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Numerical Simulation of Projectile Penetration in Reinforced Concrete Panels

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Abstract: Concrete panels are usually used to provide protection against incidental dynamic loadings such as the impact of a steel projectile. In this paper finite element technique is used to investigate the dynamic behavior and failure conditions of reinforced concrete panels subjected to the projectile impacts. Finite element model calibration was based on some experimental results conducted by M.E. Mohamed et al." Experimental Analysis of Reinforced Concrete Panels Penetration Resistance".

Nonlinear three-dimensional numerical simulation of this experimental investigation was carried out using AUTODYNE, which is probably the most extensive code dealing with penetration problems. A comparison was conducted between the results calculated by the finite element method with field measurement and show relatively good agreement.

The aim of this paper is to study numerically the penetration resistance of ferrocement panels reinforced with different number of layers and the main findings show an enhancement in the penetration resistance of about 30% with using ferrocement panels on other hand, the results showed that increasing number of layers of steel meshes have slight influence on the penetration resistance of these panels.

Keywords: Concrete Panels; Ferrocement; Penetration; 3D-simulation; AUTODYN 3D

Introduction

Understanding the response of concrete panels to impact is essential in order to determine the thickness and position of the protective layer of different types of fortifications. Numerous studies were conducted on behavior of reinforced concrete target subjected to missile impact; studies were mostly focused on concrete properties, and how to prevent excessive local damage and collapse of the target [1-5], that's by enhancement of concrete properties.

From these studies [6, 7], concrete has various states of stress, which produce different failure modes. For example, near the impacted area, the concrete slab mainly experiences compression and it may fail due to high pressure. The severe crushing-stress together with partial reflected-waves results in the formation of a crater on the impact surface. On the opposite side of the slab, the shock waves are well reflected and converted into tensile waves, which generate tensile cracking if the material tensile strength is reached and an exit crater caused by spallation can be observed [8,9].

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One of the most important ways to enhance the concrete properties is use of ferrocement. Ferrocement improves the resistance of the concrete slabs to fragmentation, and increases the ability of the slabs to withstand impact loads [10, 11].

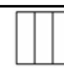
To study the behavior of concrete under the effect of projectile penetration, a lot of experiments should be conducted. These kinds of experiments especially high-speed penetration tests are very costly and tedious. In order to decrease the number of experiments required, numerical simulation plays a very important role in predicting the complex behavior of concrete during projectile penetration [12-14].

This paper employs the explicit dynamic finite element code 3D- AUTODYNE to analyze the behavior of reinforced concrete panels during projectile penetration. The results from the constitutive model RHT that includes strain-rate and damage with a pressure-dependent yield surface shows relatively good agreement with experimental results. The damage contours at the impact and exit surface from the simulation are also consistent with the post-test damage results.

Finite Element Analysis Models

Three dimensional simulation for the penetration and perforation of reinforced concrete target was performed depending on set of experimental data. The set of experimental data conducted by M.E. Mohamed, et al., “Experimental Analysis of Reinforced Concrete Panels Penetration Resistance”, [1] in which steel blunt-nose projectile with a diameter of 23 mm and a mass of 175 grams is fired with striking velocity about 970 m/s on 550 x 550 mm plain concrete panels and ferrocement panels reinforced with different number of layers of steel mesh as listed in Table (1).

Table (1) Specimens Detail

NO	Name	Thick-ness (cm)	Description	NO. of meshes		No. of panels
				Front face	Rear face	
1	SC1	60	3slabs x 20 cm control slab	-	-	
2	SC2	40	2slabs x 20 cm control slab	-	-	
5	SW 1-2	40	2slabs x 20 cm slab with 4layers	2 layer	2 layer	
6	SW 1-1	40	2slabs x 20 cm slab with 2 layers	1 layer	1 layer	

Description of the mesh

Lagrange processor has been used in AUTODYN for the analyses. In this paper two classes of target panels were considered. Unreinforced (plain) concrete, and reinforced concrete (ferrocement), projectile and the concrete target are modeled as Lagrangian meshes in all models, while the reinforcing steel bars (meshes) were described as beam elements in ferrocement models. All parts were symmetric on X=0 planes to reduce the size of the computational domain. The geometry of the projectile, concrete target and steel mesh, listed in Table (2), will be described below

