Failure Modes-Based Multi-objective Optimization of Steel Reinforced Concrete Frame Structures

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Abstract: The failure modes-based optimization of structure is that the non-idea failure modes of structure transform into idea failure modes, which causes the probability of structure collapse is reduced. Therefore, a new optimal approach based on strong column–weak beam failure modes multi-levels optimization design is proposed. The procedure of multi-levels optimization design is that the first level minimizes the cost of concrete subject to elastic displacement constraint due to a minor earthquake, and the second level minimizes the cost of shaped steels and reinforced bars subject to constraints on inelastic displacement caused by moderate and severe earthquakes. Explicit forms of the objective functions and constraints in terms of member sizing variables are formulated to enable computer solution for the optimization model. And a six-story steel reinforced concrete frame structure is cited to illustrate the method.
Keywords: frame structure; steel reinforced concrete; failure modes; Multi-levels Optimization

1. Introduction

In seismic design, the concept of strong column–weak beam and strong shear-weak bending is adopted by the existing design code, but most of the structures designed the code collapse with the destruction of columns under severe earthquake. Therefore, failure modes-based multi-levels optimization approach which the expected ideal failure modes of structure can be obtained is proposed.

Steel Reinforced Concrete (SRC) frame is composed by composite material, and SRC structural members have a relatively small sectional dimension and a high bearing capacity, but the optimization is more difficult than the steel frame. In this paper, two single-criterion phases is decomposed, that minimizes the cost of concrete subject to elastic displacement constraint due to a minor earthquake, and minimizes the cost of shaped steels and reinforced bars subject to constraints on inelastic displacement caused by moderate and severe earthquakes [1].

Optimum design solves optimal problems under certain preset conditions by applying computer and greatly improves economic benefit and design efficiency [2,3]. Accordingly, the sequential unconstrained minimization technique (SUMT) is used, which is an indirect method translating constraint optimization into an unconfined one.

2 Failure Modes-Based Multi-levels Optimization

2.1 Formulation of Objective Function.

The design objective is to minimize the material cost and the structural failure modes. Therefore, the objective function can be expressed as

$$\min F = F_1 + F_2 . \tag{1}$$

$$F_1 = f_1 . \tag{2}$$

$$F_2 = \omega_1 f_2 + \omega_2 f_3 + \omega_3 f_4 . \tag{3}$$

where F is the objective function; f_1 is the cost of concrete; f_2, f_3 are the expected structural damages, respectively; f_4 is the cost of steel. f_1, f_2, f_3 and f_4 need to adopt dimensionless expression for having different dimensional units [4].

2.2 Procedure of Optimization Design.

The process of entire optimization design is divided into two phases, which minimizes the cost of concrete subject to elastic displacement constraint due to a minor earthquake, and minimizes the cost of shaped steels and reinforced bars subject to constraints on inelastic displacement caused by moderate and severe earthquakes.

2.2.1 Optimization of concrete.

In the process of concrete optimization, it is assumed that the building is linearly elastic system under minor earthquake, and only the concrete works under minor earthquake. Therefore, the cost objective function of concrete can be expressed as

$$f_1 = \left\{ \sum_{i=1}^{n} \sum_{j=1}^{p} \rho_1 L_{ij,b} A_{ij,b}^c + \sum_{i=1}^{n} \sum_{j=1}^{m} \rho_1 L_{ij,c} A_{ij,c}^c \right\} \times C_1 / \gamma C_{\max} . \quad (4)$$

where, ρ_1 is concrete density; $L_{ij,b}$ and $L_{ij,c}$ are the length of beam and column, respectively; C_1 is the unit price of concrete; γ is amplification coefficient; $C_{\max}$ is the maximum cost obtained by experience; $A_{ij,b}^c$ and $A_{ij,c}^c$ are the concrete cross-section areas of beam and column, respectively; $A_{ij,b}^c = b_{ij,b} h_{ij,b}$, $A_{ij,c}^c = b_{ij,c} h_{ij,c}$ [5].

