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PUNCHING FAILURE OF REINFORCED CONCRETE SLABS SUBJECTED TO HARD MISSILE IMPACT, PART II: RECENT TESTS AND ANALYSES ON INCLINED IMPACT

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ABSTRACT

This paper considers two relatively recent tests with a hard oblique impact to a reinforced concrete slab, where only the impact angle of inclination is intentionally varied. The thickness of the reinforced concrete target slab is 250 mm and the span distance in both directions is 2 m. The targeted impact velocity in the oblique direction was 135 m/s. Test arrangement is described. Test results and corresponding Finite Element simulation results are presented and compared with each other. Structural behavior of the slab and the projectile were simulated reasonably accurately, although there are some different trends in the tests and simulations. In the tests, larger inclination angles led to lower residual velocities, but not as clearly as expected. In the simulations, however, the highest residual velocity was with the largest angle. The research of inclined impacts has just been started and the calculation models have to be improved for this new purpose. More tests of this type are also needed.

INTRODUCTION

Protective concrete barrier walls in nuclear power plants are required to withstand the effects of impacts by various kinds of projectiles ranging from aircraft crash to accident generated missiles. Projectiles can roughly be classified as hard, semihard or soft, depending on the deformability of the missile with respect to the target deformability. During the previous IMPACT project phases (I-III), only impacts with normal angle have been studied. Real impact scenarios, however, are often restricted to inclined impact directions. Scientific studies of impacts with oblique angle of inclination to a reinforced concrete wall are scarcely found in the literature. That is why test series focusing on both soft and hard oblique impacts have been started in the latest project IMPACT Phase IV. The series focusing on hard impacts with inclined angles that will cause a local punching cone to form is called IP (inclined punching).

TESTS

This paper considers two hard oblique impact tests named IP1 and IP2, where only the impact angle of inclination is varied being 20^o and 30^o, respectively. The main goal is to produce experimental data on the behaviour of the projectile and the response of the target slab in impacts occurring at a specified angle of incidence. Specific topics of interest in the behaviour of the projectile include possible projectile deformation, penetration or perforation of the slab and projectile velocity and rotation. Especially, the residual velocity after the perforation is important. Generally, differences of projectile and slab behaviour with respect to the orthogonal impact reference test, the punching tests in the international IRIS 2010 benchmark, have been studied. The targeted impact velocity for both tests was 135 m/s. The IP1 and IP2 tests were conducted 24.1.2020 and 16.2.2021, respectively. The IRIS tests were conducted already in 2010.

Slab and projectile

The slab design is based on the 250 mm thick slab design used in previous IMPACT phases II and III and IRIS 2010 punching tests. The span distance in both directions is 2 m. Concrete cover is 20 mm. Bending reinforcement bars with 10 mm diameter and steel grade B500B have been placed at 90 mm intervals both sides and both ways. The maximum aggregate size is 8 mm. The missile design is the same as in previous projects, but the manufacturer is different. It is essentially a hollow steel pipe with wall thickness of 12.5 mm, with a thicker head and filled with lightweight concrete (see Figure 1). The measured projectile mass in both tests was 47.52 kg.

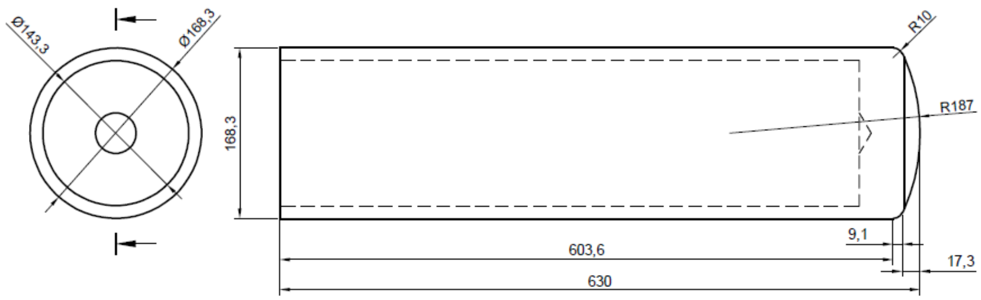


Figure 1. Dimension drawing of the hard (type H2) missile (without the tail).

Material tests

Material tests on concrete are divided in two categories: compressive tests to determine compressive concrete strength, elasticity, ductility, compressive stiffness degradation properties and triaxial behaviour on the compressive meridian on one side, and tensile tests to determine tensile strength, fracture energy and tensile stiffness degradation properties on the other side. The material tests and their results are not described in detail, but it should be noted that all the test slabs presented here have been cast from different concrete batches and the properties vary somewhat. Furthermore, there was some unexpected content in the concrete mix of IP2, which seemed to lead to underperformance in the triaxial tests. It is very likely that this has affected IP2 results. The reinforcement steel properties have also been tested.

