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SIMPLE PROCEDURE FOR PRELIMINARY DESIGN OF STRUCTURAL DAMPERS

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SUMMARY

In the preliminary design of the structure, the option of adding supplemental damper needs to be compared with other protective design options to achieve the performance objective. The trial and error process of using sophisticated computer model and selecting damper size is not practical. There is a need to efficiently obtain the structural damper design with cost estimation, construction method and interference with the existing function. In this paper, we propose a simple procedure for the design of damping device on a given structure based on its performance objectives. This procedure is primarily based on the current performance-based design guidelines. It simplifies the structure into lumped mass model for preliminary design purpose. It also gives a simple stiffness estimation method and verified it with several building structures. The approximate damping is obtained and the sizing of the device can be selected from the standard damper products, based on the structural properties and the seismic hazard. A design example of a typical mid-rise building is provided. It shows that the procedure is simple and efficient for obtaining the structural damper design with cost estimation. The issues about implementation and extension to nonlinear dampers and damper configuration optimization are discussed.

INTRODUCTION

In the seismic retrofit of existing structure or design of new structures, Energy Dissipation Dampers (EDDs) have become a popular strategy to reduce the earthquake hazard. Current design provisions also provide practical procedures for designing structural members while considering added EDDs. The design usually starts with an initial supplemental damper design on the structure, with the effect of added dampers extracted into the damping modification factor. The seismic demand on the structure, e.g., lateral force on the structural members (using linear static or response spectrum procedure) is reduced by the damping modification factor. The trial and error process of damper design continues until the performance objective is satisfied.

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In the preliminary design of the structure, the option of supplemental damper needs to be compared with other design options. Therefore, the cost, the construction method, and the interference with the existing function have to be considered. The detailed finite element model and nonlinear analysis is not practical since the structural properties are not exactly known and the process is time consuming with complicated model and many trial and errors. Engineers need an efficient method to obtain enough detail about structural damper design for the cost estimation given the performance objective and insufficient information about the structure.

There are design procedures currently available, e.g., *the 2000 NEHRP recommended provisions for seismic regulations for new buildings and other structures, - FEMA 368*, and *2000 NEHRP Guidelines for the seismic rehabilitation of Building - FEMA 356*. Although these procedures provide basic guidelines for designing structures with supplemental damping, the implementation of these procedures is not straight forward for preliminary design purpose.

This paper presents a simple, efficient, step-by-step procedure to design the dampers on a given structure based on its performance objectives. This procedure gives the preliminary sizing of the device based on the structural properties and the earthquake characteristics. This performance-based design procedure addresses the performance objective without the trial and error process.

CURRENT PRACTICE

Currently, FEMA 356 (Prestandard and commentary for the seismic rehabilitation of buildings) and FEMA 368 (NEHRP 2000 provision on seismic design of new buildings) serve as the source documents for future design code. Based on performance-based design methodology, FEMA 356 specifies the following procedures in the design for an existing building to be retrofitted by energy dissipation dampers.

- Preliminary design including sizing of the devices
- Device prototype testing
- Final design of the rehabilitated building to meet the target performance level

For the performance-based design, a structural analysis is needed to obtain the building seismic performance. Although there are four analysis procedures specified in FEMA 356 prestandard, the linear static procedure is the most efficient for preliminary design purpose. To account for the damping from added EDDs, FEMA 356 specifies a damping modification factor to reduce the seismic effect (pseudo lateral load in a given horizontal direction) on the structure. The damping modification factor comes from the estimated effective damping ratio β_{eff} , which is expressed as follows for a structure with linear viscous dampers.

$$\beta_{eff} = \beta + \frac{\sum_j C_j \cos^2 \theta_j \phi_{rj}^2}{2\omega \sum_i \left(\frac{w_i}{g} \right) \phi_i^2} \tag{1}$$

where C_j is the damping constant of device j, θ_j is the angle of inclination of device j to the horizontal, ϕ_{rj} is the first mode relative displacement between the ends of device j in the horizontal direction, ω is the fundamental frequency of the rehabilitated building including the stiffness of the velocity dependent devices, w_i is the reactive weight of floor level i, and ϕ_i is the first mode displacement at floor level i.

