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Deformation-Controlled Design of Reinforced Concrete Flexural Members Subjected to Blast Loadings

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Abstract

Both maximum displacement and displacement ductility factors should be considered in the design of a blast-resistant structure since both parameters correlate with an expected performance level of a reinforced concrete (RC) structural member during a blast event. The blast-resistant design procedure discussed in this paper takes into account both the maximum displacement and displacement ductility responses of an equivalent single-degree-of-freedom (SDOF) system, while the response of the SDOF system is made equivalent to the corresponding targets of design performance. Some approximate errors are present when comparing the actual responses of the structural member, which has been designed for blast loading, and their corresponding design performance targets. Two indices are defined to quantify the approximation errors, and their expressions are obtained through comprehensive numerical and statistical analyses. By using the error indices, the design procedure is then modified such that the approximate responses of the RC member are equivalent to the targets of the design performance. The modified procedure is implemented in three design examples and numerically evaluated. It is concluded that the modified procedure can be used more effectively in order to ensure that the actual responses of designed members reflect the respective targets of design performance.

Keywords: Displacement; Blast loads; Errors; Reinforced concrete; Deformation.

Introduction and Background

The design of reinforced concrete (RC) structural members against accidental or deliberate explosions is deemed necessary with an increasing emphasis on blast loading on structures. The blast load exerted on a structural member can be adequately simplified as a uniformly distributed dynamic loading, characterized by its peak pressure and duration, with the exception of very close-in explosion situations. Some level of inelastic deformation of the structural member is allowed in the blast-resistant design when subjected to severe blast loadings to dissipate energy, therefore, most of blast design guidelines (ASCE 1985; NFEC 1986; U.S. Army 1986, 1990; Biggs 1964), with explicit consideration of inelastic deformation, have been proposed in recent years. These design

guidelines help to ensure that a RC member is designed such that its response is equivalent to the predefined performance level under blast loading. Thus, the proposed design procedure seeks to reconcile the differences between a possibly lower response as determined by numerical methods and a possibly higher level response as predetermined by design performance.

In this paper, a new deformation-controlled blast-resistant design procedure using nondimensional energy spectra (NES) was developed. The effective depth (d) and longitudinal reinforcement ratio (ρ) of a RC member can be determined by representing a continuous RC member as an equivalent elastic–plastic single-degree-of-freedom (SDOF) system. Subsequently, the maximum displacement and displacement ductility responses (y_m^{eq} and μ^{eq}) can be made equivalent to the corresponding design performance targets, which are defined by its target displacement and target displacement ductility factor (y_t and μ_t) (ASCE 1985; NFEC 1986; U.S. Army 1986, 1990; Kottegoda and Rosso 1996). This procedure is based on an underlying assumption that the responses (y_m^{rc} and μ^{rc}) of the designed RC member at a critical location (for a fixed–fixed member, the critical location is the midspan; for a cantilever member, the critical location is the free end) can be represented by the responses of its equivalent SDOF system (y_m^{eq} and μ^{eq}) for a defined blast loading. However, the difference of y_m^{rc} and μ^{rc} with its respective y_m^{eq} and μ^{eq} can be expected due to the complexities of the nonlinear dynamic response of RC members under blast loading conditions, which cannot be captured by the equivalent elastic–plastic SDOF system. This manifests itself in the errors between the displacement ductility responses (y_m^{rc} and μ^{rc}) and the corresponding design performance targets (y_t and μ_t).

In principle, a response analysis should be capable of controlling the actual responses of a RC member (y_m^{rc} and μ^{rc}) rather than those of the corresponding equivalent SDOF system (y_m^{eq} and μ^{eq}), for a given design performance targets (y_t and μ_t). Thus, it is worthwhile determining the errors between the actual responses (y_m^{rc} and μ^{rc}) and the corresponding performance targets (y_t and μ_t) of a RC member. Application of these errors in modifying the deformation-controlled blast-resistant design procedure will actually help in controlling the responses of y_m^{rc} and μ^{rc} . This paper discusses some numerical examples to demonstrate the analysis procedure using the modified design method. Numerical simulations of the displacement and the displacement ductility responses under blast loading are performed, and the results are compared with the performance targets.

Deformation-controlled Design Procedure

Nondimensional Energy Spectrum

A nondimensional energy spectrum is an important tool in the incorporation of the target displacements and target displacement ductility factors (y_t and μ_t), which allows for determining design parameters of d and ρ for RC members. The nondimensional energy factor (C) is introduced into an elastic–plastic SDOF system (see Fig. 1),

expressing the ratio of maximum strain energy $E_{\max}$ to the ultimate elastic energy E_{el} and is given in Eq. (1)

$$C = E_{\max}/E_{el} \quad (1)$$

where $E_{el} = k_e y_e^2/2$; and $E_{\max} = k_e y_e (y_{\max} - y_e/2)$. Substituting them into Eq. (1), C becomes

$$C = 2\mu - 1 \quad (2)$$

where $\mu = y_{\max}/y_e$. The displacement ductility factor (μ) is a function of F_1/R_m (where F_1 = peak value of the force); and t_d/T and their distributions can be found in Biggs (1964). A group of curves, which represent the factor C against the ratio t_d/T with respect to various F_1/R_m , are defined as NES and are shown in Fig. 2.