Inclined target slab and frame setup

The inclined target slab and frame setup consists of the following components:

1) The front and back parts of the frame, which hold the concrete slab in place
2) Four inclination supports that provide the desired slab inclination angle
3) Two lateral flanges, which connect the inclination supports to the lateral and axial supports
4) Four variable length lateral supports, which take the lateral forces form the impact
5) Four axial supports, which take the lateral forces
6) A fixation beam to which the axial supports can be connected at a desired position

As shown in Figure 2, there are three variable parameters in the inclined frame setup: 1) the eccentricity of the axial support centreline from the impact axis, 2) the lateral distance between the axial supports, and 3) the frame inclination angle. These depend on the chosen inclination angle and on the slab or force plate thickness. These parameters are calculated in such a way that the impact axis intersects the slab mid-surface at the centre of the slab. An isometric view of the inclined target slab and frame setup is shown on the right hand side of the Figure 2.

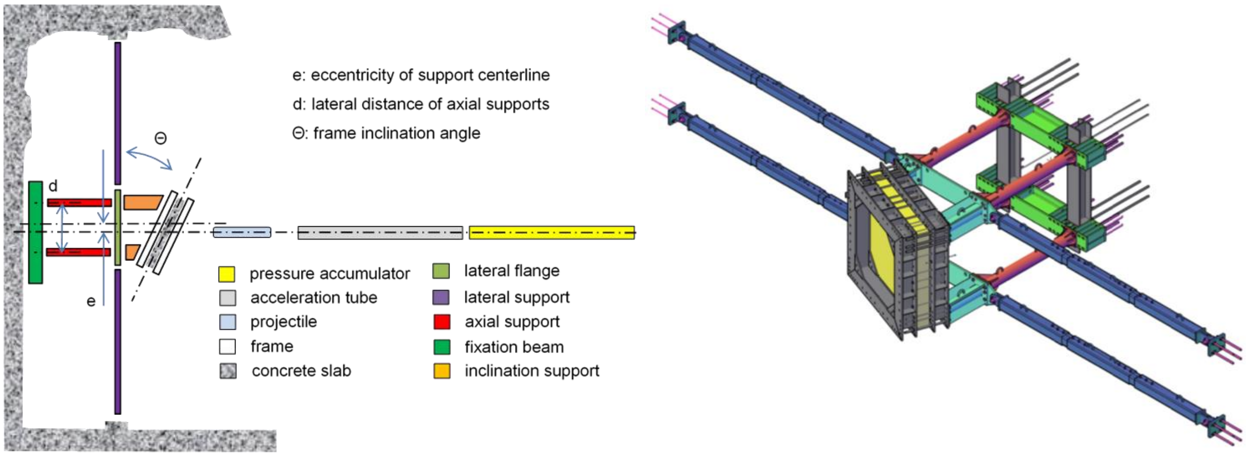


Figure 2. Parts of the inclined target slab and frame setup (left) and isometric view (right).

The slabs to be tested are mounted on a steel frame which is pneumatically tightened with bolts and screws. The support conditions of the slab are supposed to be knife-edge supports on the four sides on the slab with a free span of 2000 mm in both direction. This is realized with D=50mm round steel bars between the frame parts and the slab.

Instrumentations

The following instrumentation has been applied for the tests:

- 5 displacement sensors on the slab front surface (failed to function in test IP2),
- 4 strain gauge setups on the horizontal axial supports (back pipes) to measure the horizontal axial support forces,
- 4 strain gauge setups on the horizontal lateral supports to measure the horizontal lateral support forces,
- 2 laser devices for measurement of the impact velocity (failed to function in test IP2),
- an electric wire for detection of the impact moment,
- 2 high shutter speed video cameras located as per Figure 3: C1 (side view), C2 (top view).

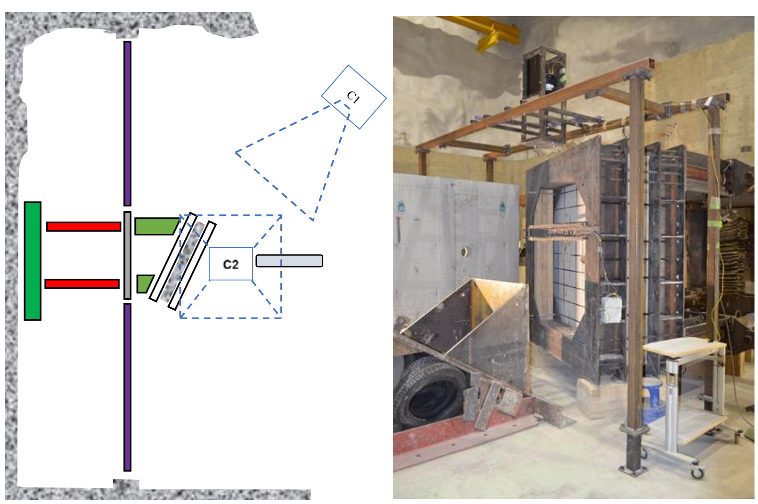


Figure 3. Locations of video cameras

TEST RESULTS

Some general results on the projectile and slab behaviour are selected to the Tables 1 and 2. The strength of concrete was slightly lower in IRIS 2010 punching tests than in tests IP1 and IP2. The measured impact velocities are near the targeted value. According to these tests, inclination decreases the residual velocity, but the effect is mild at least with angles up to 30 degrees.