For new building design, FEMA 368 provides the minimum design criteria. It adopts the same philosophy as FEMA 356 for the analysis of structures with EDDs. The force and deformation is reduced by a damping modification factor that is related to the effective damping ratio.

Although the above device configuration design can provide the structure with acceptable response reduction, it only provides the method of structural member design with given existing damping. To design a supplemental damping system, a tedious trial-and-error process is necessary to achieve the desired performance. Also, the effect of different performance indices used in the response reduction is not addressed.

PROPOSED PROCEDURE

In order to get the preliminary size and configuration the devices, we need to know the earthquake magnitude and content, the structural properties, and the damper characteristics. Because there are a lot of uncertainties in the preliminary design phase, the structural characteristics can be approximated by some simple model. The following is the proposed simple procedure for the damper size and distribution in the preliminary design of buildings. The structures are simplified into lumped mass models with concentrated mass on each story.

1. Estimate the mass of each story. This can be done by calculating all the dead load plus a portion of the live load of each story.

2. Estimate the stiffness of each story. For a moment-resistant frame, this can be done by adding all the stiffness of the columns, considering beam deformation as well. This procedure is followed by a method to estimate the stiffness for moment frame and other types of structures.

3. With the approximate stiffness and mass, also a small initial structural damping, we can obtain the fundamental period T and the mode shapes ϕ of the building.

4. The approximate base shear and the structure drift performance can be obtained by using the linear static method. The drift reduction ratio is then obtained by dividing the drift performance with the required drift level specified by the building performance objective.

$$\gamma = \frac{\max(drift)}{drift\_level} \tag{2}$$

5. Based on the drift reduction demand γ, calculate the required effective damping β_{eff} from Table 1-6 in FEMA 356. If the structure has a fundamental period T in the short period range, the reduction ratio γ is used as B_S. Otherwise γ is used as B_1. The range of short period is defined as:

$$T_s = \frac{S_{X1}}{S_{XS}} f(\beta_{eff}) \tag{3}$$

This is derived from equation (1-11) of FEMA 356, where $f(\beta_{eff}) = B_S / B_1$, it has a value from 1.0 to 1.5, depending on the value of unknown damping β_{eff}. It should be estimated as 1.0 in the beginning, then adjust after the β_{eff} value is known.

6. Using equation (4), damping coefficient C on each story can be obtained. Here we assume each story has the same amount of damping, and the device is inclined at the same angle θ. This equation is derived based on equation (1) specified in FEMA 356.

$$C = \frac{4\pi \sum_i (\frac{W_i}{g}) \phi_i^2}{T \cos^2 \theta \sum_j \phi_{rj}^2} (\beta_{eff} - \beta) \quad (4)$$

7. Reduce the pseudolateral load applied on the structure with the damping modification factor B_s or B_1.

8. Calculate the maximum damping force in each story by multiplying the damping coefficient with the maximum velocity. Then select the number and damping force for each damper. It is desirable to have four or more dampers on each story for redundancy. Normally, dampers with damping force capacity around 100 kips to 200 kips are economically. Also, the standard damper product are sized by their damping force in 25 kips or 50 kips intervals.

9. Calculate the cost of device. This cost includes the damper, the supporting members, and the installation. Note the supporting members need to be rigid enough to avoid elastic deformation under the damping force. It is also recommended to install the damper horizontally and use chevron type bracing for support. This installation method will maximize the damper effectiveness by having cos(θ)=1. It also minimizes the bending deformation of the device itself under self weight, for the case when damper is installed on the diagonal brace.

Stiffness Estimation

In the step 2 of the above procedure, stiffness estimation is necessary to obtain the structure's first mode shape. This section provides some simple method to estimate the stiffness of the structure efficiently.

