Impact Response Analysis Including Missile–Structure Interaction

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SUMMARY

In this paper, an algorithm for the analysis of missile or projectile impact on concrete structures without a priori knowledge of the loading function is presented, which takes into account penetration as well as projectile and target deformations and which allows a satisfactory evaluation of the target stresses. For the structure, a nonlinear theory for thin shells, including transverse shear deformations, is used. The structure is coupled with a contact force model during the time integration, which includes the effects of projectile deformation, penetration and target displacement. From this interaction, an impact-time function is derived, which corresponds to the contact force. Comparisonal calculations of large-scale impact tests on concrete targets verify the described methods. The proposed procedure enables an effective study of parameter effects without high costs. The dynamic forces of the structure, the penetration depth and the projectile deformation can be estimated in a good approximation, which will be illustrated by examples.

1. INTRODUCTION

Impact response calculations of reinforced concrete structures on the basis of linear and nonlinear material laws are well established, and a lot of appropriate computer programs for the solution of impact problems are available. The a priori knowledge of a deterministic load-time function of the impacting body, i.e. the contact force between missile and target, is normally necessary as precondition for a separated subsequent response calculation. Unfortunately, such a load function often is not available, but only mass and velocity and maybe the crushing load distribution of the impacting body are known.

An effective analysis of projectile impact on concrete structures is presented, where the impacting load is derived from the missile-target interaction taking into account penetration as well as projectile and target deformations. A contact force model is coupled with a nonlinear dynamic analysis of the global structure, i.e. a combined analysis of load evaluation and response calculation is carried out. Thus, the necessary information on the overall stress and strain level of the structure, which can be compared with allowable design values of the actual safety requirements, and informations on the penetration depth and the crushing length of the projectile are available as results of the computation.

2. ANALYTIC METHOD

2.1 Global Behaviour of Concrete Structure

Generally any dynamic procedure, which is qualified for recording the global behaviour of concrete structures, e.g. FEM, may be connected to the contact force model described in chapter 2.2. In the present study, a nonlinear dynamic procedure for plane bearing structures is used, which is based on Finite-Difference Method (Stangenberg, 1975). The two-dimensional description of problems used herein enlarges the scope of the classical bending theory by including transverse shear deformations. As common practice in methods for plane structures, the stresses are summarized to resultants across the thickness. The system of differential equations of motion is solved by means of direct integration with respect to time, using finite time and spatial differences, with a double staggering interval arrangement.

The fundamental constitutive relations between stress resultants and distortions follow from the integration of stresses across the thickness of structures, additionally satisfying cross sectional equilibrium conditions.

The flexural response for structural elements are assumed to follow the classic assumptions based on Bernoulli principle of linear strain distributions. The slab cross-sections are devided into layers parallel to the neutral axis as shown in Figure 1, and nonlinear stress-strain relationships for steel and concrete are employed for performing stress resultants. The effects of shear are incorporated into the shear force-distortion curve, trilinear approached for calculation, according to the amount of shear reinforcement.

2.2 Local Behaviour in the Impact Area

In the procedure described here, the load-time function is evaluated by a special interpolation between the two limit cases of hard and soft impact. Following notations are introduced (see Figure 2):

x, v - displacement, velocity in [m], [m/s]. Possible indices of x and v stand for:
u = undeformed part of missile, rear of missile
b = deformed part of missile, referring to front point of missile
t = target

M - total mass of missile in [Mg]

M_b - mass of deformed part of missile in [Mg]

Hard Impact

According to the NDRC-theory of penetration (NDRC, 1946) of a rigid projectile into concrete, the impact force F_h at time t is a function of both depth of penetration x_p and velocity of projectile penetration v_p at that time and can be presented by a separable force law (Kennedy, 1976). Taking into account the flexibility of the target, $x_p = x_u - x_t$ and $v_p = v_u - v_t$:

$$F_h(t) = \frac{C}{K\ N}\, D^{(2-\alpha)}\ (v_u - v_t)^{(2-\alpha)}\ G(z) \qquad (1)$$

where $C = \frac{1}{\alpha} * (27{,}68 * 0{,}0254^{\alpha} * 304{,}8^{\beta})$, a factor used to transform from British measure units to SI-units, D is the projectile diameter in [m], G(z) is the dependency of actual penetration depth on the impact force, cf. Table 1, and $z = x_p / D = (x_u - x_t)/D$.

