NUMERICAL SIMULATIONS OF MISSILE IMPACTS ON REINFORCED CONCRETE PLATES - IRIS 2010 BENCHMARK TEST

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ABSTRACT

This paper describes procedures and results of numerical simulations of 3 test cases in the framework of the IRIS-2010 project under OECD/NEA IAGE working group. The first numerical analysis was performed on the MEPPEN test II-4, which was conducted at the end of the seventies in Germany. Two other numerical analyses were done on the VTT tests, which were conducted for two kinds of failure mode, bending and punching, in 2010 at VTT research center in Finland. Three impact simulations were performed using explicit FEM code LS-DYNA. The CSCM concrete model was applied and the strain-rate effects of materials, such as concrete, rebar and missile steel, were considered for the analysis. The erosion of element was also allowed. The simulation results were compared with the test results in the aspect of behavior of missile and concrete plate such as missile deformation, concrete plate displacement, concrete damage characteristics, etc.

INTRODUCTION

From February to December of 2010, IRIS-2010 project [1] was performed by OECD/NEA IAGE working group. In the framework of this project, experimental missile impact tests on two types of concrete plates were performed, and numerical simulation of the experiments were also performed blindly by 27 teams of various countries including Korea. When submission of numerical simulation results was done, the results of experimental tests were opened, and participants discussed about the simulation procedures, techniques, and results during the workshop held by the organizing committee of the project.

As a participant of the project, KINS, Korea Institute of Nuclear Safety, also performed numerical simulations, and the procedures and results of the numerical simulations are described in this paper. The first numerical analysis was performed on the MEPPEN test II-4, which was conducted at the end of the seventies in Germany. Two other numerical analyses were done on the VTT tests, which were conducted for two kinds of failure mode, bending and punching, in 2010 at VTT research center in Finland.

During the modeling and simulation period, several technical decisions were needed such as selection of element type, material model, and modeling of boundary condition. Due to the time limit, sufficient sensitivity study could not be performed for the major influence factors and consequently, the simulation results showed considerable discrepancy with experimental test results. Therefore, follow-up research is now in progress, and the influences of various uncertain factors on the simulation are being investigated.

BASIC CHOICES AND PRELIMINARY INVESTIGATIONS

Material Model

LS-DYNA [2] was adopted for the simulations of the three cases since it is one of the widely utilized software for collision simulation in various fields including vehicle design and roadside safety engineering. LS-DYNA is an explicit FEM code, and it is widely known that explicit code gives reliable results for short duration contact analysis. Also, LS-DYNA provides various kinds of material models including metals, foams, soils, and concretes. Among over 300 kinds of material models, "*MAT_CSCM_CONCRETE", "*MAT_PIECEWISE_LINEAR_PLASTICITY", and "*MAT_PLASTIC_KINEMATIC" were selected for the concrete and steel materials. The CSCM concrete model was developed by FHWA for roadside safety applications in 2007 [3, 4], and supports strain rate effect, elasto-plastic damage behavior, and erosion of elements. This concrete material model was selected for concrete plate modeling since this model is one of the most recently developed models for impact analysis. However, the developers of this model suggest using CSCM concrete model for normal strength concrete with compressive strengths between 28 and 58 MPa, thus, modeling high strength concrete using this material model might cause erroneous results in simulation analysis. Among three simulation cases, two VTT test cases utilized high strength concrete with average 63.9 MPa, therefore, preliminary validation analysis was performed. Uni-axial compression test of cubic specimen with compressive strength 63.9 MPa was simulated with CSCM concrete model and the result is shown in Fig. 1. As shown in the figure, the numerical model shows approximately 6% lower compressive strength than input value, 63.9 MPa. To compensate this, input value might be increased appropriately, but input adjustment was not applied in this research since 6% error was considered within the range of deviation of material test results.