Design of RC Flexural Member Using NES

A structural member with continuous mass and stiffness can be represented by an equivalent elastic-plastic SDOF system with an equivalent mass and stiffness (Biggs 1964). The equivalent SDOF system is such that the deformation response of the concentrated mass is assumed to be the same as that for the critical point on the structural member (e.g., the midspan of a member with two ends constrained or the free end of a cantilever member). Thus, the responses of the equivalent SDOF system under a given blast loading should achieve the expected performance level defined by y_t and μ_t . To achieve this objective, there exists only one solution in the form of the initial stiffness (k_e) and ultimate strength (R_m) for the equivalent system. Therefore, it is clear with the condition $y_e = y_t/\mu_t$ having been satisfied, and the maximum displacement response of the equivalent SDOF system k_e having reached y_t exactly, the maximum displacements of equivalent systems with initial stiffness are either larger or smaller than k_e but not equal to y_t . The specific solution for k_e and R_m of the equivalent SDOF system can then be obtained by an iterative procedure. Assuming an initial stiffness k_e , the parameters F_1/R_m and t_d/T of the system are obtained and then the values, C and $E_{\max}$ are found by referring to the NES curves in Fig. 2. However, the value of $E_{\max}$ will result in a new stiffness k_{el} with

$$k_{el} = \frac{E_{\max}}{y_e y_t - y_e^2/2} \quad (3)$$

In order to make $k_e = k_{el}$, the above procedure is repeated until the convergent condition of $|k_{el} - k_e| < \varepsilon$ (where ε = convergence tolerance) is fulfilled.

A few methods to compute d and ρ for a RC member from k_e and R_m of the corresponding equivalent SDOF system are discussed in blast design guidelines (ASCE 1985; NFEC 1986; U.S. Army 1986, 1990; Biggs 1964). These ways consider the

characteristics of concrete and the embedded reinforcements. The equations are summarized as follows (Li et al. 2006):

$$d = \left(\frac{24l^3 k_e}{(\gamma + 1)\alpha K_{LE} E_c b_w} \right)^{1/3} \quad (4)$$

$$\rho = \frac{\beta R_m l}{K_{LE} f_{ds} b_w d (d - d')} \quad (5)$$

$$\rho_v = (V_u - V_c) / \phi f_{dv} b_w d \quad (6)$$

where l = length of member; K_{LE} = load transformation factor; α and β = coefficients for different boundary conditions; E_c = Young's modulus of concrete; b_w = member width; and the parameter of γ can be obtained from Fig. 3. It is observed that the coefficient varies with ρ as well as the modulus ratio (E_s/E_c), where E_s = Young's modulus of steel (U.S. Army 1986, 1990); V_u = ultimate shear force; and V_c = shear capacity of the concrete. f_{ds} and f_{dv} = dynamic yield strength for longitudinal and shear reinforcements, respectively, in which the dynamic increase factors (DIFs) are used in the design according to TM5-1300 (U.S. Army 1990).

Eq. (4) demonstrates that d is a function of γ . Since γ varies with ρ as shown by Fig. 3, d such that it considers ρ . On the other hand, Eq. (5) indicates that ρ is determined by d . Therefore, an iterative computational procedure needs to be employed to determine d and ρ of a RC member against the given blast loading. Combining it with the previous iterative procedure of determining k_e and R_m of the equivalent SDOF system for a given blast loading and the dual targets of y_t and μ_t , the design flow chart for determining d and ρ based on NES is shown in Fig. 4. In the above developed design procedure, an initial data of d_0 and ρ_0 is assumed such that the value of $E_{\max}$ for the equivalent SDOF system can be obtained. However, this $E_{\max}$ will result in a new solution of d_1 and ρ_1 and the process must be repeated until d and γ are consistent.

Implementation of the Design Procedure

To evaluate the effectiveness of applying the presented design procedure, a demonstration is given by implementing it on the design of a RC wall subjected to blast loading. The RC wall is designed to resist the blast loading perpendicular to its plane. The blast loading is simplified into a triangular pulse with the peak pressure and duration as shown in Fig. 5. The design is required to achieve the expected performance level defined by $\mu_t = 9$ and $\theta_t = 4^\circ$. Thus, y_t of the wall at the free end under the given blast condition can be obtained with an approximate expression of $y_t \approx l \tan(\theta_t)$. The area of compression reinforcement is taken to be equal to that of the tension reinforcement. This equivalent of reinforcement would consider the rebound effect of the member subsequent to its maximum displacement response, and makes provision for the possibility of the explosion occurring in the opposite side of the wall.

The design procedures for the iterative step are illustrated in Table 1. During the design process, the value of the initial effective depth (d_0) is taken as 2.0 m and the initial ρ_0 to be 3.0%. The convergence limit employed in the design is 0.001. It can be seen from Table 1 that the design procedure is insensitive to the initial values of d_0 and ρ_0 . Therefore, there is no difficulty in achieving computational convergence during the iterations. It takes only seven iterative steps in this example to find the solution and satisfy the condition of $|(d_1-d_0)/d_0| < 0.001$ and $|(\rho_1-\rho_0)/\rho_0| < 0.001$. The time taken for the computation of this design example is only 0.12 s using a program written with MATLAB (2001).

Numerical Verification

Verification of the Responses for the Equivalent SDOF System

To assess whether the responses of the equivalent SDOF system for the designed RC member under the given blast loading are controlled to be exactly equal to their performance targets, the nonlinear time–history analysis is carried out upon the equivalent SDOF system having k_e and R_m . The displacement responses are shown in Fig. 6. It is observed that y_m^{eq} and μ^{eq} of the equivalent SDOF system meet their targets exactly.

Verification of the Actual Responses of RC Member

Due to the complicated behaviors of continuous RC members, some differences between the responses of the equivalent SDOF system (y_m^{eq} and μ^{eq}) and those of the designed member (y_m^{rc} and μ^{rc}) are conceivable, as shown in Fig. 7. Therefore, some approximate errors are noticed between the actual response (y_m^{rc} and μ^{rc}) and the corresponding targets (y_t and μ_t). To evaluate the effectiveness of the presented design procedure in controlling the responses of the designed member, y_m^{rc} and μ^{rc} of the member under the same blast loading were determined using the ABAQUS software (ABAQUS 2003). The values of y_m^{rc} and μ^{rc} were compared with their respective design performance targets (y_t and μ_t).

