IASMiRT

SMiRT 26
50 Anniversary Berlin/Potsdam

Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Special Session

BENDING RESPONSE OF REINFORCED CONCRETE SLABS SUBJECTED TO SOFT MISSILE IMPACT, PART III: 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 Inclined Bending (IB) in the IMPACT4 project that had been carried out during the years of 2019 and 2020.

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 Inclined Bending (IB) in the IMPACT4 project had been carried out during the years of 2019 and 2020. Test parameters for this series included the variety of impact velocities from 110 to 130 m/s and inclination angles of projectiles from 0 to 20 degrees.

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 for the series of IB tests in the IMPACT4 project is presented in Table 1. The details of this test are reported in a previous paper (Vepsä et al. 2022). This test series consists of four tests with two different impact velocities and inclination angles as parameters.

Table 1: Summary of IB tests.

Test ID	IB1	IB2	IB3	IB4
Slab Dimensions	2100 mm × 2100 mm (slab type 6)			
Thickness	150 mm			
Bending Reinforcement	Ø 6 @ 50 mm			
Shear Reinforcement	Ø6 @ 100/200 mm, (closed stirrups)			
Missile	Soft Missile; 50 kg			
Inclination Angle	20°	10°	20°	10°
Target Impact Vel.	110 m/s	110 m/s	130 m/s	130 m/s

The main interest is to evaluate the behaviors of the projectile or reinforced concrete slab under the inclined projectile impact test and the response of the projectiles or slabs, such as displacement and strain during the respective destructive properties. The interaction between steel and concrete under high-speed loading, mainly related to friction, is rarely discussed, and data such as at what angle the projectile begins to slide on the target surface provide valuable data.

In the tests with a 20° inclination angle (IB1 and IB3), the projectiles tended to start sliding along the impact surface, and their rotation increased at the end of the impact. This resulted in the impact of the heavier rear portion of the projectile to the target.

In contrast to the behavior of IB1 and IB3, when the inclination angle was reduced to 10° in IB2 and IB4, the friction between the projectile and the target prevented it from sliding, and the behavior and the final state were similar to that observed in perpendicular impact tests.

Photographs taken from above the slab at the various time steps of impacts for tests IB1 and IB2. Shown in Figure 3.

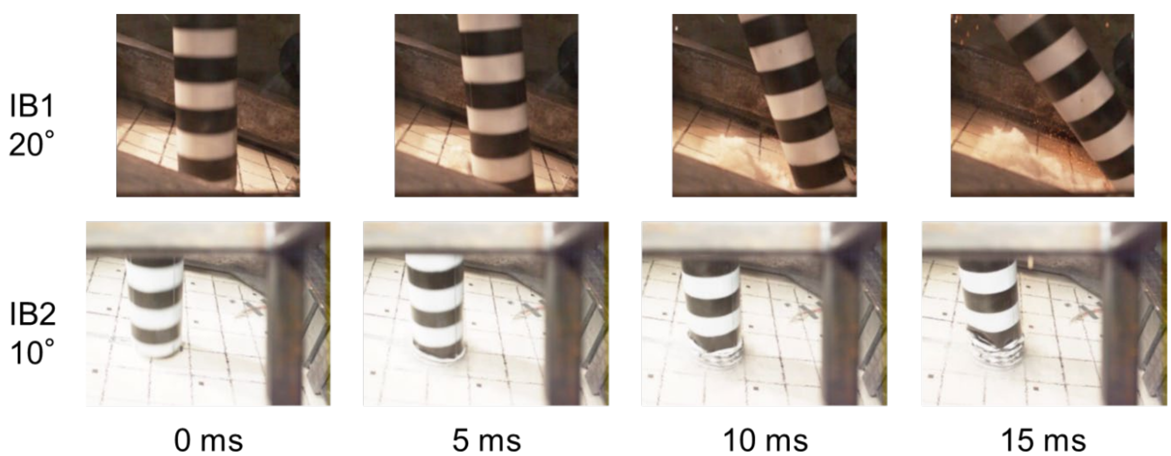

Figure 1. Top view of the impacts in tests IB1 and IB2.

NUMERICAL SIMULATION

Model Description

This chapter presents the results and discussion of the simulation for each test case.

The commercial numerical analysis code Abaqus is used, and other descriptions of this numerical simulation are listed on Table 2.

Table 2: Descriptions of numerical simulations.

