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Inelastic damage of RC slabs subject to blast loads using dynamic analysis: numerical model validation

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Abstract - Due to sad historical events in last few years, structural integrity evaluation for structures damaged by explosions has become an interesting topic for the research community. Blasts may lead to unbalanced or even total collapse of buildings. Hence, accurately representing this action and its results on structures is of high interest. In this paper, a three-dimension (3-d) finite element analysis (FEA) of reinforced concrete (RC) slab subjected to close-in blasts is considered. The dynamic analysis submitted by ABAQUS/Explicit (2014). Abaqus/explicit uses a central difference rule to integrate the equations of motion explicitly through time. The air pressure wave propagation is simulated using built in Conventional Weapon Effect Program (CONWEP). CONWEP generate pressure-time history associated with charge weight in trinitrotoluene (TNT) and stand-off distance. The inelastic behavior of concrete and steel reinforced bars has been represented through concrete damage plasticity (CDP) model and Johnson-cook model, respectively. The obtained results, expressed in terms of maximum displacements, crack pattern and damage index are compared against a set of experimental results carried out from institute of technique physics, college of science, national university of defense technology, Changsha, human, China. A good agreement between the two approaches is observed up to 90%.

Keywords: Explosions, Finite Element Analysis (FEA), Blast Load, Inelastic damage of RC slabs, High Strain Rate, Concrete Damage Plasticity (CDP) model, Johnson-cook model.

1. INTRODUCTION

Blast load and shock waves can affect a wide range of concrete structures due to increasing in number and intensity of terrorist activities, accidents and explosions **[1].** The explosion can scientifically be defined as high rise in pressure speed due to a sudden dissipation of chemical energy. This pressure rise is called a "Blast Wave" that starting from a supersonic Speed. The pressure is severely increased at start of explosion then wave front propagates decreases over time. The pressure's amplitude has two regions: the positive phase and the negative phase as illustrated in **Figure 1**.

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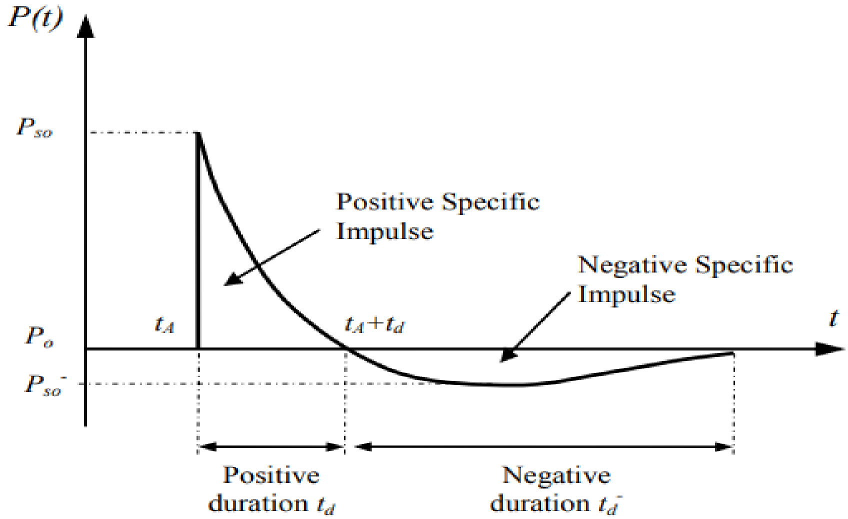

Figure 1: Blast wave pressure – Time history

According to UFC code **[2]** scaled distance ratio” Z” one of the most important parameters in blast analysis. When two explosive charges, with different standoff distance and equivalent mass of TNT, have the same Z, then they will produce the same overpressure. The following Equation provides the scaled distance:

$$\boldsymbol{Z = R/\sqrt[3]{W}}$$

Where "Z" is the scaled distance, R is the distance from the central of the explosive charge (meter), and W is the equivalent TNT mass (Kg).

