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# Numerical Assessment of Reinforcing Details in Beam-Column Joints on Blast Resistance

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**Abstract:** This numerical study investigated the effects of different reinforcing details in beam-column joints on the blast resistance of the joints. Due to increasing manmade and/or natural high rate accidents such as impacts and blasts, the resistance of critical civil and military infrastructure or buildings should be sufficiently obtained under those high rate catastrophic loads. The beam-column joint in buildings is one of critical parts influencing on the resistance of those buildings under extreme events such as earthquakes, impacts and blasts. Thus, the details of reinforcements in the joints should be well designed for enhancing the resistance of the joints under the events. Parameters numerically investigated in this study include diagonal, flexural, and shear reinforcing steel bars. The failure mechanism of the joints could be controlled by the level of tensile stress of reinforcing steel bars. Among various reinforcing details in the joints, diagonal reinforcement in the joints was found to be most effective for enhancing the resistance under blast loads. In addition, shear reinforcements also produced favourable effects on the blast resistance of beam-column joints.

**Keywords:** blast resistance, beam-column connections, reinforcement, numerical analysis.

## 1. Introduction

There have been many incidents involving explosive accidents and terrorism which may occur in unexpected places and time. Explosive accidents in densely populated area may result in immense casualties and property damage (Lee and Lee 2001; Roh 2011). Therefore, structures should be designed to resist such an extreme event load. In general, the application of blast-resistant design so far has been limited to military and some important civilian facilities like nuclear power plants. However, common structures such as high-rise building and large public structures also need to be designed for blast or impact loads in order to prepare for the terrorist attacks aiming unspecified multitudes and the unexpected explosive accidents. In spite of this global threat of terrorism, most of the countries have not established the antiterrorism design clearly. Even for a few antiterrorism design guides, they are generally limited to the military facilities. Department of Defense (DoD) of the United States deals with substantial information recorded on security documents about blast resistance because the study on blast-resistant structures is directly related to national security. Moreover, there has been a lack of studies on this topic. Therefore, establishment of design criterion and related study should be required to design blast-resistant structures including not only military facilities but also private facilities.

First and foremost, engineers should consider energy absorption capability of construction materials to design blast-resistant structures. In addition to energy absorption, the materials have to have sufficient strength and ductility to resist pressure and to control the deflection during explosion. In that sense, reinforced concrete structures are considered the suitable structural systems to resist blast loads because concrete has outstanding energy absorption ability and at the same time reinforcement can make up for sufficient ductility which could be the weakness of concrete (DoD 2008; Dusenberry 2010).

Structural members are generally dealt with as Beam or Bernoulli (B) Region in which Bernoulli's hypothesis of straight-line strain profiles applies (Park 2011) for analysis and design of these reinforced concrete whereas the joints or connections in reinforced concrete structures are mostly dealt with as disturbed or discontinuity (D) Region. Joints are critical parts of structural system where more than two elements meet because failure or disability of connections can do badly damage the whole structural system such as progressive collapse (Dusenberry 2010; Cormie et al. 2009).

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In this study, blast-resistant capacities of beam-column joints were numerically investigated according to different reinforcing details including additional flexural, shear and diagonal bars. This numerical study on the reinforced concrete structures subjected to blast loads has significant benefits over experimental investigation, given that repetitive blast tests accompany enormous cost and time. A commercial finite element analysis program, LS-DYNA, was used for the analysis of blast-resistance of beam-column joints in this study. The support rotations, deflection of member and failure shape were analysed from the numerical results by comparing with design standard.

## 2. Literature Review

### 2.1 Details of Blast-Resistant Structures

Reinforced concrete structures are believed to be suitable for blast-resistance structure, as construction materials, owing to enhanced energy absorption capacity and ductility at high strain rates (Bounds 2010; Dusenberry 2010). In order to reasonably investigate the blast resistance of reinforced concrete members by carrying out numerical simulations, the strain rate effects on the behavior of concrete as well as reinforcing steel bar should be considered because both concrete and steel reinforcing bar are subjected to very high strain rates under blast loads. The strain rate effects are mostly considered by applying dynamic increase factors (DIFs), i.e. the ratio of the dynamic to static response. As the strain rate was getting faster, the apparent strength of the materials significantly increased as shown in Fig. 1 (DoD 2008). For concrete, the DIFs for strength can be more than 2 in compression while more than 6 in tension (Bischoff and Perry 1991; Malvar and Ross 1998; Birkimer and Lindemann 1971).

The monolithic connections of reinforced concrete structures are very advantageous in blast-resistant structures. As substantial deformation is mutually transmitted between the beam and the column (or the slab and the wall), monolithic

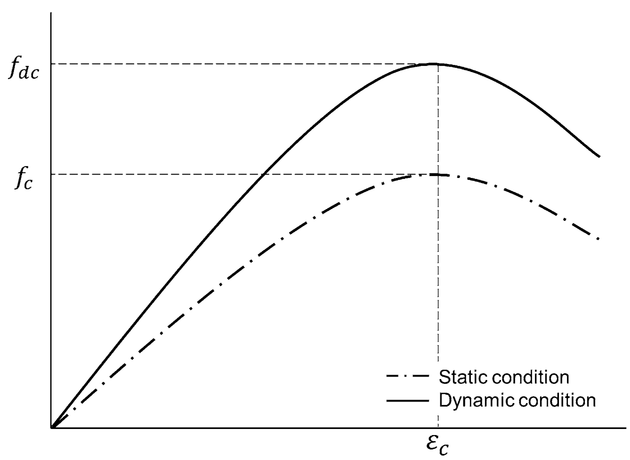


**Fig. 1** Stress–strain curve in concrete subjected to blast loads.

types of connection could more effectively resist blast loads (Dusenberry 2010).

