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Bond slip modelling and its effect on numerical analysis of blast-induced responses of RC columns

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Abstract. Reinforced concrete (RC) structures consist of two different materials: concrete and steel bar. The stress transfer behaviour between the two materials through bond plays an important role in the load-carrying capacity of RC structures, especially when they subject to lateral load such as blast and seismic load. Therefore, bond and slip between concrete and reinforcement bar will affect the response of RC structures under such loads. However, in most numerical analyses of blast-induced structural responses, the perfect bond between concrete and steel bar is often assumed. The main reason is that it is very difficult to model bond slip in the commercial finite element software, especially in hydrodynamic codes. In the present study, a one-dimensional slide line contact model in LS-DYNA for modeling sliding of rebar along a string of concrete nodes is creatively used to model the bond slip between concrete and steel bars in RC structures. In order to model the bond slip accurately, a new approach to define the parameters of the one-dimensional slide line model from common pullout test data is proposed. Reliability and accuracy of the proposed approach and the one-dimensional slide line in modelling the bond slip between concrete and steel bar are demonstrated through comparison of numerical results and experimental data. A case study is then carried out to investigate the bond slip effect on numerical analysis of blast-induced responses of a RC column. Parametric studies are also conducted to investigate the effect of bond shear modulus, maximum elastic slip strain, and damage curve exponential coefficient on blast-induced response of RC columns. Finally, recommendations are given for modelling the bond slip in numerical analysis of blast-induced responses of RC columns.

Keywords: bond slip; modelling; numerical analysis; blast-induced response; RC column; parametric studies.

1. Introduction

RC structures are made up of concrete and steel. Since great difference exists in the physical

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properties of these two materials, the bond between concrete and steel plays an important role in making the two materials work together as a composite structure (Kwak and Kim 2001). However, when the bond stress between concrete and steel exceeds the limiting value, the bond slip might occur between the two materials. This bond deterioration will significantly affect the structure response, especially when the structure is subjected to lateral load such as blast and seismic load.

Numerous researchers have investigated the slip of reinforcement in concrete bricks. Various models have been proposed, which can be classified into two broad categories, i.e., macro models and micro models. Macro models deal with the average slip behaviour and often assume a uniform bond stress over the development length of the reinforcing bar (Alsiwat and Saatcioglu 1992, Lehman and Moehle 2000, Sezen and Setzler 2008). This approach is very efficient in view of the computational cost. Micro approaches attempt to model the steel-concrete interface on a local level. In this case, a varying bond stress-local slip relationship is normally used within a numerical model (Eligehausen *et al.* 1983, Sezen and Setzler 2008). Micro models tend to agree well with experimental data, but they require complicated modelling and are very time consuming. This makes the practical application of these models computationally very intensive.

To apply the bond slip models into finite element analysis of reinforced concrete structures, two different approaches are commonly used. They are the bond-link element method and bond–zone element method. The bond-link element connects a node of a concrete element with a node of an adjacent steel element. It has no physical dimensions, i.e., the two connected nodes have the same coordinates in the finite element model. In the bond–zone element method, the behavior of the contact surface between steel and concrete and the behavior of the concrete in the immediate vicinity of the reinforcing bar are described by a material law which considers the special properties of the bond zone (Kwak and Kim 2001). Many researchers have reported their success in using these two approaches to model the bond slip behavior between steel bar and concrete (Girard and Bastien 2002, Kwak and Kim 2001, Luccioni *et al.* 2005). However, these models are difficult for practical applications in a numerical model of a realistic structure because the formulation is not straightforward to be incorporated in a general-purpose finite-element program. Therefore, in numerical analysis of RC structure response to blast loads, perfect bond between concrete and steel bar is often assumed (Luccioni *et al.* 2004, Luccioni and Luege 2006, Naito and Wheaton 2006, Zhou *et al.* 2008).

One-dimensional slide line model in LS-DYNA is designed to model the sliding of rebar along a string of concrete nodes. In this model, the slave nodes of a string of beam elements for modeling the rebar are forced to slide along a master line of nodes embedded in the solid mesh that models the concrete matrix (LS-DYNA 2006). It can be used to model the bond slip between concrete and steel bar in a pullout test. However, parameters of the one-dimensional slide line model are very difficult to define. Therefore, the one-dimensional slide line model is rarely used in the numerical simulation.

In the present paper, instead of modeling the pullout test, the one-dimensional slide line model is creatively used to model the bond slip between concrete and steel bar in RC structures. In order to model the bond slip accurately, a new approach to define the parameters of the one-dimensional slide line model from the experimental data of the common pullout test is proposed. Its accuracy and reliability are demonstrated by comparing the numerical results and data in a field blast test. A case study is carried out to study the bond slip effect on numerical analysis of blast-induced responses of a RC column through the application of the one-dimensional slide line model. Parametric studies are also conducted to investigate the sensitivity of bond shear modulus, maximum elastic slip, and damage curve exponential coefficient on RC column response under blast loads. Based on the results obtained in this study, recommendations are given for modelling the bond slip in numerical analysis of blast-induced responses of RC columns.

2. One-dimensional slide line model

The one-dimensional slide line model, which is named as CONTACT_1D in LS-DYNA, can be used to model the sliding of rebar along a string of concrete nodes. It is employed to model the bond and slip between concrete and steel bar in RC members subjected to lateral force in this paper.

In this model, the slave node of a string of beam or truss elements, modeling the rebar, is forced to slide along a master line of nodes embedded in the solid mesh, which models the concrete matrix. This kinematic constraint is applied using a penalty function approach. Fictitious springs are inserted between slave nodes and their projections over the master lines. These springs produce internal forces along the rebar and are proportional to the distance between slave nodes and master lines, as shown in Fig. 1 (LS-DYNA 2006, Weatherby 2003).

