Reinforced Concrete Punching Failure Modeling with Ansys LS-Dyna

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Abstract

Reinforced concrete (RC) structures have been used to protect critical energy infrastructure against accidental and malicious impacts. Wind-borne and man-made projectiles with high velocities can impact the outer shell structures, causing significant damage and potentially leading to a collapse. Studying the punching resistance of thinner and thicker slabs with and without shear reinforcement is an ongoing topic of research, and there are multiple full-scale impact tests available for validating the modeling techniques.

In the current studies, the punching failure of RC slabs, subjected to impacts with blunt-nosed hard or semi-hard steel projectiles, is investigated. The pre- and post-processing are fully performed using Ansys tools – SpaceClaim, Mechanical and LS-PrePost. The mesh-free Smoothed Particle Galerkin (SPG) method was employed for the concrete slabs, and it is coupled with the 3D beam-modelled layout of the reinforcement, to ensure close resemblance of the actual geometry.

The simulation results are compared against the results of multiple full-scale impact tests. The developed methodology is used for applying the techniques learned in more complex projectile-target interactions scenarios, where the severe scabbing, penetration, spalling and perforation failure of the reinforced concrete structures can compromise the functionality of the safety-critical infrastructure.

1 Introduction

Reinforced concrete (RC) structures are commonly used as protective structures in various industries, where critical infrastructure needs to remain intact, ensuring the safe operability of the equipment. The design of such protective structures requires a careful selection of the concrete thickness and cross-sectional dimensions, but specific attention is also needed for the layout of the steel reinforcement – the spacing between the rebars, the usage of shear reinforcement, ensuring proper anchoring etc. It is shown that concrete pre-stressing as well as the presence of a steel liner also positively influences the perforation resistance.

The study described in this paper aims to test the applicability of the Smoothed Particle Galerkin (SPG) method, available in LS-Dyna, for modeling punching failure of reinforced concrete slabs, impacted by hard missiles. The modeling technique is going to be tested in various impact scenarios, allowing studying the influence of the different input parameters, and ultimately validating the simulation results against publicly available test data.

For the numerical validation purposes, multiple impact tests, performed at the Technical Research Center of Finland (VTT) as part of project IMPACT – Phase I as well as Phase IV, were identified as suitable.

Test Phase I [1] included 3 punching tests P1, P2 and P3, where 3 similar impact tests of 250 mm thick RC slabs were conducted with missile velocities around 135 m/s. No shear reinforcement was present in the RC slabs. The residual velocities are measured in each of the P-tests, and images of the front and rear faces of the damaged slabs were presented as well.

The Phase IV test series consisted of Increased slab Thickness Punching (ITP) tests, where 350 mm thick RC slabs with different concrete strengths were impacted by hard missiles. Shear reinforcement in the form of T-headed bars was present in some of the ITP tests. It is reported that in tests ITP2 and ITP4 the missiles didn't behave as hard missiles, and some undesired fracture failure has been observed [2][3]. The tests have been repeated with strengthened missiles and were designated as ITP2R and ITP4R. Test ITP2R has the intended target velocity closely matched (162 m/s), but test ITP4R didn't match it (achieved was "only" 144 m/s) [3]. For that and other reasons, both tests were again repeated (ITP2RR and ITP4RR), and for these two it was reported that the target concrete strength was not reached.

Out of the ITP test series, for the current study only the ITP2R and ITP4R tests have been selected and, combined with the Phase I P-tests, can be grouped in three groups, that can generally be distinguished as follows – 250mm thick slabs without shear reinforcement, 350mm thick slabs without shear reinforcement, and 350mm thick slabs with shear reinforcement. A detailed summary of the test details is presented in Table 1.