Table 1 summarizes different values of empirical constants (K, N, α, β) due to various penetration formulae (f'_c = compressive strength of concrete in [psi]).

Table 1 Empirical constants for impact force evaluation (HN-NDRC = NDRC-formula modified by Holmes and Narver, ACE = American Corps of Engineers, A & W = Ammann & Whitney, BLR = Ballistic Research Laboratory)

	HN-NDRC	ACE	A & W	BRL	Present Study
α	1.8	1.5	1.8	1.33	1.8
β	0.2	0.215	0.2	0.2	0.2
K	$180/\sqrt{f'_c}$	$282/\sqrt{f'_c}$	$282/\sqrt{f'_c}$	6	$180/\sqrt{f'_c}$
N	0.72 ÷ 1.14	1.0	0.72 ÷ 1.14	1.0	0.72
g(z)	$\begin{cases} z/2 & \text{if } z<2 \\ 1.0 & \text{if } z \geq 2 \end{cases}$	$\begin{cases} 0 & \text{if } z<0{,}5 \\ 1.0 & \text{if } z \geq 0{,}5 \end{cases}$	1.0	1.0	$\begin{cases} z-z^2/4 & \text{if } z<2 \\ 1.0 & \text{if } z \geq 2 \end{cases}$

The equation of motion of the projectile is:

$$M \frac{dv_u}{dt} = -F_h(t) \qquad (2)$$

Soft impact
The reaction-force history in case of an ideal soft impact is generated according to an impact of a deformable missile on a rigid wall. For this evaluation, not only the mass distribution $\mu_c(x_c)$, but also the ultimate load distribution $F_c(x_c)$ of the projectile are needed, in which x_c is the corresponding projectile coordinate, counted from the nose of the projectile. Considering the flexibility of the target, $x_c = x_u - x_t$, the reaction force $F_s(t)$ in this case follows from Riera (1987):

$$F_s(t) = F_c + \mu_c (v_u - v_t)^2 - M_b \frac{dv_t}{dt} \tag{3}$$

The equation of motion of the undeformed part of the projectile is:

$$(M - M_b) \frac{dv_u}{dt} = -F_c \tag{4}$$

Coupled model and evaluation of impact force
At first, the possibility of projectile deformation at time t is examined. Assuming the projectile does not crush, eq. (1) yields to the maximum theoretically possible impact load F_{max}. On the other hand, assuming no projectile penetration, the minimum impact load F_{min}, which is necessary to crush the projectile, is evaluated from eqs. (3) and (4), in which $v_u = v_t$ and $dv_u = dv_t$. If F_{max} is less than F_{min}, no projectile deformation is possible and $F_{max} = F_h(t)$ is taken as actual impact load F(t). If not, projectile deformation as well as projectile penetration is possible and the actual impact load is derived from an equilibrium iteration, which is based on the described limit cases of hard and soft impact. Replacing x_u, v_u by x_b, v_b in eq. (1) and replacing x_t, v_t by x_b, v_b in eq. (3), the unknown velocity v_b of the projectile nose is determined by solving

$$F_h(t, v_b) - F_s(t, v_b) = 0 \tag{5}$$

and the corresponding force $F(t) = F_h(t) = F_s(t)$ is taken as impact load.

