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EFFECT OF LINKING FLUID DAMPERS ON WHIPPING EFFECT AND TORSIONAL RESPONSE OF TOWER-PODIUM SYSTEMS

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SUMMARY

With the aims of understanding the influence of linking fluid dampers on whipping effects and torsional responses of tall towers with podium structure, this paper presents a comprehensive analytical study. To obtain an universal result, a standardized 3-D model of two stories, surrounded by a 3-D one-story model, is first constructed to simulate a high tower with a podium structure based on several simplified principles. In this model system, various of parameters can be taken into account, including story number ratio and stiffness ratio of the upper part to its lower part for the tower, mass ratio, translational stiffness ratio and torsional stiffness ratio of the tower to its podium, lateral stiffness eccentricities respectively for the podium, the upper part and the lower part of the tower, supplemental damping resulted from linking fluid dampers, and plan distribution of the fluid dampers etc.. Subsequently, the equations of motion of the tower-damper-podium system are derived using the standardized model, with above-mentioned parameters involved in. Three connected cases, that is, connected by fluid dampers between tower and podium, connected by rigid connections, and without any connections, are considered respectively. A dimensionless form of these equations is then obtained through a normalized transformation for the various related matrices. Followed is the parametric analysis of various parameters to seismic responses through solving the equations of motion. The analytical results show that compared with rigid connection case, the vibration performance of a tower can usually be improved by installing fluid dampers between tower and podium and accordingly whipping effects can be effectively alleviated. In addition, most of seismic responses including torsion can be reduced for the tower and podium if the damper parameters are selected appropriately.

INTRODUCTION

Due to increasing of population, shortage of supply in land, and centralized service requirements, modern cities often need many tall buildings. Some of tall buildings are built as a tower structure with a large podium structure to achieve large open space for parking, shops, restaurants, and hotel lobby at the ground or lower levels. In most cases, the tower structure and the podium are built together on either a common box foundation or a common raft foundation. There are no settlement joints and anti-earthquake

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joints between the tower structure and its podium. The presence of the podium structure, whose lateral stiffness may be larger than that of the tower structure, leads to a suddenly large lateral stiffness change of the building at the top of the podium structure. Consequently, the seismic response of the upper part of the tower structure will be significantly amplified, leading to the so-called whipping effect. Such a problem can not be easily solved using the conventional structural modification. In addition, the complexity in plan configuration due to adding the podium structure as a appendix of the tower possibly leads to the increase of torsional response on account of the change of stiffness center and mass center for the whole tower-podium system. The concept of linking adjacent buildings or connecting podium structures to a main building using passive dampers, semi-active dampers, or active dampers has been already proposed to improve their seismic resistant performance.

The investigation of using passive dampers to connect adjacent buildings for enhancing their seismic resistant performance has been carried out by Kobori et al.[1], Luco et al. [2], Xu et al [3] among others. The use of active actuators to link a group of buildings to reduce their seismic responses has been examined by Yamada et al. [4], Seto and Matsumoto [5], and others. The experimental investigations of adjacent buildings linked by fluid dampers have been also carried out by Xu et al. [6] for the buildings under harmonic excitations and by Yang et al [7] for the buildings under seismic excitations through shaking table tests. All these investigations demonstrated that the use of dampers to link adjacent buildings of different fundamental frequencies could significantly reduce seismic response of either building if the locations and parameters of dampers are appropriately selected. However, all these investigations are limited to control their translational responses only.

The investigation of using ER/MR dampers to connect a podium structure to tower structure to prevent the whipping effect has been performed by Qu. et al. [8]. Their results demonstrated that the smart dampers with proper key parameters could not only prevent the tower building from whipping effect but also reduce the seismic responses of both tower and podium structures at the same time. Neverthness, only 2-D building models are used and accordingly torsional response can not be considered in their investigation. More important, only one tower building with fixed paramters and only El Centro wave excitation are explored in their study and therefore the universality of their conclusions need to verify further.

This paper therefore aims to improve the understanding of how supplemental viscous damping influence whipping effect and torsional response of high-tower with low podium systems. The mechanism of whipping effect due to the sudden chang of stiffness is simply analysed using a two-degree-of-freedom system prior to the main parametric study. To obtain universal results, a standardized building model is first constructed to simulate the high tower with a podium structure based on several simplified principles. The standardized model is analogous to that in the investigations of asymmetric one-story systems studied by Goel et al [9, 10, 11] and Lin et al [12]. Then, the equations of motion of the tower-damper-podium system are derived using the standardized model, with all kinds of parameters involved in. Three connected cases, that is, connected by fluid dampers between tower and podium, connected by rigid connections and without any connections, are considered respectively. Next, a dimensionless form of these equations is obtained through a normalized transformation for the various related matrices. The last is the parametric analysis of various parameters to seismic responses through solving the equations of motion.

SIMPLE ANALYSIS ON MECHANICS OF WHIPPING EFFECT DUE TO SUDDEN CHANGE OF LATERAL STIFFNESS

Basic concepts and assumptions

To reflect the whipping effect of a two-part building resulted from the sudden change of stiffness, the maximum relative displacement ratio of the upper part to the lower part is adopted as weighing criterion.

For convenience, it is called whipping effect factor hereinafter. Compared with the maximum relative displacements of the upper part and the lower part, the maximum relative displacement ratio is superior in avoiding the influence of the diversity of earthquake excitation and therefore can reflect whipping effect more clearly.

