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Numerical investigation of Reinforced-concrete beam-column joints under contact and close-in blast application

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Abstract

The behavior of the concrete and the steel material under blast loads are different. They have different mode of failures under blast loads. Also, responses differ according to the blast types concerning the proximity of the charge kept. It causes different failure modes in the structural members. Close-in or contact blast causes the spallation of concrete. In the near-field blasts, it causes bending failure in the structural members. The behavior of the mode of failure of various joint types subjected to contact-blast and close-in blast loads are numerically studied here. Three different joints simulated to carry on blast loads—exterior beam-column joint, interior beam-column joint, and knee joint simulated numerically under the close-in and contact loads. The charge for the contact blasts were applied to the joint is placed in contact with the joint core, and was not put at the beam or the column member of the joint cut section. In the current work, the failure behavior and the response of the RC beam-column joints is concluded.

Keywords: Blast loads, reinforced concrete joints, knee joint, exterior joint, interior joint, close-in blast, contact blasts

1. Introduction

The beam-column joints are very critical to the stability of the building. Most of the structures in India and abroad are made up of reinforced concrete. A number of reinforced concrete buildings have collapsed in the past due to terrorist attacks. Partial or full collapse has resulted in causalities and also loss of property. A few examples of such attacks are the World trade centre attack in 1993 caused failure to the floor slabs. But adequate redundancy in the columns provided prevented building collapse [1]; Alfred Murrah building caused 268 deaths [2]. Also, the damage is higher due to contact explosions than far-field blasts [3]. The experimental results in [3] refers that a concealed explosive of 5-25 kg can leave zero residual load carrying capacity of a 1x1m concrete column cross-section.

Therefore, it is imperative to design our structures strategically envisaged as potential target for terrorist attack. This is done by incorporating mitigation strategically to limit the contact explosions.

A lot of research has been undertaken to study the effect of far-field [4]–[8] blasts as well as near-field blasts [9]–[11] most of which are far-field blasts. However, a large number of researches have been done to study the response of columns [4]-[13] as well as on beams [14]–[18]and slabs [19], [20]. Responses on slabs, columns, under blast and impact loads have been studied with the help of analytical [21], numerical [22], [23], and experimental studies [24]. This study is undertaken on seismically complaint RC knee, exterior and interior joints. The joint dimensions are kept same for all the cases of the simulation. The boundary conditions considered were fixed on the free ends for the interest of the study.

2. Literature and background of study

2.1 Beam Column Joint

A large number of structural members such as columns [4]-[8], beams [15]-[18] and slabs [9], [19] have been tested for blast loads under close-in and also near-field blasts. These are crucial members of the reinforced concrete buildings. However, the RC joint is another important structural element that needs attention in the designing and evaluation for the construction purpose for blast mitigation and protection against blasts. Every structural member attribute a structural functionality to the building. The beam-column joint is a crucial part in the integrity of the structural members.

2.2 Numerical Modelling

There are a number of methods in which a blast load can be modelled. Namely the CONWEP modelling, MM-ALE modelling, SPH modelling, and few coupling methods of modelling a blast load. The air blast pressure is computed which is referrd to as:

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LOAD_BLAST_ENHANCED(LBE) in case of CONWEP modelling. In the MM-ALE modelling the air and the blast explosives are modeled explicitly. This is done by modeling a blast charge inside air. The blast charge is detonated inside the air domain and the impulse is tranfered through contact algorithms. It is found that the MM-ALE model is suitable for the contact blasts whereas for the far-field blasts this was not suitable. This was because primarily the MM-ALE though yielded very accurate results for contact blasts, was rendered cost heavy for close-in blasts. The time taken for the charge to interact with the structure was time intensive and needed high computational cost. Only for close-in blasts study MM-ALE was used.

2.2.1 Contact Explosion

In this type of blast loading the blast charge is kept in contact to the structural member for which the experiment or the simulation is to be conducted. In our case, i.e. the work in this study implemented a rectangular charge on the centre of the joint region as shown in the exterior joint below in figure 1. Simulations were carried in this study considering the knee, interior and the exterior joints where similar rectangular charges are kept to carry the study as in figure 1. Same weights of TNT charges and locations were chosen to carry a comparative response study of the different joints here. Charges were kept at the same location of the elements for all the types of the joints.