Figures 4, 5 and 6 show photographs of slab front and back surfaces after test. Table 3 shows photographs of section views of sawn slabs and deformed projectiles after the test. The damage to the slab is very similar in each case. The missile deformation is similar with 0 and 20 degree impact angles, but with 30 degree angle, the deformation is smaller.

Table 1: Selected general results, projectile behaviour.

Test code	Measured impact velocity from laser v_0 (m/s)	Measured impact velocity, kinematic analysis v_0 (m/s)	Residual velocity form finite difference measurement v_r (m/s)	Residual velocity from kinematic analysis at 20ms v_r (m/s)	Original angle of impact w/r to slab normal α_0 (°)	Maximum angle of impact w/r to slab normal $\alpha_{\max}$ (°)	Angle of impact at ~17ms w/r to slab normal α_r (°)
IP1	136.25	134.6	27	28.6	20.0	29.4	25.2
IP2	-	138.9	25	25.8	30.0	51.9	42.7
IRIS P1	135.9	-	-	33.8	0	-	-
IRIS P2	134.9	-	-	45.3	0	-	-
IRIS P3	136.5	-	-	35.8	0	-	-

Table 2: Selected general results, slab behaviour.

Test code	Age of concrete (d)	Concrete compressive strength (MPa)	Concrete split tensile strength (MPa)	Slab mass before test (kg)	Mass of spalled / scabbed concrete (kg)	Total mass of loose concrete (kg)
IP1	109	66.5	4.49	2704	not measured	144
IP2	64	63.2	4.78	2646	96	146
Test code	Front side spalling area (m^2)	Front side additional cracked area (m^2)	No. of front side broken rebars	Back side scabbing area (m^2)	Back side additional cracked area (m^2)	No. of back side broken rebars
IP1	0.156	0.000	2↔ , 2↕	1.045	not measured	1↔, 1↕
IP2	0.183	0.051	2↔, 1↕	0.913	0.658	1↔, 1↕

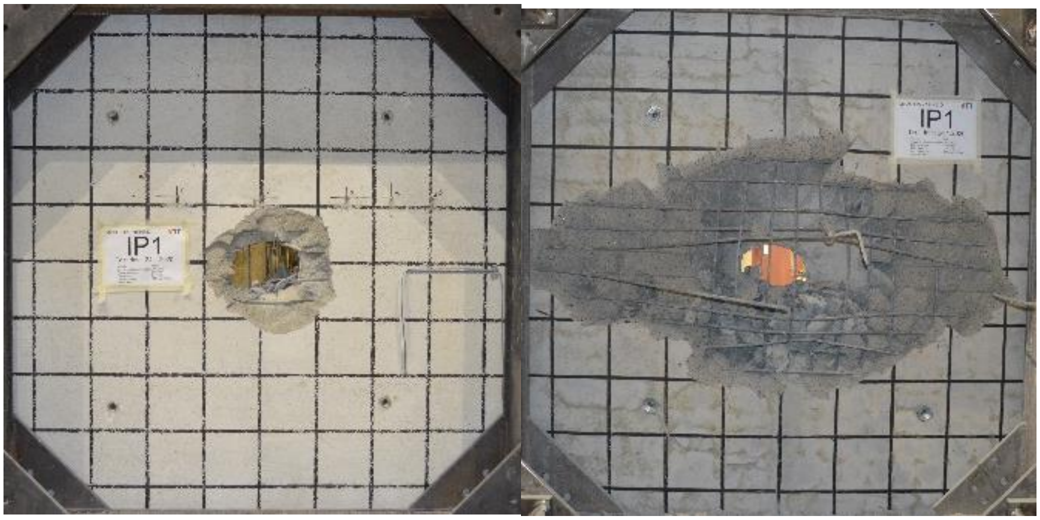


Figure 4. Front and back surfaces of the slab after test IP1 (20 degrees).

