Blast Effects on Reinforced Concrete Connections

Alireza Bahrami, Sina Matinrad

Abstract: This study is concerned with the blast effects on reinforced concrete (RC) connections. The RC connections are analysed nonlinearly. The analyses are conducted by applying the finite element software ABAQUS. The first step is to do the verification of the modelling. To achieve this goal, an experimental test performed on an RC connection is simulated utilising ABAQUS. Comparing the analysis result with the experimental test result establishes the modelling verification. In the second step, a 5-storey building is designed by the use of the ETABS software. A connection of the ground floor is selected for further analyses in ABAQUS. In the third step, the components of the selected connection are designed. Then, various variables are taken into account as the distance of the connection from the blast centre (2.5 m, 5 m, and 10 m) and the blast power (500 kg, 1000 kg, and 2000 kg TNT equivalent mass of explosive) for the further analyses of the connection. In the fourth step, the connection is analysed considering the variables. Finally, effects of these variables on the behaviour of the connection are investigated and discussed. Failure modes of the connections due to the blast loading are presented.

Index Terms: Beam, Blast, Column, Connection, Finite Element, Reinforced Concrete.

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1 INTRODUCTION

In general, blasting is the result of the rapid release of large amounts of energy in a limited space. The blasting creates sudden shock and compressive and tensile waves in the environment and also influences existing structures in its neighbourhood. Local structural damages due to the blasting may propagate into the structures and destroy them. On the other hand, terrorist threats and accidental explosions have been increasing which made the blast performance of structures become a significant structural design consideration for military and industrial structures to ensure safety of the workforces. The blast loads have considerable impacts in addition to structural collapses such as personal injuries and economic effects. Thus, the blast effects on structures have attracted special attentions of academic and industrial societies. Some researches have been done on the performance of connections and on the blast load impacts on connections [1-9]. However, study on RC connections subjected to the blast has been rare which has been performed in this paper. This study investigates the blast effects on RC connections. Nonlinear analyses of the RC connections are conducted employing the finite element software ABAQUS. An experimentally tested RC connection is modelled and its obtained result is compared with that of the experimental test which establishes the verification of the modelling. Using the ETABS software, a 5-storey building is designed. A connection of the ground floor is selected for further analyses in ABAQUS. The components of the connection are also designed. Variables for the nonlinear analyses of the connection are as the distance of the connection from the blast centre (2.5 m, 5 m, and 10 m) and the blast power (500 kg, 1000 kg, and 2000 kg TNT equivalent mass of explosive). The connection is analysed adopting the variables. Effects of these variables on the performance of the connection are assessed and discussed. Failure modes of the RC connections are evaluated.

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2 EXPERIMENTAL TESTING OF RC CONNECTION

To demonstrate the modelling accuracy of the RC connection, an experimental test done on an RC connection [10] was considered for the nonlinear analyses. Fig. 1 presents details of the tested specimen. Poisson's ratio of the concrete and reinforcements are 0.2 and 0.3, respectively. The yield stress of the longitudinal reinforcements of the RC beam and column, f_y, is 507 MPa, and the yield stress of their stirrups, f_y, is 384 MPa. The Young's modulus of the reinforcements is 200 GPa.

3 ACCURACY OF MODELLING OF RC CONNECTION

The mechanical properties of the concrete and steel materials in the modelling were considered to be exactly as the same as those of the experimentally tested specimen. Material modelling of the steel and concrete is an essential part of the finite element modelling [11,12,13]. The steel has been considered to have bilinear kinematic hardening behaviour to adopt progressive hardening and softening effects [14]. The three-dimensional (3D) concrete damage plasticity model has been used to model the concrete [15]. The 3D solid element C3D8R was utilised to model the concrete. The truss element T3D2 was used to model the longitudinal and transverse reinforcements. The contact surface between the concrete and reinforcements was applied by using the Embedded Region. By this constraint, it can be possible to insert a portion of one model with the help of a host region (or the whole model) into another region. For this purpose, a friction coefficient should be taken into account. The coefficient of friction between the steel and concrete has been adopted as 0.3 in this study. The loading of the experimental test has been simulated using the displacement loading based on the code [16]. Also, the support conditions of the experimental test have precisely been simulated in the modelling. A convergence study has been carried out on the connection using different mesh sizes. Finally, the mesh size which achieved more exact results was selected for the modelling. Fig. 2 shows the simulated RC connection. The result obtained from the modelling is plotted as the force-displacement graph. The modelling result is compared with the experimental test result (Fig. 3). As it can be seen from Fig. 3, the maximum strength of the specimen in the experimental test is 24.6 kN with the displacement of 72 mm while the maximum strength of the model is 24.8 kN with the displacement of 70 mm. As a consequence, it uncovers that the difference between the results obtained from the model and the experimental test is less than 1%. In addition, by comparing the graphs in the figure it can be observed that the graphs behave similarly.

