OPTIMUM DESIGN OF ENERGY DISSIPATION BRACES IN R/C FRAME STRUCTURES

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SUMMARY

Energy dissipation braces are very useful in improving the anti-seismic ability of R/C frame buildings. However, it is rather tough to determine the design parameters of the energy dissipation braces along the height of a multistory frame building. In this paper, the Complex Method of the nonlinear programming combining with the nonlinear time history analysis of the frame structure is used to determine the initial stiffness and the 'yielding' shift of the energy dissipation braces for each floor of a frame structure. Three kinds of target function for the optimization are proposed. This method has been realized with computer program and proved to be efficient. A 4-bay 5-story reinforced concrete frame structure is used as a demonstration example to obtain the optimum EDB parameters under the given story drift angle limitation. The optimum results with the three target functions are compared in the example and the best form of the target function is recommended.

INTRODUCTION

Energy Dissipation Brace (EDB) has been proved to be an effective way to improve the anti-seismic capability of frame structures. Under wind loads or small earthquakes, it increases the lateral stiffness of a frame structure and then decreases the deflections of the structure. While in moderate or major earthquakes, it can dissipate large amount of input energy, and besides, its stiffness could become smaller, so that the structural response can be damped efficiently. EDB does not need any article energy to work. It especially fits for the high and slender buildings or the buildings having special needs in anti-seismic design.

The key to the design of the Energy Dissipation Braced Frame (EDBF) is to determine reasonably the layout and the design parameters of the EDB along the height of the building. However, under major earthquakes, the stiffness and the damp of the main structure as well as those of the EDB system change at all times, leading to a very complicated nonlinear problem. To simplify the problem, various of assumptions were made for the EDB distribution along the height of multistory frame structures [Filiatrout and Cherry, 1990] [Vulcano, 1993] [Foti, 1997]. These assumptions would make the design not economic. Besides, in some cases EDB would not be allowed to install in several specified floors for the restriction of architecture. In this paper, not any assumption is made for the EDB distribution, and the parameters of EDB on each floor will be determined according to the response of the frame structure by the use of the Complex Method and the nonlinear time history analysis of structure. For the hysteretic EDB, the parameters are the initial stiffness and the yield shift of the EDB.

THE COMPLEX METHOD

The Complex Method is one of the direct searching in the nonlinear programming. The mathematical model of the Complex Method is expressed as:

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find the variables X_j (j =1, 2, …, n) , to minimize the target function Z(X), and satisfy the constraint conditions

$$G_i(X) \le 0 \quad (i = 1, 2, \ldots, m) \tag{1}$$

$$X_j^l \le X_j \le X_j^u \quad (j = 1, 2, \ldots, n) \tag{2}$$

where X_j^l and X_j^u are the lower bound and upper bound of the variable (X_j) respectively, n is the number of the variables.

The advantage of the Complex Method lies in: ① It has not any special requirement on the target function and the constraint functions.② Neither the derivation of the target function nor the one-dimensional searching is needed in the iterative calculation. ③All the complex vertexes are within the feasible domain. Therefore the Complex Method is a widely used bounded optimization method.

At the beginning of the optimization, the initial complex vertexes have to be formed, the number of which must greater than n+1, usually takes 2n. After that, a lot of iterative calculations will be performed. In each iteration, there includes choosing the worst point and the best point, finding the center point and the reflected point of the worst point, contracting toward the center point, and replacing the worst point with the worse point, etc. At last, the optimization result satisfying the given precision is obtained. The complex method is a fully developed method. In compiling the program, we have taken some measures to make the complex shape more tender and flexible, so that the convergent rate has been improved.

THE MODEL OF THE FRAME AND THE EDB

During the optimization, many turns of nonlinear time history dynamic analysis of the structure are needed. So the program of the nonlinear time history dynamic analysis has been compiled as one of the subroutines called by the main program of optimization. To simplify the calculation, the story shear model is used in the nonlinear time history analysis of the EDBF structure. The ideal elastoplastic force-displacement relation is supposed for both the main structure and the EDB system, as shown in Figure 1.