Table (2) The Geometry of Model Parts

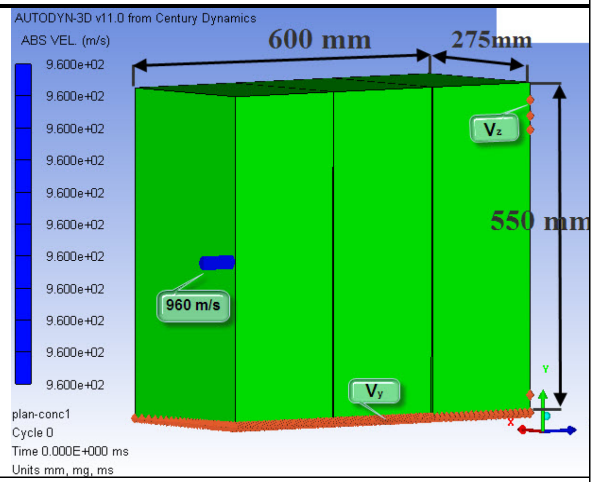
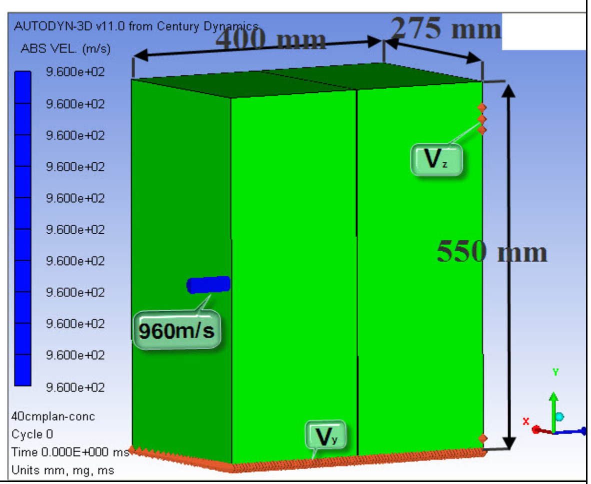
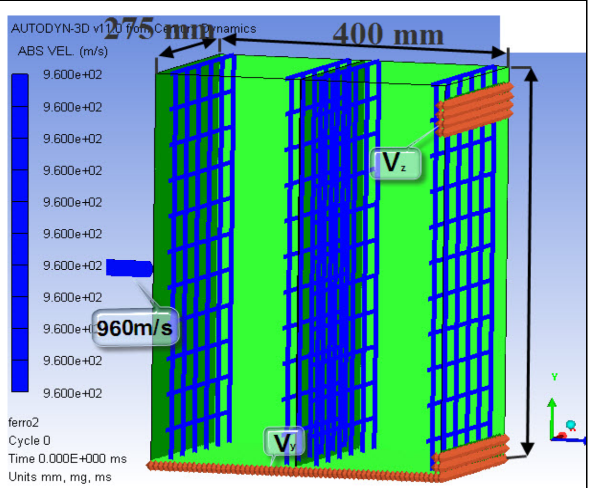
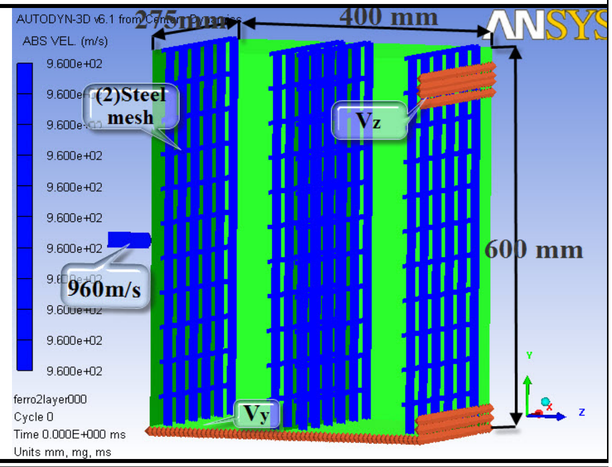
No	Model Name	Parts Name	Material	No. of Elements	Description of Model
1	SC1	Target 1& 2 & 3	Conc. 35MPa	Lagr. 360000	
		Project-ile	STEEL 4340	Lagr. 1800	
2	SC2	Target 1& 2	Conc. 35MPa	Lagr. 324000	
		Project-ile	STEEL 4340	Lagr. 1800	
3	SW1-2	Target 1,2	Conc. 35MPa	Lagr. 190920	
		Steel Mesh 1-4	STEEL 1006	Beam 4716	
		Project-ile	STEEL 4340	Lagr. 1800	

Table (3) (*Continued*) The Geometry of Model Parts

No	Model Name	Parts Name	Material	No. of Element	Description of Model
4	SW1-1	Target 1,2	Conc. 35MPa	Lagr. 190920	
		Steel Mesh 1-2	STEEL 1006	Beam 4716	
		Proje-ctile	STEEL 4340	Lagr. 1800	

Projectile Mesh

The geometry of the projectile part, as shown in Fig.(1),was defined using a structural Lagrangian mesh, and was divided to 13 nodes in the *I*-direction, 7 nodes in the *J*-direction and 26 nodes in the *K*-direction. The IJK-index corresponds to the Cartesian co-ordinate system.

