Fuzzy Seismic Damage Assessment of Steel Frame Structures with Buckling Restrained Braces under Near-field Ground Motions

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ABSTRACT :

Seismic damage assessment of structures was highly emphasized in earthquake engineering. More extensive attentions were being placed to the influence of near-field ground motions on structures, the notable long-period velocity pulse feature of near-field ground shaking would cause the structures into severe damage, and lead to shocking economic losses and casualties. Furthermore, the economical and practical buckling restrained braces can reduce the structures response effectively, avoiding unnecessary economic losses and death. Considering many uncertain factors and incontrollable conditions of the damage index, the conception of fuzzy sets and fuzzy membership is used in this paper. In order to compare, two damage assessment procedures are presented with different border points values. Regarding holistic damage index, storey damage index, storey drift ratio and number of inelastic cycles which indicates the cumulative loss of energy, the multiple fuzzy seismic damage of high-rise steel frame structure with buckling restrained braces is evaluated based on fuzzy mathematics theory, which makes the structural seismic safety assessment scientifically meaningful.

KEYWORDS: steel moment-resistant frame structure, buckling restrained brace, near-field ground motion, fuzzy seismic damage assessment

1. INTRODUCTION

Recently, the effect of near-field ground motions (Yang Dixiong *et al.* 2005) on engineering structures had become a extensive issue of earthquake engineering and structural engineering. The notable amplitude, long-period pulse characteristic of near-field ground motions would lead the structure into complex behavior, following serious damage even collapse of structures located in the near-field region. So it is necessary to investigate the structural behavior under near-field ground motions.

On the basis of earthquake resistance and prevention, the quantitative description of structure damage level is very important. Previous studies focused on material, structural component and structure levels (BERTERO *et al.* 2002; CHOPRA *et al.* 2002), and the being used damage indexes have many limitations, such as the complexity, unconvergence and so on. In this paper, the holistic damage index and storey damage index which meet the convergence rule are calculated by mechanics method. Current provisions for seismic design are based on peak demands without consideration of cumulative damage effects caused by inelastic cyclic response. The deformation demands imposed on structural components by earthquake ground motions are cyclic in nature. So the number of inelastic cycles is introduced.

In the previous seismic damage assessment procedure was based on deformation index only, which caused a big error. So in this study, with the holistic damage index, storey damage index, storey drift ratio and number of inelastic cycles, the multiple fuzzy seismic damage of steel frame structure with buckling restrained braces is evaluated based on fuzzy mathematics theory.

2. STRUCTURAL SEISMIC DAMAGE PERFORMANCE OBJECTIVES

2.1. Holistic Damage Index and Storey Damage Index

The structure's damage state was complex with the consideration of the inelastic behavior. Lots of researchers (Wu Bo *et al.* 1997) focused on calculating the structural damage index. Using the capacity spectrum method to evaluate the structure damage was simple and feasible. In this study, based on the modal pushover analysis of the 20-storey Buckling Restrained Braces Frame (BRBF) structures with consideration of the first five modes and their combination according to the SRSS rule, the floor displacement and shear force are obtained. Then the damage index is calculated by the capacity spectrum method. Using the diagram of relationship between base shear and roof displacement (P-u) (or storey shear and storey displacement, shown as figure 1) based on the pushover curve, the damage index D_n of the structure can be derived via solving the Eqn.2.1.

$$D_n = \frac{k_0 u_n - k_0 u_1 - k_1(u_2 - u_1) - \cdots - k_{n-1}(u_n - u_{n-1})}{k_0 u_n} = 1 - \frac{\sum_{i=0}^{n-1} k_i (u_{i+1} - u_i)}{k_0 u_n} \tag{2.1}$$

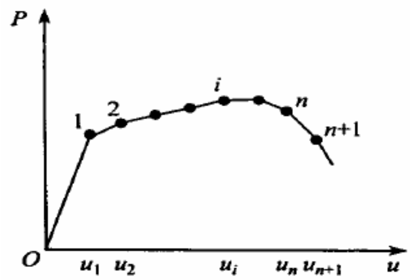

Figure 1. Diagram of relationship between force and deformation

Where k_i is the slope between points i and $i+1$, $k_i = (P_{i+1} - P_i)/(u_{i+1} - u_i)$.
This damage index D_n is sensitive to the structure characteristics and meets the convergence rule. The damage index value of the demand point D_n can be derived by Eqn.2.1 under pushover analysis. D_n can sufficiently reflect the speciality of the structure.

