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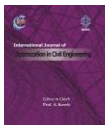

AN EFFICIENT METHOD FOR OPTIMUM PERFORMANCE-BASED SEISMIC DESIGN OF FUSED BUILDING STRUCTURES

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ABSTRACT

A dual structural fused system consists of replaceable ductile elements (fuses) that sustain major seismic damage and leave the primary structure (PS) virtually undamaged. The seismic performance of a fused structural system is determined by the combined behavior of the individual PS and fuse components. In order to design a feasible and economic structural fuse concept, we need a procedure to choose the most efficient combination of the PS and fuse systems subject to the stringent constraints of seismic performance and minimum structural cost objectives, simultaneously. In this paper, an efficient method is developed for minimum cost design of dual fused building structures using a performance-based seismic design procedure. The method involves updating a set of reference parameters to find the most suitable combination of PS and fuse structures with satisfactory seismic performance and optimum total structural cost, concurrently. For a set of preselected reference parameters, the structural design variables including primary and fuse structural member sizes are determined through individual linear elastic design processes. Therefore, a limited number of inelastic analyses are required to evaluate seismic response of the combined fused system. The proposed method is applied to seismic design optimization of a moment resisting frame equipped with BRBs as structural fuses. The obtained results indicate that proposed design optimization procedure is sufficiently robust and reliable to design cost-effective structural fuse systems with satisfactory seismic performance.

Keywords: Optimization; Performance-based seismic design; dual structural system; Structural fuse.

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1. INTRODUCTION

The structural fuse concept has matured to an efficient and resilient seismic design and retrofit philosophy. This is partly due to the rapid development and expansion in the technology and implementation of the innovative passive energy dissipation (PED) devices such as Buckling-

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Restrained Brace (BRB), Triangular Added Damping and Stiffness (T-ADAS), Shear Panel (SP), and Friction Dampers (FD). Another stimulus toward the global acceptance of the concept has certainly been the development of simple and efficient design methods to account for the stringent seismic performance objectives delineated by the fuse action.

A structural fuse is defined as a sacrificial disposable and easy to replace structural element in which the seismic damage is intended to be concentrated in the event of a strong earthquake. The main (or primary) structure is designed to remain elastic or with minor damage while the fuse elements yield and dissipate seismic energy following a damaging earthquake. After the event, only the fuse elements would need to be replaced and upon the removal of the ductile fuse devices the primary elastic structure would return to its un-deformed position.

Design methods for new building structures with metallic fuses have been proposed in the literature based on using traditional force-based method and variations of performance-based design approach. Vargas and Bruneau [1,2] conducted a comprehensive parametric study to identify viable combinations of key parameters essential to ensure adequate seismic performance for single degree of freedom (SDOF) structural fuse systems. They proposed a simple force-based design procedure for a set of preselected target parameters. About the same time, Chen et al. [3] presented a performance-based design method for steel frames with hysteretic devices as structural fuses using an equivalent SDOF model. Malakoutian et al. [4] used a forced-design method for the linked column frame (LCF) system. The LCF system has also been studied by Dimakogianni et al. [5]. Shoeibi et al. [6] proposed an alternate design for the LCF system using the performance-based plastic design (PBPD) method. Bai and Ou [7] tested the PBPD method for buckling-restrained braced reinforced concrete moment-resisting frames (RC-BRBFs). Yang et al. [8] proposed an equivalent energy design procedure (EEDP) for the seismic design of fused structures in a performance-based design framework. Liu et al. [9] presented a direct displacement-based design method for performance-based seismic design of steel braced frame structures with self-centering buckling-restrained braces (SCBRBs). Zhai et al. [10] proposed an improved performance-based plastic design method for designing seismic resilient fused high-rise buildings. Tena et al. [11], through extensive and detailed parametric studies of building models with hysteretic energy dissipation devices, concluded that resilient seismic designs can be achieved with a code-oriented methodology by a correct selection of global parameters and using the capacity design procedure.

For a successful design of structural fuse system, rational performance objectives at different earthquake intensities should be considered and followed by the design process. Performance-based seismic design (PBSD) method is the favorite approach toward such a design target. Furthermore, the fuse concept would be more attractive to the owners and other project beneficiaries if the design could be made competitive in terms of construction and maintenance costs, in addition to ensuring the desired seismic behavior. To this end, the structural optimization would be the method of choice to produce minimum cost designs. A number of performance-based seismic design optimization methods have been proposed and applied to different structural systems [12-21]. These methods could be extended to the entire fused system as a whole [22]. However, the method would be computationally intensive due to large number of design variables involved and a great deal of nonlinear analyses required. Recent studies have shown that a number of key parameters such as relative stiffness, relative strength or relative ductility between the primary structure and the fuse system influence the seismic response of the entire fused system. These findings may provide guidelines to develop simple and cost-effective systematic methods for the optimum design of fused systems.