Code; Version.	Abaqus/Explicit 3DEXPERIENCE R2019 HF2
Element Type	C3D8R,S4R (Reduced Integration)
Constitutive Low	Concrete Damage Plasticity Model
Method	Stress Deformation Analysis (Explicit/Large Deformation)
Coeff. of friction	0.2

Figure 2 shows an overview of the numerical simulation model. The model is half symmetrical, and the reinforced concrete slab, the part of the steel support, and the projectile are modeled. The reinforced concrete slab is modeled with reduced integration of the solid elements, and the projectile is modeled with reduced integration of the shell elements.

The material properties are determined based on 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} calculated from f_{cm} by CEB-FIP model code 1990 (CEB-FIP 1991), and the tension stiffening effect according to the literature (Wang et al. 2001) is considered. In both cases, strain rate dependent effects based on the modified CEB-FIP model (L. J. Malvar 1998) are considered.

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.

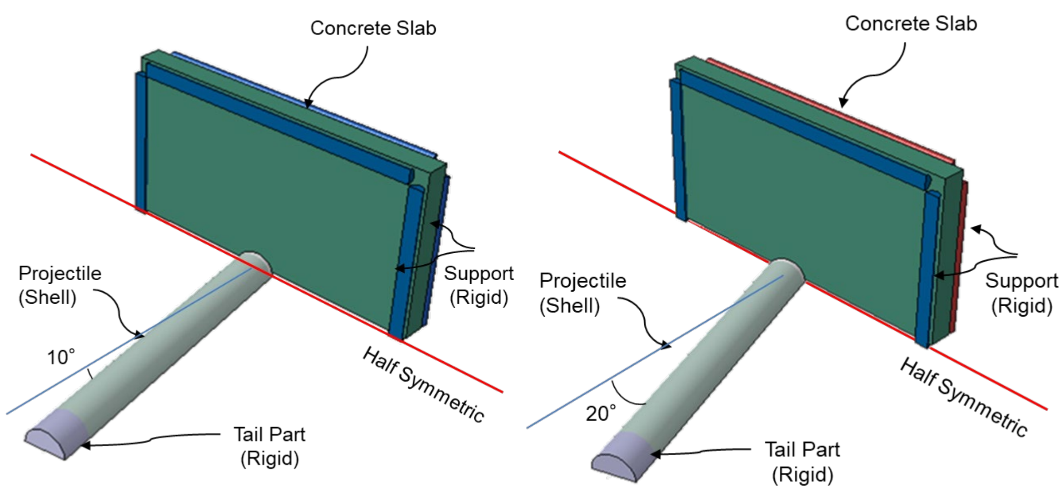

Figure 2. Overview of Numerical Simulation Model for IB1,3 (left) and IB2,4 (right).

The behavior of projectiles

Figure 3 shows the behavior of the projectile in IB1 and IB2 compared to photographs taken at the same time points. The orange dashed line is an auxiliary line indicating the same angle in both pictures. As in the test, the calculation for IB1 reproduced the rotation of the projectile, and the calculation for IB2 reproduced the behavior that the projectile was crushed from the tip without rotation.