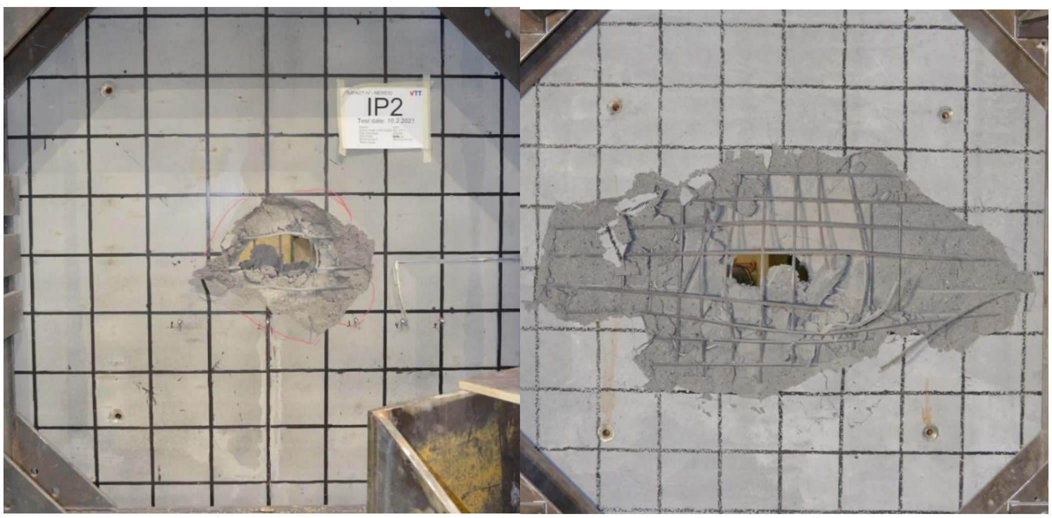


Figure 5. Front and back surfaces of the slab after test IP2 (30 degrees).

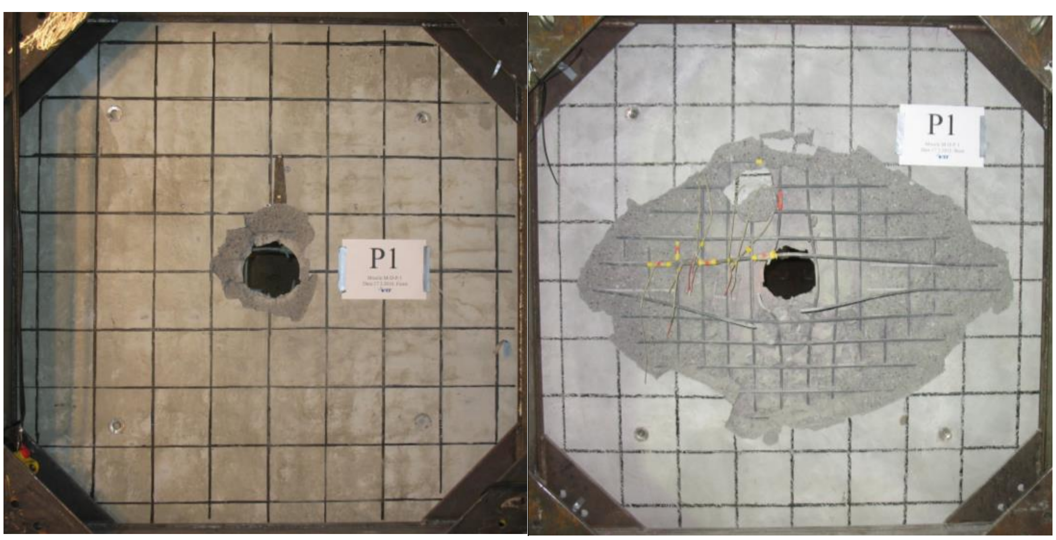
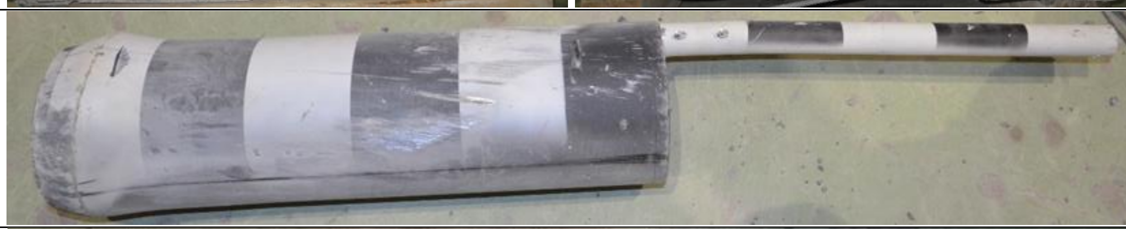


Figure 6. Front and back surfaces of the slab after IRIS P1 test (0 degrees).

Table 3: Slab after test, section view and projectiles after test.

