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PERFORATION RESISTANCE OF REINFORCED CONCRETE SLABS AFFECTED BY LOW VELOCITY DROP LOADS

Adam Fila [1], Frank Lehmann[2] , Reinhard Tropp[3]

[1] Dipl. Eng, Dept. of Civil Engineering, Senior Expert, AREVA GmbH Germany (adam.fila@areva.com)
[2] Dipl. Eng, Dept. of Civil Engineering, Adviser, AREVA GmbH Germany
[3] Dipl. Eng, Dept. of Civil Engineering, Adviser, AREVA GmbH Germany

ABSTRACT

The civil design for the slabs in nuclear facilities comprises the design check of the slab resistance for load case drop loads. Sets of impact tests have been executed to determine local damage criteria of reinforced concrete slabs affected by drop load impacts. The new calculation method to check the perforation resistance in the impacted area was evaluated and verified based on test results.

FAILURE MODES OF REINFORCED CONCRETE SLABS AFFECTED BY DROP LOADS

The drop load effects on reinforced concrete slabs depend on several impact parameters related to the missile and target conditions. On the one hand the velocity, mass, deformability and dimension of missile, on the other hand the material parameters, geometry and stiffness of target significantly impair the impact analysis.

The failure modes of reinforced concrete slabs affected by drop loads can be divided in local and global effects as follows:

Local effects related to the impacted area:

- Punching shear failure when a conical plug of concrete perforates the slab around the impacted area,
- Perforation when the impacting projectile has passed through the target completely.

In the strong reinforced nuclear concrete structures the perforation failure can first occur after the exceeding of punching shear resistance, mainly regulated by the shear reinforcement area, and the damage of bending reinforcement.

In addition the penetration, spalling and scabing of concrete can be observed:

- Penetration when the projectile has formed an indentation on the impacted face but has not perforated the target
- Spalling when fragments of the impact face of the target have been ejected
- Scabbing when fragments of the distal face of the target have been detached although perforation has not occurred

These additional local damage effects are limited in the nuclear structures by the high reinforcement amount and do not significant affect the local structural resistance.

Global effects related to the bending resistance of the structural member:

- Global collapse of the slab caused by exceeding of bending capacity.

The bending capacity of the concrete structure affected by drop loads is established in terms of limiting strains and stresses which are regarded as material properties and are independent of the structural dimensions. The strain limitation for reinforcement bars of 5 % used for accidental load conditions ensures sufficient bending flexibility of the slab. The large bending reinforcement amount in nuclear structures provides significant bending resistance which normally prevents the bending collapse of the slab affected by drop loads.

DESIGN METHODS FOR DROP LOADS

The design for the nuclear structures comprises the design check for reinforced concrete slabs affected by postulated drop loads. The design check has to prove the resistance of the structural members to avoid the damage of safety related components located in the rooms below the impacted slabs. The absorption of impact energy caused by drop loads result in extremely high stress level and nonlinear material effects in the structural members.

The common design methods for drop load impact are:

- Finite element calculations using FE shell/cubic elements,
- Simplified spring-mass-model comprising bending and punching shear resistance parameters of the slab.

The very time consuming evaluation of structural response using FE calculation is quite accurate when flexural behaviour is dominant and can be therefore only realistic calculated for soft impact conditions. In case when the punching shear mode is governing for the failure of the slab the results can differ depending on the applied calculation parameters for: tensile strength, tensile softening of concrete, crack propagation rules and residual shear stresses. This has been also confirmed in the IRIS_2010 project where the nonlinear benchmark calculations were performed to predict the failure behaviour of reinforced concrete slab subjected by missile impacts, see reference [4].

The simplified spring-mass-model is conservative calculation method to assess the bending and punching shear resistance of impacted slabs. The methodology is common used for nuclear structures and implemented in the ETCC-2012 design code used for new European Pressurized Reactor [3]. The description of the spring-mass- model in this paper will be limited only to the evaluation of shear behaviour of the slab which is strictly related to the conditions of performed impact test. The neglecting of bending effects and corresponding missing bending flexibility result in increase of impact energy portion to be absorbed by the shear resistance of the slab and is therefore conservative.

The simplified method to evaluate the local structural shear capacity of the slabs is based on three contributing factors:

- the concrete tensile strength contribution of concrete along the expected cone boundaries,
- the stirrups contribution due to the stirrups resistance after exceeding of concrete tensile strength,
- The bending reinforcement contribution due to the bending reinforcement resistance. The reinforcement bars follow a deflection path of a cable created by punching cone shape.