Test	**P1 / P2 / P3**	**ITP2R**	**ITP4R**
	IMPACT Phase I	IMPACT Phase IV	IMPACT Phase IV
Slab Thickness	250 mm	350 mm	350 mm
Concrete Compressive Strength	67.1 / 64.7 / 64.9 MPa	64.5 MPa	63.6 MPa
Bending Reinforcement	A500HW Ø10 @ 90 mm	B500B Ø10 @ 90 mm	B500B Ø10 @ 90 mm
Shear Reinforcement	No	No	Yes, Ø12 T-headed bars
Impact Velocity	136 / 135 / 136 m/s	162 m/s	144 m/s
Residual Velocity	33.8 / 45.3 / 35.8 m/s	48 m/s	-
Penetration	-	-	150 mm

Table 1. Details of the selected tests

As evident from the table above, for all selected tests the residual velocities or the penetrations have been reported (depending on whether the missile perforates or penetrates). These will be used as validation criteria together with the images of the damaged RC slabs.

2 Modeling Approach

The entire pre-processing is performed using the following Ansys tools – SpaceClaim for the geometry, Workbench / Engineering Data for the material model definitions, Mechanical Meshing for the meshing, Mechanical for the analysis setup, the connections, the initial and the boundary conditions. Post-processing was performed using LS-PrePost. [4][5]

2.1 Geometry

The geometry has been created with Ansys SpaceClaim using solid, surface and line bodies. Shared topology was used for the missile multi-body part and to connect curved line bodies representing individual rebars into single parts. Grouping was also used wherever necessary to organize the part tree structure. Fig.1 and Fig.2 show the geometry models of the missiles and the RC slabs used in the selected tests.

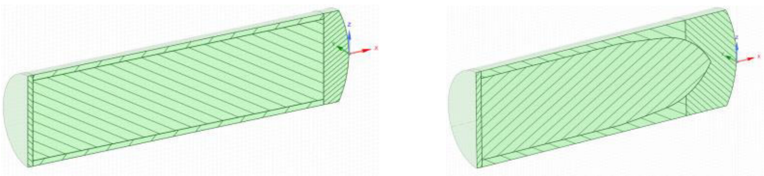

Fig.1. Missile geometry models in P1/P2/P3 tests (left) and ITP2R/ITP4R tests (right)

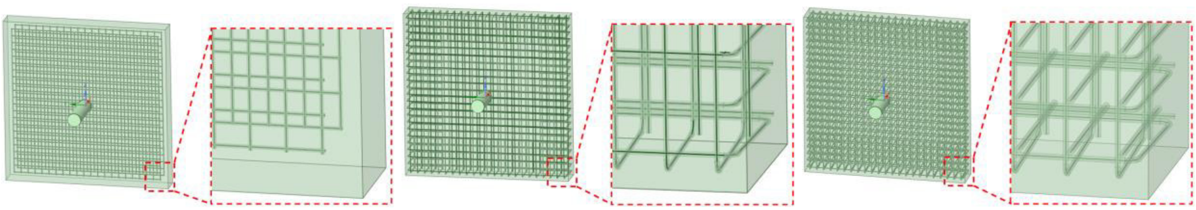

Fig.2. RC slab geometry models in the P1/P2/P3 tests (left), ITP2R (middle) and ITP4R (right) tests

2.2 Material Models

The elastic, plastic, damage and failure behaviors of the materials in the tests are described using the material models available in LS-Dyna. The missile steel material has an elastic perfectly plastic behavior, while the concrete infill is purely elastic. The concrete of the RC slab is modeled using

***MAT_CSCM**, while for the reinforcement ***MAT_PIECEWISE_LINEAR_PLASTICITY** was used. The material input parameters used are based on material information provided in [1], [2] and [6].
The Workbench Engineering Data supports the definition of many LS-Dyna-specific material models. All material models except for the ***MAT_CSCM** have been specified in the Engineering Data. ***MAT_CSCM** has been defined using a keyword snippet under the geometry part in Mechanical.

2.3 Meshing

The mesh was entirely generated with Ansys Mechanical Meshing. A global mesh sizing of 20mm is used. The standard Lagrangian mesh has been used for meshing the concrete slab, and the default formulation was changed to ***SECTION_SOLID_SPG** using a “Section” object.
Additionally, for the concrete slab a progressive mesh sizing has been defined, Fig.3 presents the gradual coarsening the particles away from the impact location. Fig.4 presents the reinforcement mesh across the thickness of the slabs for ITP2R and ITP4R.

