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A COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL STUDIES FOR REINFORCED CONCRETE SLABS UNDER BLAST LOADING

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ABSTRACT: Explosion is a special load, it rarely happens, but consequences are very serious. Research on the effect of explosive loads on reinforced concrete (RC) slabs is important to reduce unexpected consequences. This research has been an interesting topic in Vietnam during recent years because there have been accidents due to explosive loads in the country. This is the basis for the design of military structures or special buildings in civil engineering in Vietnam. This paper presents experimental and numerical studies of the fracture response of RC slabs using materials available in Vietnam under blast loading. The concrete slabs with the length of 1000mm, the width of 800mm and the thickness of 120mm are manufactured and tested. The emulsion explosive has been used. Two cylindrical explosive blocks with masses of 0.5kg and 1.22kg are considered. These tests are modeled using the finite element method. Concrete is supposed to be brittle material and follow the Johnson–Holmquist-II (JH-2) model. The steel rebar is modeled following an elasto-plastic model. The emulsion explosive is converted to TNT explosive equivalent and modeled by the SPH method. The concrete crater, spall damage and dynamic behavior of concrete slabs under blast loading are considered. The comparison between experimental and numerical results allows to validate the numerical model to modeling the behavior of our concrete under blast loading.

Keywords: Reinforced concrete, Explosive load, Fracture mechanic, Experiment, Finite Element Modeling

1. INTRODUCTION

Reinforced concrete (RC) is a material used in many parts of construction. It decides the main bearing of structures. An explosion load can occur in short time, with a high release of energy. When an explosion occurs, the blast wave propagates which contains a large part of energy release. It destroys the materials and the structure, that may lead to a potential collapse. To reduce consequences caused by blast loading on the structure, it is necessary to understand blast phenomena, the dynamic response of the concrete material under this load. It is particularly of great interest in the design of military structures and special buildings in civil engineering. However, the experimental study of explosive loads on concrete structure has many difficulties in practice. The research is mainly based on a simple experimental test of blast loading to model and validate the numerical model. After that, the complex explosion test on the concrete structure will be performed on the simulation. It allows to reduce the price and the time realized.

Many studies on the dynamic behaviors of reinforced concrete under impact of the explosive load have been published. Studies exhibit experiments, numerical simulations, or both of them. The experimental study allows to assess the effect of explosive load on the mechanical behaviors of concrete directly [1–5]. In addition, it allows to identify the model's parameters of the numerical study. Parameters affecting the destruction of concrete such as distance, explosive weight, wall thickness, strength level of concrete, concrete admixture and reinforcement content have been considered in these studies.

The blast loading modeling is usually performed using commercial softwares, such as LS-DYNA, AUTODYN, ABAQUS, etc. K. Xu and Y. Lu [6] used 3D model with a finite element method to simulate the behaviors of reinforced concrete slabs affected by explosive loads. In this study, concrete material was modeled by solid elements. Based on the numerical results, this paper highlights a way to predict damage in reality. The explosion resistance of reinforced concrete slabs retrofitted with glass fiber reinforced polymer has been studied by J.-W. Nam, H.-J. Kim, S.-B. Kim, N.-H. Yi, and J.-H. J. Kim [7] using LS-DYNA software. Concrete and reinforcement materials were modeled by solid elements and beam elements, respectively. The displacement and strain history are used to analyze structure resistance under blast loading.

The simulation studies of dynamic load which impact reinforced concrete have also been performed with ABAQUS software [8,9]. The appearance and propagation of cracks in concrete under the effect of blast loading are simulated considering blast pressure, strain and strain rate of materials. Johnson-Holmquist model [10], Brittle Damage [11], Soil and Crushable/Non-crushable Foam [12] models are employed. These studies are realized based on the numerical method, the experimental method or combining two. But the aim of each research is to study the behaviors of its concrete under its blast loading. It is the basis for design of works using this concrete.

In Vietnam, research on the effects of explosive loads on reinforced concrete works has been an interesting topic in recent years. Especially, after some accidents due to explosive loads, such as the explosion of a firework factory in Thanh Ba (Phu Tho) on October 2013. The study of mechanical behaviors of concrete manufactured in Vietnam under actual explosive loads is an important content. It is the basis for design of military structures or special buildings in civil engineering in Vietnam.

