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Application of displacement-based design method to assess the level of structural damage due to blast loads †

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Abstract

In this paper, a displacement-based design (DBD) methodology commonly used for seismic design and evaluation of structures is adopted to determine the performance of structures to blast loading. In this method, structural performance is linked to measurable quantities such as the displacement ductility. To verify the applicability of the method and the accuracy of the results, a simple structural shape, including a square steel plate, is subjected to out-of-plane blast loading with different explosive charge weights and stand-off distances. With the adaptation of the AUTODYN software, the above-mentioned examples in a similar condition are also subjected to blast loading. It is found that the results of the DBD method agree favorably with the results obtained from a numerical method. It is also shown that a good prediction of the damage level can be made for steel plates subjected to different charge weights and stand-off distances.

Keywords: Blast load; Damage level; Steel plate; Displacement-based design (DBD)

1. Introduction

Recent terrorist events around the world have emphasized the need to re-evaluate the vulnerability of structures and structural members to blast loading and to carry out protective measures against such loadings. As "protection" is not an absolute concept for any structure based on a certain criterion, a particular level of protection may thus be considered. In designing against blast loading, an acceptable level of resistance and protection should be established, as blast loads may cause different levels of damage to structures, which may range from a minor damage to a complete structural failure. In steel structures, two different levels of failure are often specified. The damage level is associated with the ratio of ultimate displacement to yield displacement of structure, which is denoted by μ [1]. The first level constitutes those that are capable of functioning after the blast. The blast effect is minor in these structures, and they can become functional again with certain repairs. The ductility level for these structures is limited to $\mu = 3$. In the second level, structures are expected to sustain heavy damage beyond repair, while the integrity of the structure remains in place. The maximum ductility level considered for these structures is $\mu = 6$, above which the stability of the structure is jeopardized.

There is a close relationship between the above damage levels and the weight of the explosive charge and its distance. In the present paper, a displacement-based method generally used in seismic analysis and design [2] is adopted to evaluate the strength of structure against blast loading. The structural system considered here is a steel plate undergoing different loading conditions. First, damage level is defined, and then considering the ductility ratio of $\mu = 1$ to $\mu = 3$, the weight and distance of the explosion causing such damage are then evaluated.

2. Evaluation of blast load

As a result of a chemical blast, an overpressure is developed, the peak of which, P_s, can be evaluated as follows [3]:

$$\frac{P_s}{P_0} = \frac{808\left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\left[1+\left(\frac{Z}{0.048}\right)^2\right]^{\frac{1}{2}} . \left[1+\left(\frac{Z}{0.32}\right)^2\right]^{\frac{1}{2}} . \left[1+\left(\frac{Z}{1.35}\right)^2\right]^{\frac{1}{2}}} \tag{1}$$

In the above equation, Z is the scaled distance and is expressed in terms of the explosive material weight, W, and the explosion distance, R, as

$$Z = R / W^{1/3} . \tag{2}$$

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We can also calculate the amount of P_s from the graphs submitted by some other references [1, 4]. In Fig. 2(a), the submitted graph in the TM5-1300 code with Eq. (1) is graphed [4].

With the transfer of the blast wave, a dynamic pressure is applied to the structure, which can be evaluated as follows:

$$q_s = \frac{5P_s^2}{2(P_s + 7P_0)}\,, \tag{3}$$

where P_0 is the pressure of the ambient atmosphere. When the blast wave reaches the surface at right angles, reflective pressure, P_r, is produced.

$$P_r = 2P_s\left[\frac{7P_0 + 4P_s}{7P_0 + P_s}\right] \tag{4}$$

The variation in pressure in time is a logarithmic function, and it is often modeled as a linear triangular relationship for simplicity, as shown in Fig. 1. In this figure, t_d is the time at which the blast impulse on the structure ends and is usually referred to as the "clearing-time." This time is dependent on the time of application of overpressure as well as on the velocity of shockwave [5]. In TM5-1300 [4], a graph is presented to calculate the duration of explosion time, t_d, and this graph can be simplified with Eq. (5).

$$\begin{aligned} &\log_{10}\left(t_d / W^{1/3}\right) = 2.5\log_{10}(Z) + 0.28 \qquad ;Z \le 1 \\ &\log_{10}\left(t_d / W^{1/3}\right) = 0.31\log_{10}(Z) + 0.28 \qquad ;Z \ge 1 \end{aligned} \tag{5}$$

In Fig. 2(b), the comparison of this equation with TM5-1300 is shown.

