Study on the Structural Principle of the Flexural Deformation Response Control System and its Practical Use

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ABSTRACT :

We devised flexural deformation response control system, which is a response control frame of new general idea composed of four elements; 1) a wall located in a center of a building plan named "Super wall", 2) cantilevers located in a building top named "Super beam", 3) columns located at perimeter of a building named "Connecting column" and 4) oil dampers for response control. We clarified basic principle of proposed flexural deformation response control system and its control effect using a simple three element Maxwell-type single mass system. We also carried out elastic vibration analyses with a model building, and confirmed meaningful vibration reduction effects for a practical section of a building. This paper describes the principal of this unique control technique for flexural structure, and demonstrates an application example in practical use.

KEYWORDS: Structural control, Oil damper, Flexural structure

1. INTRODUCTION

The newly developed "Super RC Frame" structure system, outlined in Figure 1, can provide column-free, beam-less residential spaces, and allows enough architectural flexibility in plan layout. This T-shaped super structure consists of a core wall named "Super wall" and large hat beams named "Super beams" at the top of the structure, outer columns, flat slabs and vibration control devices. The control device is introduced between the ends of the hat beams and the adjoining outer columns for vertical direction. Centrally located reinforced concrete core wall resists majority of lateral load, and when the wall deforms due to earthquakes, the ends of the hat beam moves up and down direction and this deformation activates the dampers and dissipate vibration energy during earthquakes. Concrete post-tensioned flat slabs are employed as a floor system considering serviceability criteria such as floor vibration. To insure structural safety, the core wall must be kept elastic in bending even under large earthquakes. The bending strength shall exceed 1.5 times the design stress, and the strain-energy absorption capacity shall exceed two times the design force. To insure sufficient stiffness of super beams to activate the oil dampers effectively, RC super beams are pre-stressed to minimize undesirable flexural deformation. Several tests were conducted on specimen of the super wall to confirm the validity of assumptions by the fiber modeling, the reinforcement methods for proper deformation characteristics, etc. Slabs and columns must have sufficient ductility to allow a bending deformation caused by the super wall's deformation. Punching failure at the column or wall joint must be avoided.

2. BASIC CHARACTERISTICS OF FLEXURAL DEFORMATION RESPONSE CONTROL SYSTEM

Fundamental dynamic characteristics of a conventional response controlled structure equipped with a damper at each story are expressed by the three elements Maxwell model as shown in Figure 2 in the later chapter. In this structural system, it is well known that there is an optimum value for damper's parameter, and the maximum control effect is determined by the stiffness condition. In the proposed flexural deformation response control system, however, the damper is settled at the place restraining the bending rotation of core wall, and the damper's control forces do not work directly for lateral direction. Namely, the proposed control system controls the rotation freedom that is a subordinate degree of freedom instead of lateral freedom of the target structure.

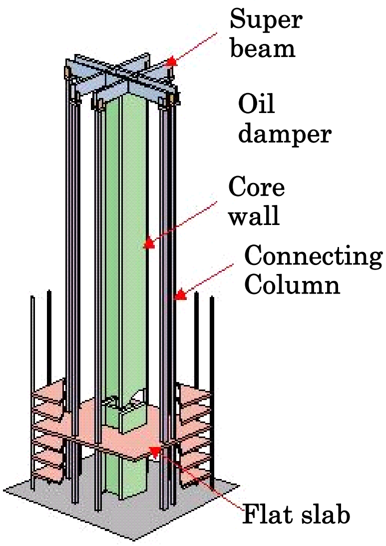


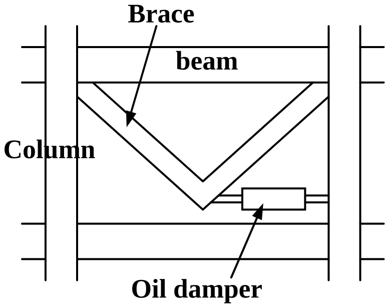
Figure.1 Super Frame Type Seismic Control Structure

In this chapter, a principle of vibration declining due to bending rotation control and a control effectiveness are clarified using a simple single-degree-of-freedom (SDOF) system. First, we describe that the basic dynamic characteristic of the proposed rotation control system van be expressed by an SDOF model consists of a mass, spring and a Maxwell model that is known as a typical mathematical model for conventional controlled structure equipped with a damper at inter-story. Second, considering the characteristics of the three elements Maxwell model, required structural performances to realize an effective response control are studied.

