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PUNCHING FAILURE OF REINFORCED CONCRETE SLABS SUBJECTED TO HARD MISSILE IMPACT, PART V: SIMULATION OF RECENT TESTS WITH THE CDP-MODEL IN ABAQUS

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ABSTRACT

Civil infrastructures are subjected to impact forces, such as collisions of artificial objects or collisions under natural phenomena, depending on the location of the structures. Therefore, it is necessary to understand the basic factors that affect the behavior of reinforced concrete structures subjected to impact forces.
IMPACT4 is a jointly funded international project regarding a series of impact loading tests of reinforced concrete structures. As a member of the project, this paper presents a summary of the numerical simulations by the commercial numerical analysis code Abaqus for a wide range of fracture modes obtained from the series of tests called Increased Thickness Punching (ITP) in the IMPACT4 project that had been carried out.

INTRODUCTION

The behavior of the structures subjected to external impact forces may differ from that of the structures subjected to static or low velocity forces. Particularly, civil infrastructures are subjected to impact forces, such as collisions of artificial objects (e.g., ships, vehicles, airplanes, etc.) or collisions under natural phenomena (e.g., rockfalls, drifting objects, tornado/wind-born missiles, etc.), depending on the location of the structures. Therefore, it is necessary to understand the basic factors (e.g., type of missile, boundary conditions, and local failure) that affect the behaviors of reinforced concrete structures subjected to impact forces.

Recently in Japan, interest in the risk of aircraft impacts against nuclear facilities has increased, and it is currently recognized as one of the urgent issues for investigation of nuclear safety after the enforcement of the new regulatory standards enacted after the Fukushima Daiichi Nuclear Power Plant accident.

IMPACT4 is a jointly funded international project regarding a series of impact loading tests of reinforced concrete structures. The overview of this project is introduced in previous papers (Vepsä et al. 2022).

The series of tests called Increased Thickness Punching (ITP) in the IMPACT4 project had been carried out during the years of 2019 thru 2021. Test parameters for this series included the variety of impact velocities from 135 to 160 m/s, and thicknesses of the slabs are 300 mm to 350 mm.

The first section presents an overview of the test plan and the results of the experimental study, which is the subject of the simulation analysis. Then, a description of the analytical conditions, results, and discussion of the simulation analysis are presented.

SUMMARY OF THE EXPERIMENTAL TEST

The plan of the series of tests called ITP tests in the IMPACT4 project is presented in Table 1 compared with the reference test called P1–P3 in the IRIS project. The details of the IMPACT4 test are reported in a previous paper (Vepsä et al. 2022), and the IRIS project is reported in the literature (Vepsä et al. 2011). This test series consists of seven tests with different slab thicknesses, impact velocities, and types of projectiles as parameters, while the four tests covered in this report are listed.

Table 1: Summary of Punching Tests (P1–3, ITP1, ITP2, ITP2R).

Test ID	P1–P3	ITP1	ITP2	ITP2R
Slab Dimensions	2100 mm × 2100 mm			
Thickness	250 mm	300 mm	350 mm	
Concrete Comp. Strength	68.0 MPa	59.0 MPa	60.5 MPa	64.6 MPa
Bending Reinforcement	Ø 10 @ 90 mm			
Shear Reinforcement	N/A			
Missile Type	Type H0	Type H2		Type H3
Impact Velocities	135–137 m/s	138 m/s	149 m/s	162 m/s
Residual Velocities	33.8–45.3 m/s	25.0 m/s	0 m/s	47.5 m/s

Testing of reinforced concrete structures for various types of impact loads is being conducted in the jointly funded international project IRIS or IMPACT. Impact testing by rigid projectiles is an essential part of these series. Test parameters for this series include impact velocity, shear and flexural reinforcement ratios, and concrete strength. The various different failure modes occurred in this series, including penetration, scabbing, spalling, and perforation. In addition to these, rigid projectile tests on thicker plates were conducted to evaluate the effect on failure modes.