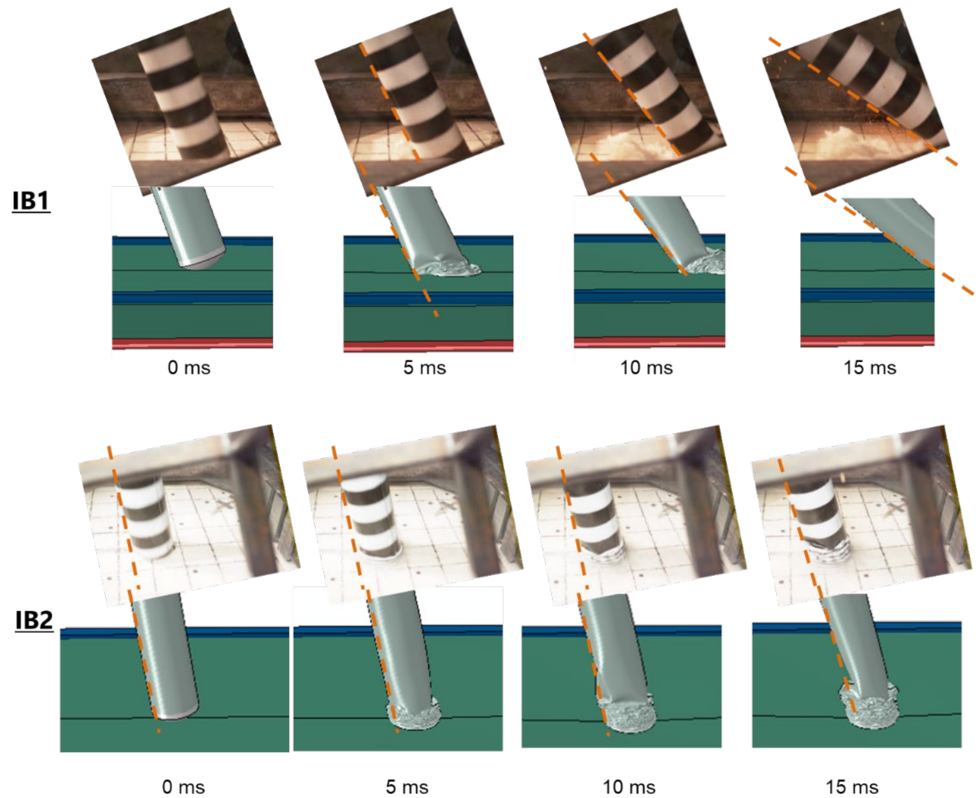

Figure 3. Behavior of the projectile in IB1(Upper) and IB2(Lower).

Figure 4 shows the deformation state of the projectile in IB1 thru IB4 at the end of the test compared to photographs taken after the tests. Each band on the missiles is painted every 10 cm.

In all cases, the deformation state and remaining length of the projectiles are accurately reproduced.

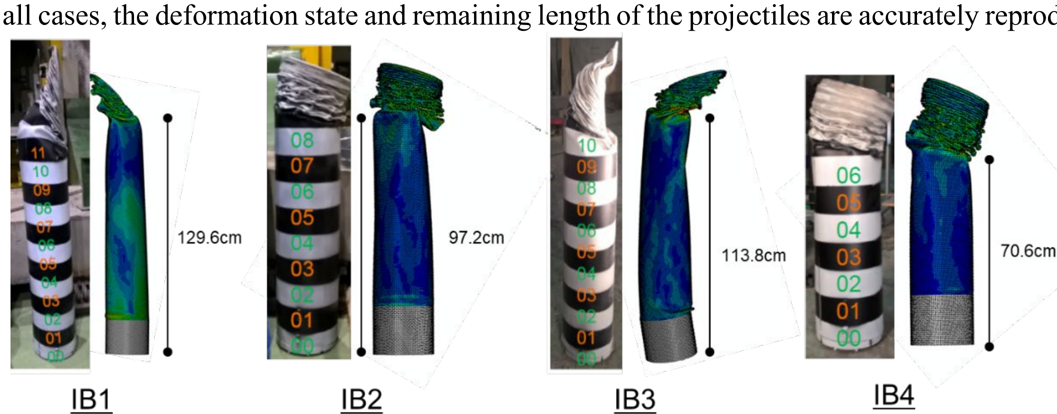

Figure 4. Behavior of the projectiles in IB1 (Upper) and IB2 (Lower).

Figure 5 shows the kinematic data of the projectiles in IB1 thru IB4 compared to measurements taken during the tests. |IT| is the length from the tail to surface of slab, |OI| is the sliding distance from the first contact point, and theta is the angle of rotation from the original projectile.

In all cases, the shortening length, sliding distance, and rotational angle of the projectiles are mostly reproduced.

