

VERIFYING MATERIAL MODELS OF CONCRETE AND REINFORCEMENT IN LS-DYNA SOFTWARE BY THE EXPERIMENTS

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Abstract

This article presents research and evaluation of a number of concrete and reinforced material models commonly used in LS-DYNA to simulate reinforced concrete structures subjected to explosion pressures. Based on that, the selections of a suitable material model with the priority input for modeling are the basic parameters of the materials. Through the simulation results and the field explosion experimental data, the verifications and evaluations of the responses of the selected material models are conducted. The method developed for the simulation of the behaviour of the reinforced concrete slabs under explosions using LS-DYNA is also presented in this article.

Keywords: *LS-DYNA; concrete model; reinforced model; explosion test.*

1. Introduction

Full-scale structural tests are always expensive, and most of the time, performing blast stress tests on the actual structures is very difficult to be carried out. Therefore, structural model analysis based on numerical simulation is an important approach to determine the behavior of reinforced concrete structures subjected to explosion pressure. To satisfy the structural behavior subjected to explosion pressure, a numerical analysis tool must have the following criteria: (1) to have a typical loading and response time within one millisecond; (2) to be capable of handling both material and geometric nonlinearities as well as other nonlinear states; (3) to allow highly nonlinear dynamic analysis simulation; (4) can handle problems of material requirements and contact between soft and hard materials; (5) to be capable of analyzing large changes or large deformations of materials subjected to stress [1]. In terms of the characteristics and requirements of the research objects and the analysis and comparison of software functions, LS-DYNA is a dynamic analysis software most suitable for simulating extreme impacts from explosions for this research on theory, material models, functions, equations of state and damage criteria. LS-DYNA is widely applied in analyzing the response of

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structures to impact and shock loads with many different models for reinforced concrete materials. Each concrete model and reinforced steel model have their own advantages and disadvantages, so choosing a material model that is suitable for the behavior when the structure is subjected to explosion pressure is very important.

The focus of this study is to evaluate the modeling of concrete materials and reinforcement in LS-DYNA through comparison with field explosion experimental data. This is done through numerical model analysis of reinforced concrete slabs subjected to explosion pressure, the behavior of the numerical model is compared with experimental data to verify and evaluate the applicability of the model. The research results allow for appropriate suggestions for choosing a model that responds well to reinforced concrete structures subjected to explosion pressure with the input objectives of the simplest models.

2. Concrete material models

There are many material models built and used for concrete. The article introduces some typical models that have been widely applied in research through the simulation of concrete materials subjected to explosion pressure by LS-DYNA.

2.1. Some typical models

LS-DYNA software provides a good library of concrete simulation models, such as “Mat_Concrete_Damage_Rel3” (KCC model or MAT_072_R3 [2, 3]), “Mat_Winfrith_Concrete” (Winfrith model or MAT_084 [4]), “Mat_CSCM_Concrete” (CSC model or MAT_159 [5, 6]), and “Mat_RHT” (RHT model or MAT_272, [7]),... Inputs for these models are the basic parameters of the material and each model is capable of providing a version of automatic parameter generation.

2.2. Discussions on the models used for simulations

Among the above models, models MAT_072_R3, MAT_084 and MAT_159 are widely used in research on structures subjected to impact and explosion pressure [2-7]. The MAT_072_R3 model requires an additional more complex equation of state than the other two models. Through research and reference, it was found that the Winfrith model has outstanding features and certain advantages, such as simplicity in input data and the ability to represent cracks on the structure, allowing up to three orthogonal crack planes for each element and cracks can be reviewed through LS-Prepost. On the other hand, in recent years, many authors have published positive and reliable results in using the MAT_084 model to simulate reinforced concrete structures affected by explosion pressure, such as Mousavi and Shafei, Sadraie and partners, Thai and Kim, Epackachi and Whittaker [8-11]. Therefore, in this article, the MAT_084 model will be selected to simulate concrete materials.