The projectiles used in the experiment had a sturdy steel dome in front, followed by a steel tube filled with lightweight concrete. The aluminum tail was used to estimate the residual velocity after penetration based on images taken by a high-speed camera. These projectiles had been modified and enhanced as needed. Three different projectiles had been used in the experiments listed in Table 1. Figure 1 shows the main differences between each version.

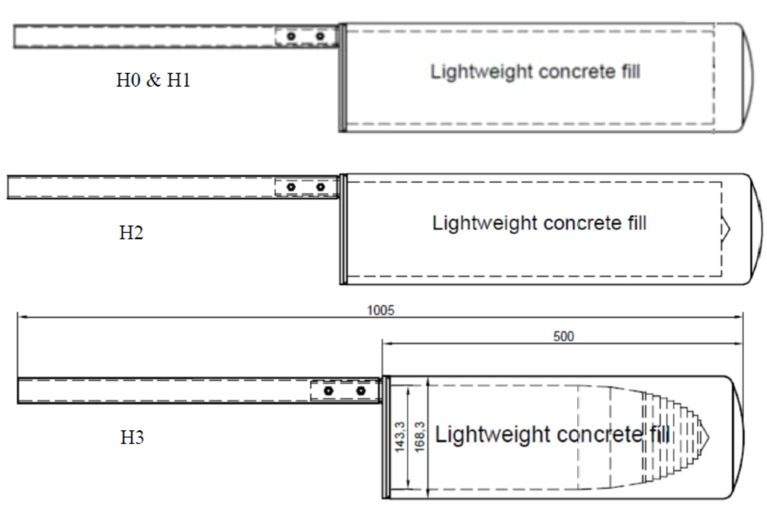


Figure 1. Types of Projectiles Used in Experiments. (Vepsä et al. 2022)

Table 2: Damage State of Projectiles (ITP1, ITP2, ITP2R)

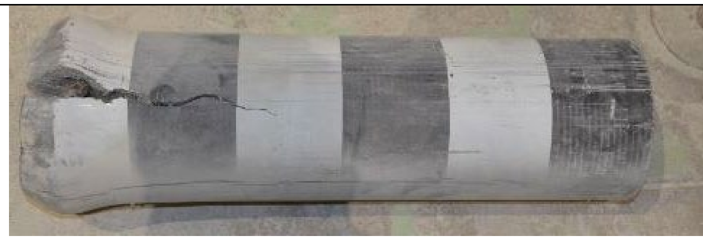
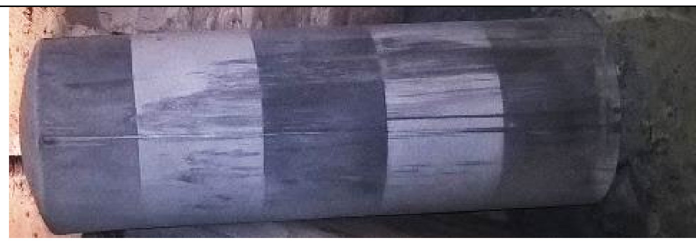
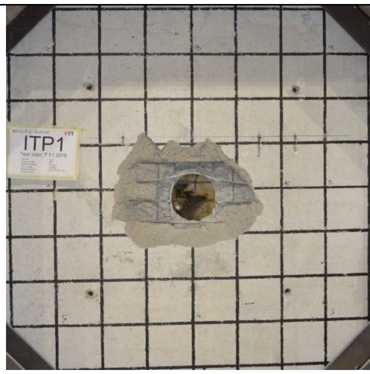
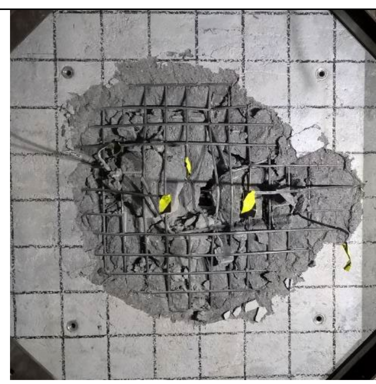
	Side View
ITP1	
ITP2	
ITP2R	

Table 3 shows the damage conditions of the RC slabs. In common, relatively small surface craters, a tunnel in the center, and wide craters due to punching failure at the rear are seen. For the rear craters, there is a tendency for a larger horizontal fracture spread, which may be attributed to the outward location of the horizontal reinforcement bars.