2.2. The Number of Inelastic Cycles

Since the dissipated energy of structures can be treated as a critical measure of the seismic resistance of the system, it is important to establish the relationship between translated dissipated energy and a cyclic demand parameter. Non-linear force-deformation behavior is a function of numerous parameters ranging from material type to internal force interaction in detail. A commonly used elastic perfectly-plastic behavior is used herein. The key idea of the number of inelastic cycles is to translate the structure dissipated hysteretic energy into the number of the energy dissipated within one cycle. The expression between the number of inelastic cycles and dissipated hysteretic energy can be derived via solving Eqn.2.2.

$$N_f = \frac{E_h}{E_D} = \frac{E_h}{4\alpha_h \mu_c V_y u_y} = \frac{m\pi^2 E_h}{\alpha_h \mu_c (V_y T)^2} \tag{2.2}$$

Where E_h is dissipated hysteretic energy, $\mu_c = u_{\max}/u_y$ is displacement ductility factor, $a_h = 1 - 1/\mu_c$ is energy shape factor, V_y is yield force, and T is fundamental period of the structure.

To complete the energy-cyclic demand relationship in a format that can be used later in the development of the demand spectra, it is necessary to eliminate the design base shear force and replace it with a description of the design spectra which also incorporates the force-reduction factor. For this purpose, considering the definition of design base shear force, Eqn2.4 is derived by the substitution of Eq.2.3 into Eqn.2.2.

$$V_y = \frac{mS_a}{R_\mu} \tag{2.3}$$

$$N_f = \left(\frac{E_h}{m}\right)\frac{\pi^2}{\mu_c \alpha_h}\left(\frac{R_\mu}{TS_a}\right)^2 \tag{2.4}$$

Where m is the seismic mass, S_a is the design spectral acceleration, R_μ is the force-reduction factor. In order to remain consistent with Eqn.2.4, the force-reduction factor expression proposed by Vidic *et al.* (1994) is used and shown as Eqn.2.5.

$$R_\mu = \begin{cases} (\mu_c - 1)T/T_0 + 1 & T \le T_0 \\ \mu_c & T > T_0 \end{cases}, \text{ and: } T_0 = 0.65 T_g (\mu_c)^{0.3} \le T_g \tag{2.5}$$

Where T_0 is the transition period, T_g is the characteristic period.
It has been shown (Kuwamura *et al.* 1994) that for an elastic undamped single-degree-of-freedom system, the Fourier amplitude spectrum of the ground acceleration $|F(\omega)|$ is equal to the equivalent input energy velocity v_e which is shown as Eqn.2.6.

$$v_e = |F(\omega)| = (\frac{2E_I}{m})^{0.5} = (\frac{2E_h}{\alpha m})^{0.5} \tag{2.6}$$

Where E_I is the input earthquake energy, α is the ratio of hysteretic energy to total seismic input energy. Here, the expression of α proposed by Fajfar and Vidic (1994) is shown in Eqn.2.7.

$$a = 1.13 \frac{(\mu_c - 1)^{0.82}}{\mu_c} \tag{2.7}$$

Substitution of Eqn.2.6 into Eqn.2.4 yields Eqn.2.8.

$$N_f = (\frac{a v_e^2}{2}) \frac{\pi^2}{\mu_c \alpha_h} (\frac{R_\mu}{T S_a})^2 \tag{2.8}$$

The amplification factor for the input energy which is given in Eqn.2.9 is found to have a significant influence on the computed cyclic demand. The following relationship is proposed to characterize the variation of the amplification factor Ω_V.

