Numerical Analysis of RC Beam Subjected to Blast Load

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***Abstract*—Behavior of structure subjected to blast and impact loads has to be analyzed with considering the effect of high strain rate. Material behavior will be changed under the condition that loads are applied to structures during a short period of time, which must be taken into account. In this paper, the nonlinear behavior of RC beams subjected to blast loads is analyzed by means of the layered-section approach. Using the proposed numerical method, the tendencies of numerical analysis are figured out with the number of element and time interval. Finally, correlation studies between analytical and experimental results are carried out in order to testify the validity of proposed numerical method. Then, it has been found that the numerical results show very good agreement with the experimental result.**

***Index Terms*—blast loads, high strain rate, layered section approach**

I. INTRODUCTION

There has been increasing interest in the effect of blast on structures because of close relation with lives. Especially in case of protection structures for military purpose, it is very important to figure out the effect of blast load especially in case of protection structures which has to have enough strength and ductility.

Recently, there has been increasing interest in these protective structures due to a series of recent terror attack. Therefore, several studies have been made on this subject as experimentally and numerically. Marais experiment identified properties of a variety of materials using the SHPB (Split Hopkinson Pressure Bar) test [1]. A numerical analysis for structures subjected to impact loading was conducted by Georgin *et al*. [2]. These obtained results have been used in commercialized programs including LS-DYNA [3] and ABAQUS [4]. The commercial programs ware used in tracing the nonlinear behavior of structures subjected to blast and impact loading.

Unfortunately, in case of blast loads, it is hard to carry out research because of national security reasons and substantial costs. However, with recent increasing need for study on this case, the body of experiments and numerical analyses subjected to blast loads has increased for concrete structures such as beams and columns and so on [5]-[7].

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This paper introduced RC beam model which can show the behavior of structures subjected to blast loads. Behavior of structures under blast loads is quite different from static condition and even general dynamic condition. Strain rate effect induced by blast loadings must be taken into consideration. Then, correlation study between analysis results and experimental results are conducted to compare the two results and then check the validity of the analysis procedure.

II. THEORETICAL BACKGROUND

A. Material Properties of Concerete

In order to define the behavior of structures subjected to blast load, strain rate effect must be considered. Material properties of concrete and steel are changed under blast loading with accompanying high strain rate [8]. In case of concrete, larger deformation is developed because of the widely distributed micro-cracks [9]. Also, concrete appears very sensitive material behavior to the strain rate dependent deformation. Therefore, nonlinearity of concrete material according to high strain rate which occurs under short duration loads should be taken into account to evaluate the behavior of concrete structures under blast and impact loading. Concrete subjected to rapid load does not have enough time to make distributed internal cracks, which produce confining stress at core of the specimen [8]. This lateral inertia confinement makes the strength of materials increase and this phenomenon is referred to as Inertial Resistance Effect. With this phenomenon, the strength of concrete increase by DIF(Dynamic Increase Factor) which can account for high strain rate [10]. Saatcioglu *et al*. [11] proposed simplified expressions for DIF and the expressions are as follows:

$$DIF = 0.03\ln\dot{\varepsilon} + 1.30 \geq 1.0 \quad \text{for} \quad \dot{\varepsilon} < 30s^{-1} \tag{1}$$

$$DIF = 0.55\ln\dot{\varepsilon} - 0.47 \quad \text{for} \quad \dot{\varepsilon} \geq 30s^{-1} \tag{2}$$

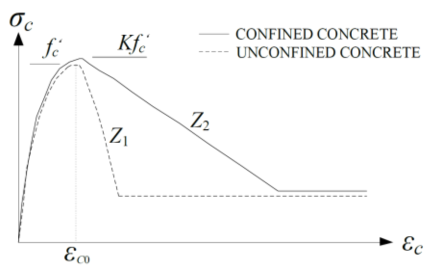

Figure 1. The stress-strain relation of modified Kent & Park model

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Fig. 1 shows the stress-strain relation of concrete adopted in this paper, which was proposed by Kent and Park and modified by Scott *et al*. [12]. Fig. 1 is representative of unconfined concrete and confined concrete for modified Kent and Park model. The effect of high rate strain was considered on the basis of this stress-strain relation.