Concrete's mechanical properties under dynamic loading conditions can differ significantly from those under static loading.**[3]** Therefore, the dynamic stiffness does not deferent from the static stiffness However, stresses that are sustained for a certain period of time under dynamic conditions can obtain values that are significantly higher than the static compressive strength. This phenomenon called Strain Rates effects. **Figure 2** shown the dynamic Properties of Concrete under deferent High Strain Rates.

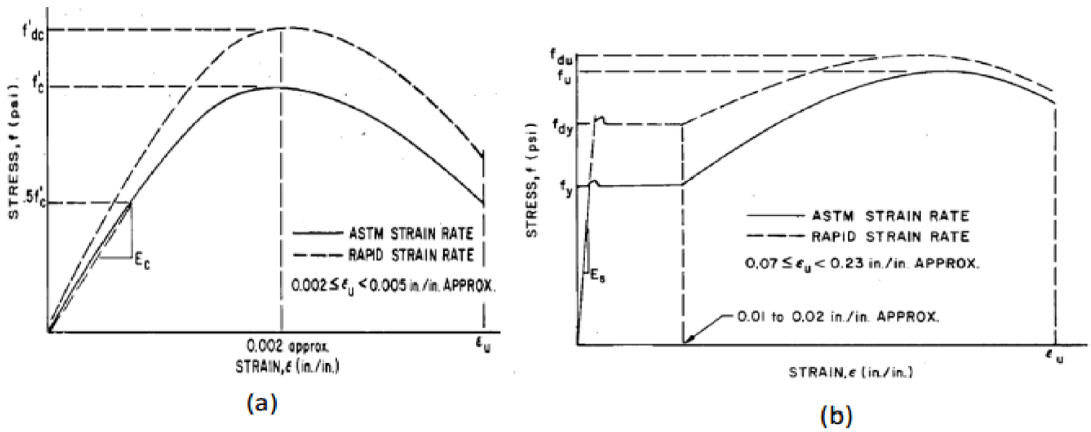

Figure 2: Stress-strain curves of (a) concrete and (b) steel at strain rates effects.

In the current paper, a numerical simulation of a reinforced concrete slab tested under close-in blast loading is presented. The main purpose of this study is to validate a numerical model against an experimental test conducted by Wand et al. [4]. The numerical model accuracy in accounting for the air blast specific effects on RC slabs is assessed by comparing the obtained structural response with the experimental one. The obtained results are expressed in terms of maximum displacements, crack pattern and damage index.

2. EXPERIMENTAL TEST

Three one-way square reinforced concrete slabs subjected to different air blast loads was conducted by Wang et al. **[4]** in the institute of technique physics, college of science, national university of defense technology, Changsha, human, China. The dimensions of the slabs were 1000mm x 1000mm x 40mm and the diameter of the steel bars used for reinforcement was 6mm, with a 75mm distance between bars. The thickness of the concrete cover was of 20mm. Four loading scenarios were considered by the authors to emphasize different damage levels. Thus, the explosive charges placed at 0.4m above the concrete slab center point with deferent wight of TNT 0.2kg, 0.31kg, 0.46kg, respectively, as illustrated in **Figure 3.**

Figure 3: (a) Wang et al [4] test setup and (b) proposed numerical model.

3. FINITE ELEMENT ANALYSIS

The Inelastic behavior of concrete has been determined by concrete damage plasticity model. In briefly CDP model considers the non-associated Drucker-Prager hyperbolic flow potential function is based on the research by Lubliner et al. **[5]** and Lee et al. **[6]**. The Drucker–Prager function is used in the model:

$$G(\boldsymbol{\sigma}) = \sqrt{(\boldsymbol{\epsilon}.\boldsymbol{\sigma_{t0}}.\boldsymbol{tan\psi})^2 + \bar{\boldsymbol{q}}^2} - \bar{\boldsymbol{p}}.\boldsymbol{tan\psi}$$

