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STRESS CONCENTRATION IN REINFORCED CONCRETE CONNECTIONS SUBJECTED TO BLAST LOADS

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ABSTRACT

Investigating the stress concentration in reinforced concrete connections under the blast loads is the purpose of the present paper. This goal was achieved by the design and analysis of the connections. The finite element package ABAQUS was used in this study to model and analyse the connections. A reinforced concrete connection which was tested experimentally was modelled and analysed in order to verify modelling. The results of modelling and experimental test were compared which demonstrated the accuracy of modelling. Afterwards, two reinforced concrete buildings with five and nine storeys were designed employing the ETABS software. A beam-column connection of the ground floor of each building was designed. The sizes of the cross-sections of the beams and columns and the spaces of their stirrups were considered differently. These connections were also modelled and analysed. The distances of the connections from the blast centre were considered as 2.5 m, 5 m, and 10 m and the blast powers were adopted as 500 kg, 1000 kg, and 2000 kg TNT equivalent mass of explosive for the analyses of the connections. The stresses created in the reinforcements of the connections owing to the blast loads were examined. It was demonstrated that as the connection was located farther from the blast centre, the stresses in the connection reinforcements were reduced. Also, the stresses in the connection reinforcements were increased by enhancing the blast power. Meanwhile, using larger cross-sections for the beam and column in the connection of nine-storey building than the connection of five-storey building transferred the stress concentration in the reinforcements to the beam and near the beam-column connection. By decreasing the stirrups spaces of the beam in the connection of five-storey building, the high stresses in the reinforcements were mainly transferred to the beam of the connection which could reduce the likelihood of the progressive collapse of the structure.

Keywords: reinforced concrete connection, stress, blast load, finite element, reinforcement.

1. INTRODUCTION

Many reinforced concrete structures exist in the world. These structures might be subjected to explosions as dynamic load. Civilian accidents, detonating high explosives, or weapons effects can cause the explosions which lead to extreme loads on neighbouring objects. Also, tremendous damage and loss of life may be made by the explosions occurring near buildings and structures. The immediate effect of these explosions can be the blast overpressures which propagate through the atmosphere. When the dynamic response of such structures is concerned, usually the effects of the blast overpressures are the governing load [1].

Reinforced concrete connections and blast loading have been evaluated through some research projects [2 - 12]. Whilst, stress concentration in blast-loaded reinforced concrete connections is assessed in the current study.

Reinforced concrete connections were subjected to different situations of blast loads in this study in order to examine their stress concentration. An experimental testing and finite element modelling of the reinforced concrete connections using ABAQUS are described. Since the modelling method of the connections was appropriately verified, the method was adopted for further analyses of the connections. ETABS was used to design two reinforced concrete buildings with five and nine storeys. Also, two beam-column connections of the ground floor of the buildings were designed. ABAQUS was utilised to model and analyse these connections as well. The connections were subjected to the blast powers as 500 kg, 1000 kg, and 2000 kg TNT equivalent mass of explosive loads at different distances as 2.5 m, 5 m, and 10 m from the blast centre. The stresses created in the reinforcements of these connections were obtained from the results of the analyses.

2. METHOD

The method of this research is described herein. This section includes verification of modelling, design of the buildings and blast loading, and also development of the connection.

2.1 Verification of Modelling

A reinforced concrete connection was experimentally tested [7] and selected for the verification of modelling [11, 12]. Figure-1 shows the details of the tested specimen. The yield stresses of longitudinal reinforcements and stirrups were 507 MPa and 384 MPa, respectively. Poisson's ratios of concrete and reinforcements were 0.2 and 0.3, respectively. The modulus of elasticity of reinforcements was 200 GPa.