In this research, a simple and efficient method is presented for seismic design optimization of fused systems. It is conjectured that the optimum design of the dual fused system, characterized by some reference parameters, may be obtained by combining the optimal designs of individual constituent systems (primary and fuse systems), provided that they are generated based on the optimally specified reference parameters. This would bring a great deal of simplification and time saving, because the search for the optimum cross-sections of the structural members would be carried out independently for individual PS and fuse systems using the simple linear elastic analyses, while the optimal reference parameters of the entire fused structure may be determined using limited number of nonlinear analyses. The proposed method is then applied to seismic design optimization of a moment resisting frame equipped with BRBs as structural fuses to demonstrate the efficiency and robustness of the proposed design optimization procedure.

2. PARAMETRIC REPRESENTATION OF THE FUSED SYSTEM DESIGN

2.1 Parametric formulation of SDOF system

A general pushover curve for a SDOF fused structure in Acceleration-Displacement (AD) format is shown in Fig. 1. The pushover curve in such representation is called a capacity diagram. The AD format has the advantage that the seismic demand may also be represented on the same graph as a composite response spectrum. The total capacity diagram is trilinear and may be thought as a superposition of two bilinear curves representing the ideal elasto-plastic behavior of the primary structure and the fuse system. The total strength of the system is the sum of the strength of the primary structure and the fuse component. Once the structural fuses reach their yield deformation, the increment in the lateral force is resisted only by the primary structure up to the point of the target displacement d_p, where the primary structure also yields and the total capacity of the system is reached.

Referring to the capacity curve in Fig. 1, two reference parameters are defined: the stiffness ratio α and the maximum displacement ductility μ_m. The stiffness ratio is the ratio of the primary structure's stiffness to the total initial stiffness of the system, calculated as

$$\alpha = \frac{K_p}{K_p+K_f} \tag{1}$$

Parameter α represents the ratio of the second slope to the initial slope of the total capacity curve, hence it is also known as the post-yielding stiffness ratio. The displacement ductility is the ratio of the target displacement to the yield displacement. In other words, μ_m is the maximum ductility capacity provided by the fuse component, right before the onset of inelastic deformations in the primary structure.

$$\mu_m = \frac{d_p}{d_y} \tag{2}$$

The ultimate and yield capacity of the system in spectral representation, A_u and A_y, respectively, are related as follows

$$A_u = A_y\big(1 + \alpha(\mu_m - 1)\big) \tag{3}$$

The capacity of the primary structure, A_{yp}, and the fuse component, A_{yf}, are calculated respectively, as

$$A_{yp} = \alpha\mu_m A_y \tag{4}$$

$$A_{yf} = (1 - \alpha)A_y \tag{5}$$

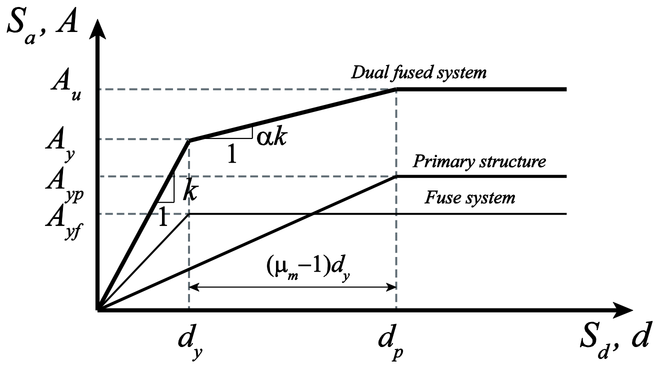


Figure 1. General pushover curve for SDOF fused system

The seismic demand is represented by an approximated inelastic composite (S_a-S_d) response spectrum shown in Fig. 2. The inelastic response of the fused system is found at the intersection of a constant ductility (μ) response spectrum with the capacity diagram. The construction of the constant ductility spectra using the elastic design spectrum (also shown in Fig. 2) is straight forward as outlined in [23]. The inelastic displacement spectrum is determined as

$$S_{dI} = \frac{\mu}{R_\mu} S_{de} \tag{6}$$

where S_{de} is the elastic displacement spectrum and R_μ is the ratio of the elastic strength demand and the yielding capacity, computed as

$$R_\mu = \frac{S_{ae}}{A_y} \tag{7}$$

Ductility demand, μ, may be estimated using an appropriate $R_\mu - \mu - T$ relation such as the one proposed by Krawinkler and Nassar [24]

$$\mu = 1 + \tfrac{1}{c}\left(R_\mu^c - 1\right) \tag{8}$$

where, the numerical coefficient c is given as a function of T, natural period, and α, the post-yielding stiffness ratio, as follows

$$c(T.\alpha) = \frac{T^a}{1+T^a} + \frac{b}{T} \tag{9}$$

The factors a and b in relation (9) have been defined for a limited number of α values [24].