B. Material Properties of Steel

The stress-strain relationship for reinforcing steel shows identical behavior of compression and tension unlike the stress-strain of concrete. However, the characteristic of steel is similar to that of concrete. The effect of high strain rate on steel causes the increase in yield strength and ultimate strength [13]. The stress-strain relation of steel adopted in this paper is illustrated in Fig. 2 and DIF factor of steel proposed by Saacioglu et al. [11] is as follow:

$$DIF = 0.34\ln\dot{\varepsilon} + 1.30 \geq 1.0 \tag{3}$$

C. Newmark Method

Dynamic analysis should be needed to figure out the behavior of structures subjected to blast loads. To obtain the solution of dynamic loaded structures, the method is roughly classified into two ways: explicit and implicit method. The implicit method is more complicated and time consuming to analyze the behavior of structures that explicit method. However, it is through implicit method that more accurate results can be obtained. The representative method of implicit is Newmark method which is used in this paper.

The way of implicit method is more complicated and time consuming to analyze structure's behavior than that of explicit method. However, it is through implicit method that more accurate results can be obtained. The representative method of implicit is Newmark method which is used in this paper. The coefficient of Newmark (β , γ) determine the exactness and stability of the solutions [14]. The conditional equation for the stability of the solution is expressed;

$$\frac{\Delta t}{T_n} \leq \frac{1}{\pi\sqrt{2}}\frac{1}{\sqrt{\gamma - 2\beta}} \tag{4}$$

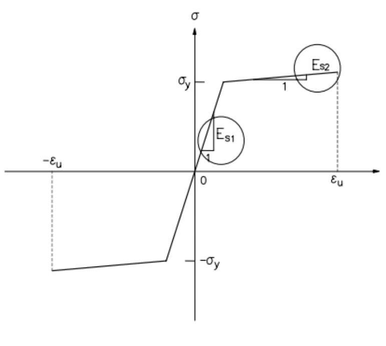


Figure 2. The stress-strain relation steel

where Δt is time interval, T_n is natural period and Table I. represents the analysis procedure for time step of Newmark method.

TABLE I. ANALYSIS PROCEDURES OF NEWMARK METHOD

1.Initial conditions

1) Calculate $\ddot{u}_o$ from the Eqn. of motion gi*****ven by $\dot{u}_o$, u_o : $\ddot{u}_o = \dfrac{p_o - c\dot{u}_o - ku_o}{m}$

2) Select Δt

3) Evaluates $a = \dfrac{1}{\beta\Delta t}m + \dfrac{\gamma}{\beta}c$, $b = \dfrac{1}{2\beta}m + \Delta t\left(\dfrac{\gamma}{2\beta} - 1\right)c$

2. Calculations for each time step, i

1) $\Delta\hat{p}_i = \Delta p_i + a\dot{u}_i + b\ddot{u}_i$

2) $\hat{k}_i = k_i + \dfrac{\gamma}{\beta\Delta t}c + \dfrac{1}{\beta(\Delta t)^2}m$

3) $\Delta u_i = \dfrac{\Delta p_i}{\hat{k}_i}$

4) $\Delta\dot{u}_i = \dfrac{\gamma}{\beta\Delta t}\Delta u_i - \dfrac{\gamma}{\beta}\dot{u}_i + \Delta t\left(1 - \dfrac{\gamma}{2\beta}\right)\ddot{u}_i$

5) $\Delta\ddot{u}_i = \dfrac{1}{\beta(\Delta t)^2}\Delta u_i - \dfrac{1}{\beta\Delta t}\dot{u}_i - \dfrac{1}{2\beta}\ddot{u}_i$

6) $u_{i+1} = u_i + \Delta u_i$, $\dot{u}_{i+1} = \dot{u}_i + \Delta\dot{u}_i$, $\ddot{u}_{i+1} = \ddot{u}_i + \Delta\ddot{u}_i$

3. Repetition for the next time step.(step 2.(1)-(5))

TABLE II. MATERIAL PROPERTIES [5]

Concrete		Steel	
Initial elastic modulus (GPa)	34.40	Elastic modulus (GPa)	210
Compressive cylinder strength (MPa)	43	Yield stress (MPa)	604
Tensile strength (MPa)	4.2	Mechanical reinforce-ment ratio	0.34
Poisson's ratio	0.2	Poisson's ratio	0.3
Density ($kg / m^{1/3}$)	2500	Density ($kg / m^{1/3}$)	7800