Reinforcement details must affect structural safety under the complicated stresses. Longitudinal reinforcements should be continuous through connectors without splices and joints of the reinforcing rebar within the distance of twice the beam depth from the connection faces, which is the required sufficient development length in connections (Bounds 2010; Dusenberry 2010). Diagonal reinforcements can be used to enhance the behavior of connections. According to Unified Facilities Criteria (UFC) 3-340-02, development length of diagonal bars for the blast-resistant joints should be more than 20 times of bar diameter over the critical section, which is generally taken at a distance 'd (effective depth)' from the face of the connections(DoD 2008; Bounds 2010). The beneficial effects of the diagonal bars on the blast-resistance of connections were studied by a few researchers, but the structural behavior of blast-resistant connections reinforced with diagonal bars has not been fully investigated (Krauthammer 1996, 1997, 1999).

### 2.2 Deformation Criterion of Blast-Resistant Structures

Department of Defense (DOD) of United States established UFC. Especially UFC 3-340-02, superseded ARMY TM 5-1300, NAVFAC P-397 and AFR 88-22, presents methods of design for protective construction. UFC 3-340-02 reported that support rotation and ductility are good indicator to evaluate blast-resistant performance of RC structure members. According to UFC 3-340-02, the limitation of support rotation is 2 degrees when the concrete structure is effective in resisting moment (DoD 2008). American Society of Civil Engineers (ASCE) suggested level of protection (LOP) and the maximum response limits of reinforcement concrete structures, as shown in Table 1 (ASCE/SEI 2011). It is noted that both manuals of DoD and ASCE suggested support rotation as the main criterion to assure the integrity of RC elements for the design of blast-resistance structures.

According to other researches, however, the support rotation alone cannot be the absolute criterion for the integrity of blast-resistant concrete connections. For instance, the numerical study on the beam-column connections subjected to blast load by Krauthammer showed that the member can fail though maximum rotation of member does not exceed the allowable limit (Krauthammer 1999). Therefore, before the application of these criteria, sufficient analysis of the potential disruptions, such as failure by repulsive forces of structural members, is necessary. In addition, various evaluation factors including not only local and global rotations, and ductility ratio but also reinforcement stress and strain should be examined thoroughly to evaluate performance of blast-resistant structural concrete.

### 2.3 Blast Loads

The typical masses of explosive materials are defined in Europe, as shown in Table 2 (Yandzio and Gough 1999).

**Table 1** Maximum response limits for reinforced concrete (ASCE/SEI 2011).

| Element type | Superficial ($\mu_{max}$) | Moderate ($\theta_{max}$) | Heavy ($\theta_{max}$) | Hazardous ($\theta_{max}$) |
|---|---|---|---|---|
| Single-reinforced slab or beam | 1 | 2° | 5° | 10° |
| Single-reinforced beam-column | 1 | 2° | 2° | 2° |
| Double-reinforced beam-column without shear reinforcement | 1 | 2° | 2° | 2° |
| Double-reinforced beam-column with shear reinforcement | 1 | 4° | 4° | 4° |

**Table 2** Typical example of terrorist explosive materials in Europe.

| Variables | Explosion method | Material | Loaded weight |
|---|---|---|---|
| Bomblet | Small briefcase | M/CE | 2–4 kg |
| | Large briefcase | M/CE | 4–12 kg |
| | Suitcase | M/CE | 12–22 kg |
| | Bicycle | M/CE | 30 kg |
| Car bomb | Sedan | HME | 250 kg |
| | Small van | HME | 1–2 ton |
| | Large van | HME | 2–3 ton |
| | Small truck | HME | 3–4 ton |
| | Large truck | HME | 4–5 ton |

M/CE refers to military and commercial explosives, such as trinitrotoluene (TNT) and home-made explosives (HME). In simulating the actual situation of explosion, this study refers to these examples.

LS-DYNA provides the LOAD_BLAST or LOAD_-BLAST_ENHANCED for modeling of blast loads. These options can be substituted for the solids model of TNT. In this case, LS-DYNA provides characteristics of TNT. These functions consider Chapman-Jouguet's explosion velocity which is one of the equivalent mass defining method, as follows (LSTC 2013a; Glenn and Bannister 1997).

$$M_{TNT} = M\frac{DCJ^2}{DCJ^2_{TNT}}$$

$M_{TNT}$is the equivalent TNT mass, M the mass, $DCJ_{TNT}$ the Chapman–Jouguet detonation velocity, DCJ the Chapman–Jouguet velocity of explosive.

## 3. Numerical Analysis Method

In this study, the LS-DYNA, used for nonlinear and transient dynamic analysis liked blast or impact using explicit time integration, was selected for numerical analysis. This is a general purpose finite element program capable of simulating complex problems such as automobile, aerospace, construction and so on (LSTC 2013a).

### 3.1 Materials

#### 3.1.1 Steel

Strain-rate effects should be considered for the properties of materials subjected to dynamic loads. In this study, ASTM Grade 60 bar was used. Its properties under normal condition and blast loads were shown in Table 3.

These properties, included strain-rate effects, could be obtained by repeated experiments (Crawford et al. 2012). For the modeling of steel, MAT_024 in LS-DYNA was selected, which is defined an elastic–plastic material with an arbitrary stress versus strain curve and arbitrary strain rate dependency. The fracture of MAT_024 is based on a plastic strain (LSTC 2013b).