However, our proposed design procedure will require that these factors be introduced as a function of continuous variable α. Such relations would be presented in section 3.2 based on using the extensive parametric investigations on the ductility demand of inelastic systems with post-yielding stiffness [2]. Our focus will be on the bilinear systems with post-yielding stiffness, since we do not expect the main structure to yield under the design level earthquake. The structure may undergo higher inelastic deformations and exhibit a trilinear behavior under more severe earthquakes such as the MCE, however they will not be considered here.

The inelastic acceleration spectrum S_{aI}, is given by

$$S_{aI} = \frac{S_{ae}}{R_\mu}[1 + \alpha(\mu - 1)] \tag{10}$$

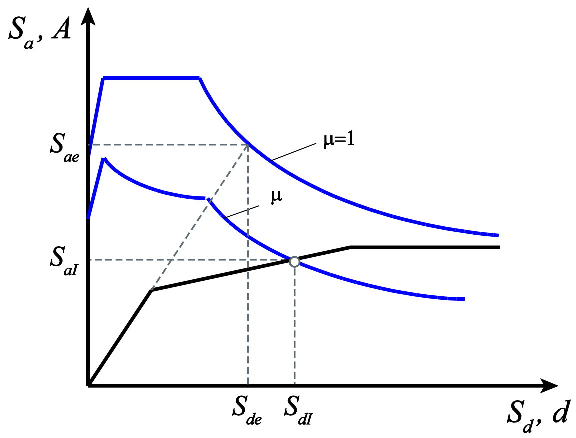


Figure 2. Elastic and inelastic demand spectra together with capacity diagram

2.2 Transformation from the MDOF to equivalent SDOF model

The force-displacement relation for a MDOF system determined in the base shear- top displacement format (*V-D* diagram), may be transformed into a force- displacement relation (*F-d*) of an equivalent SDOF system as follows

$$F = \frac{V}{\Gamma} \tag{11}$$

$$d = \frac{D}{\Gamma} \tag{12}$$

where Γ is the modal participation factor defined as

$$\Gamma = \frac{\boldsymbol{\Phi}^T \boldsymbol{M}\, \mathbf{1}}{\boldsymbol{\Phi}^T \boldsymbol{M}\, \boldsymbol{\Phi}} = \frac{m^*}{\sum m_i \Phi_i^2} \tag{13}$$

where **Φ** is any assumed displacement shape vector, normalized such that the component at the top is equal to 1. **M** is the mass matrix and **1** is a unit vector. m^* represents the equivalent mass of the SDOF system.

Finally, the capacity diagram in AD format is obtained by dividing the force in the (F-d) by the equivalent mass m^*

$$S_a = \frac{F}{m^*} \tag{14}$$

3. PERFORMANCE-BASED SEISMIC DESIGN OPTIMIZATION OF FUSED BUILDING STRUCTURE

Our implementation of the entire fused system design optimization relies on simple elastic linear static optimal design of individual PS and fuse systems. It is assumed that by an optimal proportioning of the total seismic base shear between the PS and fuse system, one can perform the optimal design of individual systems under their allocated base shear independently, and then combine them to obtain the desired optimum dual fused system. In section 3.1 we concentrate on the linear static design optimization of the individual PS and fuse systems. Then in section 3.2 we illustrate the method for allocating the seismic base shear in an optimal manner by using inelastic design optimization procedure. It involves the determination of proper values of a few reference parameters including the post-yielding stiffness ratio, strength response reduction factor and ductility capacity, with the objective of minimizing the total structural cost.

3.1 Elastic design optimization of PS and fuse system for the specified parameters

For a set of specified parameters $(R_\mu . \mu_m . \alpha . T)$, the design base shear of the primary structure V_{yp}, and the fuse system V_{yf}, are calculated respectively as

$$V_{yp} = \alpha \mu_m V_y \tag{15}$$

$$V_{yf} = (1 - \alpha) V_y \tag{16}$$

where V_y is the yielding base shear of the dual system, calculated as

$$V_y = \Gamma m^* A_y \tag{17}$$

and

$$A_y = \frac{S_{ae}}{R_\mu} \tag{18}$$

The linear static design optimization is implemented for the primary structure and the fuse system, respectively, to obtain minimum weight design of each system subject to the base shear forces of equations (15 and 16) and the top-displacement constraints of $\delta_t \leq D_p$ and $\delta_t \leq D_y$, respectively, together with the member capacity constraints of $R_u \leq \varphi R_n$. The problem of finding minimum weight design of each system under equivalent static lateral loads can be stated as follows

$$\text{Minimize:} \quad W_p(x_i) = \Sigma w_i x_i$$
$$\text{subject to:} \quad \delta_t \leq D_p \text{ and } R_u \leq \varphi R_n$$

$$x_i \in X \tag{19}$$

and

$$\begin{gathered}\text{Minimize: } W_f(y_i) = \Sigma w_i y_i \\ subject\ to\text{: } \delta_t \le D_y \text{ and } R_u \le \varphi R_n \\ y_i \in Y\end{gathered} \tag{20}$$

