EFFECT OF ELEMENT DELETION IN BEHAVIOR OF RC SLABS AND RETROFITTED WITH FRP COMPOSITES

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Abstract

Element deletion named as "erosion" is a numerical mechanism for the automatic removal of elements during a simulation. The primary reason for using erosion is to remove high distorted elements from a simulation before the elements become degenerate. The objective of this paper is the study of the erosion effect on the numerical solution of concrete elements subjected to blast loading. Both reinforced concrete (RC) slab and retrofitted with fiber reinforced polymer (FRP) composites are investigated. For this aim, several RC slabs under blast loading are simulated using ANSYS AUTODYN software. This study shows that damage pattern is significantly dependent on the erosion limit used. Moreover, it should be observed that a very fine mesh must be used to obtain the shape of the damaged zone under blast loads. Also, the results show that externally bonded FRP retrofit is an effective retrofit technique to improve the blast resistance of RC slab.

Keywords: Erosion, Concrete, Slab, Blast, ANSYS AUTODYN

1. Introduction

Concrete has been used widely to construct buildings, dams, nuclear reactor containment and various defense structures. Therefore, it is important to investigate its behavior under blast and impact loadings that cause large strains, high strain rates, spalling, fracture and crushing phenomena.
Fiber reinforced polymers (FRPs) are now used in civil applications to develop the structural integrity of deteriorated structures or to increase the load bearing capacity of defective structures (Chen and Teng, 2001; Mattaet al., 2005; Takakshi 2009; Mahini and Ronagh, 2009; Dai et al., 2008; Dogan and Anil, 2010). Externally bonded FRP retrofits have been successfully used to retrofit seismically deficient structures and structures suffering from corrosion related problems. FRPs have several advantages: adaptability, high strength-to-weight ratio and chemical inertness, high-energy absorption and lightweight and are economical as the cost associated with retrofit installation and facility down-time is usually less than similar retrofit systems. This means that a small quantity of FRP can significantly increase the resistance of a structural member to resist tensile loads and bending moments, without significantly increasing its mass and stiffness. A large volume of research has been conducted on FRP retrofitted structures under static and quasi-static loads. Previous research has resulted in the publication of numerous retrofit design methodologies, including those outlined in (ACI 440, 2008) and (CSA S806-02, 2007) documents. However, only a limited number of publications address the issue of designing FRP retrofit systems to resist blast induced impulsive loads. In blast loading condition, FRP retrofit effect should not only consider stiffness and energy absorption enhancements, but also the effectiveness of catching debris (debris catching capability) from the short wave applied by a blast load (Nam et al., 2009; Mosalam and Mosallam, 2001; Lu, 2009; Gong et al., 2009; Kumar, 2010). However, the current in-depth knowledge about fundamental behavior of FRP strengthened structures under blast loading is inadequate to do a detailed analysis and design for structural retrofitting. For example, even though the debonding failure of FRP between FRP and concrete has been commonly reported from numerous blast field tests, most of the studies have focused on the overall performance of FRP retrofitted structures by simplified FRP modeling without accurately applying the material characteristics and failure mechanisms of FRP. If the effect of material characteristics and failure mechanisms are not accurately incorporated, the retrofit design and performance evaluation of FRP retrofitted concrete structures may become inaccurate for extremely high loading rate cases (Zhou et al., 2007; Thiruppukuzhi and Sun, 2001).

These studies, and other similar ones that have not been cited here, have generally indicated the benefits of FRP in enhancing the blast resistance of concrete structures. However, the information and results provided by the studies are not sufficiently detailed to develop rational design methods for blast design of FRP retrofitted reinforced concrete elements. To develop such methods, more systematic, well-documented and detailed data are needed, including quantitative assessment of damage, measured pressure and impulse as well as concrete, steel and FRP deformations. The objective of this study is to
numerically investigate the extent to which FRP laminates, adhesively bonded to the surface of reinforced concrete slabs, can improve the slabs’ resistance to blast loads at relatively close standoff. The dynamic response and the nature of the damage are of particular interest, with special attention to the damage mechanisms, failure modes, and the bond of FRP with the concrete surfaces. The information that is provided can also be used to check the accuracy of numerical software for blast analysis of structures.