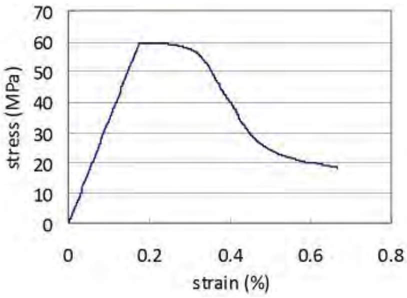


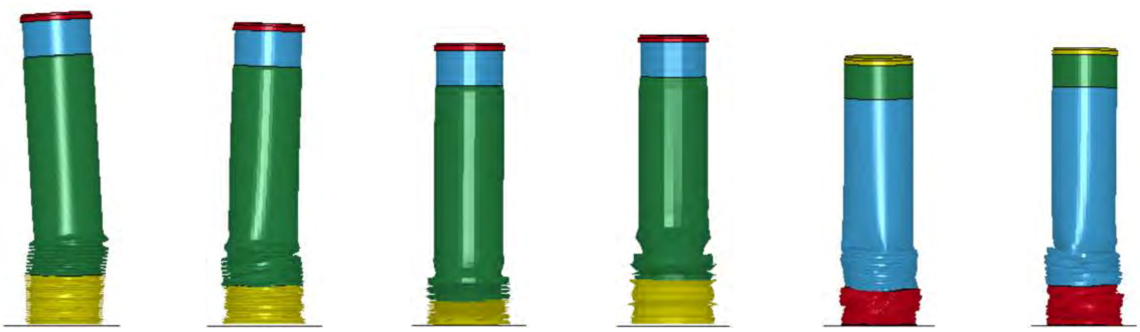
Fig. 1: Simulated stress-strain curve of high-strength concrete (63.9MPa)

"*MAT_PIECEWISE_LINEAR_PLASTICITY", and "*MAT_PLASTIC_KINEMATIC" were utilized for modeling of missile steel and rebar steel, respectively, since these models are one of the most widely used material model for metal, and include strain rate effect in the models.

Modeling of Missile

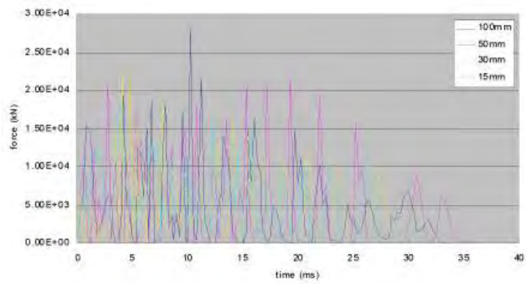
Major part of the projectiles of impact test is steel pipe, therefore, shell element is the most rational type of element for general purpose numerical analysis. However, special care has to be taken with shell element when it is applied for impact simulation since missile experiences local buckling, and is corrugated during the process of impact. In particular, impact force has to be simulated properly during impact. Therefore, several types of missile models were constructed with different element types (shell and solid) and various element edge lengths, and the behaviors were compared. In the following Fig. 2, deformed shapes obtained from the investigated numerical models are shown with the corresponding element type and edge length.

Missile models were impacted to rigid wall and contact forces were calculated and compared. Time histories of contact forces are shown in Fig. 3. As shown in the figures, contact forces using solid elements show more realistic shapes. Although longer calculation time is required for solid elements, solid element was selected to achieve realistic time histories of contact forces. To reduce calculation time while still achieving proper shape of corrugating deformation, shorter edge length in the longitudinal direction was selected. Furthermore, the longitudinal edge length is varied according to the thickness of pipe plate. Missile model of MEPPEN test is shown in Fig. 4 with pipe thickness and corresponding longitudinal edge lengths.

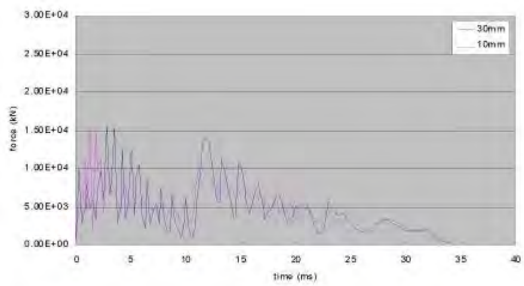


(a) shell - 15mm (b) shell - 30mm (c) shell - 50mm (d) shell - 100mm (e) solid - 10mm (f) solid - 30mm

Fig. 2: Deformed shape of investigated missile models



(a) shell elements



(b) solid elements

Fig. 3: Contact force time histories

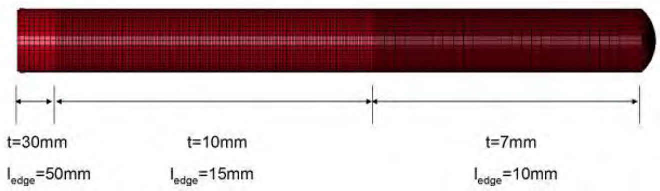
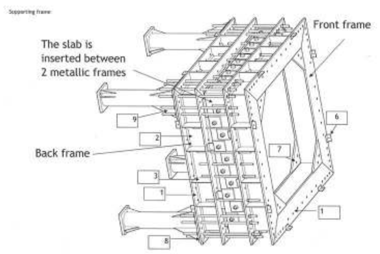