The primary structure is designed for load combinations including both gravity and lateral loads. The fuse system is designed to resist only the lateral load. The calculated base shears are vertically distributed through the height of the building, according to a distribution function proportional to the assumed mode shape $\mathbf{\Phi}$.

3.2 Inelastic design optimization of dual system

In this step of the optimization procedure, the reference parameters dictating the overall behavior of the fused system, which are taken as design variables, are updated to minimize the objective cost function for the entire system.

The minimum weight designs of PS and fuse systems, from the elastic design step under the specified reference parameters, are combined into a dual system and a non-linear pushover analysis is carried out to obtain the capacity-demand curves for the entire structure. The structural performance including the inelastic inter-story drifts are evaluated at the performance points and the optimization algorithm is applied to update the design variables (i.e. the reference parameters, including the stiffness ratio, elastic force reduction factor, ductility factor and natural period of the structure). The optimization procedure terminates when the structural cost objective function converges to the minimum value and the obtained dual fused system satisfies all seismic performance constraints, simultaneously.

Objective function

The main objective of the design optimization of a dual seismic resisting system is to minimize the structural cost including the construction and repair costs. Construction cost is assumed to be proportional to the materials weight of the structural members. The structural repair costs of a dual fused system subjected to seismic risk is limited to replacement of disposable fuse elements. This extra cost, including the material and labor costs, may be considered in the construction stage estimations as an overhead to the construction costs. Therefore, the overall cost function may be formulated as the sum of net construction cost of the primary structure and a magnified construction cost of the fuse system to account for the probable repair. Then, the total cost of a dual fused structure is denoted as

$$C_T = C_p\, W_p\, + c_m C_f\, W_f \tag{21}$$

where, C_T is the total structural cost, C_p (\$ per kg or m^3) and C_f (\$ per kg) are the average total unit costs of the materials of the primary structure and the fuse system, respectively. For steel-MRFs C_p is given as per kg of steel material. For reinforced-concrete-MRFs, C_p is considered as per cubic meters of the concrete. In estimating C_p-factor for RC structures, material and labor cost of steel reinforcement with a quantity of 70 to 120 kg per volume of concrete may also be taken into account. C_f is only estimated for metallic fuses per kg of steel material. W_p and W_f are the total weight (or volume) of the steel (or concrete) material associated with the primary and fuse structures, respectively. Coefficient c_m is the magnification factor to consider the replacement costs of the fusing elements. The worst-case scenario is $c_m = 2$, corresponding to the cost of total fuse system replacement.

Design variables

A few independent parameters define the seismic performance of a fused system when we study its behavior through a pushover analysis. As outlined in section 2, these key parameters (also termed the reference parameters in this study) include stiffness ratio, α, fundamental period of the structure, T and the ductility capacity μ_m. An optimum combination of these reference parameters will lead to an efficient fused system with minimum cost and desired seismic performance. These parameters are taken to be the design variables of the optimization process.

Design Constraints

For the implementation of performance based seismic design of dual fused system in this paper, two performance objectives are adopted. Immediate occupancy (IO) performance level subject to service level earthquake (SE) and rapid return (RR) for design based earthquake (DE). SE and DE earthquakes are defined by exceedance probabilities of 50% in 50 years and 10% in 50 years, respectively. IO performance level corresponds to elastic behavior of all fuse members and primary structural components. RR performance level corresponds to yielding of fuse members and elastic behavior of other structural members.

These performance objectives are implemented as the following design constraints:

- Drift constraints

In order to ensure the desired performance level under the specified earthquake hazard level, quantitative measures are applied to the global response parameters such as the overall building drift (roof drift) and inter-story drift as design constrains. Roof drift ratio (RDR) is limited to 0.5% and 1.5% under the SE and DE earthquake hazard levels, respectively. The maximum allowable inter-story drift ratio (ISDR) is set to maximum 1% and 2% under SE and DE earthquakes, respectively. These limits are specified based on the available experimental results of structural performance under the corresponding seismic hazard levels.

