

# A NEW BLAST-RESISTANT DESIGN METHOD OF RC MEMBERS AND ITS APPLICATION IN PERFORMANCE BASED BLAST-RESISTANT DESIGN PROCEDURE

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## ABSTRACT

Design method is very essential and important for engineers. Present study proposes a new blast-resistant design method. First, two common used blast-resistant design methods are discussed. By analyzing the disadvantage of the common procedures, a new blast-resistant design method is proposed. The new design method has less design loops, as well as good control of the maximum displacement and ductility. Then, a dimensionless P-I diagram, which is convenient for design, is proposed based on the new design method. Finally, the new blast-resistant design method is applied in the performance-based blast-resistant design (PBBD) procedure described using a detailed design example. The design example shows that the proposed design method could be easily applied in the PBBD procedure.

## KEYWORDS

Performance-based, Blast-resistant, Design procedure, P-I diagram

## INTRODUCTION

Performance-Based Design (PBD) method is firstly proposed in earthquake engineering [1]. Recently, there is a trend in civil engineering community to use PBD method in other subfields of structural engineering [2-5]. Meanwhile, blast-resistant design is necessary with an increasing attention after September 11, 2001. Thus, the application of PBD method in the field of blast-resistant design will be very meaningful [6, 7].

Performance-Based Earthquake Design (PBED) is more mature and provides a certain reference for PBBD procedure. During the development process of PBED, two generations design procedures are proposed by engineers [8]. The first-generation procedure is a deterministic framework. It includes methods of defining performance, methodologies to calculate building dynamic response and structural response parameters to assess performance levels of structures [7, 9]. The second-generation procedure is a full probabilistic framework. It considers the inherent uncertainties and variability in structural response and provides risk management decisions for engineers [9]. Similar to PBED method, studies about the PBBD procedure are also categorized into two kinds. The first one does not consider the uncertainties while the second one does. Studies of the first kind include uncertainties about blast loads [10, 11], fragility curves of RC structures [12, 13], loss estimation of buildings after explosion [14], etc. Studies of the second kind include determination of explosion scenarios [7, 15], determination of damage criteria [16, 17], optimization design methods [18, 19], etc. However, few studies pay attention to the blast-resistant design procedure.

The design method is different from the dynamic response analysis method. The design method is to calculate the structural configuration based on the objective performance, while the dynamic response method is to calculate the structural performance based on the known configuration of structures. The dynamic response method could also be used as design method by the application of try-and-error method. For example, UFC 3-340-02 [20] directly uses the dynamic response analysis method single-degree-of-freedom (SDOF) to design the RC beam. The design procedure in UFC 3-340-02 for RC beams (named as Design procedure A) is shown in Figure 1. After the determination of blast load, geometric sizes, materials and objective performances, trial designs are conducted for many times until the objective performances are satisfied. The trial designs will add extra work to designers.

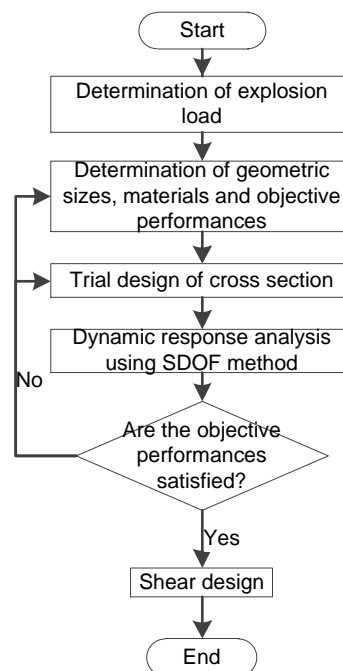


Fig. 1 – Design procedure A

In order to reduce the design loops, dynamic increase factors are calculated using SDOF method. Then, the blast load is transformed to an equivalent static load. RC members are designed using the static design method. This method is called as equivalent static load design method [21], which has less design loops, as shown in Figure 2 (named as Design procedure B). This method is more convenient to designers and widely accepted in China.