The investigation on the mechanism of whipping effect is performed by using a two-story shear-type analytical model (The basic parameters include m_1, m_2, k_1 and k_2, where m_i and k_i are, respectively, the mass and stiffness of the i^{th} story.). Four cases are considered. The first one is $m_1 = m_2$ and $k_1 = k_2$ (identical both in stiffness and mass for two stories). The second one is $m_1 = m_2$ and $k_1 = 10k_2$ (sudden change in stiffness at the top of the first story). The third one is $m_1 = 10m_2$ and $k_1 = k_2$ (sudden change in mass at the top of the first story). The last one is $m_1 = 10m_2$ and $k_1 = 10k_2$ (sudden change both in stiffness and mass at the top of the first story). The vibration modes and time history responses of the four cases are all calculated and given below.

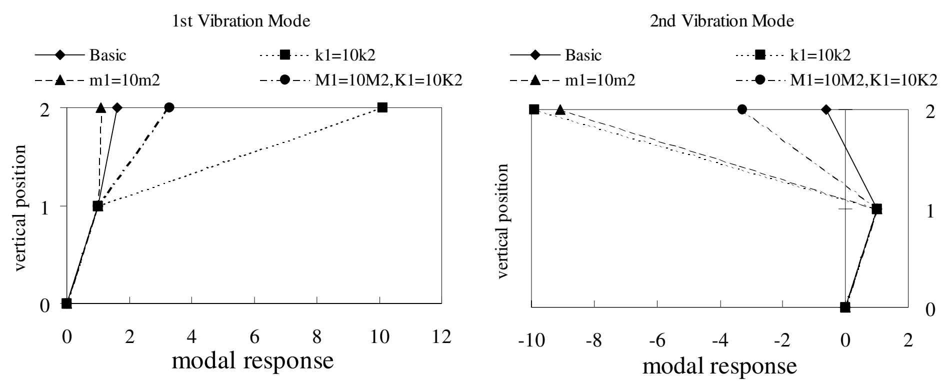

Fig.1. Vibration mode of two-story analytical model for different stiffness ratio and mass ratio

Model analysis

Compared with the basic case (case one), the effect of sudden change of stiffness or mass is shown clearly in the latter cases(shown in Fig.1). In case two, modal response is increased greatly for both the 1st and 2nd vibration mode. But for case three, only the 2nd modal response is magnified. While in case four, although the 1st and 2nd modal responses are increased, the magnified extent is relatively limited. It seems that the sudden change of stiffness makes the vibration mainly occur at the second story no matter in the 1st mode or in the 2nd mode. The sudden change of mass leads to the interesting result that modal vibration mainly takes place at the first story in the first vibration mode and correspondingly at the second story in the second vibration mode. As we know, the displacement response is mostly decided by the first modal contribution. It can therefore be inferred that the sudden change of stiffness is very likely to lead to the response magnification at the 2nd story while the sudden change of mass does not necessarily have the same effect.

Spectrum analysis

The results of time history response also proved the above points. From Fig.2, the displacement ratio of the 2nd story maximum displacement to the 1st story maximum displacement are presented. Compared with the basic case (case one) in which the response ratio is about 5.0, case two, case three and case four had the corresponding ratios of about 20.0, 1.1 and 3.5 respectively. Obviously, responses are mainly occurred at the 2nd story for case two and at 1st story for case three. As for case four, the responses may be very large for both 1st and 2nd story although the response ratio is not magnified.

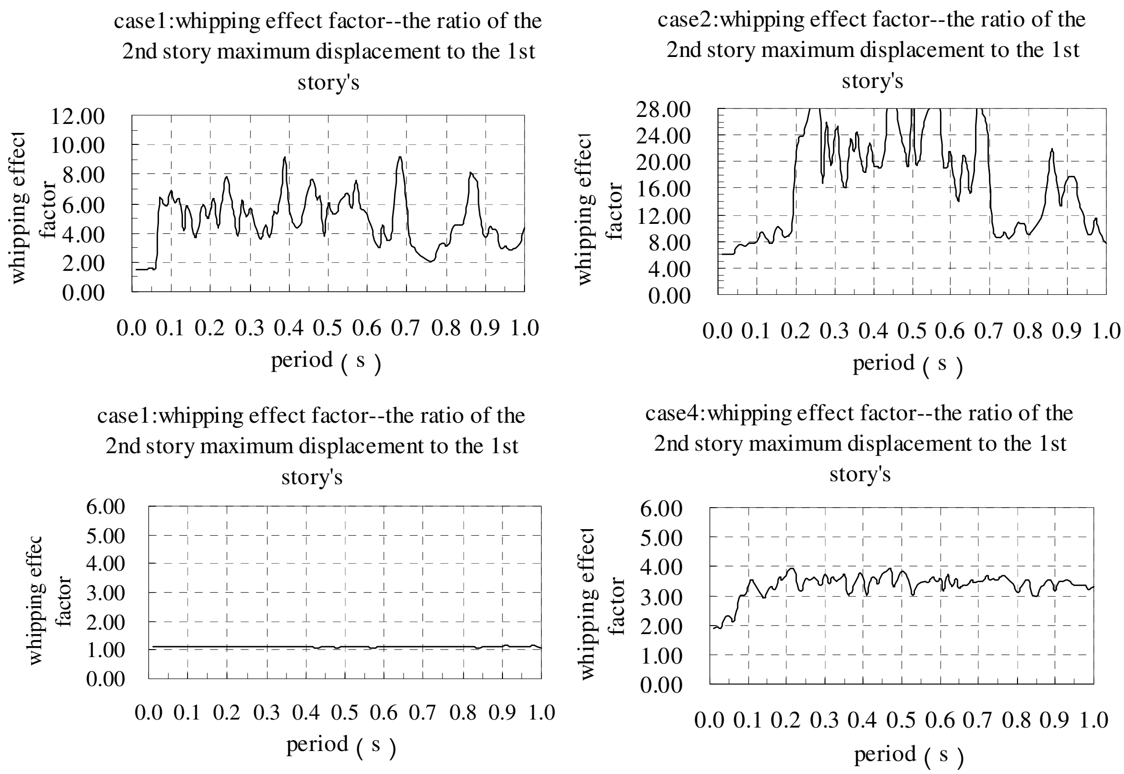

Fig.2. Whipping effect factor curves of two-story analytical model for different stiffness ratio and mass ratio