ARPN Journal of Engineering and Applied Sciences

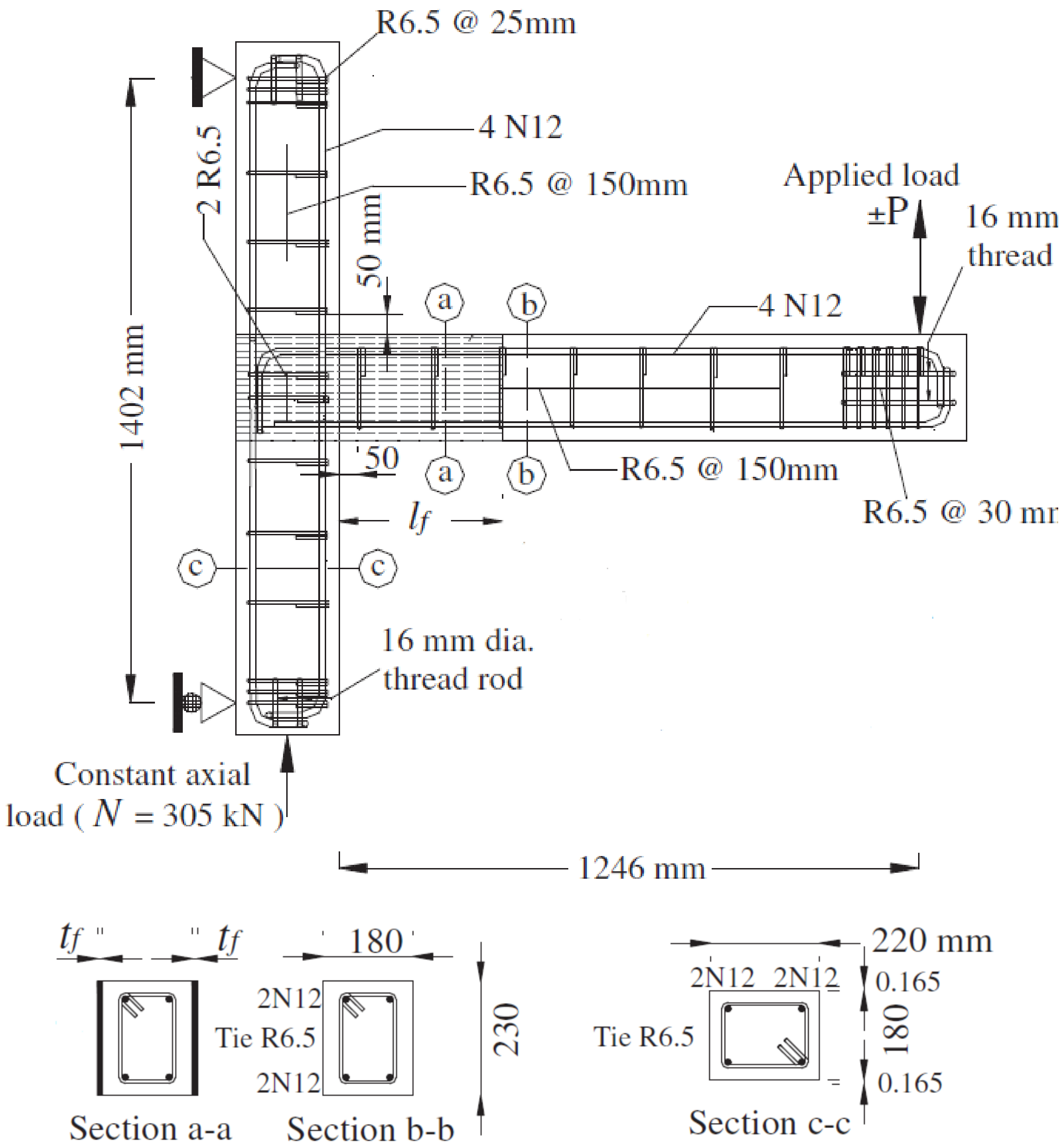

Figure-1. Details of tested specimen [7].

The aforementioned characteristics and the illustrated details in Figure-1 were considered in modelling using ABAQUS. The materials of the connection needed to be modelled completely [13]. The three-dimensional concrete damage plasticity model [14] and the bilinear model [15] were respectively adopted to model the constitutive behaviour of concrete and steel materials. The solid element C3D8R and the truss element T3D2 were respectively used to model the elements of concrete and reinforcements. The contact surface between concrete and reinforcements was modelled by the Embedded Region. The same loading and boundary conditions as the tested connection were considered in modelling. From the convergence study performed on the mesh size of the connection, the optimised mesh size was selected for modelling. Then, the model was analysed and its result was compared with the experimental test result. It was revealed that the obtained results were very similar to each other which verified the modelling method of the connection [11, 12]. Consequently, the verified modelling method was employed to model the developed connections in this research.