2.3. Winfrith model (MAT_084)

Concrete is a pressure-resistant material, so the general form of the yield function can be written as:

$$Y(I_1, J_2, J_3) = 0 \quad (1)$$

where I_1 is the first invariant of the stress tensor, representing volumetric behavior; J_2 and J_3 are the second and third invariants of the deflection stress tensor and they account for the deflection behavior.

The specific Winfrith model is based on the four-parameter model proposed by Ottosen [12]:

$$Y(I_1, J_2, J_3) = aJ_2 + \lambda\sqrt{J_2} + bI_1 - 1 \quad (2)$$

$$\lambda = \begin{cases} k_1 \cos \left[\frac{1}{3} \cos^{-1} (k_2 \cos(3\theta)) \right], & \cos(3\theta) \geq 0 \\ k_1 \cos \left[\frac{\pi}{3} - \frac{1}{3} \cos^{-1} (-k_2 \cos(3\theta)) \right], & \cos(3\theta) \leq 0 \end{cases} \quad (3)$$

$$\cos(3\theta) = \frac{3\sqrt{3}}{2} \frac{J_3}{J_2^{3/2}} \quad (4)$$

where a , b , k_1 , and k_2 are four parameters of the ratio function between tensile stress and compressive stress.

3. Reinforcement material model

LS-DYNA provides a number of material models suitable for steel materials, of which two models 003-PLASTIC_KINEMATIC (MAT_003) and 024-PIECEWISE_LINEAR_PLASTICITY (MAT_024) are commonly used in describing reinforcement materials [8-11]. With these two models, the MAT_003 model is relatively easy to use when requiring some basic parameters of steel and is suitable for the ductile materials such as steel bars.

In the MAT_003 model, isotropic hardening, kinematic hardening, or a combination of isotropic and kinematic hardening can be obtained by varying a parameter β between the two values 0 and 1, Krieg and Key proposed this model in 1976 [13]. The strain rate is calculated using the Cowper-Symonds model (Jones 1983 [14]), in which the yield stress depends on the strain rate:

$$\sigma_y = \left[1 + \left(\frac{\dot{\epsilon}}{C} \right)^{\frac{1}{q}} \right] (\sigma_0 + \beta E_q \epsilon_{eff}^q) \quad (5)$$

where q and C are input constants and the strain rates determined through the expression:

$$\dot{\varepsilon} = \sqrt{\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \quad (6)$$

The current radius of the yield surface σ_y , is the sum of the initial yield strength σ_0 plus the rehardening strength $\beta E_q \varepsilon_{eff}^q$, where E_q is the Plastic hardening modulus:

$$E_q = \frac{E_t E}{E - E_t} \quad (7)$$

and ε_{eff}^q is the effective plastic deformation:

$$\varepsilon_{eff}^q = \int_0^t \left(\frac{2}{3} \dot{\varepsilon}_{ij}^q \dot{\varepsilon}_{ij}^q \right)^{1/2} dt \quad (8)$$

The plastic strain rate is the difference between the total strain rates and elastic:

$$\dot{\varepsilon}_{ij}^q = \dot{\varepsilon}_{ij}^s - \dot{\varepsilon}_{ij}^e \quad (9)$$

During the calculation of this material model, the eccentric stresses are iteratively updated elastically:

$$\sigma_{ij}' = \sigma_{ij}^n + C_{ijkl} \Delta \varepsilon_{kl} \quad (10)$$

where σ_{ij}' is the experimental stress tensor, σ_{ij}^n is the stress tensor of the previous step, C_{ijkl} is the elastic tangent modulus matrix, and $\Delta \varepsilon_{kl}$ is the increasing strain tensor.

If the yield function is satisfied, no other additions will be made. However, if the yield function is violated then the increase in plastic strain is calculated, the stress is scaled back to the yield surface, and the yield surface center is updated.

4. Experimental study

To evaluate the impact of explosion pressure on reinforced concrete structures, field experiments were conducted (structure fabrication and explosion experiments) to determine the dynamic characteristics of reinforced concrete structures and laboratory experiments to determine characteristics of concrete and reinforced model.