According to the above-mentioned analysis, the whipping effect due to the sudden change of stiffness should be mainly caused by the sharp change of the first vibration mode. This is one of the bases for the simplification to the standardized model described in the next section.

STANDARDIZED MODEL FOR MAIN TOWER-PODIUM STRUCTURE SYSTEMS

In order to investigate the vibration characteristics in the most extensive field for the system formed by main building and podium structure, internal main building and surrounding podium are simplified to a standardized model, in which various parameters can be easily adjusted to correspond to various different types.

Standardized Model

The standardized model includes an idealized two-story building mode l (simply called model 1) and a one-story building model (called model 2), which both consists of rigid decks supported by structural elements (walls, columns, moment-frames, braced-frames, etc.). As Fig.3 shown, the internal two-story model (model 1) is used to simulate main building and the surrounding one-story model (model 2) is used to represent the podium structure. In addition, the system can include fluid viscous dampers (FVDs) installed between the two parts. The mass properties of the system are assumed to be symmetric about both the X- and Y-axis whereas the stiffness and damper properties are considered to be symmetric only about the X-axis.

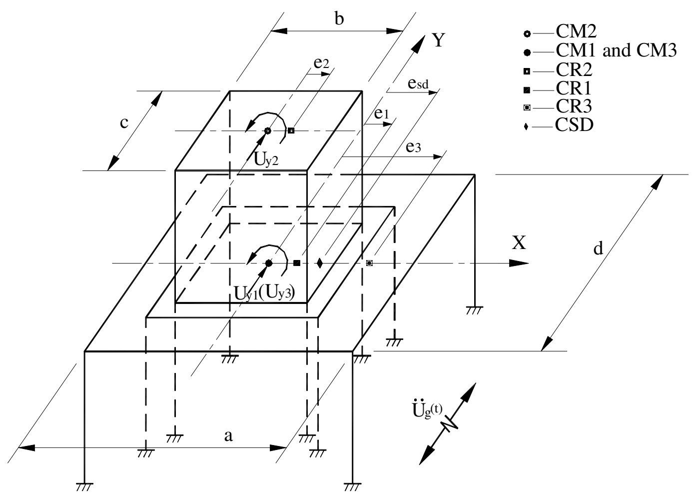

Fig.3. Sketch map of the general model defined in this paper

The center of mass (CM) of any deck floor is defined as the centroid of inertia forces of the deck when the system is subjected to a uniform translational acceleration in the direction under consideration. Since the mass is uniformly distributed about the X-and Y-axis, the CM of a deck coincides with the geometric center of the deck.

The center of rigidity (CR) is defined as the point on the deck through which application of a static horizontal force causes no rotation of the deck. For any story in this model, CR is also the centroid of resisting forces in structural elements at that story when that story is subjected to a uniform relative translational displacement in the direction under consideration. The lack of symmetry in the stiffness properties about the Y-axis is characterized by the stiffness eccentricities, e, defined as the distance between the CM and the CR. With both CM and CR defined, the edge that is on the same side of the CM and the CR is denoted as the stiff edge and the other edge is designated as the flexible edge (See Fig.3).

The center of supplemental damping (CSD) generated by the connected dampers is defined as the centroid of damper forces when the first floor of model 1 is subjected to a uniform translational relative velocity with respect to the floor of model 2 in the direction under consideration. The lack of symmetry in the damper properties about the Y-axis is characterized by the supplemental damping eccentricity, e_{sd}, defined as the distance between the CM and the CSD.

Simplification Principles to Standardized Model

For convenience, the original real main building is idealized as a shear-type building with the same $(m+n)$ stories and the corresponding podium had m stories. The lower m stories connects with podium. The parameters of m and n/m can be changed to simulate different practical cases.

To simulate the relationship of the two parts of a tall main building with a low podium, some parameters of the second story of model 1 must be restrained by the related parameters of the first story of model 1 so that model can simulate the real main building to the most extent. The related parameters are $\beta_1 = \dfrac{m_2}{m_1}$, $\gamma_1 = \dfrac{K_{y2}}{K_{y1}}$ and $\eta_1 = \dfrac{K_{\theta R2}}{K_{\theta R1}}$. (Note that all related parameters will be detailed explained in the next sections.)

For model 1, its first story is the basic unit used in this paper and it represents the part of a main building connected with the podium building substituted by model 2. The basic frequency of the first story $\omega_{y1} = \sqrt{\dfrac{K_{y1}}{m_1}}$ embodies the change of m and the change of n/m is achieved using the guideline one given in the next paragraph. The second story of model 1 represents the part of the main building above the podium building.

