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METHODS FOR SIMULATION OF HARD PROJECTILE IMPACT ON MULTIPLE RC STRUCTURES

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ABSTRACT

A significant load case for the design of new and existing nuclear or industrial structures is the impact of missiles or projectiles. Nuclear facilities usually consist of a massive outer shell and additional secondary barriers inside. The latters are often also reinforced concrete structures. These must therefore be able to withstand an intentional or unintentional projectile impact. For this reason, it is essential to investigate the resulting damage holistically, i.e. on the primary reinforced concrete walls (outer shell), but also the following, inner, secondary barriers.

In this paper, the efficiency of numerical simulation methods as well as existing empirical approaches to predict the resistance of multiple reinforced concrete structures under hard impact loads is investigated. Experimental test results from past research projects are presented and used for validation. An assessment of the effectiveness of multiple reinforced concrete structures compared to monolithic slabs of the same thickness is provided.

INTRODUCTION

In addition to the more time-consuming numerical finite element methods, empirical formulas can be used to predict the resistance under hard impact loads on reinforced concrete slabs. According to CEB (1988), to evaluate the resistance to hard impact in multiple barriers, it is suggested to use the residual velocity v_{res} after perforation of the first panel as the impact velocity v_a of the second panel, etc. With this assumption, an ideally straight impact on both target structures is assumed and thus the rotation of the projectile is neglected as well as the bond between the plates (Amde 1994).

REVIEW OF SELECTED EXPERIMENTAL INVESTIGATIONS

KOJIMA 1991

Kojima (1991) presents small-scale tests on local damage to reinforced concrete slabs due to the impact of hard projectiles. Also included are tests with multiple reinforced concrete slabs with slab thicknesses of 6, 9, 12 cm furthermore another test was performed with monolithic slabs awhere the thickness of the slab was selected to 18 cm. In test series L, a steel liner with a thickness of 3.2 mm is applied to the back of each of the 12 and 18 cm thick slabs. There is a 12 cm gap between the double-shell slabs. The reinforcement ratio of all target slabs is 0.6% for both longitudinal and transverse directions. The impact velocity of the steel projectile, which weighs about 2 kg, is approximately 200 m/s. The dimensions of the missile and the test setup are shown in figure 1.

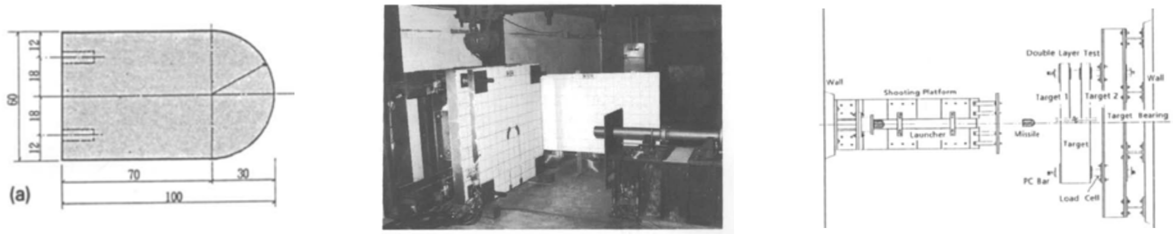


Figure 1. Projectile and impact test apparatus picture + plan Kojima (1991)

Table 1 shows the experiments and results of Kojima (1991) considered in this paper.

Table 1: List of experimental tests and results

No. of tests	Thickness [cm]	Velocity [m/s]	Penetration depth [mm]	Spalling [mm x mm]	Scabbing [mm x mm]	Damage	Reaction Force [kN]
R-18-X	18	211	78	282x217	445x435	penetrated	225
R-12-X	12	215	-	205x226	720x428	perforated	104
W-09-X	9	210	-	82x90	185x180	perforated	115
	9	100*	106	90x80	123x110	penetrated	-
W-12-X	6	206	-	100x85	170x165	perforated	191
	12	180*	59	90x85	155x180	penetrated	-
L-18-X	18	206	66	315x286	No scabbing	penetrated	253
L-12-X	12	212	125	228x255	No scabbing	penetrated	185

* measured residual velocity after first slab = impact velocity second slab

Kojima (1991) concluded that a steel liner on the back side effectively prevents perforation or scabbing, additionally that the impact resistance under the hard impact on a monolithic reinforced concrete slab with the same overall thickness is higher compared to the double-shell slab.