The peak blast pressure on the structure $(P_{\max})$ and the duration of its application (t_d) are plotted against the scaled distance Z in Figs. 2(a) and 2(b), respectively.

3. Material model of steel

To make a model of the nonlinear behavior of steel plate under blast loading, it is necessary to use a suitable material model. Since blast loading occurs in a fraction of a second, factors such as strain hardening, high strain rate, and high temperature variation, which result from plastic deformation, must be considered in addition to the behavioral characteristics of steel.

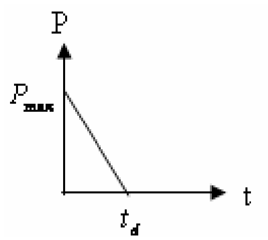


Fig. 1. The simplified pressure-time relation in blast loading.

In the Johnson-Cook model [6], the effects of strain hardening, strain hardening rate, and temperature softening must be considered in the calculation. Moreover, with great accuracy, yield stress and steel fail stress in blast can be predicted [7, 8].

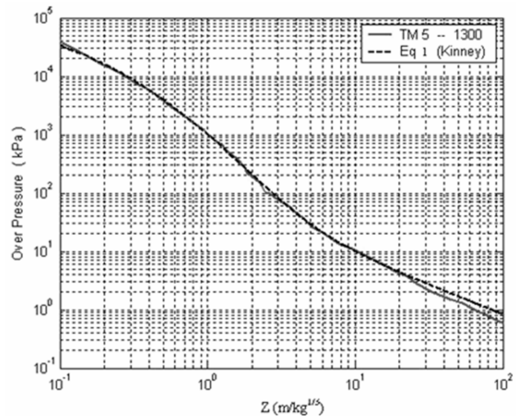
The Johnson–Cook model clearly states the material yield stress with Eq. (6) [6, 9].

$$\overline{\sigma}_y = \left[A + B\left(\overline{\epsilon}^P\right)^N\right]\left[1 + C\ln\left(\dot{\epsilon}^*\right)\right]\left[1 - \left(T^*\right)^M\right] \tag{6}$$

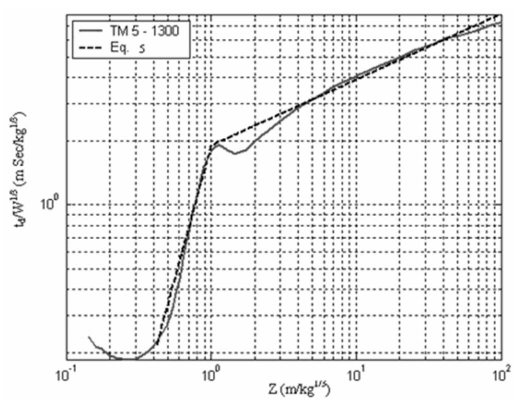
In this equation, the first brackets show the effect of strain hardening, where A is the yield stress, B and N are the hardening parameters, and $\overline{\epsilon}^P$ is the effective plastic strain. The second bracket shows the effect of the strain rate $\left(\dot{\epsilon}^*\right)$, and the third brackets show the dependency of the yield stress to temperature variation. C and M are experimental parameters, and T^* is a dimensionless quantity that can be derived from Eq. (7) as follows:

$$T^* = \left(T - T_{ref}\right)/\left(T_{melt} - T_{ref}\right) \tag{7}$$

In the above equation, T_{ref} is the ambient temperature, T_{melt} is the material melting point, and T is the temperature in which $\overline{\sigma}_y$ is calculated. The constants of A, B, C, N, and M result from the torsional test with a high strain rate along with the dynamic stress test.



(a)



(b)

Fig. 2. Peak blast pressure and its time of application.

Table 1. Parameters of mild steel.