The smeared cracking model for concrete is utilized considering that the failure of RC members under blast conditions is characterized by concrete crushing accompanied by concrete cracking. In this model, a crack appears when the maximum principal tensile stresses reach a failure surface. The von Mises yield criterion is used to describe the constitutive behavior of the reinforcement. The stress–strain relationship of reinforcement is modeled with an elastoplastic curve. The strain hardening of reinforcement is not considered in this analysis since it is hard to define under the blast conditions due to lack of experimental data. The ultimate strain value is never reported in the current literature due to the difficulty of determining exactly when the peak stress occurs as well as the confusion between ultimate strain and rupture strain. To simulate the softening effect of the concrete in tension, a bilinear tension stress–strain curve is used after cracking, where the failure strain $\varepsilon_u^{\text{cr}}$ is taken as 10^{-3} . The selection of this value is based on the

assumption that the strain softening after failure reduces the stress linearly to zero at a total strain of about 10 times of the strain at failure of concrete in tension, which is, typically, 10^{-4} in standard concretes (Hilleborg et al. 1976). For strain failure of concrete in compression, it is simulated with an elastic–plastic mode and the elastic stress state is limited by a yield surface. Once yielding had occurred, an associated flow rule with isotropic hardening is used.

Considering that both concrete and reinforcement exhibit increased strength under higher loading rates, the expressions of DIFs (Malvar and Crawford 1998a,b) are adopted. The user subroutine was developed to consider DIFs in the analysis, which allows the user to define the field variable of a material at any point as a function of any available material point quantity. Thus, by making the strain rate a variable, the strain rate-dependent material properties can be introduced in the analysis. Timoshenko beam elements were assigned to model the members while the rebar option was utilized to place each reinforcement at its exact location. A perfect bond between rebar and concrete was assumed. The finite-element models have been verified for a simply supported RC beam and a slab subjected to blast loading, where numerically determined responses are similar to experimental ones (Rong 2005; Rong and Li 2007).

Nonlinear dynamic analysis was performed on a design of a cantilever RC wall designed for a given blast loading. The plot of free-end responses of the wall in terms of displacement versus time is illustrated in Fig. 8. It is observed that y_m^{rc} for the designed RC walls under the given blast loading is slightly less than y_t . A deviation of about 10% of y_t was observed while μ^{rc} was equal to 5.18 as compared to $\mu_t = 9$. The difference between μ^{rc} and μ_t was about 42.4% of μ_t , and the error between μ^{rc} and μ_t was larger than that between y_m^{rc} and y_t .

Comparisons of Figs. 6 and 8 demonstrate that values of y_m^{eq} and μ^{eq} of the equivalent SDOF system met their targets. There still existed some errors between the actual responses (y_m^{rc} and μ^{rc}) of the RC member and the corresponding design performance targets (y_t and μ_t). This indicated that the errors occurred due to the derivation of d and ρ from k_e and R_m in the design process. Several points accounting for the errors are explained as follows:

- The load and mass factors (K_{LE} and K_{ME}) are necessary in considering the continuous RC member as the equivalent elastic–perfectly plastic SDOF system, whereby these factors are obtained in an approximate way, which is because the continuous resistance function was represented in two or three independent linear stages during the design process as a simplification. Thus, the utilization of K_{LE} and K_{ME} will cause some errors between the responses of the designed member and their design targets.
- It is known that the embedded reinforcement and the cracking propagation of the concrete have a great effect on the value of I . To simplify this problem in the design process, I obtained from the expression of $(\gamma+1)b_w d^3/24$ was used to calculate the RC member stiffness (k_a) and the corresponding deformation. However, the adoption of γ , which is dependent on the fitting experimental data, will incur some error in the design of RC members.

- It is difficult to determine ρ accurately, from which the ultimate strength of the designed member equates to the anticipated value (R_m). The use of Eq. (5) to determine ρ is quite conservative since it is assumed that concrete in the compression zone did not contribute towards the ultimate strength of a RC structural member. Thus, the reinforcement ratio ρ tends to be enlarged in the design, which causes some errors in fulfilling the design targets.
- DIFs are employed for concrete and reinforcement during the design process while the varying DIFs with the strain rate are used in the numerical analysis. The inconsistent usage of DIF, in the design and analysis produces errors between the actual responses of the designed member and their design targets.

The deformation-controlled design procedure presented attempts to equate the responses of the equivalent SDOF system to the design performance targets (i.e., $\mu^{eq} = \mu_t$ and $y_m^{eq} = y_t$). However, the numerical verification indicated that some errors existed between the responses of the designed RC member (y_m^{rc} and μ^{rc}) and the corresponding design targets (y_t and μ_t). Since the RC member was specifically designed under a given blast loading condition, the following part shows the derivation of the formulas for quantifying the errors. Also, the method used to combine the formulas for the iterative design procedure to achieve y_m^{rc} and μ^{rc} is shown.

Error Analysis

Definition of Error Indices

To obtain a consistent measurement of the degree of the errors between the actual responses (y_m^{rc} and μ^{rc}) and their respective performance targets (y_t and μ_t), two nondimensional error indices are defined as

$$s_y^{rc} = \frac{y_t - y_m^{rc}}{y_t} \quad (7)$$

$$s_\mu^{rc} = \frac{\mu_t - \mu^{rc}}{\mu_t} \quad (8)$$

where ζ_y^{rc} = displacement error index for the error between y_m^{rc} and y_t ; and ζ_μ^{rc} = displacement ductility error index representing the error between μ^{rc} and μ_t . With ζ_y^{rc} and ζ_μ^{rc} initially known, controlling of y_m^{rc} and μ^{rc} is possible in the design of blast-resistant structural members.