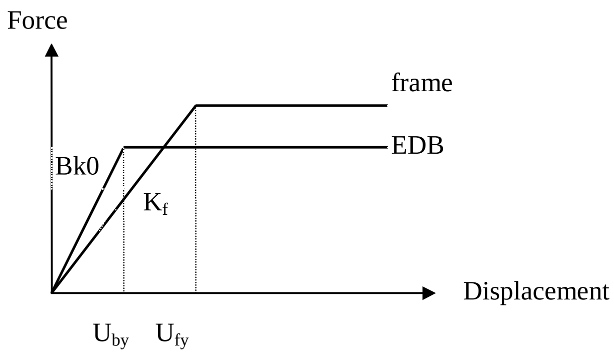

Figure 1: Force-Displacement Relationship of the frame and the EDB

Before the optimization of the EDB, the story elastic stiffness and the story yield drift of the frame must be given. There are two cases in use of the EDB in frame structures. One is in the design of a new building where both the frame and the EDB system are unknown. The other is in the design of the retrofitting of an old building where the frame is known and the EDB system is unknown. In the former case, the frame can be designed on the combination of effects of vertical loads, wind load and small earthquake according to the design code. Then the story elastic stiffness and the story yield drift of the frame can be found. The parameters of the EDB are determined by the dynamic optimizing under major earthquakes.

THE OPTIMIZATION MODEL

The variables being optimized are the initial stiffness and the story yield shift of the EDB in each floor of the structure. Because there is no restriction on the target function in the use of the Complex Method, the target function can be chosen quite freely. Here the terms of the target function are the quantities directly obtained from the nonlinear time history analysis. This avoids the complicated mathematical derivation and makes the optimization very direct and practical. Considering story drift angle is the main quantity reflecting the structure deformation, it can be taken as the chief term in the target function. Other quantities such as the energy dissipated by the hysterectic behaviour of the frame structural elements, or the maximum floor acceleration can also be taken as the terms in the target function. In the following, three kinds of target function have been considered, and the corresponding optimization results will be compared.

A) The target function is taken as the maximum story drift angle which is obtained from the nonlinear time history dynamic analysis of the EDB frame structure, as in formula (3):

$$\min \quad Z = \max_i \{ |u_i| / h_i \} \tag{3}$$

where u_i is the inter story drift of the ith floor, h_i is the height of the ith floor, 'max' means the maximum value along the height of the building as well as through the whole time domain.

B) The target function is taken as the weighting combination of the maximum story drift angle and the dimensionless maximum absolute value of floor acceleration, which are obtained from the nonlinear time history dynamic analysis of the EDBF, as in formula (4):

$$\min \quad Z = 0.7 \max_i \{ |u_i| / h_i \} + 0.3 \max_i \{ |A_i| / g \} \tag{4}$$

where A_i is the acceleration of the ith floor, g is the acceleration of gravity, 0.7 and 0.3 are the weighting coefficient, the other quantities have the same meaning as in fomula (3).

C) The target function is taken as the combination of the maximum story drift angle and the energy absorbed by the frame structural elements as result of deformation, as formula (5):

$$\min \qquad Z = \max_i \{ |u_i| / h_i \} + \sum_i \frac{\int_0^T R_i(u_i, \dot{u}_i)\dot{u}_i dt}{R_{i,y} u_{i,y}} \tag{5}$$

where $R_{i,y}$, $u_{i,y}$ are the story yielding restore force and the story yielding drift of the ith floor of the frame respectively. $\int_0^T R_i(u_i, \dot{u}_i)\dot{u}_i dt$ is the accumulated hysterectic energy dissipated by the ith floor of the frame, and T is the time domain. Using the trapezoidal rule, the continuous energy expression can be implemented in a computer code using the following discrete energy expression:

$$\int_0^t R_i(u_i,\dot{u}_i)\dot{u}_i dt = H_i(t) = H_i(t-\Delta t) + \tfrac{1}{2}[u_i(t)-u_i(t-\Delta t)][R_i(t)+R_i(t-\Delta t)] \tag{6}$$

The constraint conditions do not change when the target function takes different formulation. They are as follows:

$$\text{s.t.} \quad u_i / h_i \le [\theta] \tag{7}$$

$$K_{db,i} \le K_{ub,i} \tag{8}$$

$$K_{db,i} \ge K_{lb,i} \tag{9}$$

$$u_{by,i} \le u_{ub,i} \tag{10}$$

$$u_{by,i} \ge u_{lb,i} \tag{11}$$

$(i = 1,2,3,\cdots,n)$

where, u_i ———the story drift of the ith floor of the EDBF structure obtained from the nonlinear time history analysis.

h_i ———the height of the ith floor.

$[\theta]$ ———the given story drift angle limitation.

$K_{db,i}$ ———the initial stiffness of the EDB on the ith floor, as the optimized variable.

