinct decrease of the overall displacements is obtained (figs. 4a and 4b), as expected. On the other hand, the portion of bending deformations grows up (fig. 4c). At the same time a diminuation of the degree of damage is discernible in the experiments, even for an increasing velocity in test 4.

The reduction of bending reinforcement (μ = 1.5 - 0.9) effects again growing global displacements, whilst the portion of bending further increases. The forming crack pattern and the degree of damage, arising in the experiments, are then connected with distinct diagonal bending cracks, extending to the corners of slabs (e.g. tests 14 and 16).

Nevertheless, if the stresses of slabs resp. the strains of bending reinforcement exceed values, to be associated with a particular limit state of slabs, as e.g. scabbing limit in test 14, the degree of damage again strongly increases. Then a greater extent especially of shear resp. punching deformations again occurs in the experiments, in combination with the stiffness of systems investigated in Meppen resp. the relatively small slenderness of slabs. In that zone where punching cracks emerge on the rear face of slabs, the stirrups show the tendency to bend off their rear hook. In Meppen, the extremely stressed structural parts at last fail in punching, possibly combined with local overstress of the bending reinforcement and whilst additional effects appear.

In this connexion, with nearly identical conditions as in test 14, a significant refinement follows in test 16 with regard to the bearing resp. the deformation behaviour. This is caused by closing the stirrups in the tensile zone and clasping the rear reinforcement layers in each direction. The residual deflections decrease to less than a quarter. From all tests in Meppen, a bending behaviour was evidently realized the very best in test 16, with a very high stress level; wide residual, diagonal bending cracks were caused with a width of 1 to 4 mm.

4.2 Load conditions

The load of structural parts, from which an analytical treatment has to start when decoupling the impact problem, depends on the impact velocity as well as on the deformation behaviour, to be associated with the special structure of projectile.

The state of stress realized within Meppen experiments extends to the limit state of bearing capacity. Experimental results, e.g. the degree of damage, then generally show a high sensibility with respect to the impact velocity. For a given set of constant slab parameters, the velocities which relate to the perforation resp. the scabbing limit state lie very close together, according to the present test conditions.

For increasing impact velocities in the tests II/9-4-6 by a factor of 1.09, the deformations enlarge significantly, especially between the tests 4 and 6. In test II/6 a state tending to perforation is already reached.

This tendency is verified by the results of other test institutes. In the scope of UKAEA experiments accompanying test II/11, a difference between perforation and scabbing velocities follows from about 272 to 235 m/s, according to a ratio of about 1.16 (BARR/et al., /7/).

As in experiments referring to the impact velocity, a similar sensibility exists in the computational analyses with respect to the impact load curves to be based upon. Herein, as the following investigations demonstrate (figs. 5 and 6), not only the induced impulse and the general level of load play dominant parts. Furthermore, the shape of load-time curves is of great importance for these extreme impact loads, even when presuming unchanged impact energy and a constant impulse for different projectiles. Structural systems, subjected by such projectiles, react upon higher load peaks by accentuation of punching deformations.

From the relatively similar load histories L2 and L3 (fig. 3a), curve L2 significantly causes the greater displacements with differences up to a factor of 2 (fig. 5a). This verification of experimental results is obtained, although L2 has the lower time integral and thereby the lower induced impulse (and a lower attached impact velocity). The character of the deflection curve also slightly changes (fig. 5b).

Load time diagrams to be associated with Meppen projectiles show a typical history (e.g. curve L4 in fig. 3b for test II/8). For type 11 projectiles, the ratio F3/F1 amounts to about 1.05 - 1.1.

This characteristic shape has been modified in a parameter study, as demonstrated in fig. 3b, through which the time integral remained unchanged. The investigation was carried out for slab parameters of test 8. The influences on the overall slab deformation behaviour are pointed out in fig. 6. The most distinct variations of course follow from load histories L8 and L9. L8 nearly corresponds with projectile 17, used in test II/18. Herein a ratio F3/F1 of about 1.8 was realized.