#### 3.1.2 Concrete

In this study, MAT_072R3 is selected for concrete material model of connections applying high fidelity physics-based (HFPB) simulations to predict structural behavior (LSTC 2013b). Among the concrete models in LS-DYNA, MAT_072R3 can be the most suitable for analyzing concrete structures subjected to blast loads since it has outstanding

**Table 3** Material properties of ASTM Grade 60 rebar.

| Loading condition | Yield strength / Young's modulus | Tensile strength / Poisson's ratio | Density / etc. |
|---|---|---|---|
| Static load | 414 MPa | 620 MPa | $7.86 \times 10^{-6}$ kg/mm$^3$ |
| | $2.0 \times 10^5$ MPa | 0.30 | Elongation: 18 % |
| Impact or blast load | 475 MPa | 751 MPa | $7.86 \times 10^{-6}$ kg/mm$^3$ |
| | $2.0 \times 10^5$ MPa | 0.30 | Fracture strain: 35 % |

accuracy than other material models in LS-DYNA when comparing with experiments such as the axial static loading, bending test and impact test (Crawford et al. 2012). MAT_072R3 is a three-invariant model, uses three shear failure surfaces, and includes damage and strain-rate effects (LSTC 2013b). It is noted that many of the models in LS-DYNA do not allow failure and erosion which is the effect of local damage of blast as crater spall and breach (Ling 2013). Therefore, The ADD_EROSION option was considered to include the failure criteria since MAT_072R3 does not allow failure. Table 4 shows properties of concrete used in this numerical analysis.

### 3.2 Blast Loads

TNT can be modelled as solids to simulate blast loads. From the load options of LS-DYNA, LOAD_BLAST or LOAD_BLAST_ENHANCED can be selected to model TNT. These functions are based on CONWEP blast model (Glenn and Bannister 1997). In this study, the LOAD_BLAST_ENHANCED was selected for modelling the blast load, and consequently 30 kg of TNT, which is a bicycle bomblet, was simulated on the beam 1 m away from the column face. Figure 2 shows pressure diagram for the 30 kg of TNT.

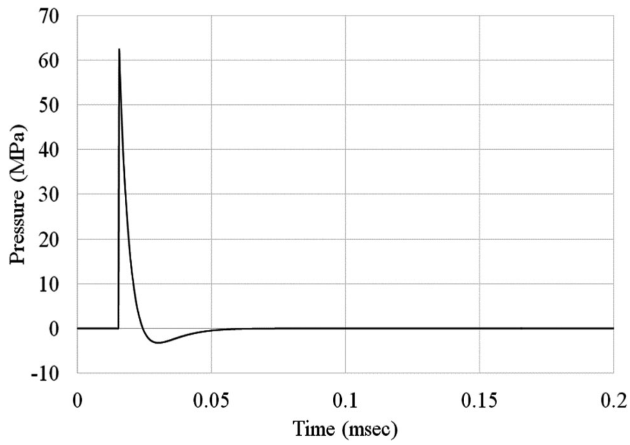

**Fig. 2** Pressure diagram under 30 kg of TNT.

### 3.3 Modelling of the Specimens

The way how to simulate the model is very important because analysis result can be different depending on it. Even though numerical analysis results may have similar tendency overall in spite of different element sizes, the analysis results consisted with the actual value were significantly affected by size effects (Krauthammer 1997; Yim and Krauthammer 2009). Foglar and Kovar (2013) performed comparative study of the experimental and numerical analyses involved with blast loads. According to their study, the experimental results were in good agreement with the numerical analysis results when concrete mesh were consist of 8-node solid elements of 30 × 30 × 30 mm using LS-DYNA. In this study, therefore, concrete mesh consists of 8-node solid elements by referring to the analysis method by Foglar and Kovar (2013) in order to assure reliability of analysis results.

The interaction between the concrete and the reinforcements is typically implicit. In this study, it was achieved by tying the rebar elements and the concrete elements as the same nodes. Explicit modelling of bond-slip phenomena considering the actual properties and performance of structural members is a quite complex analysis problem. Accordingly, various studies on RC structures subjected to blast loads suggest that the tedious details are neither needed nor desirable (Crawford et al. 2012).

## 4. Numerical Analysis Specimens

In this study, the behavior of beam-column connections was investigated when the connection was under blast loads. Specimens were designed as monolithic connections which have advantage to resist the blast loads, as mentioned earlier (Dusenberry 2010).

**Table 4** Concrete properties.

| Properties | Variables |
|---|---|
| Compressive strength | 45.2 MPa |
| Density | 2230 kg/m$^3$ |
| Poisson's ratio | 0.19 |
| Tensile strength | 3.2 MPa |

**Table 5** Description of specimen variables.

| Specimen | Description |
|---|---|
| Specimen BC | Beam-column connection designed according to ACI318 and ACI352R |
| Specimen BC-F | Additional four No. 11 flexural reinforcement based on Specimen BC |
| Specimen BC-D | Additional four No. 11 diagonal reinforcement based on Specimen BC |
| Specimen BC-F-S | Additional No. 4 shear reinforcement @300 mm based on Specimen BC-F |
| Specimen BC-A | Reinforced with all type of bars including diagonal, flexural and shear reinforcement |