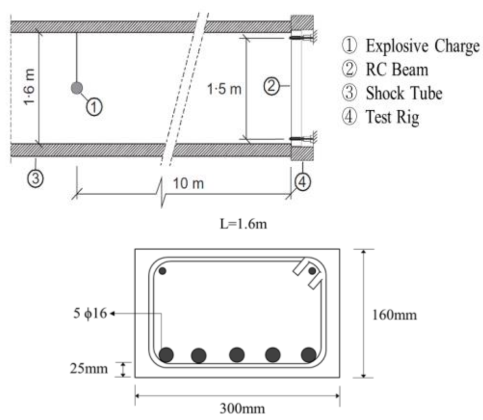


Figure 3. Experimental setup and geometric configuration of RC section [5]

III. ANALYSIS TENDENCY

In order to consider the tendency of analysis, it was assumed that surface burst took place from a certain distance. Also, the plane wave generated from surface burst was assumed to be uniformly applied to the target structure [15]. The experimental setup and geometric configuration of RC section are illustrated in Fig. 3. Also, material properties are summarized in Table II. Negative pressure phase was ignored for the computations since the effect of the phase is not significant compared to positive pressure phase [12], [15]. This paper adopted the simplified pressure-time relation shown in Fig. 4.

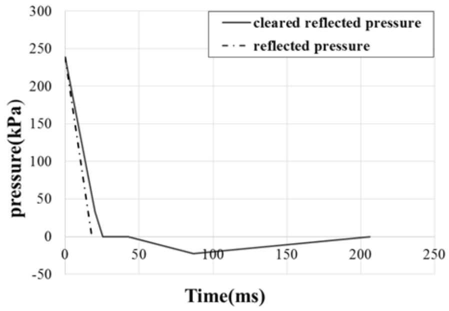


Figure 4. Simplified pressure-time curve

A. Tendency of Numerical Analysis

The stability can be guaranteed on condition of $\gamma \geq 0.50$ and $\beta \geq 0.25(0.5+\gamma)^2$. Therefore, the tendency of analysis was verified by fixing the gamma value to 0.5 and changing the beta value to 0.25 and 0.5 and 1.0, which is illustrated in Fig. 5. In case that the difference between beta and the proposed one for analysis stability is getting larger, it can be found that the accuracy of analysis results is reduced. On the other hand, in the event of setting the values of γ and β which are not satisfied for stability, the solutions of numerical analysis were not converged.

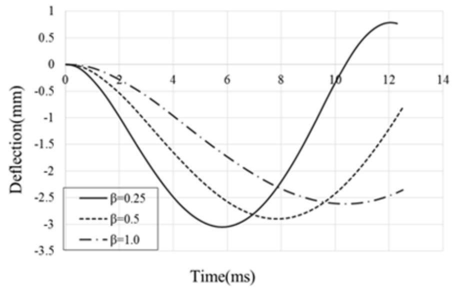
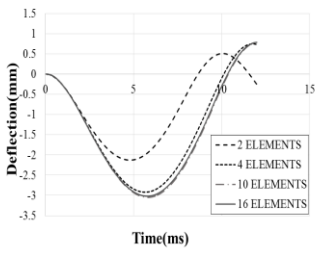
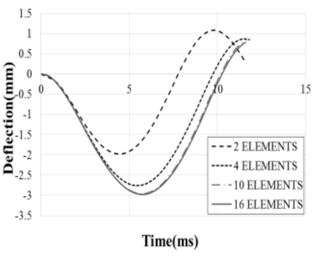


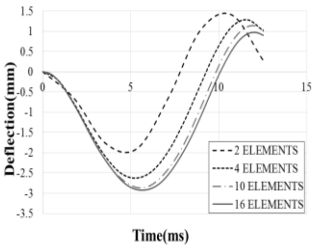
Figure 5. Analysis tendency according to β