As described in Table 2, the ITP2 test showed the fracture of the H2 type projectile at the attachment point between the tip and the cylindrical part; therefore, the H3 type was designed to prevent fracture by making the cylindrical part thicker toward the tip.

Table 3: Damage State of RC Slabs (ITP1, ITP2, ITP2R)

	Front Side	Back Side	Section
ITP1			 Horizontal  Vertical
ITP2			 Horizontal  Vertical
ITP2R			 Horizontal  Vertical

NUMERICAL SIMULATION FOR IRIS P1

Model Description

This chapter presents the results and discussion of the numerical simulation for IRIS P1–P3 (250 mm thickness) test case.

The commercial numerical analysis code Abaqus is used, and other descriptions of this numerical simulation are listed on Table 4.

Table 4: Descriptions of numerical simulations.

Code; Version.	Abaqus/Explicit 3DEXPERIENCE R2019 HF2
Element Type	C3D8R, S4R (Reduced Integration)
Constitutive Low	Concrete Damage Plasticity Model (w/ Eroding Option)
Eroding Criterion	Plastic Tensile Strain: 0.5, Plastic Compressive Strain: 0.9
Method	Stress Deformation Analysis (Explicit/Large Deformation)

The material properties are determined on the basis of the actual strength. As a constitutive law of concrete, on the compression side, the parabola obtained from the average f_{cm} by CEB-FIP model code 1990 (CEB-FIP 1991) is replaced by polyline, and the stress-strain relationship is a linear decrease from the peak to the ultimate strain value calculated from fracture energy. On the tensile side, the stress-strain relationship is based on the maximum strength determined by the tensile strength f_{ctm} and stress displacement relationship calculated from f_{cm} by CEB-FIP model code 1990 (CEB-FIP 1991). In both cases, strain rate dependent effects based on the modified CEB-FIP model (L. J. Malvar 1998) are considered. The eroding option is considered for concrete material.

For rebar and stainless steel, a bilinear-type constitutive law connecting the yield and peak strength points is used, and a strain-rate-dependent hardening law based on the literature (E. Cadoni 2011) is considered for rebar, while the general Cowper-Symonds hardening law is considered when modeling projectiles. The eroding option is considered for steel material.

Figure 2 shows an overview of numerical simulation model. The model is quarter symmetrical, and the reinforced concrete slab, the part of the steel support, and the projectile are modeled. The reinforced concrete slab, steel support, and inner lightweight concrete are modeled with reduced integration solid elements, and the cylinder part of the projectile is modeled with reduced integration shell elements. Rebars are modeled by hexahedral solid elements with equivalent cross-sectional areas, taking into account contact-peel with concrete and other reinforcing bars. Half of the cylindrical portion of the frame that is in contact with the slab is modeled and the model cut surface is fixed.

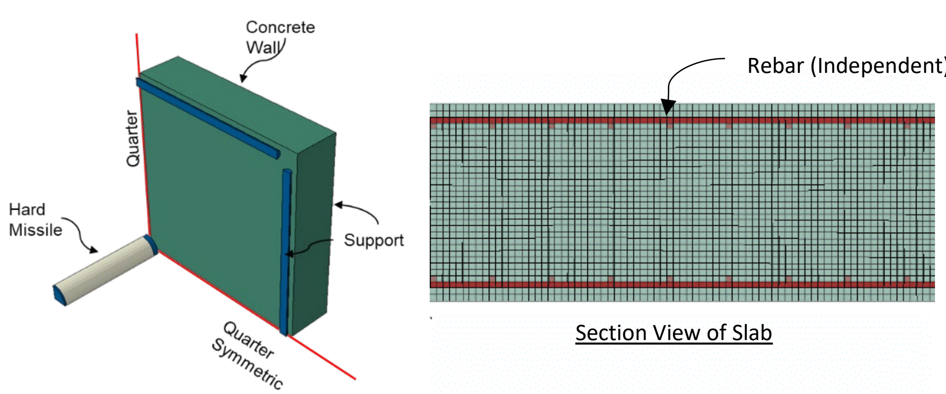


Figure 2. Overview of Numerical Simulation Model for IRIS P1.

