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Seismic Responses of Variable Stiffness Semi-Active Control System

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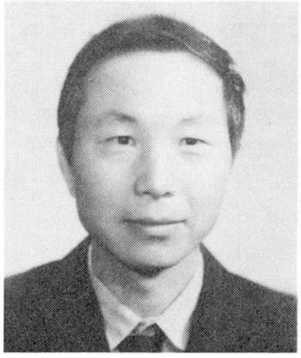

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Summary

This paper presents one type of new structural system with the variable stiffness semi-active control.The system for reducing earthquake response is composed of the control devices and the energy dissipation devices jointed to diagonal braces.According to the feedback structural information, the control devices open or close the energy dissipation devices.When the energy dissipation devices are closed,the braces work as the structural members have certain stiffness and absorb the seismic energy; When the energy dissipation devices are opened,the braces stiffness becomes zero and the absorbed seismic energy is dropped.Usually the semi-active control system uses the structural displacement as control information.The basic theory,the mathematical model,the seismic analysis of the structures,one example of the frame-shear wall structure and some conclusions are given in this paper.

1. Introduction

In the basic equation of motion of strucrures,the mass,damper and stiffness are three basic influence parameters for structural seismic responses.If any one is changed,the structural responses will be changed.Various structural control approaches including passive control,active control,seimi-active control and hybrid control can modify these dynamic parameters in a desirable manner ,all kinds of control devices have been successfully applied in many engineering structures to reduce earthquake responses.

Variable stiffness control is able to switch dynamically the stiffness of some components in a structure from a certain constant to zero,thereby modify the natural period of the structure to avoid the main seismic period,moreover,the controlled variable stiffness components can generate the hysteresis loops under earthquake,thus,a lot of seismic energy is dissipated and the seismic responses of controlled structure is reduced greatly.Semi-active control devices that typically have extremely low power requirements can achieve the variable stiffness control.

In this paper ,a new type of variable stiffness semi-active control technique is presented.The system of seismic response reduction is composed of control devices and energy dissipation devices. According to the feedback information of structural displacement the control devices switch off or switch on the control valve of the energy dissipation devices jointed to diagonal braces and main structure.When the structure reaches the maximum displacement position and begins moving to the oppose direction , the energy dissipation devices are opened by the control devices and the stiffness of braces becomes zero.The absorbed seismic energy by the braces is dropped into the energy dissipation devices , otherwise the energy dissipation devices are closed, and the braces as structural components provide the certain stiffness and absorb the seismic energy.Because the structure goes through return point two time in one period,thus,the structure is able to modify vibration property and drops seismic energy two times in every period.

2.The basic theory and mathematical model

The schematic of energy dissipation system is shown in Fig.1. The variable stiffness semi-active control system of reducing seismic response is fitted on the structural interstory as shown in Fig.2.

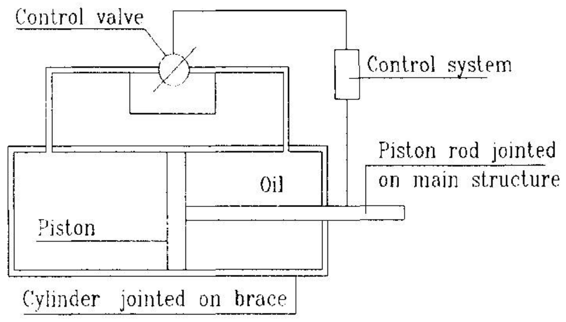

Fig.1.Schematic of energy dissipation system

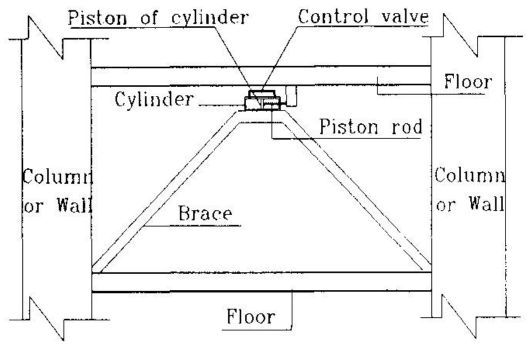

Fig.2.Scheme of structural system with variable stiffness semi-active control

The energy dissipation system is composed of the cylinder and the relative oil -way with the control valve that is controlled by the control system to close or open.The cylinder body is rigidly connected to the upper end of the braces which bottom is jointed on the floor,the piston rod of the cylinder is rigidly connected to the upper floor.When the control valve is closed,there is not the relative movement between the piston and the cylinder body.The braces go through same interstory displacement as the main structure,and provide certain lateral stiffness and restoring force absorb the seismic energy. When the control valve is opened, the relative movement between the piston and the cylinder body will be generated and the braces whose structural lateral stiffness becomes zero return to the original position.The seismic energy absorbed by the braces is dropped by the cylinder.