The Figure 1 shows the resistance of concrete ($R_C{}^u$), of stirrups ($R_S{}^u$) and of bending reinforcement ($R_B{}^u$) against punching according reference CEB report [2]., presented in terms of force-deflection diagram to be used for the dynamic calculation of the one-mass-spring model. The equivalent methodology is also used in ETCC-2012 [3].

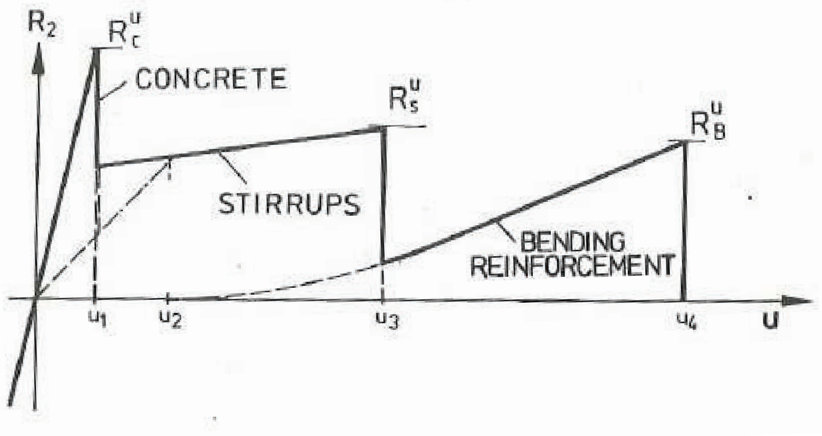


Figure 1: Local resistance, spring characteristics

The decisive contribution for design of the punching shear resistance is provided by the stirrups ($R_S{}^u$). The collapse of the concrete strength resistance ($R_C{}^u$) which initiates the activation of the stirrups is related to very small deflections (u_1) what results in negligible small absorption of impact energy provided by concrete failure. The bending reinforcement resistance ($R_B{}^u$) with the corresponding ultimate deflection (u_4), which is significant larger than the ultimate stirrups deflection (u_3), can be first reached after the exceeding of the resistance provided by the stirrups strength. The ultimate deflection (u_4) is the representative value for the perforation failure of the cross section. The calculation of local impact effects using one-mass-spring method is mainly focused on design check for stirrups resistance. The exceeding of punching shear failure and transition to the perforation failure mode has been normally not used in the analysis due to the expected larger displacement. For the cross section of slabs without shear reinforcement the design check for high energy impact can be only provided considering the bending reinforcement resistance.

DROP LOAD TEST

The 26 drop load tests were performed in the Laboratory at University Giessen in order to assess the perforation resistance of reinforced concrete slabs.

The slab span length dimensions of 2,80 m x 2,80 were chosen to minimize the bending effects during the impact. The slabs were supported on circular located rigid steel boxes in distance R= 108 cm from the centre of the slab. The geometry of the slab, support conditions and testing facility are shown in Figures 2 and 3. The slab thicknesses varied between d=25 cm and d=40 cm. The used steel yield strength is $f_{yk} = 500\ MN/m^2$ .The erected bending reinforcement areas varied between 10,05 cm^2/m (d16/20 each face in both directions) for slab thickness d=25 cm to 15,70 cm^2/m (d20/20 each face in both directions) for slab thickness d=40 cm. The stiff steel cylinder with 2 different diameters 30 cm and 60 cm was installed in the middle of the tested slabs top surface in order to centre the loads induced by the drop of a cubic concrete cube with weight up to 4 tons. At the bottom of the concrete cube a massive steel plate was installed in order to avoid the spalling effects on impacted cube surface. The drop height varied between 1,25 m and 2,92 m.