Results and discussion

Figures 3 and 4 show the result of numerical simulation. Figures are colored by the compression damage index which represent the ratio of residual strength to maximum compressive strength calculated in Abaqus compared to sectional photographs taken after the test. Table 5 shows the residual velocities of projectiles in IRIS P1 thru P3 compared to numerical simulations.

The numerical analysis reproduces small surface craters, tunneling in the center, and wide craters due to punching failure in the back as described in the previous chapter. Also, the horizontal fracture spreading of the rear craters is reproduced with high accuracy. The residual velocity is also in good agreement with the test results.

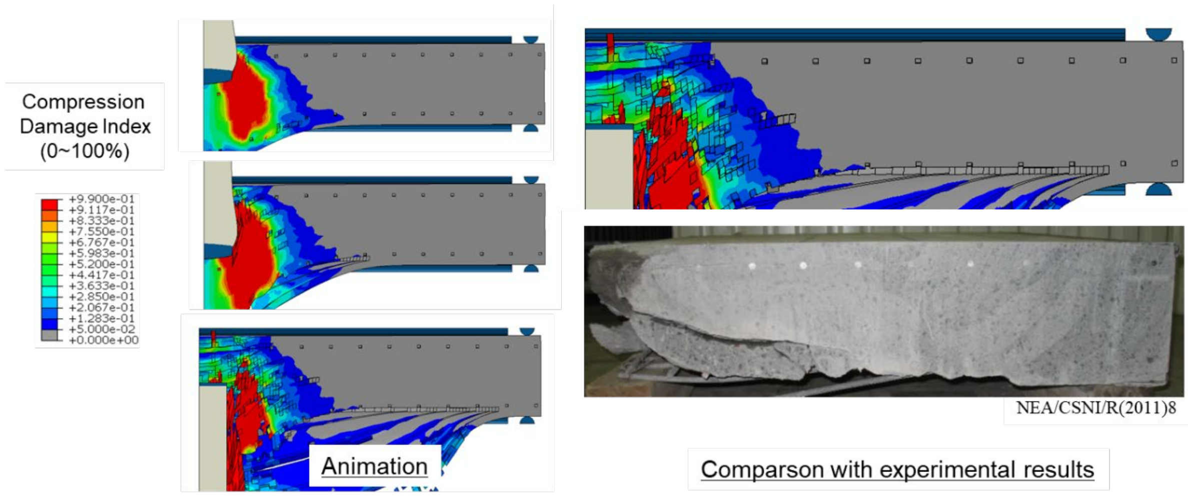


Figure 3. Animation of perforation (Left), Comparison of Damage State of the RC slab in Sectional View; Numerical (Upper Right) and Experimental (Vepsä et al. 2011) (Lower Right).

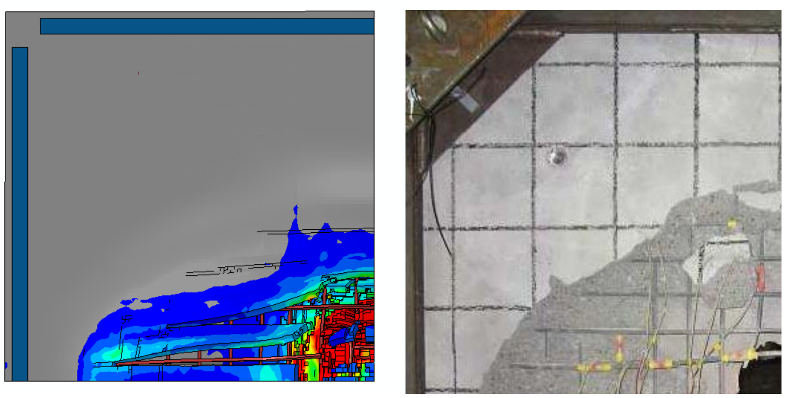


Figure 4. Comparison of Damage State of the RC slab in Rear View; Experimental (Vepsä et al. 2011) (Right) and Numerical (Left).