$K_{ub,i}$ ———the upper bound of the $K_{db,i}$, it takes some multiple of the story elastic stiffness of the frame. It takes zero when the ith floor is not going to install the EDB.

$K_{lb,i}$ ———the lower bound of the $K_{db,i}$, it takes either zero or the stiffness of the EDB needed under wind load and small earthquake. When no EDB being installed in the ith floor, it takes zero.

$u_{by,i}$ ———the story yield shift of the EDB on the ith floor, as the optimized variable.

$u_{ub,i}$ ———the upper bound of the $u_{by,i}$, it can be taken as the story yield drift of the frame for the protection of the frame, or zero when the ith floor is not going to install the EDB.

$u_{lb,i}$ ———the lower bound of the $u_{by,i}$, it usually takes zero.

n———the number of stories of the structure

If the structure has n stories, there will be 2n optimized variables, and 4n initial complex vertexes which have to be formed at the beginning of optimization. The initial complex vertexes can be given according to the practical experience, or be formed by the pseudo-random numbers. No matter how the initial complex vertexes are formed, the optimized result will be the same, but the convergent rate will be different.

As for the story drift angle limitation [θ], the anti-seismic code gives 1/50 as the critical value for the R/C frame structure to prevent collapse under the major earthquake. However, this limitation is not enough for some important building. The expensive decoration and the internal equipment of the building would have been seriously damaged if the structure underwent such a large deformation. Therefore smaller story drift angle limitation such as 1/100, 1/200, or even 1/400 will be needed. For whichever case, the program of this paper can give the optimum parameters of the EDB on each floor, according to the predetermined story drift angle limitation.

It is necessary to point out that the optimized result of this program is for the earthquake record inputted. Different input record will give different optimized result. Therefore, the earthquake record of which the predominant frequency is near to that of the building site, should be selected as the input record. The peak acceleration of the input record should be scaled to the value corresponding to the intensity of the major earthquake. Besides, as for the optimized result, several other earthquake records should be used to do the nonlinear time history dynamic analysis of the EDBF, so as to check whether the seismic responses can satisfy the requirement.

EXAMPLE

The example is a 4-bay 5-story reinforced concrete frame structure. The story elastic stiffness, story yield drift , story height and the mass of the frame are given in Table 1. The peak acceleration of the major earthquake is $5m/s^2$, and the El-Centro wave is chosen as the input record. The maximum response of the frame structure and the corresponding time are listed in Table 2, which shows that the frame structure yields in the 1^{st}, 2^{nd} and 5^{th} floor, and the story drift angle in the 2^{nd} and 5^{th} floor are over 1/50.

Table 1: Characteristics of the frame structure

Floor	1	2	3	4	5
Height (m)	3.5	5.0	3.25	2.98	4.67
Mass (ton)	84.7	269.4	108.7	130.6	224.5
K_e (kN/m)	45.0E03	16.4E03	35.0E03	44.0E03	20.7E03
u_y (cm)	1.48	3.00	1.81	0.93	0.99

Table 2: Maximum response of the frame structure (no EDB)

Floor No.	Time (s)	Displacement (m)	Time (s)	Story drift (m)	Time (s)	Acceleration (m/s/s)	Time (s)	Frame Restore Force (kN)
1	4.32	.1697E-01	4.32	.1697E-01	2.54	.9531E+01	1.54	.6660E+03
2	4.50	.1203E+00	4.50	.1156E+00	2.20	.5319E+01	1.48	.4920E+03
3	4.52	.1308E+00	2.94	.1228E-01	2.12	.5160E+01	2.94	.4296E+03
4	4.52	. 1373E+00	3.00	.8100E-02	2.12	.5233E+01	3.00	.3564E+03
5	5.72	.1740E+00	5.92	.1009E+00	2.12	.5848E+01	1.38	. 2049E+03

Supposing that the EDB are going to be installed only in the 2^{nd} and 5^{th} floor, the optimum EDB parameters obtained by the three target functions (formula (3),(4) and (5) respectively) under the story drift angle limitation of 1/50 are listed in Table 3.