Shirai 1993

Shirai et al. (1993) also investigated small-scale impact tests with hard impact on double-shell reinforced concrete structures. The slabs have thicknesses of 3, 4.5, and 6 cm and are assembled to form 9 cm slabs. As shown in figure 2, two types of double-shell RC structures (C1 & C2) with a spacing of 1.5 cm and no spacing between slabs were investigated. A Standard RC structure (M2) with a thickness of 9 cm was also tested to investigate the effect of multiple slabs vs monolithic slabs. The reinforcement is placed as mesh rebars with a diameter of 7 mm every 70 mm. The projectile is made of steel with a mass of 0.43 kg, a flat nose and has an impact velocity on the reinforced concrete slabs of 170 m/s. The test setup is shown in figure 2 and the experimental results are shown in table 2.

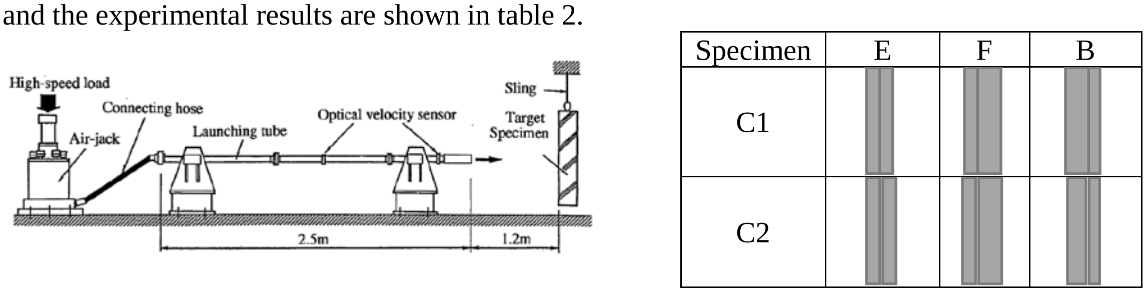


Figure 2. impact test apparatus plan + Types of double-layered RC Targets (Shirai et. Al 1993)

Table 2: List of experimental tests and results

No. of tests	Thickness [cm]	Velocity [m/s]	Scabbing [mm]	Damage
C1E	4.5	170**	150	Penetration
	4.5		280	Penetration
C1F	3.0		-	Perforation
	6.0		320	Penetration
C1B	6.0		cracks	Penetration
	3.0		250	Penetration
C2E	4.5		-	Perforation
	4.5		-[1]/cracks[2]	Perfor.[1]/Penetr.[2]
C2F	3.0		-	Perforation
	6.0		180[1]/220[2]	Penetration
C2B	6.0		-	Perforation
	3.0		-	Perforation
M2	9.0		crack	Penetration

**Impact velocity of the first slab, Number: Number of specimen

Shirai et al. (1993) concluded that for the double-layer RC slabs with a 1.5 cm spacing (tests C2-) between the slabs, it is beneficial to use the thicker concrete slab as the rear slab. However, in the C1- series of tests, a reduction in local damage is observed when the front slab is the thicker slab. A comparison between monolithic and multiple barriers is not described. Numerical simulations of the tests of Shirai et al. (1993) in Shirai et al. (1997) showed a higher impact resistance of double-layered RC slabs than of monolithic RC slabs.

NUMERICAL RESULTS OF IMPACT ON MULTIPLE RC STRUCTURES

In the following, calculations of the previously described experimental investigations on multiple barriers are performed by using verified numerical Finite Element (FE) simulations with the program LS DYNA (Lsdyna 2022). The RHT concrete model according to Riedel, Hiermeier and Thoma (Riedel 2000) serves as the material model for the concrete. A detailed mathematical description of the state equation and the underlying strength along with the failure model is prepared in detail in Riedel (2000), in project RS1550B (Heckötter et al. 2020) and 1501538A (Distler et al. 2021). For the material steel, the material model 024_Piecewise_Linear_Plasticity is used to represent the material behavior of steel or ductile materials. This includes the projectile structures as well as the reinforcing steels in the reinforced concrete structures (Livermore 2019). Contact between the missile and the RC slabs, and between the RC slabs themselves, is provided by Contact_Eroding_notes_to_surface. The contact between the reinforcement and the concrete is set by Constrained_beam_in_solid. The numerical analysis is divided into two calculations, where the impact of both slabs is considered together in one calculation (slab A+B) and two single calculations, where the residual velocity of the missile after perforation of the first slab (slab A) is used as the impact velocity for the second slab (slab B). In this case, the interconnection of the plates and the rotation of the missile after the first impact are not taken into account (Amde 1994).

Kojima 1991

Figure 3 shows the damage characteristics of the scabbing of the plates R-18-X and R-12-X as well as the cut of the test L-12-X in comparison to the FE simulations. The dimensions of the scabbing area of all simulations show good agreement with those from the experiments. The penetration depth of the missile in test L-12-X is calculated accurately.