The control system is composed of a computer and relative information transmitters.Based on the information of the structural incremental displacement or velocity,the control devices can discern the structural point of return at which the sign of velocity or incremental displacement is changed,and open the control valve if the floor is at the point of return or close the control valve if the floor is not at the point of return.

The restoring force model of controlled braces is shown in Fig.3.The points A and C are the point of return,the lines OA and BC are the process of energy absorption of the braces in which the braces remain original lateral stiffness being equal to the rate of line,the lines AB and CD are the state of energy dissipation of the braces at which the lateral stiffness of the braces is changed to zero.

As stated above,the restoring force of the controlled braces is:

$$\begin{cases} \Delta x_i \ . \Delta x_{i+1} < 0, & F = 0 \\ \Delta x_i \ . \Delta x_{i+1} \geq 0, & F = K_d(x_i - x_0) \end{cases} \tag{1}$$

where, Δx_i, Δx_{i+1} are respectively the incremental displacement relative to the ground at the i th and $(i+1)$th time moment, x_i, x_0 are respectively the relative displacement at the i th time moment and at the previous time moment at which the structure is at the point of return, k_d is the original lateral stiffness of braces, F is the restoring force of controlled braces.

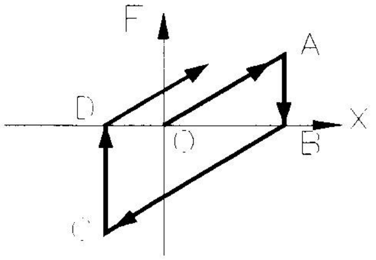

Fig. 3. Restoring force model of controlled brace

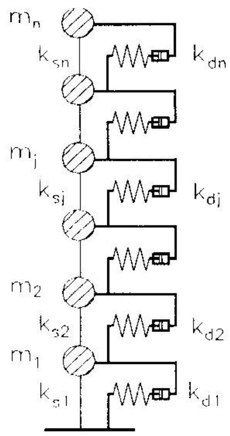

Fig. 4. Calculation schematic of the controlled structure

3.Structural seismic analysis

The Calculation schematic used for seismic analysis of a multiple-story structure system with the variable stiffness semi-active control is shown in Fig.4. The springs with the energy dissipation device connected on interstory are the modelling of controllable reducing response system and can cooperate with the main structure under earthquake.

The basic equation of motion of the controlled structural system is:

$$\begin{cases} [M]\{X''\}+[C]\{X'\}+[K_s]\{X\}+\{F_d\}=-[M]\{I\}x_g'' \\ \{F_d\}=[K_d]\{X\} \end{cases} \tag{2}$$

In which,$[M]$ is the mass matrix, $[C]$ is the damper matrix and $[C]=\alpha[M]+\beta[K]$,$[K_s]$ is the lateral stiffness matrix of the main structure,$[K_d]$ and $\{F_d\}$ are respectively the lateral stiffness matrix and the generated force vector of the reducing response devices, $\{X\},\{X'\},\{X''\}$ is respectively the relative displacement vector, the relative velocity vector,the relative acceleration vector, x_g'' is the acceleration of the earthquake ground motion.

It is convenient for finding solution by using numerical analysis method to change Eq.(2) into the half incremental equation,as follows:

$$\begin{cases} [M]\{X''\}_i+[C]\{X'\}_i+[K_s]\{\Delta X\}_i+\{F_s\}_{i-1}+\{F_d\}_i=-[M]\{I\}x_{g,i}'' \\ \{F_d\}_i=\{F_d\}_{i-1}+[K_d]_i\{\Delta X\}_i \end{cases} \tag{3}$$

where i and $(i-1)$ are the number of the time moment (Δt).The structural seismic responses at i time moment can be found by Eq.(3).Taking these responses as the initial data,the solution at next moment is able to obtain.