2.2 Design of Buildings and Blast Loading

To study the stress concentration in blast-loaded reinforced concrete connections, two reinforced concrete buildings with five and nine storeys were designed with the storey height of 3 m and five equal spans of 4 m in both planar directions perpendicular to each other based on the code ACI 318-10 utilising the ETABS software. A

ARPN Journal of Engineering and Applied Sciences

connection of the ground floor was selected from each building for the analysis under the blast loading because the most critical floor of the building against blasting is its ground floor owing to its proximity to the blast centre. The achieved results from ETABS were used to design the components of the selected connections including the number and size of longitudinal reinforcements and stirrups based on ACI 318-10 [11, 12]. Table-1 lists the characteristics of the beams and columns of the buildings. Poisson's ratios of concrete and reinforcements for the buildings were considered as 0.2 and 0.3, respectively.

The physical properties of the explosion source affect the observed features of air blast waves. A typical blast pressure profile is illustrated in Figure-2. Following the explosion, t_A is the arrival time when the pressure suddenly increases to a peak value of overpressure P_{so} over the ambient pressure P_o. Then, P_{so} decays to P_o at the time t_A+t_d and afterwards decays further to an under pressure P_{so}^- which creates a partial vacuum before returning to P_o at the time t_A+t_d+t_d^- [16, 17].

Table-1. Characteristics of reinforced concrete connections in five and nine-storey buildings [11, 12].

Building	Member	Size (cm)	Reinforcement (mm)
Five-storey building	Beam	40 × 45	4ϕ16 (longitudinal reinforcement) ϕ10 (stirrup)
	Column	50 × 50	20ϕ16 (longitudinal reinforcement) ϕ10 (stirrup)
Nine-storey building	Beam	50 × 55	4ϕ18 (longitudinal reinforcement) ϕ10 (stirrup)
	Column	65 × 65	20ϕ22 (longitudinal reinforcement) ϕ10 (stirrup)

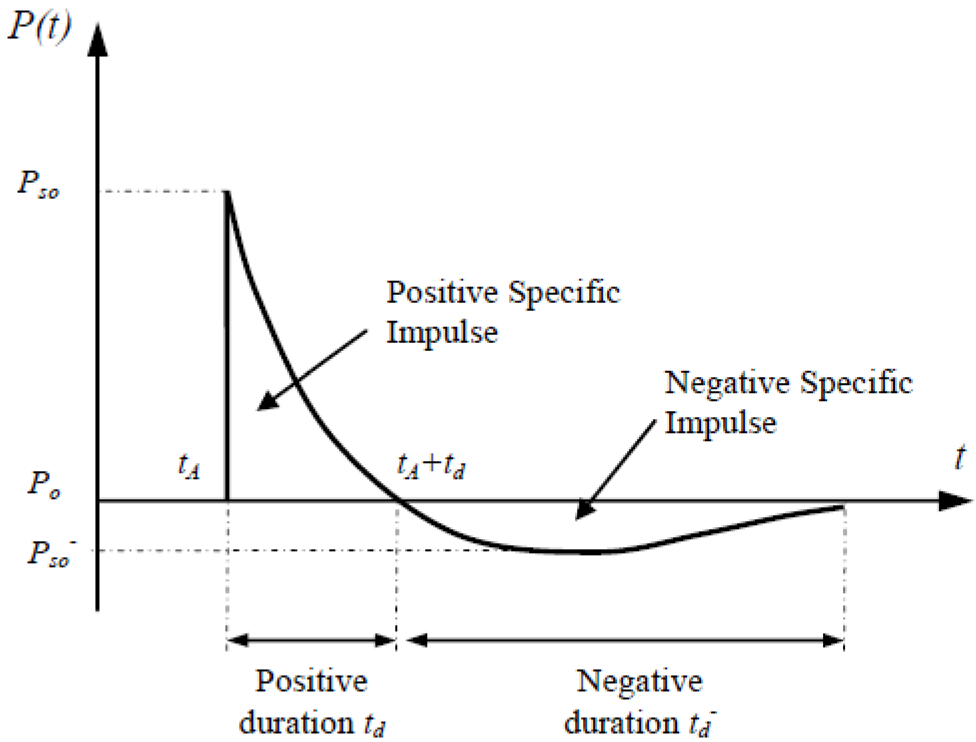

Figure-2. Blast wave pressure - time history [16].