Although hydrocodes can analyze problems with both Lagrangian and Eulerian grids, sometimes materials have to be defined using Lagrangian grids even though it is clear that these materials will be subjected to very large distortions arising from gross motion of the Lagrange grid. The element erosion function, while not a material property or physics-based phenomena provides a useful means to simulate the spalling of concrete and provides a more realistic graphical representation of the actual blast events. Erosion is characterized by a physical separation of the eroded solid element from the rest of the mesh (Wu et al., 2011).

Though element removal (erosion) associated with total element failure has the appearance of physical material erosion, it is, in fact, a numerical technique used to permit extension of the computation. Without numerical erosion, severely crushed elements in Lagrangian calculations would drive to a very small time step, resulting in the use of many computational cycles with negligible advance in the simulation time. Moreover, Lagrangian elements which have become very distorted have a tendency to lock up, thereby inducing unrealistic distortions in the computational mesh (Zukas, 2004). Erosion function allows removing such Lagrangian cells from the calculation if a predefined criterion is reached. When a cell is removed from the calculation process, the mass within the cell can either be discarded or distributed to the corner nodes of the cell. If the mass is retained, conservation of inertia and spatial continuity of inertia are maintained.

However the compressive strength and internal energy of the material within the cell are lost whether or not the mass is retained. Erosion causes losses of internal energy, strength and (possibly) mass, therefore erosion limits should be chosen so that cells are not discarded (eroded) until they are severely deformed and their compressive strength and/or mass are not likely to affect the overall results (Autodyn, 2009).

The objective of this paper is the study of the erosion effect on the numerical solution of concrete elements under blast loads. Computational analyses concerning blast loading effect on concrete and FRP are conducted by the aid of ANSYS AUTODYN 13.0 software.
2. **Nonlinear Finite Elements Modeling of RC Slabs**

Structures can be idealized as being composed of finite elements. The force displacement relation of an individual element can be derived from the constitutive modeling of materials in the element concerned, and the overall structural behavior can be computed by solving equilibrium and deformational compatibility among elements. Therefore, the accuracy of structural analysis mainly depends on the constitutive modeling defined in each finite element domain. In general, the finite element discretization and the selection of constitutive modeling are performed so that the sizes of elements and the control volume for the model meet consistency requirements (Belytschko et al., 2000). The main purpose of this study is evaluating the numerical methods available for predicting the behavior of RC slabs subjected to blast loads. In this section, the methods chosen for this evaluation are described and the software used is introduced. In order to understand the materials’ behavior under blast loading, analyses were conducted with ANSYS AUTODYN Version 13.0 (Autodyn, 2009) which is powerful software with its explicit time integration technique usage.

SOLID65 is used for the three-dimensional modeling of solids with or without reinforcing bars (rebars). The solid is capable of cracking in tension and crushing in compression. In concrete applications, for example, the solid capability of the element may be used to model the concrete while the rebar capability is available for modeling reinforcement behavior. Other cases for which the element is also applicable would be reinforced composites (such as fiberglass), and geological materials (such as rock). The element is defined by eight nodes having three degrees of freedom at each node (Figure 1).

![SOLID65 element](image)

**Figure. 1** Solid65 element (Autodyn, 2009)
2.1. Skin of reptiles

A RHT model (Riedel et al., 1999) with a P-alpha equation of state (Herrman, 1969) is used for concrete. As the analysis is performed with a hydrocode, an equation of state (EOS) is required to describe the material behavior, in addition to the constitutive model. The equation of state links together three inter-independent thermodynamic variables: pressure \( p \), density \( \rho \) and the specific internal energy \( e \).