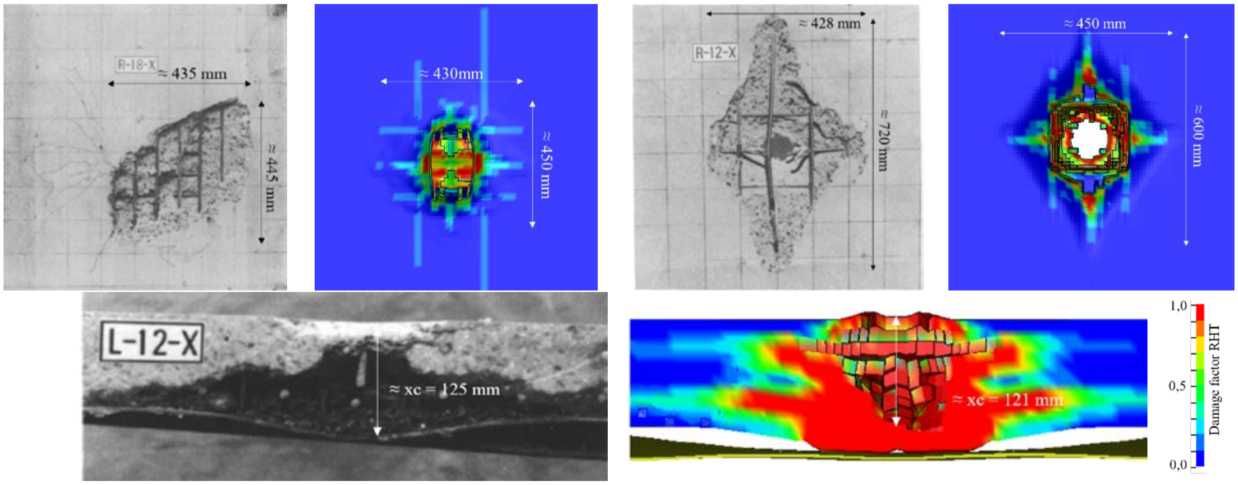


Figure 3. Calculated and measured scabbing area of R-18-X and R-12-X and penetration depth of L-18-X in Kojima (1991)

By comparing the damage characteristics in figure 4 between calculation plate A+B together and the single calculation of the front plate A separated from the rear plate B, it is noticeable that the scabbing area of plate B of the single calculation is smaller. The penetration depths are partly similar or larger for the ideal straight impact calculation of the -B plates. Since there were only two tests with multiple slabs, a clear statement about penetration depth is not significant. However, the comparison of the spalling area of the B slabs shows larger damage in the multiple analysis of two slabs (A+B) than for the ideal straight impact calculation on plate B only.

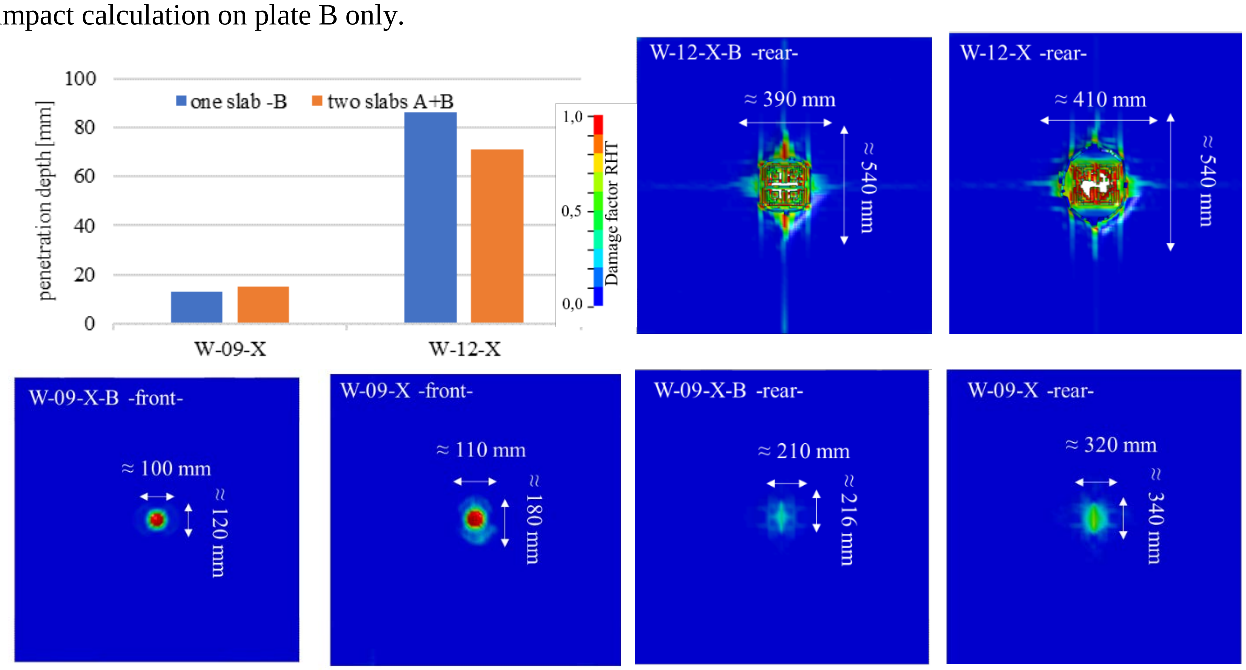


Figure 4. Penetration depth (top, left), Spalling W-09-X (bottom, left), Scabbing W09-X and W-12-X (right)