Table 5 shows the variables of beam-column connections according to reinforcement details. Control Specimen BC was designed based on ACI 318-11 and ACI 352R-02. The longitudinal steel ratio of column is 0.038 $A_g$ ($A_g$ is the gross area of column section) which is satisfied with ACI318-11. The transverse rebar of the column used the No. 4 ties; and the spacing between the sets of ties was 150 mm (5.9 inch), which should be less than or equal to 6 inches according to ACI 352R-02. The flexural rebar of beam section arranged four No. 11 bars by ACI 352R-02 (ACI-ASCE 2010; ACI 2011). By default, all other specimens were designed in the same manner as the Specimen BC, but each specimen was reinforced with different additional reinforcement, as follow. Specimen BC-F was additionally reinforced with four No. 11 rebars at the bottom of the beam in order to check if the additional flexural reinforcement is effective on the enhancement of blast-resistant capacity. For Specimen BC-D, the diagonal bar was additionally reinforced from Specimen BC. The development length of the diagonal bar was set to 720 mm by referring the UFC 3-340-02. Other studies reported that diagonal bar is essentially reinforced on connections of concrete structures to resist blast loads (DoD 2008; Bounds 2010). Therefore, the benefits of diagonal reinforcements could be verified by comparison of specimens BC and BC-D. In addition, the beneficial effect of flexural reinforcement and diagonal reinforcement on the blast-resistance can be compared from the analysis results of specimen BC-F and BC-D since the steel ratio of additional reinforcement of both specimens is equal. For Specimen BC-F-S, minimum shear reinforcements were added to Specimen BC-F in the beam region. Comparison of Specimen BC-F-S with BC-F would confirm the effects of shear reinforcements. The synergetic effects of various types of reinforcements on blast-resistant capacity could be demonstrated in Specimen BC-A which is reinforced with all types of bars including diagonal, flexural, and shear reinforcements. Figure 3 shows the details of beam-column specimens.

## 5. Results and Discussion

The main objective of the analyses is to investigate the effects of reinforcement details on blast-resistance performance of beam-column joints. From the analyses results, typical forms of pressure distribution shown in Fig. 4 were commonly observed to all specimens. This tendency of pressure development with time is quite similar to previous research (DoD 2008). Analysis results mainly focused on failure shape, beam deflection, support rotation, Stress and strain in the reinforcements, and so on. Analysis results and discussion for each analysis variable of reinforcement are as follow.

### 5.1 Effect of Flexural Reinforcement

Figure 5 shows the failure shapes of all specimens at 200 ms (milliseconds). Fractures followed by a considerable deflection were observed in the entire beam section of control specimen BC and Specimen BC-F reinforced with flexural reinforcements. In addition, severe concrete spalling occurred at the bottom surface because blast pressure transmitted from the exposed surface to opposite side.

Given that the explosive material, TNT, was near the beam surface than the column face, the blast load influenced the beam region than the column resulting in a considerably large beam deflection. To compare the performance of the beam of all specimens, deflections of beam region were measured at Points A and B, as shown in Fig. 6. Point A indicates the location where the diagonal bars end in the beam section, and Point B is located at the end of the beam section. Table 6 shows the maximum deflection during the analysis time at each points, A and B, for every specimen. When considering the deflection of beam region, Specimens BC and BC-F showed poor performances to resist blast loads. The deflections of both specimens were continuously increased even after the end of the analyses at 200 ms.

Table 7 shows the support rotation when maximum deflection during the analysis time occurred. According to UFC 3-340-02, the limitation of support rotation to effectively resist moment is 2 degrees (DoD 2008). Specimens BC and BC-F were over the limitation at both points A and B. Table 8 shows the maximum steel stress and strain during the analysis time. As the deflections of both specimens BC and BC-F continuously increased so were the stress and the strain of reinforcements.

Additional flexural reinforcements seem to be ineffective to resist blast loads.