$\rho\ (kg/m^3)$	7890	$B\ (MPa)$	275
$E\ (GPa)$	208	n	0.36
v	0.28	C	0.079
$A\ (MPa)$	250	$\dot{\epsilon}_0$	1

The effective plastic strain is calculable based on the plastic strain tensor $\left(d\,\overline{\epsilon}_{ij}^{P}\right)$,

$$\overline{\epsilon}_P = \int_0^{\epsilon} d\,\overline{\epsilon}^P \tag{8}$$

$$d\,\overline{\epsilon}^P = \left(\frac{2}{3} d\,\overline{\epsilon}_{ij}^P\, d\,\overline{\epsilon}_{ij}^P\right)^{\frac{1}{2}} \tag{9}$$

The dimensionless strain rate $\left(\dot{\epsilon}^*\right)$ can also be calculated from Eq. (10),

$$\dot{\epsilon}^* = \dot{\overline{\epsilon}}^P / \dot{\epsilon}_0\ , \tag{10}$$

where $\dot{\overline{\epsilon}}^P$ is the effective plastic strain rate, and $\dot{\epsilon}_0$ is an initial constant. Some of these experimental constants are available from the Johnson–Cook equation. Some of the constants for mild steel are presented in Table 1 [10].

4. Application of DBD method

The main feature of the DBD method is the way it associates the performance of the structure with measurable parameters [2]. In this method, the structural performance criteria selected for the design or assessment can be correlated to a measurable quantity, such as the displacement-based ductility. For reinforcement concrete structures, the ductility level in the range of 1-6 can be correlated to performance damage levels that lead to “small cracks and minor damage” or “severe damage beyond repair.” In the DBD method, first, the bilinear nonelastic response of the structure is evaluated. The idealized bilinear response, shown in Fig. 3, is determined considering the assumed ductility ratio. In this process, the complete nonelastic, force-displacement response is modeled by an effective linear stiffness K_{eff} and is shown in Fig. 3. The effectiveness can be determined as follows:

$$K_{eff} = F_a / \delta_a \tag{11}$$

In the yield displacement, δ_y and thhe selected displacement, δ_a, corresponding to a certain damage level and its associated ductility level can be evaluated as

$$\delta_a = \mu . \delta_y\ . \tag{12}$$

To determine the effective elastic period of the vibration of the structure, the effective linear stiffness is used, that is,

$$T_{eff} = 2\pi\sqrt{M / K_{eff}}\ , \tag{13}$$

where M is the mass of the structure.

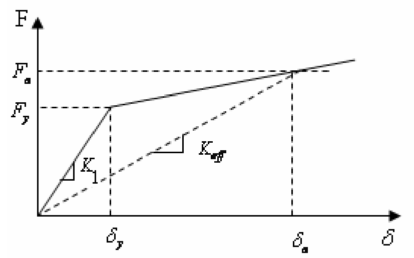


Fig. 3. Force-displacement model.

The displacement response of the structure to the blast impulse loading in the time span before and after the loading is evaluated as follows [11]:

$$\begin{aligned}
&\Delta_{(t)} = \Delta_{st}\left(\frac{\sin\omega t}{\omega t_d} - \cos\omega t - \frac{t}{t_d} + 1\right) \qquad ;\ t < t_d \\
&\Delta_{(t)} = \Delta_{st}\left[\left(\frac{\cos\omega t}{\omega t_d} + \sin\omega t - \frac{1}{\omega t_d}\right)\sin\omega t + \right. \\
&\qquad\qquad \left.\left(\frac{\sin\omega t}{\omega t_d} - \cos\omega t_d\right)\cos\omega t\right] \qquad ;\ t > t_d
\end{aligned} \tag{14}$$

In the above equations, Δ_{st} is the displacement caused by the equivalent static load P_E, that is,

$$\Delta_{st} = P_E / K_{eff}\ . \tag{15}$$

The maximum value obtained for Δ_{st} from the above equation can be considered the maximum dynamic displacement under impulse loading. This displacement, denoted by δ_a, is related to the equivalent static displacement by a dynamic magnification factor, MF, in the form;

$$MF = \delta_a / \Delta_{st}\ . \tag{16}$$

Magnification factor, MF, is plotted against different t_d / T_{eff} ratios in Fig. 4. By determining MF in Fig. 4, the plate blast loading capacity is determined as

$$P_E = \delta_a . K_{eff} / MF\ . \tag{17}$$

5. Evaluation of weight and distance of explosive charge

The step-by-step procedure for evaluating the weight and distance of the explosive charge for a specific damage level for a steel structure is as follows:

Step 1. Evaluate the force-displacement relation for the structure according to Fig. 3.