4.1. Laboratory experiments determine concrete and reinforcement material parameters

Conducting a combined compression test on a 54 mm × 108 mm cylindrical concrete sample on the MTS multi-purpose force generator and a 150 mm × 300 mm sample on the WEW-1000B tensile and compression machine to determine concrete material parameters such as tangential modulus and compressive strength of concrete

materials. Testing reinforcement samples on WEW-1000B tensile and compression machine to determine reinforcement material parameters.



Fig. 1. Fabrication of field test components.



Fig. 2. Concrete and reinforced steel samples testing.

4.2. Field explosion experiment

To measure and record field experiment results, use experimental equipment: multi-channel dynamic meter NI SCXI-1000DC, non-contact displacement probe Sharp GP2Y0A21YK0F and accelerometer PCB 353M231. The measuring heads are connected to the NI SCXI-1000DC measuring machine through appropriate measuring cards, the entire measuring system is controlled on a computer using LabVIEW SignalExpress 2015 software. Experiments were conducted to determine the dynamic characteristics of reinforced concrete slabs subjected to explosion pressure.

To determine the dynamic characteristics of displacements and accelerations of the center of the reinforced concrete slabs, explosive experiments have been conducted in the field with the object being a reinforced concrete slab with dimensions of $100\text{ cm} \times 100\text{ cm} \times 6\text{ cm}$, 1-layer $\phi 10$ one reinforced mesh, spaced by $15\text{ cm} \times 15\text{ cm}$ in the two directions, placed on four sides on a fixed base block made of reinforced concrete. Testing with a TNT

1.0 kg explosion suspended 100 cm from the surface of the slab, the measured parameters to be investigated include accelerations and vertical displacements at the center of the underside of the test slab.



Fig. 3. Experiment to determine the dynamic characteristics of reinforced concrete slabs subjected to explosion pressure.

5. Numerical test

5.1. Choose the modeling method

There are various ways to set up explosion simulation using commercial softwares in general and LS-DYNA in particular. For example:

Pure Lagrangian method for structure, and explosion pressure using CONWEP function with tag *LOAD_BLAKE_ENHANCED. This is a method that uses empirical formulas with the explosive impact only depending on the volume of explosives and the distance to the receiving surface of the structure. Because there is no need to model the explosive volume and surrounding air, calculations are faster and consume less hardware. However, this method does not fully characterize the explosive loading tasks in the model configuration complex layer.

The Lagrangian-Eulerian arbitrary method (Arbitrary Lagrangian-Eulerian - ALE) is combined simultaneously with the Lagrangian algorithm and the Eulerian algorithm. This method addresses the shortcomings of the Lagrangian algorithm and the Eulerian algorithm, allowing researchers to solve problems in the form of high-speed collisions and explosions. All components are explosive as well as the atmospheric environment and configuration are fully modeled but the shortcomings of the pure Lagrangian approach are addressed. In this section, the ALE method is simply chosen among the modeled experiments.

5.2. Material model

To perform the simulation process in this study, we will inherit the results and input parameters from a recent study for the material model of TNT and air explosives [15].

5.2.1. Model of TNT explosive

Use the material tag MAT_HIGH_EXPLOSIVE_BURN and the equation of state using Jones-Wilkins-Lee (JWL) by EOS_JWL tag to describe the behavior of the TNT material.

Table 1. TNT material model parameters

ρ (kg/m ³)	v_D (m/s)	P_{CJ} (Pa)	A (Pa)	B (Pa)
1600	9630	$2.1 \times E10$	$3.738 \times E11$	$3.747 \times E9$
R_1	R_2	ω	V	E_0 (J/m ³)
4.15	0.9	0.35	1.0	$6.0 \times E9$

5.2.2. Air model

Use the material tag MAT_NULL and the equation of state using the tag EOS_LINEAR_POLYNOMIAL to describe the behavior of the air material.

Table 2. Air material model parameters

ρ (kg/m ³)	E_0 (J/m ³)	V_0 (kg/m ³)	C_4	C_5
1.23	$2.58 \times E5$	1.0	0.4	0.4

5.2.3. Concrete model

Use model MAT_084 with material tag 084/085-WINFRITH_CONCRETE to describe the behavior of concrete, with failure energy of 65 J/m² [8], the average size of large aggregate is 10 mm.