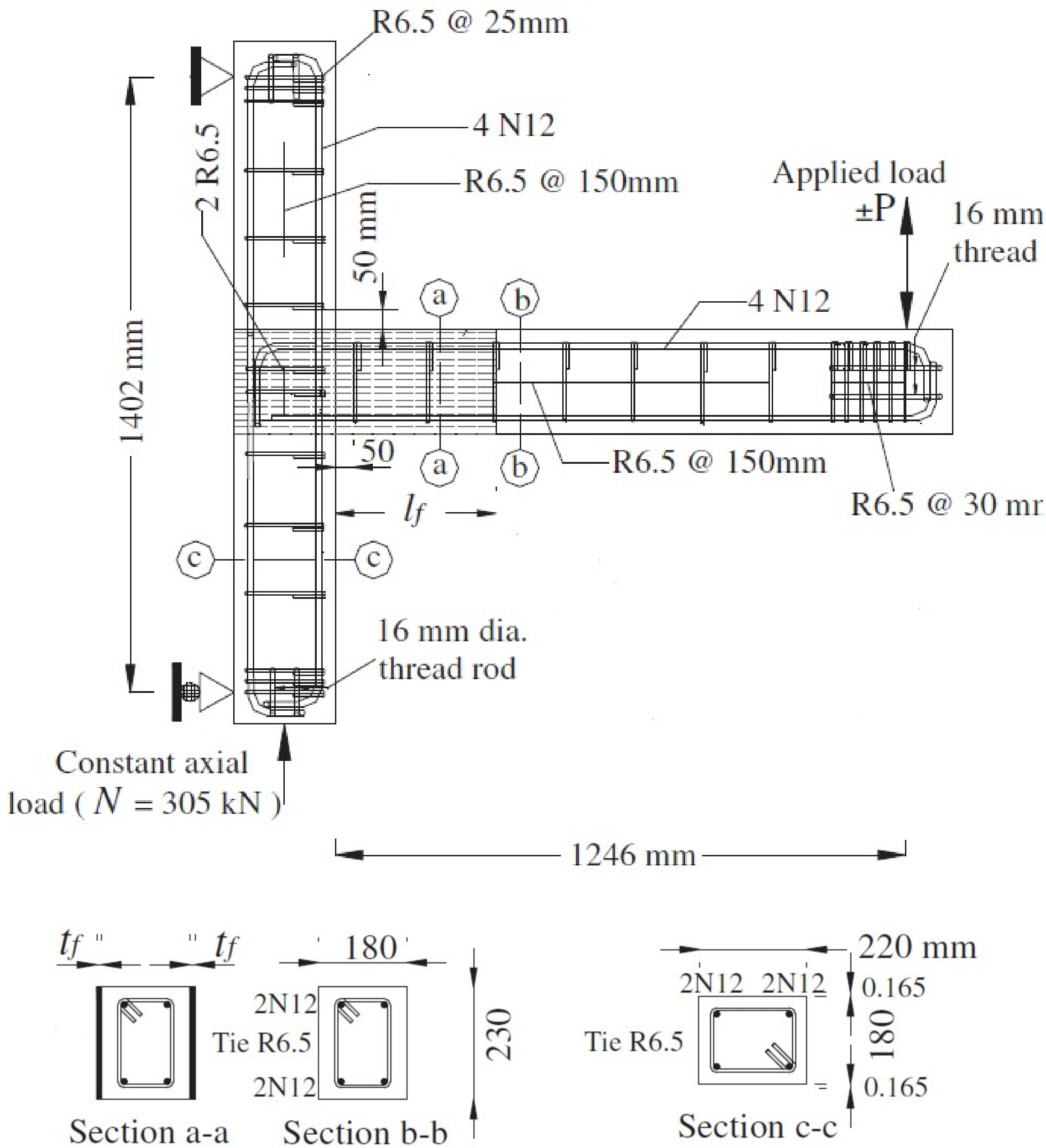

Fig. 1 *Details of experimentally tested specimen [10]*

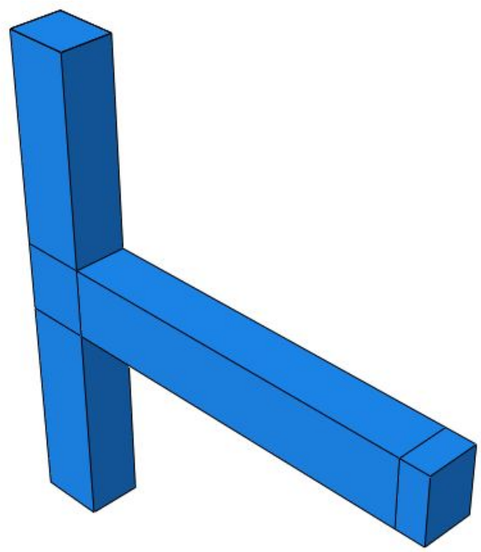

Fig. 2 *Simulated RC connection*

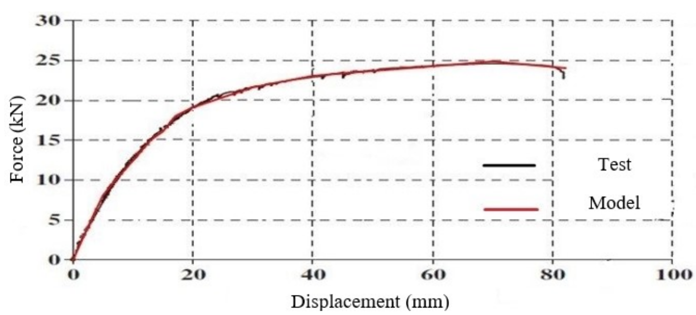

Fig. 3 *Comparison of obtained results from modelling and tested specimen*

Therefore, owing to the very small difference between the results obtained from the modelling and the experimental testing and their similar behaviour, it can be concluded that the finite element modelling of the experimental specimen has been done correctly and the modelling has been verified. Consequently, the proposed finite element modelling is perfectly capable of predicting the performance of the RC connections.

4 DESIGN OF BUILDING USING ETABS SOFTWARE

A 5-storey building with the storey height of 3 m and 5 equal spans of 4 m in both planar directions perpendicular to each other has been designed using the ETABS software to design RC connections. Since the most critical floor of the building against the surface blasting is its ground floor due to its proximity to the blast centre, a connection from the ground floor has been selected for further analyses.

5 ANALYSIS OF RC CONNECTIONS USING ABAQUS SOFTWARE

In order to model the RC connection, the number and size of longitudinal reinforcements and stirrups have been calculated based on the code ACI 318-10 applying the ETABS results. The obtained cross-sections for the beam and column are 40 × 45 cm and 50 × 50 cm, respectively. Fig. 4 presents details of the designed RC connection. Features of the reinforcements of the beam and column have been summarised in Table 1. Poisson's ratios of the concrete and reinforcements have been considered as 0.2 and 0.3, respectively. The pre-mentioned specifications of the tested specimen have been adopted in the simulation utilising the ABAQUS software. TNT is known as one of the most commonly used explosives which is employed alone or with other explosives in blasts. In general, TNT is considered as a reference for other explosives which means that when a strong explosive is other than TNT, its equivalent energy can be obtained using the explosive coefficient. The coefficient of an explosive to convert it to its equivalent TNT is defined as below:

$$C.F = \frac{explosive\ mass}{TNT\ equivalent\ mass}$$

Conwep as an acronym of Conventional Weapons is a method of calculating the effect of an explosion on a target. This calculation is based on the distance between the target and explosive and the mass equivalent to the explosive. This is one of the numerical methods for the analysis. Conwep can be used in the ABAQUS software to apply blast loads. For this purpose, it is necessary to introduce the following issues in the software:

- the point where the explosion occurs,
- the surface on which the explosion pressure should be applied,
- and the weight of the explosive as the TNT equivalent mass.