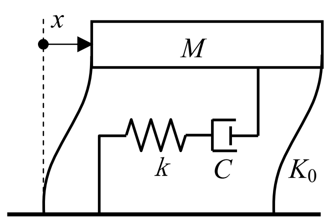
2.1. Basic Characteristics of Response Control Damper System Settled in Inter-story

Figure 2 shows a basic vibration model which represents a structural characteristic of a structure with damper settled at inter-story. M represents a building mass and K_0 represent a building stiffness. A portion of Maxwell model represents a damper including a bracing element. K represents a stiffness of a supporting element such a brace connected to the damper, and C represents the damping coefficient of the damper. Considering a harmonic excitation force with a circular frequency p, a complex stiffness k^* of a Maxwell model is expressed as an Equation (1).

$$k^* = \frac{kCpi}{k + Cpi} \tag{1}$$



(a) Damper installation



(b) Three element Maxwell vibration model

Figure 2 Structural model of response control damper system settled in inter-story

Total damping ratio h of the three element Maxwell model is given by h=Im[K_0+k^*]/(2Re[K_0+ k^*]). It is known that this h becomes maximum at a certain C, and the optimum damping coefficinet C_{opt} which makes h maximum is determined by conditions of $\partial h / \partial \lambda = 0$ and Re[K_0+k^*/=p^2], where λ=Cp. Final solutions (the resonance frequency Pr, the optimum damping coefficient C_{opt} and the maximum damping ratio h_m are summarized as follows [Kurino et al. 2003].

$$p_r = \omega_0 \sqrt{\frac{2(1+\alpha)}{2+\alpha}} \tag{2}$$

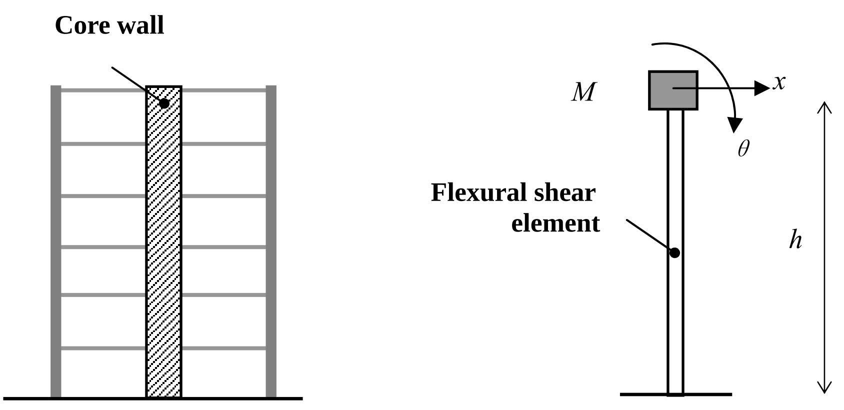
$$C_{opt} = \frac{k}{\omega_0} \sqrt{\frac{2+\alpha}{2(1+\alpha)^2}} \tag{3}$$

$$h_m = \frac{\alpha}{4\sqrt{1+\alpha}} \tag{4}$$

Where α is stiffness ratio between the frame and the damper, ω_0 is a principal frequency of the original frame.

$$\alpha = k / K_0 \tag{5}$$

$$\omega_0 = \sqrt{K_0 / M} \tag{6}$$



（a）Core wall structure （b）Flexural shear model

Figure 3 Flexural predominant structure

2.2. Relation between Proposed Rotation Control System and 3-elemens Maxwell model

Consider the structure that the flexural deformation is predominant shown in Figure 3(a). If we model the structure as a simple single-mass system shown in Figure 3(b), the equation of the motion is generally expressed as below.

$$\begin{Bmatrix} q \\ m \end{Bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{Bmatrix} x \\ \theta \end{Bmatrix} \tag{7}$$

Where q is a lateral force, m is a rotational moment force, x is a lateral freedom and θ is a rotational freedom of the mass. Considering the symmetrical structure of the stiffness matrix, we say the each element of the stiffness matrix k_{11}=r, k_{12}=-u, .k_{22}=s. Values of r, u and s depend on structural construction (Section property). By placing m=0 and reduce the Equation (7) regarding the lateral freedom, the following relation can be obtained.