IP1	
IP2	
IRIS P1	 
IP1	
IP2	
IRIS P1	

Kinematic analysis

Kinematic analysis denotes here the process of using individual frames from high-speed video footage to extract information about the behaviour of the projectile during the impact. The projectile is considered as a rigid body. The best position for the camera in inclined target tests is directly above the target with the camera direction pointing downwards (camera C2 in Figure 3, shooting at 2700fps). However, practically this is hard to achieve, and therefore the camera is usually installed with a small tilt angle, α. This means that the distances on the projection plane are given by the orthogonal distance multiplied by the cosine of the tilt angle. As long as the tilt angle is small, and since the still frames are scaled in the CAD application to the required scale, the foreshortening effect is not of large importance. In the CAD application, the following quantities are measured from the still frames: 1) distance from projectile tail end point, T, to the intersection point, I, of the missile axis with horizontal slab centerline, 2) angle of the actual axis line of the projectile from the initial trajectory line.

The summary graph of kinematic analysis results for tests IP1 and IP2 is shown in Figure 7. The graph shows the projectile velocity magnitude (computed from the displacement fit function) as a function of time together with the missile angle data points (computed from the slab normal) as a function of time. One can see the influence of slab global flexural behaviour becoming more important as the angle of impact is closer to the slab normal. One can also notice that the missile angle grows up to a maximum, after which it starts to decrease. It is yet hard to tell based on only two tests whether this is a trend or whether this is caused by the arbitrariness of vertical reinforcement positioning with respect to the projectile incidence position and angle.

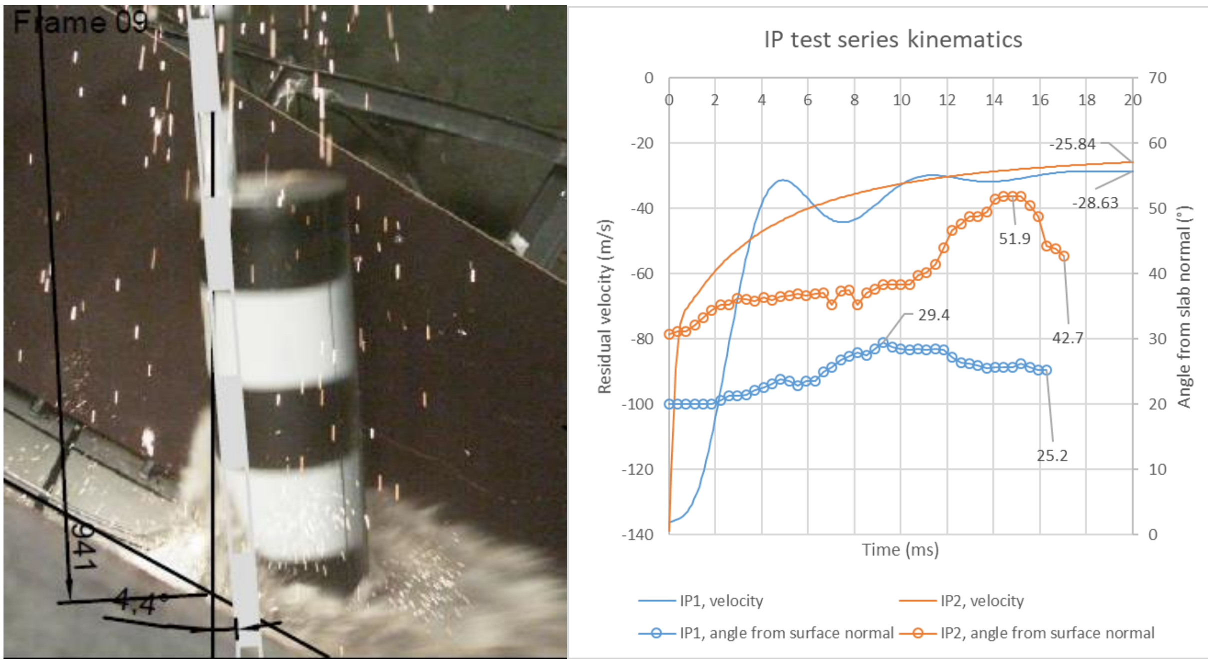


Figure 7. Frame from IP2 kinematic analysis and a summary graph of IP test series kinematics.

FINITE ELEMENT SIMULATIONS

A commercial finite element (FE) code Abaqus/Explicit (Abaqus, 2019) was used for the nonlinear dynamic numerical simulations of the tests described above. The analysis time is 20 ms. The target velocity 135 m/s, which somewhat differs from the actual measured velocities, has been used for all the simulations. The main purpose of these simulations was to validate the used modelling methods, especially the concrete material model, against the empirical results as well as to study the effect of impact inclination angle on the perforation resistance of the slabs. For the FE model of the target wall, the Concrete Damaged Plasticity material model of Abaqus with in-house developed enhancements (Fedoroff et al., 2020) was applied. Obtained numerical results are compared with the corresponding experimental findings. Figure 8 shows the FE half-model of IP2 test employing the symmetry. The concrete slab is bounded by steel channels in order to withstand the contact pressure from the steel rods on both sides of the slab. These steel rods are attached to the frame that holds the slab in place. In these simulation models, the steel frame is not modeled at all. The steel rods, which are assumed to simulate hinged boundary conditions, are modeled as rigid bodies and they are rigidly fixed to the frame of reference.