$$v_e = \Omega_V(\dot{x}_{g,\max}) = \begin{cases} \Omega_V^* \left(\frac{2T}{T_g} - \left[\frac{T}{T_g} \right]^2 \right) ; T \le T_g \\ \Omega_V^* \left[\frac{T}{T_g} \right]^{-\lambda} ; T > T_g \end{cases}, \quad \Omega_V^* = \frac{\ddot{x}_{g,\max}}{4\dot{x}_{g,\max}} \sqrt{t_d T_g} \sqrt{\frac{\lambda + 0.5}{2\lambda + 2}} \tag{2.9}$$

Where Ω_V^* is the peak amplification factor for the input energy spectrum, λ is a parameter that characterizes the spectral shape of the input energy spectrum for $T > T_g$ ($\lambda = 0.5$ was more appropriate for the earthquake ground motions suggested by Kunnat, 2004), t_d is the strong motion duration based on the definition by Trifunac and Brady (1975), $\dot{x}_{g,\max}$ is the peak ground velocity, $\ddot{x}_{g,\max}$ is the peak ground acceleration.

3. STRUCTURAL FUZZY DAMAGE ASSESSMENT METHOD

3.1. Fuzzy Sets and Membership Functions

Table 3.1 Performance objectives for seismic damage of steel structure with three level aseismic design

Earthquake hazard levels	Frequent earthquake	Occasional earthquake		Rare earthquake	
Damage state	No damage	Repairable	Irreparable	Severe	collapse
holistic damage index	0~0.10	0.10~0.30	0.30~0.55	0.55~0.85	0.85~1.00
storey damage index	0~0.10	0.10~0.30	0.30~0.55	0.55~0.85	0.85~1.00
storey drift ratio	0~0.2%	0.2%~0.5%	0.5%~1.5%	1.5%~2.5%	>2.5%
number of inelastic cycles	—	15~30	5~15	2~5	0~2

Based on the structural performance objectives discussed in the previous section, Table 3.1 lists the performance objectives for seismic damage of steel structure with three-level aseismic design.

The Gaussian membership function is used to build the fuzzy damage assessment procedure which is described by Eqn.3.1.

$$f(x,\sigma,c)=e^{-\frac{(x-c)^2}{2\sigma^2}} \tag{3.1}$$

Where σ and c are the characteristic parameters, whose value are based on following functions.
When evaluation factors are the interval's representative points (general the interval's midpoints), the membership is 1. With the consideration of level V imprecise upper bounds, its membership can be got via Eqn.3.2.

$$X_5 = X_5^L + 0.5(X_4^U - X_4^L) \tag{3.2}$$

Where X_i is the damage level and X_i^U, X_i^L is upper or lower bound.

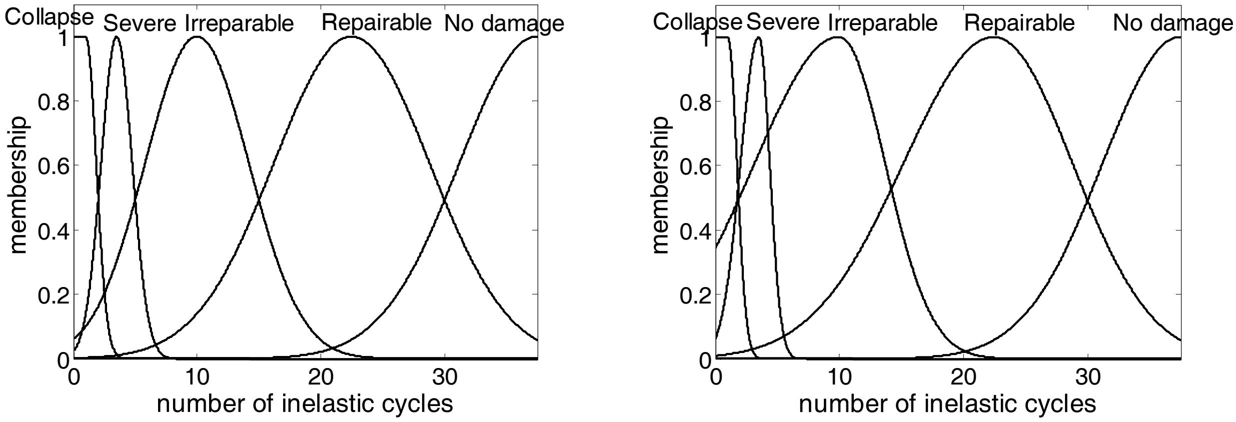

Figure 2. Built-in membership functions of number of inelastic cycles (0.5 and Eqn.3.4 respectively)