Whereas $\bar{p} = -\frac{1}{3}\mathrm{trace}(\bar{\sigma})$ and $\bar{q} = \sqrt{\frac{3}{2}}\bar{S}.\bar{S}$ are the hydrostatic pressure stress and Von-Mises equivalent effective stress, respectively where $\bar{S}$ represents the deviatoric part of the effective stress tensor $\bar{\sigma}$. *(ψ)* is the concrete dilation angle measured in meridian plane $\bar{p} - \bar{q}$ at high confining pressure. ABAQUS user manual Gide **[7]** considers a default value of *(ψ)* equals to 37°. Literature checked values of *(ψ)* ranges from (20 ° -45 °) as attempts to adopt numerical model under static load. (σ_{t0}) is the ultimate tensile strength of concrete .*(ϵ)* is a small positive dimensionless value, known as the flow potential eccentricity. *(ϵ)* defines in ABAQUS software as default value 0.1. ($\sigma_{bo}/\sigma_{co.}$) is the uniaxial compressive strength that defines in ABAQUS guide as default recommended value equal to 1.16, *(Kc)* is the ratio between tension meridian and compression meridian in the deviatoric cross section. The value of *(Kc)* ranges from 0.5 to 1. ABAQUS user manual considers a default value for *Kc* to be equal to 0.667. The CDP model failure criteria and its Parameters (*ψ*, *ϵ*, *Kc* and $\sigma_{bo}/\sigma_{co.}$) shown in **Figure 4.** The CDP ABAQUS user manual Guide recommended values clarified in **table 1.**

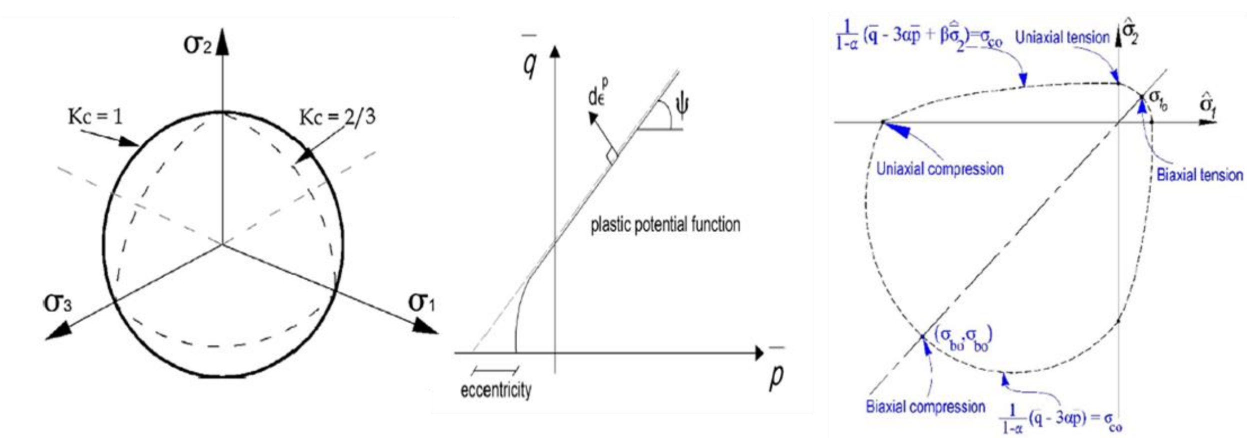

Figure 4: CDP Model Yield Surface and its Parameters (ψ, ϵ, and Kc)

Table 1: The CDP recommended values.

Parameter Item	Ψ	Kc	e	σ_{bo}/σ_{co}	μ
Value	20:45	0.5:1	0.1	1.16	0

Figure 5 plotted the non-liner compressive and tensile behavior of concrete, respectively. The non-liner compressive behavior of concrete FE Model depends on CIB code **[8]** formula, However the non-liner tensile behavior of FE Model depends exponential relationship based on the research by Cornelissen et al **[9]**, respectively.