Since Conwep has a great accuracy, it has been used in this study to model the blast loading on the building.

6 RESULTS AND DISCUSSIONS

The RC connections were modelled considering the mentioned variables as the distance of the connections from the blast centre (2.5 m, 5 m, and 10 m) and the blast power (500 kg, 1000 kg, and 2000 kg TNT equivalent mass of explosive). The results obtained from the analyses of the connections are presented herein. Effects of these variables on the performance of the connections are also compared and discussed.

6.1 Effect of Distance of Connection from Blast Centre

The modelled connection was subjected to 1000 kg TNT blast load at different distances of 2.5 m, 5 m, and 10 m to investigate the effect of varying the blast centre distance from the connection on its performance. The forces applied to the connection due to the blasting at the mentioned distances have been plotted in Fig. 5. As can be seen from the figure, these forces decreased with increasing the distance of the blast centre from the connection, however, this decrease is not linear. Table 2 lists the maximum stresses occurred in the connection region which have been obtained from the analyses.

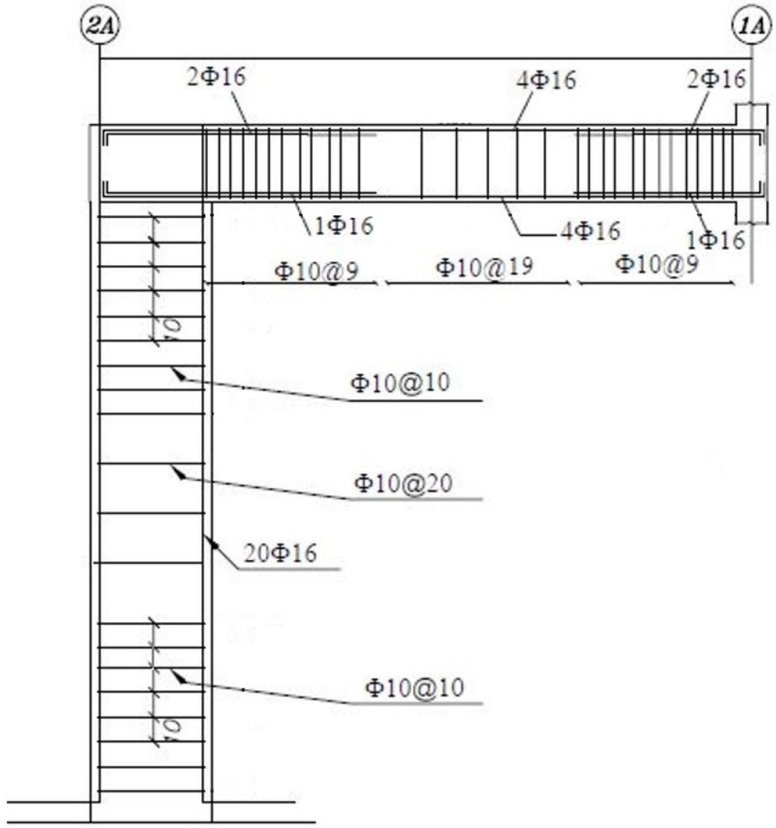

Fig. 4 *Details of designed RC connection for 5-storey building (Units are in mm)*

Table 1 *Features of RC connection*

Member	Cross-section (cm)	Reinforcement (mm)
Beam	40 × 45	$4\varphi_{16}$ (longitudinal reinforcement) φ_{10} (stirrup)
Column	50 × 50	$20\varphi_{16}$ (longitudinal reinforcement) φ_{10} (stirrup)

It can be noticed that the maximum stress values in the connection have been decreased by the distance increase. Meanwhile, the maximum force applied to the connection due to the blast loading decreases 66.7% as the distance of the connection from the blast centre increases from 2.5 m to 10 m (Fig. 5) and also the decrease of the applied maximum stress for the same distance increase is 21.3% (Table 2). As a result, the distance of the connection from the blast centre is one of the main variables in estimating the impact of the blast forces and stresses on the connection.

6.2 Failure Modes of RC Connections

The failure modes of the connections by the blast loading of 1000 kg TNT at 2.5 m and 10 m distances are presented in this section. Figs. 6 and 7 illustrate the cracks in the concrete which demonstrate the concentration of the stresses on the concrete and reinforcements of the beams and columns of the connections. According to the above results and the figures, the increase of the blast distance from the connections sharply decreases the concrete damage of the connections and also reduces the stresses in the reinforcements.