The concrete of the slab is modeled using eight-node reduced integration elements with Abaqus default distortion and hourglass control (C3D8R in Abaqus nomenclature). The element size is 10 mm, which means that there are 25 elements over the thickness of the slab. The steel reinforcement is modelled as stringers using two-node linear beam elements (B31 in Abaqus nomenclature) that are tied node-to-node to the C3D8R elements. They are located in the same level like as rebar web, whereas in reality they are placed in different levels, the horizontal rebars being closer to the slab surface. The concrete cover is 20 mm.

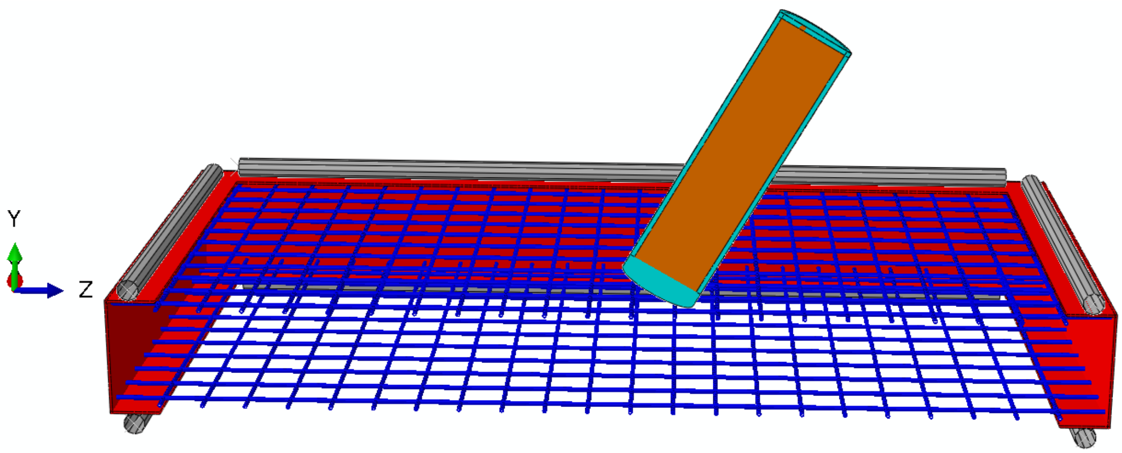


Figure 8. FE half-model of test IP2 showing steel reinforcement (concrete is hidden).

All the material properties are based on material test results of each individual test. Results of two simulations, one for both tests, are presented here. The simulations were completed successfully and the energy balance was well maintained. Figure 9 shows the energy components of the IP1 simulation, where for instance the green curve (ALLKE) is the kinematic energy of the whole model. Figure 10 shows the projectile velocity as function of time in both simulations and respective tests. The simulated residual velocities for IRIS P, IP1 and IP2 tests were 50.1 m/s, 43.2 m/s and 56.9 m/s. Figure 11 shows the projectile angle as function of time in both simulations and respective tests.

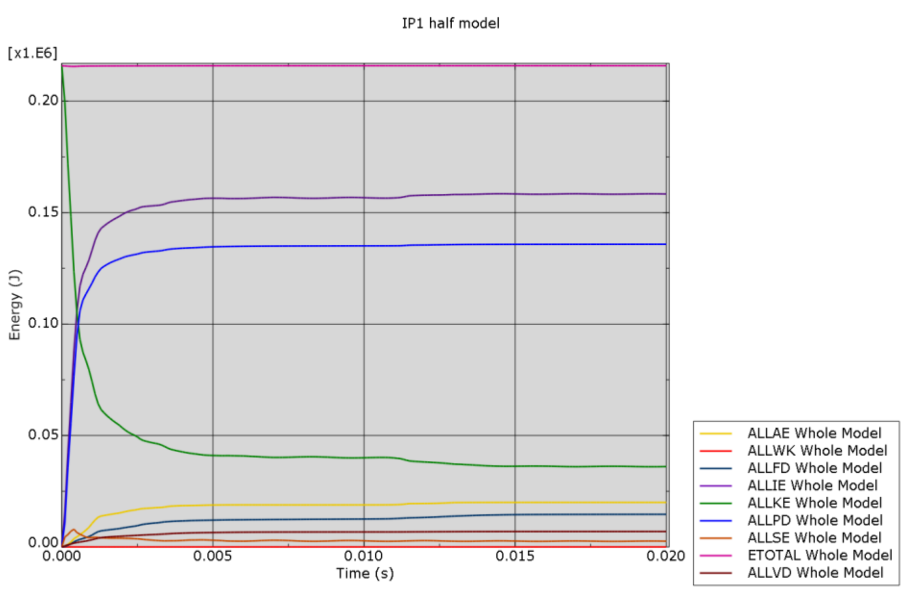


Figure 9. Energy components in the IP1 simulation as function of time.