Step 2. Select the displacement ductility ratio, which is equivalent to the state of seismic damage due to blast loading.

Step 3. Calculate the equivalent stiffness K_{eff} from Eq. (11).

Step 4. Calculate the fundamental period of vibration of the structure, T_{eff}, from Eq. (13).

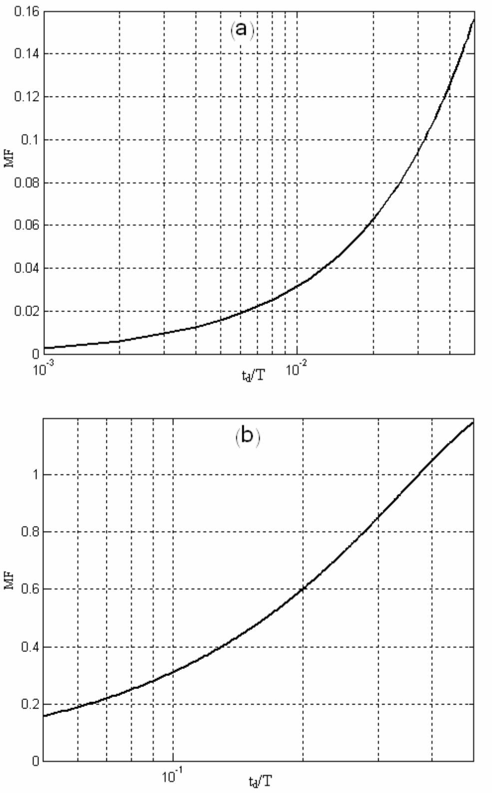


Fig. 4. Dynamic magnification factor, MF.

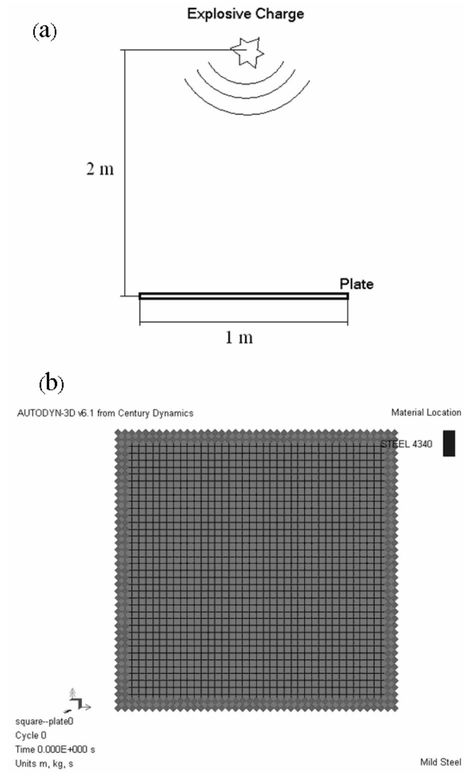


Fig. 5. Configuration of the modeling. (a) situation of the charge and plate, (b) meshed plate along with the boundary condition.

Step 5. Select the initial amount *Z* with consideration of *R* and *W* from Eq. (2).

Step 6. Calculate the blast loading time, t_d , from Eq. (5) or Fig. 2(b).

Step 7. Determine the magnification factor, MF, from Fig. 4, or derive it from Eq. (14).

Step 8. Calculate the blast loading capacity of the structure, P_E , from Eq. (17).

Step 9. Calculate the scaled distance, Z, from Eqs. (1) and (3).

If the scaled distance, *Z*, determined in step 9 , falls within a specific tolerance compared with the distance evaluated in the previous step, the process stops; otherwise, steps 6-9 are repeated until the required convergence is achieved. When reaching the convergence, the weight and distance of the explosive charge capable of creating the deformation or the damage level can be evaluated. This process enables the user to forego a laborious dynamic analysis and to obtain acceptable results with a simple static analysis.