Figure 5 display the scabbing of the second plate of simulation with both slabs compared in a calculation of W-09-X, W-12-X and plate R-18-X in comparison. It is clear that the maximum local damage occurs in test W-12-X, followed by R-18-X. W-09-X shows the minimum scabbing, but the depth of penetration is greater than for test R-18-X. Scabbing does not occur in the tests with steel liner L-12-X and L-18-X, moreover, the penetration depth is less than in the equivalent monolithic slabs R-12-X and R-18-X. The steel liner even prevents complete perforation of the plate in test L-12-X compared to the equivalent test R-12-X without a steel liner.

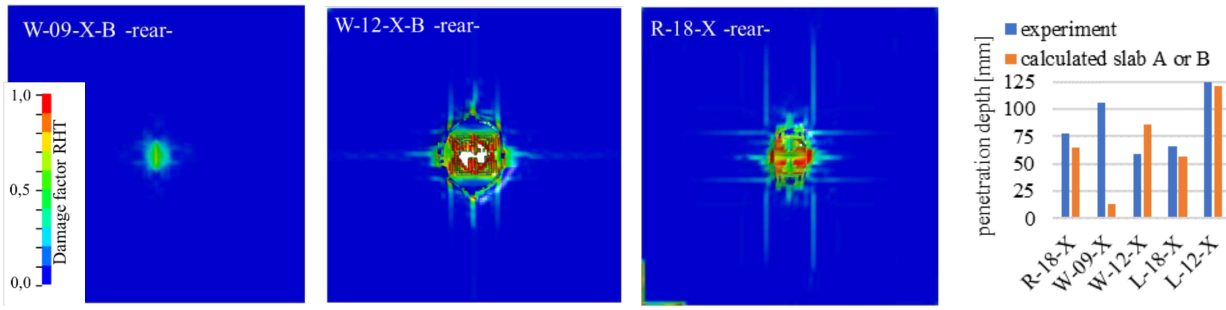


Figure 5. Scabbing area multiple barrier vs. monolithic slab and penetration depth

The reaction forces of the FE calculations are well reproduced with small deviations downwards (figure 6 left). In figure 6, similarly to the experimental investigations, the reaction force rises with the thickness of the plate. The triangular shape represents tests with perforation whereas the circular ones are with penetration of the slab. The short cut -A means the first slab and -B the second slab of a test. Even if the projectile has the same impact velocity and thus the same kinetic energy, the reaction force grows proportionally to the resistance of the target. This indicates that the greater the thickness of the specimen, the less the damage, which is also confirmed by the damage characteristics shown in Figure 3 (Kojima 1993).

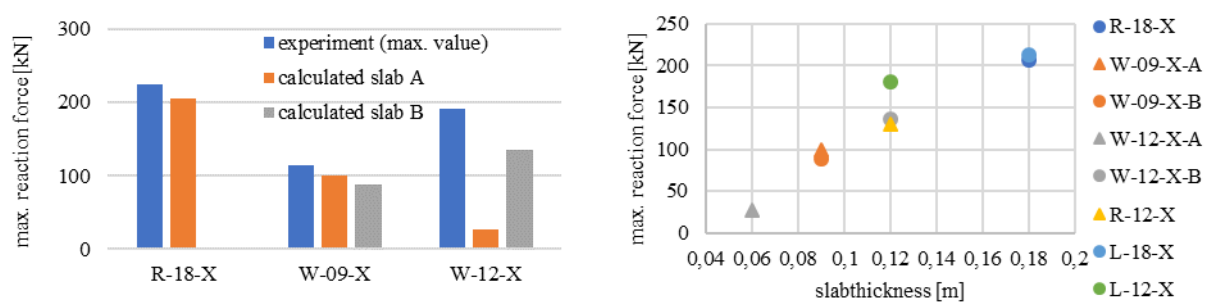


Figure 6. Reaction force experiment and calculation (left), Relationship between target thickness and reaction force (right)

Shirai 1993

Figure 7 shows the comparison of the FE calculations of the impact processes separately, in two single calculations, where the residual velocity of the projectile after perforation of the first slab (slab A) is used as the impact velocity for the second slab (slab B) and both slabs considered in one calculation (A+B). A clear underestimation of the damage patterns becomes visible when considering the two slabs separately. Furthermore, the damage case is different and assumed too conservatively for the reason that all plates show a clear perforation with a residual velocity of the projectile. For this reason, the FE simulations of the impact process with both plates calculated together are used to evaluate the damage patterns of the double-shell slabs with and without the gap.