- Strength constraints

Member design for strength requirements is carried out in the elastic design step using the governing design code provisions. However, an additional control of member capacities is envisaged in this step for elements that are not governed by drift constraint (i.e. primary structural members). The early control of strength demand vs capacity for such members can reveal possible under-design due to the allocation of inadmissible reference parameters, in which case, the elastic design should be replicated with modified parameters.

Capacity-spectrum analysis

A nonlinear static procedure based on the capacity-spectrum analysis method is employed in the optimization process to design-check the dual system so that it fulfills the selected performance constraints. The main steps of the method are as follows:

1. Perform pushover analysis to obtain base shear-top displacement, V-D, relationship for the entire structure.
2. Convert the pushover curve to a capacity diagram of the equivalent SDOF system. Obtain yield capacity and yield displacement.
3. Determine seismic demands for equivalent SDOF system at DE and SE seismic hazards, respectively:
   DE:
   Obtain elastic acceleration demand from the elastic composite design spectrum.
   Determine reduction factor.
   Determine ductility demand using an $R_\mu - \mu - T$ relation, then calculate the corresponding displacement demand.
   SE:
   Obtain elastic demand from the elastic composite spectrum for service level earthquake.
4. Transform SDOF displacement demands to the top displacements of MDOF model.
5. Evaluate system response at the performance points
6. Compare the system response (inter-story and roof drift ratios) at the corresponding top-displacement demands with the allowable response values for the associated performance levels (IO and RR).

The main issue encountered in the first step of the above procedure, i.e. pushover analysis, is to choose the appropriate lateral load pattern. A good approximation is obtained by assuming a vertical distribution proportional to the first mode of vibration. The second step is implemented using the transformation method outlined is section 2.2, where the modal participation factor and equivalent mass are the fundamental parameters.

The third step, i.e. determination of seismic demands, is graphically represented in Fig. 3, where the intersection of capacity diagram with two composite response spectra; i.e. constant ductility inelastic design spectrum and elastic SE spectrum indicates seismic demands at the corresponding earthquakes. Ductility demand is obtained by using $R_\mu - \mu - T$ relations involving the post-yielding stiffness, α. The available relations do not support trilinear behavior (perfect plastic behavior after post-yield stiffening), thus the obtained μ is only valid for ductility demands below the maximum ductility capacity of the structure, μ_m. This is not a restriction for design level estimations, since the desired performance is $\mu < \mu_m$. However, for more intensive hazard levels such as the MCE, where greater ductility demands are acceptable, these relations have to be modified to consider the trilinear structural behavior.

In Fig. 4, typical graphs of $R_\mu - \mu - T$ relations for different values of post-yielding stiffness, α, are presented. These graphs are based on the relations of Krawinkler and Nassar [24], with numerical coefficient extended to include different α values.