Based on studies above in bibliography, to simplify, the objective of this paper is to study the mechanical behaviors of RC slabs under blast loading using an experimental and numerical method. The comparison between experimental and numerical results allows to validate the numerical model for our concrete using materials available in Vietnam with actual explosives.

This paper begins by an introduction to our concrete material and manufacture of test specimen. Next, the experiment of blast loading test is detailed. The 3D numerical simulation of the previous test is presented in next Section. The simulation is conducted with ABAQUS explicit software. The paper ends with conclusion.

2. FABRICATION OF SAMPLES

2.1 Material

The concrete used is grade C30, aggregates composition included: cement PCB40, sand (fine aggregate) with fineness modulus has a value of 2.82 [13,14], macadam (coarse aggregate) with a grain size of 1-2cm. The material weight is shown in Table 1:

Table 1 Aggregates of concrete proportions

Concrete Grade	Sand	Cement PCB40	Macadam 1x2cm	Water
	Kg	Kg	Kg	Kg
C30	626	395	1210	183

The rebar used in this study include plain bar and deformed bar with diameters Ø8 and Ø12, respectively. Mechanical properties are complied with TCVN 1651:2008 [15].

2.2 Manufacturing

The samples of experiment are the concrete slabs with dimensions 1000×800×120mm. The reinforcement is introduced in both directions of the slab (Fig.1). 8 bars of Ø12 and 6 bars of Ø8 are used for longitudinal and horizontal, respectively.

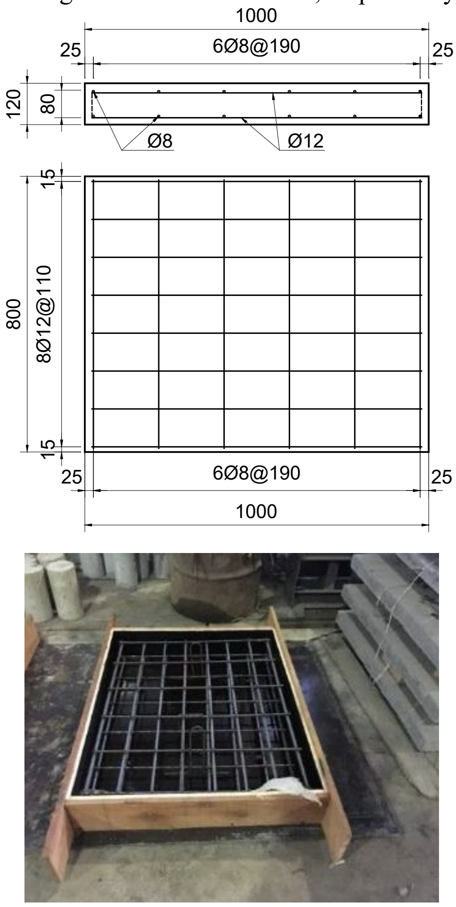


Fig. 1 Dimensions of formwork

2.3 Mechanical characterization

Elastic modulus of concrete is determined through compression cylinder testing according to ASTM C469M [16]. The dimension of samples is 150×300mm.

The compressive strength and flexural strength of concrete were identified according to TCVN 3118-1995 [17] and ASTM C1609M [18]. These cubes have dimensions of 150×150×150mm and 150×150×600mm, respectively.

Test results are shown in the Table 2

Table 2 Mechanical properties of concrete

Concrete grade	Compressive strength MPa	Flexural strength MPa	Elastic modulus GPa
C30	30	3	30

3. EXPERIMENTS

In this study, the emulsion explosive is used. Two cylindrical explosive blocks with masses of 0.5kg and 1.22kg are considered (Fig.2). Details of explosive blocks are shown in Table 3:

(a) Mass 0.5kg (b) Mass 1.22kg

Fig. 2 Explosive blocks were used in the study

Table 3 The dimension of explosive blocks

Block	Mass Kg	Diameter mm	Height mm
Block 1	0.50	80	86.5
Block 2	1.22	120	94

The blast testing is realized on the concrete slabs that is placed on the steel rig using a crane (Fig. 3). The explosive block is placed directly at the center of the upper surface.