The control condition shown in Eq.(4) that must be checked at every moment,relevantly,the stiffness matrixes,the story shear vectors and the restoring force vectors must be modified by the control condition.

$$\begin{cases} \Delta x_{i,j} \cdot \Delta x_{i+1,j} < 0, V_{i,d,j} = 0 \\ \Delta x_{i,j} \cdot \Delta x_{i+1,j} \geq 0, V_{i,d,j} = V_{i-1,d,j} + k_{d,j} \cdot \Delta x_{i,j} \end{cases} \tag{4}$$

where $\Delta x_{i,j}$, $\Delta x_{i+1,j}$ are incremental j th floor displacement relative to the ground at the i th and $(i+1)$th time moment respectively, $V_{i,d,j}$, $V_{i-1,d,j}$ are the shears of the reducing response devices at the i th and $(i-1)$th time moment in j th story respectively, $k_{d,j}$ is the j th story lateral stiffness of the reducing response devices.

4. Numerical Example

Taking a 16 story R.C. frame-shear wall structure with the variable stiffness semi-active control system for the numerical example,the structural plane and elevation are shown in Fig.5.,the main structural characteristic parameters are shown in table 1.

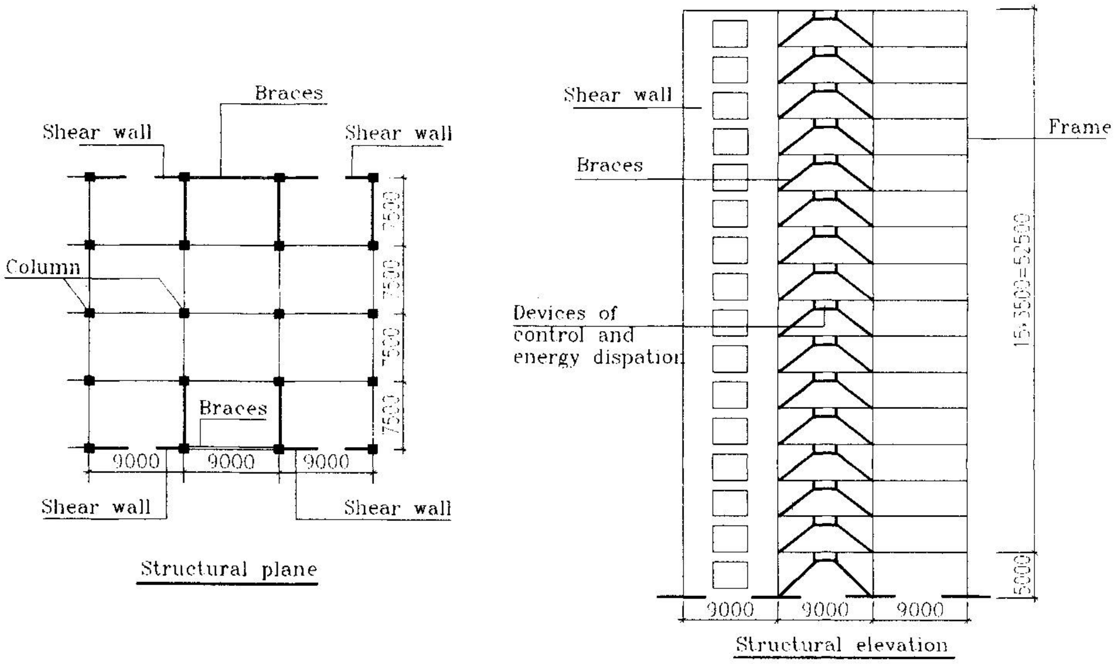

Fig.5.Structural plane and elevation

Table 1. main structural characteristic parameters

Floor No.	Column section(cm)	Wall thickness(cm)	Mass (t.sec.^{2}/m)	Elastic module of concrete(t/m^2)	Story height (m)
1	90×90	25	93.3	3250000	5
2-8	90×90	25	93.3	3250000	3.5
9-15	80×80	18	93.3	3250000	3.5
16	80×80	18	77.8	3250000	3.5

The horizontal seismic analysis is made in the transverse direction.The EL centro(in 1940,N-S) earthquake is used for the seismic ground motion whose peak acceleration is adjusted to 200gal and the time moment is 0.02sec..The lateral story stiffness of the controlled braces is r times the lateral story stiffness of the frames in main structure, r is called the rate of stiffness written as follows:

$$r = {k_{d,j}}\big/{k_{f,j}} \tag{5}$$

where, $k_{d,j}$ and $k_{f,j}$ are respectively the lateral stiffness of the braces and the frames, j is number of floors.The structure is considered to be linear-elastic in the analysis.

Based on the analysis results,the maximum interstory displacements and maximum story shears of the structure are respectively shown in Fig.6. and Fig.7. Four curves given in above Figs. indicate respectively the structural response results in no control (r=1) and control(r=0.5,1.0,1.5) state.