It should be noted that because of the very short duration of blast loading, the usual dynamic solution based on implicit methods do not generally reach convergence, and it is necessary to employ explicit methods. With every step of the dynamic analysis, the deformation corresponding to the blast with a specific weight of explosive at a certain distance from the structure is also obtained. Therefore, to reach the required deformation or damage level, repeated dynamic solutions are necessary, which increase the solution time.

6. Numerical simulation

Autodyn hydrocode is used for numerical simulation, and an explicit method is adopted in this software. The explosive is placed at a distance away from plate and above the midpoint. Therefore, the load is vertical to the plate, and the displacement is in the vertical direction as well [Fig. 5(a)]. This problem is modeled in a 3D environment, and Lagrangian shell elements are used for modeling.

The plate perimeter has been fixed against bending. Therefore, two rows of neighboring nodes are constrained under vertical displacements. A schematic of the meshed plate along with the boundary conditions is shown in Fig. 5(b).

Dynamic load is applied in distributed form and is perpendicular to the plate. The material behavior is modeled using the Johnson–Cook model, and the equation of state is linear. The needed constants for the material model and equation of state are shown in Tables 1 and 2, respectively. The initial time step is assumed to be 2.7334×10^{-6}.

To examine the effect of meshes on result accuracy, a 1m*1m plate is divided into the elements of different dimensions such as 25, 50, 100 and 225 mm. This plate is subjected to compression loading of a 1 kg TNT explosive material in the distance of 2 m. Using equations 1 to 5,

$Z = 2\ \mathrm{m/kg}^{1/3}$; $P_s = 207.9$ kPa; $P_r = 968.6$ kPa
$q_s = 117.8$ kPa; $t_d = 2.36$ mSec

Table 2. Linear equation of the state parameters.

Bulk modulus (Gpa)	Specific heat (J/kg°K)	Reference temperature (°K)
159	477	300

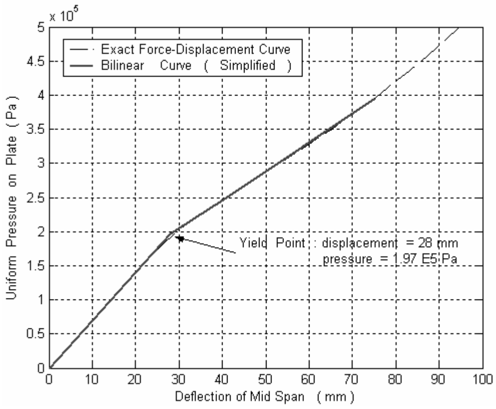


Fig. 6. Result of the convergence in the midpoint of the plate; a) deflection, b) velocity.

Therefore, the plate is subject to a triangular load with a maximum pressure of $P_r + q_s$ = 816.4 kPa in 2.36 (ms). The displacement and velocity of the plate midpoint from the beginning of the loading to 0.01 (s) are shown in Figs. 6(a) and 6(b), respectively. Figs. 6(a) and 6(b) show that the results converge with decreasing mesh size. This convergence is such that the difference between meshes with 25 and 50 mm dimensions is not noticeable. Selecting smaller sizes for the meshes does not have a noticeable change in the accuracy of the results. However, the calculation time increases more. Thus, elements with a 25 mm dimension are used in the preceding calculations.

7. Examples

To show the above process, we use a steel plate with dimensions of 1×1 m^2 and with a thickness of 5 mm. The clamp-supported plate is then subjected to various static pressures. The idealized graph for force-displacement is calculated and plotted, as in Fig. 7. This plate is analyzed under different ductility ratios and through the above-mentioned nine steps. The results of this analysis are the weight and the distance of the explosive charge, which bring about the displacement. The Johnson-Cook material model is used for the behavior of the mild steel, and its constants are shown in Table 1.

I. If ductility ratio of the plate is $\mu = 1$, then the corresponding parameters are

$$\delta_a = 0.028\, m, F_a = 1.97\ E5\ Pa, K_{eff} = 7.04E6\ Pa/m,$$
$$T_{eff} = 0.0149 \sec$$

Table 3(a) shows the nine steps for 1 kg of TNT charge at 1 m away from the steel plate.