The Constraint Conditions are following [6, 7]:

(1) Shear carrying capacity requirements of columns

$$V_i \le \frac{1}{\gamma_{\mathrm{RE}}} \left[\frac{0.20}{\lambda + 1.5} f_c b_{ij,c} h_{o,ij,c} + 0.07 N_i \right] . \quad (5)$$

$$V_i = \sum_{i=i}^{n} F_i . \quad (6)$$

$$F_i = \frac{G_i h_i}{\sum_{j=1}^{n} G_j h_j} F_{EK} \left(1 - \delta_n\right) \quad (i = 1, 2 \ldots n) . \quad (7)$$

$$F_{\mathrm{EK}} = \alpha G_{eq} . \quad (8)$$

$$\alpha = \left(\frac{T_g}{T} \right)^{\gamma} \eta_2 \alpha_{\max} \quad \alpha_{\max} = 0.04 . \quad (9)$$

$$G_{eq} = 0.85 \sum_{i=1}^{n} G_i . \quad (10)$$

$$N_i = \sum_{i=i}^{n} G_i . \quad (11)$$

(2) Lateral displacement requirements of columns

$$\sum_{i=1}^{n} \Delta_{i,s} = \sum_{i=1}^{n} \frac{V_i}{\sum_{j=1}^{k} D_{ij}} \le [\Delta] = [\theta_e] H, \quad \theta_e = \frac{1}{800} . \quad (12)$$

(3) Axial compression ratio requirements of columns

$$N_i / \left(f_c A_{ij,c} \right) \le 0.75 . \quad (13)$$

(4) Requirements on height, width and ratio of height and width of column

$$300\text{mm} \le b_{ij,c} \le \frac{h_i}{2}, \quad 300\text{mm} \le h_{ij,c} \le \frac{h_i}{2}, \quad \frac{b_{ij,c}}{h_{ij,c}} \le 3 . \quad (14)$$

$$V_i' \le 0.25 f_c b_{ij,c} h_{ij,c} \quad V_i' = 2 V_{i,c} . \quad (15)$$

(5) Shear carrying capacity requirements of beams

$$V_{i,b} \le \frac{1}{\gamma_{\mathrm{RE}}} \left[0.056 f_c b_{ij,b} h_{o,ij,b} \right] . \quad (16)$$

$$V_{i,b} = \frac{G_i}{l} \frac{L_{il,b}}{2} . \quad (17)$$

(6) Requirements on height, width and ratio of height and width of beam

$$1.4b_{ij,b}h^3_{ij,b} \le b_{ij,c}h^3_{ij,c} \,. \tag{18}$$

$$b_{ij,b} \ge 300\text{mm}, \quad h_{ij,b} > 300\text{mm}, \quad h_{ij,b} \le 4b_{ij,b} \,. \tag{19}$$

2.2.2 Optimization of steels.

In the process of optimization of steels, the design process is decomposed into three phases. First of all, the reinforced bars quantities are defined as fixed value according to minimum reinforcement ratio of the members with the biggest cross-section and stirrup ratio. Second, an optimization that minimizes the interstory drift subject to displacement and shear constraint is involved under moderate earthquakes. Third, an optimization that controls the damage values of columns subject to the limit damage values and minimizes the cost of steel is involved under severe earthquakes. So the objective function of steel can be expressed as [8]