When the damage accumulation is not considered, the bond between concrete and steel bar is assumed to be elastic-perfect-plastic; when the damage accumulation is considered, in the plastic range, the bond shear stress will decay exponentially with the increment of plastic slippage. In the elastic range, the bond shear stress, τ, varies linearly with the elastic slip, s ($s < s_{\max}$), up to a maximum value, $\tau_{\max}$, as shown in Fig. 2.

The constitutive relation between shear stress and slip is represented by

$$\tau = \begin{cases} G_s s, & s \le s_{\max} \\ \tau_{\max} e^{-h_{\mathrm{dmg}} D}, & s > s_{\max} \end{cases} \tag{1}$$

where, G_s : bond shear modulus

$s_{\max}$: maximum elastic slip

h_{dmg} : damage curve exponential coefficient

D : the damage parameter, which is defined as the sum of the absolute values of the plastic displacement increments Δs_p as

$$D_{n+1} = D_n + \Delta s_p \tag{2}$$

The shear force, acting on the bond area per unit length of rebar A_s ($A_s = 2\pi R_e$, R_e is the outer radius of the rebar), at step n+1 is given as

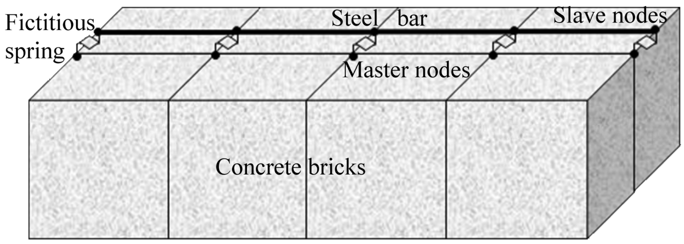


Fig. 1 Sketch of fictitious spring between master and slave nodes in one-dimensional slide line model

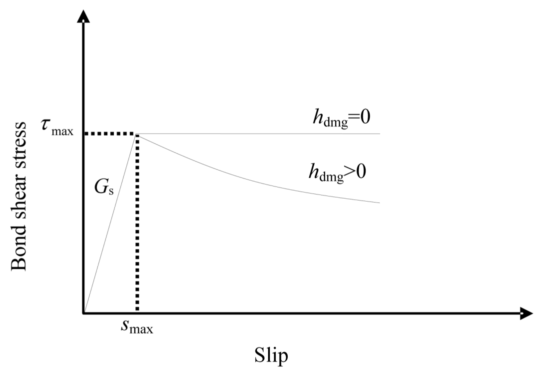


Fig. 2 Bond shear stress-slip relationship for the one-dimensional slide line model

$$f_{n+1} = \min(f_n + G_s A_s \Delta s,\ G_s A_s s_{\max}) \tag{3}$$

According to Eq. (1)-(3), the typical bond shear stress-slip relationship is shown in Fig. 2.

3. Derivation of the parameters in one-dimensional slide line model

As discussed above, in order to use the one-dimensional slide line model in LS-DYNA, three parameters need be defined first. They are the bond shear modulus G_s, the maximum elastic slip $s_{\max}$ and the damage curve exponential coefficient h_{dmg}. In this section, bond stress and slip curves obtained from experiments are used to define the parameters for the one-dimensional slide line model.

The relationship between bond stress and slip has been investigated by many researchers through experimental study since 1960s. The earliest work was done by Nilson (1968), Morita and Houde (1979) and Morita and Fujii (1985). They studied the bond stress and slip under monotonic loads through their own designed pullout tests. Based on the experimental data, several empirical formulae were proposed using the least squares fitting method to predict the bond stress-slip relationship. These formulae are presented in the following

Nilson's formula (Nilson 1968)

$$\tau = 9.78 \times 10^2 s - 5.72 \times 10^4 s^2 + 8.35 \times 10^5 s^3 \tag{4}$$

Mirza & Houde's formula (Mirza and Houde 1979)

$$\tau = 5.29 \times 10^2 s - 2.52 \times 10^4 s^2 + 5.87 \times 10^5 s^3 - 5.47 \times 10^6 s^4 \tag{5}$$

Morita & Fujii's formula (Morita and Fujii 1985)

$$\tau = 87 \times \left(\frac{s}{D_b}\right)^{0.556} \tag{6}$$

where τ is the local bond stress in MPa, s is the local bond slip in mm, D_b is the diameter of the steel bar in mm. Obviously, Morita & Fujii's formula considered the effect of bar size on bond slip behavior.

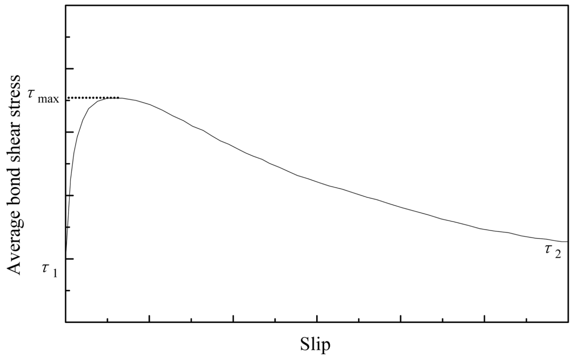


Fig. 3 Bond shear stress-slip relationship from typical pullout test

Some researchers extended the slip range up to very large values within their pullout tests. Malvar (1991, 1992), Gambarova *et al.* (1989), Eligehausen *et al.* (1983), Tepfers and Olsson (1992), Oh and Kim (2007) and Moetaz and Sameer (1996) did intensive experimental study on bond slip behaviour between concrete and steel bar. A typical average bond stress and slip curve obtained by their pullout tests is shown in Fig. 3.