Seperatly calculation (-B with v_{res} of -A) Holistic calculation (A+B) Experiment

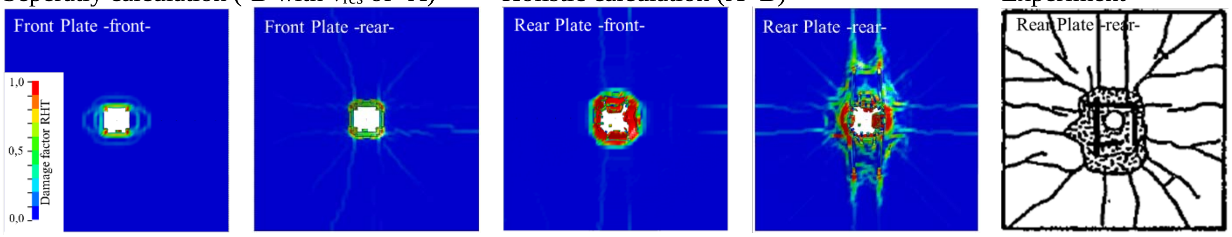
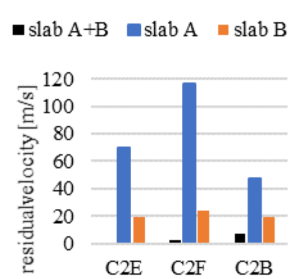


Figure 7. Damage of rear/front face of separately calculation, holistic calculation and experimental results of C2E (Shirai et al. 1993)

Figure 8 shows an example of the damage patterns of the scabbing of the first and second slab of the tests C1F and C2F in comparison with the FE simulations. The crack formation, as well as the local damage, are reproduced with satisfactory accuracy. The damage case (penetration/perforation) is also correctly reproduced in all FE simulations (table 3). In contrast to the C2- tests, the C1- tests with a 1.5 cm gap between the plates show a higher impact resistance in both the experimental tests and the FE simulations. The lowest damage with only slight scabbing in the FE simulations and cracks on the back-side of the slab in the experimental test, is shown by test M2 with the 9 cm monolithic slab.

Since no residual velocities were measured after the first plates in Shirai et al. (1993), a completely numerical FE comparison of the residual velocities of the tests is carried out. Table 3 (right) shows the residual velocities after the perforation of the first and second plate of the C2-tests. It is noticeable that a thicker slab results in a lower residual velocity. It also indicates that the velocities after projectile impact of the second slab are almost identical at the end of the two separately calculations where the impact velocity of the second slab is the impact velocity of the first slab. However, in direct comparison to the simulations of both slabs A+B in one numerical FE calculation, the residual velocities are much higher.

Table 3: Calculation results of Shirai (1993) (left) and numerical simulations (right)

Results Shirai (1993)					Numerical simulations	
No. of tests	Thickness [cm]	Velocity [m/s]	Scabbing [mm]	Damage	V_{res} separately [m/s]	V_{res} A+B [m/s]
C2E	4,5	170* *Impact velocity of first slab	140 x 140	Perforation	70**	0
	4,5		300 x 170	Just. Perforation	19	
C2F	3,0		110 x 100	Perforation	117**	2
	6,0		270 x 160	Perforation	24	
C2B	6,0		160 x150	Perforation	47**	7
	3,0		240 x 170	Perforation	19	
C1E	4,5		160 x 130	Perforation	** Impact velocity of second slab	
	4,5		310 x 220	Penetration		
C1F	3,0		150 x 150	Perforation		
	6,0		300 x 190	Penetration		
C1B	6,0		170 x 150	Perforation		
	3,0		280 x 200	Penetration		
M2	9,0		270 x 170	Penetration		