Moment-resistant Frame

The lateral stiffness of the moment-resistant frame can be estimated from the lateral force and the resulting deformation. If the beams are rigid, the lateral stiffness k for each story is expressed as follows:

$$k = \sum_{columns} \frac{12EI_c}{h^3} \quad (5)$$

If the beams have no stiffness, stiffness k is expressed as follows:

$$k = \sum_{columns} \frac{3EI_c}{h^3} \quad (6)$$

For frames with realistic beam stiffness, we can separate them into two categories, strong column – weak beam and weak column – strong column. For frames with strong columns and weak beams ($I_b<I_c$), the total deformation under lateral force is composed of column deformation and beam deformation, with a ratio around 0.4 and 0.6 of the total deformation respectively. Therefore, the lateral stiffness can be approximated as follows:

$$k = \sum_{columns} \frac{4.8EI_c}{h^3} \quad (7)$$

For frames with weak column – strong beam design, the column deformation and beam deformation have ratio around 0.6 and 0.4 of the total deformation respectively. Therefore, the stiffness can be approximated as follows:

$$k = \sum_{columns} \frac{7.2EI_c}{h^3} \quad (8)$$

To evaluate the above equation for approximating the structural stiffness; we applied the equations to several building structures. Three typical steel structures, 3-, 9-, and 20-story buildings designed for the SAC project for Los Angeles, CA are used. Another structure is the example frame (frameth.s2k) in the software package SAP2000. Table 1 gives the structural fundamental period using different approaches. The first column is the period estimation using the empirical equation (3-7) specified in FEMA 356. The second column is the fundamental period using the finite element analysis. The third column is the result obtained using the above stiffness approximation and a shear model of the structure. The results show that the period obtained using the approximated stiffness is always between the empirical estimation (specified in FEMA 356 and design codes) and the accurate FEM result. The approximation gives good stiffness estimate.

Table 1. Comparison of calculated fundamental period (second)

	Empirical	FE model	Approximate
SAC 3	0.66	1	0.83
SAC 9	1.63	2.26	1.99
SAC 20	3.03	3.83	3.03
7-story	1.04	1.27	1.15

To verify the above method for stiffness estimation using lumped mass shear model, we also obtained the stick model for the 7-story building used in the table. The stick model has a full stiffness matrix obtained by flexibility analysis, while the shear model has a narrow band in the stiffness matrix. The stick model shows the fundamental period as 1.27 second. It also gives close value for other modes of the building. Although the stick model is more accurate than the shear model, it is not possible without a finite element model. The shear model can give good estimation for a quick preliminary cost estimate. The stick model can be used in the final design phase to represent the detailed building.

Braced Frame

For structures with braced frame as lateral resistant system, the story stiffness can be expressed as the sum of the bracing stiffness in the lateral direction.

$$k = \sum_{braces} \frac{EA_i \cos^2 \theta_i}{L_i} \tag{9}$$

where A_i is the cross sectional area of brace i, θ_i is the angle of inclination of brace i to the horizontal, L_i is the length of the brace. Note that this procedure is only applicable to the structures in the elastic range, it does not consider the structure with buckled compression braces.

Shear Wall Structure

For structures with reinforced concrete shear wall as major lateral resistant system, the inter-story drift is usually small, which may not be enough to activate the dampers. This is the reason that those structures are usually not considered to be good candidate for retrofitting with supplemental damping device. However, there are special mechanisms (such as the toggle brace damper by Constantinou [3]) to be used so that the dampers can be effective with the amplified response at the damper ends. Therefore, for stiff structural systems, supplemental dampers can be designed to dissipate the seismic energy.

The story stiffness of the shear wall can be estimated by treating the shear wall as a vertical cantilever beam.

$$k = \sum_{walls} \frac{3EI}{h^3} \tag{10}$$

Nonlinear Damper

The proposed procedure assumes the dampers as linear viscous damper. It is also applicable to nonlinear viscous dampers. The force-velocity relationship of the nonlinear damper is expressed as:

$$F = C_\alpha V^\alpha \tag{11}$$

The exponent α usually has a value from 0.4 to 0.6 for building seismic application. The sublinear dampers (α<1) have the advantage of smaller damper force in applications where large structural velocities can occur. Therefore reduce the demand on the structural members for transferring the damping force. This is a desirable property since sometimes the structural members may not be designed to take the large force transferred from the damper during the seismic event.