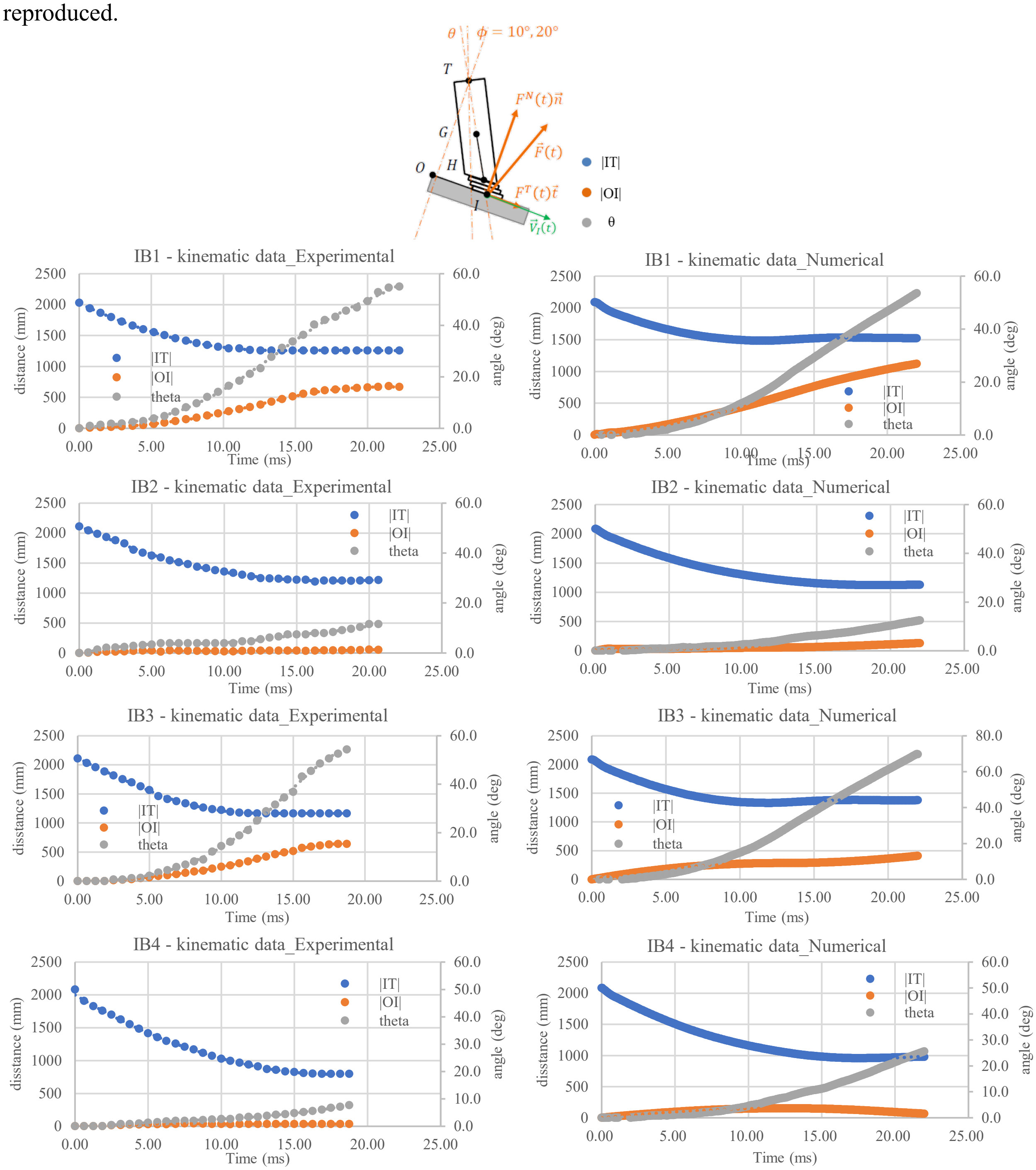

Figure 5. Comparison of Kinematic Data of the Projectiles; Experimental (Left) and Numerical (Right).

These analyses indicate that the numerical analysis adequately reproduces the behavior of the projectiles under the action of impact loads.

The behavior of reinforced concrete slabs

Figure 6 shows the comparison of out-of-plane displacement of IB1 thru IB4 compared to measurements taken during the tests. The single-dashed line indicates the peak position of the numerical analysis results in the same color.

The behavior in the test is generally reproduced up to the maximum displacement, but the phenomenon of subsequent displacements is not captured. The reproducibility of the maximum displacement is higher at the periphery, such as sensors 4 and 11, and tends to be overestimated in the analysis for the central sensor 1. This is due to the straightness of the projectile by using a symmetrical model.