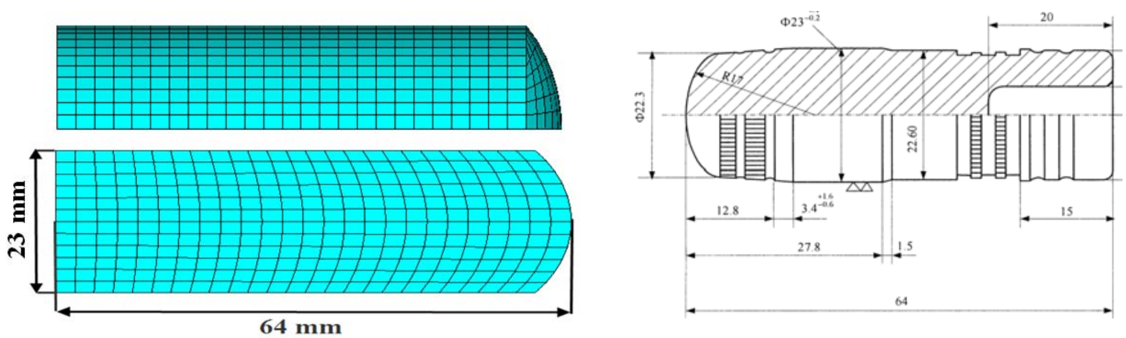


Fig. (1) Geometry and Meshing of the Projectile Part

Plain Concrete Mesh

For model SC1 and SC2, target 1&2 of plain concrete material (Conc.35MPa) were defined using a structural Lagrangian mesh, everyone was divided to 46 nodes in the *I*-direction, 91 nodes in the *J*-direction and 41 nodes in the *K*-direction. Zoning technique was used to densify the meshes in critical regions. Fig (2) shows the geometry and meshing of model SC1 & SC2.

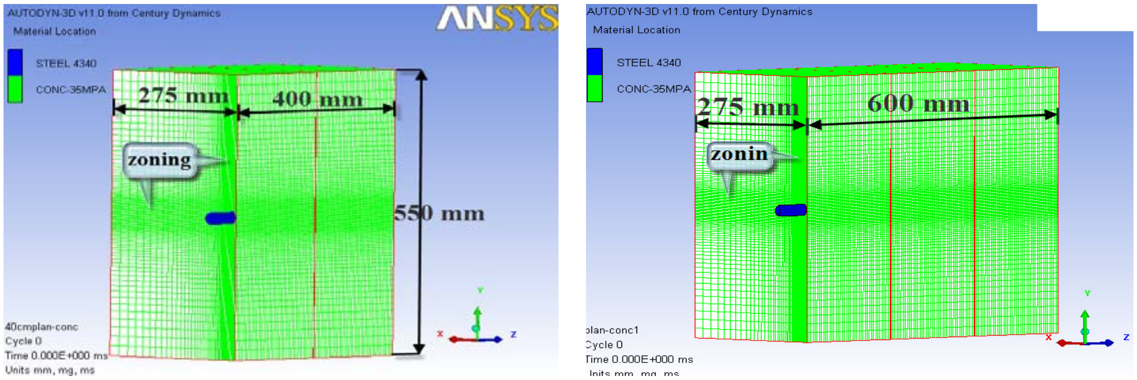


Fig. (2) Geometry and Meshing of the Model SC1 & SC2

Ferrocement Mesh

The ferrocement model SW1-2 and SW1-1 contains targets 1&2 of concrete material (Conc.35MPa) and steel mesh layers of (STEEL 4340) beside projectile part.

Targets 1&2 were defined using a structured Lagrangian mesh, every one was divided to 44 nodes in the I-direction, 75 nodes in the J-direction and 31 nodes in the K-direction,
Steel layer was defined using 1197 beam element for each layer. Zoning technique was used to refine the mesh in the critical regions as shown in Fig (3). Nodes of steel layer are attached to the concrete nodes one to one at the intersections preventing the two materials from sliding.