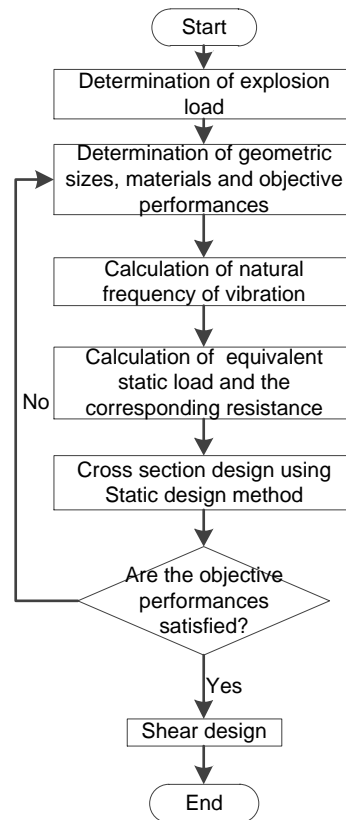


Fig. 2 – Design procedure B

An efficient design procedure is very important in the actual design practices. It should be time-saving and accurately control the objective performances. The common used performance indexes are maximum displacement and ductility ratio, which are used in Design procedure A and Design procedure B respectively. However, the both indexes represent the performances. Designing the RC members using two performance indexes will be helpful to control the objective performances.

In present study, a new blast-resistant design procedure was presented. The new procedure combines the advantages of Design procedures A and B. The maximum displacement and ductility ratio are simultaneously used as performance indexes in the new procedure. Then, a neat PBBD procedure is present based on the new design procedure.

## THEORETICAL BASICS OF DESIGN PROCEDURE FOR RC MEMBERS

RC member subjected to blast load is simplified into a perfect elastic-plastic SDOF system shown in Figure 3.

Equation (1) is used to calculate the dynamic response

$$M_e \ddot{y} + R(y) = P(t)L \quad (1)$$

where  $L$  is the span length,  $R(y)$  is the resistance function, and  $P(t)$  is the linear blast load.

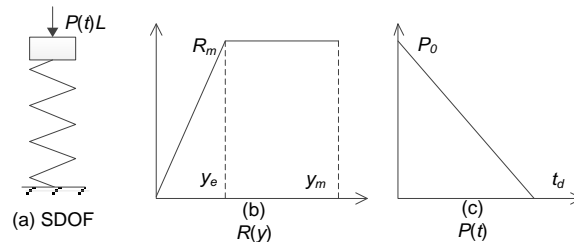


Fig. 3 – SDOF system

The resistance  $R_m$  is calculated by Equation (2) according to [22] (Bounds 2010)

$$R_m = P_0 \left[ \frac{2}{\omega t_d} \sqrt{2\mu - 1} + \frac{2\mu - 1}{2\mu(1 + 4/\omega t_d)} \right]^{-1} \quad (2)$$

where  $\mu$  is the ductility ratio,  $P_0$  is the peak pressure,  $t_d$  is the blast load duration,  $\omega$  is the natural frequency of vibration.

$\omega$  is calculated by Equation (3)

$$\omega = \sqrt{K_e/M_e} \quad (3)$$

where  $K_e$  is the equivalent elastic stiffness,  $M_e$  is the equivalent mass.

The resistance  $R_m$  is also computed by Equation (4), shown as

$$R_m = K_e y_m / \mu \quad (4)$$

where  $y_m$  is the maximum mid-span displacement.

Then, Equation (2) is re-arranged as Equation (5) combined with Equations (3) and (4),

$$\frac{\omega^2 y_m M_e}{\mu P_0} = \left[ \frac{2}{\omega t_d} \sqrt{2\mu - 1} + \frac{2\mu - 1}{2\mu(1 + 4/\omega t_d)} \right]^{-1} \quad (5)$$

Equation (5) shows that the natural frequency of vibration  $\omega$  can be calculated if the performances  $y_m$  and  $\mu$  are known. After the calculation of  $\omega$ , parameters of blast-resistant function  $R_m$  and  $K_e$  are easily determined according to Equations (3) and (4).

