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Numerical simulations on the dynamic response of a full-scaled steel frame structure subject to a surface burst explosion using LS-DYNA

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ABSTRACT

In this paper, numerical studies are carried out to estimate the response and damage level of a full-scaled steel frame structure subject to a high-explosive loading using LS-DYNA. A terrorist attack is assumed to be a vehicle bomb detonating within 5 m of the structure exterior. The strain rate effects of steel are considered by using the Cowper-Symonds material model. A diaphragm effect of each floor is idealized as rigid body motion of the floor. As results of the simulation, the maximum von-mises stress and effective plastic strain are evaluated for checking the structural failure. Also, the lateral displacement of the nearest column from a detonation point is shown as time history data. The support rotation at both ends of the column is calculated from the deflection at the midpoint. Finally, the damage level of the structure is predicted and compared with the DoD response criteria. In conclusion, it can be confirmed that the blast effect analysis using LS-DYNA is helpful to understand global behaviors of the entire structure and provides reasonable results about the post-failure motion of the local member of a steel frame structure.

1. INTRODUCTION

According to statistics from U.S. State Department, individuals killed worldwide as a result of terrorism incidents were estimated at 14,602 and 24,705 people injured in 2005 (Dusenberry 2010). Another statistics on the worldwide terrorism show that 1,566 commercial facilities were struck by terrorists between 1998 and 2003 (FEMA 452). To cope with the terrorist threats, there have been a lot of efforts to protect buildings against bomb explosions. In the U.S.A. or Europe Union, standard practice, technical

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manual and guidelines for the protective design of buildings have been well prepared to mitigate human casualties and damage on the building caused by potential terrorist attacks. They are also incorporated into the design process of buildings for minimum antiterrorism. After the September 11 terrorist attacks on World Trade Center, the Unified Facilities Criteria as to DoD (Department of Defense) minimum antiterrorism standards (DoD 2003) has been applied to all constructions which include new buildings, existing buildings and leased buildings. Even the construction project outside of the United States is also governed by the Criteria. Meanwhile, most of people in Korea have no experiences in such terrors and they feel to be free from them. However, the Korean government announced a new policy on a high-rise building design in April 2010, prepared a guideline for the protective design of buildings against terrorist attacks. The new guideline is expected to be gradually applied to high-rise buildings exceeding 20,000 m^2 spaces including general hospitals and public facilities. Furthermore, the R&D project on the development of design and construction technologies of a super high-rise building had kicked off in April 2009, as a part of the V-10 project supported by a grant from Korea government. One of their aims is to reduce damage of buildings caused by a bomb explosion. Recently, Korean government and U.S. government agreed to move U.S. forces stationed north of the Han River to Pyeongtaek. With the agreement between the two countries, a large building project was launched at last year and major building companies in Korea have joined the project. Since DoD antiterrorism standard is expected to be applied to the building design of the project, the building companies joined the project have a deep interest in the protective design of buildings. On the background of the social interests in antiterrorism, more research works for the blast resistant design of buildings are necessary than ever before.

Because of the demands for security layers of buildings, designers should consider providing adequate stand-off distance if possible. In case that it is not possible to provide a sufficient stand-off distance, the hardening of building can be an alternative choice. When considering the protective design of structures, buildings may be designed to withstand a bomb explosion, and it should suffer less damage if attacked. In the design process, numerical simulations of structural response subject to a blast load have been commonly used as an effective way for the verification of structural resistance of the buildings. In this paper, numerical simulations are carried out to estimate the response and damage level of a full-scaled steel frame structure subject to a high-explosive loading using the commercial program, LS-DYNA (Gladman 2009). The structure mainly consists of several steel beams and columns. In particular, reinforced concrete wall is located at the core of structure. A terrorist attack is assumed to be a vehicle bomb detonating within 5 m of the structure exterior. The blast load is predicted based on the empirical method in LS-DYNA. Strain rate effects of the steel are considered by using the Cowper-Symonds (1957) material model. A diaphragm effect of each floor is idealized as rigid body motion of the floor. As results of the simulations, the maximum von-mises stress and effective plastic strain are evaluated for checking the structural failure. Also, the lateral displacement of the column member is shown as the time history data and the support rotation at both ends of the column is calculated from the deflection at the midpoint. Finally, the damage level of the structure is predicted and compared with the DoD response criteria.