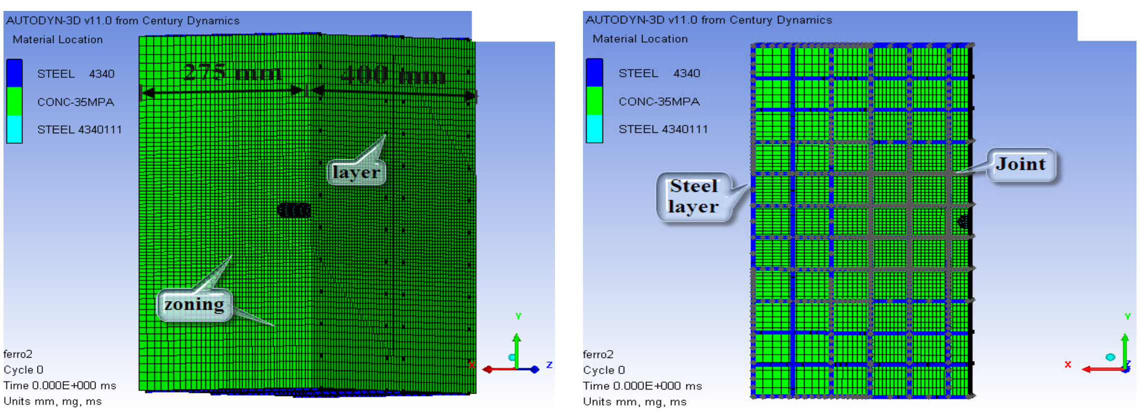


Fig. (3) Geometry , Meshing and Joining of the Model SW1-1 & SW1-2

Material Modeling

The governing equations are the conservation of mass, momentum and energy. To complete the description of the continuum, additional relations describing the material behavior are needed (besides the load and boundary conditions): it is the material model, which has typically four basic types of information to be specified for each material:

1. Equation of State: Pressure as function of density and internal energy.
2. Strength model: Strength model, which defines the yield surface.
3. Failure model: Failure model prescribing when the material no longer has strength
4. Erosion model: Erosion criteria. When a material is eroded, it is transformed from solid element to a free mass node (Lagrange only).

According to [6,15,16] and many other researches, RHT material model, which is a modular strength model for brittle materials developed by Riedel, [15] is particularly useful for modeling the dynamic loading of concrete. That is because the model computes the following phenomena associated with brittle materials: Pressure hardening, Strain hardening, Strain rate hardening, Third invariant dependence for compressive and tensile meridians, damage effects (strain softening),volumetric compaction (using the P-alpha equation of state), crack-softening.

The main material parameter for concrete was chosen from the AUTODYN material library (Concrete 35 MPa) and modified according to the values investigated experimentally as reported in Table (3). The material model used to represent the steel mesh material was Johnson Cook strength model [17]. The main material parameter for steel was chosen from the AUTODYN material library (STEEL 1006) and modified according to the values obtained from material data sheet and listed in Table (4). The main material parameter for steel used in projectile was chosen from the AUTODYN material library (STEEL 4340) and modified according to the values obtained from material data sheet and listed in Table (5). The erosion model used was geometric strain.

Table (4) Mechanical Properties of Concrete

Properties	Density (kg/m^3)	Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
Value	2360	35	3.1	29

Table (5) Mechanical Properties of Steel Mesh

Properties	Density (kg/m^3)	Yield Strength (MPa)	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)
Value	7850	250	460	210

Table (6) Mechanical Properties of the 23 AP Projectile Materials

Brinell hardness Number [HB]	Yield strength [MPa]	Ultimate strength, [MPa]	Strain to fracture [%]
475	1726	1900	**7**

Model Interaction and Boundary Conditions

Projectile – concrete interaction was achieved using the *gap* interaction logic. In the *gap* interaction logic, each surface segment is surrounded by a contact detection zone. The radius of this contact detection zone is called the *gap* size. Any node entering the contact detection zone of a surface segment are repelled by a force proportional to the depth of penetration of the node into the contact detection zone.

The initial condition for projectile part in all models was 960 m/sec in Z direction and the boundary conditions in all model for all target parts were constant velocity in Y direction $V_y = 0$ and for target were constant velocity in Z direction $V_z = 0$.

Results and Discussion

Four finite element models were performed in this paper. The responses of the concrete panels were determined in terms of penetration depth, front and rear damaged areas. These parameters are used to identify the penetration resistance of ferrocement panels. A comparison between finite element models results and experimental results is presented in Table (6) and figures from Fig (4) to (11).

