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A RATIONAL DYNAMIC ANALYSIS PROCEDURE FOR THE DAMAGE CONTROLLED STRUCTURES (DCS)

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SUMMARY

Since the Hyogoken-Nanbu earthquake 1995, damage controlled seismic structures with damper system which is a kind of passive energy dissipation system, simply called the damage controlled structures (DCS), have been dramatically increased in Japan. The DCS is suitable not only to the newly constructing structures, but also to the retrofitting of existing structures. The advantage of DCS is easy to control the damage caused by the earthquake into the specific members or devices. The primary structure hence can be prevented from the damage and can be continuously reused even after a extreme earthquake as long as the damaged members or devices are adjusted or replaced. An obvious characteristic of DCS is that the distribution of elastic and inelastic parts of the whole structure is known in the design stage. Suitable numerical analysis methods can be used for the elastic and inelastic structures in order to achieve the maximum computation performance. This paper reports a rational dynamic analysis procedure for DCS. In the proposed procedure, let the elastic part of the global stiffness matrix remained on the left side of the dynamic equation and the inelastic part expressed by the form of forces and moved to the right side of the equation. The advantage of this transformation is not only that the global transient stiffness matrix does not need to be re-established during the step by step computation, but also that it is easy to treat various newly developed damper systems as long as the relationship between force and deformation are given. Mathematical models of some typical damper systems are also presented.

INTRODUCTION

During the Northridge earthquake in the USA 1994 and the Hyogoken-Nanbu earthquake in Japan 1995, there were a great number of damages occurred even in steel structures. In recent years, researches on the earthquake-resistant design of steel structures have been mainly concentrated in two fields. One is the design details of beam and column connections to increase their ductility (Bleiman 1996, Engelhardt 1995, Tsai 1996, etc.). Some designs try to shift the position of large plastic deformations from the beam ends to the inside of the span. However, a large part of the earthquake input energy should be still absorbed by the primary structural members. Another research field is to control the damage caused by an earthquake into some specific members, devices or components called damper systems (Connor 1997, Wada 1992 1995 1997, Iwata 1995, Soong 1997, Kasai 1993 1997, etc.) This kind of structure is called damage controlled structure (DCS). The basic function of the damper system is to reduce the energy dissipation/absorption demand of the primary structure and achieve the purpose of controlling structural damage. The primary structure can still behave elastically even during an extremely large earthquake, provided that sufficient suitable damper systems are installed in the structure. The application of damper system in seismically designed structures is paid extensive attention in the world-wide seismic active regions.

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For conventionally designed structures, it is impossible to predict which part of the whole structure will suffer plastic deformation under extreme earthquake. The transient stiffness matrix of an element and the global stiffness matrix have to be re-established during the step by step computation. It is very complex and will consume a lot of computing time if non-linear dynamic analysis is needed for a large scale structure. For the DCS, however, It is obvious that the distribution of elastic and inelastic parts of the whole structure has been known in the design stage. Different reasonable numerical analysis methods can be applied for the elastic and inelastic structures in order to achieve the maximum computation performance.

This paper reports a rational dynamic analysis procedure for three dimensional damage controlled structures. In the proposed procedure, let the elastic part of the global stiffness matrix remained on the left side of the dynamic equation and the inelastic part expressed by the form of forces and moved to the right side of the equation. The advantages of this transformation are: (1) the global transient stiffness matrix does not need to be re-established during the step by step computation; (2) to avoid the transient stiffness of damper element becoming too large or too small which will cause the numerical computation unstable; (3) it is easy to treat numerically various newly developed damper systems as long as the relationship between force and deformation are given. In the later part of this paper, mathematical models of some typical damper systems are presented.

BASIC DYNAMIC ANALYSIS MODELS

In the conventional approaches of dynamic response analysis, the contribution of inelastic members such as hysteretic dampers are considered as a part of global stiffness matrix. The dynamic equation is usually written in the form of Eq.(1).

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K_T}\Delta\mathbf{X} + \mathbf{F_T} = -\mathbf{M}\ddot{\mathbf{X}}_\mathbf{g} \qquad (1)$$

where, $\mathbf{M}$ is the lumped mass matrix; $\mathbf{C}$ is the natural damping matrix; $\mathbf{K_T}$ is the transient stiffness matrix which includes the elastic and inelastic properties of the whole structure; $\mathbf{F_T}$ is the internal force vector at previous computing step; $\mathbf{X}$ is the response displacement vector including rotational components; $\dot{\mathbf{X}}$ is the response velocity vector; $\ddot{\mathbf{X}}$ is the response acceleration vector; $\Delta\mathbf{X}$ is the vector of displacement increment from previous step to current step; $\ddot{\mathbf{X}}_g$ is the acceleration vector of ground motion.