2.2.1 Close-in Explosion

The other type of simulations that were conducted in this study is the close-in explosions. A distance of 6m was kept between the TNT charge and the RC joints. Here also all the joints types namely the knee, exterior and the interior joints were conducted under the close-in explosion simulation. A self-explanatory diagram is shown in the figure2 below. The type of blast is an air blast where the blast waves hit the structure after hitting the surface of the earth.

3. Modeling

The numerical modeling of contact explosion effects and behavior of RC members was performed in LS-DYNA.

The lack of experimental work in the Reinforced concrete joints has led to validate our Finite Element (FE)

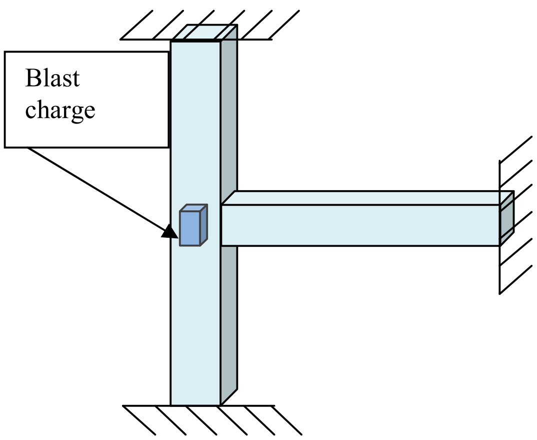

Fig1: Exterior joint under contact blast

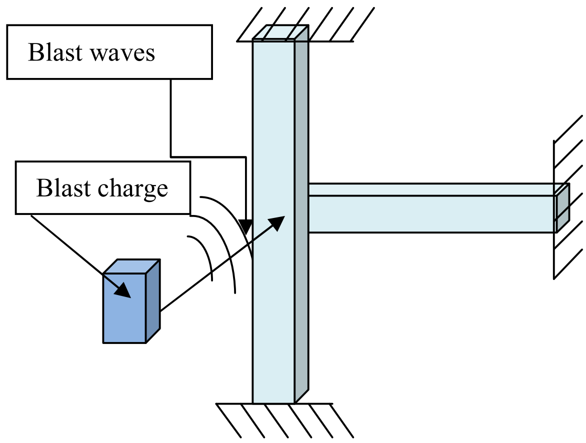

Fig2. Example of RC joint hit by a TNT charge from Close-in blast

models with FE models of other work of their experimental studies. An experimental column of [25] has been modeled as a part of the validation for the blast load generation, the responses of the blast on the structure and the material model generation. The previous work has been used for FE validation. A mesh size of 20-mm is being used for the concrete and the reinforcement as well. This size captured the results of the responses of the experimental work by [25]. The material properties for the air, concrete and the reinforcements are kept same as that of the [25].

3.1. Material models

3.1.1. Concrete

Mat_159 or MAT_CSCM_CONCRETE was chosen and implemented for modeling on concrete based on the results from a study by Dua et al. [26]; Dua and Braimah [27]. The material input parameters in the adopted unit system are presented in Table 1.

3.1.2. Reinforcement

The MAT_ PLASTIC_KINEMATIC, (Mat_003) constitutive model was adopted for modeling the reinforcement. The input parameters for the constitutive model adopted are presented in Table 2. The material properties of steel are as per the manufacturer.

3.1.3. Air and TNT for MM-ALE modelling

The MM-ALE formulation was adopted for modeling the air and explosive domains. In MM-ALE formulation the air domain is defined as MAT_NULL which

Table-1 Parameters of input for Mat_CSCM_CONCRETE

Density, Kg/m^3	Unconfined compressive strength, MPa	Aggregate size, m	Erosion criteria	Rate effects
2400	47.00	0.01	1.2	on

Table-2 Parameters of input for MAT_ PLASTIC_KINEMATIC

Density, Kg/m^3	Modulus of elasticity, MPa	Poisson's ratio	Yield strength, MPa	Tangent modulus, MPa
7850	2x10^{11}	0.3	400	1600

Table-3 Parameters of input for MAT_NULL

Density, Kg/m^3	Pressure cutoff
1.29	-1X10^{-6}

Table-4 Inputs for EOS_LINEAR_POLYNOMIAL

C_0	C_1, C_2, C_3, C_6	C_4 andC_5	E_O, MPa	V_O
-1X10^{-6}	0	0.4	0.2531	1

allows the equation of state (EOS) to be considered without computing deviatoric stresses. The linear polynomial EOS (EOS_LINEAR_POLYNOMIAL) defines the air domain and permits it to behave like a fluid. The pressure, P in an air element is given by Eq. (2)

$$P = C_0 + C_{1\mu} + C_{3\mu}{}^3 + (C_4 + C_{5\mu} + C_{6\mu}{}^2)E \qquad (2)$$

Where, C_0 to C_6 are polynomial equation coefficients and variable $\mu = \frac{\rho}{\rho_O} - 1$ (ρ is the reference density and ρ_0 is the current density). E is the internal energy and V_0 is the relative volume.