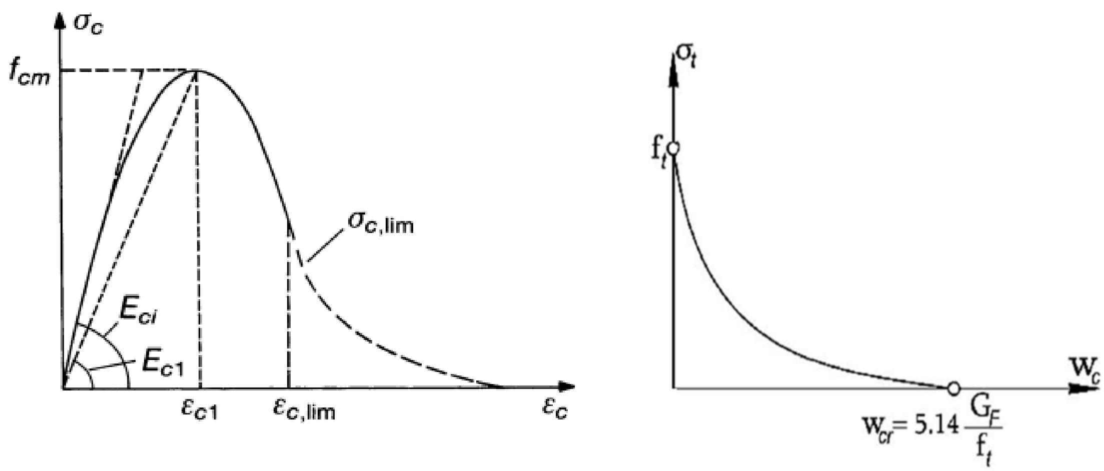

Figure 5: (a) Uniaxial concrete compressive stress–strain (b) exponential tension–softening model.

The Johnson-cook model was used to characterize the elastic and plastic behavior of steel reinforcing bars and stirrups depend on the research by Johnson and cook **[10].** The Johnson-cook model taking into account the effects of blast loading failure criterion, the effect of strain path, strain rate and temperature in the fracture strain expression The Johnson and cook model recommended values shown in **Table 2**.

Table2: The Johnson and cook model recommended values.

Descriptions	Notations	Value
Density of materials	*p (Tonne/mm3)*	7.80E-09
Elastic Models	E (Mpa)	200000
Poisson Ratio	V	0.3
Yield Stress constant	A (Mpa)	Fy
Strain hardening constant	B (Mpa)	1500
	N	0.26
Thermal softening constant	M	1.03
Viscus effect	C	0.014
Melting Temperature	θm (K)	1793
Transition Temperature	θT (K)	293
Specific Heat	T (mJ/Tonne.K)	452000000
Johnson-Cook Damage Constant	D1	0.05
	D2	3.44
	D3	-2.12
	D4	0.002
	D5	0.61

4. RESULTS

High numbers of trail were performed with considered Strain rate effect in the analysis to adopt the behavior of specimens. Five main parameters are adopted: the yield surface shape (Kc), the eccentricity (ϵ), the stress ratio (σbo/σco,), and the dilation angle (ψ). According to Literature and ABAQUS (2014) user Gide the eccentricity (ϵ), and the stress ratio (σbo/σco,) can be fixed at 0.1 and 1.16 respectively. For purpose of calibration, the different values for concrete dilation angle (ψ=20, 30 and 40) and the yield surface shape Kc (Kc= 0.5, 0.667 and 1) are considered. As shown in **figure 6**, the optimum values of CDP parameter kc it has been found no effect on dynamic analysis of structure's response under blast loads unlike and static analysis. Therefore, concrete dilation angle ψ and have been found limited effect. In static loading, the shape of yield surface kc and dilation angle ψ have been significant effect on analysis results However, in the dynamic analysis, their effect was very slight. That's because loading occurs in very short time in what is known as a strain rate phenomenon. **Figure 7** show the maximum numerical slab deflection versus experimental deflection and **Figure 8** show the experimental results versus numerical results of tested Slab deflection. The result clarifies a good agreement between the two approaches is observed up to 90% However, Experimental compression damage and crack pattern for TNT charges: 0.31kg, 0.46kg, and 0.55kg versus numerical ones show in **Figure 9** and **11**, respectively.