The angle in the simulations first follows the test results, but the projectile then turns to the different direction. In the tests, the projectile turns to the in-plane direction of the slab during the impact. The projectile is decelerated more in the tests than in the simulations. Table 4 shows deformed model shapes after 2 ms, 5 ms and 10 ms and contour plots of maximum principal strain. Concrete coloured in dark blue is still intact, otherwise it is crushed or cracked. A quarter model is used for IRIS punching test simulation.

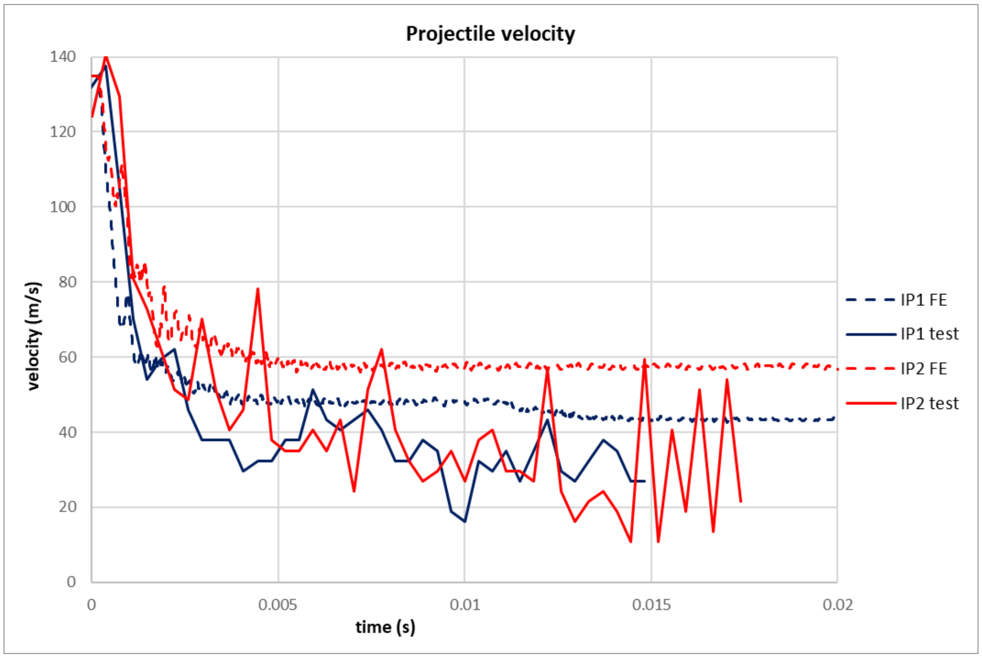


Figure 10. Projectile velocity in both simulations (dashed lines) and respective tests.