Analytical Approach

It is almost impractical to derive explicit expressions of Eqs. (7) and (8) since the behaviors of RC members will exhibit significantly complicated geometric and material

nonlinearity under most blast conditions. A curve fitting technique with a large amount of reliable data for ζ_y^{rc} and ζ_μ^{rc} , which are determined according to Eqs. (7) and (8), was used. y_m^{rc} and μ^{rc} obtained through nonlinear finite-element analyses of the designed members was executed together with the statistical analyses so as to find simplified explicit expressions of ζ_y^{rc} and ζ_μ^{rc} . The procedure is listed as follows:

1. Select the type of support conditions (SCs) of RC members to be designed;
2. Sample the design variable vector of $\{P_r, t_d, y_t, \mu_t, l, f_{dc}, E_c, f_{ds}, E_s, f_{dv}\}'$, where 2,000 samples are randomly taken to en-sure the accuracy of the statistical analysis;
3. Design an RC member using the above procedure with each sample of the design variable vector to obtain d , ρ , and ρ' , ρ_v , and b_w as a ratio of d ;
4. Repeat Step 3 until 2,000 sampled design cases are accomplished;
5. Select 500 design cases with ρ ranging from 0.31 to 2.2%;
6. Perform the numerical analyses on the selected 500 design cases to find y_m^{rc} and μ^{rc} using ABAQUS (2003);
7. Compute ζ_y^{rc} and ζ_μ^{rc} of the 500 design cases with Eqs. (7) and (8);
8. Plot the distributions of ζ_y^{rc} and ζ_μ^{rc} with the basic design variables;
9. Carry out the curve fitting of the distributions of ζ_y^{rc} and ζ_μ^{rc} , followed by statistical analyses;
10. Establish the simplified formulas to estimate ζ_y^{rc} and ζ_μ^{rc} ; and
11. Change the type of SCs of the members and repeat the above steps.

Based on the above analytical procedure, the distributions of ζ_y^{rc} and ζ_μ^{rc} versus ρ for the designed RC members under various support conditions are shown in Fig. 9.

Formulas of Error Indices

Nonlinear curve fittings of ζ_y^{rc} and ζ_μ^{rc} versus ρ for various SCs are carried out as shown in Fig. 9, where the functions are expressed as $f(\rho, SC)$ and $g(\rho, SC)$, respectively. The effects of variables other than ρ and SC are dealt with by introducing two nominal random variables of e_y and e_μ , which are assumed to represent the deviation of ζ_y^{rc} and ζ_μ^{rc} around the fitting curves. As a result, ζ_y^{rc} and ζ_μ^{rc} are written as

$$\zeta_y^{rc} = f(\rho, SC) + e_y \quad (9)$$

$$\zeta_\mu^{rc} = g(\rho, SC) + e_\mu \quad (10)$$

A second-order polynomial function is selected for the curve fitting given by

$$f(\rho, SC) \text{ and } g(\rho, SC) = a_1 + a_2\rho + a_3\rho^2 \quad (11)$$

With the result functions of $f(\rho, SC)$ and $g(\rho, SC)$, the nominal random variables of e_y and e_μ , can be obtained with

$$e_y = \zeta_y^{rc} - f(\rho, SC) \quad (12)$$

$$e_\mu = \zeta_\mu^{rc} - g(\rho, SC) \quad (13)$$

For members with various SCs, the results of the parameters a_1 , a_2 , and a_3 are listed in Table 2. The histograms of e_y and e_μ , which demonstrated that e_y and e_μ follow a normal distribution with the mean values of e_y and e_μ (E_{e_y} and E_{e_μ}) approximated to zero. Also, the standard deviations of e_y and e_μ , (σ_{e_y} and σ_{e_μ}) being relatively minor, which indicates that the least effect of the variables other than ρ and SC, can be found in the reference (Rong 2005).

Modification of the Design Procedure with Error Indices

Eqs. (7) and (8) provide a valuable tool for modifying the design procedure in order to keep the actual responses (y_m^{rc} and μ^{rc}) under control rather than those of equivalent SDOF system response (y_m^{eq} and μ^{eq}), with respect to the design performance targets (y_t and μ_t). For the convenience of the following discussion, the design targets are distinguished from two different viewpoints. From a physical viewpoint, design targets are the final goals for designed members under certain blast loading conditions and should remain unchanged within the design. They are called the physical design targets (PHY-DTs). However, from another point of view, design targets are only part of the primary parameters involved in the design to control the responses of the designed members in reaching their PHY-DTs. In this sense, they are named the parametric design targets (PAR-DTs). For the blast design procedure presented above, the values of PAR-DTs are simply fixed to be equal to those of PHY-DTs. However, this action induces some inevitable errors between the member's responses (y_m^{rc} and μ^{rc}) and the PHY-DTs. By properly adjusting the values of PAR-DTs within the design, such errors can easily be eliminated.