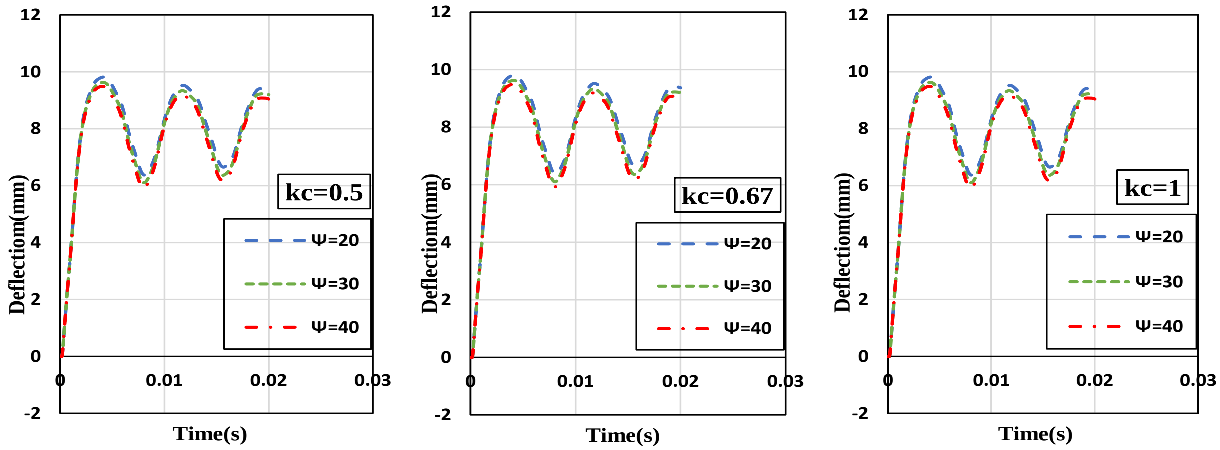

Figure 6: Deflection- Time Attempts for Specimen S-A

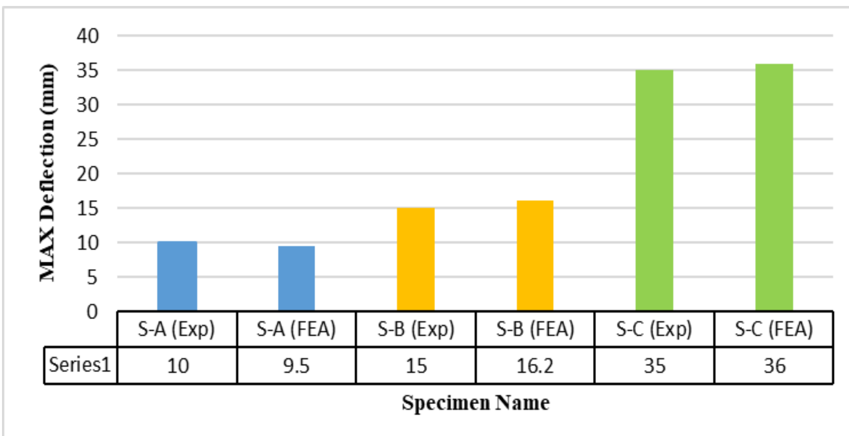

Figure 7: Maximum numerical slab deflection versus experimental ones.