From Fig. 3, one can see that when the average bond stress increases from zero to τ_1, there is no slip between concrete and steel bar. This is because the main stress transfer mechanisms between concrete and steel bar are represented by adhesion in this stage. As the bond shear stress increases, the transfer forces are dominated by the mechanical interaction concentrating at the faces of the ribs, and the slip occurs between the two materials. Before the concrete near the ribs fails, the bond stress reaches its maximum value τ_{max}. Hereafter if the slip between concrete and steel bar further increases, the bond stress will slowly decrease to a relatively small value τ_2, which is governed by the friction between the two materials.

By comparing Fig. 2 and Fig. 3, one could find that the average bond shear stress-slip relationship from typical pullout tests could be used to define the parameters in the one-dimensional slide line model after proper simplification. In order to do this, the following assumptions and simplifications are made:

a) Slip begins at the beginning of bond stress development. Before the average bond shear exceeds the maximum value, i.e., τ_{max}, the nonlinear relationship between the bond shear stress and slip is simplified to be linear. That is to say, the bond shear modulus is assumed as a constant before the bond stress reaches the maximum value. Its value is taken as the same as the one when the bond shear stress reaches τ_1, but shear slip starts when shear stress is zero, as shown in Fig. 4. This assumption provides a reasonable representation of the bond shear modulus, but a less accurate model for the maximum elastic slippage. This simplification is acceptable because the bond shear modulus is more important than the maximum elastic slippage for precisely defining the one-dimensional slide line model. This will be further discussed in section 6.

b) The maximum elastic slip s_{max} is defined as the slippage when the bond shear stress reaches the maximum value. After that, the increment of the slip will be considered to be plastic slippage;

c) An exponential decay is utilized to represent the bond shear stress decrease with the increase of the slip.

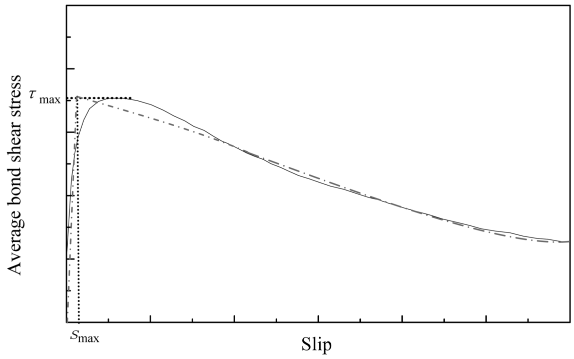


Fig. 4 Simplification of the bond shear stress-slip relationship from pullout test

Fig. 4 compares the typical pullout test data and the one-dimensional bond shear stress-slip relation with the parameters determined according to the above steps. As can be seen, the simplified bond shear stress-slip relationship represents the pullout test data reasonably well, implying the one dimensional slide line model can be used to model the bond shear stress-slip relation. In this case, three parameters of the contact model could be easily defined, as shown in Fig. 4. Firstly, the bond shear modulus G_s is the slope of the bond stress-slip curve at the point when the bond stress equals τ_1. Then the maximum elastic slip s_{max} is derived by

$$s_{max} = \frac{\tau_{max}}{G_s} \tag{7}$$

herein τ_{max} could be easily obtained from the pullout test. Finally, the damage curve exponential coefficient h_{dmg} can be derived through the least squares fitting of the curve to the test data.

It should be noted here that in theory, the average bond-slip relationship in a pullout test is different from the local bond-slip relationship, which is required in structural modeling of bond slip. Herein it is used to define parameters of one-dimensional slide line model for the following reason. It is very difficult to use the local bond shear stress-slip relationship to define the numerical model. The local shear stress-slip relationship obtained from pull-out tests varies from point to pint, it is very difficult to choose which one should be used to define the numerical model. What one could do is supposing that the bond shear stress is uniformly distributed along the rebar-concrete interface and using the average bond shear stress instead of the local bond shear stress. In this case, the defined one-dimensional slide line model might not necessarily precisely represent the bond slip locally, but it can reliably model the overall bond slip behavior in a structure.

As mentioned above, many bond stress-slip curves have been obtained from pullout tests. The available pullout test data in the literature were digitized using software ORIGIN 6.0. The bond shear modulus G_s, maximum elastic slip s_{max} and the damage curve exponential coefficient h_{dmg} can be obtained using the above proposed procedures, as given in Table 1.

As shown in the Table, the bond shear modulus G_s, the maximum elastic slip s_{max} and the damage curve exponential coefficient depend on the concrete properties and the diameter of the rebar, and vary significantly with the concrete properties and rebar diameter. The bond shear modulus listed in Table 1 ranges from 9.5 MPa/mm to 80.4 MPa/mm; while the maximum elastic slip s_{max} varies from 0.18 mm to 1.19 mm; and the exponential coefficient h_{dmg} is between 0.05 and 0.24. Therefore, it is very important to reliably define these parameters with respect to the properties of

Table 1 Parameters of the one-dimensional slide line model from pullout test data