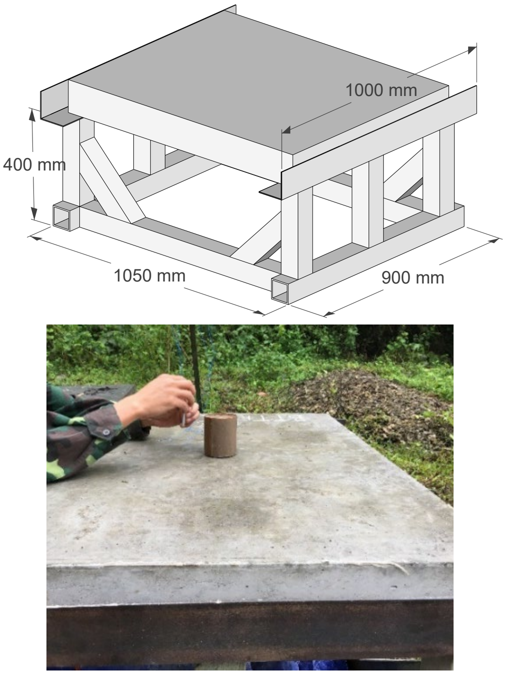


Fig. 3 Steel rig configuration

4. NUMERICAL MODELING

The simulation was conducted under the same conditions as in reality. Dimensions are completely accurate, the interaction between objects is described, boundary conditions are included. The most important thing, materials must be simulated with models to work accurately compared to reality.

4.1 Materials model

4.1.1 Concrete model

Concrete is supposed as a brittle material with a highly compressive strength, but a much lower tensile strength. Under blast loading, it tends to accumulate fracture. The Johnson-Holmquist model is a suitable model to simulate the destruction of concrete under the effect of explosive load. There are two models developed by Johnson and Holmquist. The first model is called JH-1 [19], it is used to describe the large deformations of a material but does not account for the accumulation of damage over time. The 2nd version was built in 1994, called JH-2 [20]. It solves the problems of the first version and is used to simulate the working of brittle materials. JH-2 model consists of 3 components: Strength, Damage and Pressure. These factors directly affect behaviors of concrete materials. Fig. 4 described the Strength curve of brittle material in the JH-2 model.

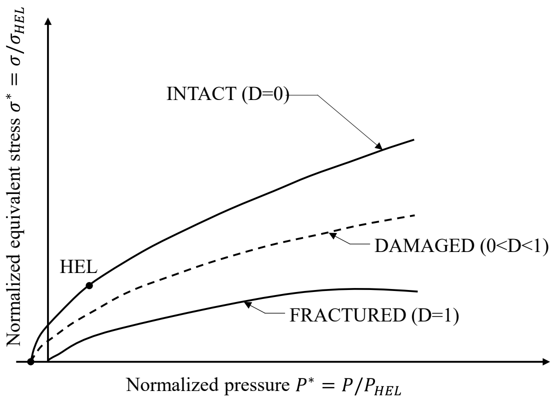


Fig. 4 Strength component in the JH-2 model

Under impact loads, the behaviors of material are divided into three working states: intact state, damaged state and fractured state. The differences among these states are expressed through the relationship of pressure P^* and stress σ^*. At the damage state (*0< D <1*), the stress is determined by the formula as shown:

$$\sigma^* = \sigma_i^* - D\left(\sigma_i^* - \sigma_f^*\right) = \sigma / \sigma_{HEL}$$

Where σ_i^* σ_f^* is stress at destructive state (D=1); D is the destructive factor ($0 \le D \le 1$); σ_{HEL} is stress at elastic limit Hugoniot (HEL); σ is the actual stress by Von Mises:

$$\sigma = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2\right]}$$

with $\sigma_1, \sigma_2, \sigma_3$ are principal stress.

Stress at the intact and fracture state are determined by formulas below, respectively:

$$\sigma_i^* = A\left(P^*+T^*\right)^N\left(1+C\ln\dot{\varepsilon}^*\right)$$

$$\sigma_f^* = B\left(P^*\right)^M\left(1+C\ln\dot{\varepsilon}^*\right) \le \sigma_{f\max}^*$$

where *A, B, C, M, N* is the material constant; normalized pressure $P^* = P/P_{HEL}$ with P is the actual pressure, P_{HEL} is pressure at Hugoniot Elastic Limit (HEL); normalized maximum tensile hydrostatic pressure $T^* = T/P_{HEL}$ with T is maximum tensile hydrostatic pressure of material (T^* come to 0 when D come to 1) [21]. $\sigma_{f\max}^*$ is the stress limit for normalized fracture strength, $\sigma_f^* \le \sigma_{f\max}^*$; the dimensionless strain rate is: $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$, with $\dot{\varepsilon}_0 = 1.0s^{-1}$ - is the reference value, $\dot{\varepsilon}$ is the actual strain rate.