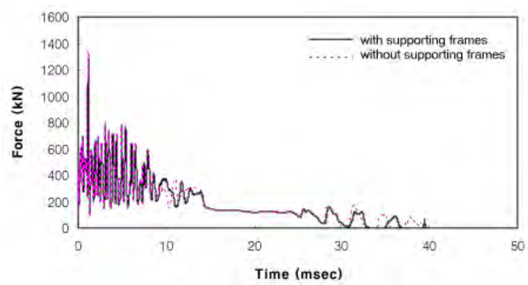
Fig. 4: Missile model of MEPPEN test

Boundary Conditions

During the impact test, concrete plate is fixed by supporting frames as shown in Fig. 5(a). If the supporting frames are rigid enough and give negligible effect to the structural behavior of the concrete plate under impact, then they can be simply replaced by boundary conditions applied directly to the concrete plate without modeling supporting frames. To investigate the effect of the supporting frames on the time history of contact force, comparative analyses were performed with and without supporting frames. As shown in Fig. 5(b), differences in contact force between two cases are negligible, therefore, the supporting frame was excluded in the modeling to reduce computational time of numerical simulations.



(a) Supporting frames [1]



(b) Comparison of simulated contact forces

Fig. 5: Effect of the supporting frames to the contact forces

Modeling of Rebar

There are two methods of incorporating rebar into the concrete mesh. One is to use common nodes between the rebar and concrete, and the other is to couple the rebar to the concrete via the *CONSTRAINED_ LAGRANGE_IN_SOLID command [4]. In this study, the first method, using common nodes, was adopted. Therefore, unnecessary large computation time was consumed due to the fine mesh locally generated to match locations of nodes. Application of the second method is now in progress, and considerable reduction in computation time is expected. In the following Fig. 6, an example of generated mesh is shown.

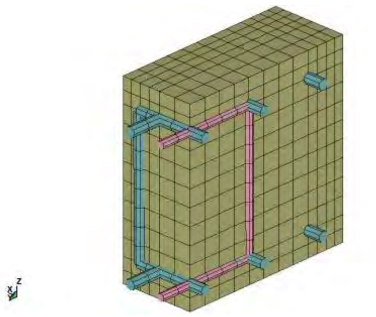


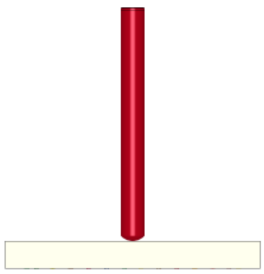
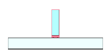
Fig. 6: Incorporating rebar into the concrete mesh by using common nodes

NUMERICAL SIMULATION OF THE THREE IMPACT TESTS

Overview of the impact tests

Within the boundary of this numerical simulation study, three experimental impact tests were considered such as MEPPEN test II-4 [5], which was conducted at the end of the seventies in Germany, and two VTT tests, which were conducted for two kinds of failure mode, bending and punching, in 2010 at VTT research center in Finland. Size of the projectiles and the concrete plates, impact speed, and expected failure modes are summarized in the following Table 1.

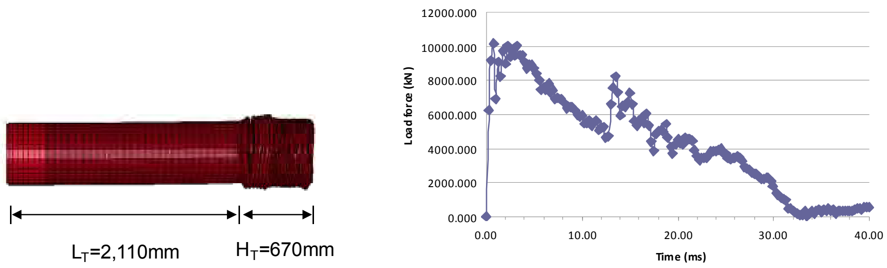
Table 1: Overview of the three impact tests

	MEPPEN II-4	IRSN-VTT	IRSN-CNSC-VTT
Overall shape			
Plate size (m)	6.5 × 6.0 × 0.7	2.1 × 2.1 × 0.15	2.1 × 2.1 × 0.25
Missile size (L×D) (m)	5.99 × 0.60	2.11 × 0.25	0.64 × 0.17
Missile mass (kg)	1016	49.99	47.0
Impact velocity (m/s)	247.7	110	135
Failure mode	Bending	Bending	Punching shear

Simulation result 1: MEPPEN II-4

Calculated shock duration was about 28 ms, and the speed of the missile decreased to zero after the shock ended. Vibration of the target ceased at about 60 ms, which was 32ms after the shock ended. Calculated maximum impact force was 10.3 MN. Total length of the missile decreased to 2.78 m from initial length 5.99 m. Deformed shape of the missile and calculated impact force are shown in Fig. 7.