3. NUMERICAL EXAMPLES

The above described procedure is appropriate for the computation of hard and soft impacts and all cases inbetween, and, in particular, for the evaluation of missile deformation history, missile penetration and load duration (Schwarzkopp, 1987). In the following, examples of computations of predominant soft impacts are presented, in order to verify the procedure. The computations refer to so-called "Meppen slab tests" in Germany, where large-scale impact tests have been performed to investigate the ultimate load-bearing behaviour of reinforced concrete structures under high-speed impact loads.

The mass of the (deformable) impacting body was about 1000 kg, the impact velocities were in the range of 200 up to 250 m/s. The projectile is a steel projectile with length 6 m, diameter 0.6 m and a wall thickness of 7 and 10 mm. Figure 3 gives the distributions of mass and crushing load of the projectile. The target is a reinforced concrete slab of total dimension 6.5 m x 6.5 m; the amount of steel reinforcement has been varied during the tests. In Table 2, the data of projectiles and targets for the last test series II/11 - II/21 are listed.

Table 2 Test data of Meppen slab tests (* steel BSt 1100)

Test	Mass	Projectile Velocity	Target slab Thickness	Concrete strength f_c'	Steel reinforcement (BSt 420) Bending r. each way Upper face	Lower face	Stirrups
	kg	m/s	cm	N/mm^2	cm^2/m	cm^2/m	cm^2/m^2
II/11	1000	222.5	70	32.9	20.4	40.1	37.7
II/12	980	241.5	70	39.6	20.4	40.1	52.3
II/16	970	247.1	70	32.0	15.4	31.4	50.2
II/17	954	178.4	50	33.9	23.1	56.0	64.9
II/18	1060	237.4	70	31.2	20.4	40.1	52.3
II/19	980	240.3	70	29.1	20.4	40.1	52.3
II/20	972	197.7	50	33.7	23.1	58.2	87.0
II/21	1000	237.0	90	33.2	10.5	25.5	26.5
II/22	1001	248.8	70	36.8	11.6*	23.1*	52.3

The shape factor of the projectile has been set to N = 0.72 for all computations. All other input data for the computations have been inserted according to Figure 3 and Table 2, respectively.

The resulting computed time histories of projectile displacements, velocities as well as target displacements and penetration of missile into concrete for tests II/11 and II/21 are shown in Figures 4 and 5 versus measured data. The penetration values of the tests are only known as final values.

It can be seen from Figures 4 and 5 that calculated and measured data are generally in good agreement. Only the penetration depth values have been overestimated in the calculations; this might be based on the undeformed projectile diameter of 0.6 m which has been used in the computations instead of the (higher) value of the already deformed projectile part. On the other hand, the penetration could be affected by the steel reinforcement, which is not accounted for in the utilized NDRC-formula.

Table 3 summarizes the most important results of the tests versus computations for the test series II/11 - II/21.

Table 3 Measured vs. computed results of Meppen slab tests
(* = original length of crushed missile part, 1) failure)

Test	Missile deformation*		Max. Target displacement		Penetration depth		Load duration	
	Meas. cm	Comp. cm	Meas. cm	Comp. cm	Meas. cm	Comp. cm	Meas. ms	Comp. ms
II/11	470	409	4.7	5.3	7	9	36-38	36
II/12	458	440	5.2	5.6	7	11	32-37	31
II/16	428	1)	-	1)	20	1)	28-32	1)
II/17	353	305	5.5	5.2	11	9	30-35	30.5
II/18	538	518	9	6.0	13.5	13.4	31-35	33.5
II/19	388	1)	-	1)	Perfor.	1)	28	1)
II/20	306-345	349	10	7.4	22	10	29-33	31
II/21	414	436	5.5	5.8	7.5	10	33	32
II/22	456-472	461	10	8	15	12	31-34	32

4. CONCLUSIONS

Impact response calculations of reinforced concrete structures can be carried out without a priori knowledge of load-time functions by simultaneously analyzing local effects and global structural response. As illustrated by examples, additional informations of the response characteristics (e.g. missile deformation, penetration depth, load duration) can be obtained, which are not available in usual response calculations. The procedure enables an effective study of parameter effects due to low computer times.