Table 5. Comparison of Residual Velocities Experimental vs. Numerical

Test Name	Exp. P1	Exp. P2	Exp. P3	Numerical
Initial Velocity	136 m/s	135 m/s	136 m/s	135 m/s
Residual Velocity	33.8 m/s	45.3 m/s	35.8 m/s	42.5 m/s

NUMERICAL SIMULATION FOR ITP1

Model Description

This chapter presents the results and discussion of the simulation for the IMPACT IV ITP1 test.

Figure 5 shows an overview of the numerical simulation model. The model is half symmetrical, and the cylindrical part of the projectile was changed to a solid element in consideration of the fracture. These modifications were made to improve the reproducibility of damage to the projectile. The other basic settings are the same as in the previous study.

Test Descriptions

Test Name	ITP1
Concrete Wall	2000 x 2000 x 300 (mm)
Fc	**60 (Mpa)**
Missile	Hard Missile
Impact Velocity	**137.8 (m/s)**

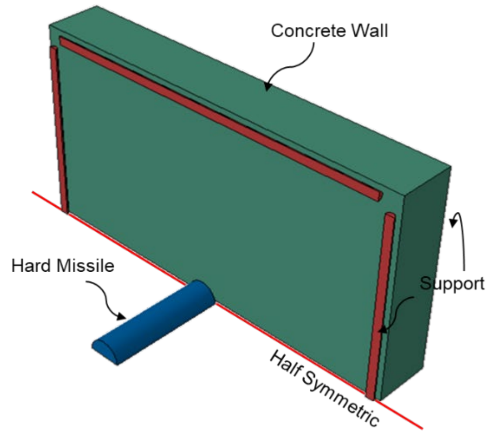


Figure 5. Overview of Numerical Simulation Model for IMPACT IV ITP1.

Results and discussion

Figure 6 shows the damage state of the RC slab compared to sectional photographs taken after the test. Table 6 shows the residual velocities of projectiles in ITP1 compared to numerical simulations.

The numerical analysis reproduces the damage and failure state as perforation described in the previous chapter. Also, the residual velocity is also in good agreement with the test results.

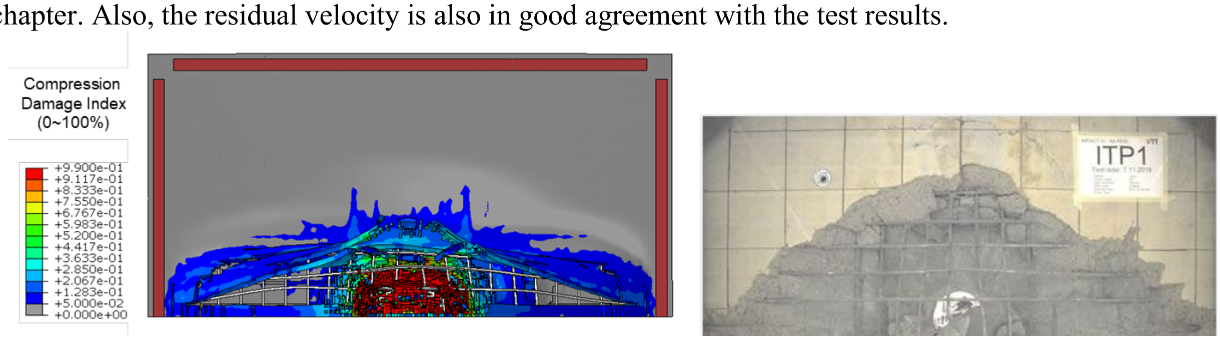


Figure 6. Comparison of Damage State of the RC slab; Experimental (Right) and Numerical (Left).

Table 6. Comparison of Residual Velocities Experimental vs. Numerical

Test Name	Exp. ITP1	Numerical
Initial Velocity	138 m/s	138 m/s
Residual Velocity	25.0 m/s	22.5 m/s

NUMERICAL SIMULATION FOR ITP2

Model Description

This chapter presents the results and discussion of the simulation for the IMPACT IV ITP2 test.