To apply blast loads to the connections in ABAQUS, the Conwep method was utilised. The effect of an explosion on a target can be determined by the use of the Conwep method in ABAQUS based on the distance between them and the mass equivalent to the explosive. To implement Conwep, the explosion centre was introduced in the software. Since the explosion pressure was supposed to apply to a surface, the surface was also determined. Moreover, the weight of the explosive as the TNT equivalent mass was considered. When a strong explosive is other than TNT (as the reference for other explosives), its equivalent energy can be obtained utilising the coefficient of the explosive as below:

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

2.3 Development of Connection

Three reinforced concrete connections were designed [12]. These reinforced concrete connections (C1, C2, and C3) were modelled using ABAQUS taking all the above-mentioned details and characteristics into consideration (Figure-3). C1 and C2 were the connections for five and nine-storey buildings, respectively. C3 was like C1, but the stirrups spaces in the beam and column of C3 were half of those in C1. Characteristics of C1, C2, and C3 were as the same as those of the connection explained previously.

3. RESULTS AND DISCUSSIONS

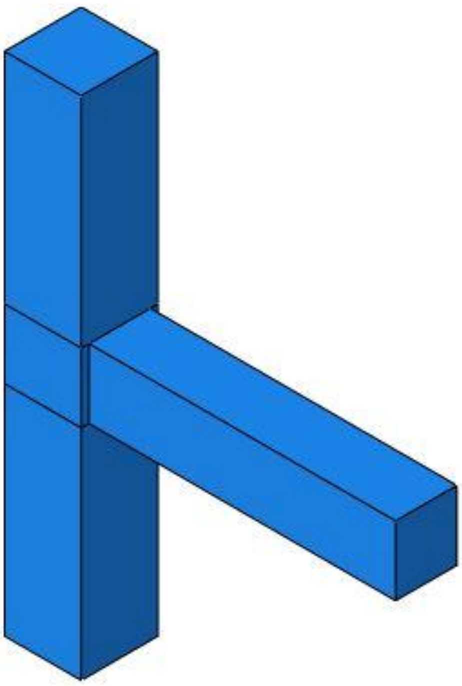
The designed and modelled connections C1, C2, and C3 were nonlinearly analysed under the blast loading using ABAQUS to examine the stress distribution in their reinforcements. The obtained results are presented and discussed in the following.

3.1 Effect of Connection Distance from Blast Centre on Stress in Connection Reinforcements

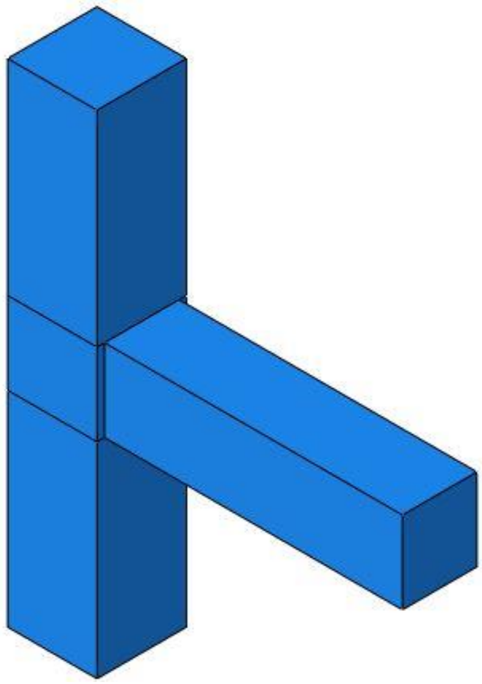
Figures 4-6 show the effect of distance of connection C1 from the blast centre on the stress in the connection reinforcements. It can be witnessed from the figures that the stresses in reinforcements were decreased as the connection distance from the blast centre was increased from 2.5 m, to 5 m and 10 m. The maximum stresses in reinforcements were obtained about 426 MPa, 410 MPa, and 279 MPa for the connection subjected to 1000 kg TNT blast load respectively at distances of 2.5 m, 5 m, and 10 m. This issue implies the nonlinear increase of the stresses in the connection reinforcements.