A \( p-\alpha \) equation of state (Herrmann, 1969) is used for concrete. This EOS has been proved to be capable of representing well the concrete thermodynamic behavior at high pressures and it also allows for a reasonably detailed description of the compaction behavior at low pressure ranges (Tu and Lu, 2009). It assumes that the initial specific internal energy for the porous material is the same as the solid material under the same pressure and temperature.

The equation of state of the fully compacted or solid material is described with a polynomial function as:

\[
p = A_1 \mu + A_2 \mu^2 + A_3 \mu^3 + (B_0 + B_1 \mu) \rho_0 e \quad \text{for } p \geq 0 \text{(compaction)}
\]

\[
p = T_1 \mu + T_2 \mu^2 + B_0 \rho_0 e \quad \text{for } p < 0
\]  

where \( A_i, B_i \) and \( T_i \) are coefficients, \( \rho_0 \) is the initial density and is the relative volume change.

\[
\mu = \frac{\rho}{\rho_0} - 1 \quad \text{(2)}
\]

The EOS for the porous material is calculated by substituting a new variable \( \alpha \rho_p \) for \( \rho \) in Eq. 2 and Eq. 1, i.e.:

\[
p = A_1 \bar{\mu} + A_2 \bar{\mu}^2 + A_3 \bar{\mu}^3 + (B_0 + B_1 \bar{\mu}) \rho_0 e \quad \text{for } p \geq 0
\]

\[
\bar{\mu} = \frac{\alpha \rho_p}{\rho_0} - 1 \quad \text{(4)}
\]

Where \( \rho_p \) is the density of the porous material and \( \alpha \) is called material porosity that can be defined as:

\[
\alpha = \frac{\rho_s}{\rho_p} \quad \text{(5)}
\]

where \( \rho_s \) and \( \rho_p \) refer to the density of the solid and the porous material at the same pressure and temperature respectively. In the \( p-\alpha \) equation of state the following definition is used:

\[
\alpha(p) = 1 + (\alpha_{init} - 1) \left[ \frac{p_{lock-out}}{p_{lock-out} - p_{crush}} \right]^n
\]  

where: \( p_{lock-out} \) and \( p_{crush} \) are the lock-out and crushing pressures, respectively.
where $\alpha$ is the initial porosity of the intact concrete; crush $p_{\text{crush}}$ corresponds to the pore collapse pressure beyond which concrete plastic compaction occurs and lock $p_{\text{lock}}$ is the pressure at which the concrete porosity $\alpha$ reaches unity.

The RHT strength model (Riedel et al., 1999) is a combined plasticity and shear damage model in which the deviatoric stress $Y = \sqrt{3J_2}$ is limited by a generalized failure surface defined as:

\[
(\sqrt{3J_2})_{\text{fail}} = Y_{\text{fail}}(p^*, \theta, \dot{\varepsilon}) = Y_c(p^*)r_3(\theta)F_{\text{rate}}(\dot{\varepsilon})
\]  
(7)

\[
Y_c(p^*) = f_c \left[ A \left( p^* - p_{\text{split}}^*F_{\text{rate}}(\dot{\varepsilon}) \right)^N \right]
\]  
(8)

Where $f_c$ is the uniaxial compression strength; $A$ and $N$ are material constants; $p^* = p/f_c$ is the normalized pressure, $p$ is the hydrostatic pressure and $p_{\text{split}}^* = f_t/f_c$, where $f_t$ is the uniaxial tension strength; $F_{\text{rate}}(\dot{\varepsilon})$ represents the dynamic amplification factor (DIF) as a function of strain rate $\dot{\varepsilon}$.

\[
r_3(\theta) = \frac{r}{r_c}
\]  
(9)

\[
r_3(\theta) = \frac{2(1-\psi^2) \cos \theta + (2\psi-1)\sqrt{4(1-\psi^2) \cos^2 \theta + 5\psi^2 - 4\psi}}{4(1-\psi^2) \cos^2 \theta + (1-2\psi)^2}
\]  
(10)

\[
cos 3\theta = \frac{3 \sqrt{3} I_3}{2 (J_2)^{3/2}}
\]  
(11)

\[
\psi = \frac{r_t}{r_c} = Q + BQp^*
\]  
(12)