If the blast load is rectangular long-time load, calculations of  $R_m$  and  $K_e$  are simplified as

$$R_m = \frac{2\mu P_0}{2\mu - 1} \quad (6)$$

$$K_e = \frac{2\mu^2 P_0}{y_m(2\mu - 1)} \quad (7)$$

If the blast load is impulse-controlled load, calculations of  $R_m$  and  $K_e$  are simplified as

$$R_m = \frac{I^2 \mu}{M_e y_m (2\mu - 1)} \quad (8)$$

$$K_e = \frac{I^2 \mu^2}{M_e y_m^2 (2\mu - 1)} \quad (9)$$

After the calculation of  $R_m$  and  $K_e$ , parameters of cross section could be designed [22]. Present study takes a simple supported RC beam as an example. The resistance  $R_m$  is given by Equation (10),

$$R_m = 8 M_u / l^2 \quad (10)$$

where  $M_u$  is the ultimate moment capacity at the mid-span, given by Equation(11),

$$M_u = \rho_1 f_{dy} b d^2 \left( 1 - \frac{\rho_1 f_{dy}}{1.7 f'_{dc}} \right) \quad (11)$$

where  $f_{dy}$  is the dynamic yield stress of the longitudinal reinforcement,  $f'_{dc}$  is the dynamic concrete compressive strength,  $\rho_1$  is the longitudinal reinforcement ratio,  $b$  is the width of beam,  $d$  is the distance from the extreme compression fiber to the centroid of the longitudinal tension reinforcement.

$K_e$  is given by Equation (12),

$$K_e = \frac{384 E_c I_a}{5 l^4} \quad (12)$$

where  $E_c$  is the concrete modulus of elasticity,  $I_a$  is the average moment of inertia of the beam

given by Equation(13) [22].

$$I_a = 0.5(bh^3/12 + Gbd^3) \tag{13}$$

The coefficient  $G$  in Equation (9) is evaluated by Equation (14) [13], where  $E_s$  is the steel modulus of elasticity.

$$G = (3320.3\rho_1^3 - 181.98\rho_1^2 + 5.8624\rho_1) \left(\frac{E_s}{7E_c}\right)^{0.7} \tag{14}$$

Equations (6) ~ (10) are used to compute the design variables of cross section.

The stirrup reinforcement ratio is calculated by Equation (15) [23]

$$\rho_2 = \frac{(V_u - V_c)}{\phi f_{dv} b d} \tag{15}$$

where  $V_u$  is the ultimate shear force,  $V_c$  is the shear capacity of the concrete,  $f_{dv}$  is the dynamic yield strength for shear reinforcements,  $\phi$  is the capacity reduction factor.

### NEW DESIGN PROCEDURE FOR RC MEMBERS

Equations (3)~(9) show that the maximum displacement  $y_m$  and the ductility ratio  $\mu$  can be calculated using  $R_m$  and  $M_u$ . Therefore, the designers control the objective performances  $y_m$  and  $\mu$  by the design of  $R_m$  and  $M_u$ . The new design procedure is shown in Figure 4. Compared with Design procedure A and B, both maximum displacement and ductility ratio are controlled without increasing the design loops.

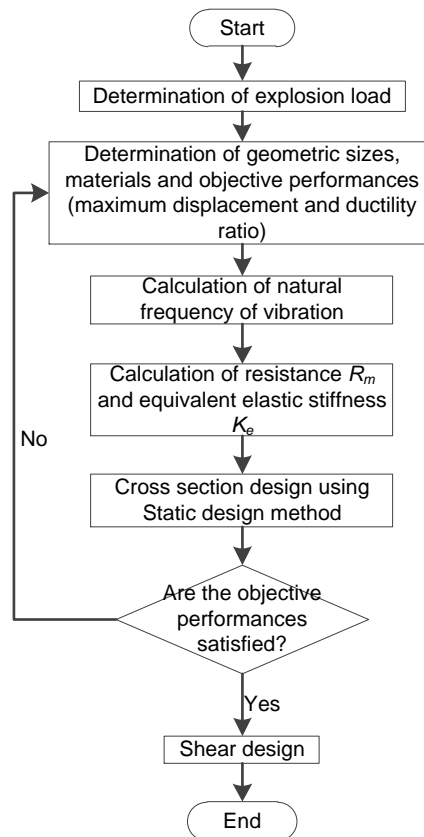


Fig. 4 – New design procedure

For convenience of design, non-dimensional P-I diagrams are proposed in Figure 5. The black lines represent the ductility ratio  $\mu$ . The red lines represent the maximum displacement  $y_m$ . Drawing method of the non-dimensional P-I diagrams are described as follows.