And the left and right border points' values are got by Eqn.3.3.

$$\begin{cases} \mu_i(x_i)=1 \\ \mu_i(x_i^L)=\mu_i^L \qquad \mu_i(x_i^U)=\mu_i^U \end{cases} \qquad i=1,2\cdots,5 \tag{3.3}$$

Generally, the border points' values are 0.5, for the adjacent intervals with different length the border points' values are proposed by Eqn.3.4.

$$\begin{cases} \mu_i^L = \Delta_i/(\Delta_i+\Delta_{i-1})\, i=2,3,\cdots,5 \\ \mu_i^U = \Delta_i/(\Delta_i+\Delta_{i+1})\, i=1,2,\cdots,4 \end{cases} \tag{3.4}$$

Where $\Delta_{i-1}, \Delta_i, \Delta_{i+1}$ are adjacent intervals lengths respectively.
According to different values two evaluation procedures are built here for four performance objectives, which just listed the number of inelastic cycles' membership as shown in Figure 2 (left one represents the border points' values are 0.5, right one represents the border points' value are proposed by Eqn.3.4, and numbered as 1 and 2 respectively). The two procedures overcome the levels' unreasonableness caused by subjective understanding of the people.

3.2. Structural fuzzy damage assessment model

The five damage levels are defined as domain $X=\{x_1,x_2,\cdots,x_n\}$ by fuzzy comprehensive evaluation methods. This domain is a general collection which describes the fuzziness of every damage level. Fuzzy judgment is represented by holistic damage index, storey damage index, storey drift ratio and number of inelastic cycles to judge the damage states' membership for the domain which is caused by the performance objectives. Define the domain's fuzzy sets as $A=a_1/x_1+a_2/x_2+\cdots+a_n/x_n$, where x_i is the damage state level, a_i is the membership of x_i for A.

Considering Table 3.1, the damage domain $X = \{\text{no damage, repairable, irreparable, severe, collapse}\}$. Fuzzy structural damage vector $A_0 = \{a_1, a_2, a_3, a_4, a_5\}$ is comprised by memberships. Assumption of the factors domain $R = \{r_1, r_2, \cdots, r_m\}$ is comprised by m damage assessment factors. The factors domain $R = \{$holistic damage index, storey damage index, storey drift ratio, number of inelastic cycles$\}$ in this study. The effect for levels judgment by factors $r_i (i = 1, \cdots, m)$ is considered by factor fuzzy vector $B = \{b_1, b_2, \cdots, b_m\}$ whose sum of all elements is 1. $B = \{0.40, 0.25, 0.25, 0.10\}$ (He Hao-xiang *et al.* 2006) in this study.

Judge the fuzzy damage vector A_0 by the fuzzy relationship between R and X. Calculate the membership of r_i for x_i and get the fuzzy relations vector $f_i = \{f_{i1}, f_{i2}, \cdots, f_{ij}, \cdots, f_{in}\}$, where $f_{ij} = f_{ij}(r_i)$. Integrated f_i and get the fuzzy matrix described as Eqn.3.5.

$$F = \begin{bmatrix} f_1 \\ \vdots \\ f_m \end{bmatrix} = \begin{bmatrix} f_{11} & \cdots & f_{1n} \\ \vdots & \ddots & \vdots \\ f_{m1} & \cdots & f_{mn} \end{bmatrix}_{m \times n} \tag{3.5}$$

A_0 can be got via function $A_0 = B \cdot F$ which was described as Eqn.3.6.

$$A_0 = [a_1, \cdots, a_n] = [b_1, \cdots, b_m] \cdot \begin{bmatrix} f_{11} & \cdots & f_{1n} \\ \vdots & \ddots & \vdots \\ f_{m1} & \cdots & f_{mn} \end{bmatrix}_{m \times n} \tag{3.6}$$

Structural damage state belongs to every damage level's degree explained by A_0 elements' value. And the composite index of overall injury is calculated via Eqn.3.7.

$$D_0 = \sum_{i=1}^{5} a_i^2 D_{mi} / \sum_{i=1}^{5} a_i^2 \tag{3.7}$$

Where D_{mi} is the representative point value of the holistic damage index in level i. D_0 is distributed in interval [0,1] strictly and evaluates the structural performance accurately.