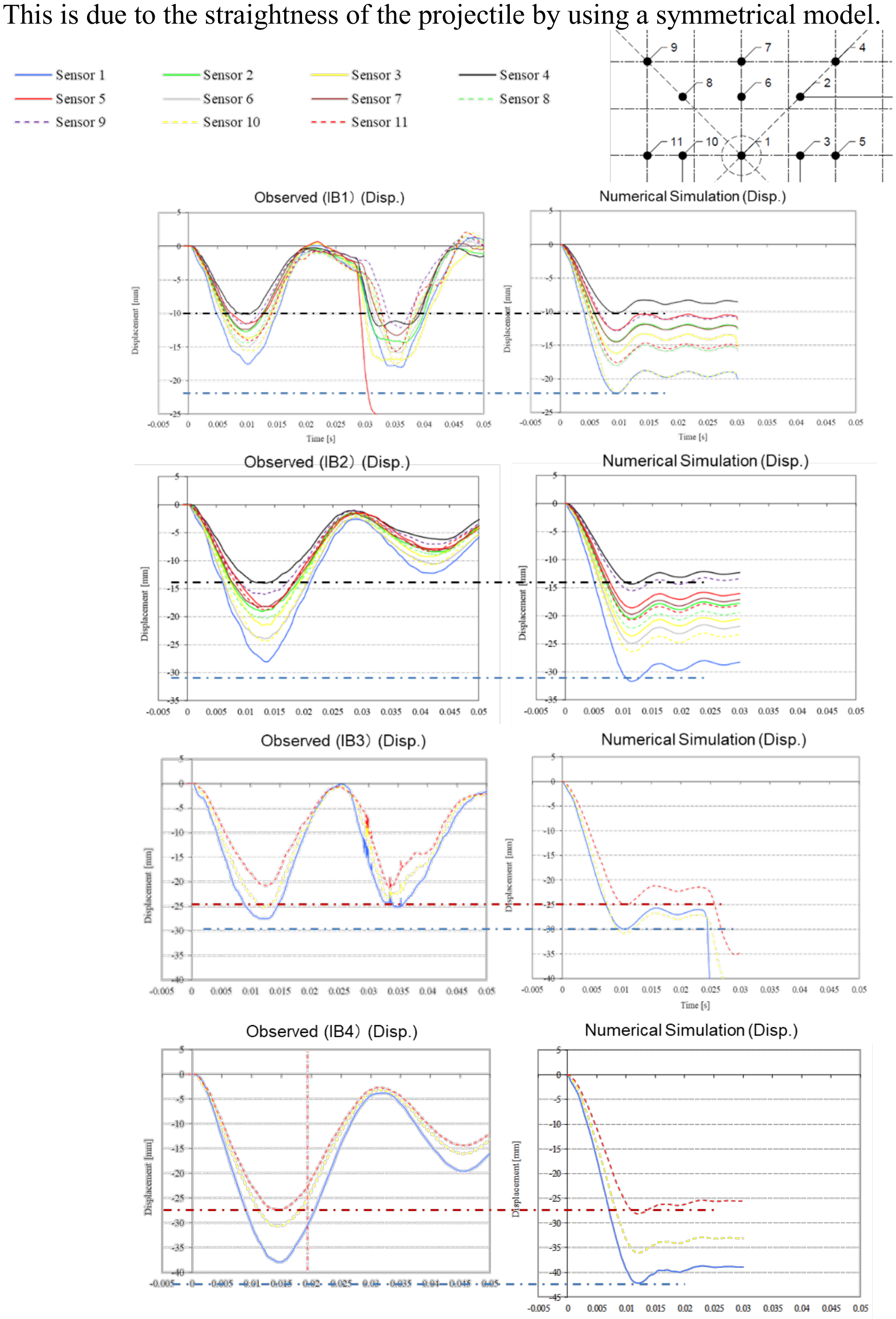

Figure 6. Comparison of Displacement of the RC Slab; Experimental (Left) and Numerical (Right).

SENSITIVITY ANALYSIS

This chapter presents the results and discussion of the sensitivity analysis for IB1 and IB2. In the sensitivity analysis, the coefficient of friction (CoF) in the calculations in the previous chapter was changed from 0.2 to 0.3 to check the effect on the behavior of the projectile.

Figure 7 shows the kinematic data of the projectiles in IB1 and IB2 with CoF 0.2 and 0.3 compared to measurements taken during the tests. From the figure, the friction coefficient of 0.3 is reproducible in IB1. Conversely, IB2 has a high reproducibility with a friction coefficient of 0.2.