Significant results obtained from experiments are summarized in Table 2. As listed in the table, a peak load obtained from the simulation is about 21.4% lower than the experimental result, and the deformation of the missile is also underestimated by the simulation. Therefore, it can be interpreted as follows. The model is less stiff than the actual slab specimen, or the model is stiffer than the actual missile specimen.



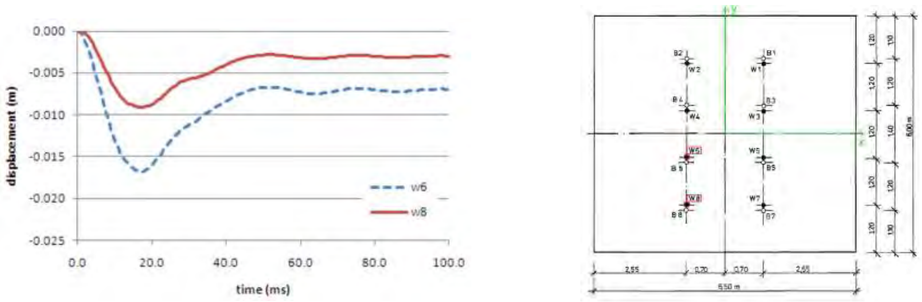
(a) Deformed shape of missile (b) Impact force time history

Fig. 7: Missile behavior of MEPPEN II-4 simulation

Table 2: Comparison of simulation and experiment results of MEPPEN II-4 test

Response	Experiment	Simulation	Error
Load peak	13.1 MN	10.3 MN	-21.4 %
Shock duration	26 ms	28 ms	7.1 %
L_T of missile	1450~1540 mm	2110 mm	41.1 %
H_T of missile	640 mm	670 mm	4.7 %

Obtained displacement time histories and measurement locations are shown in Fig. 8 and the maximum displacements are compared with the experiment results as shown in Table 3. Calculated maximum displacements are around 50% of the experiment results.



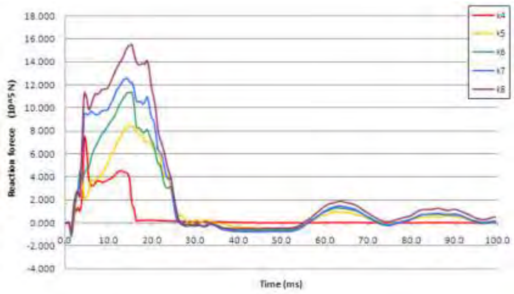
(a) Displacement time history (b) Measurement location

Fig. 8: Deformation of concrete plate of MEPPEN II-4 simulation

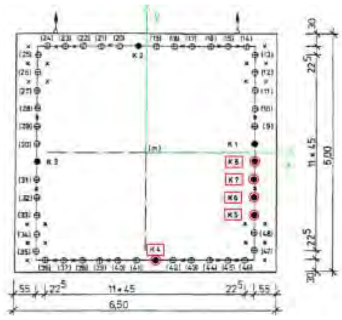
Table 3: Comparison of maximum plate displacement of MEPPEN II-4 test

Location	Experiment	Simulation	Ratio
W6	42mm	17mm	40.5 %
W8	16mm	9mm	56.3 %

Reaction force time histories of the selected supports and the locations of the supports are shown in Fig. 9. The maximum reaction forces are also compared with the experiment results in Table 4. Calculated maximum reaction forces in the vertically arranged supporting points (k5 ~ k8) are approximately twice of the experimental results; however, the maximum reaction force of k4, located at the lower horizontal support line, is close to the experimental result.



(a) Reaction force time history



(b) Measurement location

Fig. 9: Reaction force of concrete plate of MEPPEN II-4 simulation

Table 4: Comparison of maximum reaction force of MEPPEN II-4 test

Location	Experiment	Simulation	Ratio
K4	0.89 MN	0.75 MN	88.2 %
K5	0.30 MN	0.85 MN	283.3 %
K6	0.52 MN	1.14 MN	219.2 %
K7	0.66 MN	1.25 MN	189.4 %
K8	0.81 MN	1.55 MN	191.4 %

Plate damage patterns of front surface, rear surface and vertical section are shown in Fig. 10. Radial cracks and spalling (erosion of elements) is observed on the front side of the plate.