There are total three guidelines in simplifying the main buildings to the standardized model. First, the mass ratio of $\beta_1 = \dfrac{m_2}{m_1}$ is set to be equal to story number ratio n/m. Correspondingly, the guideline two is, for the model 1 and real main building, to set the same value in the first frequency value. Thus, the stiffness ratio of $\gamma_1 = \dfrac{K_{y2}}{K_{y1}}$ can be specified. This point also accords with the requirement of keeping the first modal vibration as close as possible for model 1 and real main building. The last guideline is to choose the same values for translational stiffness ratio and corresponding torsional stiffness ratio, namely, $\dfrac{K_{\theta R2}}{K_{\theta R1}} = \dfrac{K_{y2}}{K_{y1}}$ and $\dfrac{K_{\theta R3}}{K_{\theta R1}} = \dfrac{K_{y3}}{K_{y1}}$. This will simplify the research without losing the universality in practical significance.

DERIVATION OF EQUATIONS OF MOTION

The equations of motion of the main building model linked by fluid dampers with the podium building model can be expressed as:

$$\mathbf{M}\ddot{\mathbf{U}}(t) + (\mathbf{C}_s + \mathbf{C}_d)\dot{\mathbf{U}}(t) + (\mathbf{K}_s + \mathbf{K}_d)\mathbf{U}(t) = -\mathbf{M}\boldsymbol{\Gamma}\ddot{u}_g(t) \tag{1}$$

where $\mathbf{U}(\mathrm{t})$, $\dot{\mathbf{U}}(\mathrm{t})$, and $\ddot{\mathbf{U}}(\mathrm{t})$ are, respectively, the displacement vector, the velocity vector, and the acceleration vector of the system relative to the ground; $\ddot{u}_g(t)$ is the translational ground acceleration in the Y direction applied at the base of the system; $\boldsymbol{\Gamma}$ is the transformation vector; $\mathbf{M}$ is the mass of the system; and $\mathbf{K}_s$, $\mathbf{K}_d$ are the stiffness matrices of the system and the connector respectively. In this paper, the connector is viscous damping damper and therefore the matrix of $\mathbf{K}_d$ is none; $\mathbf{C}_s$, $\mathbf{C}_d$ are the damping matrices of the system and the connector.

Related Variables Used in the Analysis

α group (Geometric dimension group)

$$\alpha_1 = \frac{a}{d};\ \alpha_2 = \frac{b}{c};\ \alpha_3 = \frac{a}{b}; \tag{5}$$

α_1 —Aspect ratio of the model 2;

α_2 —Aspect ratio of the model 1;

α_3 —Geometric dimension ratio of model 1 and model 2;

β group (Mass group)

$$\beta_1 = \frac{m_2}{m_1};\ \beta_2 = \frac{m_3}{m_1}; \tag{6}$$

β_1 — Mass ratio of the second floor to the first floor for model 1 in the standardized model;

β_2 — Mass ratio of the podium floor to the first floor of model 1 in the standardized model;

γ group (Lateral stiffness group)

$$\gamma_1 = \frac{K_{y2}}{K_{y1}};\ \gamma_2 = \frac{K_{y3}}{K_{y1}} \tag{7}$$

γ_1 — Lateral stiffness ratio of the second story to the first story for model 1 in the standardized model;

γ_2 — Lateral stiffness ratio of model 2 to the first story of model 1 in the standardized model;

η group (Torsional stiffness group)

$$\eta_1 = \frac{K_{\theta R2}}{K_{\theta R1}};\ \eta_2 = \frac{K_{\theta R3}}{K_{\theta R1}} \tag{8}$$

η_1 — Torsional stiffness ratio of the second story to the first story for model 1 in the standardized model;

η_2 — Torsional stiffness ratio of model 2 to the first story of model 1 in the standardized model;

$\overline{\rho}$ *group (Normalized radius of gyration: distribution)*

$$\overline{\rho}_{sd} = \frac{\rho_{sd}}{b};\ \text{And}\ \rho_{sd} = \sqrt{\frac{C_{\theta Rsd}}{C_{ysd}}} \tag{9}$$

$\overline{e}$ *group (Normalized eccentricity group: plan position)*

$$\overline{e}_1 = \frac{e_1}{b};\ \overline{e}_2 = \frac{e_2}{b}\ \text{And}\ \overline{e}_3 = \frac{e_3}{a};\ \overline{e}_{sd} = \frac{e_{sd}}{b}; \tag{10}$$

$\overline{e_1}$ — Relative location of the CR from CM for the first floor of model 1 in the standardized model;

$\overline{e_2}$ — Relative location of the CR from CM for the second floor of model 1 in the standardized model;

$\overline{e_3}$ — Relative location of the CR from CM for the floor of model 2 in the standardized model;

$\overline{e_{sd}}$ — Relative location of the CSD from CM for supplemental damping damper in the standardized model;

ξ *group (Formal supplemental damping ratio)*

$$\xi_{sd1} = \frac{C_{ysd}}{2m_1\omega_{y1}} \tag{11}$$

Note that ξ_{sd1} is just an expressive index of the amount of supplemental damping in the forms of damping ratio but it is not the real damping ratio of the system. Furthermore, the value of ξ_{sd1} could exceed 1.0 if necessary.

ω *group (Formal translational vibration frequency)*

$$\omega_{y1} = \sqrt{\frac{K_{y1}}{m_1}}; \tag{12}$$

Analogous to the item of ξ_{sd1}, ω_{y1} is the angle frequency of the model that is made up of the first story of model 1. Although ω_{y1} is not the real frequency of model 1, it can really indicate the magnitude of the real of mode1 frequency because there is a definite proportional relationship between according to the simplification guidelines.