$J_2$ and $J_3$ represent the second and the third invariants of the deviatoric stress tensor. Figure 2 shows the intersections of the failure surface with different deviatoric planes. The input parameter $Q$ defines the ratio of strength at zero pressure and the coefficient $BQ$ defines the rate at which the fracture surface transitions from an approximately triangular form to a circular form with increasing pressure.

![Figure. 2 Typical failure curves in a deviatoric plane for different hydrostatic pressures](image)
Strain rate effects are represented through increases in fracture strength with plastic strain rate. Two different terms can be used for compression and tension with linear interpolation being used in the intermediate pressure regime.

\[
F_{Rate} = \begin{cases} 
1 + \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^\alpha & \text{for } p > \frac{1}{3} f_c (\text{compression}) \\
1 + \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^\delta & \text{for } p < \frac{1}{3} f_t (\text{tension}) 
\end{cases}
\]  

(13)

\( \Delta \) is the compression strain rate factor and \( \alpha \) is the tension strain rate factor.

Strain hardening is represented in the model through the definition of an elastic limit surface and a hardening slope. The elastic limit surface is scaled down from the fracture surface:

\[ Y_{elast} = Y_{fail}(p^*)F_{elast}F_{cap}(p) \]  

(14)

\( Felas \) is the ratio of the elastic strength to failure surface strength derived from two input parameters (elastic strength/fc) and (elastic strength/ft). The pre-peak fracture surface is subsequently defined through interpolation between the elastic and fracture surfaces using the hardening slope \( G_{elas}/(G_{elas} - G_{plas}) \).

The model presents the option of including a cap to limit the elastic deviatoric stress under large compressions. This option effectively leads to the assumption that porous compaction results in a reduction in deviatoric strength. The elastic, fracture and residual failure surfaces are shown schematically in Figure 3.

![Figure 3. Elastic, fracture and residual surfaces](image)

A residual (frictional) failure surface is defined as:
where $B$ is the residual failure surface constant and $M$ is the residual failure surface exponent, both input parameters.

Damage is assumed to accumulate due to inelastic deviatoric straining (shear induced cracking) using the relationships:

$$D = \sum \frac{\Delta \varepsilon_{pl, i}}{\varepsilon_p^i}$$

(16)

where $D_1$ and $D_2$ are material constants used to describe the effect strain to fracture as a function of pressure.

Damage accumulation can have two effects in the model:

1) Strain softening (reduction in strength). The current fracture surface (for a given level of damage) is scaled down from the intact surface:

$$Y_{fract}^* = (1 - D)Y_{f, i}^* + DY_{resid}^*$$

(17)

2) Reduction in shear stiffness:

$$G_{frac} + (1 - D)G_{elas} + DG_{resid}$$

(18)

2.2. Material model for reinforcement steel

The reinforcement steel is modeled by the Johnson and Cook material model (Johnson and Cook, 1983), which is suitable to model the strength behavior of materials subjected to large strains, high strain rates and high temperatures. The model defines the yield stress $Y$ as:

$$Y = \left[ A + B \varepsilon_p^n \right] \left[ 1 + c \log \varepsilon_p^* \right] \left[ 1 - T_H^n \right]$$

(19)

where $\varepsilon_p^*$ is the effective plastic strain, $\varepsilon_p^*$ is the normalized effective plastic strain rate for $T_H = (T - T_{room})/(T_{melt} - T_{room})$ (Troom is room temperature and Tmelt is melting temperature), and $A$, $B$, $C$, $n$ and $m$ are five material constants. The constant $A$ is the basic yield stress at low strains while $B$ and $n$ represent the effect of strain hardening. The second and third brackets in Eq. (19) represent the effects of strain rate and temperature, respectively.