First, non-dimensional impulse and pressure are defined as

$$I = \frac{\omega}{R_m} I_m = \frac{\omega}{R_m} \frac{P_0 t_d}{2} \tag{16}$$

$$P = P_0 / R_m \tag{17}$$

Then, Equation (5) is re-arranged as Equation (18)

$$I = \frac{AP+B+\sqrt{A^2P^2+CP+D}}{-AP+A+1} P \tag{18}$$

where  $A = -2\mu$ ,  $B = -2\mu\sqrt{2\mu-1}$ ,  $C = 4\mu^2\sqrt{2\mu-1}$ ,  $D = 2\mu^3 - \mu^2 - 8\mu^2\sqrt{2\mu-1} + 4\mu\sqrt{2\mu-1}$ .

According to Equation (18), black P-I curves are obtained.

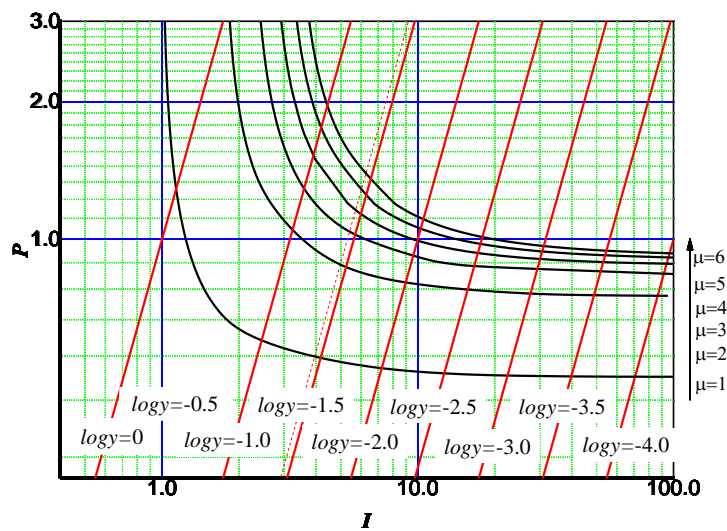


Fig. 5 – Non-dimensional P-I diagram

According to Equation (16) and Equation (17), Equation (19) is gotten as follows

$$P/I = P_0 / (\omega I_m) \tag{19}$$

Because

$$P = P_0 / R_m = \frac{\mu P_0}{\omega^2 M_e y_m} \tag{20}$$

Then, Equation (21) is obtained based on Equation (19) and Equation (20).

$$P/I^2 = y' \tag{21}$$

where

$$y' = y_m M_e \frac{P_0}{\mu I_m^2} \tag{22}$$

According to Equation (21), red P-I curves are obtained.

A simple example is present here to describe the design procedure in detail. A simply support RC rectangular beam needs to be designed. The design variables is the width  $b$ , the height  $h$  and the longitudinal reinforcement  $\rho_1$ . The other parameters and corresponding values are listed in Table 1.

Tab. 1 – Design parameters and corresponding values

Parameters	$f_c$	$f_y$	$bh \times l$	$\rho_c$	$d'$	$\mu$	$y_m$	$P_0$	$t_d$
Values	14.3MPa	300MPa	0.06×4m	2400kg/m <sup>3</sup>	20mm	6	0.0349m	15.0kN/m	60ms

**Step 1** is to calculate  $y'$  according to Equation (22).

**Step 2** is to find the intersection point ( $I', P'$ ) of P-I curves according to the value of  $y'$  and  $\mu$ . From Figure 4, we find that the intersection point ( $I', P'$ )  $\approx$  (5.5, 1.4).

**Step 3** is to computer  $R_m$  and  $K_e$  according to Equation (19).  $R_m = 10.7 \text{ kN/m}$ ,  $K_e = 1777.8 \text{ kN/m}^2$ .

**Step 4** is to calculate design variables based on values of  $R_m$  and  $K_e$  using Equations (10)~(14).  $b = 0.191, h = 0.314, \rho_1 = 0.038$ .

The dynamic response of the designed RC beam is shown in Figure 6. The calculated results,  $y_m = 0.0336\text{m}$  and  $\mu = 5.9$ , are quite close to the objective performances. This means that the new design procedure has good control of  $y_m$  and  $\mu$ .