TABLE 3: OPTIMUM EDB PARAMETERS WITH DIFFERENT TARGET FUNCTIONS UNDER [θ]=1/50

Case	Target function	EDB parameter	1^{st} floor	2^{nd} floor	3^{rd} floor	4^{th} floor	5^{th} floor
A	Formula (3)	$K_{db,i}$ (kN/m)	0	1108.964	0	0	694.3141
		$u_{by,i}$ (mm)	0	9.9	0	0	6.8
B	Formula (4)	$K_{db,i}$ (kN/m)	0	1363.785	0	0	756.9903
		$u_{by,i}$ (mm)	0	13.5	0	0	7.7
C	Formula (5)	$K_{db,i}$ (kN/m)	0	1298.636	0	0	1314.219
		$u_{by,i}$ (mm)	0	13.9	0	0	5.4

The maximum responses of the EDBF structure with the EDB parameters of the three cases are shown in Table 4, Table 5, and Table 6 respectively. It is shown that all of the story drift angles are less than 1/50.

Table 4: The maximum response of the EDBF structure with the EDB of Case A

Floor No.	Time (s)	Displacement (m)	Time (s)	Story drift (m)	Time (s)	Acceleration (m/s/s)	Time (s)	Frame Restore Force (kN)
1	4.38	.26179E-01	4.38	.26179E-01	4.88	.76636E+01	1.52	.66600E+03
2	8.90	.96293E-01	1.74	.85879E-01	2.20	.58263E+01	1.48	.49200E+03
3	8.88	.10746E+00	3.06	.15164E-01	2.12	.54730E+01	3.06	.53075E+03
4	8.88	.11875E+00	5.44	.15128E-01	2.12	.60127E+01	2.10	.40920E+03
5	4.50	.13521E+00	5.20	.50525E-01	2.12	.60408E+01	1.36	.20493E+03

TABLE 5: THE MAXIMUM RESPONSE OF THE EDBF STRUCTURE WITH THE EDB OF CASE B

Floor No.	Time (s)	Displacement (m)	Time (s)	Story drift (m)	Time (s)	Acceleration (m/s/s)	Time (s)	Frame Restore Force (kN)
1	4.42	.26422E-01	4.42	.26422E-01	2.62	.72257E+01	1.52	.66600E+03
2	8.90	.11028E+00	8.90	.98619E-01	2.20	.58524E+01	1.48	.49200E+03
3	8.88	.12118E+00	5.50	.15180E-01	2.12	.54981E+01	5.50	.53129E+03
4	8.88	.13001E+00	3.02	.14241E-01	2.12	.60180E+01	2.10	.40920E+03
5	5.60	.13771E+00	2.76	.38411E-01	2.12	.60577E+01	1.36	.20493E+03

Comparing the EDB parameters of the three cases in Table 3, it can be seen that their differences are not great, and the Case A has the smallest initial stiffness while the Case C has the greatest one. Comparing Table 4, Table 5 and Table 6, it can be seen that the maximum responses of the three cases are very close. Therefore, it can be concluded that the three kinds of target function are similar. The target function of Case A is recommended because its simple form and the smallest EDB parameters.

Table 6: The maximum response of the EDBF structure with the EDB of Case C

Floor No.	Time (s)	Displacement (m)	Time (s)	Story drift (m)	Time (s)	Acceleration (m/s/s)	Time (s)	Frame Restore Force (kN)
1	4.42	.26719E-01	4.42	.26719E-01	2.62	.72161E+01	1.52	.66600E+03
2	8.90	.10738E+00	8.88	.96078E-01	2.20	.58577E+01	1.48	.49200E+03
3	8.88	.11744E+00	3.06	.15294E-01	2.12	.55129E+01	3.06	.53529E+03
4	8.90	.12554E+00	3.00	14214E-01	2.12	.60373E+01	2.10	.40920E+03
5	8.92	.16109E+00	5.74	.51081E-01	2.12	.60617E+01	1.36	.20493E+03

CONCLUSION

The method proposed in this paper tries to find the optimum parameters of the EDB in frame structures under the given story drift angle limitation. The combination of the Complex Method and the nonlinear time history dynamic analysis makes the optimization very direct and practical. This dynamic optimization of the EDB parameters has been proved to be very effective.

Three kinds of target function have been used and compared in the example. The preliminary conclusion is that the target function shown in Formula (3) is most effective.

REFERENCES

Filiatrault, A. and Cherry, S. (1990), "Seismic design spectra for friction-damped structures", *J. of Structural Engineering, ASCE*, 116, No.5.

Foti, D. et al (1997), “Optimal design criteria of energy dissipators for building structures”, *Proceeding of International Post-SMiRT Conference Seminar.*
Vulcano, A. (1993), “Design criteria of damped steel bracing systems for earthquake protection of framed structures”, *Proceeding of International Post-SMiRT Conference Seminar.*