Denoting the PHY-DTs for maximum displacement and displacement ductility responses as y_t and μ_t while those for PAR-DTs as y_{te} and μ_{te} , the two error indices can be expressed another form

$$\zeta_y^{rc} = \frac{y_{te} - y_m^{rc}}{y_{te}} = f(\rho, SC) + e_y \quad (14)$$

$$\zeta_\mu^{rc} = \frac{\mu_{te} - \mu^{rc}}{\mu_{te}} = g(\rho, SC) + e_\mu \quad (15)$$

In the design process, the responses of y_m^{rc} and μ^{rc} are required to be controlled for achieving the PHY-DTs of y_t and μ_t (i.e., $y_m^{rc} = y_t$ and $\mu^{rc} = \mu_t$). By substituting them into Eqs. (14) and (15), the PAR-DTs of y_{te} and μ_{te} are obtained as

$$y_{te} = \frac{y_t}{1 - f(\rho, SC) - e_y} \quad (16)$$

$$\mu_{te} = \frac{\mu_t}{1 - g(\rho, SC) - e_\mu} \quad (17)$$

Eqs. (16) and (17) can be utilized to adjust the PAR-DTs so as to gain better control of the responses of y_m^{rc} and μ^{rc} within the design. The random variables e_y and e_μ , indicate the uncertain influences of the design variables other than ρ and SC on error indices. Certain quantities of $e_{y,n}$ and $e_{\mu,m}$ corresponding to n and m percentages of nonexceedance probabilities for e_y and e_μ , have to be selected (Kottegoda and Rosso (1996)). Hence, Eqs. (16) and (17) are modified into

$$y_{te} = \frac{y_t}{1 - f(\rho, SC) - e_{y,n}} \quad (18)$$

$$\mu_{te} = \frac{\mu_t}{1 - g(\rho, SC) - e_{\mu,m}} \quad (19)$$

The physical meaning of such an action can be explained as follows. Subtracting Eqs. (18) and (19) from Eqs. (14) and (15), respectively, and rearranging them leads to

$$y_t - y_m^{rc} = y_{te}(e_y - e_{y,n}) \quad (20)$$

$$\mu_t - \mu^{rc} = \mu_{te}(e_\mu - e_{\mu,m}) \quad (21)$$

The item $e_y - e_{y,n}$ in the bracket provides a random variable with a probability of $n\%$, whose value is less than zero as shown in Fig. 10. Since y_{te} is always positive, it is concluded from Eq. (20) that the maximum displacement response y_m^{rc} of the members designed according to Eqs. (18) and (19) will have a probability of $(1-n)\%$ not exceeding the PHY-DT of y_t (or a probability of $n\%$). Eq. (21) can be explained in the same way where the displacement ductility response μ^{rc} will have a probability of $(1-m)\%$ not exceeding the PHY-DT of μ_t .

Another point to be emphasized is that the determination of PAR-DTs of y_{te} and μ_{te} from Eqs. (18) and (19) is dependent on ρ . Therefore, an iterative procedure is necessary in the design. After assuming d and ρ values, the PAR-DTs of y_{te} and μ_{te} are adjusted from the given α and PHY-DTs of y_t and μ_t . However, to attain y_{te} and μ_{te} , a new set of d and ρ will have to be established for the member. Hence, the process must be iterated until d and ρ are consistent. The flowchart of the modified blast resistant design depending on ς_y^{rc} and ς_μ^{rc} is shown in Fig. 11.

Illustrative Examples

By incorporating error indices, the modified blast resistant design procedure is applied to three numerical examples. This demonstrates its use in the design practices. Fig. 12 shows a simply supported beam, a cantilever wall, and a fixed/roller-supported beam subjected to a variety of blast loadings. Examples I and III tend to control the member's responses at a very low performance level (Schmidt 2003). Thus, a relatively higher target support rotation of $\theta_t = 4^\circ$ [$y_t \approx l \tan(\theta_t)/2$] and $\mu_t = 10$ are used. However, to control the response at a low performance level (Schmidt 2003), Example II adopts the values of $\theta_t = 2^\circ$ [$y_t \approx l \tan(\theta_t)$] and $\mu_t = 6$. Taking into account of the rebound effect of the structural member subsequent to its maximum displacement response, the area of compression reinforcement is taken to be equal to that of tension reinforcement. In these numerical examples, the values for n and m are taken to be 5 so as to ensure a 95% probability for y_m^{rc} and μ^{rc} of the designed members not exceeding the PHY-DTs of y_t and μ_t . The convergence conditions for ρ and d are defined as $|(\rho_1 - \rho_0)/\rho_0| \leq 0.001$ and $|(d_1 - d_0)/d_0| \leq 0.001$, respectively.

The initial values of ρ_0 and d_0 are taken as 1.00% and 1,000 mm, respectively. Iterative values of key terms during the design process for these three numerical examples, with the modified procedure depending on the error indices, are listed in Tables 3–5. For comparison, the design of the members with the original procedure is also listed in Tables 3–5. It is noticed that there is no difficulty in reaching convergence with the modified design procedure. However, due to the adjustment of PAR-DTs from Eqs. (15) and (16) within the modified design procedure, more iterative steps and computation time are needed to reach the convergence as compared to those from the original design procedure. Also, the member design shows an obvious decline in ρ and some increase in d with the modified procedure.

Numerical Verification

In order to check whether y_m^{rc} and μ^{rc} of the designed RC members under the given blast loadings are controlled effectively by the modified procedure, nonlinear finite-element analysis of the members is performed. The simulation results are demonstrated in Fig. 13, which shows the comparison between the modified and the original design procedure y_m^{rc} and μ^{rc} values of the members.