2. FINITE ELEMENT MODEL OF THE ENTIRE STRUCTURE

In many cases, the numerical model of a structure is mainly focused on the local structural members since local behaviors of the structure are dominant in near field explosion problems. However, it is often necessary to build up the numerical model of entire structure in order to comprehend the global behaviors of the structure. The structure is a six-story building with a height of 26 m and designed to be conventional construction type. The steel frame consists of beam-column connections. In particular, a reinforced concrete wall is located at the core of the structure. All of the steel column and beam are idealized as shell elements with an effective thickness. The core wall is also modeled by shell elements and the reinforced steel is idealized as a truss element with an effective sectional area considering the total sectional area of the steel. The strain rate effects of steel can be considered by using the Cowper-Symonds material model. The dynamic yield stress is defined as a function of static yield stress and strain rate in the Cowper-Symonds model as shown in Eq. (1).

$$\sigma_{dy} = \left\{ 1 + \left[\frac{\dot{\varepsilon}}{C} \right]^{1/p} \right\} \sigma_y \tag{1}$$

Where, $\sigma_{dy} =$ Dynamic yield stress

$\sigma_y =$ Static yield stress

$\dot{\varepsilon} =$ Strain rate

$C, p =$ Rate dependent constant of material

The diaphragm effect of each floor can be simulated by rigid body motion of the floor. All the nodes involved in elastic members are constrained at the rigid body motion of the corresponding floor. The final finite element model of the entire structure is depicted in Fig. 1.

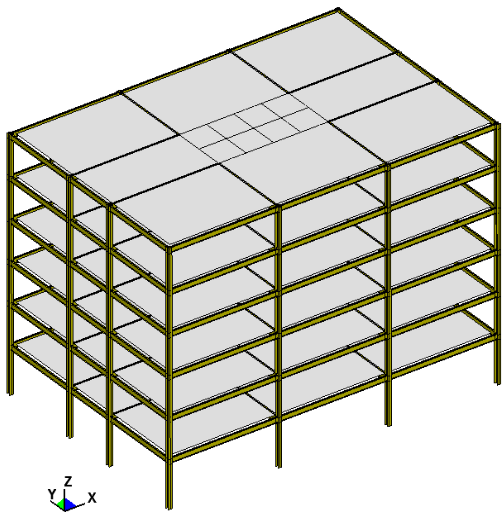
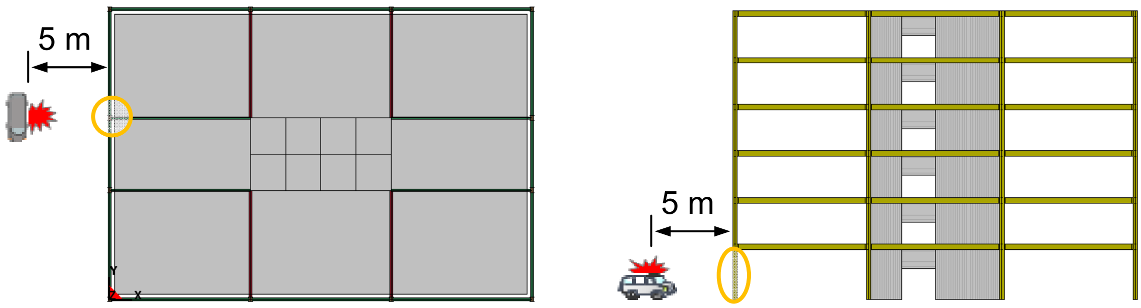


Fig. 1 Aerial view of the finite element model

3. BLAST EFFECT ANALYSIS

3.1 Blast load

A terrorist attack is assumed to be a van-vehicle bomb detonating within 5 m of the structure exterior. The explosive material is determined to TNT with a 454 kg weight according to “explosives environments” of FEMA 452. The shock wave caused by a surface burst involves the ground reflections of the initial wave. The blast load is predicted based on the empirical method in LS-DYNA. The predicted value of peak reflected pressure is about 22.1 MPa at the target column where the angle of incident is zero. The detonation point is shown in Fig. 2 with a plan and front view of the structure.



(a) Plan view (b) Front view

Fig. 2 Location of the detonation point and the target column

3.2 Von-mises stress and effective plastic strain

The maximum von-mises stress has occurred in bottom area of the target column at an early stage. The peak stress occurred in bottom of the column moves upward along with propagation of the reflected pressure. Fig. 3 shows the snap shot of von-mises stress of the column. From the stress contour of the column, it can be seen that the peak stresses are dominant in three areas involved bottom, middle and top elements. In those areas, the stress and strain time histories are shown in Fig. 4. The peak value of maximum von-mises stress is about 447 MPa and the effective plastic strain is 0.04. When considering the ultimate strength of high-tensile steel is in the range of 500 to 600 MPa, catastrophic failure of the column is not expected to occur under the given loading condition.