Input parameters for air are MAT_NULL and EOS_LINEAR_POLYNOMIAL in the adopted unit system are presented in Table 3 and 4.

The explosive domain was defined by the help of INITIAL_VOLUME_FRACTION keyword. The explosive material was defined with MAT_HIGH_EXPLOSIVE_BURN which allows the modeling of detonation of a high explosive when defined with an EOS. EOS_JWL was adopted for the detonation modeling which defines the pressure, p as Eq. (3)

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \qquad (3)$$

where, A, B are constants with units of pressure, E_0 is the detonation energy per unit volume, V_0 is the initial relative volume and R_1, R_2 & ω are unitless constants.

The input parameters for the above keywords required to define the explosive domain, material and the EOS are presented in Table 5, 6 and 7 respectively. CONTTYP 5 was used as the charge used as rectangular in shape. The dimension of the charge that was used was taken as 0.08x0.08x.12m in the x, y and the z directions respectively. The weight of the TNT charge maintained for the simulation according to the volume obtained.

Table-5 Input parameters for explosive domain INITIAL_VOLUME_FRACTION

CONTTYP
5

Table-6 Parameters of input for MAT_HIGH_EXPLOSIVE_BURN

Density Kg/m^3	Detonation velocity, mm/s	Chapman-Jouguet pressure, MPa
1400	6930	6.328X10^9

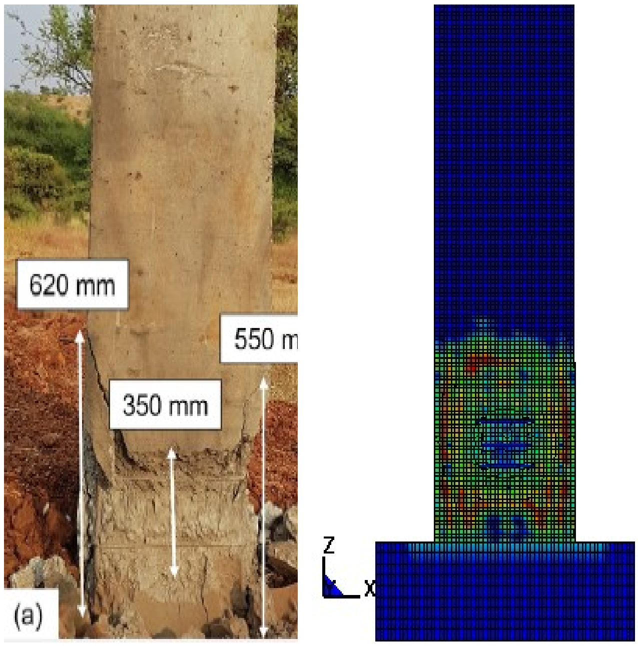

Fig3: Experimental [23] and Simulation comparison for validation

Table-7 Parameters of input for EOS_JWL

A	B	R1	R2	ω	EO	Vo
3.738x 10^{11}	3.747x 10^9	4.15	0.9	0.35	4.90x 10^6	1

3.2. Mesh sensitivity analysis

A mesh sensitivity analysis is conducted to find out the convergent mesh size for the simulations. Very coarse mesh or very fine meshes are not recommended as the results need to yield to the experimental results. Very coarse meshes will give vague results, whereas very fine meshes will also incur lot of computational costs on the program. So, mesh sizes of suitable configurations are chosen for the simulations. For the studies in this work, a mesh size of 20mm for the concrete and the reinforcement and mesh size of 50mm for the air is selected after iterations. This size has found out to have converged to the experimental model for validation purpose only.

3.2.1 Simulation of the experimental tests for mesh sensitivity simulations

For the validation purpose the experimental model of [25] has been simulated as follows. The erosion span of the rectangular column has been simulated and matched with the experiment as graphically represented in figure3.

