Assessment of Typical Concrete Material Models used in Simulation of Concrete Slab under Blast in Air

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Abstract. To evaluate the suitability of three typical concrete material models, which are HJC material model, RHT material model and K&C material model respectively, in simulating concrete’s dynamic damage under air blast, a comparison between experiment observations and numerical simulation results is conducted. The three typical concrete material models are reviewed briefly at first. Then the experiment and numerical model information are presented. According to the comparison results, K&C material model shows the best suitability in simulating the damage mode of the concrete slab. RHT material model takes the second place for underestimating the concrete’s strength resistance. HJC material model, however, is no recommended for simulating concrete in such a situation.

1. Introduction
Concrete is an important material in civil and military structure field. In microcosm, concrete is a composite material mixed by cement, aggregate, water and air. However at macro level, concrete can be treated as an isotropic material with uniform stress and strain properties. Thus it is possible to build an effective material model for concrete which can be used in numerical simulation. Dozens of concrete material model have been built based on different theories [1]. Among them there are three typical concrete material models which could be found frequently used for describing the dynamic properties of concrete under blast loading. These models are generally named HJC [2], RHT [3] and K&C [4], respectively. Usually different concrete material model has different applicability for a certain situation. Hence it is necessary to evaluate the accuracy of the concrete material model before apply the model for a certain engineering problem [5].

In this paper, a reinforcement concrete slab is exposed to an explosive in air which is a situation usually seen in the blasting area. The three typical concrete material models are briefly introduced at first. Based on the commercial explicit dynamic software LS-dyna, a finite element model using the three typical concrete materials respectively is constructed subjected to an experiment of concrete slab under air blast. The differences between the experiment observations and the simulation results are discussed next. Conclusions are then drawn on the applicability of the three typical concrete materials for simulation of concrete slab under air blast.

2. Review of Typical Concrete Material Models
2.1. HJC Material Model
In HJC material model the strength failure function is defined as
\[ \sigma^* = [A(1 - D) + Bp^*][1 + C \ln(\dot{\varepsilon}^*)] \]  

(1)

where \( \sigma^* \), \( p^* \) and \( \dot{\varepsilon}^* \) are normalization parameters which represent actual equivalent stress, pressure and strain rate respectively. \( A \), \( B \), \( C \) and \( N \) are strength parameters which are decided by the material’s property. \( D \) is the damage parameter which is related to equivalent plastic strain \( \Delta \varepsilon_p \) and plastic volumetric strain \( \Delta \mu_p \). \( D \) is defined as

\[ D = \sum \frac{\Delta \varepsilon_p + \Delta \mu_p}{D_1(p^* + p^*_f)^{D_2}} \]  

(2)

where \( p^*_f \) is normalized maximum tensile hydrostatic pressure. \( D_1 \) and \( D_2 \) are material damage constant. The equation of state is divided into three parts. The first two parts are linear function. After the concrete is compacted, the third part of the equation of state is expressed as

\[ P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 \]  

(3)

where \( K_1 \), \( K_2 \) and \( K_3 \) are material constant. \( \mu \) is modified volumetric strain which is defined as

\[ \mu = \frac{\mu - \mu_{lock}}{1 + \mu_{lock}} \]  

(4)

where \( \mu \) is volumetric strain and \( \mu_{lock} \) is the locking volumetric strain.

2.2. RHT Material Model

Compared to HJC material model, the advantage of RHT material model is that the influence of the third invariant and the strain hardening is considered. In this model, three strength surfaces are established, which are the yield strength surface, the failure strength surface and the residual strength surface respectively. The yield strength surface is defined as a fraction of the failure strength surface with a cap that closes the closes the current pore crush pressure. The failure strength surface is defined as

\[ Y_{fail}(p^*, \theta, \dot{\varepsilon}) = Y_c(p^*) \times R_3(\theta, p^*) \times F_{rate}(\dot{\varepsilon}) \]  

(5)

where \( Y_c(p^*) \) is the compressive meridian and is defined as

\[ Y_c(p^*) = f_c \times [A \times (p^* - p_{spall}^*) \times F_{rate}(\dot{\varepsilon})]^N \]  

(6)

in which \( f_c \) represents the material’s uniaxial compressive strength. \( p_{spall}^* = f_t / f_c \), where \( f_t \) is the material’s uniaxial tensile strength. \( F_{rate}(\dot{\varepsilon}) \) represents the function of the dynamic increase factor (DIF). In Eq. (5), \( R_3(\theta, p^*) \) is a function related to the Lode angle \( \theta \) and is defined as

\[ R_3(\theta, p^*) = \frac{2(1 - Q^2) \cos \theta + (2Q - 1) \sqrt{4(1 - Q^2) \cos^2 \theta + 5Q^2 - 4Q}}{4(1 - Q^2) \cos^2 \theta + (1 - 2Q)^2} \]  

(7)

where \( Q \) is a linear equation of normalized pressure \( p^* \).

The residual strength surface is defined as an exponential function of \( p^* \). With the three strength surface, the loading path and the softening path is established by interpolation between the yield strength surface and the failure strength surface and between the failure strength surface and the residual strength surface, respectively.
2.3. K&C Material Model
K&C material model is similar to RHT material model in definition of the three strength surface and the path of loading and softening. In K&C material model, the compressive meridian of the three strength surface is defined in a unified form which is shown as

\[ Y_i = a_{0i} + \frac{p}{a_{1i} + a_{2i}p}, \quad i = y, m, r \]  

where \( p \) is pressure. \( a_{0i} \), \( a_{1i} \) and \( a_{2i} \) are material constants in which \( i = y, m, r \) represent yield surface, maximum failure surface and residual surface, respectively.