5. REFERENCES

F. Stangenberg: Dynamic Ultimate Load Analysis Using a Finite Difference Method. Proceedings of the ELCALAP - Seminar, Berlin 1975, paper T 3/3

NDRC: Effects of impact and explosion, Summary Technical Report of Division 2, National Defense Research Commitee, Vol. 1, Washington D.C. (1946)

R.P. Kennedy: A Review of Procedures for the Analysis and Design of Concrete Structures to resist Missile Impact Effects, Nuclear Engineering and Design 37 (1976) 183 - 203

J.D. Riera: On Scabbing and Perforation of Concrete Structures hit by Solid Missiles, 9th SMiRT-Conference, Lausanne 1987

D. Schwarzkopp, R. Zinn: Simplified Nonlinear Analysis of Reinforced Concrete Plates under Projectile Impact Including Penetration and Projectile Deformation Effects, 1st Int. Conf. on Concrete for Hazard Protection, Edinburgh, September 1987

H. Riech, E. Rüdiger: Meppener Versuche II/11 bis II/22, II. Technischer Bericht, Hochtief AG Frankfurt, Januar 1984

Comite Euro-International du Beton (CEB): Concrete Structures under Impact and Impulsive Loading, Bulletin d'Information No 187, August 1988

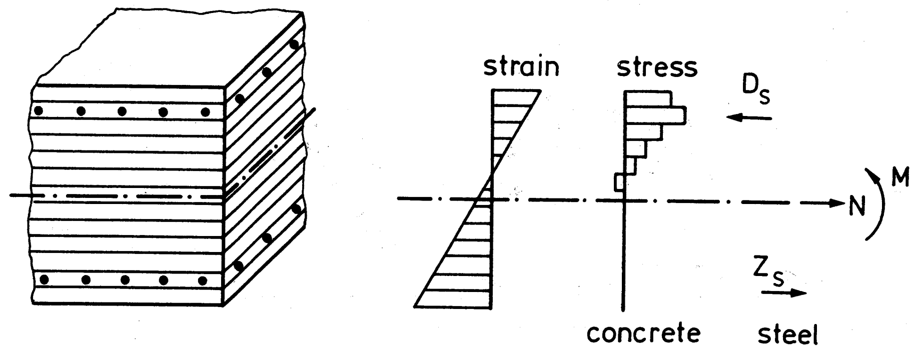
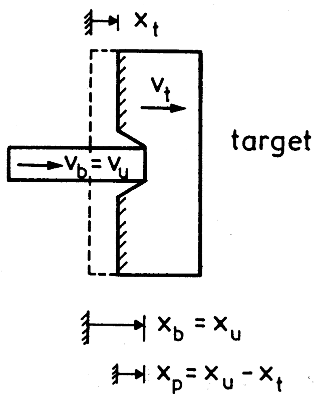
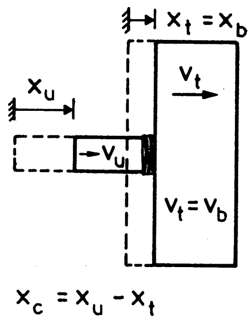