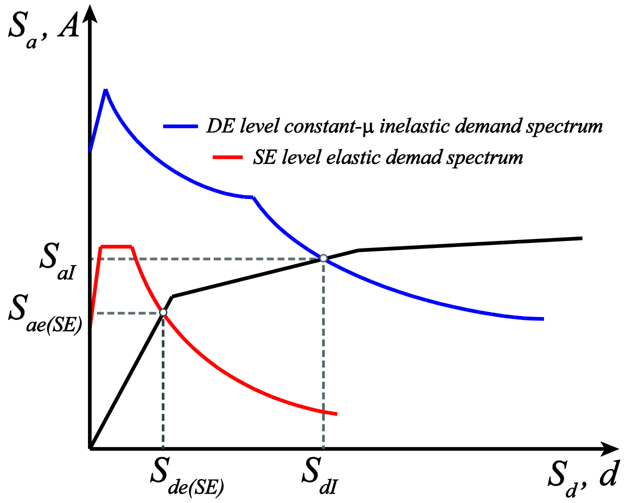


Figure 3. Seismic demands at DE and SE earthquakes

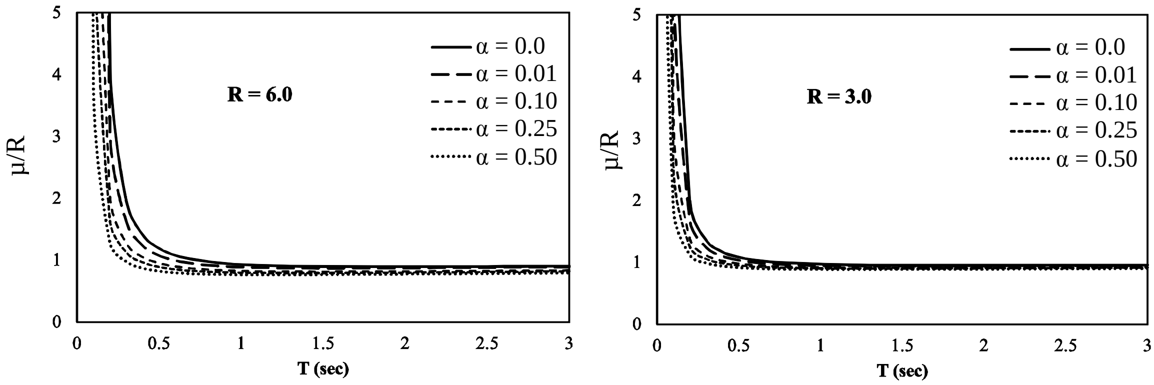


Figure 4. Typical $R_\mu - \mu - T$ relations

Formulation of the optimization problem

While minimum weight designs of primary and fuse systems for a preselected set of parameters are obtained in the elastic design step, the combined fused system should be examined to see if the total structural cost is minimum and also the seismic performance is acceptable. Inelastic design optimization is implemented with the objective of minimizing the total structural cost as a function of the reference parameters of the dual fused system:

$$\text{Minimize:} \quad C_T(z) = C_p W_p + c_m C_f W_f$$
$$\text{subject to:} \quad g_k^i(z) = \frac{\theta_k^i}{\theta_{all}^i} \leq 1\,, i = IO, RR, \quad k = 1,2,\ldots,ns$$
$$\text{and:} \quad h^i(z) = \frac{\Theta^i}{\Theta_{all}^i} \leq 1. \quad i = IO, RR$$
$$z = \{\alpha, \mu_m, R_\mu \text{ and } T\} \tag{23}$$

where θ_k^i and θ_{all}^i are respectively the obtained and allowable ISDR values at the *k*th story associated with the *i*th performance level and *ns* is the number of stories. Similarly, Θ^i and Θ_{all}^i refer to the calculated and allowable RDR values at the *i*th performance level.

Design variables z include reference parameters to be modified in order to find the best proportioning of seismic demand between PS and fuse systems. Structural period T varies from small values close to zero (say 0.1) for low-rise structures to values greater than 4 seconds for high-rise buildings. Stiffness ratio varies between 0 and 1. Maximum displacement ductility ranges from 1 to values as great as 10. The strength reduction factor takes values between 1 and 10.

3.3 Overall design optimization procedure

Given data:

Structural mass M.

Service level and design level elastic composite spectra, $(S_{ae} - S_{de})_{SE}$ and $(S_{ae} - S_{de})_{DE}$, respectively.

Allowable inter-story and roof drift ratios, θ_{all} and Θ_{all}, respectively. Given the roof drift limits at IO and RR performance levels, the associated roof-displacement limits D_y and D_p, respectively, are calculated.

Procedure:

1. Initialize the parameters $\alpha.\mu_m.R_\mu$ and T
2. Start form an initial design of the dual system.
3. Calculate the yielding base shear of the dual system, V_y as follows:

3.1. Calculate yield acceleration using the elastic design level acceleration spectrum and the strength reduction factor, R_μ, as $A_y = S_{ae}^{(DE)}/R_\mu$.

3.2. Obtain the acceleration and displacement demand from service level composite spectrum $S_{ae}^{(SE)}$ and $S_{de}^{(SE)}$, respectively.

3.3. Using roof-displacement limits D_y and D_p, calculate the equivalent SDOF system displacements d_y and d_p utilizing the available (or assumed) mode shape $\mathbf{\Phi}$.

3.4. Calculate the equivalent mass of the SDOF system, m^*.

3.5. If $A_y < S_{ae}^{(SE)}$, then $A_y = S_{ae}^{(SE)}$ and update the $R_\mu = S_{ae}^{(DE)}/A_y$.

3.6. If $d_y < S_{de}^{(SE)}$, then update T to a value that results in $S_{de}^{(SE)} = d_y$. Go to step 3.2 above.

3.7. Calculate $V_y = \Gamma m^* A_y$.

4. Calculate the yielding base shear of the primary structure, V_{yp} and the fuse system, V_{yf}, respectively.
5. Perform the elastic design optimization of the primary structure and the fuse system and obtain the corresponding weight functions, W_p and W_f.
6. Combine the two designs from the elastic design step to form the dual fused system. Perform the capacity-spectrum analysis and evaluate system response.
7. Evaluate objective cost function: $C_T = C_p\, W_p + c_m C_f\, W_f$
8. If the cost is optimum and the design constraints are all satisfied, then terminate the procedure, else, update the design variables and go back to step 3.