The concrete's damage is the cumulative fracture damage, defined by Johnson-Cook destructive paradigm (1985) [22]:

$$D = \frac{\sum \Delta\varepsilon^p}{\varepsilon_f^p}$$

where $\Delta\varepsilon^p$ is the plastic strain in a circle, $\varepsilon_f^p = f(P)$ is the plastic strain under a constant pressure P, specific

$$\varepsilon_f^p = \sum\Delta\varepsilon^p / \left[D_1\left(P^*+T^*\right)^{D_2}\right],\ \left(\varepsilon_{f\min}^{pl} \le \varepsilon^{pl} \le \varepsilon_{f\max}^{pl}\right)$$

where D_1, D_2 are constants; $\varepsilon_{f\min}^{pl}$, $\varepsilon_{f\max}^{pl}$ are deformation limit of damage.

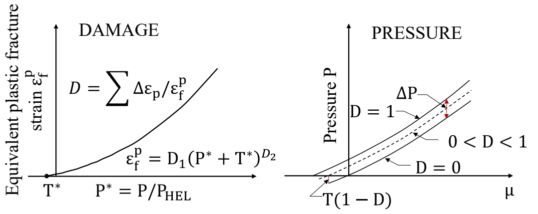


Fig. 5 Damage and Pressure components in the JH-2 model

Under the explosion load, the equation-of-state (EoS) for brittle materials can be expressed by equation of pressure P and weight ratio μ (Fig. 5). Accordingly, the two stages of material are expressed as linear stage and nonlinear stage:

$$\begin{cases} P = K_1\mu + K_2\mu^2 + K_3\mu^3 & (D=0) \\ P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P & (0<D<1) \end{cases}$$

where *K1, K2, K3* are constants determined by the impact tests of materials; $\mu = \rho/\rho_0 - 1$ with ρ_0 is the initial density, ρ is the actual density; ΔP is the added pressure at the start of fracture accumulation (D>0). The pressure increment is determined from energy considerations. It varies from $\Delta P = 0$ at $D=0$ to $\Delta P = \Delta P_{\max}$ at $D=1$.

The general expression for the elastic internal energy of the shear and deviator stresses is determined by the expression:

$$U = \sigma^2/6G$$

where G is shear modulus, energy loss ΔU is determined according to 2 consecutive stages when fracture occurs:

$$\Delta U = U_{D(t)} - U_{D(t+\Delta t)}$$

Energy loss ΔU is mostly converted into fractural energy ΔF, determined by formula:

$$\Delta F = \beta.\Delta U$$

where $\beta=1$ $(0<\beta<1)$ is converted ratio.

Material specifications for the paradigm are determined according to JH-2 model [23] as shown in the Table 4 to Table 6:

Table 4 Strength's parameters of concrete

A	B	N	C	M	G GPa	P_{HEL} MPa	$\dot{\varepsilon}_0$
0.79	1.6	0	0.007	0.61	14.86	30	1.0

Table 5 Damage's parameters of concrete

D_1	D_2	$\varepsilon_{p,\min}^{f}$	$\varepsilon_{p,\max}^{f}$	$\sigma_i^{\max}$ GPa	$\sigma_f^{\max}$ GPa
0.04	1.0	0.001	1	8.1	1.1

Table 6 Pressure's parameters of concrete

K_1 GPa	K_2 GPa	K_3 GPa	HEL GPa	T GPa	β
85	-171	208	0.8	0.0354	1

4.1.2 Reinforced model

Steel used in the experiment include CB300-T plain bar and the CB400-V deformed bar with the diameter is Ø8 and Ø12. Within the elastic limit, steel has modeled by Hooke's law with the material specification conform to the TCVN 1651:2008 standard, summarized in Table 7:

Table 7 The specification of steel material

Steel type	Diameter mm	Elastic module MPa	Tensile strength MPa
CB300-T	Ø8	200 000	300
CB400-V	Ø12	200 000	400

4.1.3 Explosive model

The explosive using in the experiment is emulsion explosive. The state equation by Lee Tarver and Jones Wilkin Lee (JWL EOS) [24] was used to model explosive and the propagation of blast wave.