4.3 Slab thickness

In comparison with those tests investigating 70 cm thick slabs, the greatest effects on the occurring stress state of slabs arose in tests II/10 and 21 (d = 90 cm) resp. 15, 17 and 20 (d = 50 cm).

With respect to the nominal design level, an increase in bearing capacity is to registrate for a thickness of 90 cm; on the contrary a distinct diminuation is discernible for structural parts with a thickness reduced to 50 cm.

Hence, the fundamental parameter for the design and the corresponding system behaviour is the thickness of members; this parameter cannot be substituted by reinforcement to any desired extent.

In this connexion, the realization of a minimal thickness for structural parts is reasonable even for soft missile impact and the associated low penetrability of projectiles, as for Meppen tests and for aircraft impact.

However, for structural parts extremely stressed by an impact, some bearing mechanisms have to be further investigated, perhaps strongly influenced by the thickness. This may concern with such phenomena as e.g. the computational stress propagation across the thickness to the reference face, the activation of stirrups, etc.

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Table I Data of Meppen slab tests

test No	projectile type	projectile mass	projectile impact velocity	slab thickness	actual concrete strength min β_w/min β_c	reinforcement (BSt 420/500) bending (each way) front face a_{s1}	bending (each way) rear face a_{s2}	shear $a_{s\tau}$	μ $\frac{a_{s2}}{a_{s\tau} \cdot d}$
		kg	m/s	cm	N/mm^2	cm^2/m	cm^2/m	cm^2/m^2	
II/1	11	1014	247.6	70	~18	50.2	88.5	24,6	5,14
2	"	1016	172,2	"	~30	27,3	53.6	"	3,11
4	"	1016	247.7	"	35,0 / 35,1	"	"	50,2	1,53
5	"	974	234.9	"	32,8 / 35,5	"	"	12,6	6,08
6	"	956	257.6	"	29,4 / 31,8	"	"	50.2	1,53
7	"	940	225.3	"	26,5 / 30,8	"	"	24.6	3,11
8	"	990	235.9	"	31,0 / 36,7	"	"	37.6	2,04
9	"	970	235.8	"	29,9 / 33,4	28.5	56.0	50,2	1,59
10	"	965	245.6	90	28,9 / 37,7	27.3	53.6	12,6	4,73
11	"	1000	222.5	70	30,2 / 31,2	20.4	40.1	37.6	1,52
12	"	980	241.5	"	31,5 / 37,9	"	"	52.3	1,10
13	"	996	244,8	"	31,5 / 32,8	8,0 (high-tensile steel BSt 1100)	15,5	50,2	0,44
14	"	960	247,8	"	30,0 / 30,6	15,4	31,4	50,2	0,89
15	"	1000	236,3	50	31,5 / 34,4	23,1	56,0	64,9	1,73
16	"	970	247,1	70	34,4 / 27,9	15,4	31,4	50,2	0,89
17	"	954	178,4	50	37,5 / 31,8	23,1	56,0	64,9	1,73
18	17	1060	237,5	70	31,1 / 30,5	20,4	40,1	52,3	1,10
19	11		240,3	70		20,4	40,1	52,3	1,10
20	"		197,7	50		23,1	56,6	83,2	1,36
21	"		237,0	90		10,3	25,2	25,4	1,10

slab
outer dimensions 6,50 x 6,00 m
effective span 5,40 x 5,40 m

min β_w: minimum value from compressive test, according to 200 mm cubes, storage of cubes beside test slab during hardening

min β_c: minimum value from compressive test with drilled cores, cylinder D = 100 mm, L = 100 mm

projectile mild steel 37
outer diameter 600 mm

	type 11	type 17
total length	5990	6650 mm
front part thickness/length	7/2500	5/3600 mm
rear part thickness/length	10/3300	13/2860 mm