If nonlinear viscous damper is desired, the proposed procedure can be used by an equivalent linear viscous damping, which is derived based on energy-equivalent principles. The energy dissipated by the nonlinear damper during a cycle of harmonic motion, $u = u_0 \sin \omega t$, can be represented by:

$$E_D = \pi\beta_\alpha C_\alpha \omega u_0^{\alpha+1} \tag{12}$$

where $\beta_\alpha = \dfrac{2^{2+\alpha}\Gamma^2(1+\alpha/2)}{\pi\Gamma(2+\alpha)}$, with Γ(.) is the Gamma function. Since we require the nonlinear damper to dissipate the same amount of energy per cycle as the linear damper, the nonlinear damping coefficient C_α can be derived as:

$$C_\alpha = \frac{(\omega u_0)^{1-\alpha}}{\beta_\alpha} C \tag{13}$$

The linear damping coefficient C obtained in step 6 can be used with equation (13) to obtain the desired C_α, given the dominant vibration frequency ω and amplitude u_0, which is related to the maximum story drift. The damper force can then be obtained using equation (11). This force is rounded up to the standard damper capacity for sizing the damper.

DESIGN EXAMPLE

The example building is chosen as the 9-story structure designed by Brandow & Johonston Associates for the SAC Phase II Steel Project. It represents the typical medium height building designed for Los Angeles, California. It is also a benchmark structure for the SAC studies. The structure is 150 by 150 ft (45.73 by 45.73m) in plan and 122 ft (37.19m) in elevation. The lateral load-resisting system is comprised of steel perimeter moment-resisting frame. The interior bay of the structure contains simple framing with composite floors. The building has a basement level shown as B-1. The floor height of each story is shown with the north-south elevation in Figure 1.

The structure columns are wide-flange grade 50 (345 MPa) steel. The beam and the floor system is comprised of grade 36 (248 MPa) wide-flange beams acting compositely with the floor slab. Each frame resists one half of the seismic force associated with the entire structure. The mass to calculate the seismic horizontal force is 66 kips-sec^2/ft (9.65x105 kg) for the ground level, 69 kips-sec^2/ft (1.01x106 kg) for the first level, 67.7 kips-sec^2/ft (9.89x105 kg) for the second through eighth levels, and 73.2 kips-sec^2/ft (1.07x106 kg) for the roof.

The stiffness of each story is calculated following the estimation method in this paper. The structure is assumed to have strong column-weak beam. The fundamental period is obtained as 1.99 second using the approximate the stiffness. Then, the pseudo-lateral load is obtained using the FEMA 356 linear static procedure.

Figure 2 shows the design spectrum used in this example. The total base shear is obtained as 3968 kips. Based on the lumped stiffness of the simplified structure, we can obtain the roof displacement as 13.6 inch (34.6 mm). The maximum story drift occurs at the first story with a value of 2.9 inch (7.4 mm), which means a drift ratio of 1.3%.