$$\begin{aligned} F_2 &= \omega_1 f_2 + \omega_2 f_3 + \omega_3 f_4 \\ &= \omega_1 \left\{ (1/n) \sum_{s=1}^{n} \left[\left(\left(\sum_{i=1}^{s} \Delta_i \right) / \Delta \right) \left(H / \sum_{i=1}^{s} H_i \right) - 1 \right]^2 \right\}^{\frac{1}{2}} \\ &+ \omega_2 \left[\eta_1 \left(\frac{1}{n \times m} \right) \times \sum_{i=1}^{n} \sum_{j=1}^{m} \left(1 - D_{ij,c} \right) + \eta_2 \left(\frac{1}{n \times p} \right) \times \sum_{i=1}^{n} \sum_{j=1}^{p} \left(1 - D_{ij,b} \right) \right] \\ &+ \omega_3 \left\{ \sum_{i=1}^{n} \sum_{j=1}^{p} \rho_2 L_{ij,b} A^s_{ij,b} + \sum_{i=1}^{n} \sum_{j=1}^{m} \rho_2 L_{ij,c} A^s_{ij,c} \right\} \times C_2 / \gamma C_{\max} \end{aligned} \,. \tag{20}$$

where n is number of stories; H and H_s are distances from the building ground level to roof and story S, respectively; Δ_i and Δ are lateral translations of story S and the building roof at the reverse earthquake, respectively. And Δ is structure displacement under moderate earthquakes; $D_{ij,b}$ and $D_{ij,c}$ are the damage value of beam and column, respectively; η_1 and η_2 are the combination factors of beam and column, respectively; ω_1, ω_2 and ω_3 are the influence coefficient; ρ_2 is steel density; $A^s_{ij,b}$ and $A^s_{ij,c}$ are the shaped-steel cross-section areas of beam and column, respectively; C_2 is the unit price of steel.

It is assumed that the building is elastic-plastic system under moderate earthquakes, and the main Constraint conditions are following [7]:

(1) Shear carrying capacity requirements of columns

$$V_i \le \frac{1}{\gamma_{\text{RE}}} \left[\frac{0.20}{\lambda + 1.5} f_c b_{ij,c} h_{o,ij,c} + 0.8 f_{\text{yv}} \frac{A_{\text{sv}}}{s_{\text{sv}}} h_0 + 0.07 N_i \right]. \tag{21}$$

where A_{sv} is the cross-section areas of stirrups; s_{sv} is range interval of stirrups; the $\alpha_{\max}$ in Eq.(9) is defined 0.08 in this step.

(2) Lateral displacement requirements of columns

$$\sum_{i=1}^{n} \Delta_{i,m} = \sum_{i=1}^{n} \frac{V_i}{\sum_{j=1}^{k} D_{ij}} \le [\Delta] = [\theta_e] H, \quad \theta_e = \frac{1}{500} \,. \tag{22}$$

(3) Requirements on range interval of stirrups:

$$S_{\text{sv}} \le \min\left[1, \text{int}\left(\frac{0.999 \cdot V}{0.07 f_c b h_0}\right)\right] \cdot 50 \left\{4 + \min\left[1, \text{int}\left(\frac{h}{525}\right)\right] + \min\left[1, \text{int}\left(\frac{h}{825}\right)\right]\right\} + \text{int}\left[\frac{\min\left(V, 0.07 f_c b h_0\right) + 1}{V + 1}\right] \cdot 300 \tag{23}$$

$$S_{\text{sv}} > 100 \tag{24}$$

(5) Requirements on the stirrup ratio:

$$A_{\text{sv}} / b S_{\text{sv}} \ge 0.24 f_t / f_{\text{yv}} \tag{25}$$

It is assumed that the building is plastic system under severe earthquakes, and the main Constraint conditions are following:

(1) Shear carrying capacity requirements of columns

$$V_i \le \frac{1}{\gamma_{\text{RE}}} \left[\frac{0.20}{\lambda + 1.5} f_c b_{cj} h_{o,cj} + 0.8 f_{\text{yv}} \frac{A_{\text{sv}}}{s} h_{0,ij,c} + 0.07 N_i + \frac{0.58}{\lambda} f_a t_w h_w \right]. \tag{26}$$

where t_w and h_w are the web thickness and web height of shaped-steel, respectively; the $\alpha_{\max}$ in Eq.(9) is defined 0.16 in this step.