Figure 7 shows an overview of the numerical simulation model. Basic settings are the same as in the previous study for ITP1.

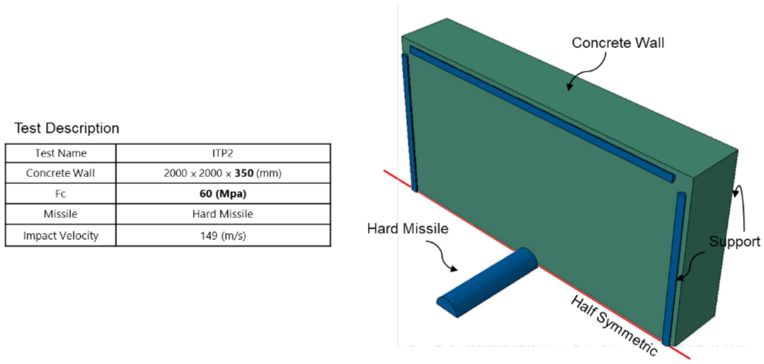


Figure 7. Overview of Numerical Simulation Model for IMPACT IV ITP2.

Results and discussion

Figures 8 and 9 show the damage state of both the RC slab and projectile compared to sectional photographs taken after the test. Table 7 shows the residual velocities of projectiles in ITP2 compared to numerical simulations.

The numerical analysis reproduces the damage and failure state as scabbing. Although there are differences in fracture modes in the projectile due to the use of symmetric models, imbalances from fabrication, or roll direction, the projectile is fracturing from a similar origin. The residual velocity is also in good agreement with the test results.

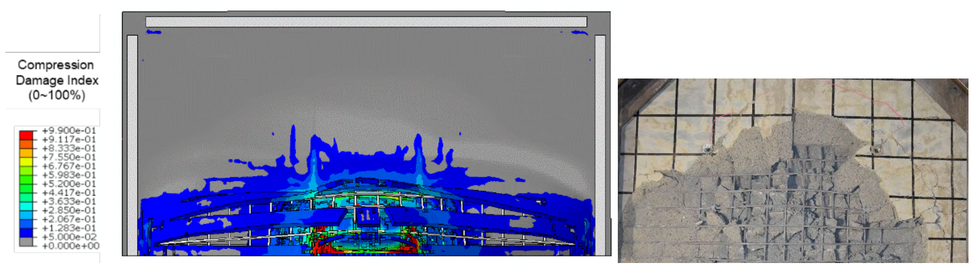


Figure 8. Comparison of Damage State of the RC slab; Experimental (Right) and Numerical (Left).

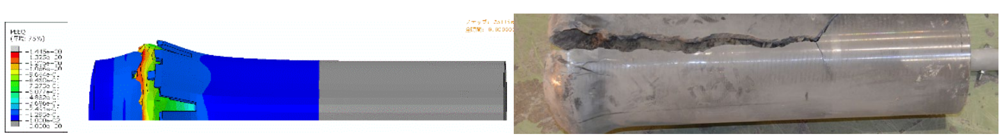


Figure 9. Comparison of Damage State of the Projectile; Experimental (Right) and Numerical (Left).

Table 7. Comparison of Residual Velocities Experimental vs. Numerical

Test Name	Exp. ITP2	Numerical
Initial Velocity	149 m/s	149 m/s
Residual Velocity	No Perforation	No Perforation

NUMERICAL SIMULATION FOR ITP2R

Model Description

This chapter presents the results and discussion of the simulation for the IMPACT IV ITP2R test.

Figure 10 shows an overview of the numerical simulation model. Basic settings are the same as in the previous study for ITP2R. The model of projectile has been replaced by the H3 type.