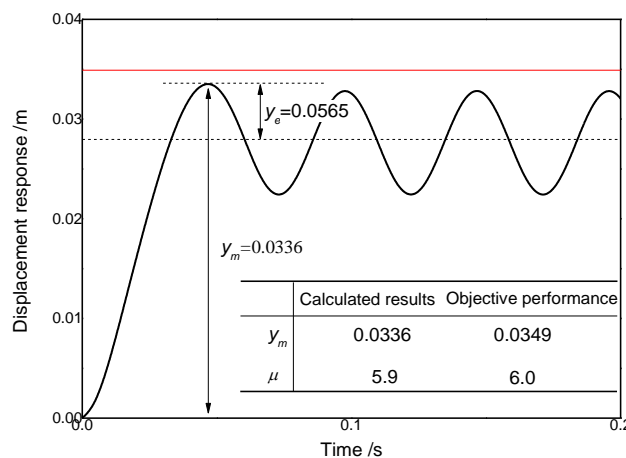


Fig. 6 – Dynamic responses of RC beam

## APPLICATION OF NEW DESIGN PROCEDURE IN THE PBBD PROCEDURE

The object of PBBD procedure is to control the performances of structures under blast load to satisfy the request of building owners. However, it is hard to predict the magnitude of blast hazards [24]. The recommend method is to assume some blast scenarios which may be determined by building owners, decision maker or engineers [25]. Several blast scenarios are very necessary for design, because only one blast scenario may be unsafety, which will be illustrated in the following part.

The procedure of PBBD for RC members is shown in Figure 7. The new design procedure is used after the determination of blast load and the corresponding objective performances. The blast loads should represent the possible explosive scenarios and be determined using explosive

possibility analysis. The objective performances represent the loss expectation and determined using loss risk analysis. In order to clearly describe the application of the new design procedure, present study skips the explosive possibility analysis and the loss risk analysis.

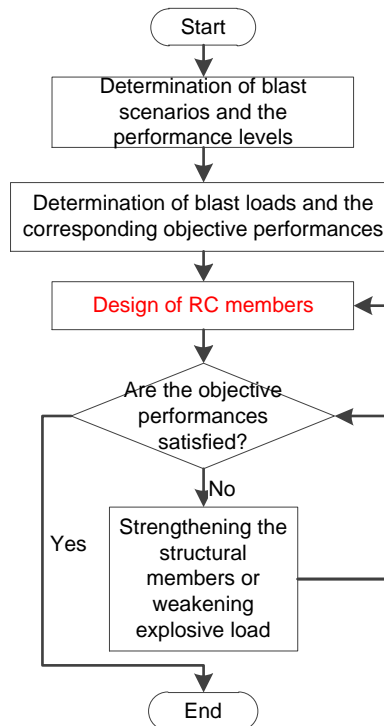


Fig. 7 – Procedure of PBD for RC members

The new design procedure is used to design the RC beams according to several blast loads and objective performances. The key point is to find the relations between  $(R_m, \omega)$  and  $(y_m, \mu)$ . Steps are listed as follows:

**Step 1** is to find the  $(P_i, I_i)$  ( $i=1, 2, 3\dots$ ) corresponding to the objective performance  $\mu$  using Figure 5;

**Step 2** is to calculate the  $(R_{mi}, \omega_i)$  corresponding to  $(P_i, I_i)$ ;

**Step 3** is to find the  $(P_j, I_j)$  ( $j=1, 2, 3\dots$ ) corresponding to the objective performance  $y_m$  using Figure 5;

**Step 4** is to calculate the  $(R_{mj}, \omega_j)$  corresponding to  $(P_j, I_j)$ ;

**Step 5** is to determine the ranges of  $(R_m, \omega)$  which satisfies the objective performance;

**Step 6** is to determine a design point  $(R_m, \omega)$ ;

**Step 7** is to design the RC members and check performances. If the objective performance is not satisfied, return to Step 6.

A simple design example is presented here. Parameters of a simply supported RC beam are shown in Table 2. After the explosive possibility analysis and loss risk analysis. We assume that three reverse triangle blast load are considered, listed in Table 3.  $y_m$  and  $\mu$  are both used as performance index. The assumed performance levels are listed in Table 4. The objective performance is shown in Table 5. The objective performance is that the RC beam should satisfy Performance level 1 under blast load 1, simultaneously satisfy performance level 2 under blast load 2 and satisfy performance level 3 under blast load 3 at the same time.