For conventional structures, as mentioned in the introduction, the transient global stiffness matrix $\mathbf{K_T}$ in Eq.(1) will include the elastic part and inelastic part. For DCS, however, the global transient stiffness matrix $\mathbf{K_T}$ can be divided into two independent parts: elastic part and inelastic part. The elastic part denotes the contribution of primary structure and the inelastic part denotes the contribution of the damper system. Furthermore, the damper system can be expressed by the force vector and moved to the right side of the dynamic equation. Therefore, Eq. (1) can be rewritten in the form of Eq.(2)

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = -\mathbf{M}\ddot{\mathbf{X}}_\mathbf{g} - \mathbf{F_d} \qquad (2)$$

Where, $\mathbf{K}$ on the left side of Eq.(2) is the elastic global stiffness matrix of the primary structure and always remains in constant during the whole step by step computation. $\mathbf{F_d}$ on the right side of Eq. (2) is the force vector of the damper system and depends on the displacement, velocity, temperature and the properties of damper material. $\mathbf{F_d}$, therefore, should be a very complicated function of such factors.

$$\mathbf{F_d} = f_d(X, \dot{X}, \theta, P) \qquad (3)$$

where, $f_d()$ denotes the function of the damper force vector, θ is the temperature of the damper (especially for a viscoelastic damper), P denotes the damper material properties.

All items on the left side of Eq. (2) are linear functions of displacement, velocity and acceleration. Those on the right side are the earthquake force subtracted by the damper force. The basic concept of Eq. (2) was first proposed by Huang (1995) and was used in the dynamic analysis of a shear-bending model with a multiple mass-spring-dashpot system for damage controlled seismic design of tall steel buildings. It is very easy to expand the concept to the dynamic response analysis of a three-dimensional frame model. Eq.(2) obviously shows that there will be no damage to the primary structure if sufficient and reasonable energy dissipation/absorption capacity of supplemental damper system is provided.

In the numerical time integration of Eq.(2), the force equilibriums are taken at the next time step $t+\Delta t$. However, the force vector of damper $\mathbf{F}_{\mathbf{d,t+\Delta t}}$ at time $t+\Delta t$ had not been known before the acceleration at time $t+\Delta t$ is resolved. Here, we propose that the deformation of the damper at time step $t+\Delta t$ is predicted from the values at 3 steps by means of the Lagrange interpolation. If the time increment Δt is a constant, the second order Lagrange interpolation formula can be simplified in the following simple form.

$$\boldsymbol{\delta}_{\mathbf{d,t+\Delta t}} = \boldsymbol{\delta}_{\mathbf{d,t-2\Delta t}} - 3\boldsymbol{\delta}_{\mathbf{d,t-\Delta t}} + 3\boldsymbol{\delta}_{\mathbf{d,t}} \tag{4}$$

The damper force $\mathbf{F}_{\mathbf{d,t+\Delta t}}$ at time step $t+\Delta t$ can be calculated from the damper deformation $\boldsymbol{\delta}_{\mathbf{d,t+\Delta t}}$ at time step $t+\Delta t$ and the assumed hysteresis model of the damper. The unbalanced damper forces should be eliminated through the repetitive calculation during one time increment.

MECHANICAL MODELS OF VARIOUS DAMPER SYSRTEMS

The relationship between force and deformation of the damper is usually obtained from the experimental results of an individual damper or calculated from the constitutive law of the damper's materials. However, the damper deformation greatly depends on the member stiffness that are used to attach the damper to the primary structure. Figs. 1(a) and (b) show two typical damper installations in primary structures. Fig. 1(a) shows a brace-type damper connected to a primary structure with two elastic connecting members. This kind of damper is subjected to axial force and axial deformation only. Fig. 1(b) shows a shear-deformed damper connected to a primary structure by two short elastic columns which are also called connecting members. It is very important to determine the elastic stiffness of the connecting member because it will affect greatly the damping effect.