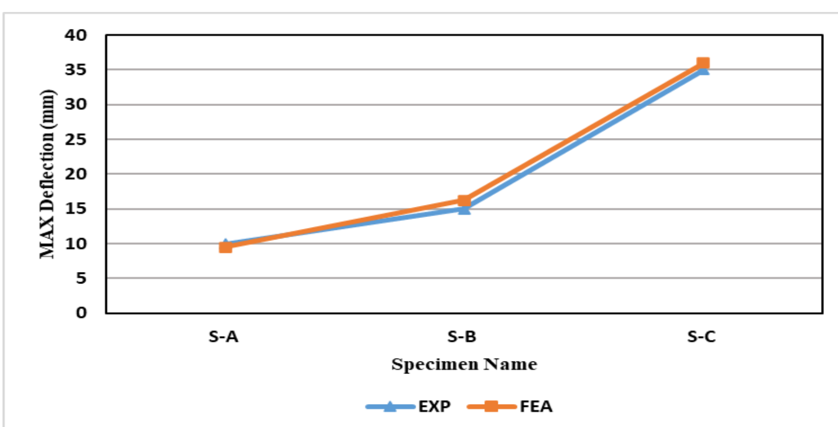

Figure 8: Experimental results versus numerical results of tested Slab deflection.

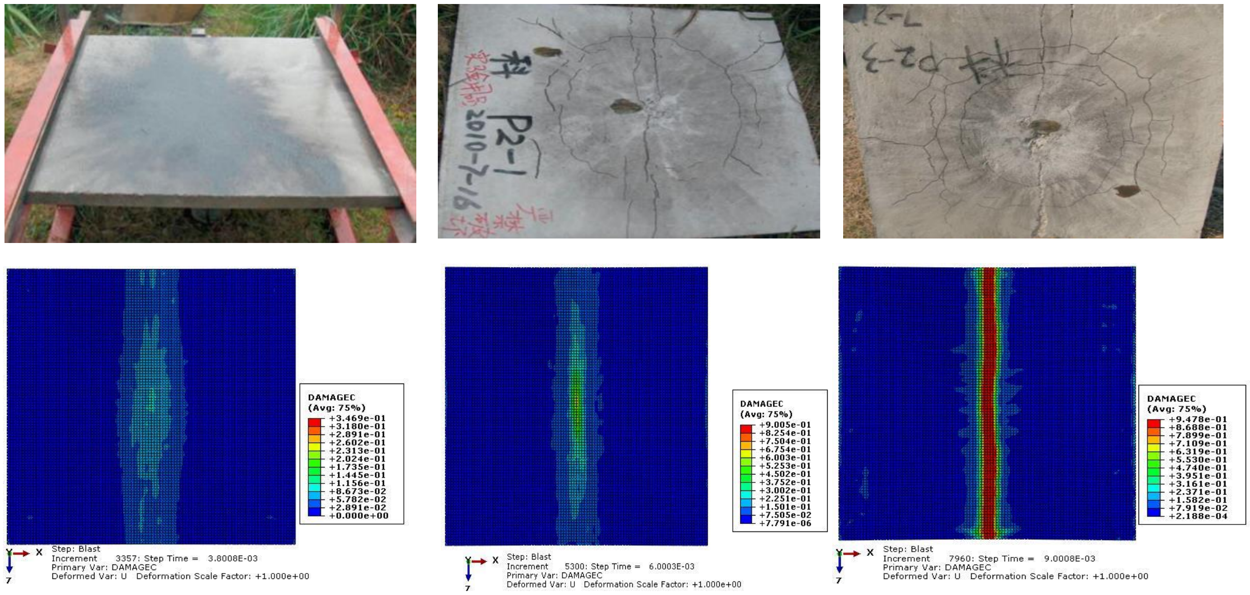

Figure 9: Experimental compression damage at top face of RC slab for TNT charges: 0.31kg, 0.46kg, and 0.55kg versus numerical ones.