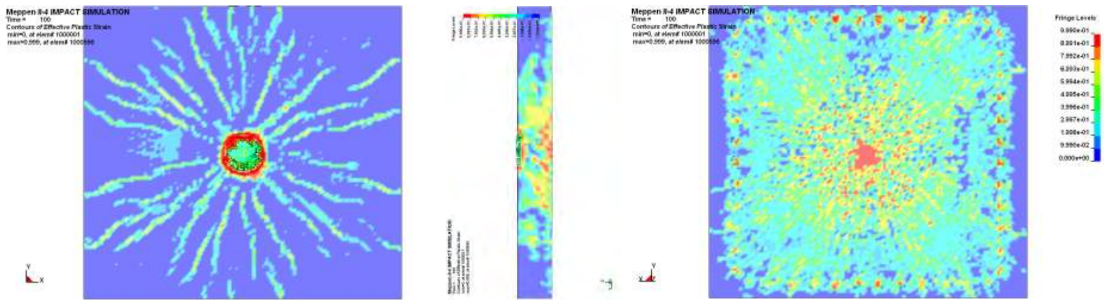


Fig. 10: Damage pattern of concrete plate of MEPPEN II-4 simulation

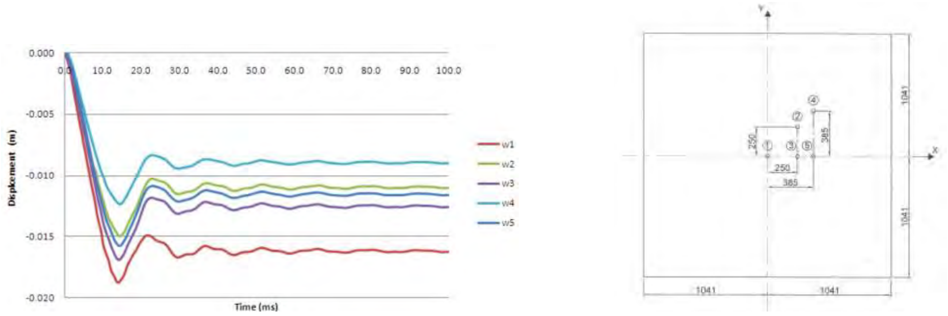
Simulation result 2: IRSN-VTT

The calculated shock duration was about 14 ms, and the calculated maximum impact force was 0.588 MN. Since impact force was not measured during the experimental test, forces were not compared with experiment results. Deformations of the missile are compared in Table 5. Similarly to the MEPPEN case, missile deformations were also underestimated.

Table 5: Comparison of simulation and experiment results of IRSN-VTT test

Response	Experiment	Simulation	Error
L_T of missile	930~970 mm	1295 mm	36.3 %
H_T of missile	160~210 mm	169 mm	-8.6 %

Displacement time histories and measurement locations of concrete plate are shown in Fig. 11 and the maximum displacements are compared with the experimental results in Table 6. Since the experimental test was performed twice with the same test conditions, two sets of the experimental results were averaged and listed in Table 6. Calculated maximum displacements are around 30~60% of the experimental results.



(a) Deformation time history (b) Measurement location

Fig. 11: Deformation of concrete plate of IRSN-VTT simulation

Table 6: Comparison of maximum plate displacement of IRSN-VTT test

Location	Experiment	Simulation	Ratio
W1	30.5 mm	18.0 mm	59 %
W2	22.5 mm	6.6 mm	26 %
W3	24.0 mm	7.4 mm	31 %
W4	16.0 mm	5.0 mm	31 %
W5	20.5 mm	5.8 mm	28 %

Plate damage patterns of front surface, rear surface and vertical section are shown in Fig. 12. Damage on contact area of front surface and diagonal bending cracks on rear surface is observed.