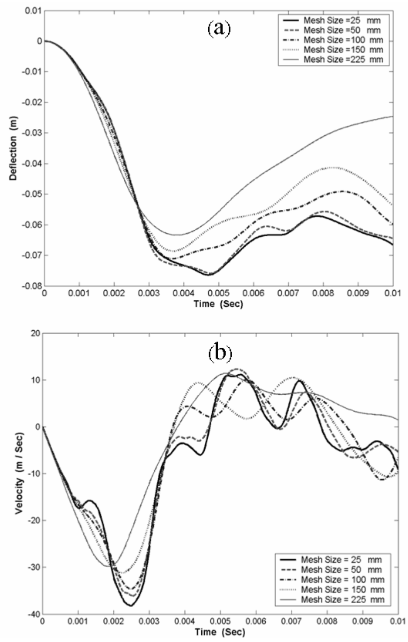


Fig. 7. Force-deformation curve for the middle of the plate.

This plate with identical geometry and boundary conditions under blast loading $P_E = 3.86E5\ Pa$ has been analyzed using AUTODYN hydrocode [12]. In Fig. 8(a), the midpoint displacement of the plate under blast loading is shown. Fig. 8(a) also shows that the DBD method can clearly predict the maximum displacement. Time history of the displacement in the figure shows that the plate mainly has an elastic behavior, and its permanent displacement is very minute.

II. In this stage, the ductility ratio for the plate is $\mu = 1.5$. The corresponding parameters are shown in Table 3(b). Nine steps are observed.

$$\delta_a = 0.042\, m, F_a = 2.50\ E5\ Pa, K_{eff} = 5.95E6\ Pa/m,$$
$$T_{eff} = 0.0162 \sec$$

In Fig. 8(b), the result of the analysis with AUTODYN is shown. This figure not only indicates the exactness of the DBD method but also indicates the ductility ratio of $\mu = 1.5$, which ends up with a permanent displacement of the plate.

III. The plate ductility ratio is $\mu = 2$. The corresponding parameters are

$$\delta_a = 0.056\, m, F_a = 3.2\ E10\ Pa, K_{eff} = 5.7E6\ Pa/m,$$
$$T_{eff} = 0.0165 \sec$$

The results are presented in Table 3(c).

In Fig. 8(c), the exactness of the displacement is shown by using the DBD method of evaluation. The ductility ratio of $\mu = 2$ also causes considerable plastic displacement in the structure.

IV. When the ductility ratio of the steel plate is $\mu = 2.5$, the corresponding parameters are

$$\delta_a = 0.070\, m, F_a = 3.7\, E5\, Pa, K_{eff} = 5.3E6\, Pa/m,$$
$$T_{eff} = 0.0171 \sec$$

Table 3(d) shows the results.

In Fig. 8(d), plate analysis with AUTODYN is shown. The permanent displacement is so high that it is practically impossible to repair the plate after the blast loading.

V. When the ductility ratio for the steel plate is $\mu = 3$, the corresponding parameters are

$$\delta_a = 0.084\, m, F_a = 4.4E5\, Pa, K_{eff} = 5.24E6\, Pa/m,$$
$$T_{eff} = 0.01724 \sec$$

The results are presented in Table 3(e).

Table 3. Results of the 9-step analysis for steel plate.

(a) Ductility level=1

Z $(m/kg^{1/3})$	t_d ($m\sec$)	t_d/T_{eff}	MF	P_E (Pa)
1	1.91	0.128	0.40	4.93E5
2.24	2.45	0.164	0.50	3.94E5
2.42	2.51	0.168	0.51	3.86E5
2.44	2.51	0.168	0.51	3.86E5

(b) Ductility level=1.5

Z $(m/kg^{1/3})$	t_d ($m\sec$)	t_d/T_{eff}	MF	P_E (Pa)
1	1.91	0.118	0.365	6.85E5
2.0	2.36	0.146	0.45	3.56E5
2.15	2.42	0.149	0.46	5.44E5
2.17	2.42	0.150	0.46	5.44E5