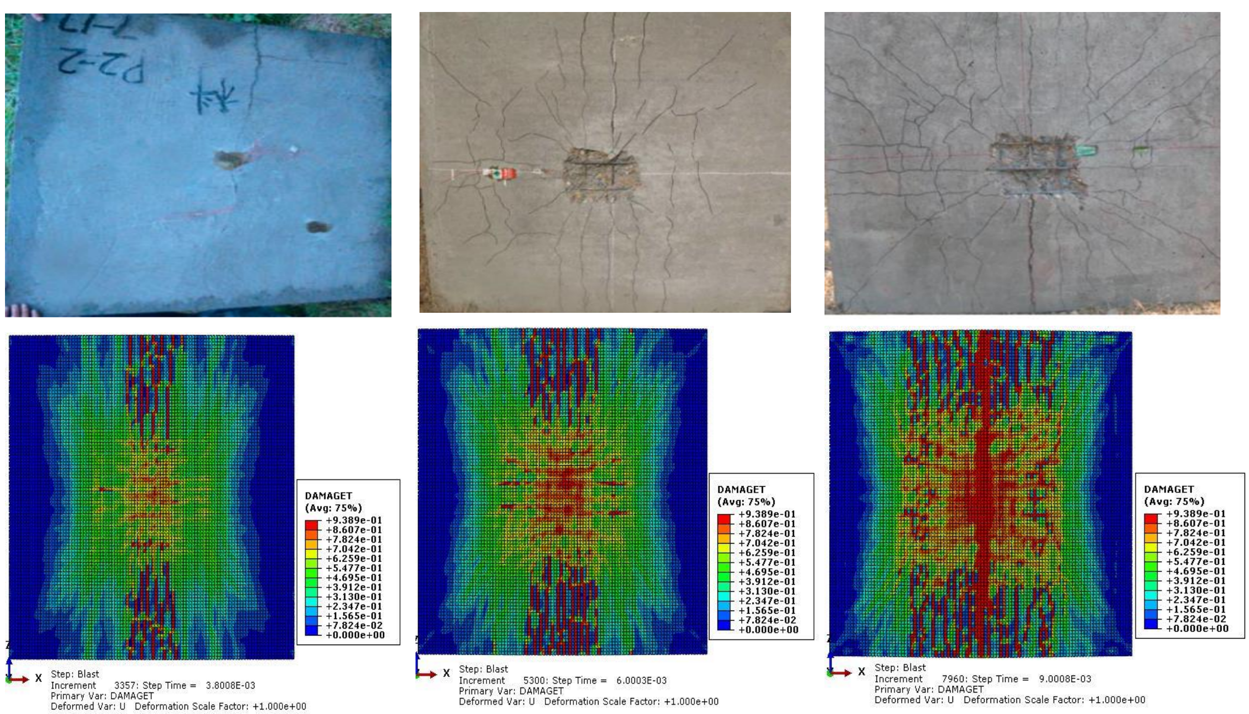

Figure 10: Experimental crack pattern at bottom face of RC slab for TNT charges: 0.31kg, 0.46kg, and 0.55kg versus numerical ones.

5. CONCLUSION

The current study aims to a FE model was developed to predict the response the behavior of an RC slab subjected to close-in blast loads. Three experimental RC slabs carried out from institute of technique physics, college of science, national university of defense technology, Changsha, human, China are analyzed in Abaqus/Explicit using a 3D numerical model. CONWEP method is used to represent the air wave propagation caused by the TNT charges. Concrete damage plasticity (CDP) model and Johnson-cook model represent concrete materials and steel reinforcement, respectively. The numerical results show a good agreement with experimental one up to 90%. The complete results can draw in the following:

1- Concrete Damage Plasticity and Johnson-cook model accurately predict the full materials behavior of Blast resistance of RC slabs.
2- CONWEP facilely and accurately represent the air wave propagation.
3- The shape of yield surface (Kc) it has been found no effect on dynamic analysis of structure's response under blast loads unlike and static analysis. Therefore, concrete dilation angle (ψ) and have been found limited effect. In static loading, the shape of yield surface kc and dilation angle (ψ) have been significant effect on analysis results However, in the dynamic analysis, their effect was very slight.
4- Strain rate effect should be considered in the analysis.
5- The damage degree and crack width increased with increasing the weight of mass of explosion at the same stand-off distance.

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