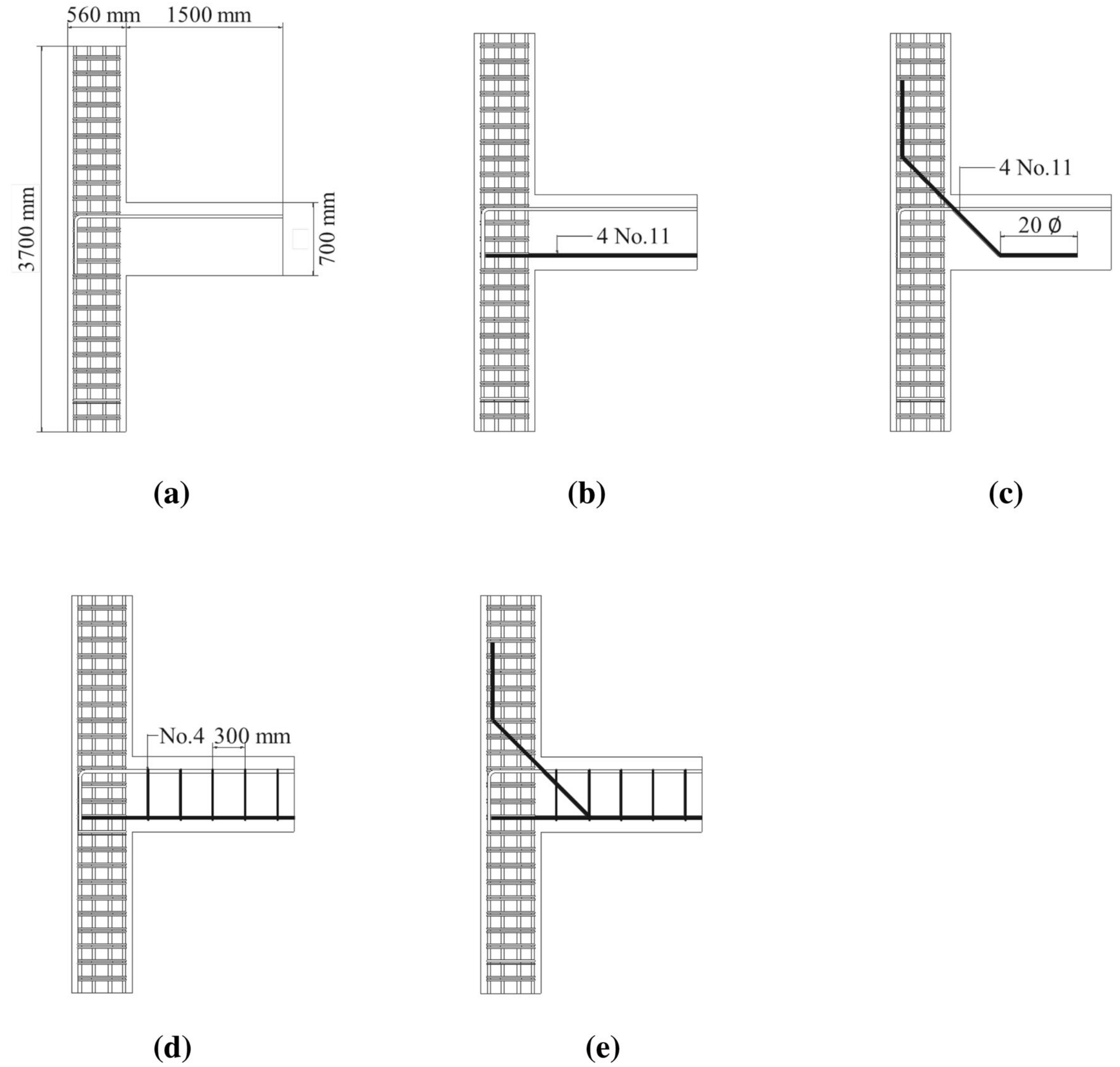


**Fig. 3** Details of specimens. **a** Specimen BC. **b** Specimen BC-F. **c** Specimen BC-D. **d** Specimen BC-F-S. **e** Specimen BC-A.

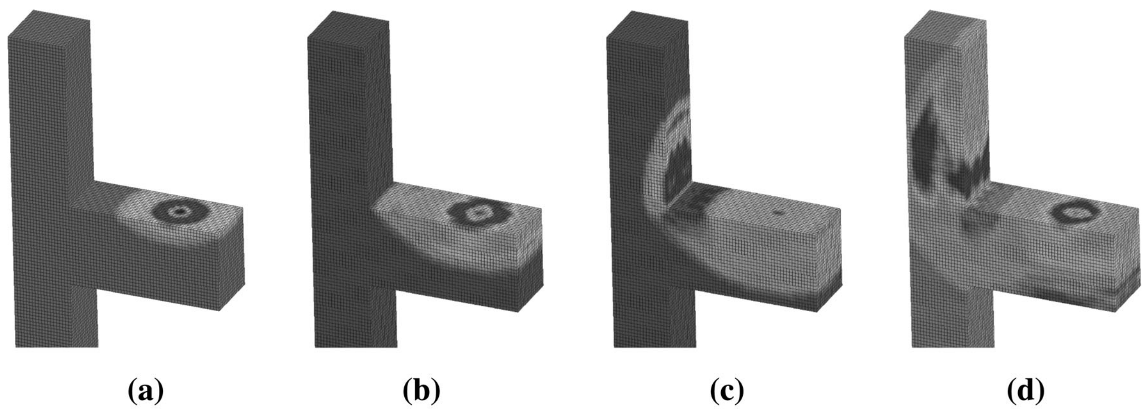


**Fig. 4** Pressure contours of Specimen BC-A. **a** t = 0.10 ms, **b** t = 0.20 ms, **c** t = 0.30 ms, **d** t = 0.50 ms.

### 5.2 Effect of Diagonal Reinforcement

Specimen BC-D reinforced with additional diagonal reinforcements showed that deflections at Points A and B were effectively controlled when comparing to Specimen BC, as shown in Table 6. It shows that diagonal bars are essential in concrete joints subjected to blast loads, which is consistent with previous studies (ACI 2011; DoD 2008). Also, deflection of Specimen BC-D at Point A was about 3 times less than that of Specimen BC-F reinforced with additional flexural bars whose steel ratio is same as diagonal