Table (7) Experimental and Numerical Result of Penetration Resistance

NO	Name	Velocity (m/s)*	Penetration Depth(cm)*	Dim. of damage front/ rear face*	Penetration Depth(cm)**	Dim. of damage front/ rear face**
1	SC1	974	40	70/non	40	55/non
2	SC2	976	40	Full/Full	40	55/55
3	SW1-2	996	28.7	32.5/F.C.	28.2	30/F.C.
4	SW1-1	994	29	37/F.C.	28.6	34/F.C.

* Experimental ** Numerical F.C. Fine cracking

Effect of Using Ferrocement on Penetration Depth

Penetration depth is the most important factor determines the range of enhancement penetration resistance of concrete. From previous results in Table (6) and Figs.(4-7) note the following:

- In comparison with plain concrete models (SC1& SC2), using ferrocement in models (SW1-2) & (SW1-1) reduced the penetration depth by about 30.0 %.
- Increasing the number of layers from one layer in SW 1-1 to two layers in SW 1-2 had little effect on the perforation resistance (penetration depth).

Effect of Using Ferrocement on Damage in Front Face

Spalling or damage in front face of target was affected mainly by tensile strength of concrete of which is enhanced by using Ferrocement. From previous results in Table (6) and Figs.(8-11) note the following:

- In comparison with plain concrete models (SC1& SC2), using ferrocement in models (SW1-2) & (SW1-1) reduced the damage in front face between (47.5-53.5) percent.
- Increasing the number of layers decreased the damage in front face from 100 % when using no layer in (SC1&SC2) to 47.5% when using one layer in (SW 1-1) to 53.5% when using two layers in (SW 1-2).

Effect of Using Ferrocement on Damage in Rear Face

Scabbing or damage in rear face is the second mode of failure after perforation; it is mainly affected by the tensile strength of concrete, and is enhanced by using Ferrocement. From previous results in Table (6) and Fig. (8-11) note the following:

In comparison with plain concrete models (SC1& SC2), using Ferrocement in model (SW1-2) & (SW1-1) reduced the damage in rear face.