Specimens	D_b (mm)	f_c/f_t (MPa)	G_s (MPa/mm)	$S_{\max}$ (mm)	h_{dmg}
Malvar					
Specimen 1	19.05	40.2/4.93	55.2	0.22	0.15
Specimen 2	19.05	40.2/4.93	55.2	0.28	0.12
Specimen 3	19.05	40.2/4.93	55.2	0.32	0.09
Specimen 4	19.05	40.2/4.93	55.2	0.35	0.08
Specimen 5	19.05	40.2/4.93	55.2	0.38	0.09
Specimen 6	19.05	40.2/4.93	46.2	0.18	0.16
Specimen 8	19.05	40.2/4.93	62.0	0.31	0.12
Specimen 10	19.05	40.2/4.93	57.9	0.40	0.11
Gambarova *et al*. Phase C	17.3	40.2/4.08	80.4	0.23	0.11
Eligehausen *et al*.					
Specimen 1	24.7	30/2.66~2.89	10.0	1.19	0.09
Specimen 3	24.7	30/2.66~2.89	16.8	0.82	0.09
Specimen 5	24.7	30/2.66~2.89	49.8	0.33	0.08
Tepfers and Olsson					
Test 1	16	25.5/2.4	14.1	0.98	-
Test 3	16	27.6/3.0	12.7	1.09	0.24
Series 4					
Test 12	16	22.0/1.9	25.2	0.34	0.05
Test 13	16	22.0/1.9	25.2	0.34	0.05
Test 14	16	22.0/1.9	25.2	0.38	0.06
Test 15	16	22.0/1.9	25.2	0.38	0.07
Test 16	16	22.0/1.9	25.2	0.33	0.07
Oh and Kim	16	37/-	34.2	0.69	0.18
Moetaz *et al*.					
Specimen 1	6	24/-	10.3	-	-
Specimen 2	8	24/-	9.5	-	-
Specimen 3	10	24/-	11.4	-	-

* D_b: bar diameter, f_c/f_t: concrete compressive and tensile strength, the value of h_{dmg} corresponds to the slip in mm.

the concrete and reinforcement bars in numerical simulations. The values in Table 1 can be used in numerical simulation of bond slip between concrete and rebar only if they have the similar conditions as those given in Table 1. Besides the bar diameter, concrete compressive and tensile strength, other properties such as the cover thickness, geometry of bar deformations (ribs), and steel yield strength, also affect the bond stress-slip relationship between concrete and steel rebar. Therefore, for accurate simulation, pullout tests need be carried out to derive the parameters for the bond stress-slip model if the corresponding test data is not available.

4. Verification of the one-dimensional slide line model

A simply supported reinforced concrete beam is investigated with the objective of establishing the ability of the one-dimensional slide line model in simulating bond and slip between concrete and steel bar in RC members and verifying the proposed parameter derivation method. The beam was tested by Gaston *et al.* (1972). The material properties of the tested specimen are summarized in Table 2. Fig. 5 gives the geometry of the beam and configuration of the test. In the Figure, B = 152.4 mm, H = 304.8 mm, d = 272.3 mm, b = 900.0 mm. The concentrated loads are applied at one-third location of the structure.

Two 3D numerical models of the test are established in software LS-DYNA. One considers the bond slip between concrete and steel bar through the one-dimensional slide line model, and another one assumes perfect bond between the two materials. The material model CONCRETE_DAMAGE_REL3 (MAT_72_REL3) available in LS-DYNA is utilized to model concrete. Material model PLASTIC_KINEMATIC (MAT_003) is used to model steel (LS-DYNA 2006). Solid elements of 8.5 mm cube are used to model the concrete, and 8.5 mm long beam elements are used for the reinforcement bars.

The point loads applied to the beam are increased gradually to obtain the load-deflection curve. Since pullout test was not done with the same steel bar and concrete in the specimen, the parameters for the one-dimensional slide line model are chosen to be the same as those derived from Oh & Kim's pullout test data (Oh and Kim 2007). This is because both the steel bar diameter and the concrete compressive strength are almost the same in these two cases (18 mm .vs. 16 mm, 32.4 MPa .vs. 37 MPa respectively). The three parameters for the slide line model used in this section are: G_s = 34.2 MPa/mm, $S_{\max}$ = 0.69 mm, and h_{dmg} = 0.18.

The numerical results are compared with the experimental data in Fig. 6. As can be seen, when the perfect bond between concrete and steel bar is assumed, numerical analysis will overestimate the load carrying capacity of the beam. When the bond slip is considered, the result shows satisfactory agreement with the measured curve. Through the numerical analysis of this example structure, it can be concluded that the inclusion of the bond-slip effect in numerical simulation yields a better result as compared with the model with perfect bond assumption. The one-dimensional slide line model can be used to model the bond and slip between concrete and steel bar in RC members.

Table 2 Concrete and steel properties of the specimen

E_c (MPa)	f_c (MPa)	ν_c	E_s (MPa)	f_y (MPa)	ν_s	$\rho = A_s/Bd$
27157.86	32.36	0.167	198406.74	323.64	0.3	0.0062