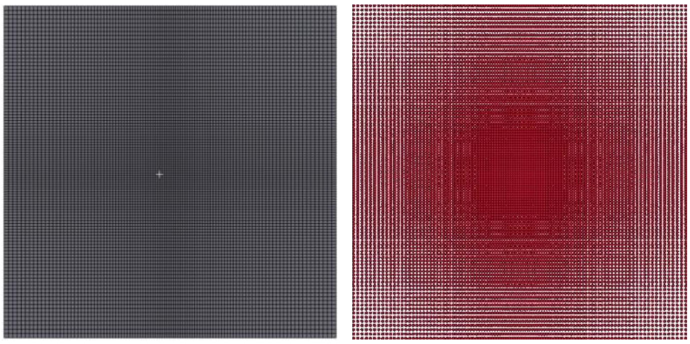

Fig.3. Concrete slab mesh in Mechanical (left) and SPG visualization in LS-PrePost (right)

Fig.4. Top view of the reinforcement mesh for ITP2R (left) and ITP4R (right)

2.4 Connections

Various connection types have been used to allow for the meshes of the different parts to interact. ***CONTACT_AUTOMATIC_GENERAL** definition has been used for the missile-reinforcement frictional contact, and ***CONTACT_AUTOMATIC_NODES_TO_SURFACE** for the concrete-missile frictional contact. For the concrete-reinforcement connection, a ***CONSTRAINED_IMMERSED_IN_SPG** keyword is used, and for the SPG particle-to-particle self-contact, a ***CONTACT_SPG** has been defined. Table 2 presents a summary of all the part-to-part connections in a matrix form.

Model Parts	Missile	Concrete slab	Reinforcement
Missile	-	***CONTACT_AUTOMATIC_NODES_TO_SURFACE**	***CONTACT_AUTOMATIC_GENERAL**
Concrete Slab	***CONTACT_AUTOMATIC_NODES_TO_SURFACE**	***CONTACT_SPG**	***CONSTRAINED_IMMERSED_IN_SPG**
Reinforcement	***CONTACT_AUTOMATIC_GENERAL**	***CONSTRAINED_IMMERSED_IN_SPG**	***CONTACT_AUTOMATIC_GENERAL**

Table 2. Part-to-part connections in the models

Both the ***CONSTRAINED_IMMERSED_IN_SPG** and the ***CONTACT_SPG** are inserted using keyword snippets, while the contacts have been defined by the “Frictional Contact” and the “Body Interaction” objects.

2.5 Initial and Boundary Conditions

Initial velocity with normal incidence is defined for the missile part using the “Initial Velocity” object, which defines the ***INITIAL_VELOCITY_GENERATION** keyword. The slabs in the tests have been simply supported using steel cylinders, but for the simulations they have been replaced by fixed supports at the 4 side faces of the concrete slab. This follows the assumption that the most significant damage and failure would rather be local, i.e. at the center of the slab. A ”Fixed Support” object has been used, which defines the ***BOUNDARY_SPC** keyword for all SPG particles lying in the side faces.

2.6 Damage and Failure Modeling

The ***MAT_CSCM** has an in-built damage model [7] where the damage constant, **d**, incrementally evolves from 0 to 1, where 0 defines an un-damaged state and 1 defines complete damage. In the SPG method failure is defined by the means of a bond failure mechanism. If a material model has a damage law associated with it, and when using IDAM=1 in ***SECTION_SOLID_SPG**, then the FS parameter defines the critical value of the damage parameter which triggers bond failure. For the ***MAT_CSCM** concrete model, FS=0.99 combined with STRETCH=1.01 has been used.

3 Simulation Results and Comparison

Both the damage of the RC slabs and the residual velocities and maximum penetrations have been used for the validation of the numerical models.