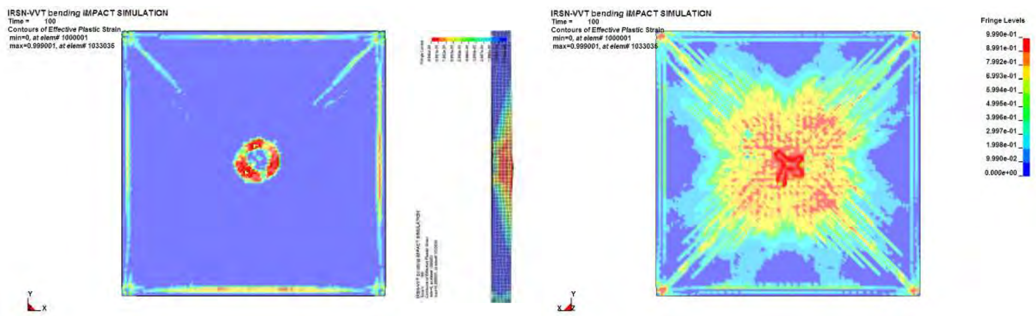
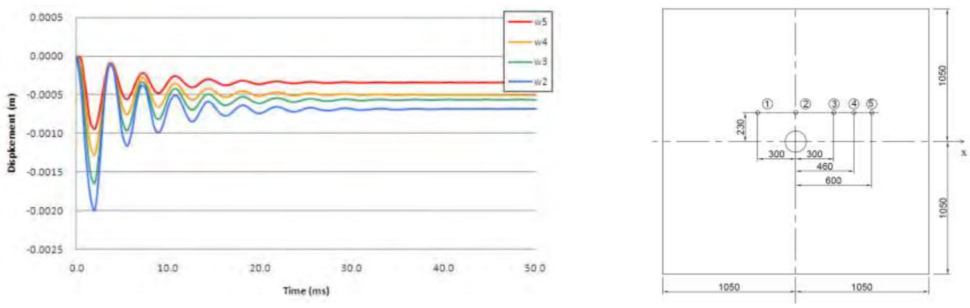


Fig. 12: Damage pattern of Concrete plate of IRSN-VTT simulation

Simulation result 3: IRSN-CNSC-VTT

For the punching mode impact test, concrete filled rigid missile was used. Therefore, shorter impact duration was observed and missile was slightly deformed elastically in simulation. Calculated shock duration was about 6.3ms, and the maximum impact force was 2.714 MN. Since impact force was not measured during the experimental test, comparison of forces between two cases was not done.

Displacement time histories and measurement locations of concrete plate are shown in Fig. 13 and the maximum displacements are compared with the experimental results in Table 7. After the experimental test was performed twice with the same test conditions, two sets of experimental results were averaged and listed in the table. Calculated maximum displacements are around 30~40% of the experimental results.



(a) Deformation time history (b) Measurement location

Fig. 13: Deformation of concrete plate of IRSN-CNSC-VTT simulation

Table 7: Comparison of maximum plate displacement of IRSN-CNSC-VTT test

Location	Experiment	Simulation	Ratio
W2	5.1 mm	2.0 mm	39 %
W3	4.4 mm	1.6 mm	36 %
W4	4.1 mm	1.3 mm	32 %
W5	3.0 mm	0.9 mm	30 %

Plate damage patterns of front surface, rear surface and vertical section are shown in Fig. 14. Projectile perforated the target and severe damage is observed on the rear side of the plate.

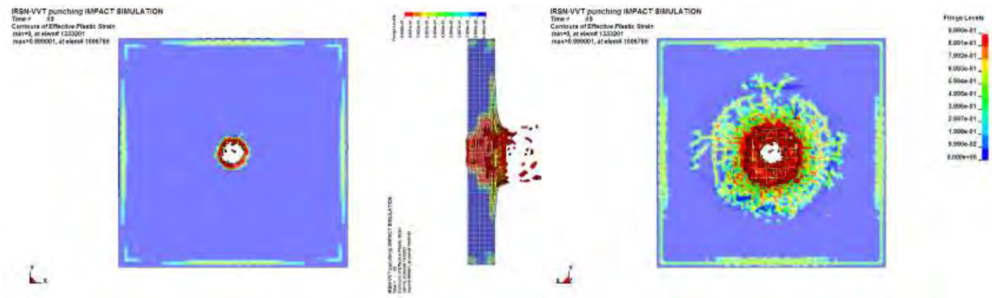


Fig. 14: Damage pattern of concrete plate of IRSN-CNSC-VTT simulation

CONCLUSION

Three numerical impact simulations were performed using the explicit FEM code LS-DYNA, and the simulation results were compared with the experimental results. Through the three simulation cases, underestimated impact forces and plate displacements were consistently observed.

Several presumptive causes for this discrepancy such as overestimated strain rate effect, simplified modeling of boundary condition, effect of material input parameters, etc. have been discussed among the participating researchers, and follow-up research including investigation of the influences of various uncertain factors is now in progress.

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