(2) Lateral displacement requirements of columns

$$0.6 \le D_{ij,c} \le 0.8 . \tag{27}$$

$$D_{ij,c} = \frac{\sum_{i=1}^{n} \Delta_{i,l}}{\left[\theta_p\right] H} \qquad \theta_p = \frac{1}{300} . \tag{28}$$

$$\sum_{i=1}^{n} \Delta_{i,l} = \sum_{i=1}^{n} \frac{V_i}{\sum_{j=1}^{k} D_{ij}} . \tag{29}$$

(3) Requirements on height, width and ratio of height and width of beam

$$\left(\sum_{j=1}^{m} \frac{E^c A^c_{ij,b}}{h^c_{ij,b}} + \sum_{j=1}^{m} \frac{E^s A^s_{ij,b}}{h^s_{ij,b}} \right) \le 1.4 \left(\sum_{j=1}^{m} \frac{E^c A^c_{ij,c}}{h^c_{ij,c}} + \sum_{j=1}^{m} \frac{E^s A^s_{ij,c}}{h^s_{ij,c}} \right) \tag{30}$$

(4) Deflection requirements of beams

$$0.7 \le D_{ij,b} \le 0.99 . \tag{31}$$

$$D_{ij,b} = \frac{f}{f_{\lim}} \qquad f_{\lim} = \frac{L_{ij,b}}{200} . \tag{32}$$

$$f = s \frac{M L^2_{ij,b}}{(EI)_b} . \tag{33}$$

where $D_{ij,b}$ and $D_{ij,c}$ are the damage value of beam and column, respectively; $\Delta_{i,l}$ is structure displacement under severe earthquakes; 0.7 and 0.6 are the damage values of beam and column respectively when plastic hinge appears, which are obtained by the test results of steel reinforced concrete frame structures; s is the influence coefficient of deflection; f and $f_{\lim}$ are the practical deflection and limit deflection, respectively [9,10].

2.2.3 Design variables.

For this study, the sizes of the concrete and shaped steel cross-section of structural members are defined as the design variables.

3. Mixing Penalty Function Method of Discrete Variables

The failure modes-based multi-levels optimization design can be solved by using sequential unconstrained minimization technique (SUMT), which is an indirect method translating constraint optimization into an unconfined one. The following is its primary principles [11, 12].

The mathematic model of constraint optimization is written as

$$\begin{aligned} &\min \quad \boldsymbol{f}(\boldsymbol{X}) \qquad \boldsymbol{X} \in \boldsymbol{R}^n \\ &\text{s.t.} \quad \boldsymbol{g_i}(\boldsymbol{X}) \le 0 (i = 1, 2 \cdots, p) \\ &\qquad \boldsymbol{h_j}(\boldsymbol{X}) = 0 (j = 1, 2 \cdots, p) \end{aligned} \tag{34}$$

where $\boldsymbol{X} = [x_1, x_2, \cdots, x_n]^{\mathrm{T}}$ is decision-making vector; $\boldsymbol{f}(\boldsymbol{x})$ is objective function vector; $\boldsymbol{g_i}(\boldsymbol{X}) \le 0$, $\boldsymbol{h_j}(\boldsymbol{X}) = 0$ is constraint functions.

Adding $\boldsymbol{g}(\boldsymbol{X})$ and $\boldsymbol{h}(\boldsymbol{X})$ to $\boldsymbol{f}(\boldsymbol{x})$, the original optimization question is translated into an equivalent unconfined one shown as

$$\begin{aligned} &\min \quad \boldsymbol{F}(\boldsymbol{X}, r_k, t_k) \qquad \boldsymbol{X} \in \boldsymbol{R}^n \\ &\qquad \boldsymbol{X} = [x_1 \quad x_2 \quad \cdots \quad x_n]^T \\ &\qquad k = 0, 1, 2, \cdots \end{aligned} \tag{35}$$