4. NUMERICAL EXAMPLE

4.1 Basic information

Consider the dual structural fused system consisting of a nine-story steel moment frame and Buckling Restrained Braced (BRB) frame as shown in Fig. 5. The primary structure has rigid moment connections, with all column bases fixed at ground level. Based on the tributary areas, the seismic weights are taken as 75 ton per each story. The design variables consist of 18 types of column sections (C1 to C18), 9 types of beam sections (B1 to B9) and 9 groups of BRB elements (F1 to F9), as indicated in the figure. Beam and column sections are chosen from the European standard rolled steel sections (IPE sections for beams and HE sections for columns). Grouping of the BRB elements is based on the cross-section area of the steel core, and it is considered to be a continuous variable. Minimum yield strength of steel material is assumed to be f_y=360 MPa for frame elements and f_y=290 MPa for BRBs. The structural cost of steel construction for the frame is evaluated by assuming a unit price $C_p = 3$ USD per kilogram of steel mass. This value is much higher for BRB elements and is considered as $C_f = 11$ USD per kilogram of the steel-core mass. Replacement cost of the fusing elements is considered in the evaluation of total structural cost by assuming the worst-case scenario of total fuse system replacement ($c_m = 2$). Required parameters for constructing the elastic response acceleration spectra at different seismic hazard levels are given in Table 1.

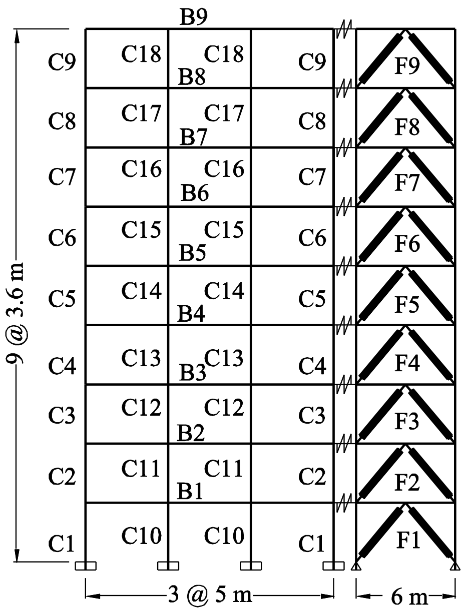


Figure 5. A dual structural fused system (9-story BRB frame)

4.2 Results and discussion

Table 2 summarizes the properties of the optimum design obtained using the proposed method, while the convergence history of the total cost objective function with respect to the number of iterations is presented in Fig. 6. to a direct method of optimization in which, all the design variables (The performance of proposed algorithm is compared including the cross-sections of both frame components and BRBs) are governed collaboratively in a nonlinear analysis approach. According to Fig. 6, the proposed method is able to produce a competitive solution in a few iterations, while the direct method slowly converges to the optimum design.

Table 1: Site parameters for design example

Performance level	Earthquake hazard level	S_s(g)	S_1(g)
IO	SE	0.5	0.25
RR	DE	0.75	0.37

Table 2: Design optimization results for the example problem

				Design variable					
				Optimization result					
Columns	C1	C2	C3	C4	C5	C6	C7	C8	C9
	HE260A	HE240A	HE240A	HE220A	HE220A	HE180A	HE180A	HE160A	HE160A
	C10	C11	C12	C13	C14	C15	C16	C17	C18
	HE280A	HE280A	HE260A	HE260A	HE240A	HE240A	HE240A	HE200A	HE180A
Beams	B1	B2	B3	B4	B5	B6	B7	B8	B9
	IPE300	IPE300	IPE270	IPE270	IPE270	IPE240	IPE220	IPE200	IPE180
BRBs	F1	F2	F3	F4	F5	F6	F7	F8	F9
Steel core cross-section area (cm^2)	27	26	24	21	19	16	13	10	5
Reference	α		μ_m		T (sec)				
parameters	0.217		3.31		1.67				
Objective function			C_T						
Total structural cost ($)			59,690						

The base shear – roof drift ratio relationship (pushover curve) for the final design of the dual fused system is plotted in Fig. 7. Decomposed pushover curves corresponding to the PS and fuse structures are also shown in the plot. Reference parameters are determined as $\alpha = 0.217$ $\mu_m = 3.31$ and $T = 1.67\ sec$. Two performance levels IO and RR under the corresponding SE and DBE earthquakes are indicated on the graph. It is observed that the total structure remained elastic at the IO performance level, while the structural fuse objective is fully satisfied at the RR performance level (i.e. beams and columns remain elastic and BRBs yield at each story). Seismic performance of structure can be verified with reference to Fig. 8a and b. This figure presents the height-wise distribution of story displacement (Fig. 8a) and inter-story drift ratio (Fig. 8b) at two performance levels. It is indicated that the structural response including roof displacement and inter-story drift ratios do not exceed maximum allowable limits at the corresponding performance levels.