Tab. 2 – Parameters of RC beam

Parameter	$f_c$	$f_y$	$bh \times l$	$\rho_c$	$d'$
Value	14.3MPa	300MPa	0.06×4m	2400kg/m <sup>3</sup>	20mm

Tab. 3 – Three blast loads

	Blast load 1	Blast load 2	Blast load 3
Reflected peak pressure/ (kN/m)	20	30	40
Duration time/ ms	20	30	40

Tab. 4 – Performance levels

	$y_m$	$\mu$	Description
Performance level 1	$\leq 0.020m$	$\leq 4$	Superficial damage
Performance level 2	$\leq 0.035m$	$\leq 5$	Moderate damage
Performance level 3	$\leq 0.054m$	$\leq 6$	Heavy damage

Tab. 5 – Objective performance

		Performance level		
		Performance level 1	Performance level 2	Performance level 3
Blast loading	Blast load 1	√		
	Blast load 2		√	
	Blast load 3			√

Using the proposed design method and the corresponding non-dimensional P-I diagrams, the contour lines of  $y_m$  and  $\mu$  are for blast loads 1~3 are shown in Figure 8.

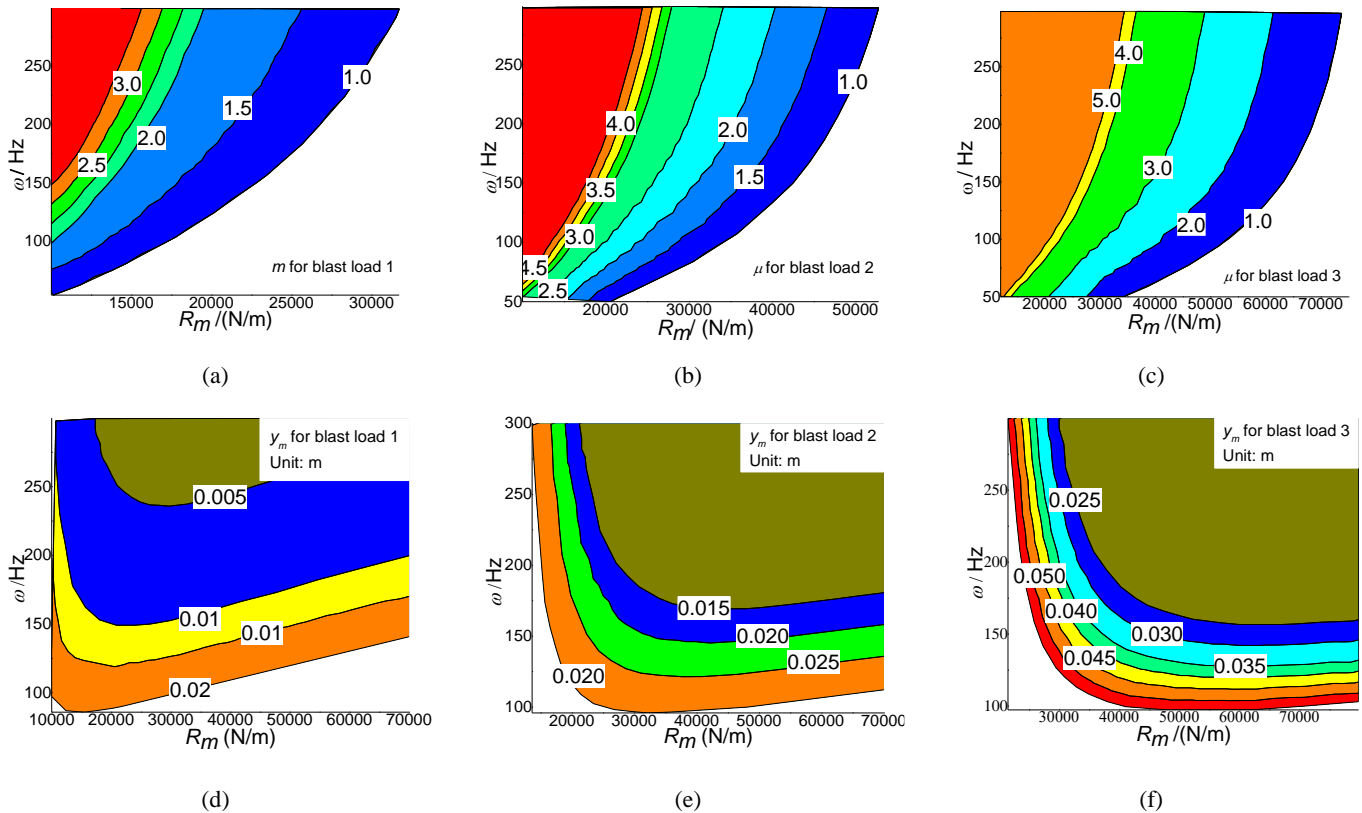


Fig. 8 – Contour lines of  $y_m$  and  $\mu$  for different blast loads

According to the objective performance, the design ranges of  $(R_m, \omega)$  are shown in Figure 9. And a design point  $(R_m = 30 \text{ kN/m}, \omega = 150 \text{ Hz})$  is selected. Then, the design results  $b = 0.19\text{m}$ ,  $h = 0.31\text{m}$  and  $\rho = 0.012$  are obtained using Equations (10)–(14).

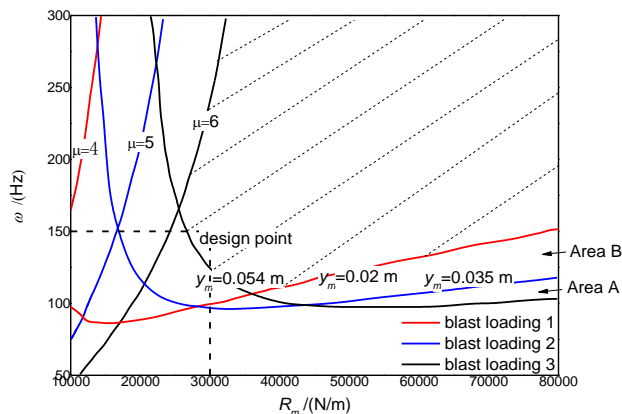


Fig. 9 – Design range of  $R_m$  and  $\omega$

Figure 9 shows the necessity of using several blast loads to design the RC members. The designers usually use a larger blast load to design and believe that the designed result can satisfy the objective performances under smaller blast load if the objective performances under larger blast load are satisfied. However, the design points in area A do not satisfy the objective performances under blast load 1 and 2 but satisfy the objective performances under blast load 3, even blast load 3 is the largest one. In the area B, the design points do not satisfy the objective