Test Description

Test Name	ITP2R
Concrete Wall	2000 x 2000 x **350** (mm)
Fc	**60 (Mpa)**
Missile	**New Hard Missile**
Impact Velocity	162 (m/s)

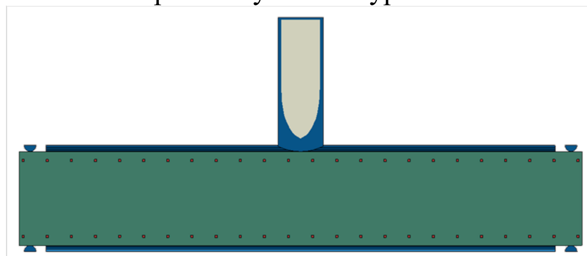


Figure 10. Overview of Numerical Simulation Model for IMPACT IV ITP2R.

Results and discussion

Figures 11 and 12 show the damage state of both the RC slab and projectile compared to sectional photographs taken after the test. Table 8 shows the residual velocities of projectiles in ITP2R compared to numerical simulations.

The numerical analysis has been able to reproduce the damage mode of the RC slab as perforaton. It also confirmed the prevention of excessive damage by modifying the projectile and the perforation of the projectile due to the reduction of energy loss. However, the residual velocity of the projectile was evaluated to be lower than the previous reproducibility. Since this test was a retest, the mixture of concrete was changed even though the strength was almost the same, and it may be possible that such conditions affected the results.

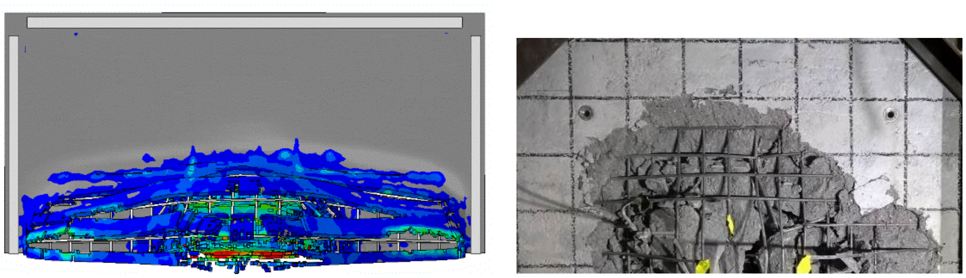


Figure 11. Comparison of Damage State of the RC slab; Experimental (Right) and Numerical (Left).

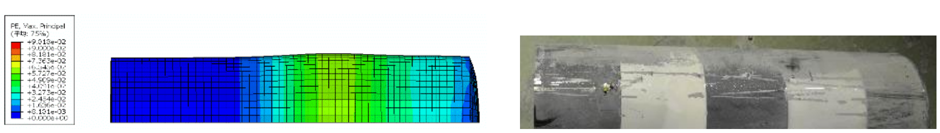


Figure 12. Comparison of Damage State of the Projectile; Experimental (Right) and Numerical (Left).

Table 8. Comparison of Residual Velocities Experimental vs. Numerical

Test Name	Exp. ITP2R	Numerical
Initial Velocity	162 m/s	162 m/s
Residual Velocity	47.5 m/s	14.4 m/s

CONCLUSION

This paper presents a summary of the numerical simulations by the commercial numerical analysis code Abaqus for a wide range of fracture modes obtained from the series of tests called Increased Thickness Punching (ITP) in the IMPACT4 project.

The first section presents an overview of the test plan and a summary of the experimental study, which is the subject of the simulation analysis. Then, a description of the analytical conditions, results, and discussion of the simulation analysis are presented.

The models are quarter or half symmetrical, and the reinforced concrete slab, part of the steel support, and the projectiles are modeled.

In all numerical analyses, the punching failure mode, such as small surface craters, tunneling in the center, and wide craters in the rear were reproduced. Also, the horizontal fracture spreading of the rear craters is reproduced with high accuracy. Regarding the projectile, the failure modes of scabbing and perforation were reproduced in each case, but the residual velocity was evaluated to be smaller for ITP2R. This may be due to the variability of the test itself and differences in the properties of the concrete material due to retests.

Throughout the numerical simulations, it appeared useful that the commercial numerical analysis code Abaqus and its CDP model with the eroding option can simulate the macroscopic behavior of a wide range of fracture modes of the punching failure mode of RC slabs and projectiles.

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