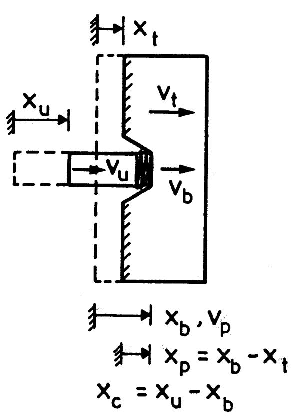
Figure 1. Layered concrete model



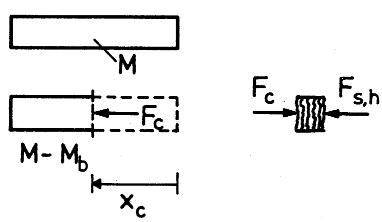
2a. Hard impact



2b. Soft impact



2c. Coupled model



2d. Missile notations

Figure 2. Model for evaluating the contact force

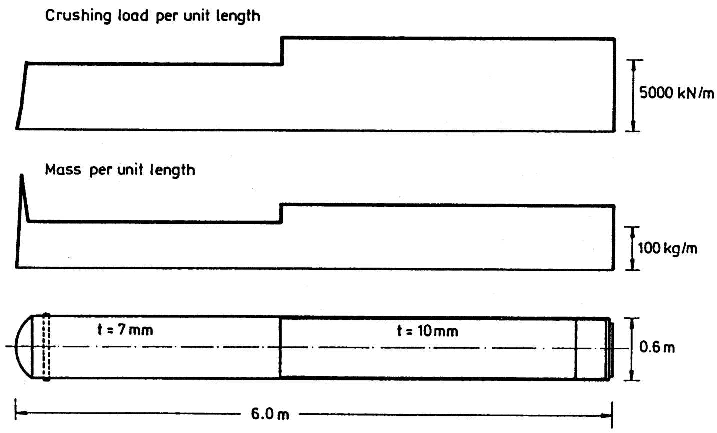
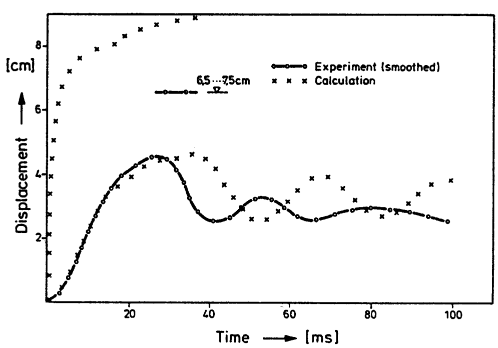
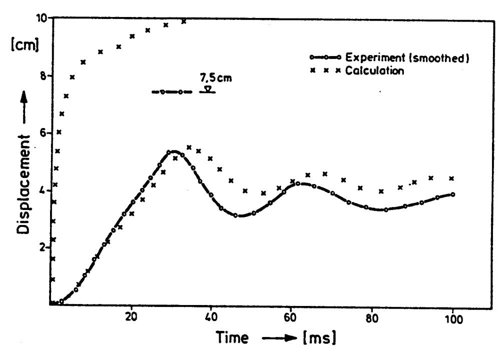


Figure 3. Projectile data of Meppen slab tests

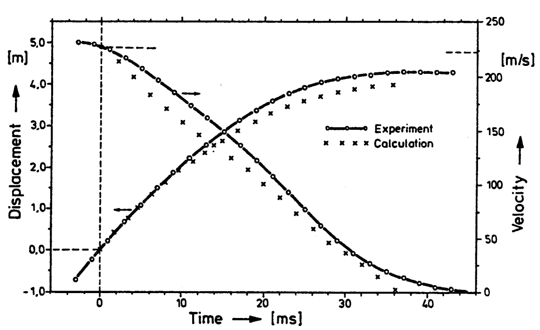


4a. Meppen test II/11, d = 0.7 m

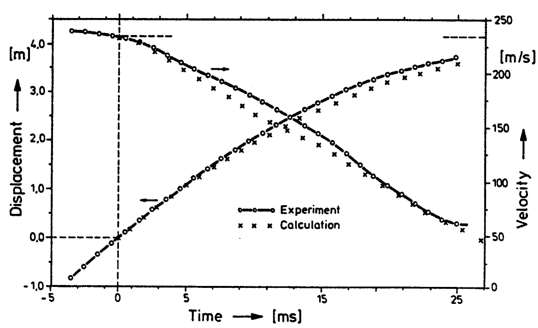


4b. Meppen test II/21, d = 0.9 m

Figure 4. Target displacement and penetration



5a. Meppen test II/11, $v_o = 223$ m/s



5b. Meppen test II/21, $v_o = 237$ m/s

Figure 5. Displacement and velocity of rear missile part