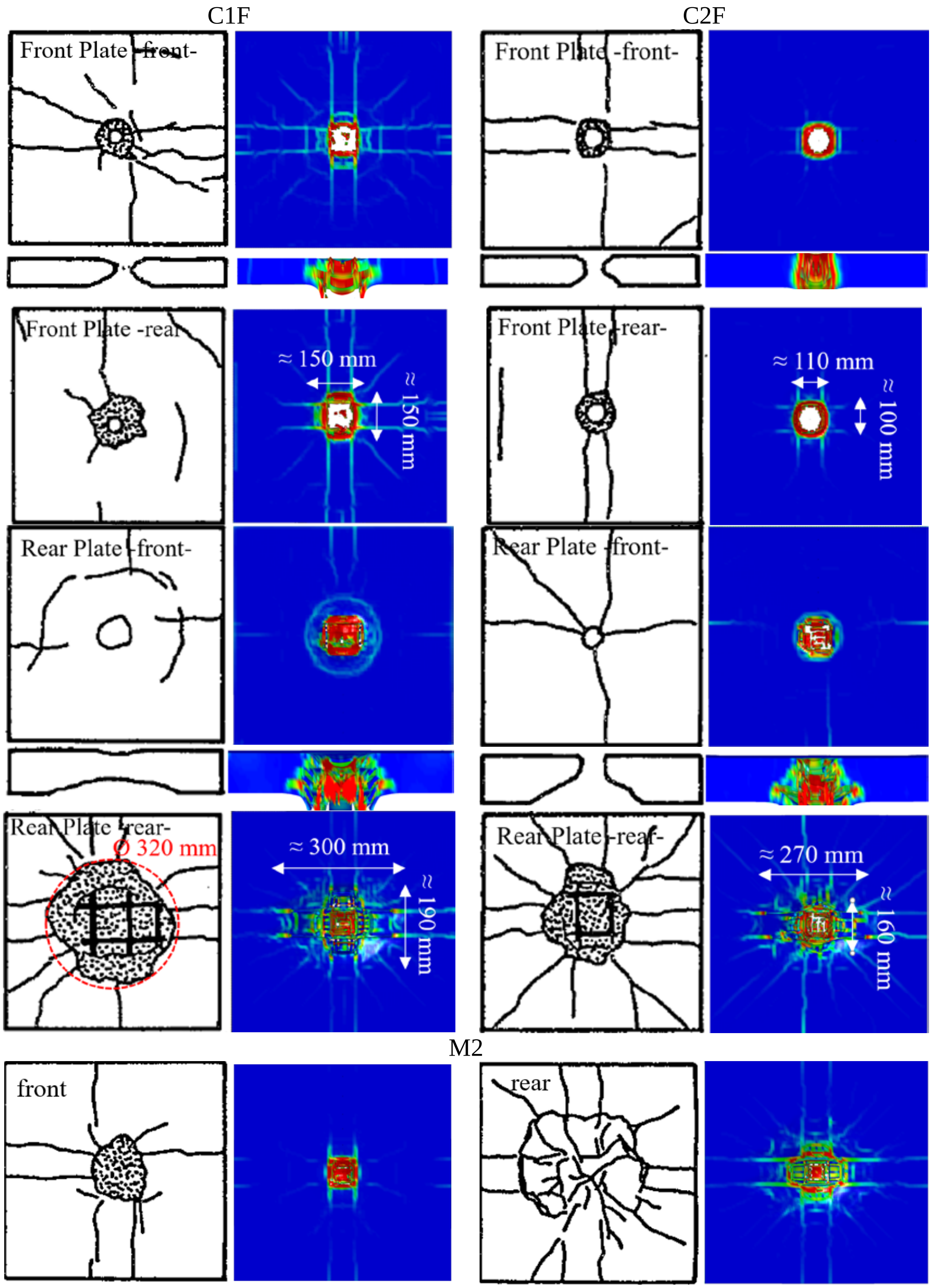


Figure 8. Scabbing area experiment in Shirai et al. (1993) and calculated

EMPIRICAL METHODS FOR PERFORATION RESISTANCE

Review of empirical formulas for perforation resistance

Several empirical approaches and different formulas already exist (Li et al. 2005). Especially for the impact of hard missiles on reinforced concrete structures in the field of nuclear engineering, a number of them have become established and are embedded in international guidelines and standards (NEI 2011, AFCN 2012, CEB 1988). Therefore, an overview of these formulas along with their application limits will first be prepared in table 5 and table 6. Table 4 gives an overview of the parameters used in the empirical formulas.

Table 4. Parameter of empirical formulas

Symbol	Name	SI-Units
$\boldsymbol{M}$	Missile mass	kg
$\boldsymbol{D}$	Missile diameter	m
$\boldsymbol{t_p}$	Perforationthickness	m
$\boldsymbol{v_p}$	Perforation velocity missile	m/s
$\boldsymbol{x_c}$	Penetration depth	m
$\boldsymbol{r}$	reinforcement	-
$\boldsymbol{\alpha_p; \alpha_c}$	Reduction factor	-
$\boldsymbol{N}$	Nose shape factor	-
$\boldsymbol{\gamma}$	Factor of steel layers	-
$\boldsymbol{\rho}$	Concrete density	kg/m³
$\boldsymbol{fc}$	Compressive strength	N/mm²