Table 3. Concrete material model parameters

ρ (kg/m ³)	E_{tt} (Pa)	ν	σ_n (Pa)	σ_k (Pa)
2400	$26.41 \times E9$	0.2	$30.01 \times E6$	$3.0 \times E6$

5.2.4. Reinforcement model

Use material tag 003-PLASTIC_KINEMATIC to describe the behavior of steel reinforcement in concrete.

Table 4. Reinforcement material model parameters

ρ (kg/m ³)	E (Pa)	ν	σ_{ch} (Pa)
7850	$2.05 \times E11$	0.3	$2.4 \times E8$

5.3. Build the model

To reduce the number of elements for the problem, use the semi-system symmetry problem when simulating TNT and air. TNT, air and concrete slabs are used with an 8-node cubic elements with a mesh dividing the TNT explosion amount by 1/30 of the length of the explosion side [15]. To describe the pressure transfer process between TNT and the air environment surrounding, use the tag *ALE-MULTI-MATERIAL_GROUP_PART and the nodes between the two material domains are linked together. The tag *CONSTRAINED-LAGRANGE_IN_SOLID is used to describe the coupling between air and the concrete slab (built independently of air) with CTYPE equal to 4.

There are many different methods to model reinforcement such as the reinforcement streak method, which considers reinforcement as a volume embedded into concrete, this volume is modeled as a layer of elements in the concrete slab structure. This method is good for small deformations where the reinforcement remains elastic. The second method is the nodal method, where the steel bars are modeled by beam elements and connected to the concrete by connecting common mesh nodes. This method requires the nodes of the steel element meshes and the concrete element meshes must be coincided. This may be easy when dealing with the steel layers, but it is very difficult when modeling the stirrups. In this study, the method of embedding reinforcing bars in concrete will be used and the steel mesh system will be described independently of the concrete slab and use the tag *CONSTRAINED-LAGRANGE_IN_SOLID to describe the connection between the steel mesh and concrete slab with CTYPE equal to 2. To describe the reinforcing bar, use the tag *SECTION_BEAM with parameters ELFORM = 1 (Hughes-Liu beam) and QR = 2, CST = 1 for circular cross-section.

Use the recommended meshing, air meshing densities and TNT, boundary widths, and time step scaling factors as recommended in previous research [15]. For the reinforced concrete slab structure, use a grid of 10 mm × 10 mm × 10 mm, the reinforcement uses a bar element of 30 mm, and the base block uses an element of size 20 mm × 20 mm × 20 mm.

Describe the contact between the base block and the concrete slab using the two-way contact description (*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE).