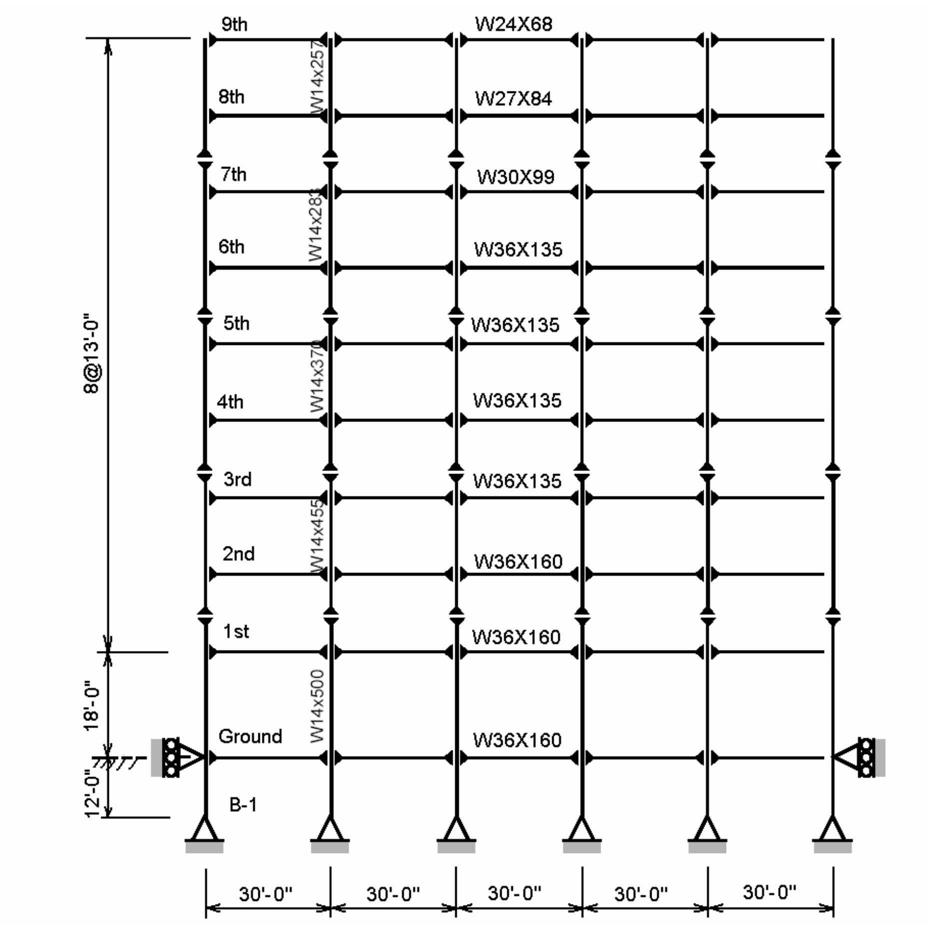

Figure 1 SAC 9-story structure

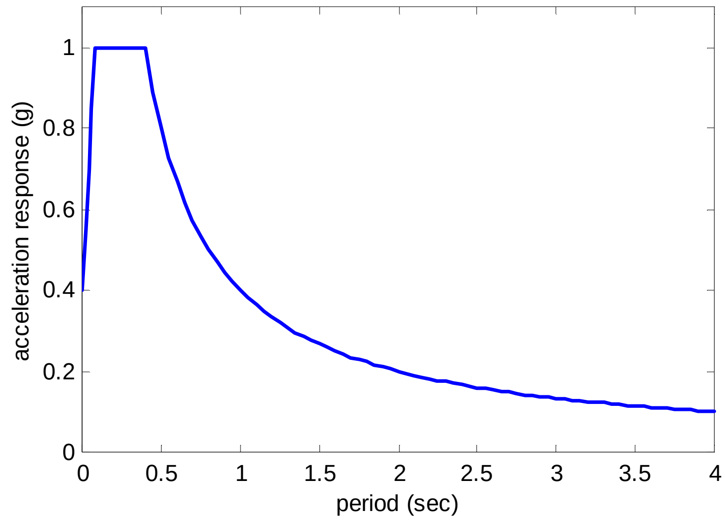

Figure 2 Design spectrum

Assume the building is required to have a performance objective with a drift ratio less than 1%. This performance level is between the life safety and the immediate occupancy level as suggested by FEMA 356 for steel structures. We can achieve this objective by installing supplemental damping devices. Following the proposed procedure, the drift reduction demand γ is 1.3. The desired effective damping is obtained from the table as 13% using interpolation.

Using equation (4), the uniform damping coefficient C on each story can be obtained as 94 kips-sec/in (16450 KN-sec/m). The damping force is related to the damping coefficient C and the maximum relative velocity of the story. We can estimate the maximum velocity using the relationship $V = \omega D$, where D is the maximum story drift. The story damping force is then obtained as 142 kips (823 KN). Since FEMA 356 suggests that the velocity dependent device shall be capable of sustaining the force associated with a velocity equal to 130% of the maximum calculated velocity if four or more devices are provided in a given story (200% for fewer than four), the total design damping force on each story is 185 kips. This number is round up to four 50 kips devices for each story. Then the cost can be quoted for 36 dampers and their support members, each of the damper has a capacity of 50 kips (222 KN). Note that the damper cost also depends on the damper stroke, which is related to the reduced maximum story drift.

To verify the effectiveness of the proposed procedure, the dynamic response of the lumped mass model is obtained for both the original structure and the structure with supplemental damping devices. The design earthquake excitation is represented by an artificial record, which is compatible with the design spectrum. Figure 3 shows the roof displacement under design earthquake with and without the supplemental dampers. Figure 4 gives the comparison of the maximum inter-story drift response. These results show that the structure with supplemental dampers achieves a maximum inter-story drift of 1.9 inch (4.9 mm) or a 0.9% drift ratio, below the performance objective of 1% drift ratio. The results also show that the proposed procedure can be used as a preliminary design tool for choosing supplemental dampers as a structural design alternative.