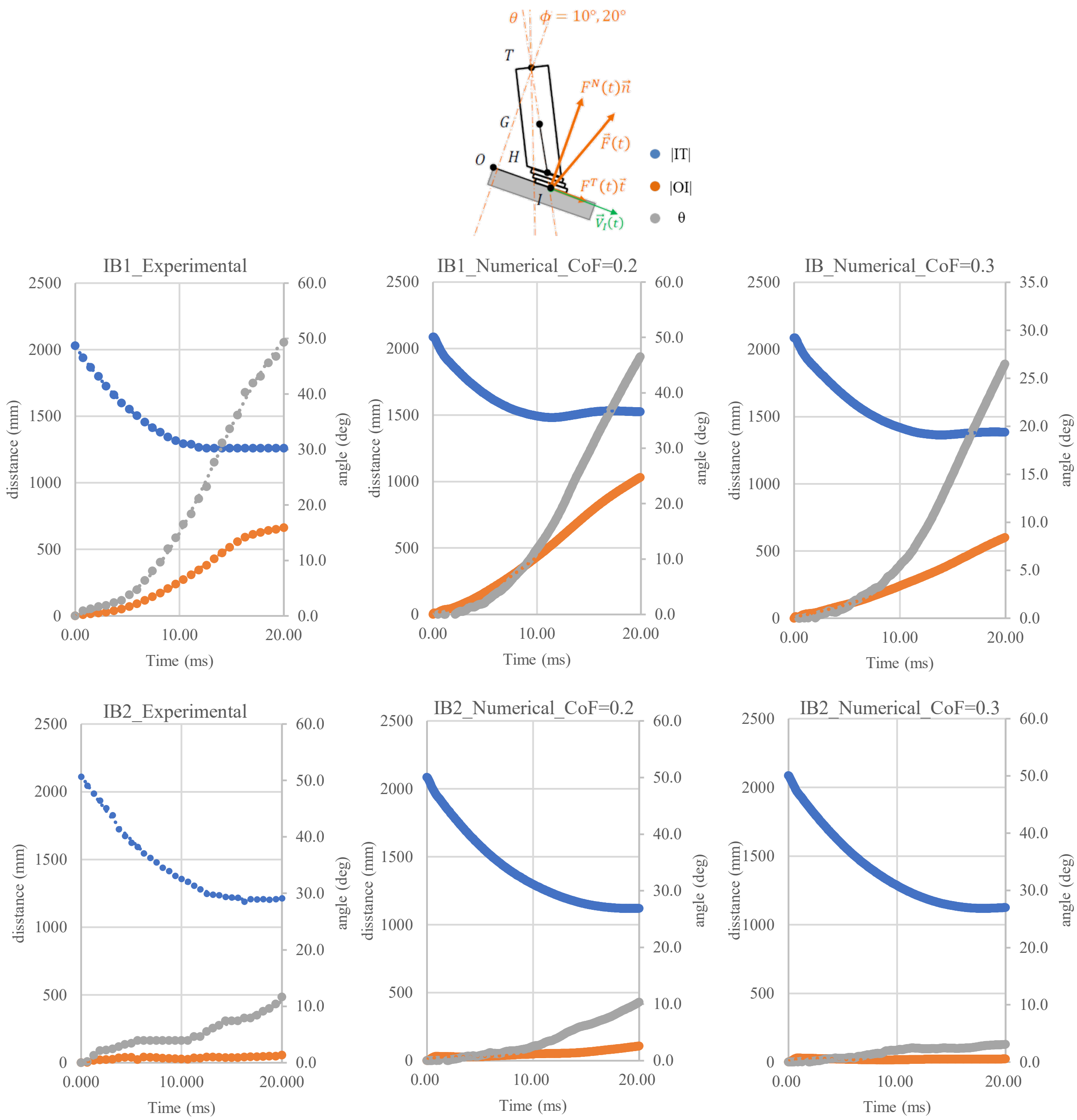

Figure 7. Comparison of Kinematic Data of the Projectiles; Experimental (Left), Numerical Cof = 0.2 (Center), and Numerical Cof = 0.3 (Right)

Although there is a problem in using a unified friction coefficient to represent complex frictional phenomena, such as initial penetration, individual surface conditions, impact angles, and impact velocities, a coefficient of friction of 0.2 to 0.3 appears useful to simulate macroscopic behavior, such as tip sliding and rotation at a 20-degree impact and tip crush without rotation at a 10-degree impact.

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 Inclined Bending (IB) of which interest is to evaluate the interaction between steel and concrete under high-speed loading, mainly related to friction.

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 model is half symmetrical, and the reinforced concrete slab, part of the steel support, and the projectiles are modeled with a coefficient of friction of 0.2. Analyses about kinematic behavior and the damage state of projectiles and displacement of reinforced concrete slabs indicate that the numerical analysis adequately reproduces the behavior of both projectiles and reinforced concrete under the action of impact loads.

In the sensitivity analysis, a coefficient of friction was changed to 0.3 to evaluate how the coefficient of friction in the calculations influences the behavior of the projectile.

Throughout the tests, a friction coefficient of 0.2 to 0.3 appears useful to simulate the macroscopic behavior of the interaction between steel and concrete under high-speed loading.

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