$$q = \left(r - \frac{u^2}{s} \right) x \tag{8}$$

In Equation (8),(r—u^2/s) represents an equivalent lateral stiffness of a structure shown Figure 3. Here we say this value K_0

$$K_0 = r - \frac{u^2}{s} \tag{9}$$

Next, consider the structure installed with the damper to control the rotation deformation shown in Figure 4. The mathematical model of the structure that damper is settled vertically between a super beam and a connecting column is shown by Maxwell model which can only resist against rotational freedom. A damping coefficient C_R of the rotational dash-pot depends on a damping coefficient C_v of the damper settled vertically and a radius of gyration. It is same for rotational spring k_R. Here we consider a harmonic excitation with a circular frequency p, a complex stiffness of a Maxwell model adds to (2, 2) element of the stiffness matrix in Equation (7), therefore a equivalent lateral stiffness of a whole structure becomes complex stiffness as follow.

$$K^* = r - \frac{u^2}{s + k_R^*} \tag{10}$$

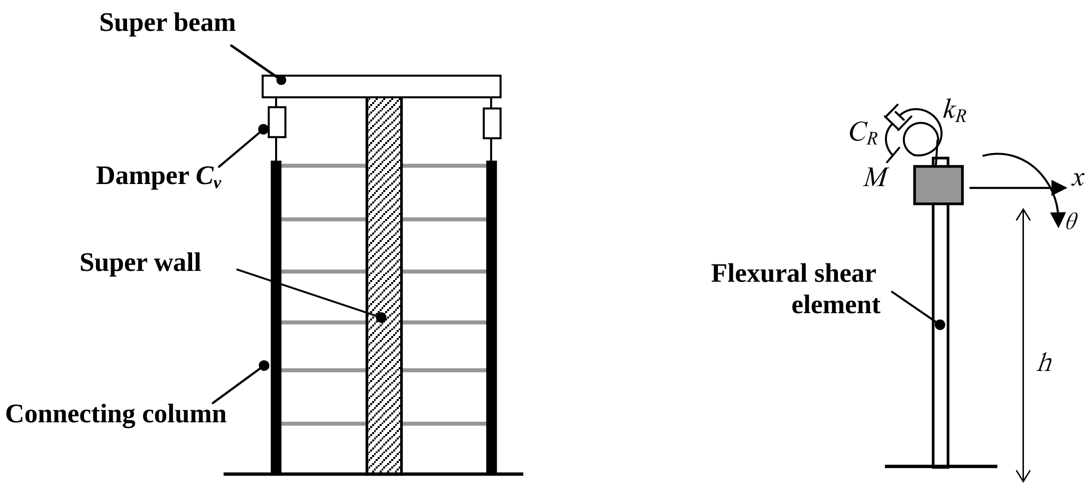
Where k_R^* is a complex stiffness of a rotational Maxwell model given below.

$$k_R^* = \frac{k_R C_R pi}{k_R + C_R pi} \tag{11}$$

Here we separate the total Equation (11) into the original frame stiffness K_0 and an additional stiffness s Δk as bellow.

$$K^* = K_0 + \Delta k = \left(r - \frac{u^2}{s} \right) + \Delta k \tag{12}$$

Transforming and expanding the Δk, we obtain a following expression.



（a）Placing model of damper （b）Flexural shear model

Figure 4 Flexural deformation response control system

$$\Delta k=\frac{u^2}{s}-\frac{u^2}{s+\dfrac{k_R C_R pi}{k_R+C_R pi}}=\frac{\dfrac{u^2}{s(s+k_R)}k_R\,\dfrac{u^2}{s^2}C_R pi}{\dfrac{u^2}{s(s+k_R)}k_R+\dfrac{u^2}{s^2}C_R pi} \tag{13}$$

Comparing Equation (13) with Equation (1), it is noted that Equation (13) is equivalent to the ordinary complex stiffness of a Maxwell model consists of a lateral stiffness $\tilde{k}$ and a lateral dashpot $\tilde{C}$.

$$\frac{u^2}{s(s+k_R)}k_R=\tilde{k} \qquad \frac{u^2}{s^2}C_R=\tilde{C} \tag{14}$$

Therefore a flexural deformation response control structure shown in Figure 4 corresponds strictly to a three elements Maxwell model shown in Figure 2, and all the results obtained from the study based on the ordinary response controlled structure installed with the damper at inter-story also can be applicable to this system. The key issue of making the proposed flexural deformation control system much effective can be summarized as realizing a large additional stiffness by the damper portion. Various feasibility studies on response control device, elastic changes of both super wall and beam, influences of out-of plane moment stiffness of slab which suffer a whole structure have been conducted [Omika et al. 2006]. The influences of plasticity of main earthquake-resistant members have been also clarified through the further study [Omika et al. 2007].