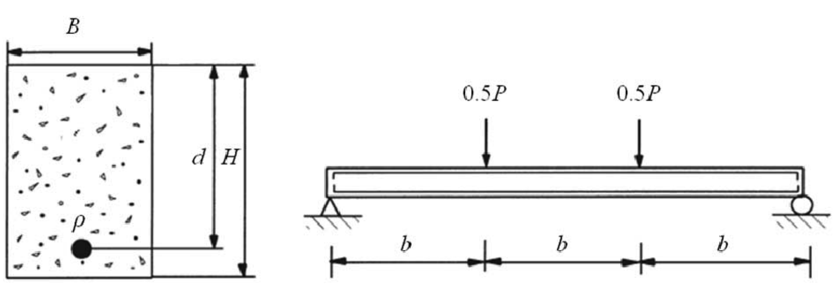


Fig. 5 Beam geometry and configuration of the test

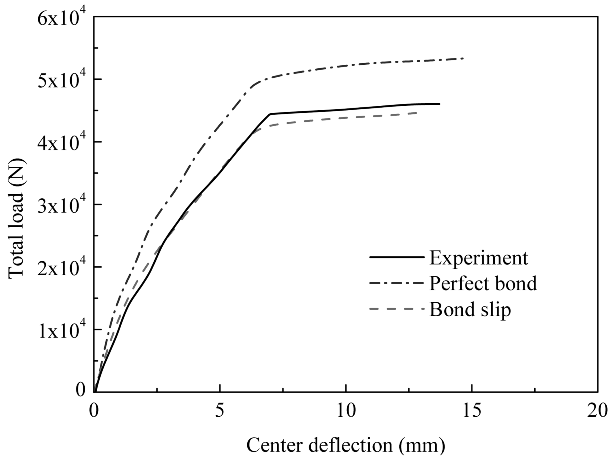


Fig. 6 Comparison of the load-deflection curves

5. Bond slip effect on blast-induced responses of RC columns

Since the one-dimensional slide line model has been proven to be effective in modelling the bond and slip between concrete and steel bar under static load, its ability of simulating the bond and slip between concrete and steel bar under dynamic load is studied through simplify modelling a steel bar pulled out and pushed into concrete bricks. The results show the unloading-reloading behaviour of one-dimensional slide line model as following: when the slippage is in the elastic range, the unloading slope of bond stiffness is the same as the case of first loading; when the slippage is in the plastic range, unloading is considered to take place at a constant slope of bond stiffness. The same slope of bond stiffness is retained during reloading. Therefore, this model is able to simulate the bond and slip between concrete and steel bar under dynamic load Thus, in this section, one-dimensional slide line is used to model the bond slip effect on blast-induced responses of a RC column. Numerical analysis of a quarter-scale RC column, which was tested by other researchers, under blast loads is performed and the results are compared with the test data to investigate the accuracy and reliability of the model in modeling the bond and slip of RC structures under blast loads.

5.1 Numerical model of the RC column

A series of field blast tests of five two-story, quarter-scale RC frames were conducted by Woodson and Baylot (1999, 2000) to study the progressive collapse phenomenon. The first-floor center column in test No. 2 is analyzed to investigate the bond slip effect. Fig. 7(a) shows the sketch of the experiment. The studied column is the center column at the ground floor. The details of the geometry and material properties of the column are given in Table 3 and Table 4, respectively.

Table 3 Configuration of the analysed quarter-scale RC column

Column width mm	Column depth mm	Column height mm	Cross tie/Hoop	Longitudinal reinforcement	Cover depth mm
85	85	900	D1.6 @100	8D3.2	8.5

Table 4 Material properties

Unconfined Concrete strength MPa	Yield stress of longitudinal steel MPa	Ultimate stress of longitudinal steel MPa	Fracture strain of longitudinal steel	Yield stress of cross tie/ hoop MPa	Ultimate stress of cross tie/ hoop MPa	Fracture strain of cross tie/ hoop
42	450	510	18%	400	610	18%

Two 3D numerical models for the quarter-scale RC column are set up in LS-DYNA, one includes the one-dimensional slide line model for the bond slip effect between concrete and steel bar, another one assumes perfect bond between the two materials. Both the concrete and steel models are the same as those used in the previous section, but the material properties used are given in Table 4. Moreover, the strain rate effects of the two materials are considered. This will be discussed later.

Solid elements of 8 mm cube are used to model the concrete, and 8 mm long beam elements are used for the vertical reinforcement bars and the ties. In order to provide higher fidelity for the column constraints, a foot and a head are included in the numerical model, as shown in Figs. 7(b)-(c). The outer vertical face of the foot and head are constrained against horizontal motions (i.e., in the *x*- and *y*- direction) and the bottom face of the footing is further constrained to against vertical motion (i.e., in the *z*- direction).

Since pullout test was not done for this test model, the parameters for the one-dimensional slide line model are derived from the pullout test data available in the literature with the similar concrete and steel bar properties, i.e., similar rebar diameter and concrete compressive strength (Malvar 1991, Malvar 1992, Weatherby 2003) as given in Table 1. The three parameters of the slide line model used in this section are: $G_s = 50$ MPa/mm, $S_{max} = 0.36$ mm, and $h_{dmg} = 0.2$. It should be mentioned here that since the steel diameter and concrete strength are not exactly the same, the parameters used herein to define the one-dimensional slide line model are only approximate, which may introduce some errors. For a more reliable definition of the parameters, pullout tests should be carried out. However, this is out of the scope of this paper.

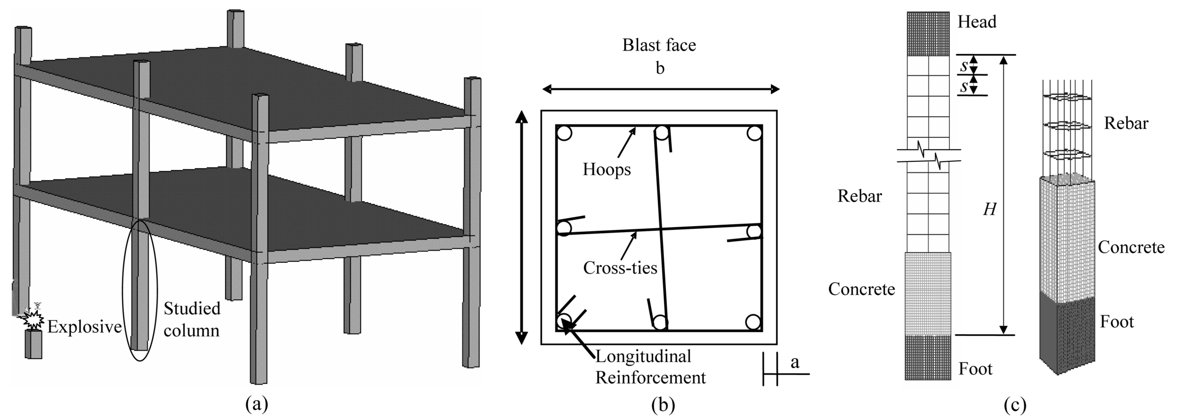


Fig. 7 Numerical model of RC column (a) sketch of the field test; (b) column cross section; (c) detail of the rebar