Results indicate that the modified design procedure has overcome the disadvantages existing in the control of y_m^{rc} and μ^{rc} for both the simply supported beam and the cantilever wall. Using the original design procedure y_m^{rc} slightly exceeds the target of y_t , and μ^{rc} is too conservative. The modified design procedure values of y_m^{rc} and μ^{rc} for these two members both are approximated to their respective targets and restricted to be a little on the conservative side. Besides, y_m^{rc} seems to be controlled closer to its target than μ^{rc} due to the smaller standard deviation of e_y . As for the fixed/ roller-supported beam, due to the strict requirement of 95% probability for y_m^{rc} not exceeding y_t , the control of y_m^{rc} seems to be slightly more conservative than that by the original design procedure. However, in this example, μ^{rc} controlled is still much closer to μ_t by the modified procedure. Therefore, comparison of these results demonstrates that the modified

procedure by keeping y_m^{rc} and μ^{rc} under control with respect to the design performance targets is quite effective

Conclusions

A blast-resistant design procedure for RC flexural members has been presented in this paper. For blast-resistant designs, it would be more ideal that the RC member does not exhibit a brittle failure associated with shear failure during loading, and is allowed to experience flexural deformation. For this, adequate shear reinforcement should be present to mitigate against the brittle failure associated with shear failure. The proposed design method aims to provide an iterative procedure for the design of the longitudinal reinforcement and effective depth more closely related to the design of members for flexure. It has been demonstrated that the proposed procedure could incorporate the design performance criteria of maximum displacement and displacement ductility simultaneously to give a unique design of a RC member under a given blast loading on the basis of nondimensional energy spectra. Thus, the design values of d and ρ of the RC member can be specifically determined. It could also keep the actual deformation responses of the designed member under control in meeting design performance criteria.

Although the design procedure presented tries to keep the responses of the equivalent SDOF system under control such that the design performance targets are met (i.e., $\mu^{eq} = \mu_t$ and $y_m^{eq} = y_t$), numerical verification indicates that some errors do exist between the responses of designed RC member (y_m^{rc} and μ^{rc}) and their respective design targets (y_t and μ_t). This is due to some simplifying assumptions made in the derivation of d and ρ by converting a continuous RC member into its equivalent SDOF system. However, since the RC member specifically is designed under a given blast loading condition by the modified procedure, the formulas for quantifying the approximate errors are derived from extensive numerical analysis and used for modifying the design procedures.

Through the adjustment of parametric design targets using the formulas for ζ_y^{rc} and ζ_μ^{rc} , the modification of the design procedure is accomplished to keep y_m^{rc} and μ^{rc} under control. The implementation of the modified design procedure into three numerical examples indicates that more iterative steps are needed to reach convergence as compared to those of the original design procedure. However, the responses of y_m^{rc} and μ^{rc} for the member designed by the modified procedure from the nonlinear numerical analysis are controlled. These are controlled approximately similarly to the design performance targets in a conservative manner.

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Notation

The following symbols are used in this paper:

- C = Nondimensional energy factor;
- DIF = dynamic increase factor;
- d = effective depth of the element measured from the extreme compression fiber to the centroid tensile reinforcement;
- d' = distance from the extreme compression fiber to the centroid of compression reinforcement;
- E_c = Young's modulus of elasticity for concrete;
- E_{el} = ultimate elastic energy;
- E_{max} = maximum strain energy;
- E_s = Young's modulus of elasticity for steel;
- F_1 = peak value of the force;
- f_c, f_{dc} = strength of concrete in compression for the static and dynamic conditions;
- f_s, f_{ds} = strength of flexural steel in static and dynamic conditions, respectively;
- f_t, f_{dt} = tensile strength of concrete in static and dynamic conditions, respectively;
- K_{LE}, K_{ME} = transformation load and mass factors, respectively;
- k_a = equivalent elastic stiffness for the RC elements;
- k_e = initial stiffness of the equivalent SDOF system of the designed RC member;
- l = length of the member;
- m = equivalent mass of the equivalent SDOF system;
- m_a = mass of the RC member;
- R_m = ultimate strength of the equivalent SDOF system;
- T = period;
- t_d = load duration;
- V_c = shear capacity;
- V_u = ultimate shear force;
- y_e^{eq} = elastic displacement response of the equivalent SDOF system of the designed RC member under the given blast loading;
- y_e^{rc} = Elastic displacement response of the designed RC member at the significant point under the given blast loading;

y_m^{eq} = maximum displacement response of the equivalent SDOF system of the designed RC member under the given blast loading;
 y_m^{rc} = maximum displacement response of the designed RC member at the significant point under the given blast loading;
 y_t = target maximum displacement;
 y_{te} = Parametric design target of displacement;
 ε = convergence tolerance;
 γ = reduction coefficient;
 μ^{eq} = displacement ductility response of the equivalent SDOF system of the designed RC member under the given blast loading;
 μ^{rc} = displacement ductility response of the designed RC member at the significant point under the given blast loading;
 μ_t = target displacement ductility factor;
 μ_{te} = parametric design target of displacement ductility factor;
 ρ, ρ' = longitudinal tension and compression reinforcement ratio, respectively; and
 $\sigma_{e_y}, \sigma_{e_\mu}$ = standard deviations.