Ω *group (Ratio of the formal torsional and translational frequencies)*

$$\Omega_\theta = \frac{\omega_{\theta 1}}{\omega_{y1}} \; ; \; \omega_{\theta 1} = \sqrt{\frac{K_{\theta R1}}{m_1 \rho_1^2}} \tag{13}$$

Ω_θ is indicative of the degree of the coupling of lateral and torsional motions in the elastic range.

Basic Formulas

Mass radius of gyration

$$\rho_1 = \rho_2 = \sqrt{\frac{b^2 + c^2}{12}} = b\sqrt{\frac{1+\alpha_2^2}{12\alpha_2^2}}$$

$$\rho_3 = \sqrt{\frac{ad\left(a^2 + d^2\right) - bc\left(b^2 + c^2\right)}{12(ad - bc)}} = a\sqrt{\frac{\left(1+\frac{1}{\alpha_1^2}\right) - \frac{1}{\alpha_2\alpha_3^2}\left(\frac{1}{\alpha_3^2} + \frac{1}{\alpha_2^2\alpha_3^2}\right)}{12\left(1 - \frac{\alpha_1}{\alpha_2\alpha_3^2}\right)}} = a\sqrt{f_1(\alpha_i)} \tag{2}$$

ρ_1, ρ_2, ρ_3 — The mass radiuses of gyration for the first floor, the second floor of model 1 and the podium floor, respectively;

Stiffness quantities for the first story of model 1

$$K_{y1} = \sum_i k_{yi} \; ; \; K_{\theta 1} = \sum_i k_{xi} y_i^2 + \sum_i k_{yi} x_i^2 \; ; \; e_1 = \frac{\sum_i k_{yi} x_i}{K_{y1}}$$; And therefore:

$$K_{\theta 1} = K_{y1} e_1^2 + K_{\theta R1} \tag{3}$$

k_{yi}, x_i —The lateral stiffness and the distance from the CM of the *i*th resisting element along the Y-axis;
k_{xi}, y_i —The lateral stiffness and the distance from the CM of the *i*th resisting element along the X-axis;
K_{y1}, $K_{\theta 1}$, $K_{\theta R1}$ — The translational stiffness of the system along the Y-axis, the torsional stiffness of the system about a vertical axis at the CM and , the torsional stiffness of the system about a vertical axis at the CR. Deck2 and deck3 are similar to the deck1.

Supplemental damping of the connected fluid dampers

Supplemental damping:

$$C_{ysd} = \sum_i c_{sdyi} \; ; \; C_{\theta sd} = \sum_i c_{sdxi} y_i^2 + \sum_i c_{sdyi} x_i^2 \; ; \; e_{sd} = \frac{\sum_i c_{sdyi} x_i}{C_{ysd}}$$ And therefore:

$$C_{\theta sd} = C_{ysd} e_{c1}^2 + C_{\theta Rsd} \tag{4}$$

c_{sdyi}, x_i —The lateral damping coefficient and the distance from the CM of the *i*th FVD along the Y-axis;
c_{sdxi}, y_i —The lateral damping coefficient and the distance from the CM of the *i*th FVD along the X-axis;
C_{ysd}, $C_{\theta sd}$, $C_{\theta Rsd}$—The translational damping coefficient of the system along the Y-axis, the torsional damping coefficient of the system about a vertical axis at the CM and the torsional damping coefficient of the system about a vertical axis at the CSD;

Related Matrices for the System with Damper Connections or Without Any Connections

Degree of freedom

The one-way symmetric system has six degrees of freedom (DOF) when subjected to ground motion along the Y-axis: one translation along the Y-axis and rotation about a vertical axis at mass center for each deck. The displacement vector $\mathbf{U}$ for the system is defined by $\mathbf{U}^T = \{u_{y1} \quad bu_{\theta 1} \quad u_{y2} \quad bu_{\theta 2} \quad u_{y3} \quad au_{\theta 3}\}^T$ where u_{yi} is the Y-direction horizontal displacement relative to the ground for the i^{th} deck; $u_{\theta i}$ is the rotation about the vertical axis at the center of mass for the i^{th} deck.

Mass matrix of the system

Let m_1, m_2 and m_3 represent the total mass of deck1, deck2 and deck3, respectively. And let ρ_1, ρ_2 and ρ_3 represent the mass radius of gyration. Then, the mass matrix is given by:

$$\mathbf{M} = \begin{bmatrix} m_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & m_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{66} \end{bmatrix} \tag{14}$$

where various items are given as:

$m_{11} = m_1$; $m_{33} = m_2$; $m_{55} = m_3$;

$$m_{22} = \frac{1+\alpha_2^2}{12\alpha_2^2} m_1;\; m_{44} = \frac{1+\alpha_2^2}{12\alpha_2^2} m_2;\; m_{66} = f_1(\alpha_1, \alpha_2, \alpha_3) m_3 \tag{15}$$

Stiffness matrix of the system

$$\mathbf{K}_s = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & 0 & 0 \\ k_{21} & k_{22} & k_{23} & k_{24} & 0 & 0 \\ k_{31} & k_{32} & k_{33} & k_{34} & 0 & 0 \\ k_{41} & k_{42} & k_{43} & k_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & k_{55} & k_{56} \\ 0 & 0 & 0 & 0 & k_{65} & k_{66} \end{bmatrix} \tag{16}$$