Table 5. Selected empirical formulas for perforation resistance

NDRC / Degen	$t_p = \alpha_p \cdot D \cdot \left(2{,}2 \cdot \frac{x_c}{\alpha_c \cdot D} - 0{,}3 \cdot \left(\frac{x_c}{\alpha_c \cdot D}\right)^2\right)$	Chang	$t_p = \left(\frac{61}{v_p}\right)^{\frac{1}{4}} \cdot \left(\frac{M \cdot {v_p}^2}{D \cdot f_c}\right)^{\frac{1}{2}}$
	$x_c = \alpha_c \cdot \left(4 \cdot \frac{180}{\sqrt{f_c}} \cdot M \cdot N \cdot D \cdot \left(\frac{v_p}{1000 \cdot D}\right)^{\frac{9}{5}}\right)^{\frac{1}{2}}$	CRIEPI	$t_p = 0{,}9 \cdot \left(\frac{61}{v_p}\right)^{\frac{1}{4}} \cdot \left(\frac{M \cdot {v_p}^2}{D \cdot f_c}\right)^{\frac{1}{2}}$
CEA-EDF	$t_p = 0{,}82 \cdot \frac{M^{\frac{1}{2}} \cdot {v_p}^{\frac{3}{4}} \cdot D}{{\rho_c}^{\frac{1}{8}} \cdot {f_c}^{\frac{3}{8}} \cdot D^{\frac{3}{2}}}$	RCC-CW	$t_p = \left(\frac{M}{\rho \cdot D} \cdot \left(\frac{1}{1{,}89} \cdot \left(\frac{\rho \cdot {v_p}^2}{10^6 \cdot f_c}\right)\right)^{\frac{3}{4}}\right)^{\frac{1}{2}}$
CEA-EDF-Fullard	$t_p = \left(\frac{{v_p}^{\frac{1}{2}}}{1{,}3 \cdot {\rho_c}^{\frac{1}{6}} \cdot {f_c}^{\frac{1}{2}} \cdot \left(\frac{D}{M}\right)^{\frac{2}{3}} \cdot (r + 0{,}3)^{\frac{1}{2}}}\right)^{\frac{3}{4}}$	RCC-Extended	$t_p = \left(\frac{{v_p}^2}{1{,}9 \cdot f_c \cdot \rho^{\frac{1}{3}} \cdot \left(0{,}35 \cdot \left(\frac{r}{200}\right)^{\gamma} + 0{,}65\right)^2 \cdot \left(\frac{f_c}{36 \cdot 10^6}\right)^{-\frac{1}{2}}}\right)^{\frac{3}{8}} \cdot \sqrt{\frac{M}{D}}$

A significant number of the formulas is based on experimental studies, so the application limits listed in table 6 should be noted.

Table 6. Application limits of the empirical formulas according to Table 4. (Li et al. 2005, NEI 2011, CEB 1998, Berriaud et al. 1978, AFCEN 2012)

CEA-EDF 1974	$v < 200\ m/s$ $23\ MPa < f_c < 46\ MPa$ $f_c = 46\ MPa\ für\ f_c > 46\ MPa$ $20\ kg < M < 300\ kg$ $D \leq 0{,}3\ m$ $0{,}35 < D/t_d < 4{,}17$	CEA-EDF (Full)	$45\ m/s < v < 300\ m/s$ $15\ MPa < f_c < 37\ MPa$ $f_c = 37\ MPa\ für\ f_c > 37\ MPa$ $0{,}33 < D/t_d < 5$ $0 < r < 0{,}75\ \%\ ewef$
Chang/ CRIEPI	$16\ m/s < v < 311{,}8\ m/s$ $22{,}8\ MPa < f_c < 45{,}5\ MPa$ $f_c = 45{,}5\ MPa\ für\ f_c > 45{,}5\ MPa$ $0{,}0508\ m < D < 0{,}3048\ m$ $0{,}11\ kg < M < 342{,}9\ kg$	AFCEN-RCC extended	$v < 250\ m/s$ $15\ MPa < f_c < 80\ MPa$ $f_c = 80\ MPa\ für\ f_c \geq 80\ MPa$ $0{,}25 < D/t_d < 3{,}3$ $symmetrische\ Bewehrung$
NDRC/ Degen	$25\ m/s < v < 311{,}8\ m/s$ $28{,}4\ MPa < f_c < 43{,}1\ MPa$ $f_c = 43{,}1\ MPa\ für\ f_c > 43{,}1\ MPa$ $0{,}1\ m < D < 0{,}31\ m$ $0{,}15\ m < t_d < 0{,}61\ m$	AFCEN-RCC	$v > 20\ m/s$ $25\ MPa < f_c < 45\ MPa$ $f_c = 45\ MPa\ für\ f_c \geq 45\ MPa$ $0{,}5 < D/t_d < 3{,}3$ $0{,}5 < M/(\rho \cdot t_d{}^2) < 5$ $100 kg/m^3 < Bew.gehalt\ (sym.)$ $250 kg/m^3 > Bew.gehalt\ (sym.)$