5.2 Strain rate effect

When the RC structures are subjected to the blast loads, both concrete and steel may respond at very high strain rates in the order of 10 s^{-1} to 1000 s^{-1} or even higher. At these high strain rates, the apparent strength of these materials might increase significantly. In this section, the dynamic increase factor (DIF) of concrete strength is derived according to the Comite Euro-international du Beton (CEB) (Bischoff and Perry 1991, Malvar and Ross 1999) recommendation. In tension, the dynamic increase factor (DIF) of the concrete tensile strength is given by the following equations

$$TDIF = \frac{f_{td}}{f_{ts}} = \left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_{ts}}\right)^{1.016\delta} \quad \text{for} \quad \dot{\varepsilon}_d \le 30s^{-1} \tag{8}$$

$$TDIF = \frac{f_{td}}{f_{ts}} = \beta\left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_{ts}}\right)^{1/3} \quad \text{for} \quad \dot{\varepsilon}_d > 30s^{-1} \tag{9}$$

where f_{td} is the dynamic tensile strength at the strain rate $\dot{\varepsilon}_d$, f_{ts} is the static tensile strength at the strain rate $\dot{\varepsilon}_{ts}$ ($\dot{\varepsilon}_{ts} = 3\times10^{-6}s^{-1}$), and $\log\beta = 7.11\delta - 2.33$, in which $\delta = 1/(10+6f_c'/f_{co}')$, $f_{co}' = 10$ MPa, and f_c' is the static uniaxial compressive strength in MPa. In compression the empirical formulae are given as

$$CDIF = \frac{f_{cd}}{f_{cs}} = \left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_{cs}}\right)^{1.026\delta} \quad \text{for} \quad \dot{\varepsilon}_d \le 30s^{-1} \tag{10}$$

$$CDIF = \frac{f_{cd}}{f_{cs}} = \gamma(\dot{\varepsilon}_d)^{1/3} \quad \text{for} \quad \dot{\varepsilon}_d > 30s^{-1} \tag{11}$$

where f_{cd} is the dynamic compressive strength at the strain rate $\dot{\varepsilon}_d$, $\dot{\varepsilon}_{cs} = 30\times10^{-6}s^{-1}$, $\log\gamma = 6.156\alpha - 0.49$, $\alpha = (5+3f_{cu}/4)^{-1}$, f_{cs} is the static compressive strength, and f_{cu} is the static cube compressive strength in MPa.

Because of the complex of strain rate effect of concrete-like materials, there are still debates about the reasonable values of concrete DIF, as well as the current experimental methods of deriving DIF when concrete deforms at a very high strain rate (Li and Lu 2008, Meng and Li 2003). It is normally believed that when the strain rate is very high, the current formulae and even experimental methods might give inaccurate prediction of DIFs. Therefore, in this section, the maximum compressive and tensile DIF for concrete considered are the ones corresponding to the strain rate 300 s^{-1}. For the case of the strain rate higher than 300 s^{-1}, DIFs used are the same as those at strain rate 300 s^{-1}.

For steel, the strain rate effect from the K&C model (Malvar 1998) is utilized. The dynamic increase factor (DIF) is given as

$$DIF = \left(\frac{\dot{\varepsilon}}{10^{-4}}\right)^{\alpha} \tag{12}$$

$$\alpha = 0.074 - 0.040\frac{f_y}{414} \tag{13}$$

where $\dot{\varepsilon}$ is the strain rate of the steel bar in s^{-1} and f_y is the steel bar yield strength in MPa. This formulation is valid for steel bars with yield stress between 290 and 710 MPa and for strain rate between 10^{-4} s^{-1} and 225 s^{-1} (Malvar 1998).

5.3 Numerical results

In Woodson & Baylot's tests, 7.10 kg of C-4 at a standoff distance (center of charge to the face of column) of 1.07 m was used to generate the blast environment, as shown in Fig. 7 (Woodson and Baylot 1999, Woodson and Baylot 2000). The details of the blast configuration are given in Table 5. In the experiment, only the pressure and impulse of 3 points on column front surface is recorded, since the difference between the three is insignificant because the standoff distance of the explosive is larger than the column height, the blast load acting on the front face of the column is assumed to be uniform. The blast pressure and impulse are defined to be the average of the three gauge points. Because the blast load curve was not available, herein the blast load is simplified to be a triangular curve decaying from the maximum to zero, ignoring the negative phase. The positive peak pressure and impulse are 7000 kPa and 1100 kPa · ms respectively, which is the average of the three measurements from the test data obtained by Woodson & Baylot. The axial load of the column is also considered with a 2.1 MPa of initial axial stress applied to the column before the application of blast load.