3.1 Damage of the RC slabs

Due to the repetitive nature of the P-series tests, the simple average values of the concrete compressive strength (65.6 MPa), the missile mass (47.5 kg] and the impact velocity (135 m/s] have been used as input for the simulations. Similarly, the simple average of the residual velocity (38 m/s) has been used as output for result comparison.

Images from the front and back faces of the RC slabs have been compared with those from the LS-Dyna simulations. A comparison for the P-series test is presented in Fig.5, while Fig.6 and Fig.7 present the ITP2R and ITP4R tests.

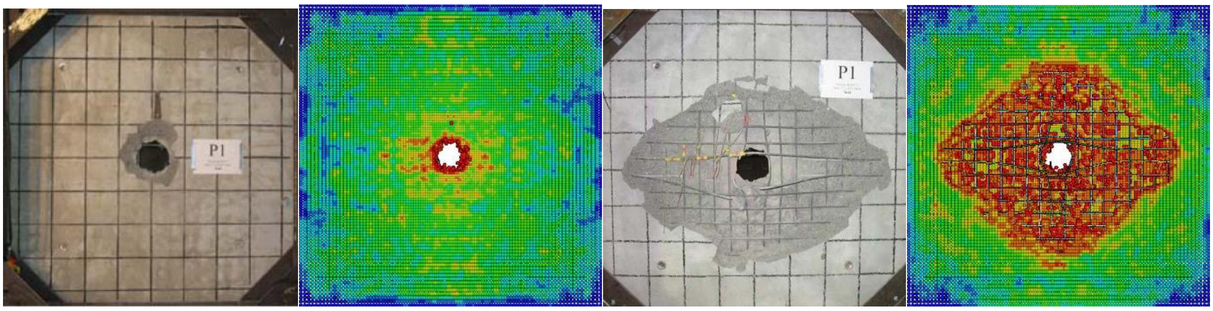

Fig.5. Front face and back face [8] from the P1 test and from the LS-Dyna simulation

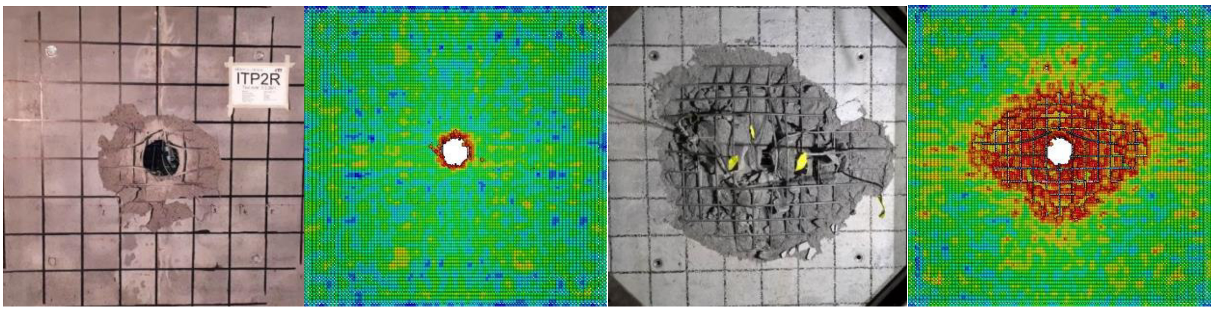

Fig.6. Front face and back face [9] from the ITP2R test and from the LS-Dyna simulation

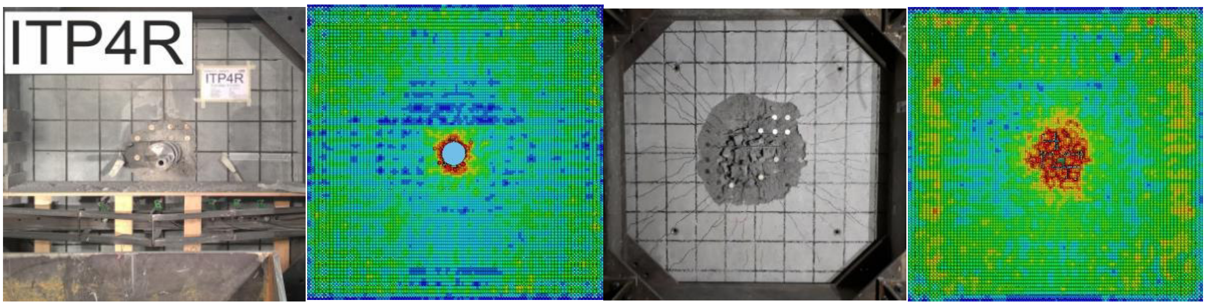

Fig.7. Front face and back face [10] from the ITP4R test and from the LS-Dyna simulation