References

- [1] ABAQUS. (2003). ABAQUS standard user's manual, Hibbert, Karlsson, and Sorensen, Inc., Pawtucket, R.I.
- [2] ASCE. (1985). "Design of structures to resist nuclear weapons effects." ASCE manual 42, ASCE, Reston, Va.
- [3] Biggs, J. M. (1964). Introduction to structural dynamics, McGraw-Hill, New York.
- [4] Hilleborg, A., Modeer, M., and Petersson, P. E. (1976). "Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements." *Cem. Concr. Res.*, 6, 773–782.
- [5] Kottogoda, N. T., and Rosso, R. (1996). Statistical, probability, and reliability for civil and environmental engineers, McGraw-Hill, New York.
- [6] Li, B., Huang, Z., Rong, H.-C., and Huang, Z. (2006). "Deformation-controlled design of RC flexural members subjected to blast loadings." *Proc., 2nd Int. Conf. on Design and Analysis of Protective Structures*, November 13–15, Singapore.
- [7] Malvar, L. J., and Crawford, J. E. (1998a). "Dynamic increase factors for concrete." *Proc., 28th of the Department of Defense Explosives Safety Board Seminar*, Orlando, Fla., U.S. Department of Defense, Washington, D.C.
- [8] Malvar, L. J., and Crawford, J. E. (1998b). "Dynamic increase factors for steel reinforcing bars." *Proc., 28th of the Department of Defense Explosives Safety Board Seminar*, Orlando, Fla., U.S. Department of Defense, Washington, D.C.
- [9] MATLAB. (2001). The language of technical computing, The Math-Works, Inc., Natick, Mass.
- [10] Naval Facilities Engineering Command (NFEC). (1986). "Blast resistant structures." *Design Manual 2.08*, NFEC, Alexandria, Va.
- [11] Rong, H.-C. (2005). "Performance-based blast resistant design of reinforced concrete frame structures under distant explosions." *Ph.D. thesis*, Nanyang Technological Univ., Singapore.
- [12] Rong, H.-C., and Li, B. (2007). "Probabilistic response evaluation for RC flexural members subjected to blast loadings." *Struct. Safety*, 29(2), 146–163.
- [13] Schmidt, J. A. (2003). "Structural design: Structural design for external terrorist bomb attacks." *Structure Magazine (A Joint Publication of NCSEA/ICASE/ISEI)*, March, 1–5.

- [14] U.S. Army. (1986). "Fundamentals of protective design for conventional weapons." TM5-855-1, U.S. Army, Washington, D.C.
- [15] U.S. Army. (1990). "Structures to resist the effects of accidental explosions." TM-1300, U.S. Army, Washington, D.C.

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Table 1. Iterative Procedure for the Design of a Cantilever Wall Using NES

γ_0	ρ_0 (%)	d_0 (m)	m (kg)	I (m ⁴)	k_e (N/m)	T (s)	R_m (N)	T/t_d	F_1/R_m	E_{el} (Nm)	C	E_{max} (Nm)	K_{e1} (N/m)	q_u (N/m)	M_u (Nm)	d_1 (m)	ρ_1 (%)	γ_1
1.0000	3.000	2.0000	3979	0.667	2.21e9	8.43e-3	5.16e7	0.5731	0.048	6.02e5	3.82e-3	2.30e3	4.97e5	4.30e7	1.936e8	0.1216	9.858	1.0000
1.0000	9.858	0.1216	242	1.498e-4	4.97e5	1.39e-1	1.16e4	0.0348	215.1	135.38	2889.5	3.91e5	8.45e7	9.67e3	4.351e4	0.6736	1.025	0.7494
0.7494	1.025	0.6736	1340	1.909e-2	6.33e7	2.89e-2	1.48e6	0.1671	1.689	1.7244	0.742	1.28e4	2.76e6	1.23e6	5.542e6	0.2371	2.644	1.0000
1.0000	2.644	0.2371	472	1.111e-3	3.69e6	7.11e-2	8.60e4	0.0679	29.01	1.003.7	38.04	3.82e4	8.25e6	7.17e4	3.226e5	0.3102	1.486	0.8617
0.8617	1.486	0.3102	617	2.142e-3	7.11e6	5.85e-2	1.66e5	0.0825	15.05	1.935.3	14.98	2.90e4	6.27e6	1.38e5	6.221e5	0.2974	1.566	0.8811
0.8811	1.566	0.2974	591	1.931e-3	6.41e6	6.04e-2	1.49e5	0.0800	16.69	1.744.4	17.36	3.02e4	6.54e6	1.24e5	5.607e5	0.2995	1.550	0.8772
0.8772	1.550	0.2995	595	1.963e-3	6.51e6	6.01e-2	1.52e5	0.0804	16.42	1.773.4	16.95	3.01e4	6.50e6	1.26e5	5.700e5	0.2992	1.551	0.8775

Note: Design results: $d=299.2$ mm; ρ or $\rho'=1.551\%$; $\rho_0=0.15\%$. Initial data: $E_s=200$ GPa; $E_c=28$ GPa; $f_s=460$ MPa; $f_c=506$ MPa; $f_{dt}=275$ MPa; $f_{du}=250$ MPa; $f_{dv}=275$ MPa; $f_{du}=275$ MPa; $f_{dv}=275$ MPa; $b_w=1.0$ m; $P_r=2,080$ KPa; $t_d=4.83$ ms; and density of concrete $\rho_{con}=2,500$ kg/m.

Table 1

Nondimensional error indices	SC	a_1	a_2	a_3
ε_y^{rc}	Simply supported	-0.10369	-2.20114	160.30932
	Fixed/free	-0.01712	0.80877	66.84997
	Fixed/roller supported	0.01276	-1.67032	100.93644
	Fixed/fixed	0.55459	-34.63653	735.20353
ε_μ^{rc}	Simply supported	0.80257	-50.10919	675.55356
	Fixed/free	0.83085	-47.05548	911.90338
	Fixed/roller supported	0.84443	-45.30174	800.57689
	Fixed/fixed	0.99826	-18.99113	-354.75711