(1) Elastic stiffness of a connecting member in a brace-type damper system

If the damper is installed in the centre of an elastic brace, the stiffness of the connecting members at each end of it can be determined from the relationship between the force and deformation of the connecting members. For the dampers shown in Fig. 1(a), the stiffness of the connecting members of the damper is given by Eq. (5).

(a) **Brace type damper** **(b) Shear type damper**

Fig. 1 Installation of two types of damper

$$k_c = E\frac{A_1 A_2}{l_1 A_2 + l_2 A_1} \tag{5}$$

where, A_1, A_2, l_1, and l_2 are the areas and lengths of the two braces at ends of the damper shown in Fig. 1(a).

(2) Elastic stiffness of a connecting member in a shear-type damper

For the damper installed midway between two connecting members adjoining the upper and lower floor beams shown in Fig. 1(b), the stiffness k_c (Eq.(6)) of the connecting members is determined from the relationship between the force acting at the tip in the direction of the connecting member, and the shear, as well as the bending deformation.

$$k_c = \frac{1}{\frac{l_{i1}}{GA_{si1}} + \frac{l_{i2}}{GA_{si2}} + \frac{l_{i1}^3}{3EI_{i1}} + \frac{l_{i2}^3}{3EI_{j2}}} \quad (6)$$

where, A_{si1}, A_{si2}, l_{i1}, l_{i2} are the shear areas and lengths of the lower and upper connecting members shown in Fig. 1(b).

The dampers shown in Fig. 1 can be modelled as a multiple directional inelastic springs shown in Fig. 2. The axial spring denotes the brace-type damper whose axial force is denoted by $\boldsymbol{N_d}$. The shear spring stands for the shear type damper whose shear force is denoted by $\boldsymbol{Q_d}$. The bending moment $\boldsymbol{B}$ of elastic bending spring can be calculated from the bending stiffness and the rational angle produced from the rotational deformation θ_i and θ_j at each end of the i'th damper and is

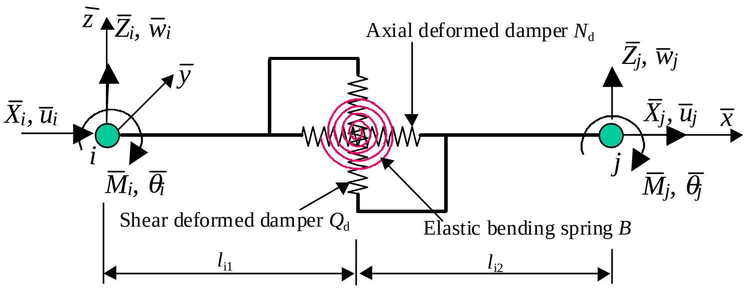


Fig. 2 A single damper model

shown in Eq. (7).

$$B = k_b(\theta_j - \theta_i) \quad (7)$$

$$k_b = \left(\frac{l_{i1}}{EI_{i1}} + \frac{l_{i2}}{EI_{i2}} + \frac{l_{id}}{EI_{id}} \right)^{-1} \quad (8)$$

where, EI_{i1}, EI_{i2}, and EI_{id} are the bending stiffness of the two connecting members and the damper.

All the dampers are assumed to be effective only in the $\bar{x}\bar{o}\bar{z}$ plane of the local coordinate system shown in Fig. 2. This means that the forces $\bar{Y}_i$, $\bar{Y}_j$ along with $\bar{y}$ axial direction are zero and the bending moments $\bar{M}_{\bar{x}i}$, $\bar{M}_{\bar{z}i}$, $\bar{M}_{\bar{x}j}$, $\bar{M}_{\bar{z}j}$ about the $\bar{x}$ and $\bar{z}$ axes are zero. The forces at nodes i and j of the damper in the local coordinate system can be calculated by Eqs. (9) and (10).

$$\bar{X}_i = -N_d, \qquad \bar{Z}_i = -Q_d, \qquad \bar{M}_{\bar{y}i} = l_{i1}Q_d - B \quad (9)$$

$$\bar{X}_j = N_d, \qquad \bar{Z}_j = Q_d, \qquad \bar{M}_{\bar{y}j} = l_{i2}Q_d + B \quad (10)$$

CALCULATION OF DAMPER FORCE AT THE NEXT STEP

A series connected elastic springs have to be considered in all of these damper systems. Figs. 3(a), (b), and (c) show the models of three typical different dampers: a hysteretic damper, a viscous fluid damper, and a viscoelastic damper.