4. Response of Reinforced concrete joints under the contact and close-in blast loads

It is important to understanding the failure loading mechanism of these reinforced concrete joints; namely the knee, exterior and the interior in mitigating the joint failure due to the various blast loads proximity. In this study we have tried to find out the cause of failure in the RC joints due to the above-mentioned loads, the contact and the close-in loads. Studies done on beams have shown that these various loads have impacted the beams in different ways. Close-in explosions have caused bending in the joint cores. Contact explosions have caused

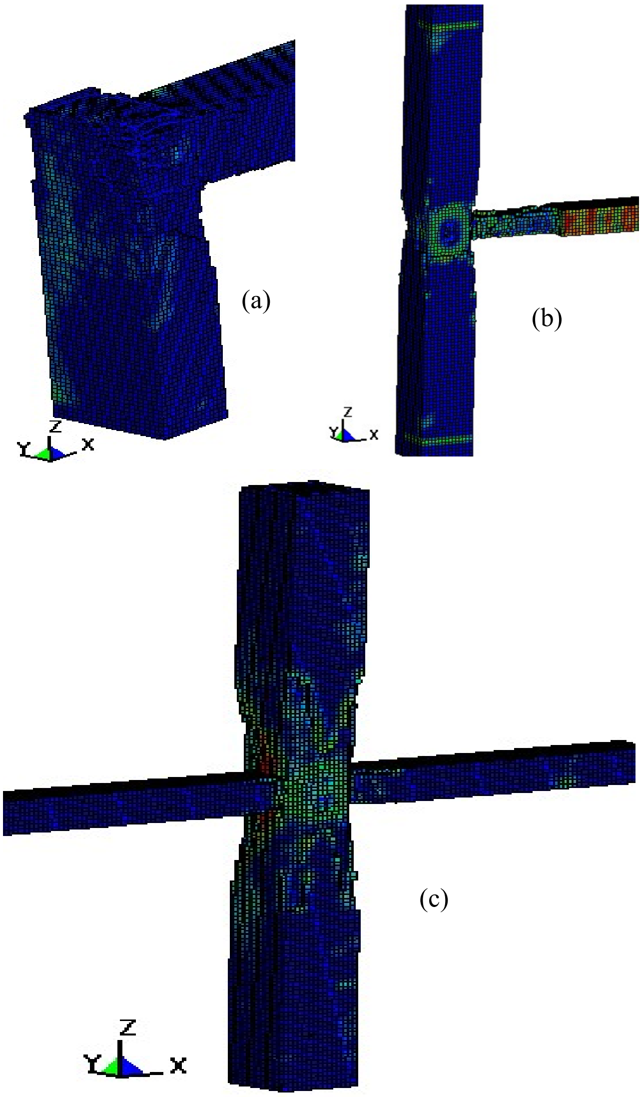

Figure 4: Reinforced joint response to Contact blast

4.1 Reinforced Concrete joints under Blast loads

failure of joints due to spallation of the joint core. This has motivated the study of the RC joints under blast loads of different distances.

The pressure loading of the blast loads on the reinforced concrete structures causes the pressure to increase suddenly to a peak and then instantly decreasing it to a negative level. Causing a compressive damage to the structure followed by spallation of the structure due to the tensile stresses as a result of suction [14], [23], [28]. The severity of the damage and the type of failure depends on the detonation energy of the explosion and also the standoff distance from the charge.

4.1.1 Contact blast loads

In close-in blasts, the blast pressure shape does not fall on the structure uniformly. The blast wave is more concentrated on the nearby area and thus causes spallation of the structure. In contact blasts the ratio of the loading duration to the natural frequency of the structure, t_d/T is