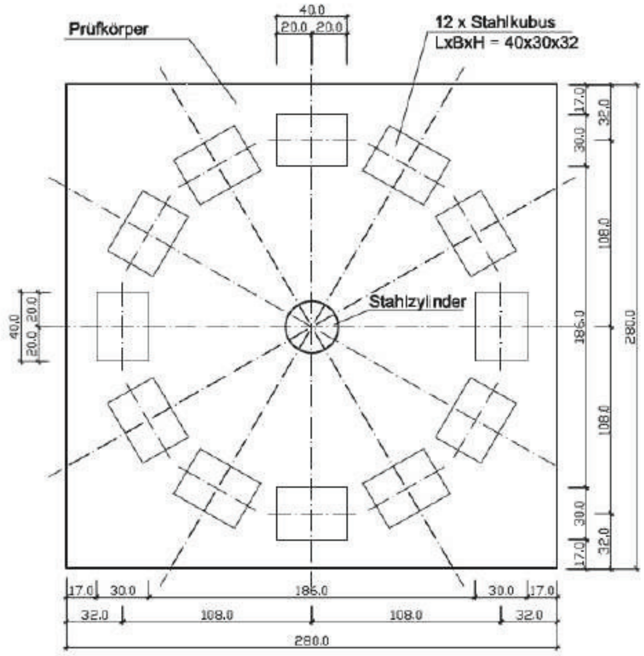


Figure 2: Slab Geometry and Location of Supports

Unfixed profiles for protection of measurement devices

Figure 3: Testing Facility

The tests have been performed in 2 steps. The results of first 6 tests DL1 to DL6 have been used to develop the design method to assess the perforation resistance of impacted slabs based on energy balance principle. The test parameters for following 8 tests DL9 to DL16 have been defined close to expected structural perforation capacity, as calculated by energy balance method, in order to verify and confirm the developed design criteria.

The drop load parameters and measured results for the main test set related to the impacts on the slabs without shear reinforcement are shown in Table 1 as follows:

- Test label
- Slab thickness
- Slab reinforcement
- Impact diameter
- Drop load height
- Drop mass
- Impact energy
- Measured visible punching cone diameter
- Evaluated punching cone angle
- Maximum measured slab deformation
- Absorbed energy

It can be concluded that in all test for slabs without shear reinforcement the shifting of punching cone, local penetration and extensive scabbing effects at the slab bottom surface were observed. Furthermore in the test DL2 the perforation resistance of the slab has been exceeded. The measured deflections at the bottom surface varied between 22 mm for test DL6 and 106 mm for test DL11. The maximum penetration depth measured at the top surface was 84 mm. In test DL2, DL10 and DL11 the cut of top reinforcement layers could be observed. The measured punching cone angle varied between 18,4 and 27,8 degrees depending on the slab thickness. The Figures 4 and 5 show exemplary the slab DL1 after the impact with visible local scabbing and penetration effects at bottom and top surface

In addition to the tests for slabs without shear reinforcement eight drop load tests have been executed for slabs with installed stirrups (d8/20/20). It can be concluded that the perforation resistance of slabs with existing shear reinforcement is significant higher compared with the slabs reinforced only with bending bars.

The most important contribution provided by the shear reinforcement is the activation of the top reinforcement bars which are able to accumulate additional portion of energy during the movement of punching cone. This additional energy accumulation can be suddenly stopped by damage of top reinforcement bars. The risk to cut through the top bars during the impact is very high and has been observed for test DL2, DL10 and DL11. As a consequence the increase of perforation resistance provided by shear reinforcement will not be taken into account in the developed energy method.

Figure 4: Bottom face of Slab DL1 with visible punching cone diameter of 1,50 m

Figure 5: Penetration effects on the impacted face of slab DL1

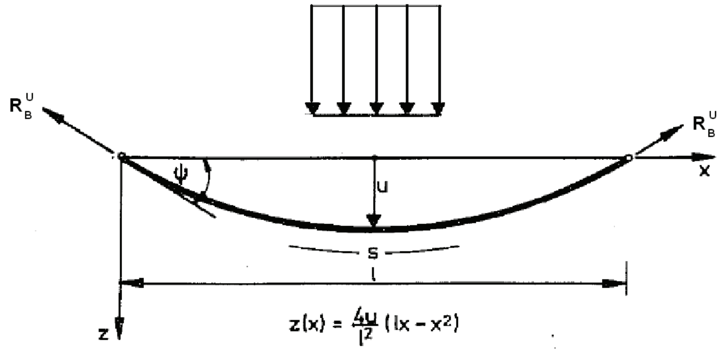
Tab1e 1- Test parameters, measured maximum slab displacement and calculated energy balance values