6.3 Effect of Blast Power on Connection

In this section, 500 kg, 1000 kg, and 2000 kg TNT have been placed at 5 m distance from the connection. The results of the analyses have been plotted in Fig. 8. The figure shows that increasing the TNT masses at a constant distance from the connection (5 m) increases the forces applied to the connection. However, this is a nonlinear increase of the applied forces. The maximum stresses in the connection corresponding to the different TNT masses have been summarised in Table 3. The stress values in the table illustrate that increasing the TNT masses at 5 m distance from the connection increases the maximum stresses created in the connection. According to the table, 4-fold increase of TNT mass from 500 kg to 2000 kg leads to the stress increase from 435 MPa to 546 MPa which uncovers 25.5% increase of the stress in the connection. Accordingly, this 4-fold increase of the TNT mass does not result in a very huge increase of the stress in the connection. However, the explosive mass is an important factor in evaluating the forces and stresses applied to the connection.

6.4 Failure Modes of RC Connections

Figs. 9 and 10 present the failure modes of the connections by the blast load of 500 kg and 2000 kg TNT at 5 m distance from the connections. The figures demonstrate the concentration of stresses on the beams and columns of the connections which result in the concrete cracks. As can be seen from the figures, increasing the blasting masses for the constant distance of 5 m increases the stress concentration that leads to the damage of the connections.