3.3. Multiple Fuzzy Seismic Damage Assessment Procedure

Based on the analysis in previous section structural multiple fuzzy damage assessment procedure is following.

(1) Determine the damage domain $X = \{x_1, x_2, \cdots, x_n\}$ which describes the damage levels. The corresponding fuzzy damage vector of fuzzy set A is $A_0 = \{a_1, a_2, a_3, a_4, a_5\}$.

(2) Select the damage domain $R = \{r_1, r_2, \cdots, r_m\}$ which is comprised by m damage assessment factors and give the factor fuzzy vector $B = \{b_1, b_2, \cdots, b_m\}$.

(3) Calculate the factors domain $R = \{r_1, r_2, \cdots, r_m\}$ by nonlinear analysis.

(4) Calculate $f_{ij} = f_{ij}(r_i)$ and get the fuzzy matrix F.

(5) Obtain the fuzzy damage vector A_0 via solving function $A_0 = B \cdot F$.

(6) Calculate the composite index of overall injury D_0.

4. CHARACTERISTICS OF THE MODEL AND THE ANALYSIS RESULT

4.1. 20-Storey Steel Frame Structure with Buckling Restrained Braces

This study deals with modeling and analysis of two-dimensional braced frames consisting of beams, columns and diagonal bracing members. The structural model is comprised of three element types: beam elements for the beams; beam column elements for the columns; and link elements for the buckling restrained braces. In the beam elements, plastic hinge moment capacities are defined for the plastic hinges M3; however, axial force-moment interaction curves are defined for column behavior at the plastic hinges PMM. The buckling restrained braces are defined by bilinear force-deformation relationship (Wu Bo *et al.* 1997). For nonlinear static analysis P-Δ effects are taken into account. The aseismic design parameters are: seismic intensity Ⅷ, type of venue Ⅱ and seismic division Ⅰ.

Table 4.1 The important parameters of steel frame structure

Analytical model	Floor	Column size /mm (middle, side)	Beam size /mm	Storey /m	Span /m	Dead / live load (kN/m)	Steel
20-storey model	1~8	□450×450×28 □450×450×25	I 650×200×22×12	3.3×20	7.5/6/6/7.5	20.4/9.6	Q235
	9~15	□450×450×25 □450×450×22					
	16~20	□450×450×22 □450×450×18					

The important parameters of steel frame structures are summarized in Table 4.1 which meet current earthquake code in China (GB 50011-2001). Main parameters of Buckling Restrained Braces with material of Q235, core section area is 706.5mm^2, elastic stiffness is 1.23×10^5 kN/m, the yield force F_y is 166kN and the ultimate force F_u is 264.9kN.

4.2. The Selected Earthquake Records

Avoiding the focal mechanism's effects on the response of structure, nine near-field ground motions are selected for analysis and are divided into three groups according to PGA/PGV value in this study. The characteristic parameters are summarized in Table 4.2. The peak values of the earthquake records input are scaled to 400 gal.

Table 4.2 Characteristic parameters of the selected earthquake records

STATION	PGA (gal)	PGV (cm/s)	PGV/PGA	Closest to fault rupture(km)	Strong motion duration (s)	Characteristic period (s)
TCU052W(A)	341.0	159.0	0.466	0.24	16.64	1.02
TCU068N(A)	452.8	263.1	0.581	1.09	13.08	0.80
TCU102W(A)	292.0	112.4	0.385	1.79	15.11	1.34
1940 El-Centro(B)	306.7	29.8	0.097	8.30	24.10	0.46
1995 Kobe(B)	804.6	81.3	0.101	0.6	8.36	0.36
1952 Taft(B)	174.4	17.5	0.100	41	28.78	0.43
TAP046N(C)	529.2	6.6	0.125	127.26	28.67	0.65
TAP059N(C)	382.2	6.5	0.170	125.93	32.22	0.255
TAP069N(C)	323.4	5.8	0.179	135.31	20.56	1.06