Test	Slab Thick-ness [cm]	Bending Reinforcement	Impact Diameter [cm]	Drop Height [m]	Drop Mass [t]	Impact Energy [kNm]	Visible Punching Cone Diameter [cm]	Punching Cone Angle [Degree]	Associated Absorbed Eenergy [kNm]	Admissible Absorbed Energy [kNm]	Maximum Slab Deformation [mm]
DL1	25	Ø16/20 top Ø16/20 bottom	Ø30	1,25	3,0	36,8	150,0	22,6	55	42,1	48,0
DL2	25	Ø16/20 top Ø16/20 bottom	Ø30	2,77	3,0	81,5	178,0	18,7	76	42,1	Perforation
DL3	40	Ø20/20 top Ø20/20 bottom	Ø30	2,62	3,0	77,1	182,0	27,8	140	152,5	30,0
DL4	40	Ø20/20 top Ø20/20 bottom	Ø30	2,62	4,0	102,8	186,0	27,1	147	152,5	63,0
DL5	35	Ø20/20 top Ø20/20 bottom	Ø60	2,74	4,0	107,5	217,0	24,0	200	170,9	40,0
DL6	35	Ø20/20 top Ø20/20 bottom	Ø60	2,74	3,0	80,6	198,0	26,9	168	170,9	22,0
DL13	25	Ø16/20 top Ø16/20 bottom	Ø30	1,67	3,05	50,0	178,0	18,7	76	42,1	45,0
DL14	25	Ø16/20 top Ø16/20 bottom	Ø60	2,63	3,05	78,7	188,0	21,3	92	67,7	48,0
DL16	30	Ø16/20 top Ø16/20 bottom	Ø30	2,29	3,05	68,5	168,0	23,5	73	58,5	53,0
DL12	25	Ø16/20 top Ø16/20 bottom	Ø60	2,00	4,0	78,5	198,0	20,0	100	67,7	73,0
DL15	30	Ø16/20 top Ø16/20 bottom	Ø60	2,60	4,0	102,0	210,0	21,8	123	88,2	56,0
DL11	30	Ø20/20 top Ø20/20 bottom	Ø30	2,65	4,0	104,0	210,0	18,4	171	89,2	106,0
DL9	35	Ø16/20 top Ø16/20 bottom	Ø30	2,13	4,0	83,6	173,0	26,1	80	77,6	55,0
DL10	35	Ø16/20 top Ø16/20 bottom	Ø30	2,50	4,0	98,1	218,0	20,4	126	77,6	89,0

ENERGY METHOD

The energy method to assess the perforation resistance of impacted slabs has been developed based on [1].

The energy balance check was performed to compare the amount of impact energy E_{impact} provided by the drop of concrete cube with available associated absorbed energy W_R which could be accumulated in the slab due to plastic elongation of bending reinforcement bars along the deflection path of a cable (s. Figure 6). Thereby, the deflection path of the cable follows the shape of created punching cone as measured in the impact test. The maximum plastic cable strain is limited by 5%. The area of activated bending reinforcement A_S is limited by the amount of bottom bars crossing one quarter of punching cone circle (in both directions). The results of energy balance calculation confirm the test results for all impacted slabs including the perforation failure of the slab DL2 where the impact energy E_{impact} exceeded the available associated absorbed energy W_R (s. Table 1). Due to the variation of measured punching cone angle it will be recommend to evaluate the admissible absorbed energy portion for the fixed punching cone angle of 26,6 degrees according to EC2. This energy amount reduced by safety factor f=1,1 has to be compared with the activated impact energy to check the perforation resistant of impacted slabs.



Elastic cable elongation:

$$s_{el} = \frac{l}{2}\left[\sqrt{1+\left(\frac{4u_{el}}{l}\right)^2} + \frac{l}{4u_{el}}\ln\left(\frac{4u_{el}}{l} + \sqrt{1+\left(\frac{4u_{el}}{l}\right)^2}\right)\right] \qquad \text{and} \qquad 0.25\% = \frac{s_{el}-l}{l}$$

Plastic cable elongation:

$$s_{pl} = \frac{l}{2}\left[\sqrt{1+\left(\frac{4u_{pl}}{l}\right)^2} + \frac{l}{4u_{pl}}\ln\left(\frac{4u_{pl}}{l} + \sqrt{1+\left(\frac{4u_{pl}}{l}\right)^2}\right)\right] \qquad \text{and} \qquad 5\% = \frac{s_{pl}-l}{l}$$

Figure 6: Cable Shape of Bending Reinforcement

Energy absorption provided by bending reinforcement:

$$W_R = R_B^u * \Delta s_{pl} \text{ with: } R_B^u = A_s * f_{yk} \text{ and } \Delta s_{pl} = s_{pl} - s_{el}$$

Impact energy:

$$E_{impact} = m * g * H$$

Check of energy balance:

$$W_R \text{ versus } E_{impact}$$

CONCLUSION

The drop load test showed that the perforation of the slabs affected by drop loads can be avoided even if the punching shear cone was created. The new developed design method based on energy balance confirms test results and shows that the deflected bending reinforcement is able to absorb sufficient energy to avoid the perforation of the slab after the creation of punching shear cone. The new energy method can be used for the assessment of perforation risk and so replace the very time consuming FE calculations or conservative simplified calculation methods.

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