Where various items are given as:

$$k_{11} = K_{y1} + K_{y2};\; k_{12} = \frac{e_1}{b} K_{y1} + \frac{e_2}{b} K_{y2};\; k_{13} = -K_{y2};\; k_{14} = -\frac{e_2}{b} K_{y2}$$

$$k_{21} = k_{12}; k_{22} = \left[\left(\frac{e_1}{b}\right)^2 K_{y1} + \frac{1}{b^2} K_{\theta R1}\right] + \left[\left(\frac{e_2}{b}\right)^2 K_{y2} + \frac{1}{b^2} K_{\theta R2}\right];\; k_{23} = -\frac{e_2}{b} K_{y2};$$

$$k_{24} = -\left[\left(\frac{e_2}{b}\right)^2 K_{y2} + \frac{1}{b^2} K_{\theta R2}\right];\; k_{31} = k_{13};\; k_{32} = k_{23};\; k_{33} = K_{y2};\; k_{34} = \frac{e_2}{b} K_{y2};$$

$$k_{41} = k_{14}; k_{42} = k_{24};\; k_{43} = k_{34};\; k_{44} = \left[\left(\frac{e_2}{b}\right)^2 K_{y2} + \frac{1}{b^2} K_{\theta R2}\right];$$

$$k_{55} = K_{y3};\; k_{56} = \frac{e_3}{a} K_{y3};\; k_{65} = k_{56};\; k_{66} = \left[\left(\frac{e_3}{a} \right)^2 K_{y3} + \frac{1}{a^2} K_{\theta R3} \right]; \tag{17}$$

Structural damping matrix of the system
The proportional damping assumption is given directly in the next dimensionless stage.

Damper damping matrix

$$\mathbf{C}_d = \begin{bmatrix} c_{d11} & c_{d12} & 0 & 0 & c_{d15} & c_{d16} \\ c_{d21} & c_{d22} & 0 & 0 & c_{d25} & c_{d26} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ c_{d51} & c_{d52} & 0 & 0 & c_{d55} & c_{d56} \\ c_{d61} & c_{d62} & 0 & 0 & c_{d65} & c_{d66} \end{bmatrix} \tag{18}$$

Where various items are given as:

$$c_{d11} = C_{ysd};\; c_{d12} = \frac{e_{sd}}{b} C_{ysd};\; c_{d21} = c_{d12};\; c_{d22} = \left[\left(\frac{e_{sd}}{b} \right)^2 + \left(\frac{\rho_{sd}}{b} \right)^2 \right] C_{ysd};$$

$$c_{d15} = -C_{ysd};\; c_{d16} = -\frac{e_{sd}}{a} C_{ysd};\; c_{d25} = -\frac{e_{sd}}{b} C_{ysd};\; c_{d26} = -\left[\frac{e_{sd}^2}{ab} + \frac{\rho_{sd}^2}{ab} \right] C_{ysd};$$

$$c_{d51} = c_{d15};\; c_{d52} = c_{d25};\; c_{d61} = c_{d16};\; c_{d62} = c_{d26};$$

$$c_{d55} = c_{ysd};\; c_{d56} = \frac{e_{sd}}{a} C_{ysd};\; c_{d65} = c_{d56};\; c_{d66} = \left[\left(\frac{e_{sd}}{a} \right)^2 + \left(\frac{\rho_{sd}}{a} \right)^2 \right] C_{ysd} \tag{19}$$

Excitation vector

$\mathbf{\Gamma} = \{1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0\}^T$; Hence,

$$-\mathbf{M\Gamma} \ddot{u}_g(t) = -\{m_1 \quad 0 \quad m_2 \quad 0 \quad m_3 \quad 0\}^T \ddot{u}_g(t) \tag{20}$$

Normalization to Dimensionless Form for Various Matrices

The dimensionless formula can be obtained through dividing the equations of motion by m_1 and substituting the related variables into them. The process of the normalization is omitted to save space.

CONTROLLING PARAMETERS OF THE SYSTEMS

To investigate and evaluate the control performance of supplemental fluid dampers on reduction of the whipping effect and the seismic responses of both main buildings and podium structures, three cases are investigated. The first case is that model 2 is rigidly connected to model 1 (B-Case1). The second case is model 2 totally separated from model 1 (B-Case2). The last case (B-Case3) is model 2 connected to model 1 by fluid dampers as specified above.

Equation (1) indicates that the linear elastic response of the system depends on two sets of parameters if the excitation is fixed. The first set of parameters corresponding to the system without FVDs consists of

(1) transverse vibration period of the basic unit, which is the first story of model 1, $T_{y1} = 2\pi / \omega_{y1}$; (2) mass ratio of the second story to the first story of model 1, β_1 (two kind stiffness ratios, γ_1 and η_1, are dependent on β_1 according to the standardized guideline of the standardized model); (3) mass ratio of model 2 to the first story of model 1, β_2 (two teams of stiffness ratios, γ_2 and η_2, are independent on β_2); (4) stiffness ratio of model 2 to the first story of model 1, γ_2 and η_2; (5) normalized stiffness eccentricity, $\bar{e}_1$, $\bar{e}_2$ and $\bar{e}_3$; (6) ratio of torsional and transverse frequencies, Ω_θ; (7) various aspect ratios, α_1, α_2 and α_3; (8) natural damping ratios, ξ_1 to ξ_6, which are used to specify structural damping matrix. The aspect ratios are included as one set of the system parameters because it facilitated a more appealing definition of the stiffness eccentricity as a percentage of the plan dimension.