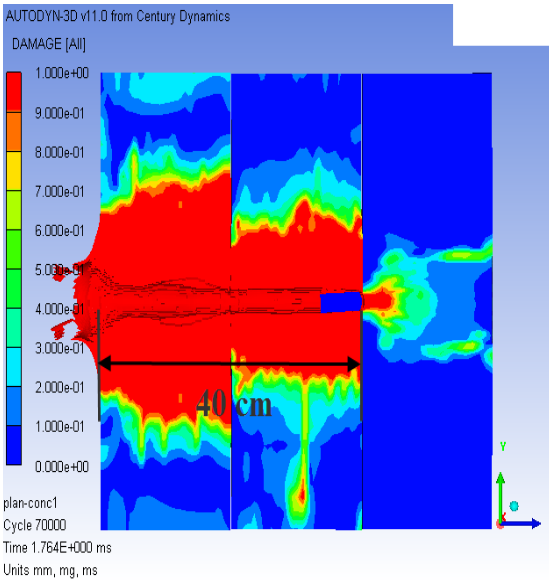


Fig.(4)Depth of Penetration for Model SC1

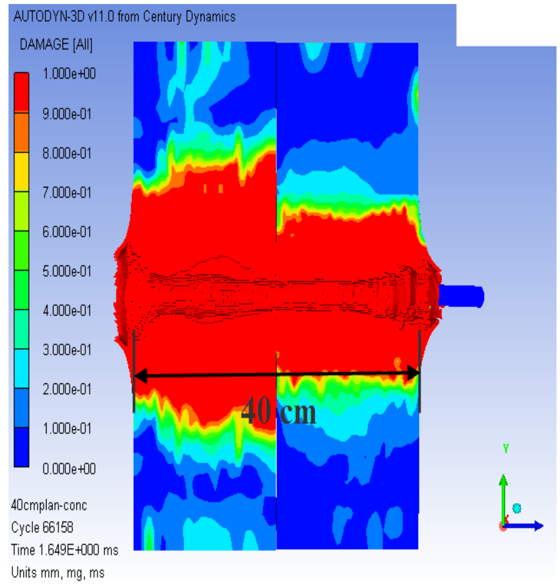


Fig.(5) Depth of Penetration for Model SC2

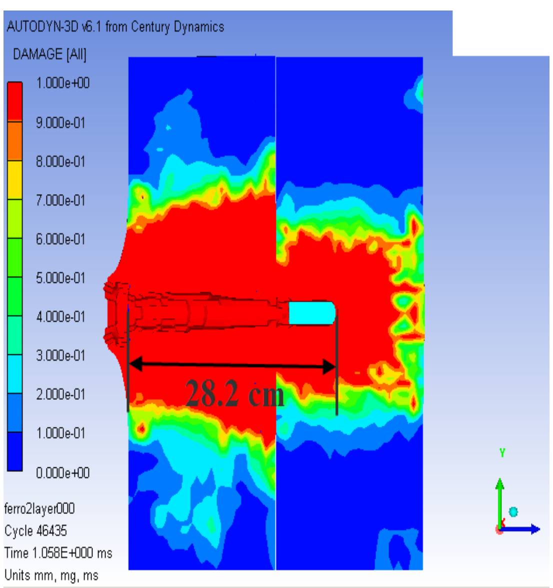


Fig.(6) Depth of Penetration for Model SW 1-2

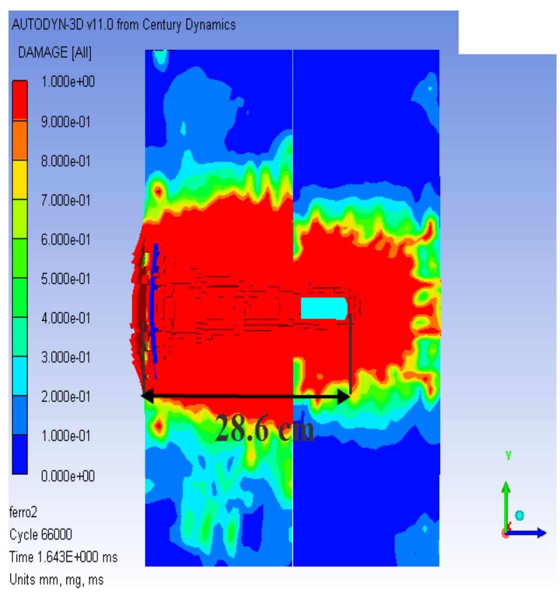


Fig.(7) Depth of Penetration for Model SW 1-1

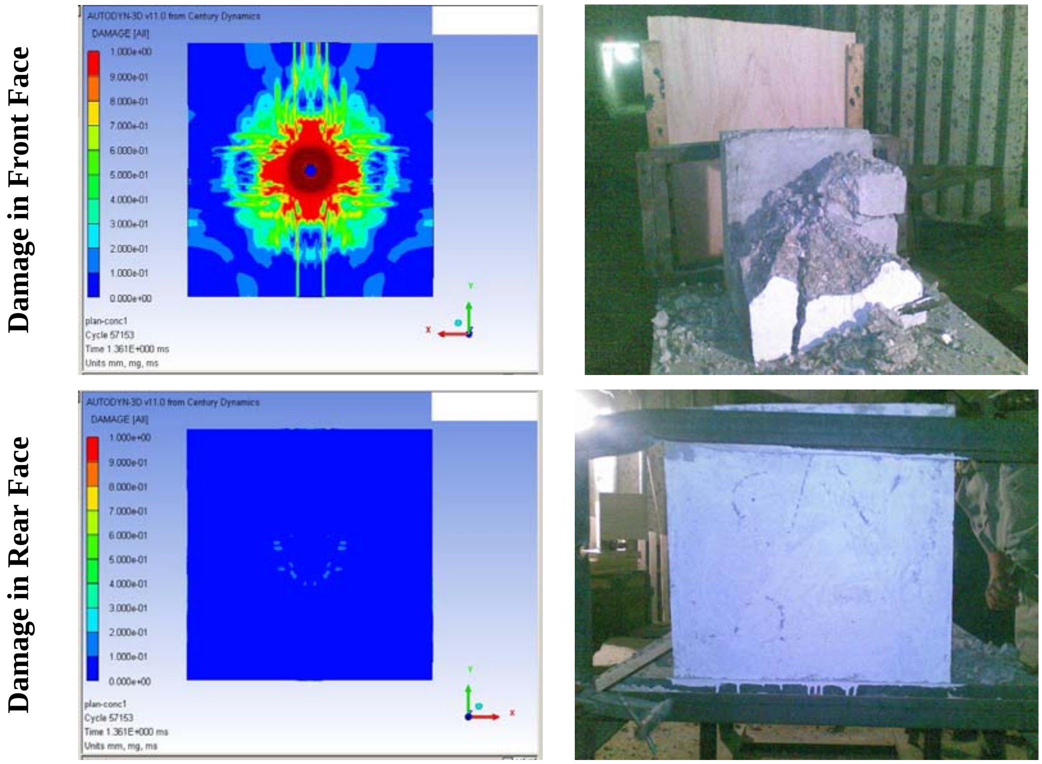


Fig. (8) Front and Rear Damage for Concrete Model SC1

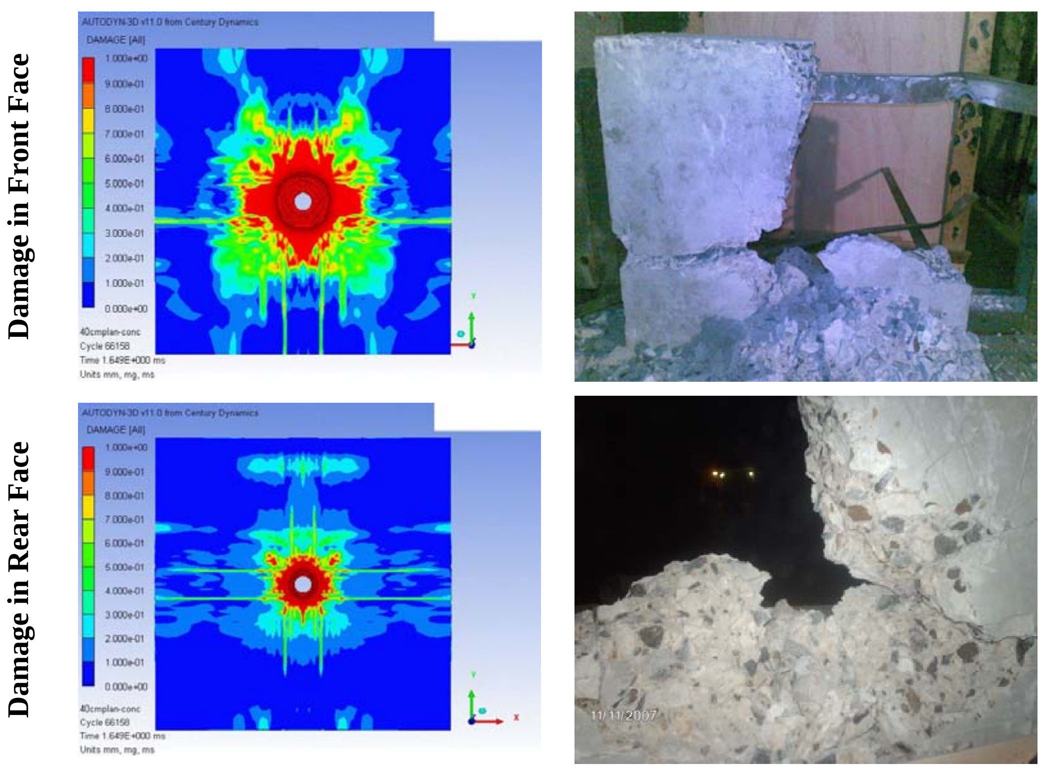