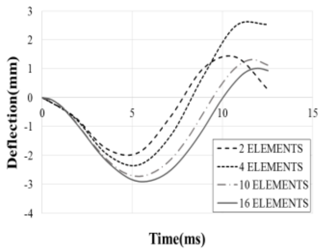
(a) $\Delta t = \Delta t_{max}$



(b) $\Delta t = 4\Delta t_{max}$

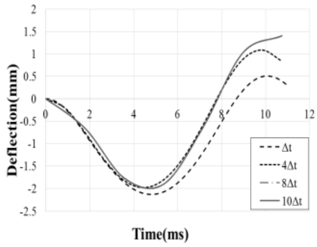


(c) $\Delta t = 8\Delta t_{max}$

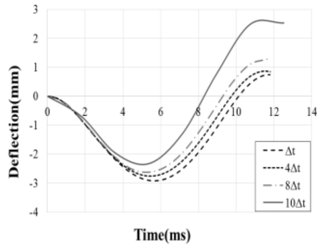


(d) $\Delta t = 10\Delta t_{max}$

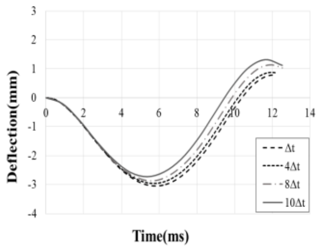
Figure 6. Analysis tendency according to the number of element with different time interval



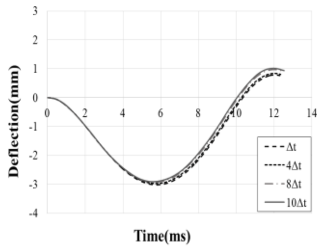
(a) 2elements



(b) 4 elements



(c) 10 elements



(d) 16 elements

Figure 7. Analysis tendency according to time interval with the number of elements

Tendency of analysis was investigated according to the number of element and time interval. First, the trend of analysis according to the number of element using the same time interval was considered. A relation between time and deflection at midpoint of the beam is illustrated in Fig. 6 which shows good agreement between results except for using 2 elements in case of $\Delta t = \Delta t_{max}$. However, in other cases, the difference of the results occurred depending on the number of element. Also, the accuracy of results is getting increase with the number of element regardless of the time interval.

Second, the trend of analysis according to the time interval using same element number was considered. Time interval was set 4 times, 8times and 10times greater than reference time. The same relation at midpoint of beam is shown in Fig. 7. In case of the results of using 2 elements and 4 elements, the solutions was more sensitively affected by the time interval than other cases. Also, is can be found that the results converged to the certain solutions with setting the time interval narrowly regardless of the number of elements.

IV. Experiment Verification

In order to testify the validity of the numerical method, RC Beam subjected to blast load was considered. The experimental data used in this paper was conducted by Magnusson, J. *et al*. [5]. In this experiment, blast load generated from a certain distance was assumed to be a plane wave passing through the box tube. The experimental setup, geometric configuration and material properties are same as the data used in III. Analysis tendency.

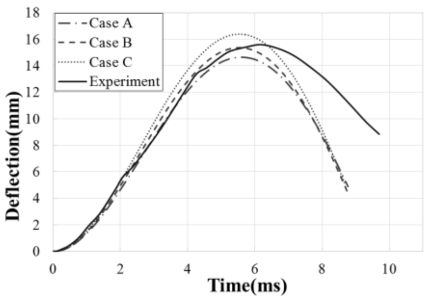


Figure 8. Results of analysis according to the number of element

TABLE III. Results of Numerical Analysis and Experiment

	Reflecting Pressure (kPa)	Total support reaction (kN)	Ultimate deflection (mm)
Experiment	1249±80	348	17.5
Case A	1169	296.3	14.7
Case B	1249	306.3	15.4
Case C	1329	320.1	16.4

Even though the value of impulse from experiment results seemed to be constant, the value of maximum reflected pressure was distributed ±80 based on the reference value of 1249kPa. Therefore, numerical results were obtained using mazimum reflected pressure as 1169kPa, 1249kPa, 1329kPa and illustrated in Fig. 8. As shown in Fig. 8, the results of numerical analysis gives very satisfactory agreement with the result of experiment data, especially case B. Table. Table III represents the results of numerical analysis and experimental data in order to compare the ultimate deflection at mid-span of beam in addition to total support reaction. As shown in Table III. The results of numerical analysis was more conservative than that of experimental data

V. Conclusions

This paper introduces numerical analysis method that can simulate the behavior of concrete beam subjected to blast loads. High strain rate induced by short duration load was taken into consideration on the basis of the layered-section approach. First, tendency of numerical analysis was check with variation of the number of element and time interval. Then, through correlation study between analysis results and experimental data from RC beam subjected to blast loads, the numerical procedure can be effectively used to estimate the behavior of RC beam.

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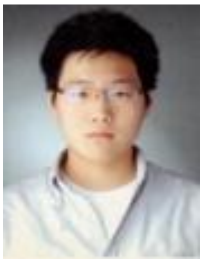

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