The second set of parameters corresponding to supplemental damping consists of (1) supplemental damping index in terms of damping ratio, ξ_{sd1}; (2) normalized supplemental damping eccentricity, $\bar{e}_{sd}$ and (3) normalized supplemental damping radius of gyration, $\bar{\rho}_{sd}$. ξ_{sd1} is indicative of the amount of additional damping, as a fraction of the critical value, which is provided by FVDs with the same value as in the case that a structure, same as the first story of model 1, is connected to a fixed object by the same FVDs. $\bar{e}_{sd}$ is indicative of how evenly FVDs are located within the system in the Y direction. A zero value of $\bar{e}_{sd}$ implies that FVDs are located symmetrically about the CM, whereas non-zero values indicate uneven distribution. $\bar{\rho}_{sd}$ indicates how much farther apart from the CSD the FVDs are located. This parameter is also indicative of the damping in the torsional mode of vibration. Zero value of $\bar{\rho}_{sd}$ implies that all FVDs are located at the CSD and that they provide zero damping in the torsional mode, whereas large values indicate that FVDs are located farther from the CSD and that damping is increased in the torsional mode.

SELECTED SYSTEM PARAMETERS

Responses of the system are presented for the above-mentioned three cases. The related parameters are introduced below. Values of T_{y1} are selected in the range of 0.1–1.0 to represent many low-rise and mid-rise buildings for which supplemental damping is expected to evidently influence the response. The mass ratios of β_1=2, 4, 6 and 8 represented that the story number ratio of upper part to lower part for the main building are 2, 4, 6 and 8 respectively. Furthermore, the stiffness ratios of γ_1 and η_1 are specified correspondingly as 0.764, 0.482, 0.348 and 0.272 respectively according to the simplification guidelines of the standardized model. The mass ratio of model 2 to the first story of model 1 β_2 is generally set as 1.0 while the stiffness ratios of γ_2 and η_2 are selected as 0.5, 1.0, 2.0 and 4.0 such that the effects of sudden stiffness change with different degrees can be investigated. In order to show effects of the coupling of lateral and torsional motions, the typical value of $\Omega_\theta = 2$ is adopted when stiffness eccentricities existed. The normalized stiffness eccentricities varies from 0.05 to 0.4 for $\bar{e}_1$ and $\bar{e}_2$ and –0.1 to 0.1 for $\bar{e}_3$ in most cases. The aspect ratios, α_1, α_2 and α_3, are fixed at one, one and two respectively. Various modal damping ratios, from ξ_1 to ξ_6, are selected as 0.05 to calculate the structural damping matrix.

Although the damping coefficient of FVDs depends on the frequency and amplitude of motion as well as on the operating temperature, the damping force of fluid dampers are considered to only depend on the relative velocity and the damping coefficient is only related to the FVDs themselves in this paper. It should be noted that the used ξ_{sd1} is just a substitute of damping coefficient c_0 and not real damping ratio. The value of ξ_{sd1} is selected at 0.5 for most related cases. For a limited number of cases, however, variations of ξ_{sd1} in the range of 0.0-3.0 are considered. In general, four values of $\bar{e}_{sd}$ = -0.3, -0.2, -0.1, and 0 are selected. In all related cases, the value of $\bar{\rho}_{sd}$ is fixed at 0.5 to keep considerable damping effects on torsional modes.

N-S 1940 El Centro earthquake wave is used as the seismic excitation and inputted in the Y direction only. The peak value of El Centro excitation is selected as 0.2g and the time interval of inputting point is 0.02s.

INVESTIGATION ON TRANSLATIONAL WHIPPING EFFECT

In this section, whipping effect of the translational motion resulted from the only Y direction excitation is first investigated for the system without any stiffness eccentricities. Then the control effects of supplemental viscous damping on the whipping effects are studied. Lastly, the influences of supplemental viscous damping on responses of the system are also involved.

Whipping Effect of Translational Motion

Whipping effect index used in this part is defined as the ratio of whipping effect factors of B-Case1 to B-Case2. The whipping effect factor, B-Case1 and B-Case2 are already defined before.

Fig.4 depicts the whipping effect index against the period T_{y1} for four different stiffness values of $\gamma_2 = 0.5$, 1.0, 2.0 and 4.0. The results show that whipping effect depends significantly on the stiffness ratio of mode2 to the first story of model 1 (γ_2). When γ_2 is equal to 0.5, there is nearly no any sign of whipping effect. When γ_2 is larger than 1.0, whipping effect becomes large with the largest value of 3.5 and it is evident for almost all T_{y1}. Obviously, the larger γ_2 is, the more evident whipping effect is. This denotes that the whipping effect is resulted from the sudden increase of the lateral stiffness. As a contrast, Fig.5 gives the whipping effect index against the same period T_{y1} for four different mass values of $\beta_2 = 1.0$, 2.0, 4.0 and 8.0. It shows that whipping effect does not necessarily exist for the whole interested scope of T_{y1}, especially for the cases of selecting relative large value of β_2. This also verifies the reason causing whipping effect, which is discussed before.