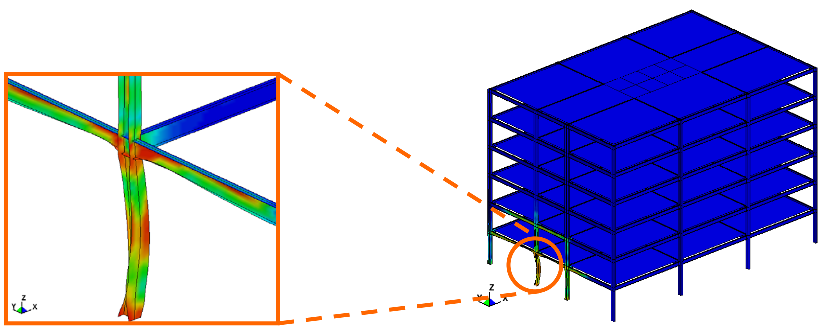
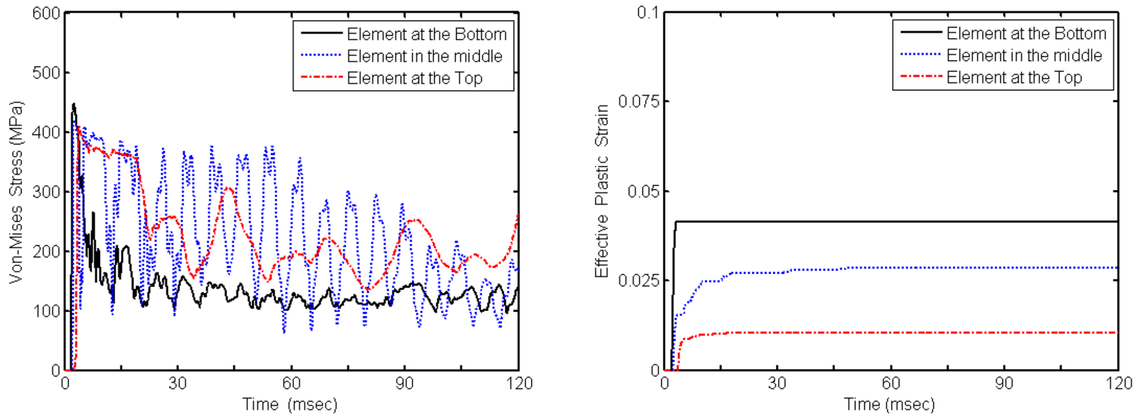


Fig. 3 Von-mises stress occurred in the target column at an early stage



(a) Von-mises stress (b) Effective plastic strain

Fig. 4 Von-mises stress and effective plastic strain of the target column

3.3 Lateral displacement and the support rotation

If the structural response is in plastic range, the support rotation at both ends of the beam can be obtained from the deflection at the midpoint as follows.

$$\theta_{1d} = \tan^{-1}(2\delta_{\max}/L) \tag{2}$$

Where, $L =$ Length of the beam

$\delta_{\max} =$ Deflection at a midpoint

$\theta_{1d} =$ Support rotation at both ends of the beam

The large displacement is observed at the midpoint of the target column. Meanwhile, the displacement of beams is relatively small because of the diaphragm effects. The average of the displacement is calculated around several nodes at midpoint and shown in Fig. 5. The first peak of the displacement in Fig. 5 is about 156 mm. The support rotation estimated from Eq. (2) is about 4.5 degree. According to DoD response criteria for a steel structure, the 4.5 degree of support rotation indicates that the damage level of the structure is expected to be heavy (Dusenberry 2010).

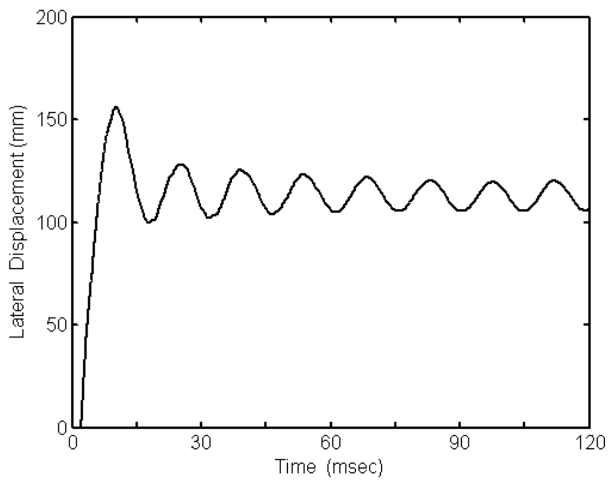


Fig. 5 Displacement time histories at midpoint of the target column

4. CONCLUSIONS

Through the blast effect analysis using LS-DYNA, the process for evaluation of dynamic response of the entire structure could be addressed in a detailed manner. Although the procedure is applied to the simplified steel frame structure instead of a real structure, the evaluation process described in this paper may be applied to a real structure with the complete drawings. In conclusions, it can be confirmed that the blast effect analysis using LS-DYNA is helpful to understand the global behaviors of the entire structure and provides the reasonable results about the post-failure motion of the local member.

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