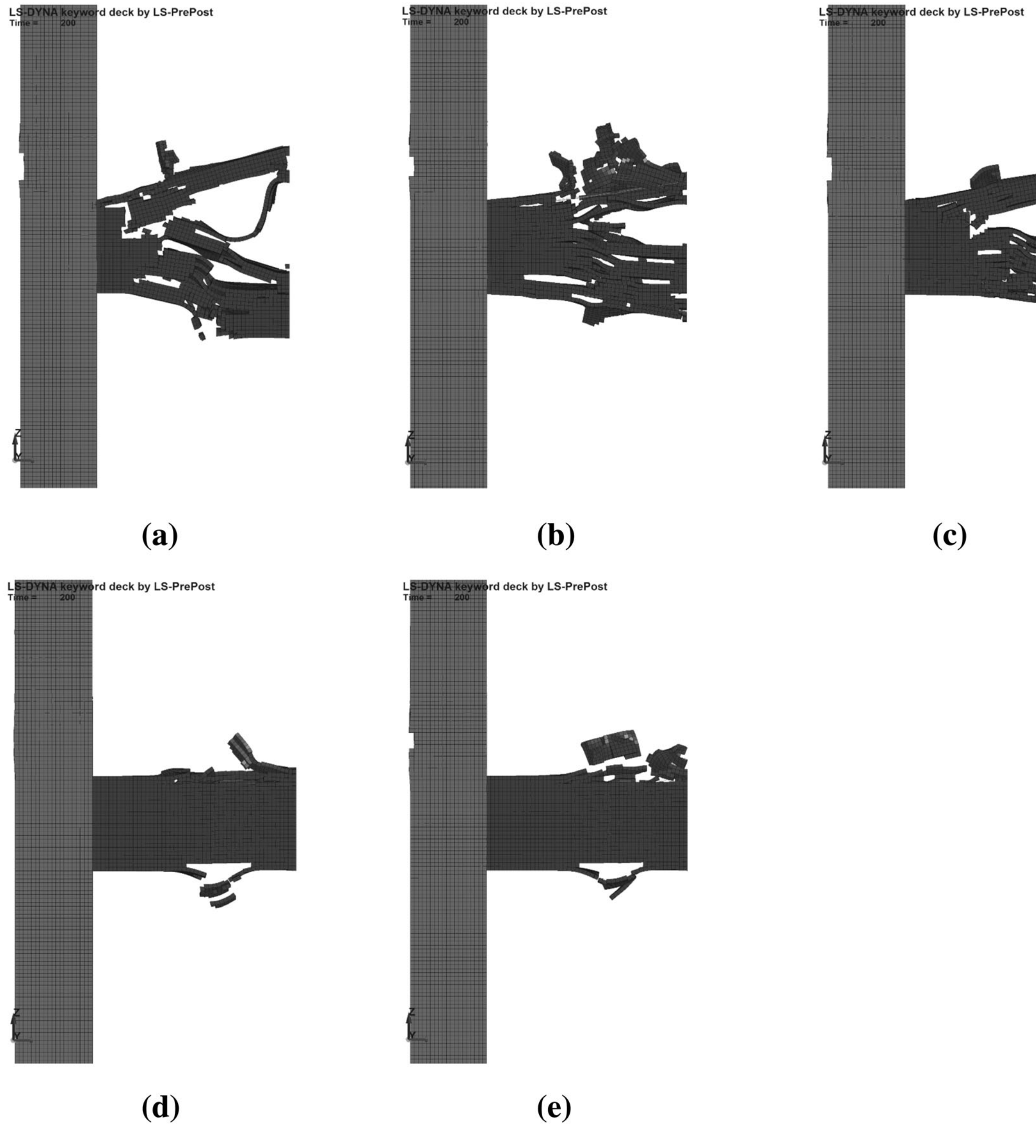


**Fig. 5** Failure shapes of specimens. **a** Specimen BC. **b** Specimen BC-F. **c** Specimen BC-D. **d** Specimen BC-F-S. **e** Specimen BC-A.

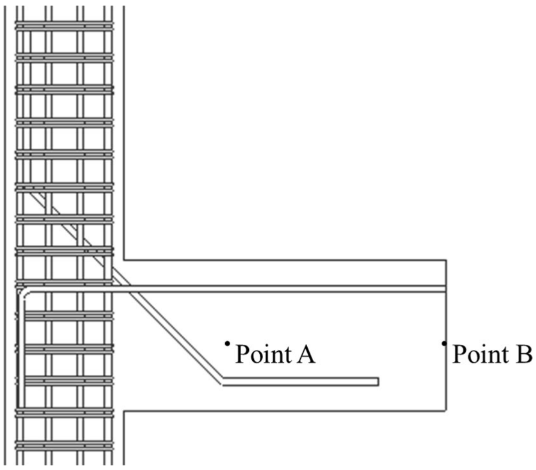


**Fig. 6** Location of points A and B.

bars of Specimen BC-D. Therefore, it can be another finding that diagonal reinforcements would be more effective to resist blast loads than additional flexure reinforcements.

Figure 7 shows the maximum deflection of specimens according to the distance from the column faces. The maximum deflection during the analysis time was obtained for main nodes of the beam, so each data of the maximum deflection could be observed at slightly different times. It is interesting to note that large deflection occurred at location beyond the end of diagonal reinforcements. For Specimen BC-D, plastic hinge zone was relocated from the column face to the beam region due to the diagonal reinforcement. Given that beam region from the column face to the distance 'd' (effective depth of beam) is typically considered as critical section according to ACI 318-11 (2011), this phenomenon could make the structure safer because failure behavior of the beam must be more ductile than that of beam-column joints.

As shown in Table 7, diagonal reinforcement showed beneficial effect on support rotation, too. Support rotation of Specimen BC-D at Point A was smaller than failure criteria, 2 degrees, but at Point B, it was still larger than 2 degrees even though the support rotation considerably decreased due to the diagonal reinforcement.

**Table 6** Maximum deflection of beam.

| Specimen | At the point A | | At the point B | |
|---|---|---|---|---|
| | Max. deflection (mm) | Time (ms) | Max. deflection (mm) | Time (ms) |
| BC | −63.0 | 200.0 | −313.0 | 200.0 |
| BC-F | −10.3 | 61.1 | −143.7 | 200.0 |
| BC-D | −3.6 | 21.3 | −82.6 | 81.0 |
| BC-F-S | −4.2 | 12.3 | −23.0 | 25.2 |
| BC-A | −2.0 | 2.8 | −17.9 | 19.2 |

**Table 7** Support rotation of specimens.

| Specimen | At the Point A | | At the Point B | | Deflection |
|---|---|---|---|---|---|
| | Support rotation | Comparison to criteria | Support rotation | Comparison to criteria | |
| BC | 17.18° | NG | 37.56° | NG | Failed |
| BC-F | 2.81° | NG | 17.24° | NG | Failed |
| BC-D | 0.99° | OK | 9.91° | NG | Controlled |
| BC-F-S | 1.15° | OK | 2.76° | NG | Controlled |
| BC-A | 0.55° | OK | 2.15° | NG | Controlled |