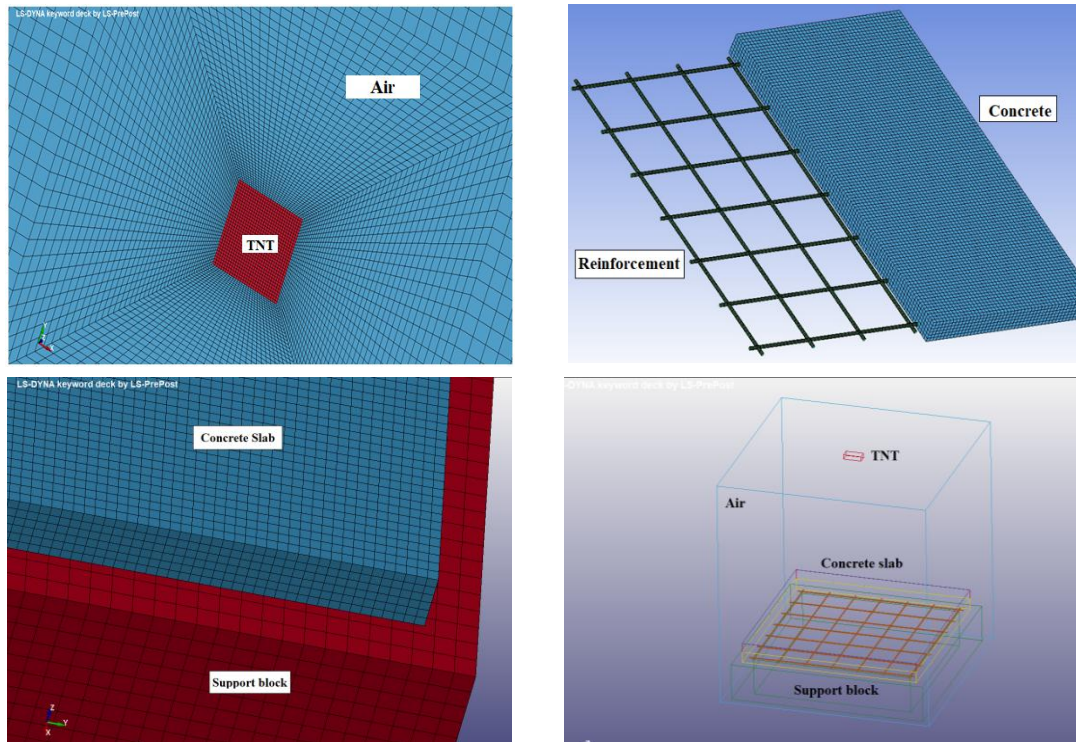


Fig. 4. Construction of geometric model for numerical simulation.

5.4. Numerical simulation results

The simulation process on LS-DYNA gives intuitive results both on the change in internal forces on the structure as well as describing the process of cracking of the reinforced concrete slab. The cracking morphologies obtained from the numerical simulation and the experiment are quite similar. Besides, the displacement and acceleration values at the mid-slab position of the simulation and experiment also show good agreements in both of the graph form and the maximum peak values.

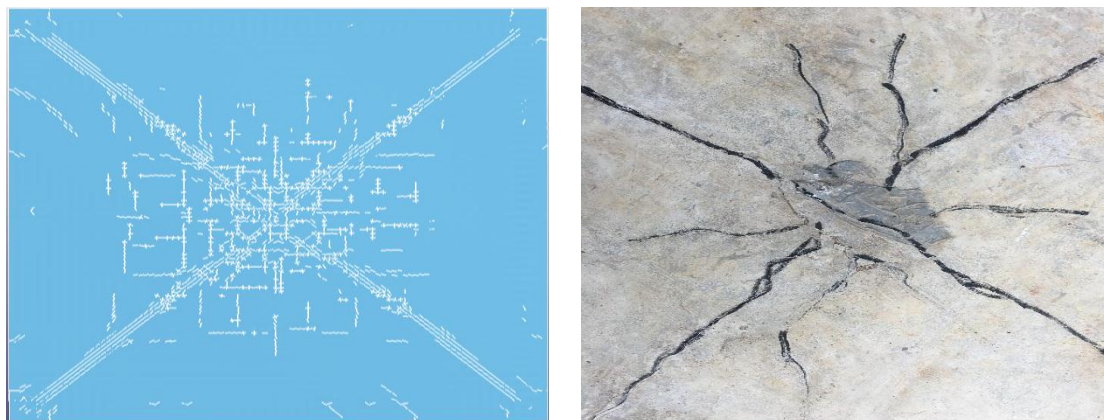


Fig. 5. Crack formation on the underside of the reinforced concrete slab.

Table 5. Comparison table of results between experiment and simulation

No.	Parameter	Unit	Experiment	Simulation	Difference (%)
1	Displacement	cm	0.61	0.56	8.15
2	Acceleration	g	1395.77	1258.21	9.86

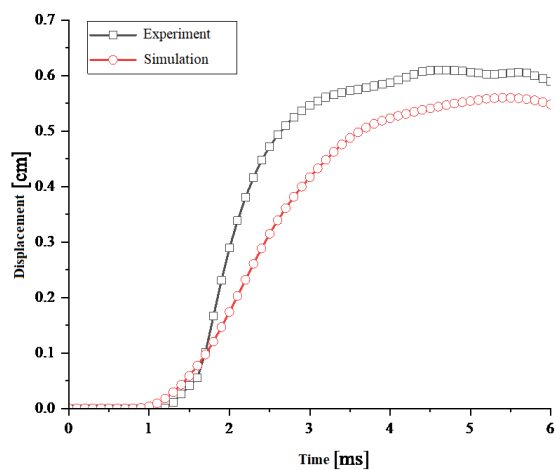


Fig. 6. Displacements of the reinforced concrete slabs.