Fig. (9) Front and Rear Damage for Concrete Model SC1

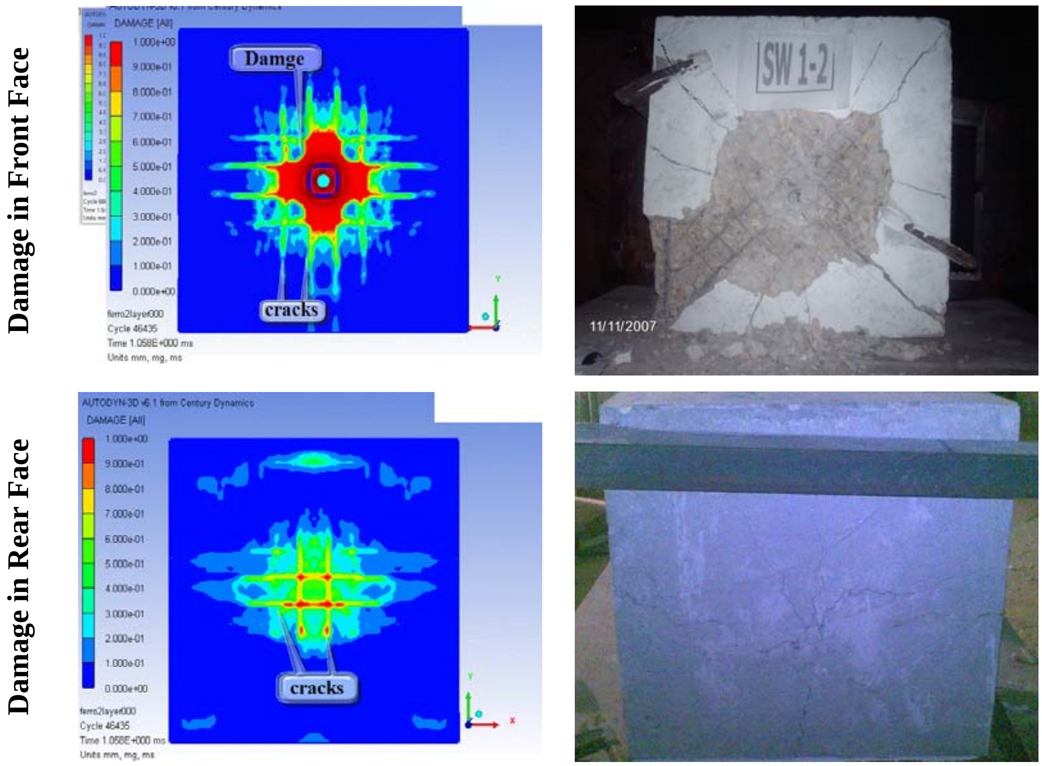


Fig. (10) Front and Rear Damage for Concrete Model SW1-1

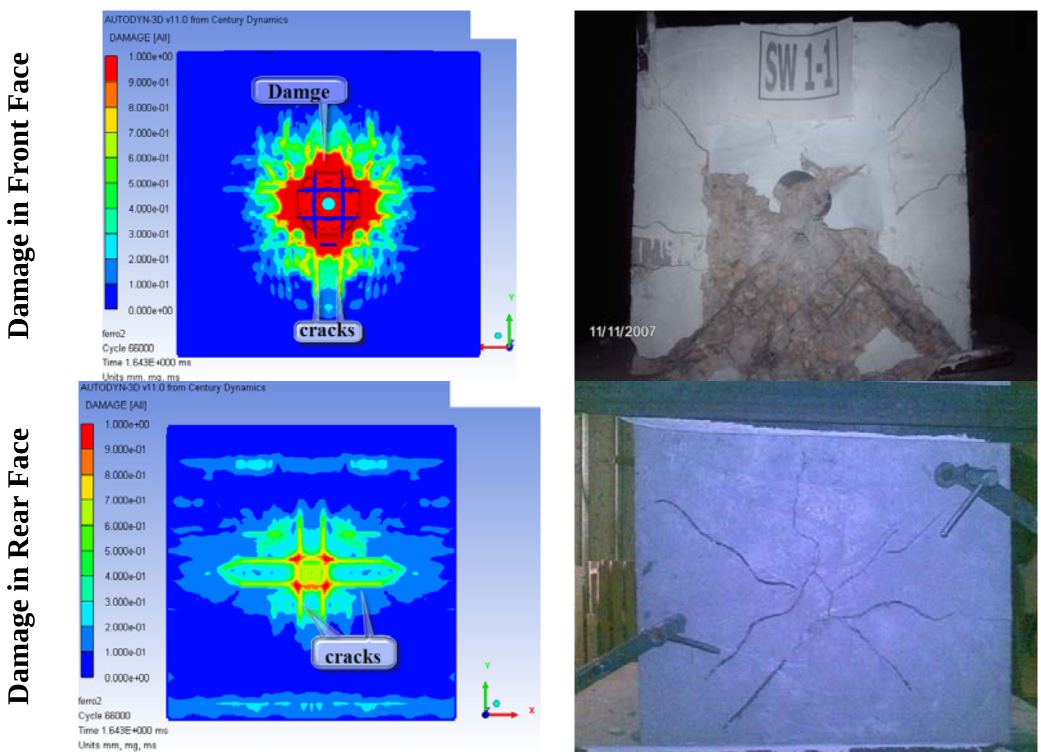


Fig. (11) Front and Rear Damage for Concrete Model SW1-2

Conclusions

The proposed finite element model can be used efficiently in characterizing the behavior of concrete panels under the effect of projectile penetration. The reliability of this model performance is demonstrated by a comparison between finite element models results and experimental ones. It exhibited qualitatively correct behavior compared with the experimental investigation results.

Also, using ferrocement enhances the penetration resistance of concrete panels by reducing the penetration depth and reducing the front and rear face damage. On the other hand, increasing number of layers of wire mesh in ferrocement panels has slight influence on the depth of penetration, but it has a remarkable effect on face damage (front and rear).

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