$\boldsymbol{F}(\boldsymbol{X}, r_k, t_k)$ is an artificial objective function, named as penalty function, and it is expressed as

$$\min \boldsymbol{F}(\boldsymbol{X}, r_k, t_k) = \boldsymbol{f}(\boldsymbol{X}) + r_k \sum_{i=1}^{p} \boldsymbol{G}\left[\boldsymbol{g_i}(\boldsymbol{X})\right] + t_k \sum_{j=1}^{q} \boldsymbol{H}\left[\boldsymbol{h_j}(\boldsymbol{X})\right] \tag{36}$$

where $G\left[g_i(X)\right]$, $H\left[h_j(X)\right]$ are fonctionelles of $g_i(X)$ and $h_j(X)$ respectively, a group of inequality constraint conditions and equality constraint conditions in regard to the original optimization question; r_k and t_k are called penalty factors or penalty parameters, which are adjusted according to increase of k ; $\sum_{i=1}^{p} G\left[g_i(X)\right]$, $\sum_{j=1}^{q} H\left[h_j(X)\right]$ are called penalty items, and they are non-negative.

It is visible that value of $F(X, r_k, t_k)$ is usually larger than value of the original objective function $f(x)$. In order to astringe penalty function $F(X, r_k, t_k)$ to the constraint optimum solution x^* of original question, the penalty must own the following character

$$\left.\begin{aligned} \lim_{k\to\infty} r_k \sum_{i=1}^{p} G\left[g_i(X)\right] = 0 \\ \lim_{k\to\infty} t_k \sum_{j=1}^{q} H\left[h_j(X)\right] = 0 \end{aligned}\right\} \tag{37}$$

which means penalty effect on penalty function will disappear gradually along with continuous adjustment of penalty factors, i.e.

$$\lim_{k\to\infty} \left| F(X, r_k, t_k) - f(X) \right| = 0 \tag{38}$$

If objective function and constraint function are both continuous and differentiable, it is necessary to satisfy the following equation in gaining extreme point of penalty function, which is K-T condition for constraint extreme point.

$$\nabla F(X, r_k, t_k) = \nabla f(X) + r_k \sum_{i=1}^{p} \nabla G\left[g_i(X)\right] + t_k \sum_{j=1}^{q} \nabla H\left[h_j(X)\right] = 0 \tag{39}$$

Optimum question with both equality and inequality constraints can be solved by combining inner point method and outer point method, which is mixing penalty function method.

When constraint conditions are $g_i(X) \leqslant 0$ and $h_j(X) = 0$, the general expression of penalty function is as follows:

$$F(X, r_k) = f(X) - r_k \sum_{i\in I_1} \frac{1}{g_i(X)} + t_k \sum_{i\in I_2} \left\{\max\left[0, g_i(X)\right]\right\}^2 + t_k \sum_{j=1}^{q} \left[h_j(X)\right]^2 \tag{40}$$

$$\begin{cases} I_1 = \left\{ i \left| g_i\left(X^{(0)}\right) < 0 \quad (i = 1, 2, \cdots, p) \right.\right\} \\ I_2 = \left\{ i \left| g_i\left(X^{(0)}\right) \geqslant 0 \quad (i = 1, 2, \cdots, p) \right.\right\} \end{cases} \tag{41}$$

where r_k is a decreasing sequence of positive real number; t_k is an increasing sequence of positive real number, $X^{(0)}$ is initial point; I_1, I_2 are two constraint sets.

In the optimization of practical structural engineering, parts even all of the design variables are often discrete variables, which can only take special and discrete values. This means will add several equation constraint conditions to mathematical model, so it can be solved by using mixing penalty function method.