Damper forces are usually calculated from the hysteretic model of the damper materials. Different types of dampers, of course, have different hysteretic models. A bilinear model is usually used for the hysteretic dampers, an elliptical hysteretic model is usually used for the viscous fluid damper, and a complicated non-linear elliptical hysteretic model with inclined axes relying on the temperature and frequency is usually needed for the viscoelastic dampers. Three different models shown in Fig. 3 with elastic connecting members to the damper have to be considered.

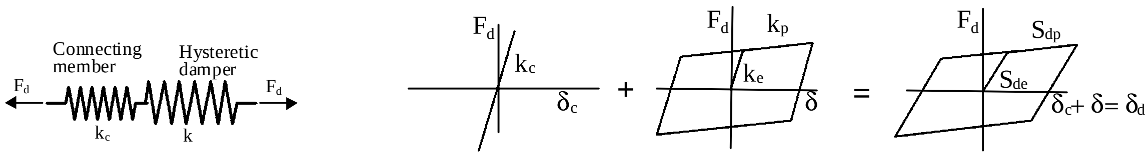
(1) Hysteretic damper (Fig. 3(a))

The stiffness of the elastic connecting spring is denoted by k_c, the elastic stiffness of the hysteretic damper by k_e and the second stiffness of the damper by k_p. Then, the hysteretic model of the combined connecting member and hysteretic damper is still a bilinear shape. The elastic stiffness and the second stiffness after yielding of the combined damper system are given by Eq. (11).

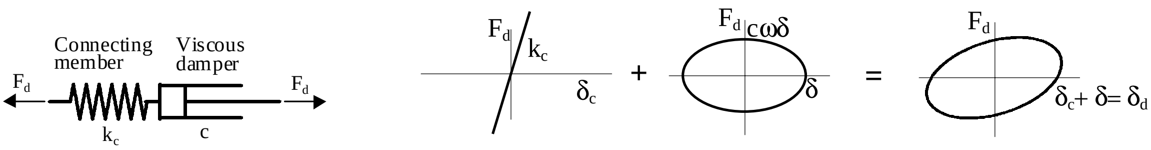
$$S_{de} = \frac{k_c k_e}{k_c + k_e}, \qquad S_{dp} = \frac{k_c k_p}{k_c + k_p} \tag{11}$$

The damper force at time step $t+\Delta t$ is obtained by Eq. (12) where the deformation of the damper $\delta_{d,t+\Delta t}$ is predicted by Eq. (4).

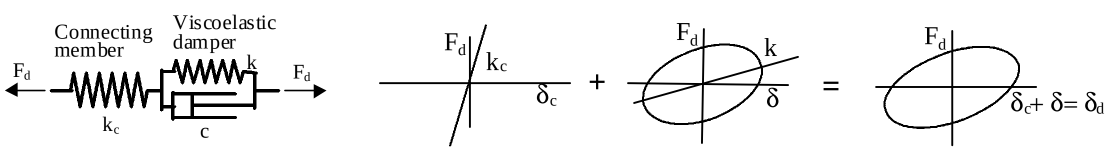
$$F_{d,t+\Delta t} = \begin{cases} S_{de}\delta_{d,t+\Delta t} & (\delta_{d,t+\Delta t} < \delta_{dy}) \\ F_{dy} + S_{dp}\left(\delta_{d,t+\Delta t} - \delta_{dy}\right) & (\delta_{d,t+\Delta t} > \delta_{dy}) \end{cases} \tag{12}$$



(a) Hysteretic damper with series connecting member



(b) Viscous damper with series connecting member



(c) Visco-elastic damper with series connecting member

Fig. 3 Damper system with connecting member

(2) For the viscous oil damper (Fig.3(b))

The deformations of the connecting member and the viscous damper are assumed to be δ_c and δ, respectively. The differential equation governing the relationship of force and deformation is expressed by Eq. (13).

$$c\dot{F}_d + k_c F_d = ck_c\dot{\delta}_d \tag{13}$$

where, k_c is the stiffness of the connecting member, c is the damping coefficient of the viscous damper, and F_d and δ_d are the force and deformation respectively of the combined damper system.