3.2 Effect of Blast Power on Stress in Connection Reinforcements

The effect of the blast power on the stress in the connection reinforcements (C1) is illustrated in Figures 7 and 8. As can be seen from the figures, enhancing the TNT masses from 500 kg to 2000 kg at a constant distance of 5 m from the connection increased the stresses in the reinforcements which can also enhance the collapse risk of the structure.



(a)



(b)

Figure-3. Connections [12]: a) C1 and C3, b) C2.

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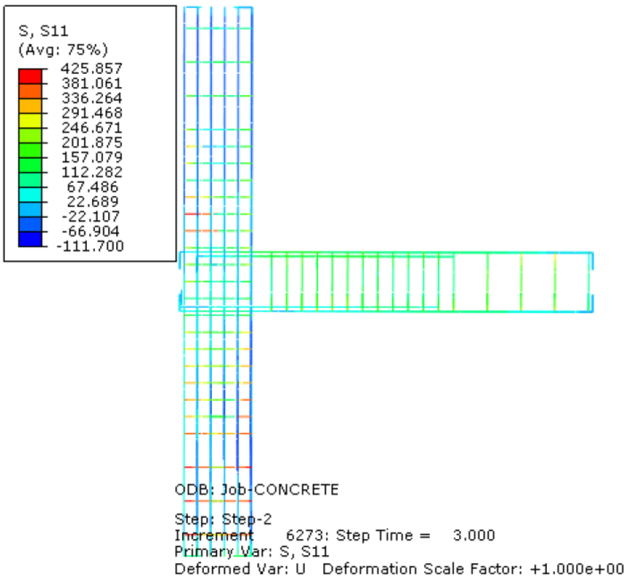

Figure-4. Stress distribution in connection reinforcements caused by blasting 1000 kg TNT at 2.5 m distance.

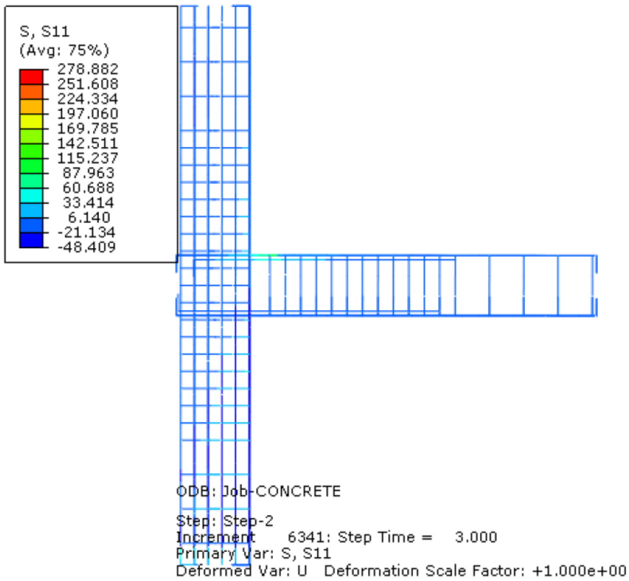

Figure-6. Stress distribution in connection reinforcements caused by blasting 1000 kg TNT at 10 m distance.

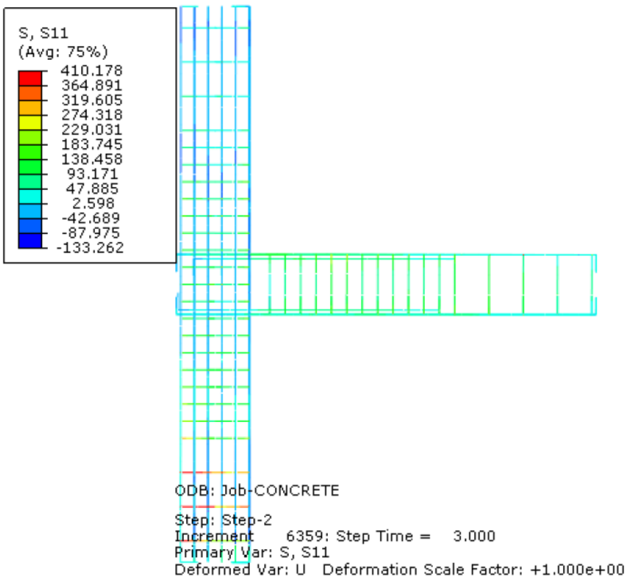

Figure-5. Stress distribution in connection reinforcements caused by blasting 1000 kg TNT at 5 m distance.