On the assumption that the number of discrete variables is l in design variables, and the rest are continuous variables, in which discrete variables are given as $X^d = \left[x_1, x_2, \cdots, x_l\right]^{\mathrm{T}}$, then penalty function can be expressed as

$$F(X, r_k, t_k, s_k) = f(x) - r_k G_1\left[g_i(X)\right] + t_k H\left[h_j(X)\right] + s_k D(x_u) \tag{42}$$

where r_k and t_k are the same as formula (42). On the right side of equation, the first item is original objective function; the second is punitive item of interior point method considering the constraint condition of $g_i(X) \le 0$; the third is punitive item of outside point method considering the constraint condition of

$h_j(X) \le 0$; the fourth is punitive item to assure specified discrete value for the design variables, s_k is penalty factor, which is an increasing sequence of positive real number.

The items in penalty function are as follows

$$G_1\left[g_i(X)\right] = \sum_{i \in I_1} \frac{1}{g_i(X)} \tag{43}$$

$$H\left[h_j(X)\right] = \sum_{j=1}^{q}\left[h_j(X)\right]^2 \tag{44}$$

$$D(x_u) = \sum_{u=1}^{l}\left[\prod_{v=1}^{m_u}\left(\frac{x_u - z_{uv}}{\bar{x}_u - z_{uv}}\right)\right]^2 \tag{45}$$

$$D_u(x_u) = \left[\prod_{v=1}^{m_u}(x_u - z_{uv})\right]^2 \tag{46}$$

where z_{uv} $(v = 1 \sim m_u)$ is discrete value of variable x_u; m_u is the discrete value number of variable x_u; $\bar{x}_u$ is the average value of z_{uv} and $z_{u,v+1}$, i.e. $\bar{x}_u = \frac{1}{2}\left(z_{uv} + z_{u,v+1}\right)$.

4. Example of Failure Modes-Based Design

As shown in Fig.1, a six-story and three-bay steel reinforced concrete framework is considered, and the design variables are shown in Fig.2. The known conditions are as followings: concrete strength grade is C30; steel grade is Q235; HPB235 is used for longitudinal reinforcement and stirrup; shaped-steel grade is HRB235; the price of concrete is 500 yuan per cubic meter; the price of shaped-steel is 3700 yuan per ton, the price of longitudinal reinforcement is 3000 yuan per ton, the price of stirrup is 2700 yuan per ton.