(c) Ductility level=2

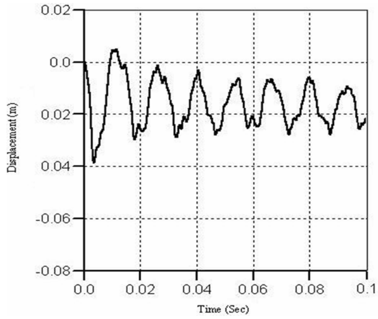
Z $(m/kg^{1/3})$	t_d ($m\sec$)	t_d/T_{eff}	MF	P_E (Pa)
1	1.91	0.116	0.358	8.94E5
1.85	2.31	0.140	0.430	7.44E5
1.96	2.35	0.142	0.438	7.30E5
1.98	2.36	0.143	0.439	7.27E5

(d) Ductility level=2.5

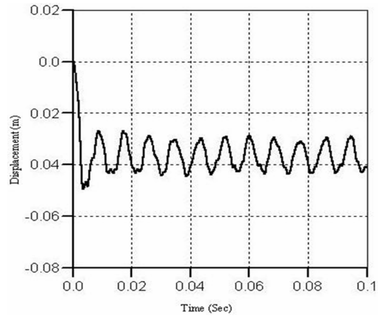
Z $(m/kg^{1/3})$	t_d ($m\sec$)	t_d/T_{eff}	MF	P_E (Pa)
1	1.91	0.112	0.346	1.07E6
1.74	2.26	0.132	0.407	9.09E5
1.84	2.30	0.135	0.414	8.94E5
1.85	2.31	0.135	0.416	8.90E5

(e) Ductility level=3

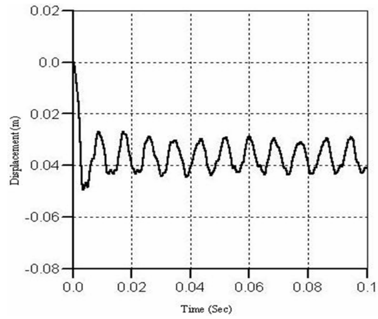
Z $(m/kg^{1/3})$	t_d ($m\sec$)	t_d/T_{eff}	MF	P_E (Pa)
1	1.91	0.111	0.343	1.28E6
1.65	2.23	0.129	0.399	1.10E6
1.77	2.27	0.132	0.406	1.08E6
1.785	2.28	0.132	0.407	1.08E6



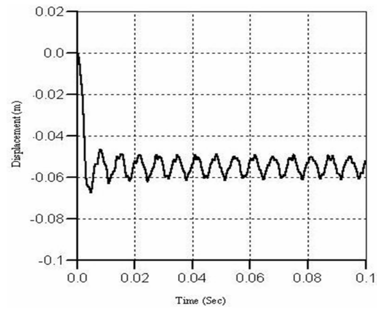
(a) Ductility level=1



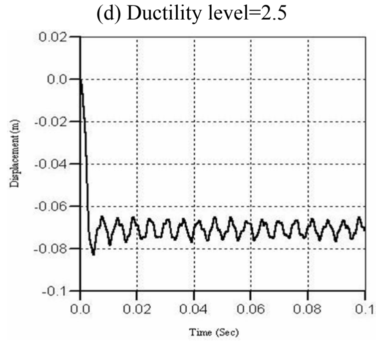
(b) Ductility level=1.5



(c) Ductility level=2



(d) Ductility level=2.5



(e) Ductility level=3

Fig. 8. Time history of the midpoint displacement (AUTODYN output).

In Fig. 8(e), the application of the DBD method shows the exactness of the displacement. It also shows that the plastic displacement is such that the structure is practically beyond repair.

8. Conclusion

In this paper, a displacement-based method DBD is presented by which the weight of the charge and its distance from the steel plate are evaluated for a specific level of damage. The proposed numerical examples confirm the correctness of such method. Moreover, the ductility ratio of $\mu = 2-3$ causes massive permanent displacement in the plate, which in turn represents a very severe permanent displacement. Investigations also show that the damage in the plate with a ductility ratio of $\mu = 1.5$ is relatively severe.

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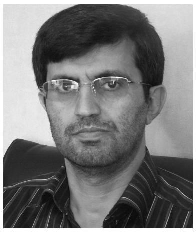

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