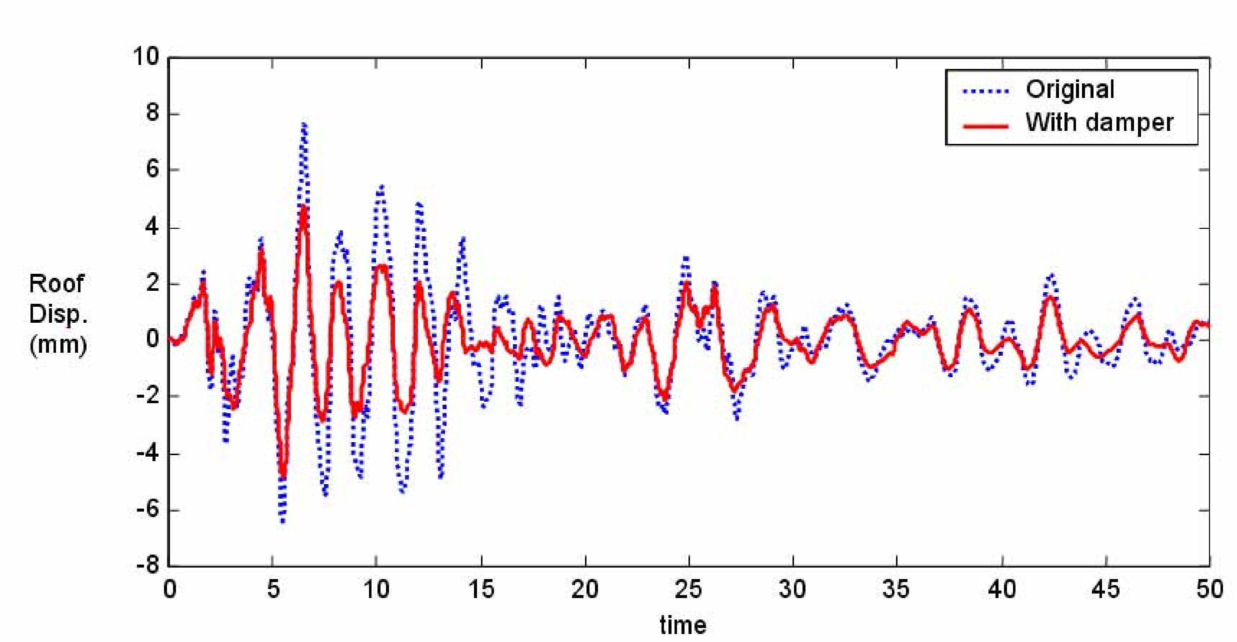

Figure 3 Structural roof displacement comparison

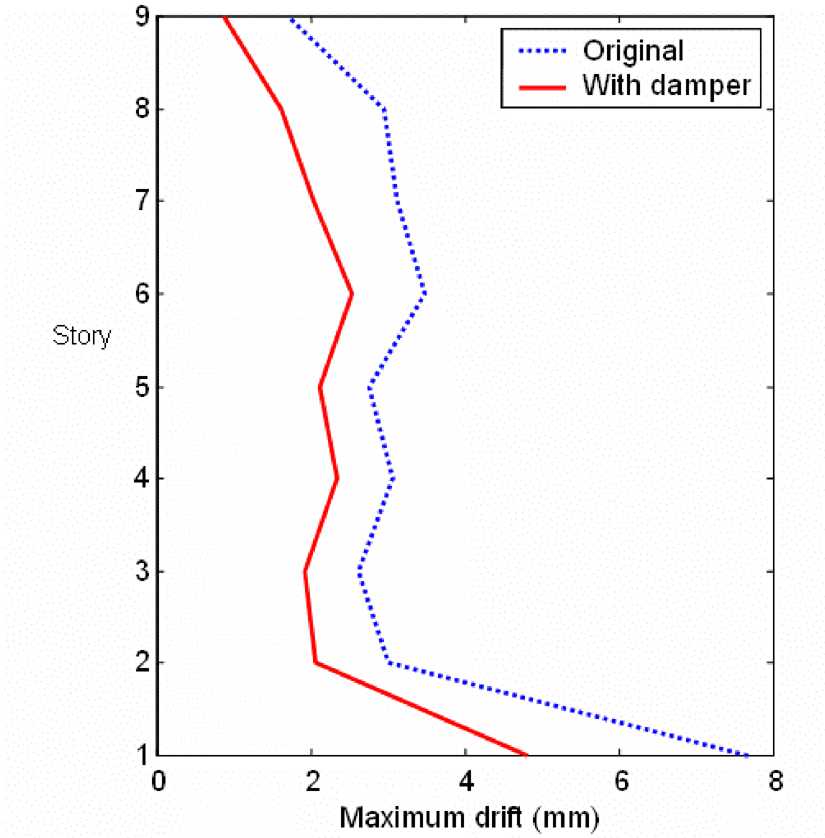

Figure 4 Inter-story drift comparison

DISCUSSION

Implementation Issues

The proposed procedure provides some preliminary basis for the final design of the building with supplemental damping devices. Since it is based on the linear static procedure, it is only applicable to preliminary design. For very flexible structures and structures with vertical or torsional irregularities, there are more issues to consider in the further design stages. The final design need to use applicable procedures to achieve the desired performance level at different seismic events. If the higher modes of the structure contribute a large portion in the total seismic response, dynamic procedures need to be used. If the structure is expected to have significant nonlinear behavior, nonlinear static or dynamic procedure has to be used.

If the structure is expected to be very flexible or with vertical or torsional irregularities, the proposed procedure can be extended to the response spectra method for better estimate. A sufficient modal contribution has to be considered to capture at least 90% of the participating mass of the building in each of the two horizontal directions.

Nonlinear Damper

In the proposed procedure, the damping coefficient of the sublinear damper is obtained using equation (13). The assumption is equal energy dissipation under harmonic motion. Also, the damping coefficient depends on the amplitude of the harmonic motion. Since the earthquake force is composed of many frequency components, the real effect of sublinear damper is different than the response under single frequency motion. For those frequency components with smaller amplitude, the sublinear damper is more efficient than linear damper. Therefore, the damping coefficient C_α determined by equation (13) tends to be conservative for earthquake excitations.

Damper Supporting Member Design

In order for the damper to function effectively in the structure, the supporting member has to be designed properly. It is usually preferable to design the supporting member and the connections as rigid as possible, so that there is no additional deformation to offset the damper stroke. However, depending on the earthquake excitation and the modal frequencies of the structure, the effect of the damper to the structural seismic response maybe different. There might be local resonance of the damper, or the serially connected damper and stiff spring could bring a large force, and then damage the structural members during the seismic event. Therefore, the stiffness of the supporting member should be chosen carefully.