**Table 8** Maximum stress and strain in reinforcements.

| Type of reinforcements | | Max. stress (MPa) | Max. strain | Time (ms) |
|---|---|---|---|---|
| BC | Flexural bars in the top | 602.13 | 0.0386 | 200 |
| BC-F | Flexural bars in the top | 513.64 | 0.018 | 200 |
| | Flexural bars in the bottom | 479.14 | 0.0079 | 58.3 |
| BC-D | Flexural bars in the top | 577 | 0.0327 | 169.6 |
| | Diagonal bars | 479.75 | 0.0089 | 58.4 |
| BC-F-S | Flexural bars in the top | 354.77 | 0.0017 | 12.3 |
| | Flexural bars in the bottom | 397.4 | 0.0019 | 9.7 |
| | Shear reinforcement | 527.55 | 0.0214 | 191.3 |
| BC-A | Flexural bars in the top | 401.44 | 0.002 | 9.1 |
| | Flexural bars in the bottom | 472.67 | 0.0026 | 9.5 |
| | Diagonal bars | 472.67 | 0.0027 | 9.5 |
| | Shear reinforcement | 527.54 | 0.0214 | 136 |

### 5.3 Effect of Shear Reinforcement

As shown in Fig. 5, Specimen BC-F-S showed good shape of failure with less deflection and less concrete spalling because the beam region could be constrained by shear reinforcement. Especially, Specimen BC-F-S showed negligibly small deflection for the region from column face to 500 mm, but the deflection increased steeply for beyond the region. In addition, support rotation of Specimen BC-F-S dramatically decreased as shear reinforcements were added. The support rotation at Point A was satisfied with the criteria, and that at Point B was only 2.76° which was slightly over the criteria. Furthermore, as shown in Table 8, the reduced stress in the flexural reinforcing bar was observed due to the shear reinforcement bearing the substantial portion of stress and confining the beam section.

From Specimens BC-F and BC-F-S, it can be found that flexural reinforcement alone cannot be effective to enhance blast resistance, but shear reinforcements with flexural bars can give beneficial effects on blast resistance by reducing deflection and relocating plastic hinge zone (ASCE/SEI 2011).

### 5.4 Synergetic Effect of All Reinforcement

Specimen BC-A, which was reinforced with various reinforcements including flexural, diagonal and shear rebars, showed the best performance in terms of failure shape,

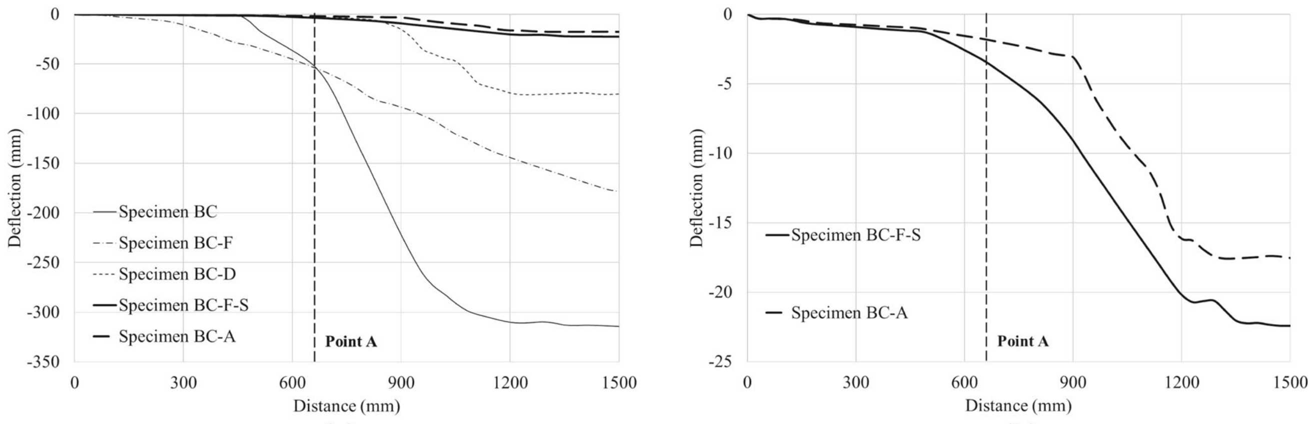


**Fig. 7** Maximum beam deflection versus distance from column face. **a** All specimens. **b** Specimen BC-F-S and BC-A.

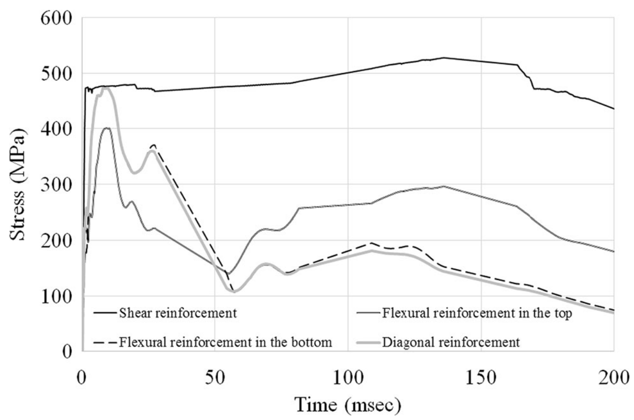


**Fig. 8** Stress evolution in reinforcements of Specimen BC-A.

maximum deflection, support rotation, and relocation of plastic hinge zone. This excellent behavior can be regarded as mutual synergistic results of the moment resisting performance of flexural reinforcement, strengthening the unity of column and beam by diagonal reinforcement, and confinement effect of shear reinforcement. Figure 8 shows the maximum stresses in each type of reinforcements versus elapsed time after explosion for Specimen BC-A. As shown in Fig. 8, among the various types of reinforcements, shear reinforcement should bear the greatest stress throughout the entire analysis. Given in order of the amount to bear the stress, shear, diagonal, bottom flexural, and top flexural reinforcements are in order. Approximately 50 ms after the explosion, however, the top flexural reinforcement should bear a greater stress than the diagonal reinforcement.