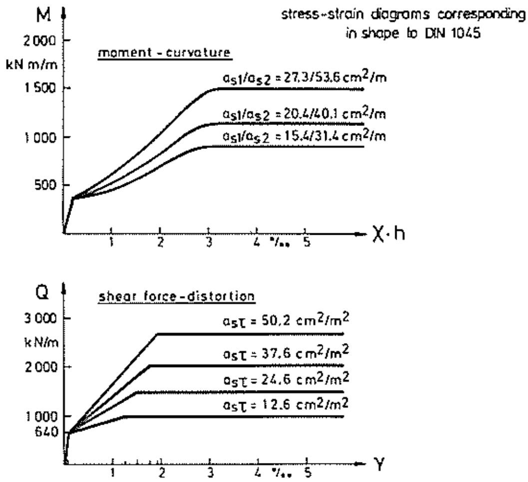


Fig. 1 Relations between forces and distortions

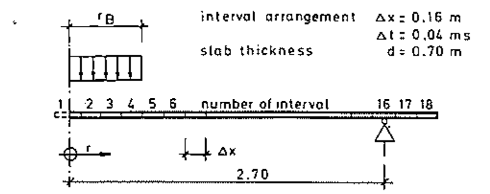
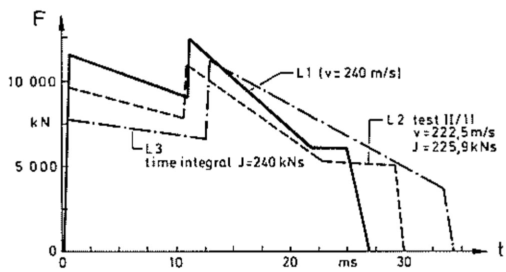
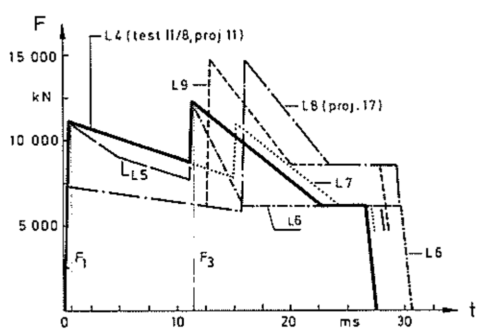