$$P = C_1\left(1-\frac{\omega}{r_1 v}\right)e^{-r_1 v} + C_2\left(1-\frac{\omega}{r_2 v}\right)e^{-r_2 v} + \frac{\omega e}{v}$$

where P is pressure of explosion; $v = 1/\rho$ with ρ is density of explosive; C_1, C_2, r_1, r_2, ω are other parameters of explosive material. These parameters are shown in Table 8:

Table 8 The parameters of the emulsion explosive

Parameters	Values	Unit
Density	1.15	g/cm^3
Velocity of detonation	4095	m/s
Energy per one explosion	2800	KJ/Kg
Pressure of explosion	21	GPa
C_1	373.77	GPa
C_2	3.75	GPa
r_1	4.15	
r_2	0.90	
ω	0.35	

These parameters of emulsion explosive need to be converted to TNT equivalent. The reason is that the simulation software can only represent the state equation for TNT. The mass of emulsion explosive is converted to TNT's mass by equation:

$$W_{TNT} = W_E \frac{Q_E}{Q_{TNT}}$$

where W_{TNT} is the same amount as TNT; W_E is the mass of emulsion explosive; Q_E is explosion heat of emulsion explosive; Q_{TNT} is explosion heat of TNT, Q_{TNT} = 4521 KJ/Kg.

After conversion, the weight and dimensions of the TNT blocks included in the numerical model are shown in Table 9:

Table 9 Dimensions of explosion in the numerical model

Mass of emulsion Kg	Mass of TNT Kg	Diameter mm	Height mm
0.50	0.31	80	37.8
1.22	0.75	120	41.0

4.2 Numerical configuration

The numerical configuration is shown in the Fig. 6. This simulation is implemented based on Abaqus software. Components that have been used include: Concrete – Solid element, Rebar – Frame element, Explosive – SPH particle [19].

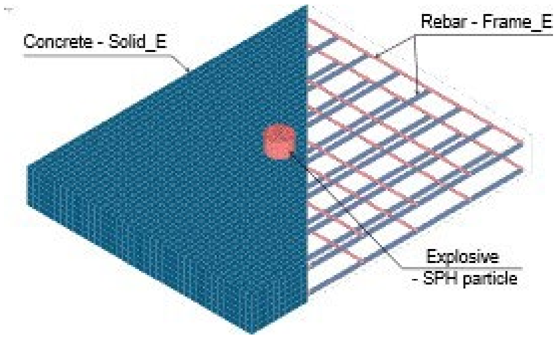


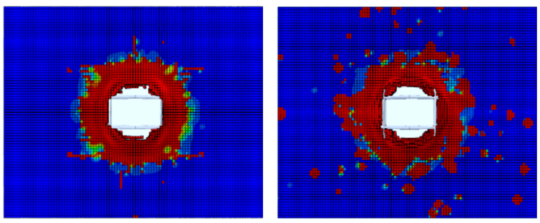
Fig. 6 Components of numerical model

5. EXPERIMENTAL AND NUMERICAL RESULTS

The experimental and numerical results of slab specimen test correspond to 0.5kg explosive are shown in Fig. 7 and Fig. 8. This comparison is depicted in Fig. 9. The reinforced concrete slabs have been penetrated with a hole. The top surface crater diameter is 23cm for both experimental and numerical results. Whereas, the bottom surface crater diameter is 35cm with experiement and 30cm with simulation. The simulation result also obtained similar compared with the experimental results on the hole diameter and the damage on the slab.

a. Upside b. Downside

Fig. 7 Experimental results using 0.5kg of explosive



a. Upside b. Downside

Fig. 8 Simulation results using 0.5kg of explosive

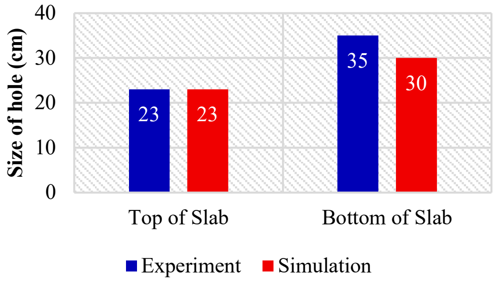
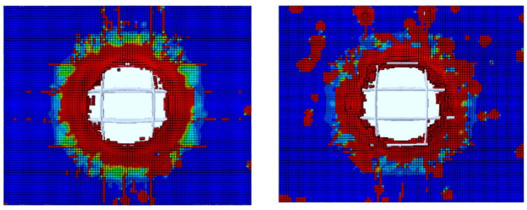