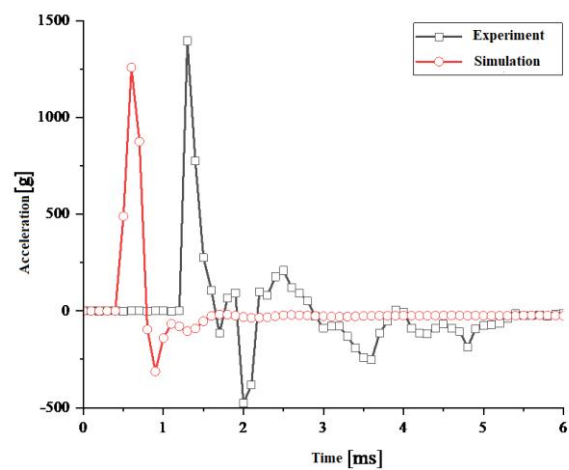


Fig. 7. Accelerations of the reinforced concrete slab.

The results of the investigated dynamic parameters (displacements and accelerations) at the middle (center) position of the slab using experiment and numerical simulation indicated: (i) the graph (chart) shapes are quite similar and (ii) the peak values are almost the same with the difference less than 10% is an acceptable result.

6. Conclusions

From results of the experiments and the numerical simulation, the following conclusions can be made regarding to the establishing simulation models for reinforced concrete slabs subjected to explosion pressures by using LS-DYNA, specifically as follows:

- Comparisons to the the experiment have shown that both the damage morphologies on the reinforced concrete slabs, as well as the graph-forms and the displacement values (of the center of the slab) show the use of LS-DYNA to simulate reinforced concrete slabs subjected to the explosion pressures can be conducted and possibly reliable;

- From the numerical simulation results verified by field explosion tests, it can be said that model MAT_084 for concrete and model MAT_003 for reinforcement when simulating reinforced concrete slabs under explosions can be actually useful;

- With the input data being the basic parameters of the material and basic laboratory experiments can be used to determine the recommendation to use model MAT_084 for concrete and model MAT_003 for reinforcement in simulating reinforced concrete slabs subjected to explosion pressures;

- In addition, the numerical simulation results also show that using the full modeling method with constraints between concrete and air, concrete and reinforcement and boundary conditions in this research has allowed obtaining good results.

From the positive results of the study, it is recommended to use these material models and modeling methods for the future simulations regarding to the concrete structures against explosions.

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KIỂM CHỨNG MÔ HÌNH VẬT LIỆU BÊ TÔNG VÀ CỐT THÉP TRONG LS-DYNA BẰNG THỰC NGHIỆM

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Tóm tắt: Bài báo trình bày việc nghiên cứu và đánh giá một số mô hình vật liệu bê tông và vật liệu cốt thép thường dùng trong LS-DYNA để mô phỏng kết cấu bê tông cốt thép chịu tác dụng của áp lực nổ. Trên cơ sở đó lựa chọn mô hình vật liệu phù hợp với ưu tiên đầu vào cho mô hình là các tham số cơ bản của vật liệu. Thông qua kết quả mô phỏng và dữ liệu thực nghiệm nổ hiện trường để kiểm chứng và đánh giá đáp ứng của mô hình vật liệu được lựa chọn. Nội dung bài báo còn trình bày phương pháp xây dựng bài toán mô phỏng áp lực nổ tác động lên kết cấu bê tông cốt thép bằng LS-DYNA.

Từ khóa: LS-DYNA; mô hình bê tông; mô hình cốt thép; thí nghiệm nổ.

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