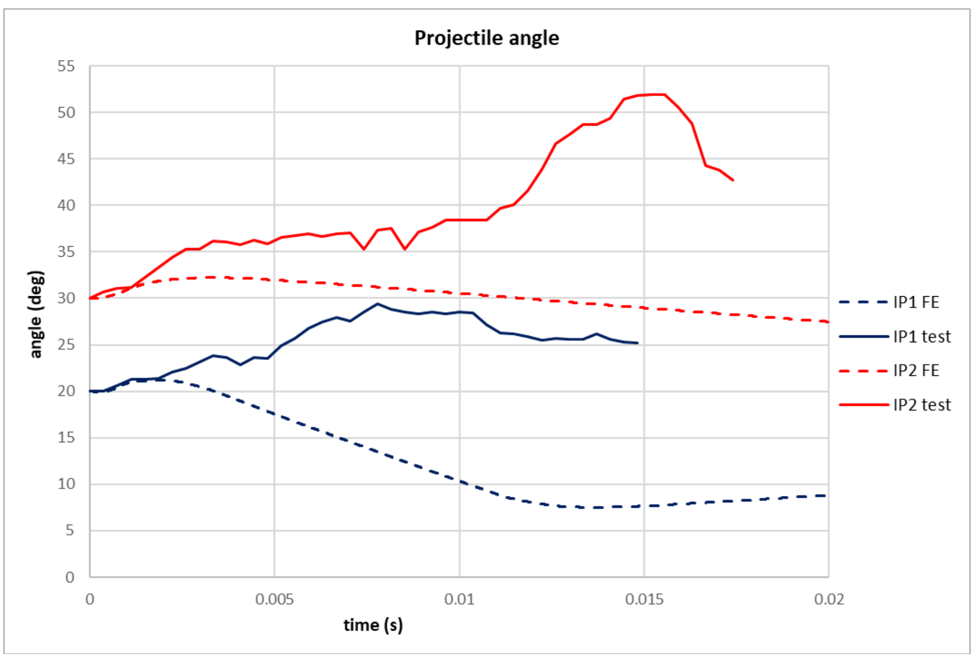
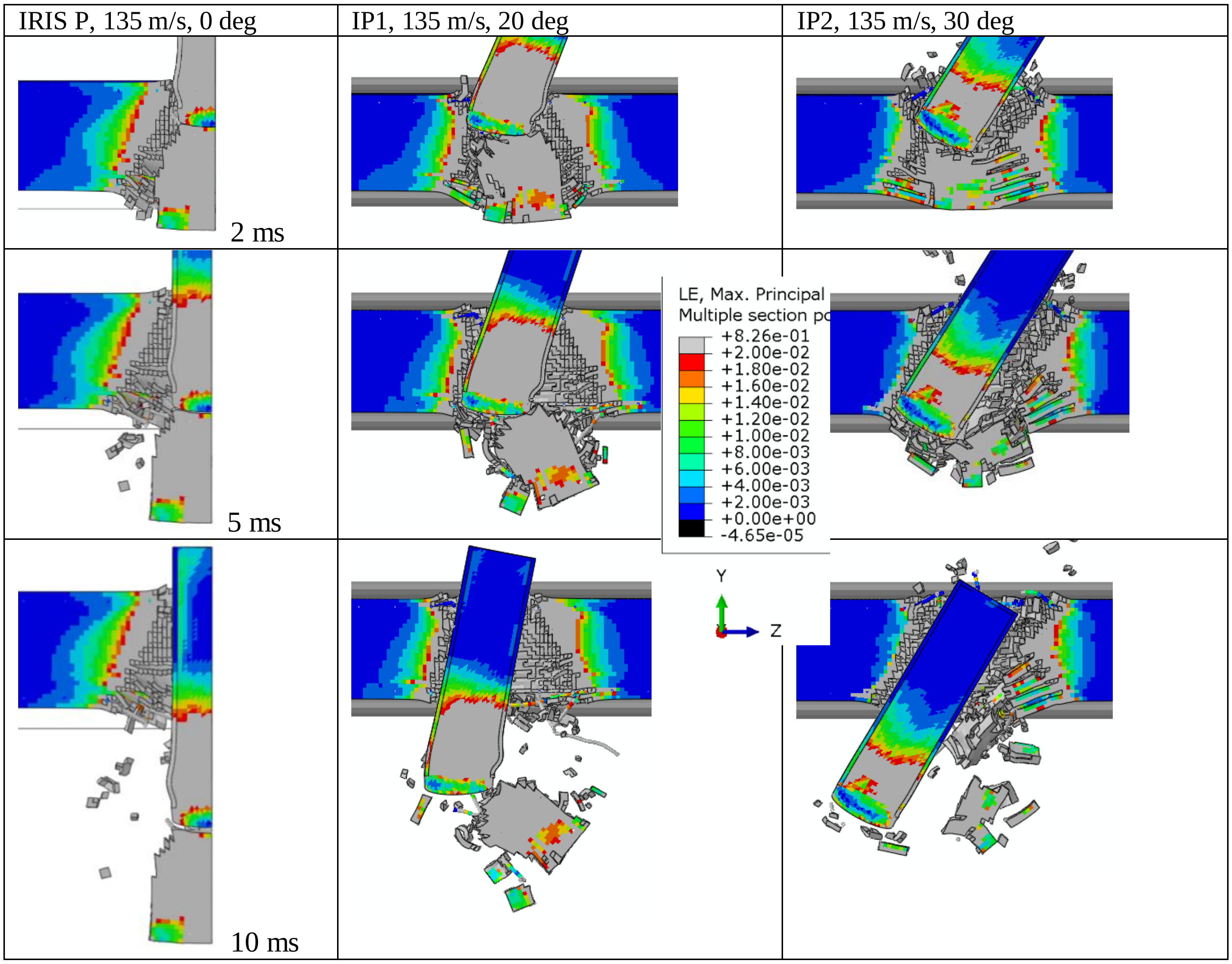


Figure 11. F Projectile angle in both simulations (dashed lines) and respective tests.

Table 4: Deformed model shapes after 5 ms and 20 ms and contour plots of maximum principal strain.



CONCLUSION

Two inclined punching tests have recently been conducted. Some measurements failed, but fortunately their importance was not significant. Furthermore, the concrete properties differed notably, since they were from different batches and there was some problems with the concrete mix. Test results and corresponding FE simulation results are presented and compared with each other. Structural behavior of the slab and the projectile were simulated reasonably accurately, although there are some different trends in the tests and simulations. In the tests, larger inclination angles led to lower residual velocities, but not as clearly as expected. The damage of the slab is also surprisingly similar in each case. In the simulations, the highest residual velocity was with the largest angle. The research of inclined impacts has just been started and the calculation models have to be improved for this new purpose. More tests of this type are also needed.

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