Evaluation of empirical formulas

In the following, the tests of Kojima (1991) and Shirai et al. (1993) are evaluated with the empirical formulas and compared with FE simulations. Kojima (1991) roughly estimated the projectile residual velocities to be 180 m/s (W-12-X) and 100 m/s (W-09-X) after the first slab. In the numerical simulations, the test W-12-X, the residual velocity of the first slab is calculated to be 172 m/s (figure 9, yellow line). According to figure 9, the determined perforation velocities, the velocity at which the missile just perforates the plate with v_{res} = 0 m/s, of the empirical formulas of all examined slabs of Kojima (1991) show very good agreement with the damage case perforation/penetration from the experimental investigations (figure 9, grey line).

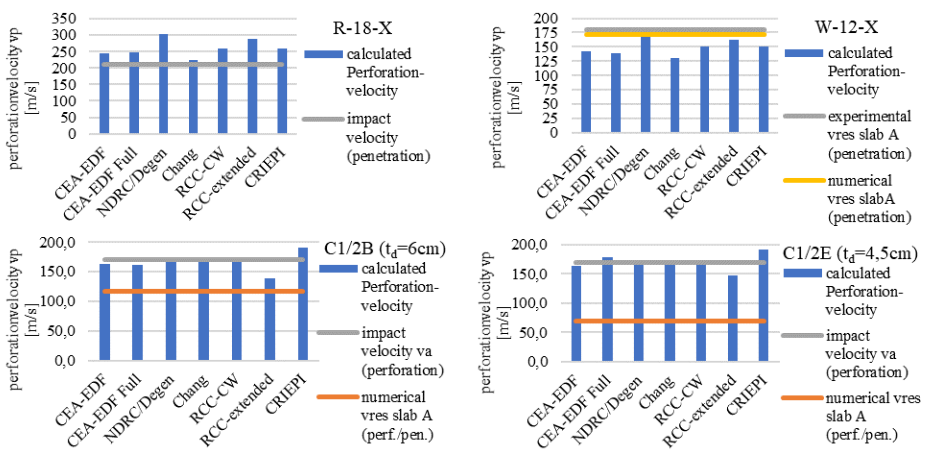


Figure 9. Calculated perforation velocity of empirical formulas and numerical simulations

For the tests of Shirai et al. (1993), the empirical formulas overestimate the perforation resistance in all tests. In some tests, the formulas indicate a perforation thickness close to the impact velocity (figure 9, grey line), but at this velocity the slab is already perforated with a high residual velocity. This conclusion is also illustrated by the numerically calculated v_{res} of plate A (figure 9, orange line), which represents the perforation velocity for the second plate of test C2E and approximately that for C2B.

CONCLUSION

In this paper, the application of empirical formulas as well as numerical simulations to describe and evaluate the damage of multiple RC structures is investigated. The damage characteristics together with the damage class perforation/penetration incl. the residual velocity of the projectile or penetration depth between the different types of barriers: thick + thin slab, thin + thick slab, two slabs of equal thickness, with/without gap, with/without steel liner as well as a monolithic slab of equal thickness in total are investigated and evaluated. The Kojima (1991) and Shirai et al. (1993) tests are used as experimental references and to verify the empirical formulas as well as damage characteristics. It is observed that in order to evaluate the damage of scabbing, spalling or cracking in the numerical tests, it is important to take into account the damage of the spalled concrete of the first slab, otherwise, underestimation of the actual damage of the slabs will be recognized. The interaction between the first and the second slab increases when the slabs are closer to each other. Also, the interaction of the two plates affects the determination of the residual velocity at perforation of the second slab in the FE simulations. However, the numerical calculations confirm the assumption of using the residual velocity of the first plate as the impact velocity on the second plate, since the rotation of the projectile and the interaction of the plates are neglected here and this energy can thus be used as the kinetic impact energy in a conservative approach (CEB 1988). Based on this, the empirical formulas for monolithic reinforced concrete slabs can also be used for multiple barriers. The empirical formulas show very satisfactory results for the tests of Kojima (1991), on the other hand, for tests of Shirai et al. (1993) did not, which could be related to the very thin RC slabs and the single-layer reinforcement. A final evaluation confirms the statements of Kojima (1991) as well as Ben-Dor (2009) that monolithic RC slabs show better resistance to hard impact loads than any type of multiple barriers. For the least scabbing, a thin steel liner on the backside is proper. To get further information about the impact resistance to multiple barriers, further experiments and data should be evaluated and analyzed together with numerical finite element simulations for soft impact and further hard impacts.

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