Fig. 9 Comparison of hole sizes between experiment and simulation results on the top and bottom of slabs under the effect of 0.5kg of explosive

The experimental and numerical results with 1.22kg explosive are shown in Fig.10 and Fig. 11. This comparison is depicted in Fig.12 The top surface crater diameter obtained is 30cm in experiment and 33cm in simulation. The bottom surface crater diameter is 55cm and 50cm with experiment and simulation, respectively. As in the case of 0.5kg of explosive, the simulation results obtained are also quite similar to the experimental results on the hole diameter and the damage on the slabs.

a. Upside b. Downside

Fig.10 Experimental results using 1.22kg of explosive



a. Upside b. Downside

Fig. 11 Simulation results using 1.22kg of explosive

The propagation of blast wave leading to the destruction of the concrete slabs is shown in Fig. 13. After the explosion, blast wave will form from the center of the explosion. When it reaches the open face, the wave will return to form a reflected wave. These waves carry mechanical energy causing tensile, compression and shear stress in concrete, lead to the destruction of reinforced concrete slabs. At centroid of explosion, due to the huge pressure on the surface, it almost immediately destroyed the concrete in this area and created a hole.

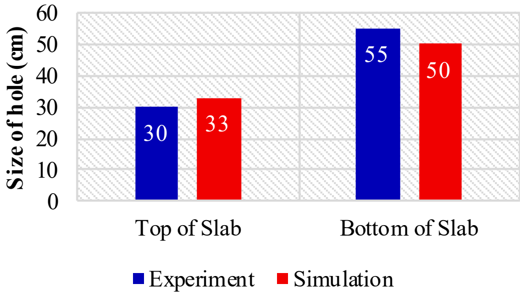


Fig. 12 Comparison of hole sizes between experimental and simulation results on the top and bottom of slabs under the effect of 1.22kg explosive

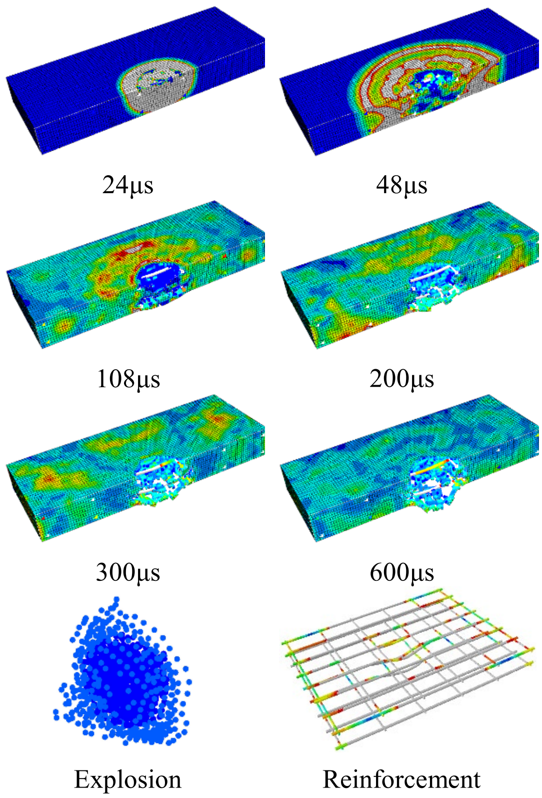


Fig. 13 Pressure contour of blast wave

6. CONCLUSIONS

The numerical and experimental studies of the mechanical behavior of RC slabs using materials available in Vietnam under explosive loading are presented in this paper. The blast loading testing uses two cylindrical explosive blocks with masses of 0.5kg and 1.22kg. The emulsion explosive is used in this study. The fracture response of concrete slabs under explosive loading is considered and compared between experiment and simulation. For the numerical modeling, the concrete material is supposed to be brittle material and follows the

Johnson–Holmquist-II (JH-2) model. The explosive load is modeled by the SPH method. The reinforcement is modeled using elasto-plastic model. The simulation results obtained are quite similar to the experimental results on the hole diameter and the damage on the slab (at top and bottom surface) with two explosive blocks. These results confirm that the JH-2 model can be used to model the mechanical behaviors of our concrete under blast loading of emulsion explosive. These results are the important basis for our future research concerning the application of concrete materials for special projects against the blast loading in Vietnam.

7. ACKNOWLEDGMENTS

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