Table 2

y_t (mm)	μ_t	$e_{y,5}$	$e_{\mu,5}$	d_0 (mm)	ρ_0 (%)	f (ρ_0 , SC)	g (ρ_0 , SC)	y_{te} (mm)	μ_{te}	d_1 (mm)	ρ_1 (%)	CPU [time (s)]
(a) With modified procedure												
210.00	10.0	−0.028	−0.089	1,000.00	1.000	−0.10966	0.36910	184.35	13.885	583.36	1.374	0.178
				583.36	1.374	−0.10364	0.24154	185.33	11.796	637.94	1.111	
				637.94	1.111	−0.10835	0.32950	184.56	13.161	658.28	1.005	
				658.28	1.005	−0.10961	0.36744	184.36	13.853	669.83	0.951	
				669.83	0.951	−0.11011	0.38709	184.28	14.241	675.79	0.925	
				675.79	0.925	−0.11032	0.39692	184.24	14.443	678.86	0.912	
				678.86	0.912	−0.11042	0.40190	184.23	14.547	680.45	0.905	
				680.45	0.905	−0.11046	0.40443	184.22	14.601	681.26	0.902	
				681.26	0.902	−0.11049	0.40573	184.22	14.629	681.67	0.900	
681.67	0.900	−0.11050	0.40639	184.21	14.643	681.89	0.899					
(b) With original procedure												
210.00	10.0			1,000.00	1.000			210.00	10.0	478.57	2.172	0.102
				478.57	2.172					563.23	1.449	
				563.23	1.449					558.18	1.464	
				558.18	1.464					559.22	1.457	
				559.22	1.457					559.14	1.458	
Note: f_{ds} =506 MPa; f_{dc} =40 MPa; E_c =40 GPa; E_s =200 GPa; and f_{dv} =275 MPa. Convergence conditions: $ (\rho_1 - \rho_0)/\rho_0 \leq 0.001$ and $ (d_1 - d_0)/d_0 \leq 0.001$.												

Table 3

y_t (mm)	μ_t	$e_{y,5}$	$e_{\mu,5}$	d_0 (mm)	ρ_0 (%)	$f(\rho_0, SC)$	$g(\rho_0, SC)$	y_{te} (mm)	μ_{te}	d_1 (mm)	ρ_1 (%)	CPU [time (s)]
(a) With modified procedure												
139.70	6.0	-0.048	-0.089	1,000.00	1.000	-0.00235	0.45148	132.95	9.418	359.94	1.370	0.172
				359.94	1.370	0.00651	0.35733	134.08	8.205	467.57	0.731	
				467.57	0.731	-0.00764	0.53560	132.28	10.850	503.69	0.567	
				503.69	0.567	-0.01038	0.59327	131.94	12.113	520.56	0.509	
				520.56	0.509	-0.01127	0.61479	131.83	12.663	526.68	0.490	
				526.68	0.490	-0.01156	0.62222	131.79	12.865	528.77	0.483	
				528.77	0.483	-0.01165	0.62471	131.78	12.934	529.47	0.481	
				529.47	0.481	-0.01168	0.62553	131.78	12.957	529.70	0.481	
				529.70	0.481	-0.01169	0.62580	131.77	12.965	529.77	0.480	
(b) With original procedure												
139.70	6.0			1,000.00	1.000			139.70	6.0	299.68	2.259	0.109
				299.68	2.259					414.93	1.041	
				414.93	1.041					403.24	1.076	
				403.24	1.076					405.70	1.062	
				405.70	1.062					405.42	1.064	

Note: f_{ds} =506 MPa; f_{dc} =40 MPa; E_c =40 GPa; E_s =200 GPa; and f_{dv} =275 MPa. Convergence conditions: $|(p_1 - p_0)/p_0| \leq 0.001$ and $|(d_1 - d_0)/d_0| \leq 0.001$.

Table 4

y_t (mm)	μ_t	$e_{y,5}$	$e_{\mu,5}$	d_0 (mm)	p_0 (%)	f (p_0 , SC)	g (p_0 , SC)	y_{te} (mm)	μ_{te}	d_1 (m)	p_1 (%)	CPU [time (s)]
(a) With modified procedure												
210.00	10.0	−0.034	−0.082	1,000.00	1.000	0.00615	0.47134	204.14	16.371	318.17	1.793	0.171
				318.17	1.793	0.01526	0.28944	205.96	12.614	400.33	1.071	
				400.33	1.071	0.00645	0.45110	204.19	15.846	425.99	0.865	
				425.99	0.865	0.00587	0.51233	204.08	17.548	441.04	0.774	
				441.04	0.774	0.00588	0.54162	204.08	18.499	447.94	0.735	
				447.94	0.735	0.00594	0.55445	204.09	18.949	451.09	0.719	
				451.09	0.719	0.00597	0.56010	204.10	19.154	452.52	0.711	
				452.52	0.711	0.00599	0.56262	204.10	19.247	453.16	0.708	
				453.16	0.708	0.00599	0.56375	204.11	19.289	453.44	0.706	
453.44	0.706	0.00600	0.56425	204.11	19.307	453.57	0.706					
(b) With original procedure												
210.00	10.0			1,000.00	1.000			210.00	10	263.55	3.016	0.109
				263.55	3.016					356.72	1.201	
				356.72	1.201					367.90	1.330	
				367.90	1.330					360.55	1.401	
				360.55	1.401					360.90	1.402	
Note: f_{ds} =506 MPa; f_{dc} =40 MPa; E_c =40 GPa; E_s =200 GPa; and f_{dv} =275 MPa. Convergence conditions: $ (p_1-p_0)/p_0 \leq 0.001$ and $ (d_1-d_0)/d_0 \leq 0.001$.												

Table 5

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Simply supported members

Fixed/free members

fixed/roller-supported members

fixed/fixed members

Fig. 9

Fig. 10

Fig. 11

(a). A simply supported beam under the blast loading (Design example I)

(b). A cantilever wall under the blast loading (Design example II)

(c). A fixed/roller-supported beam under the blast loading (Design example III)

Fig. 12

(a). Designed with the modified procedure

(b). Designed with the original procedure

(Example I)

(a). Designed with the modified procedure

(b). Designed with the original procedure

(Example II)

(a). Designed with the modified procedure

(b). Designed with the original procedure

Fig. 13