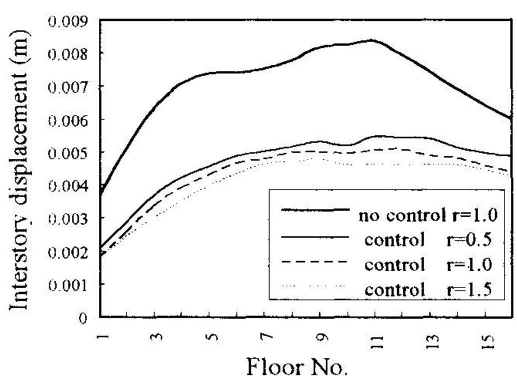

Fig.6.Maximum interstory displacement comparison

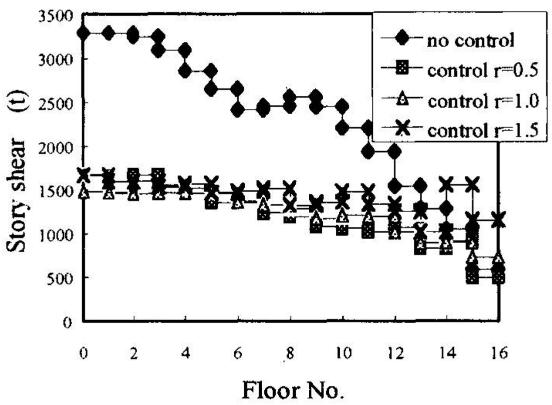

Fig.7.Maximum story shear comparison

From the Figs.,the efficiency of reducing seismic responses by means of the variable stiffness semi-active control system is obvious and is different with the different rate of stiffness(r),as a general rule,the reduction of response increases with increment of rate of stiffness.The maximum interstory displacement is reduced by 51% of the uncontrolled response,the maximum story shear is reduced by 60%. The maximum interstory displacement angle is about 1/700 and indicates that the controlled structure remains the elastic state.

To study effect of reducing response of such cases that the controlled braces are fitted on some stories and other stories have no braces,the main structure remains unchanged,but the braces (r=1.0) are only fitted on 1-3 story in case 1 and on 1,9,16 story in case 2.The seismic analysis is made for two cases,the analysis results about the maximum interstory displacements and maximum story shears are respectively shown in Fig.8 and Fig.9 in which the results of every story control (1-16) are given for comparison.

From Fig.8 and Fig.9, the difference of three cases is not big,particaly the difference of story shears is small,so the notional design including notional select of brace stiffness and notional select of stories in which the braces are fitted can get the better economical effect.

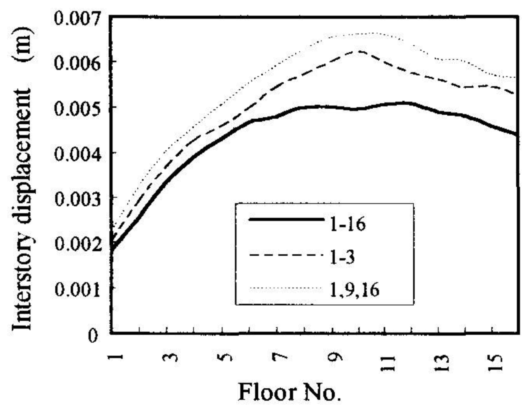

Fig.8.Maximum interstory displacement comparison

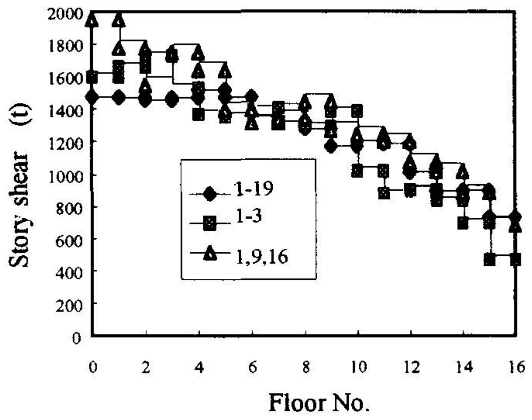

Fig.9.Maximum story shear comparison

5.Conclusions

1.The variable stiffness semi-active control system is effective to reduce seismic response of controlled structures ,the controlled structures can remain elastic state under strong earthquake.

2.The lateral stiffness of the controlled braces has obvious influence on the effect of reducing seismic response,it is necessary in design to select notional rate of stiffness.

3. The effect of reducing response of such case that the controlled braces are fitted on some stories and other stories have no braces is satisfactory.

4.The restoring force model of controlled braces and the analysis procedure of controlled structure can be used for the seismic analysis of this kind of structures.

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