3.2 Residual Velocity / Penetration

A comparison of the residual velocities in the P-series and the ITP2R together with the maximum penetration in the ITP4R tests is presented in Table 3. Time-histories for the same results are presented in Fig.8.

	P1 / P2 / P3 Residual Velocity	**ITP2R** Residual Velocity	**ITP4R** Penetration
Test	38.3 m/s	48.0 m/s	150 mm
LS-Dyna	37.5 m/s	46.2 m/s	237 mm (maximum)

Table 3. Comparison of the residual velocities and the penetrations for each test

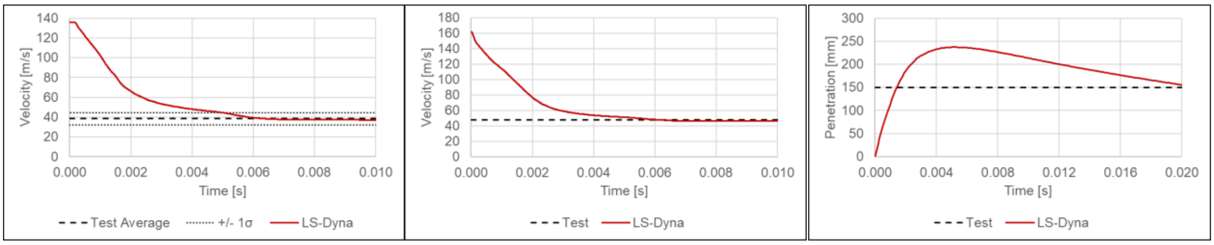

Fig.8. Residual Velocity and Penetration time-histories for the P-series (left), ITP2R (middle) and ITP4R (right)

4 Discussion

The P-series repeatability of the test results quantified the uncertainty, and this is also confirmed by the simulation results - a very good match for the spalling is obtained, the residual velocity is also captured very well. The lack of repeated tests with similar material properties and impact velocities for the ITP RC slabs increased in the uncertainty of the results. For the ITP2R test, even though the residual velocity is very well captured, the simulation underpredicts the amount of spalled concrete in the back face. The simulation of the ITP4R test confirms previous observations that adding shear reinforcement reduces the amount of spalled concrete [2][10]. Furthermore, for the ITP4R test, the maximum penetration distance was noted to be very sensitive to multiple parameters, the biggest influence among others having the impact location with respect to the reinforcement layout, the failure strain of the reinforcement. The friction coefficients between the materials also play a significant role.

Although the current models seem to capture the perforation/penetration behavior to an acceptable level, it is worth investigating the effects of:

- increasing the details of the support conditions, i.e. modelling the actual cylindrical supports instead of the assumed fixed supports;
- adding the T-heads of the shear reinforcement.

Additionally, testing the same methodology using other material models for the concrete, for example **`*MAT_CONCRETE_DAMAGE_REL3`** or **`*MAT_RHT`**, would also be of interest for a continuation of the current study.

5 Summary

The Smoothed Particle Galerkin method proves promising in modeling punching failure of reinforced concrete structures. Bending and shear reinforcement can be modelled with increased detail of the 3D layout, allowing for accurately capturing the local failure modes of the reinforced concrete sections.

The pre-processing using Ansys Workbench tools provides very convenient modeling not only during model creation, but also when changes need to be made. The post-processing routines in LS-PrePost can be automated, which additionally enhances the user experience when using the SPG mesh-free solver.

6 Literature

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