4. PPRACTICAL USE OF THE FLEXURAL DEFORMATION RESPNSE CONTROL SYSTEM

By applying the knowledge mentioned above, we designed a lot of actual buildings with the flexural deformation control system. Here we present one example that is the most typical case of the application of the "Super RC Frame" structural system. The columns and beams are totally eliminated from the residential space, and the resulting wide-open interior allows for greater flexibility in architectural layout. Each slab composed of half precast panel is 350mm thick void flat slab, and the noise and vibration serviceability criteria are fully satisfied. Typical floor plan is rectangular 29.55×36.05. The main earthquake-resistant elements consist of the super walls (H-shaped walls, 1.2m−2.0m thick) that surround the centrally located elevator shaft and stairwell, and the perimeter frames formed by the outer columns. These super walls are designed to resist majority of lateral load. Also, 4.5m depth hat beams (super beams) are double-crossed at the top of the super walls with vibration control devices (oil dampers named "HiDAM") located at the ends for energy dissipation under earthquakes. From Figure 5 to 8 show a building perspective, typical floor plan, building section, inner space under-construction, respectively.

5. CONCLUSION

We clarified basic principle of proposed flexural deformation response control system and its control effect using a simple three element Maxwell-type single mass system. Regarding the practical use of the proposed structural system, it is verified that it can provide column-free, beam-less residential apace and allows enough architectural flexibility in plan or section layout by the result of application example.

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Building Outline:	
- Location:	Kanda Chiyoda-ku, Tokyo
- Designed by:	Kajima Corporation, Architectural and Engineering Design Group
- Type of occupancy:	Apartment houses, stores
- Site area:	3,045,43 m²
- Building area:	1,065,28 m²
- Gross floor area:	39,518,61 m²
- No. of stories:	40 stories, 1 basement levels
- Building height:	136,7m
- Construction period:	June 2002－August 2004
Structural Outline	
- Type:	Reinforced Concrete
- System:	Super RC Frame
- Foundation:	Concrete drilled piers with belled bottom

Figure 5　Building Perspective

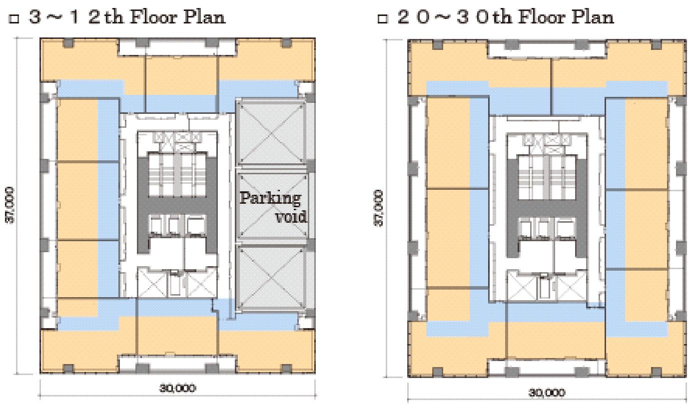

Figure 6　Typical Floor Plan

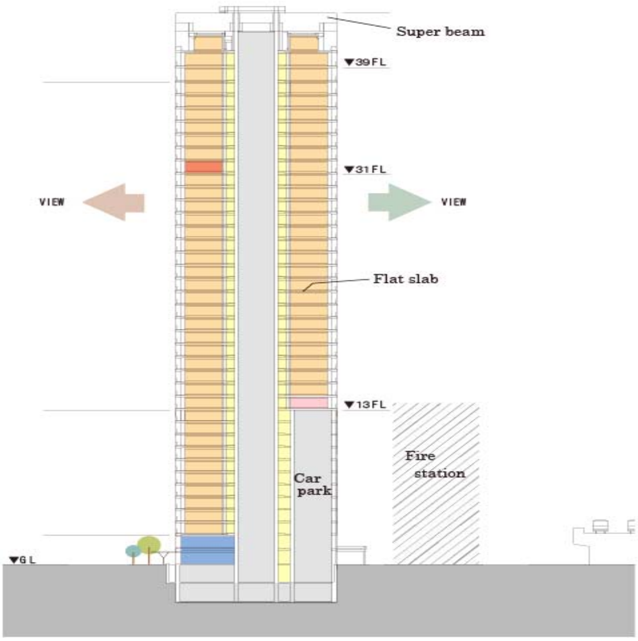

Figure 7　Building Section

Figure 8　Inner Space under Construction