The comparison of the calculated and measured deflection time histories at the middle of the center column is shown in Fig. 8. From this Figure, one can find that: (1) a better prediction of the column response can be achieved when using the one-dimensional slide line model to account for the bond slip effect. Without considering the bond slip, the column experiences only little plastic deformation with a small residual deflection, although the predicted peak deflection is quite close to the test data. Considering the bond slip in the numerical model gives a better prediction of the peak deflection and the residual deflection of the column under the blast load; (2) the peak response of the numerical result is lagged. This might be because that the strain rate effect of the bond-slip action was not considered and the blast load acting on the column is simplified and not exactly the

Table 5 Blast load configuration

Charge weight (C-4) g	Equivalent weight of TNT charge g	Stand-off distance mm	charge height mm	Initial Axial stress MPa
7100	8000	1070	229	2.1

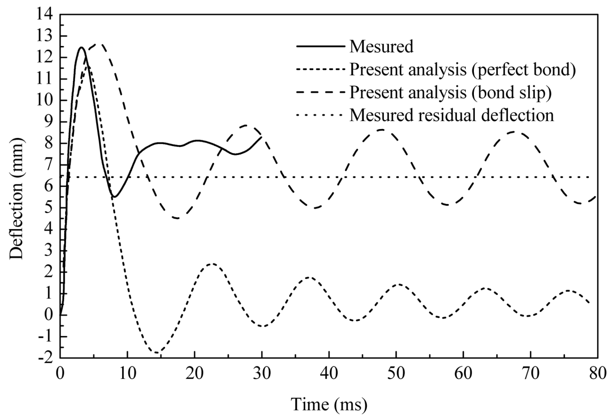


Fig. 8 Comparison of the middle column deflection

same as the one in the field test. Despite of this, the numerical model gives reasonably good prediction of RC column response under blast loads.To sum up, considering the bond slip between concrete and steel bar is important for reliable prediction of blast-induced response of RC columns in numerical analysis

6. Parametric studies

As discussed above, including bond slip in numerical analysis of RC columns under blast loads yields better predictions. However, in most of the numerical analyses reported in the literature, perfect bond is assumed. Therefore, it is interesting to do parametric studies to investigate the effect of each parameter in the bond slip model and the perfect bond assumption on the accuracy of numerically obtained blast-induced responses of RC columns. This will not only give recommendations for modelling bond and slip between concrete and steel bar in blast response analysis but also provide direction of designing new tests to obtain parameters for numerical model of bond slip.

Table 1 summarizes most of the previous pullout test data available in the literature and gives corresponding parameters of the one-dimensional slide line model from each test. Since the number of test data is limited, those given in the table can only serve as a guideline in searching for the proper parameters. Based on those in Table 1, the ranges of the parameters considered in this parametric study are listed in Table 6.

To investigate the effect of these parameters on RC column response under blast loads, the middle deflection of the RC column is calculated. The RC column, as well as the applied blast load, used in this section is the same as the one used in section 5.

6.1 Bond shear modulus

To study the effect of bond shear modulus on blast-induced RC column response, several simulations are carried out using the one-dimensional slide line model with varied bond shear modulus, keeping other two parameters unchanged. The comparison of the middle column deflection with different bond shear modulus is shown in Fig. 9. For all the cases in the Figure, s_{max} = 0.3 mm, h_{dmg} = 0.1. From the Figure, one can see that both the maximum deflection and the residual deflection at the middle column decrease significantly with the increase of the bond shear modulus. With the increase of the shear modulus, the column response converges to the case with the perfect bond assumption. This is because a larger bond shear modulus, which indicates a better bond between concrete and rebar, results in higher adhesion and a larger interaction force between the steel bar ribs and concrete. A larger bond stress is developed if the shear modulus is larger for a

Table 6 Ranges of the parameters considered in parametric studies

G_s (MPa/mm)	S_{max} (mm)	h_{dmg}
50	0.1	0.05
80	0.5	0.1
100	1.0	0.2
120		

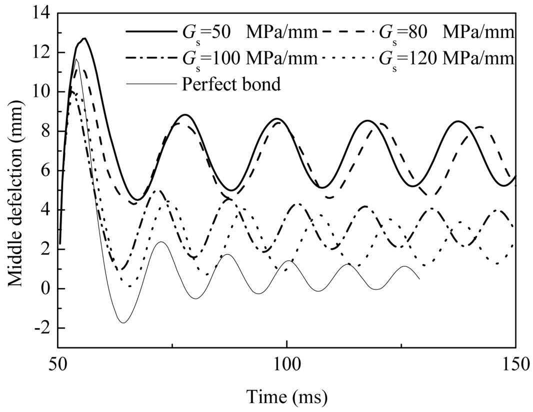
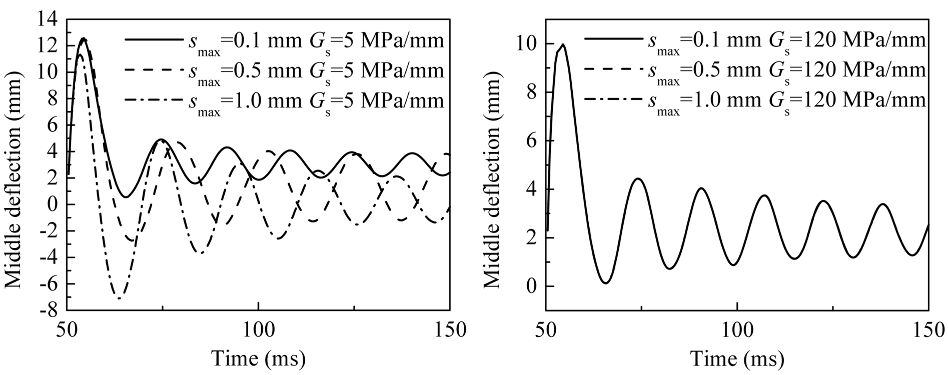


Fig. 9 Variation of the middle column deflection with bond shear modulus

certain elastic slip. The better bond between the two materials increases the stiffness of the column therefore reduces both the maximum deflection and the residual deflection of the column.