The material constants adopted here are based on the typical data for steel 4340. The material parameters are: reference density $\rho = 7.83 \, \text{g/cm}^3$, bulk modulus $K = 159 \, \text{GPa}$, reference room temperature $T_{room} = 20 \, \text{C}$, and reference temperature $T_{melt} = 1400 \, \text{C}$.
Troom=300K, specific heat=477 J/kgK, shear modulus G=81.8Gpa, basic yield stress A=792MPa, hardening constant B=510MPa, hardening exponent n=0.26, strain rate constant C=0.014, thermal softening exponent m=1.03,and melting temperature Tmelt=1793K (Autodyn, 2009).

2.3. Material model for air and high explosive

In the numerical model, air is modeled by an ideal gas EOS, which is one of the simplest forms of EOS. The pressure is related to the energy by:

\[ p = (\gamma - 1)\rho e \]  \hspace{1cm} (20)

where \( \gamma \) is a constant, \( \rho \) is air density and \( e \) is the specific internal energy. In the simulation, the standard constants of air from the AUTODYN material library are used, that is, air density, \( \rho = 1.225 \) kg/m3 and \( \gamma = 1.4 \). The air initial internal energy is assumed to be \( 2.068 \times 10^5 \) kJ/kg.

High explosives (TNT) are typically modeled by using the Jones–Wilkins–Lee (JWL) EOS, which models the pressure generated by chemical energy in an explosion. It can be written in the form:

\[ p = C_1 \left( 1 - \frac{\omega}{r_1 v} \right) e^{-r_1 v} + C_2 \left( 1 - \frac{\omega}{r_2 v} \right) e^{-r_2 v} + \frac{\omega e}{v} \]  \hspace{1cm} (21)

where \( p \) is the hydrostatic pressure; \( v \) the specific volume; \( e \) the specific internal energy; and \( C_1, r_1, C_2, r_2 \) and \( \omega \) are material constants. The values of the constants for many common explosives have been determined from dynamic experiments and are available in AUTODYN (Fu et al., 1991).

2.4. Equation of State (EOS)

In the material models part of AUTODYN, a simple definition is given to state that the EOS is used to represent the material’s hydrostatic response which is the general behavior of gases and liquids that can sustain no shear. Response of gases and liquids to dynamic loading is strictly hydrodynamic, with pressure varying as a function of density and internal energy. Similarly, this is also the primary behavior of solids at high deformation rates when hydrostatic pressure is far beyond the material’s yield stress.

3. Erosion Algorithm

Erosion is a numerical mechanism for the automatic deletion of elements during a simulation. In order to simulate the progressive collapse process of the RC slab, the so-called erosion algorithm is used. This algorithm is employed to capture the physical fracture process of the material if no significant reverse loading occurs to the fractured elements (Xu and Lu, 2006).
The different erosion criteria available in the literature can be classified according to the type of variable used to control erosion: strain based and stress based. Incremental geometric strain, instantaneous geometric strain, maximum principal strain and principal stress are some examples for erosion criteria available in the literature.

4. Numerical simulations

The study of the effect of erosion criterion and limits on the numerical results is developed in this section based on applications related to a RC slab and retrofitted with FRP composites subjected to blast loading. In this study, models are analyzed using ANSYS AUTODYN software.

4.1. RC Slab

The numerical simulation of a square RC slab tested by (Wang et al., 2012) under blast loads at different scaled distances is presented in this section. The dimensions of slab and the reinforcement are shown in Figure 4. The slab was subjected to cylindrical explosive charges consisting of 0.94 kg of TNT suspended at a standoff distance of 500 mm.

![Figure 4 Geometry of the RC slab (Wang et al., 2012)]

Figure 5 shows the slab after its exposure to the blast event. The reinforcement has yield strength of 600 MPa and a Young’s modulus of 200 GPa.
The properties of concrete are presented in Table 1.