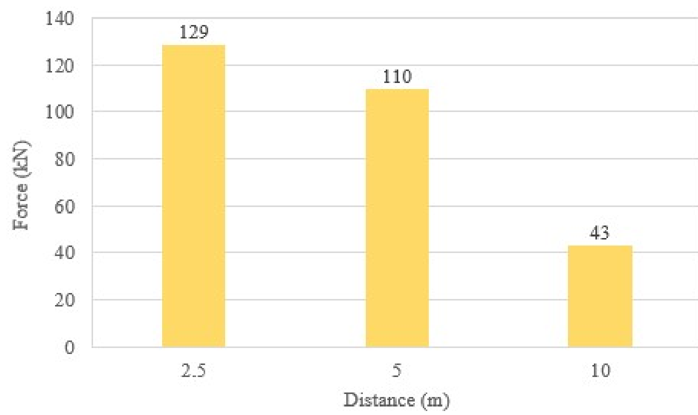

Fig. 5 *Forces applied to RC connection due to blasting at different distances*

Table 2 *Maximum stresses in RC connection*

Distance (m)	Maximum Stress (MPa)
2.5	550
5	484
10	433

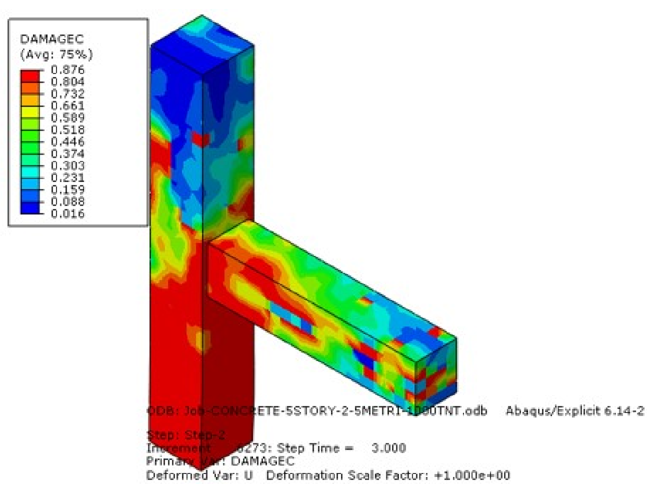

Fig. 6 *Concrete cracks caused by blasting 1000 kg TNT at 2.5 m distance*

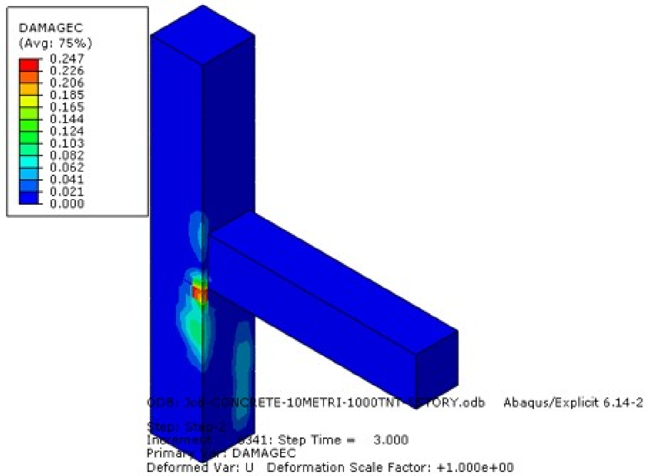

Fig. 7 *Concrete cracks caused by blasting 1000 kg TNT at 10 m distance*

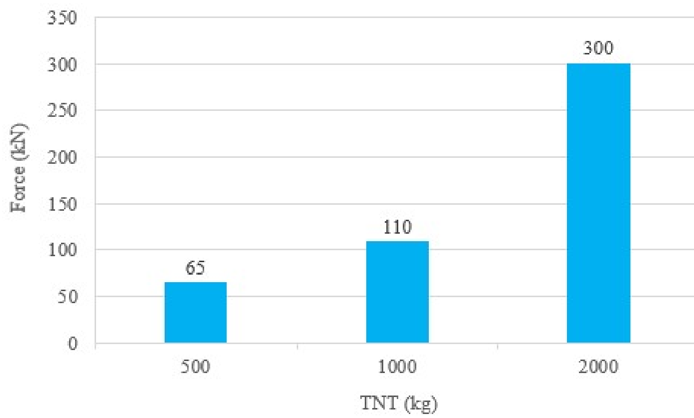

Fig. 8 *Forces applied to RC connection due to blasting with different TNT masses*