3. Experiment Setup and Numerical Model Construction
In the present study of Ref. [6], a 1000mm × 1000mm × 40mm square concrete slab is made with a reinforcement ratio of 1.43% which is shown in figure 1. The concrete’s unconfined compressive strength and uniaxial tensile strength is 39.5MPa and 4.2MPa, respectively. The rebar’s diameter is 6mm. The rebars are placed side by side with a distance of 75mm from two directions in the middle plane. The rebar’s yield strength is 600MPa and the Young’s modulus is 200GPa. The concrete slab is fixed by the opposite side and a TNT explosive which mass ranges from 0.31kg to 0.5kg is suspended above the concrete slab’s centre. As shown in figure 2, the distance between the explosive and the concrete slab is 400mm. Other details can be found in Ref. [6].

Figure 1. Geometry of the RC slab (in mm).  
Figure 2. Illustration of the experiment.

Figure 3 illustrates the basic components of the numerical model for the experiment. According to the symmetry, the model is divided into a quarter with symmetric boundary in the symmetry plane. To avoid the huge deformation of the fluid element, the ALE method is adopted in this model. The reinforcement concrete slab and the steel plate for fixing are built in Lagrange while the explosive and the air are built in Euler. The element mesh edge for all parts is set to 5mm which is small enough for accuracy. The air zone is set big enough to cover the whole RC slab and the explosive with non-reflection boundary outside for simulating infinite field.

Materials for steel, TNT and air can be found in Ref. [6], which are recognized applicable for blast simulation. For concrete, the reviewed three models are applied respectively. In LS-dyna, the parameters for RHT and K&C material model will be automatically generated when giving the unconfined compressive strength. The parameters for HJC material model are manually calculated according to Ref. [7].
4. Comparison of Results between Experiment and Simulation

Figure 4 to figure 9 show the comparison between experiment observations and simulation results of the three typical concrete materials. The experiment observations tell the typical damage mode for a RC slab under blast in air. On the upside of the slab, two main long cracks along Y axis accrue in the middle while circular cracks accrue in the centre. On the backside, a square domain of the concrete in the centre is spalled with several long cracks accruing along the X axis, Y axis and diagonals.

Figure 4. Comparison of the RC slab’s upside for 0.31kg TNT: (a) experimental result, (b) simulating result of HJC, (c) simulating result of RHT, (d) simulating result of K&C.

Figure 5. Comparison of the RC slab’s backside for 0.31kg TNT: (a) experimental result, (b) simulating result of HJC, (c) simulating result of RHT, (d) simulating result of K&C.
Along with the mass increase of the explosive, the cracks’ quantity increases and damage domain enlarges which the centre of the concrete is absolutely damaged when the explosive’s mass is 0.55kg.

**Figure 6.** Comparison of the RC slab’s upside for 0.46kg TNT: (a) experimental result, (b) simulating result of HJC, (c) simulating result of RHT, (d) simulating result of K&C.

**Figure 7.** Comparison of the RC slab’s backside for 0.46kg TNT: (a) experimental result, (b) simulating result of HJC, (c) simulating result of RHT, (d) simulating result of K&C.

**Figure 8.** Comparison of the RC slab’s upside for 0.55kg TNT: (a) experimental result, (b) simulating result of HJC, (c) simulating result of RHT, (d) simulating result of K&C.

**Figure 9.** Comparison of the RC slab’s backside for 0.55kg TNT: (a) experimental result, (b) simulating result of HJC, (c) simulating result of RHT, (d) simulating result of K&C.
In the simulation results, the damage degree of the concrete is represented by different colors and numbers which 1.0 in red means total destruction while 0.0 in blue means intactness. Large deformed elements are deleted to simulate the concrete’s spall.

Basically, K&C material model reflects the concrete damage mode best. It can give most of the damage mode shown in the experiment observations. Besides it could clearly tell which area in the concrete is suffering strength soften state which could not be seen in the experiment. The disadvantage of this model is that it has some difficulties in simulating the circular cracks on the upside of the concrete and the spall in the centre. However, the tendency in those two damage aspects is still obviously.

For RHT material model, it could reflect the cracks of the concrete to some degree. Despite of this, the biggest problem of this model is that it is too soft that the centre spall area of the concrete is too large compared to the experiment. Thus, this model underestimates the strength resistance ability of concrete.

HJC material model is completely opposite to the RHT model in which it overestimates the strength resistance ability of concrete. It could not tell the generation of the cracks and even could not reflect the spall of the concrete when the explosive’s mass is very large. So in simulating concrete slab under air blast, HJC material model is not recommended.

5. Conclusion
Three typical concrete material models are introduced to show how they describe the strength surfaces of concrete. To verify the suitability of these concrete material models in simulating concrete under blast in air, an experiment and corresponding numerical simulations are conducted and different results are compared. According to the comparison, K&C material model shows the best suitability in simulating concrete’s dynamic damage while RHT material model takes the second place. HJC material model, however, is not recommended to be adopted in such a situation.

6. References
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