## 6. Conclusions

Blast resistance of beam-column connections was numerically assessed according to reinforcement details. Analysis results included failure shape, deflection, support rotation, and stress in reinforcement. Based on the analysis results, the following conclusions were drawn in this study.

(1) The beam-column connection designed based on the specification for members under static load should be too vulnerable to resist the blast loads. As a result, a considerably large deflection can be caused by blast loads because the plastic hinge region is formed throughout the beam region. For this reason, the guideline specifically developed for structural members subjected to blast loads is necessary to improve the blast-resistance.

(2) Diagonal reinforcement can give better blast-resistance performance than flexural reinforcement in terms of deflection and support rotation. In addition, by relocation of plastic hinge zone from column face to beam region, the diagonal reinforcement would contribute to the ductility of beam-column connection when considering that plastic hinges are usually formed in the critical section near column face which may result in a brittle failure.

(3) Shear reinforcements considerably affect blast-resistance capacity. To add flexural reinforcement only without shear reinforcement is not very effective to enhance blast-resistance, but the combination of flexural and shear reinforcements can yield comparatively superior blast-resistant performance mainly because the shear reinforcement confine the beam. It confirms that shear stress should be importantly considered to design reinforced concrete structures subject to blast loads.

(4) When beam-column connection is reinforced with all types of reinforcements at once, blast-resistant behavior can be much improved in terms of failure shape, deflection, support rotation, and so on. It seems due to synergistic effect by the combination of flexural, diagonal and shear reinforcements.

(5) According to the analysis result in this study, support rotation of some specimens exceeded the failure criteria despite they have shown good behavior with regard to failure shape and deflection. Therefore, to evaluate structural behavior of the concrete members subjected to blast loads, not only support rotation but also additional factors such as ductility ratio, deflection, plastic hinge region, and reinforcement stress should be investigated.

## Acknowledgments

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## References

American Concrete Institute-American Society of Civil Engineers (ACI-ASCE) Committee 352, ACI 352R-02 Reapproved. (2010). *Recommendations for design of beam-column connections in monolithic reinforced concrete structures*. Farmington Hills, MI: ACI.

American Concrete Institute (ACI) Committee 318, ACI 318-11. (2011). *Building code requirements for structural concrete & commentary*. Farmington Hills, MI: ACI.

American Society of Civil Engineers-Structural Engineering Institute (ASCE/SEI). (2011). *ASCE/SEI 59-11: blast protection of building*. Reston, VA: ASCE.

Birkimer, D. L., & Lindemann, R. (1971). Dynamic tensile strength of concrete materials. *ACI Journal Proceedings, 68*(1), 47–49.

Bischoff, P. H., & Perry, S. H. (1991). Compressive behavior of concrete at high strain rates. *Materials and Structures, 24*, 425–450.

Bounds, W. L. (2010). *Design of blast-resistant building in petrochemical facilities*. Reston, VA: ASCE.

Cormie, D., Mays, G., & Smith, P. (2009). *Blast effects on buildings*. London, UK: Thomas Telford.

Crawford, J. E., Wu, Y., Choi, H. J., Magallanes, J. M. and Lan, S. (2012). *Use and validation of the release III K&C concrete material model in LS-DYNA*. Karagozian & Case Technical Report TR-11-36.5, Livermore, CA.

Department of Defense (DoD). (2008). *UFC 3-340-02: structures to resist the effects of accidental explosions*. Sacramento, CA: Department of Defense.

Dusenberry, D. O. (2010). *Handbook for blast resistant design of buildings*. Hoboken, NJ: Wiley.

Foglar, M., & Kovar, M. (2013). Conclusions for experimental testing of blast resistance of FRC and RC bridge decks. *International Journal of Impact Engineering, 59*, 18–28.

Glenn, R. P., & Bannister, K. A. (1997). *Airblast loading model for DYNA2D and DYNA3D*. Washington, DC: Army Research Laboratory ARL-TR-1310.

Krauthammer, T. (1996). A hybrid computational approach for the analysis of blast resistant connections. *Computers & Structures, 61*(5), 831–843.

Krauthammer, T. (1997). Mesh, gravity and load effects on finite element simulations of blast loaded reinforced concrete structures. *Computers & Structures, 63*(6), 1113–1120.

Krauthammer, T. (1999). Blast-resistant structural concrete and steel connections. *International Journal of Impact Engineering, 22*(9-10), 887–910.

Lee, S. S., & Lee, J. W. (2001). Building design for blast resistance. *Journal of the Architectural Institute, 45*(10), 58–62.

Ling, L. (2013) *Load damages and blast resistance of RC slabs subjected to contact detonation*. Master's Dissertation, Korea University.

Livermore Software Technology Corporation (LSTC). (2013a). *LS-DYNA keyword user's manual volume I*. Livermore, CA: Livermore Software Technology Corporation.

Livermore Software Technology Corporation (LSTC). (2013b). *LS-DYNA keyword user's manual volume II material models*. Livermore, CA: Livermore Software Technology Corporation.

Malvar, L. J., & Ross, C. A. (1998). Review of strain rate effects for concrete in tension. *ACI Materials Journal, 95*(6), 735–739.

Park, J. Y. (2011). *Modern protective structures*, CIR.

Roh, J. E. (2011). *Analytical evaluation of blast resistance capacity of H-shaped columns in steel frame structures*. Master's Dissertation, Dankook University.

Yandzio, E., & Gough, M. (1999). *Protection of buildings against explosions*. England: Steel Construction Institute, London, UK.

Yim, H. C., & Krauthammer, T. (2009). Load-impulse characterization for steel connections in monolithic reinforced concrete structures. *International Journal of Impact Engineering, 36*(5), 737–745.

Yoon, Y. S. (2013) *Mechanics & design of reinforced concrete*. CIR.