Table 3 *Maximum stresses in RC connection*

TNT Mass (kg)	Maximum Stress (MPa)
500	435
1000	484
2000	546

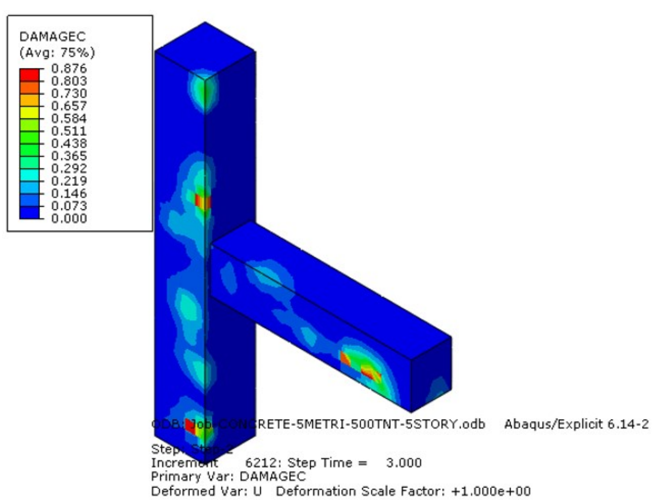

Fig. 9 *Concrete cracks caused by blasting 500 kg TNT at 5 m distance*

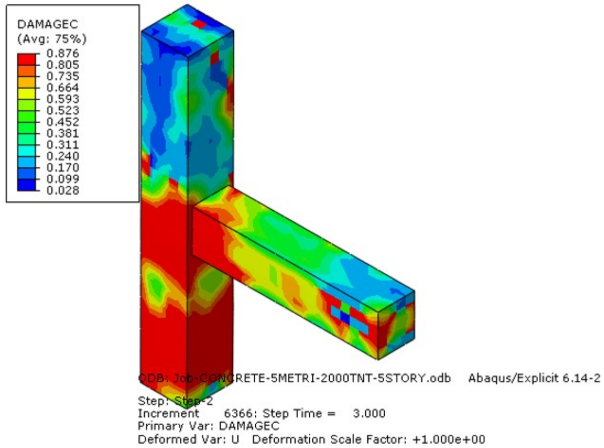

Fig. 10 *Concrete cracks caused by blasting 2000 kg TNT at 5 m distance*

7 CONCLUSIONS

In this study, the blast effects on the RC connections were investigated. The finite element software ABAQUS was employed to do the analysis of the connections. An experimentally tested RC connection was modelled to uncover the modelling verification. The modelling accuracy was carried out by comparing the results from the modelling analysis with the experimental test. Then, the ETABS software was used to design a 5-storey building. A connection of the ground floor was analysed using ABAQUS. Various variables were taken into account as the distance of the connection from the blast centre (2.5 m, 5 m, and 10 m) and the blast power (500 kg, 1000 kg, and 2000 kg TNT equivalent mass of explosive). Effects of these variables on the performance of the connection were discussed. It was found that the maximum forces and stresses applied to the connections have been reduced by the increase of the connection distance from the blast centre. Also, increasing the TNT masses at a constant distance from the connection increases the maximum stresses and forces created in the connections. Failure modes of the connections owing to the blast loading were presented.

REFERENCES

[1] N. W. Hanson and H. W. Connor, “Seismic resistance of reinforced concrete beam-column joints,” Journal of the Structural Division, vol. 93, no. 5, pp. 533-560, 1967.
[2] R. Park and T. Paulay, “Reinforced concrete structures,” John Wiley & sons, 1975.
[3] D. F. Meinheit and J. O. Jirsa, “Shear strength of RC beam-column connections,” Journal of the Structural Division, vol. 107, pp. 2227-2244, 1981.
[4] T. Krauthammer, “Blast-resistant structural concrete and steel connections,” International Journal of Impact Engineering, vol. 22, no. 9–10, pp. 887-910, 1999.
[5] J. M. LaFave, “Behavior and design of reinforced concrete beam-column connections with wide beams,” Proceedings of the Structures Congress, American Society of Civil Engineers, Washington, D.C., United States, 2001.
[6] C-C Chen and K-T Lin “Behavior and strength of steel reinforced concrete beam–column joints with two-side force inputs,” Journal of Constructional Steel Research, vol. 65, no. 3, pp. 641-649, 2009.
[7] I. Fadwa, T. A. Ali, E. Nazih and M. Sara, “Reinforced concrete wide and conventional beam-column connections subjected to lateral load,” Engineering Structures, vol. 76, pp. 34-48, 2014.
[8] M. A. Najafgholipour, S. M. Dehghan, A. Dooshabi and A. Niroomandi, “Finite element analysis of reinforced concrete beam-column connections with governing joint shear failure mode,” Latin American Journal of Solids and Structures, vol. 14, pp. 1200-1225, 2017.
[9] B-O-B Sentosa, Q-B Bui, O. Ple, J-P Plassiard and P. Perrotin, “Assessing damage to beam-column connections in reinforced concrete structures from vibrational measurement results,” Structural Engineering International, vol. 29, no. 3, pp. 396-403, 2019.
[10] S. S. Mahini and H. R. Ronagh, “Web-bonded FRPs for relocation of plastic hinges away from the column face in exterior RC joints,” Composite Structures, vol. 93, no. 10, pp. 2460-2472, 2011.
[11] A. Bahrami, W. H. Wan Badaruzzaman and S. A. Osman, “Structural behaviour of tapered concrete-filled steel composite (TCFSC) columns subjected to eccentric loading,” Computers and Concrete, vol. 9, no. 6, pp. 403-426, 2012.
[12] A. Bahrami, W. H. Wan Badaruzzaman and S. A. Osman, “Investigation of concrete-filled steel composite (CFSC) stub columns with bar stiffeners,” Journal of Civil Engineering and Management, vol. 19, no. 3, pp. 433-446, 2013.
[13] A. Bahrami, W. H. Wan Badaruzzaman and S. A. Osman, “Numerical study of concrete-filled steel composite (CFSC) stub columns with steel stiffeners,” Latin American Journal of Solids and Structures, vol. 11, pp. 683-703, 2014.
[14] A. Bahrami and S. Matinrad, “Response of steel beam-to-column bolted connections to blast loading,” International Journal of Recent Technology and Engineering, vol. 8, no. 3, pp. 3639-3648, 2019.
[15] A. Bahrami and M. Yavari, “Hysteretic assessment of steel-concrete composite shear walls,” International Journal of Recent Technology and Engineering, vol. 8, no. 2, pp. 5640-5645, 2019.
[16] ATC-24, “Guidelines for seismic testing of components of steel structures,” Report 24, Applied Technology Council, Redwood City: CA, 1992.