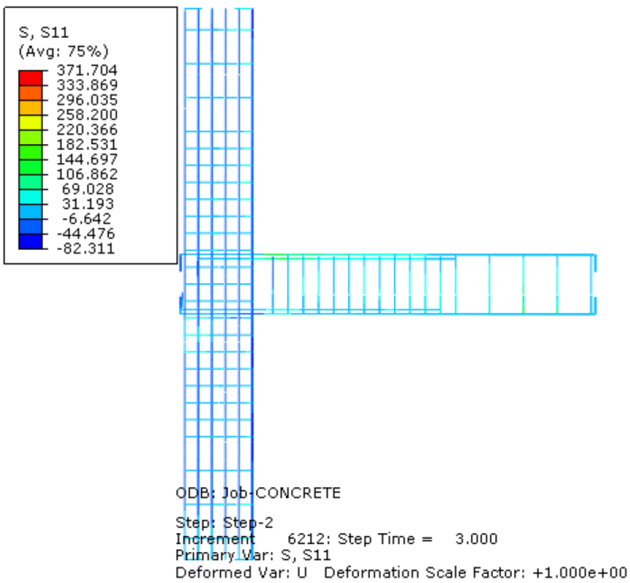

Figure-7. Stress distribution in connection reinforcements caused by blasting 500 kg TNT at 5 m distance.

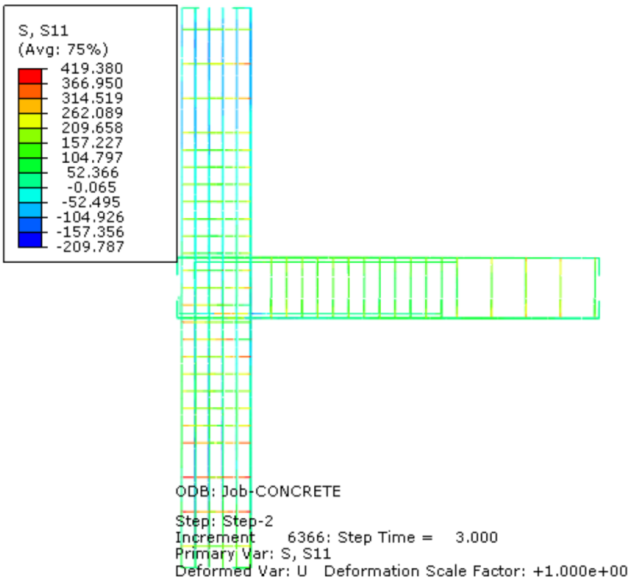

Figure-8. Stress distribution in connection reinforcements caused by blasting 2000 kg TNT at 5 m distance.

3.3 Failure Modes of Connections Based on Stress Distribution in Connection Reinforcements

Failure modes of the connections under the blast loads are investigated in this section. The stress concentration in reinforcements of C1 was on the bottom of the column (Figure-5) so that it could lead to the sudden removal of the column member from the structure which could also result in the sudden collapse of the structure. However, the stress concentration in reinforcements was transferred to the beam and near the beam-column connection in C2, as indicated in Figure-9. This issue was because of using larger cross-sections for the beam and column in C2 in nine-storey building than C1 in five-storey building which accomplished the increased moment of inertia and stiffness of the column and beam in C2. On the other hand, the maximum reinforcement stress of about 410 MPa in C1 was decreased to about 402 MPa by using C2. Moreover, the stress concentration in C3 (Figure-10) with the maximum stress of about 553 MPa was more on the beam than column in C1, because the stirrups spaces of the beam were reduced in C3. In C3, due to the concentration of stresses in reinforcements of the beam, first the beam fails while in C1 owing to the concentration of stresses in reinforcements of the column, first the column fails. As a consequence, failure of the column prior to the beam in C1 could largely be prevented by the decrease of the spaces of the beam stirrups in C3. With regard to the point that if in the design of connections especially in reinforced concrete frames, the plastic hinge could be transferred to the out of the connection area, then the performance of the system would be better, thus by reducing the spaces of the beam stirrups in C3, the performance of the structure would be more desirable than C1 owing to the place of the plastic hinge formation in the beam. This point accomplishes lower risk of the progressive collapse of the building structure.