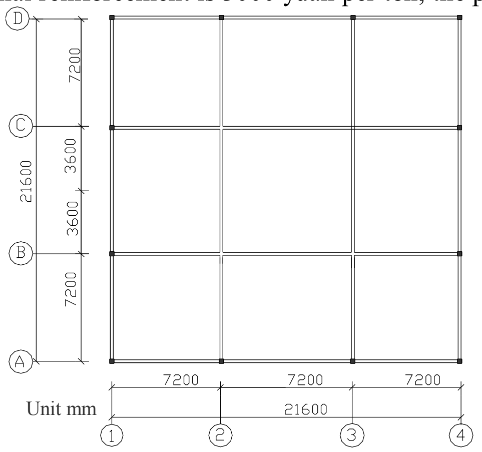

Fig.1 the plan of structure

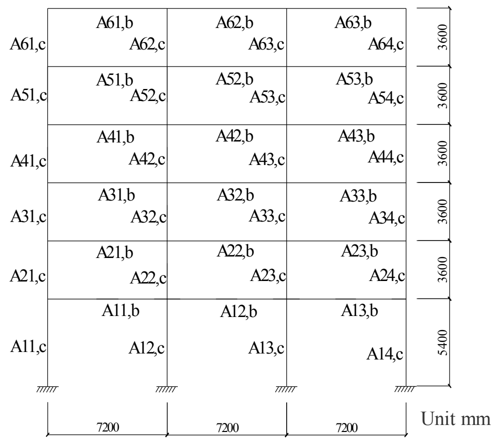

Fig.2 Three-bay steel reinforced concrete framework

Table.1 The cross-section of concrete by optimization

Variable	$A^c_{11,c}$–$A^c_{14,c}$	$A^c_{21,c}$–$A^c_{24,c}$	$A^c_{31,c}$–$A^c_{34,c}$	$A^c_{41,c}$–$A^c_{44,c}$
Concrete cross-section(mm^2)	550×550	550×550	500×500	500×500
Variable	$A^c_{51,c}$–$A^c_{54,c}$	$A^c_{61,c}$–$A^c_{64,c}$	$A^c_{11,b}$–$A^c_{13,b}$	$A^c_{21,b}$–$A^c_{23,b}$
Concrete cross-section(mm^2)	450×450	450×450	600×350	500×350
Variable	$A^c_{31,b}$–$A^c_{33,b}$	$A^c_{41,b}$–$A^c_{43,b}$	$A^c_{51,b}$–$A^c_{53,b}$	$A^c_{61,b}$–$A^c_{63,b}$
Concrete cross-section(mm^2)	500×350	450×350	450×300	450×300

In the first level of failure modes-based optimization, the min F_1 can be obtained according to Eq.(4)-(19) and mixing penalty function method. And the results are shown in table 1.

In the second level of failure modes-based optimization, the stirrup of columns are defined ϕ 8@120 according to Eq.(23)-(25), and the stirrup of beams are defined according to code [7], $\omega_1 = 0.4$, $\omega_2 = 0.5$ and $\omega_3 = 0.1$ are defined, then the min F_2 can be obtained according to Eq.(20)-(33) and mixing penalty function method. And the results are shown in table 2.

Table.2 The cross-section of shaped steel by optimization

Variable	$A^s_{11,c}$–$A^s_{14,c}$	$A^s_{21,c}$–$A^s_{24,c}$	$A^s_{31,c}$–$A^s_{34,c}$	$A^s_{41,c}$–$A^s_{44,c}$
Shaped steel cross-section(mm^2)	HW458×417	HW458×417	HW428×407	HW414×405
Variable	$A^s_{51,c}$–$A^s_{54,c}$	$A^s_{61,c}$–$A^s_{64,c}$	$A^s_{11,b}$–$A^s_{13,b}$	$A^s_{21,b}$–$A^s_{23,b}$
Shaped steel cross-section(mm^2)	HW400×408	HW400×400	HM488×300	HM482×300
Variable	$A^s_{31,b}$–$A^s_{33,b}$	$A^s_{41,b}$–$A^s_{43,b}$	$A^s_{51,b}$–$A^s_{53,b}$	$A^s_{61,b}$–$A^s_{63,b}$
Shaped steel cross-section(mm^2)	HM440×300	HN390×300	HM340×250	HN396×199

In the process of optimization design, equivalent-static pushover analysis is adopted, and the results are shown in Fig 3 according to Eq.(27)-(33).

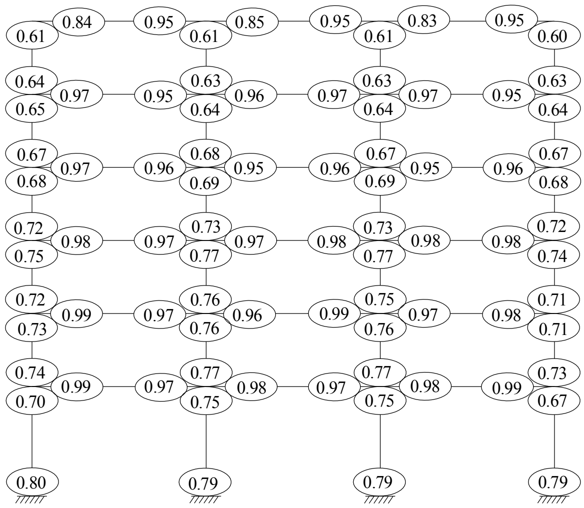

Fig.3 Damage value under severe earthquake

5. Conclusions

Failure modes-based multi-levels optimization design is discussed in this paper, which the first level to optimize the concrete and the second level to optimize the steel supply an effective way to reduce both the damage and the cost of SRC frame structure. And the most important conclusion that can be drawn from the study is that the expected strong column–weak beam failure modes are obtained according to multi-levels optimization design.

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