### Table 1 Concrete Properties

<table>
<thead>
<tr>
<th>Equation of State P-alpha</th>
<th>Strength RHT Concrete</th>
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<tbody>
<tr>
<td>Reference density</td>
<td>2.75 g/cm³</td>
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<tr>
<td>Porous density</td>
<td>2.33 g/cm³</td>
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<tr>
<td>Initial compaction pressure</td>
<td>2.40E+04 kPa</td>
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<tr>
<td>Solid compaction pressure</td>
<td>2.50E+05 kPa</td>
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<tr>
<td>Compaction exponent</td>
<td>3.00E+00</td>
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<tr>
<td>Solid EOS</td>
<td>Polynomial</td>
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<tr>
<td>Bulk Modulus A₁</td>
<td>3.527E+07 kPa</td>
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<tr>
<td>Parameter A₂</td>
<td>3.958E+07 kPa</td>
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<tr>
<td>Parameter A₃</td>
<td>9.04E+06 kPa</td>
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<tr>
<td>Parameter B₆</td>
<td>1.22E+00</td>
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<tr>
<td>Parameter B₇</td>
<td>1.22E+00</td>
</tr>
<tr>
<td>Parameter T₁</td>
<td>3.527E+07 kPa</td>
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<tr>
<td>Parameter T₂</td>
<td>0.00E+00 kPa</td>
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<td>Compaction Curve</td>
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</table>

To compare the influences of modeling parameters, this problem simulated with 3 modeling assumptions as follows:
4.1.1. Simulation of RC slab without erosion model

Due to the symmetry of the problem, only 1/4 of the slab is actually modeled using 5 mm side cells. In this model the nonlinear properties of steel and concrete are applied while the erosion model is neglected. The analysis result of one fourth of slab is shown in Figure 6. It can be seen that without erosion model leads to significant difference between test result and simulation.

![Figure 6. Damage in a quarter of slab without erosion model (mesh size: 5mm)](image)

4.1.2. Simulation of RC slab with erosion model

The second model is simulated similar to slab in sub-section 4.1.1 but the erosion model is applied to simulation of concrete. There are 3 options for erosion models in AUTODYN. Chosen for simulations here is the “instantaneous geometric strain” option. The reason of choosing it among others is: instantaneous geometric strain is directly calculated from principal strain components and therefore, it can increase and decrease by loading and unloading while this behavior is not valid neither for effective plastic strain, nor for incremental geometric strain since they always increase monotonically (Autodyn, 2009). Several erosion values are tried to see the effect on blast loading. Figure 7 shows the damage obtained with a 5mm cell size. Results show that the more appropriate value for the erosion geometric strain limit is 0.5%.

![Figure 7. Damage in a quarter of slab with erosion model (mesh size: 5mm)](image)
4.1.3. Simulation of RC slab with erosion model and a coarser mesh

In order to study the relation between the erosion algorithm and the mesh size the same problem in sub-section 4.1.2 is solved but with a coarser mesh (25 mm). The erosion limit is taken as 0.5%. The resulting damage is presented in Figure 8 and does not represent the actual damage.

It can be observed that damage pattern is strongly dependent not only on erosion model but also on mesh size. This conclusion suggests that strain based erosion limit cannot be independent of mesh size.

![Damage in a quarter of slab with erosion model (mesh size:25mm)]

**Figure. 8** Damage in a quarter of slab with erosion model (mesh size:25mm)

4.2. FRP-retrofitted RC slab

To evaluate the overall structural effect from the erosion algorithm, a simulation on the blast field test performed by (Tanapornraweekit et al., 2011) is carried out. The blast test was performed on a GFRP-retrofitted one-way RC slab with dimensions of 2000×1000×75mm. The reinforcement yield and ultimate strengths are 356MPa and 412MPa, respectively. Concrete with an average 28-day compressive strength of 32MPa and was used to cast the specimen. The slab was retrofitted on the top face with one layer of GFRP. The material properties of GFRP sheets are presented in Table 2.