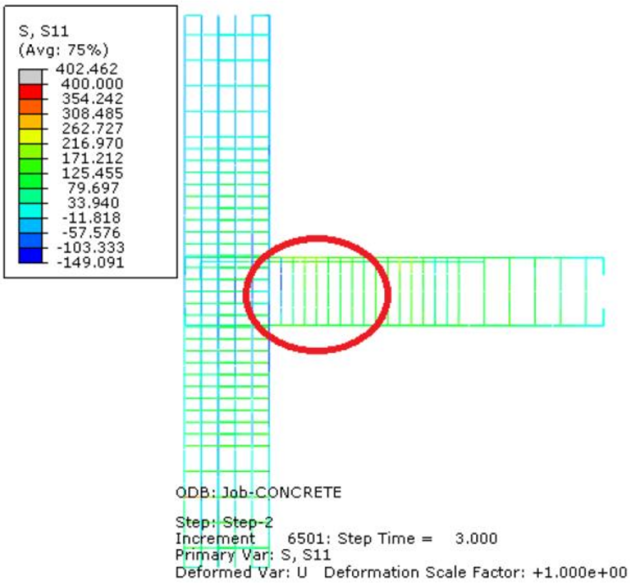

Figure-9. Failure mode of C2.

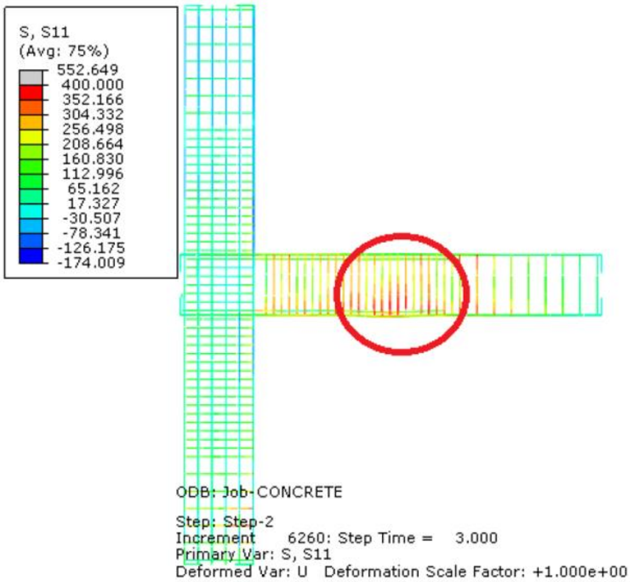

Figure-10. Failure mode of C3.

4. CONCLUSIONS

This paper focused on the stress states in the reinforced concrete connections subjected to the blast loads. Modelling and analysis of the connections were conducted using the ABAQUS software. The modelling method was verified. The design of two reinforced concrete buildings with five and nine storeys were done utilising the ETABS software. Then, a beam-column connection of the ground floor of each building was designed. ABAQUS was used to model and analyse the connections. Different distances as 2.5 m, 5 m, and 10 m from the blast centre were considered for the connections. Also, the blast powers as 500 kg, 1000 kg, and 2000 kg TNT equivalent mass of explosive were used for the blast loading of the connections. It was found that increasing the connection distance from the blast centre reduced the stresses in reinforcements. As the blast power was

ARPN Journal of Engineering and Applied Sciences

enhanced, the stresses in the connection reinforcements were increased. The stress concentrations in the connection of five-storey building were found on the bottom of the column which could increase the risk of progressive collapse of the structure, however, the stress concentrations in the connection of nine-storey building were on the beam and near the beam-column connection owing to using larger cross-sections for the beam and column in the connection. The risk of the progressive collapse could be reduced by decreasing the stirrups spaces of the beam in the connection of five-storey building which led to the concentration of the stresses in the beam reinforcements of the connection.

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