performances under blast load 1 but satisfy the objective performances under blast load 3. This indicates that using several typical blast scenarios to design the RC members is more safety.

The performances of designed RC beam are check out using SDOF method. Calculated results are listed in Table 6. It shows that the objective performances are well satisfied.

*Tab. 6 – Actual performance of the designed beam*

	$y_m$	$\mu$
Performance level 1	0.010m≤0.020m	1.0≤4
Performance level 2	0.019m≤0.035m	1.6≤5
Performance level 3	0.046m≤0.054m	3.8≤6

## CONCLUSIONS

The common used design procedures of RC members have many design loops, which adds much work to engineers and limits the development of PBBD procedure. Presented study proposed a new design procedure of RC members which has less design loops. The new design procedure is based on the SDOF method, which is widely accepted by designers. This indicates that the new procedure is convenient to use because SDOF is familiar to designers.

The new design procedure controls both the maximum displacement and the ductility very well. This means that the new procedure controls the performance well. For the convenience of design, non-dimensional design chart is proposed corresponding to the new design procedure. It shows that the new design chart is very convenient to design as well as to control the performance well.

The new design method is very suitable for the PBBD procedure. The application of the new design method in the PBBD procedure is presented in detail and explained using a design example. The example shows the importance of PBBD procedure because the PBBD procedure gives more safety design results than the common design methods.