Optimizing Damper Configuration

Since the damper cost is directly related to the maximum damping force, the designed damping force has to be round up to meet with the capacity of the available products. Therefore, part of the capacity of the implemented damper is not used. This may lead to uneconomical design. Furthermore, the assumed uniform distribution along the building height does not lead to optimal damper configuration. One optimization strategy proposed by Liu [5] can be used to obtain the optimal design of damper size and configuration. This strategy is based on the modal contribution to the structural performance index, and the contribution of device at different locations. The optimized damper configuration is expected to be different for different performance-based design requirements.

With optimized device configuration among the stories, the devices are more concentrated on the most effective stories. It is less likely to over design the damping on less effective stories, since FEMA 356 penalize those design with small damping on certain story, which has less than 4 devices. Engineers can therefore avoid the extra cost of not-so-useful devices and the installation of them.

The structural tortional effect due to unsymmetrical structure or translation-torsion coupling effect can be minimized by optimal damper configuration in the floor. For the performance index as story drift, the procedure by Ou et.al. [9] can be used. For other performance index such as acceleration, the modal contribution has to be investigated before optimization.

CONCLUSION

In this paper, a simple procedure is proposed for the preliminary design of damping device on a given structure based on its performance objectives. This procedure gives the preliminary sizing of the device from standard damper product, based on the structural properties and the seismic hazard. The structure is simplified into lumped mass model with stiffness estimation for each story or each component. A design example of a typical mid-rise building is provided. It shows that the procedure is simple and efficient for obtaining the structural damper design with cost estimation.

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