6.2 Maximum elastic slip

The deflections of the same RC column with different maximum elastic slip in the one-dimensional slide line model are derived. Fig. 10(a) shows the comparison of the defections with different maximum elastic slip s_{max} but same bond shear modulus G_s (G_s = 5 MPa/mm) and damage curve exponential coefficient h_{dmg} (h_{dmg} = 0.1). As can be seen, both the maximum middle deflection and the residual middle deflection increase as the maximum elastic slip decreases, but the increase of the maximum deflection is less significant as compared to those in Fig. 9 by reducing the bond shear modulus. This can be explained by the fact that when the bond shear modulus is a constant, a smaller maximum elastic slip means a smaller maximum bond shear stress. Then the bond slip effect will become more significant because of the rapid development of the slip between the two materials in the plastic slip region. However, when the bond shear modulus becomes larger, for



(a) (b)

Fig. 10 Variation of the middle column deflection with the maximum elastic slip

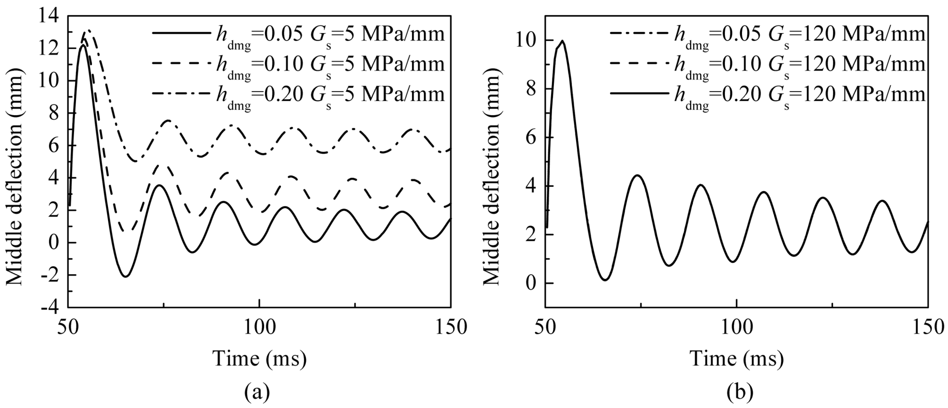


Fig. 11 Variation of the column deflection with damage curve exponential coefficient (G_s = 5 MPa/mm, s_{max} = 0.1 mm)

example, 120 MPa/mm, its effect on blast-induced response is becoming insignificant, as shown in Fig. 10(b), in which using the three maximum elastic slip in the current numerical simulation results in the same column deflections. This is because the bond shear stress under the considered blast load does not reach the maximum elastic limit yet for the three cases. Therefore, the results are exactly the same. The above observations indicate that the bond slip effect on blast-induced response of RC columns depends on both the shear modulus and elastic limit slip, but is more sensitive to the bond shear modulus than the maximum elastic slip. It is worth noting that the conclusion might be coupled with the applied blast load. When the blast load is so big that the bond slip could easily develop into plastic range, the maximum elastic slip might also have significant influence on responses.

6.3 Damage curve exponential coefficient

RC columns with different damage curve exponential coefficient and different bond shear modulus for the one-dimensional slide line model are analyzed to obtain the corresponding middle column deflection. The comparison of these deflection time histories is shown in Fig. 11. The Figure illustrates that the effect of damage curve exponential coefficient on the column response is also dependent on the bond shear modulus of the one-dimensional slide line model. When the bond shear modulus is small, i.e., 5 MPa/mm, the concrete and rebar interface yields easily and the residual deflection of the column then increases significantly with the increase of the damage curve exponential coefficient. However, when the bond shear modulus is large, the corresponding yield shear stress is large at the same maximum elastic slip limit, the bond between the concrete and rebar does not yield, then changing the exponential coefficient, which controls the plastic deformation, has no effect on the response as shown in Fig. 11(b). These observations indicate that when the bond shear modulus is small, it is easier for the development of slip from elastic to plastic. Larger plastic deformation results in a larger residual deflection of the RC column. The residual deflection does not change if the bond between the concrete and rebar does not yield.

7. Conclusions

In the present study, the one-dimensional slide line model in LS-DYNA for modelling sliding of rebar along a string of concrete nodes is used to model bond slip between concrete and rebar in reinforced concrete columns. A new approach to define the parameters of the one-dimensional slide line model from the pullout experimental data is proposed. The reliability of using this one-dimensional slide line model in modeling the bond and slip between concrete and steel bar in RC structures under both static and blast loads is validated through comparison of the numerical simulation results and test data. Using this model, parametric studies are conducted to investigate the sensitivity of the bond shear modulus, maximum elastic slip, and damage curve exponential coefficient on RC column response to blast loads. The results show that the maximum deflection and residual deflection at the middle column decrease with the increase of the bond shear modulus. The maximum elastic slip and damage curve exponential coefficient influence both the maximum and residual deflection of the column. The increase of the maximum elastic slip will lead to the decrease of both the maximum deflection and the residual deflection of the column because it reduces the plastic deformation; while the increase of the damage curve exponential coefficient will increase the residual deflection of RC column if the bond between the concrete and rebar yields. Because the bond shear modulus governs the slip between the concrete and rebar, it is the most critical parameter for the one-dimensional slide line model.

It should be noted here that in the current numerical analysis, the strain rate effect on the bond slip model is not considered because there is no data available in the literature, although the strain rate effect on concrete and steel bar material properties are considered. Further investigation of the strain rate effect on bond slip between concrete and steel needs be carried out in the future to more reliably model RC structure responses to high-speed loads.

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