4.3. Multiple Fuzzy Seismic Damage Assessment Results

The performance objectives of steel frame structures are listed in Table 4.3. UBF represents steel frame structure and BRBF represents steel frame structure with buckling restrained braces. Table 4.3 shows that structures response under group A which PGV/PGA>0.2 are bigger than other groups'. Performance objectives results show that the buckling restrained braces improve the structure performances effectively and should be widely used.

Table 4.3 Performance objectives of steel frame structures

Structures	Records	Holistic damage index	Largest storey damage index	Largest storey drift ratio	N_f
20UBF	A	0.646	0.621	2.039	0
	B	0.005	0.074	0.710	3
	C	0.059	0.132	0.788	157
20BRBF	A	0.623	0.735	1.585	0
	B	0.275	0.446	0.425	4
	C	0.312	0.459	0.516	246

Damage assessment results listed in Table 4.4 and Table4.5 are based on two procedures shown in Figure 2.

Table 4.4 Fuzzy damage vector of steel frame structures (No.1)

Structures	Records	No damage	Repairable	Irreparable	Severe	collapse	D_0
20UBF	A	0	0.0002	0.0945	0.8261	0.1183	0.701
	B	0.6124	0.1133	0.2230	0.0947	0.0063	0.109
	C	0.5281	0.2844	0.2261	0.0039	0	0.126
20BRBF	A	0	0.0002	0.1714	0.7280	0.1035	0.690
	B	0.0002	0.4827	0.5232	0.1268	0.0002	0.333
	C	0.1	0.2774	0.5901	0.0441	0	0.378

Table 4.5 Fuzzy damage vector of steel frame structure (No.2)

Structures	Records	No damage	Repairable	Irreparable	Severe	collapse	D_0
20UBF	A	0	0.0009	0.1149	0.8287	0.1195	0.699
	B	0.5949	0.2205	0.2910	0.0968	0.0026	0.141
	C	0.4999	0.3864	0.2506	0.0042	0	0.149
20BRBF	A	0	0.0009	0.1861	0.7455	0.1012	0.688
	B	0	0.4349	0.6597	0.1321	0	0.366
	C	0.1	0.1898	0.6777	0.0594	0	0.404

Fuzzy damage vector A_0 of 20UBF under near-field ground motions group A shows that it belongs to level severe and its membership is 82.87%, second damage state belongs to level collapse and its membership is 11.95%. With buckling restrained braces, 20BRBF belongs to level severe and its membership is 74.55%, and the composite index of overall injury D_0 is 0.688 which is smaller than 20UBF's and meets the nonlinear history analysis results. Table 4.4 and Table 4.5 show that the two procedures analysis results are very close, however, procedure 2 built by Eqn.3.4 is more reasonable.

5. CONCLUSION

The fuzzy seismic damage assessment of steel frame structures with BRB under near-field ground motions is evaluated and main conclusions can be presented as follows:

(1) Structures response under near-field ground motions which PGV/PGA>0.2 are much bigger than others'. More attention should be placed to the influence of near-field ground motions on structures. The economical buckling restrained braces can reduce the structure deformation and damage state effectively which have a good future in practical application.
(2) The number of inelastic cycles which indicates the cumulative loss of energy and the composite index of holistic injury are introduced and obtained in this study, which has guiding significance.
(3) With diverse indices assessing the damage state of steel frame structures based on fuzzy mathematics theory, the structural seismic safety assessment becomes more scientifically meaningful.

ACKNOWLEDGEMENTS

This research is supported by the National Major Basic Research Program (973 Program) under grant 2007CB714024 and the National Scientific and Technological Support Projects under grant 2006BAJ03B06. These financial supports are gratefully acknowledged. The authors also appreciate the valuable suggestions of the reviewers.

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