Fig. 2 Slab system for analyses

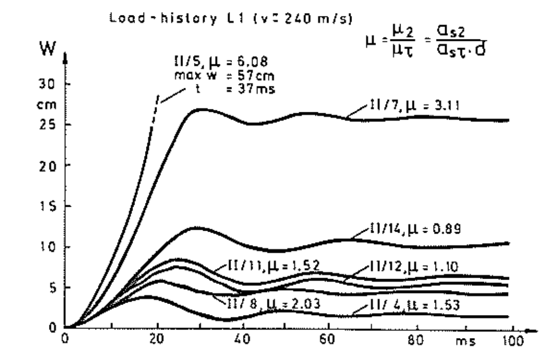


a) Variation of reinforcement ratio

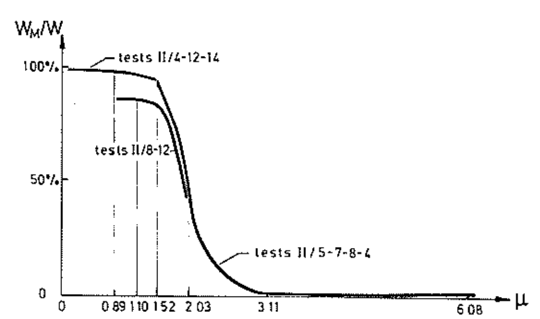


b) Variation of load history

Fig. 3 Load time curves

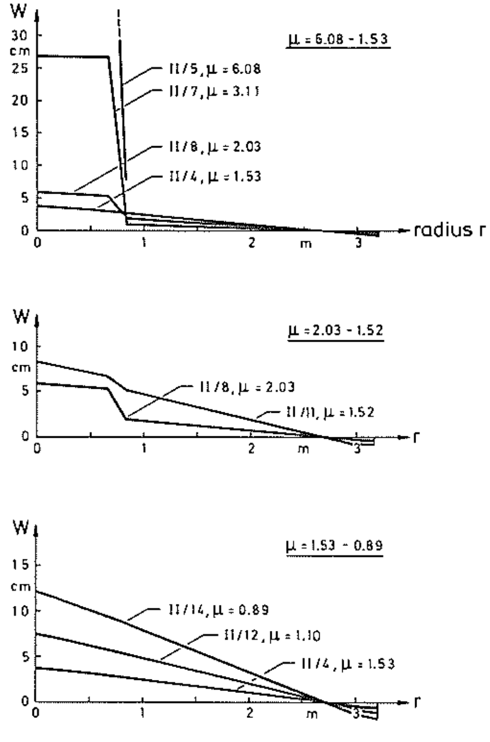


4 a) Deflection-time curves, center of slab

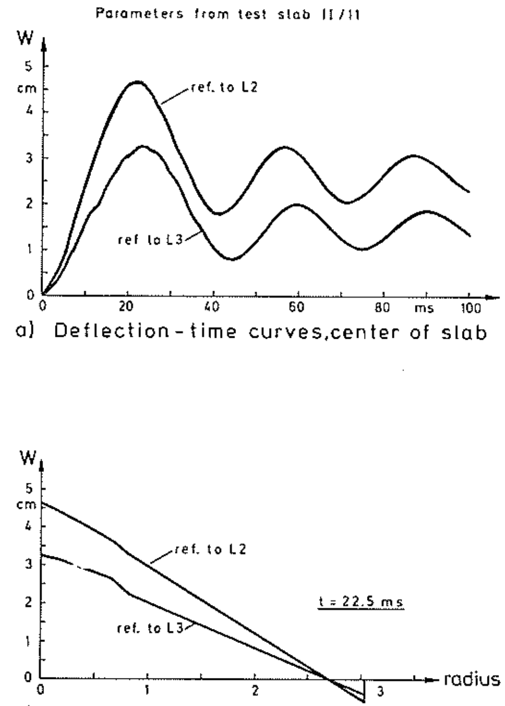


4 c) Correlation between bending deflection W_M and reinforcement ratio

Fig. 4 Analysis for different reinforcement ratios



4 b) Deflection-curves along the radius
Time of maximum displacements, center of slab



a) Deflection-time curves, center of slab

b) Deflection curves along the radius

Fig. 5 Analysis for load histories L2 and L3

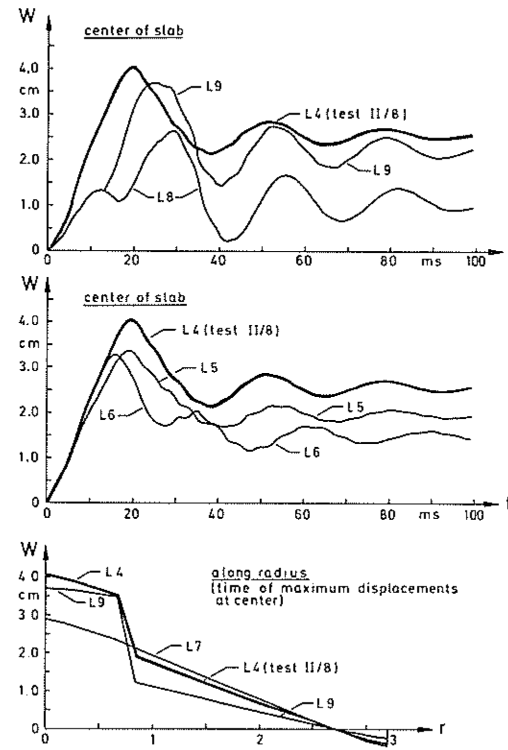


Fig. 6 Displacement curves for variation of load history