In the time integration, the damper force F_d at time step $t+\Delta t$ can be obtained from the results of previous step t by Eq. (14).

$$F_{d,t+\Delta t} = e^{-k_c\Delta t/c}\left(F_{d,t} + k_c\int_0^{\Delta t}\dot{\delta}_d(\tau)e^{k_c\tau/c}d\tau\right) \tag{14}$$

If the time increment Δt used in the time integration is sufficiently small, the velocity $\dot{\delta}_d(\tau)$ during the Δt can be considered as a constant and taken out of the integration. Therefore, $F_{d,t+\Delta t}$ can be solved from Eq.(14) and expressed by Eq. (15).

$$F_{d,t+\Delta t} = F_{d,t}e^{-k_c\Delta t/c} + c\frac{\delta_{d,t+\Delta t} - \delta_{d,t}}{\Delta t}\left(1 - e^{-k_c\Delta t/c}\right) \tag{15}$$

(3) For the viscoelastic damper (Fig.3(c))

The viscoelastic damper with elastic connecting members is modelled as shown in Fig. 3(c). The relationship between force and deformation can be expressed in the form of Eq. (16).

$$c\dot{F}_d + (k_c + k)F_d = ck_c\dot{\delta}_d + k_c k\delta_d \tag{16}$$

Integrating Eq. (16) from time t to $t+\Delta t$, the damper force at time $t+\Delta t$ can be obtained by Eq. (17).

$$F_{d,t+\Delta t} = e^{-(k_c+k)\Delta t/c}\left[F_{d,t} + \int_0^{\Delta t}\left(k_c\dot{\delta}_d(\tau) + \frac{k_c k}{c}\delta_d(\tau)\right)e^{(k_c+k)\tau/c}d\tau\right] \tag{17}$$

If the deformation $\delta(t)$ of the damper at time increment Δt is assumed to be a linear function, the damper force at time $t+\Delta t$ can be expressed by the state variables at time t. The calculation formula is given by Eq. (18).

$$\begin{aligned} F_{d,t+\Delta t} = {} & e^{-(k_c+k)\Delta t/c}F_{d,t} + \frac{k_c k}{k_c + k}\left(\delta_{d,t+\Delta t} - e^{-(k_c+k)\Delta t/c}\delta_{d,t}\right) \\ & + c\left(\frac{k_c}{k_c + k}\right)^2\frac{\left(\delta_{d,t+\Delta t} - \delta_{d,t}\right)}{\Delta t}\left(1 - e^{-(k_c+k)\Delta t/c}\right) \end{aligned} \tag{18}$$

If the stiffness k of the viscoelastic damper is very small compared to the stiffness k_c of the connecting member, the value of stiffness k can be taken as 0. Thus, Eq. (18) can be reduced to Eq. (15) which is the formulation of a viscous fluid damper with a connecting member. On the other hand, if the stiffness k_c of the connecting member is infinitely large compared with the stiffness k of the viscoelastic damper, Eq. (18) can be reduced to Eq. (19) which is the formulation of the Kevin model for the viscoelastic material.

$$F_{d,t+\Delta t} = k\delta_{d,t+\Delta t} + c\frac{\delta_{d,t+\Delta t} - \delta_{d,t}}{\Delta t} \qquad (19)$$

(4) Cumulative deformation of a damper

The cumulative deformation or its ratio is usually used to estimate the damage extent of a hysteretic damper. It should be noted that a damper deformation must be subtracted from the deformation of the connecting member. Therefore, the cumulative deformation of a damper should be calculated by Eq. (20).

$$\delta_{p,\max} = \delta_{d,\max} - \frac{F_d}{k_c} \qquad (20)$$

CONCLUSIONS

This paper proposed a rational dynamic analysis procedure for a three dimensional elastic frame structure incorporating with a damper system which is called as damage controlled structure. The characteristics of the proposed procedure are that the elastic part of the global stiffness matrix contributed by the primary structure remains on the left side of the dynamic equation, and the inelastic or non-linear part contributed by the damper system is expressed in the form of force and moved to the right side of the dynamic equation. The advantages of this transformation are: (1) the global transient stiffness matrix does not need to be re-established during the step by step computation; (2) to avoid the transient stiffness of damper element becoming too large or too small which will cause the numerical computation unstable; (3) it is easy to treat numerically various newly developed damper systems as long as the relationship between force and deformation are given. Some calculation formula of damper force from the damper deformation for three typical damper systems were also derived.

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