## REFERENCES

- [1] Allin C., 2000. Progress and challenges in seismic performance assessment. PEER newsletter, vol. 3(2): 1-3.
- [2] Ali R. M. and Louca L. A., 2008. Performance based design of blast resistant offshore topsides, Part I: Philosophy. Journal of Constructional steel research, vol. 64(9): 1030-1045.
- [3] Barbato M., Petrini F., Unnikrishnan V. U., and Ciampoli M., 2013. Performance-based hurricane engineering (PBHE) framework. Structural safety, vol. 45: 24-35.
- [4] Sharma H., Hurlbauss S. and Gardoni P., 2012. Performance-based response evaluation of reinforced concrete columns subject to vehicle impact. International journal of impact Engineering, vol. 43: 52-62.
- [5] Ciampoli M., Petrini F. and Augusti G., 2011. Performance-based wind engineering: towards a general procedure. Structural safety, vol. 33(6): 367-378.
- [6] Hamburger R. O. and Whittaker A. S., 2003. Considerations in performance-based blast resistant design of steel structures. In: AISC-SINY Symposium on Resisting Blast and Progressive Collapse, 1-10.
- [7] Yu R.Q., Fang Q., Chen L. and Yan H.C., 2016. Performance-based blast-resistant design of building structural components. Engineering Mechanics, vol: 33(11): 75-83.
- [8] Hall W.J., 1997. Seismic Design Methodologies for the Next Generation of Codes. Earthq. Spectra, vol 27(2): 379-380.
- [9] Hamburger R., Rojahn C., Moehle J., Bachman R., Comartin C. and Whittaker A., 2004. The ATC-58

project: development of next-generation performance-based earthquake engineering design criteria for buildings. In: the 13th World Conference on Earthquake Engineering, 1-15.

[10] Stewart M.G., 2018. Reliability-based load factor design model for explosive blast loading. *Structural Safety*, vol. 71: 13-23.

[11] Campidelli M., Tait M.J., El-Dakhakhni W.W. and Mekky W., 2015. Inference of blast wavefront parameter uncertainty for probabilistic risk assessment. *Journal of structural Engineering*, vol. 141(12): 04015062.

[12] Yu R.Q., Chen L., Fang Q. and Huan Y., 2018. An improved nonlinear analytical approach to generate fragility curves of reinforced concrete columns subjected to blast loads. *Advances in structural engineering*, vol. 21(3): 396-414.

[13] Olmati P., Petrini F. and Gkoumas K., 2014. Fragility analysis for the Performance-Based Design of cladding wall panels subjected to blast load. *Engineering structures*, vol. 78: 112-120.

[14] Nagata M., Beppu M., Ichino H. and Yashiro H., 2017. Proposal on risk assessment of reinforced concrete structures subjected to explosive loads, *International journal of protective structures*, vol. 8(3): 407-432.

[15] Asprone D., Jalayer F., Prota A. and Manfredi G., 2010. Proposal of a probabilistic model for multi-hazard risk assessment of structures in seismic zones subjected to blast for the limit state of collapse. *Structural safety*, vol. 32(1): 25-34.

[16] Yu R. Q., Chen L., Fang Q., Yan H. C. and Chen G. L., 2019. Generation of pressure–impulse diagrams for failure modes of RC columns subjected to blast loads. *Engineering failure analysis*, vol. 100: 520-535.

[17] Yu R.Q., Zhang D.D., Chen L. and Yan H.C., 2018. Non-dimensional pressure–impulse diagrams for blast-loaded reinforced concrete beam columns referred to different failure modes. *Advances in structural engineering*, vol. 21(14): 2114-2129.

[18] Taha M.M.R., Colak-Altunc A.B. and Al-Haik M., 2009. A multi-objective optimization approach for design of blast-resistant composite laminates using carbon nanotubes. *Composites part B-engineering*, vol. 40(6): 522-529.

[19] Yu R.Q., Zhang D.D. and Yan H.C., 2017. Embodied Energy and Cost Optimization of RC Beam under Blast Load, vol. 2017: 1907972.

[20] UFC 3-340-02, 2008. Structures to resist the effects of accidental explosions (Unified Facilities Criteria) 1943 pp.

[21] Standard GB 50038-2005, 2005. Code for design of civil air defence basement (Ministry of construction of the People's Republic of China) 48 pp.

[22] Bounds W.L., 2010. Design of Blast-resistant Buildings in Petrochemical Facilities (ASCE Publications) 311 pp.

[23] Rong H.C. and Li B., 2008. Deformation-controlled design of reinforced concrete flexural members subjected to blast loadings. *Journal of structural engineering*, vol. 134(10): 1598-1610.

[24] FEMA 452, 2005. Risk Assessment: A How-To Guide to Mitigate Potential Terrorist Attacks against Buildings (Federal Emergency Management Agency) 248 pp.

[25] ASCE Standard ASCE/SEI 59-11, 2012. Blast Protection of Buildings (American Society of Civil Engineers) 126 pp.