**Table. 2** Material Properties of GFRP (Tanapornraweekit et al., 2011)

<table>
<thead>
<tr>
<th>Properties</th>
<th></th>
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<tbody>
<tr>
<td>Longitudinal Young’s modulus, E&lt;sub&gt;x&lt;/sub&gt; (GPa)</td>
<td>75.6</td>
</tr>
<tr>
<td>Transverse Young’s modulus, E&lt;sub&gt;y&lt;/sub&gt; (GPa)</td>
<td>17.7</td>
</tr>
<tr>
<td>Longitudinal tensile strength (MPa)</td>
<td>1330</td>
</tr>
<tr>
<td>Transverse tensile strength (MPa)</td>
<td>69</td>
</tr>
<tr>
<td>Longitudinal compressive strength (MPa)</td>
<td>547</td>
</tr>
<tr>
<td>Transverse compressive strength, (MPa)</td>
<td>262</td>
</tr>
</tbody>
</table>
The explosive used for the test was approximately 0.9 kg of TNT with 0.5 m standoff distance. The deformed shape and crack pattern of specimen is shown in Figure 9.

![Crack pattern after test](image)

**Figure. 9** Crack pattern after test (Tanapornraweekit et al., 2011)

To compare the influences of modeling parameters, this problem simulated with 3 modeling assumptions as follows:

**4.2.1. Simulation of FRP-retrofitted RC slab without erosion model**

Only 1/4 of the slab is considered because of symmetry. A mesh size 5 mm is applied to model. In this model the nonlinear properties of steel and concrete are applied while the erosion model is neglected. Figure 10 shows the damage obtained with a 5 mm cell size.

![Damage in 1/4 of slab without erosion model](image)

**Figure. 10** Damage in 1/4 of slab without erosion model (mesh size: 5mm)
4.2.2. Simulation of FRP-retrofitted RC slab with erosion model

In this example the same properties used in sub-section 4.2.1 is applied to modeling but the erosion model is considered for simulation of concrete. The erosion strains are taking 0.5% and 2% for concrete and GFRP sheet, respectively. The result obtained using a 5 mm mesh size for the plate is presented in Figure. 11.

![Damage in 1/4 of slab with erosion model (mesh size: 5mm)](image1)

**Figure. 11** Damage in 1/4 of slab with erosion model (mesh size: 5mm)

4.2.3. Simulation of FRP-retrofitted RC slab with erosion model and a coarser mesh

The same problem in sub-section 4.2.2 is simulated with a 25 mm mesh size and an erosion criterion based on failure. From Figure 12 it is clear that, like in previous case, a coarse mesh can be led to wrong results.

![Damage in 1/4 of slab with erosion model (mesh size: 25mm)](image2)

**Figure. 12** Damage in 1/4 of slab with erosion model (mesh size: 25mm)
This shows that the erosion limit is not independent of mesh size, thus it cannot be considered as a material property. It is normally expected to obtain different results when the same problem is solved with different mesh sizes. Nevertheless the difference tends to disappear when the mesh is refined. If strain based erosion criteria is considered another type of mesh size dependency is introduced in numerical solution.

5. Conclusions

Influence of the erosion strain (value of strain for which cells are removed) onto the overall behavior of slabs subjected to blast loading are investigated. Results show that if erosion model is ignored a significant difference between test result and simulation is achieved. It can be observed that damage pattern is strongly dependent not only on erosion limit but also on mesh size. This conclusion suggests that strain based erosion limit cannot be independent of mesh size.

This paper also presents numerical results for the behavior of RC slabs strengthened by a FRP sheet subjected to blast loading. Results indicate that externally bonded FRP retrofits significantly increase the strength and stiffness of RC slabs. Without exception, a significant reduction in maximum displacement and time-to-maximum displacement for all specimens retrofitted with externally bonded FRP is observed over corresponding slabs.

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