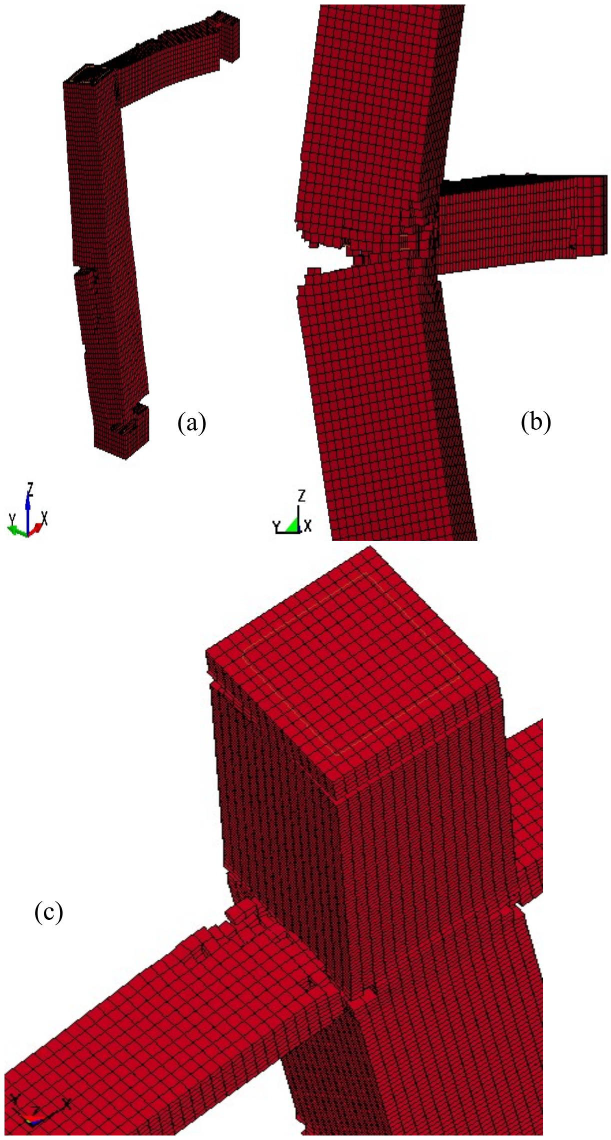

Figure5: Reinforced joint response to Close-in blast

smaller [29]. Literatures carried out on beams reported that localized failures such as spallation of concrete and fragmentation were caused [14] under contact blast loads.

4.1.2 Close-In blast loads

The structure tends to fail in global shear failure mode in direct or inclined shear failure propagating from the supports towards the impacted zones. For beam structures under far-field blast loads it is observed that blast loads can cause a global flexural failure with ductile deformations with flexural cracks [14].

The RC, joint in our case was found to bend in similar fashion as that of beams under close-in blasts, where its beams and column ends are fixed supported.

5. Results and Discussions

5.1. Reinforced concrete joints under contact blast loads

The reinforced concrete joints under contact blast loads acts differently than under the close-in blast loads. The concrete in the joints are failed due to the spallation which reduces the joint capacity. The spallation occurs at the face of the blast load. However, the other side of the joint is less susceptible to the stress, unless there is a progress in the blast loads. Which means the capacity is reduced in the RC joints due to the progress in the blast loads propagating towards the back of the RC joints. Figure 4. shows the joint under the contact blast load. Figure 4 (a) is a knee joint (b) is an exterior joint and (c) is an interior reinforced concrete joint under close-in blasts loads.

The fringes in the figure show the plastic strain in the RC joint of the concrete. The stress in the joint is captured and is responsible for the weakening of the joint capacity. As mentioned above, the study [Alok Dua] is used for the convergence of the simulation results; the erosion percentage is assumed to be at 2% when the elimination of the concrete and the reinforcement elements are reached.

The RC joint experiences merger spallation damage under the contact blast loading. It is because of the wind pressure being generated is disbursed in the various directions in the air under contact blasts. Only the direct pressure being generated scrapes away the concrete from the joint, creating a capacity failure of the joint.

5.2. Reinforced concrete joints under close-in blast loads

The blast load interaction in close-in is different from that of the other blast loads. In the close-in blast loads there is a tendency of the joint to have a global shear failure, shown in the figure 5(a)-(c). The blast load was applied at the core of the joint from a standoff distance. It is seen in the figures (b) and (c) that the joint core failed in shear at the cores and this propagated to the supports.

The RC joint is also under the influence of flexural load caused due to the non-uniformly distributed load of the close-in loads.

6. Conclusion

As seen in the report in the study, we have seen that the distances of the charge to the structure that is standoff distance play a major role in the type of failures the cause in case of blast loading. The failures that were recorded in the above report are due to spallation in interaction with close-in blast.

In case of blasts under close-in blasts, flexure and shear failures were caused to joint. Therefore, protecting our joints with honeycomb will be recommended to mitigate failure due to close-in blast loads. Also, designing the RC joint reinforcement for flexures is recommended.

Disclosures

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