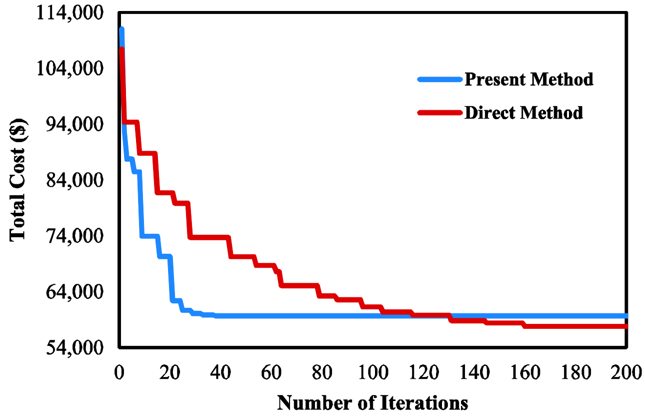


Figure 6. The convergence history of proposed and direct optimization method

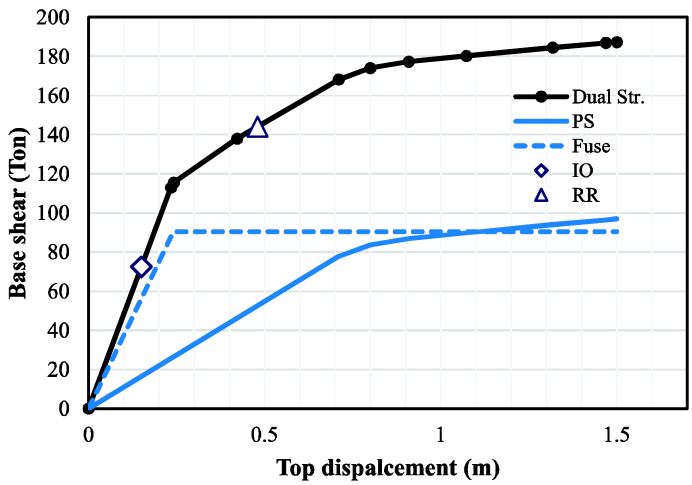
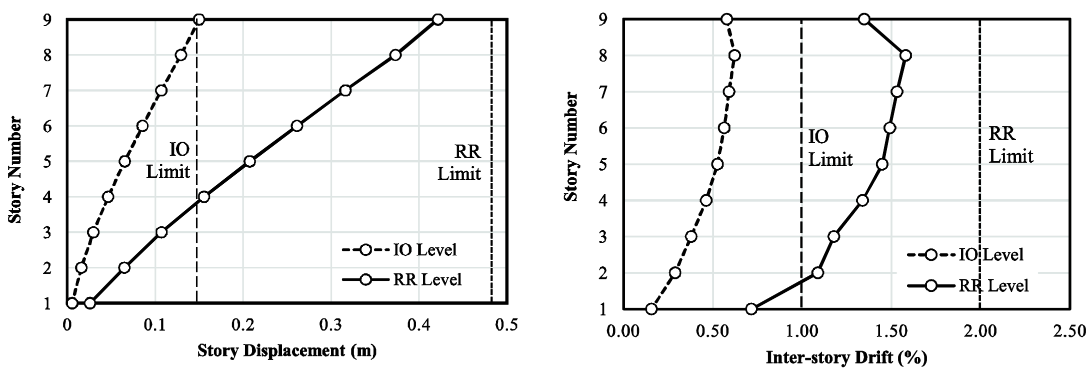


Figure 7. Pushover curve for example problem



(a) lateral story displacement (b) inter-story drift ratio

Figure 8. Seismic response of the example problem

5. CONCLUSIONS

A simple and efficient computer-aided design optimization procedure was developed for performance based seismic design of structural fused systems, utilizing the parametric characterization of their seismic behavior. The objective function was defined as the total structural cost including the construction price and the previsioned expenses for the replacement of fusing elements. The proposed method was applied to design a steel moment frame equipped with BRB element as structural fuses. Based on the obtained results, following conclusions can be derived:

1. The proposed design algorithm considerably reduces the overburden of enormous inelastic analyses required by the direct optimization methods and hence it is able to produce fairly optimum cost designs in substantially lower computational time.
2. Another advantage of the proposed method is that the contribution of each constituent system (PS and Fuse) towards the response of dual fused structure to seismic demands is essentially represented with the aid of a few characterizing parameters. With regard to the case study presented in this paper, in an optimally designed dual fused system (of course with the specific assumptions made for the cost function), the primary structure should provide approximately 20 to 25 percent contribution to the base shear force of the total structure at the first yield. However, the frame should be designed to resist the ultimate shear force of about 3 (exactly, 3.31) times the magnitude of its base shear at the fuse yielding.

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