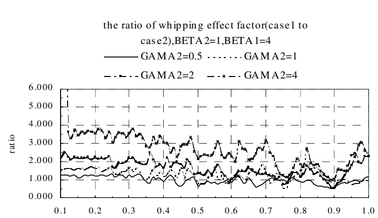

Fig.4. Whipping effect index for different stiffness ratio values of GAMA2

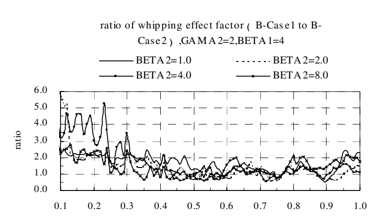

Fig.5. Whipping effect index for different mass ratio values of BETA2

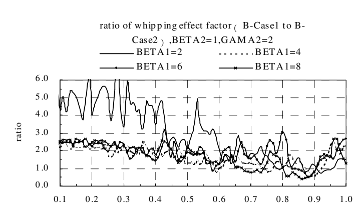

Fig.6. Whipping effect index for different mass ratio values of BETA1

Presented in Fig.6 are whipping effect indexes against the period of T_{y1} for four different mass ratio values of $\beta_1 = 2.0$, 4.0, 6.0 and 8.0. The whipping effect indexes generally keep near 2.0 or so except the case with mass ratio value β_1 of 2.0, in which the whipping effect index can reach 5.0. This demonstrates that whipping effect will exist universally for various story number ratios of n/m in a $(m+n)$-story main building.

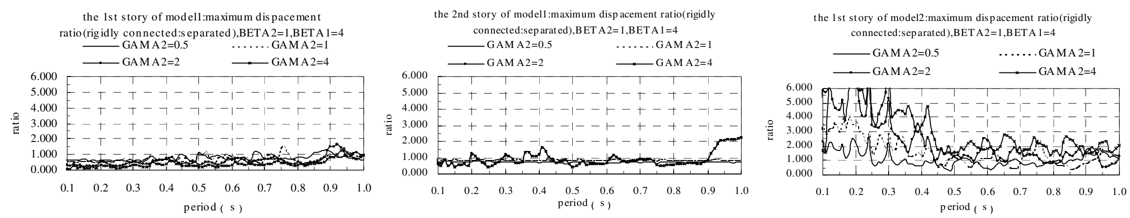

Fig.7. Various relative displacements of model 1 and model 2 for different stiffness of the 1st story

It should be noted that whipping effect index over 1.0 just means the occurrence of whipping effect but it does not denote the necessary increase for displacement responses at different floors. This is because whipping effect index is just a relative weighing index of upper displacement to lower displacement. Due to the sudden increase of lateral stiffness at the first story for model 1, displacement responses of both the first floor and the second floor of model 1 have the tendency to be mitigated although the tendency is more intense for the first story. Therefore, it is possible that the displacement responses of the first floor and second floor are both decreased when the whipping effect factor is increased. In order to clearly show this point, Fig.7 presents the various relative displacements of model 1 and model 2 against the period of T_{y1} for the four different stiffness ratios of $\gamma_2 = 0.5$, 1.0, 2.0 and 4.0. When lateral stiffness ratio γ_2 is larger than 1.0, a general rule of relative displacements can be observed: the relative displacement (1) is almost decreased at various periods for the first floor of model 1; (2) is often decreased but sometimes increased at different periods for the second floor of model 1; (3) is almost magnified at various periods for model 2. Therefore, only for some periods of T_{y1}, displacement of the second floor of model 1 will be magnified due to the sudden increase of lateral stiffness although whipping effects will widely occur for various periods.

Influence of Supplemental Dampers on Whipping Effect

In order to widely show the effects of supplemental damping that is resulted from the fluid dampers connected at the first floor between model 1 and model 2, the whipping effect indexes of B-Case3 to B-Case1 are presented against the damping ratio ξ_{sd1} for the four different periods $T_{y1} = 0.2$, 0.4, 0.6 and 0.8 [(See Fig.8). Several rules can be observed. First of all, whipping effect indexes are generally less than 1.0 and therefore whipping effect can be mitigated in most cases. Secondly, control effects on whipping effect are different for different periods. From the period of 0.2 to 0.8, the control effect is gradually deteriorated with the corresponding maximum reduction ratios from 58% to 24%. Thirdly, the control effects are gradually deteriorated with the increase of ξ_{sd1} when ξ_{sd1} are more than certain values. As a comparison, Fig.9 presents the whipping effect indexes of B-Case3 to B-Case2. With the increase of ξ_{sd1}, the whipping effect indexes are generally increased but the increase is slow. Furthermore, the indexes can be less than 1.0 at a few values of period.

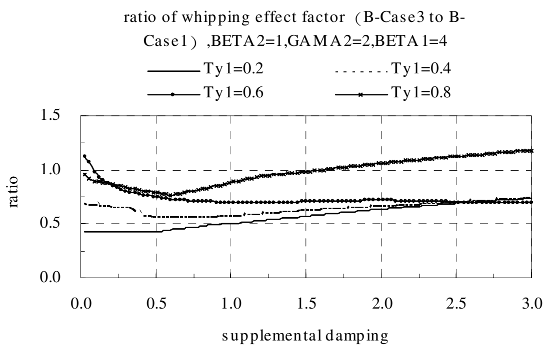

Fig.8. Influence of supplemental dampers on whipping effect(B-Case3 to B-Case1)

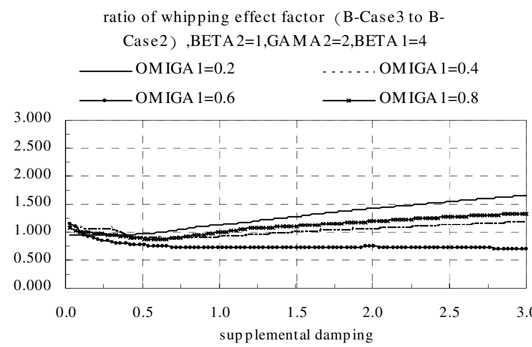

Fig.9. Influence of supplemental dampers on whipping effect(B-Case3 to B-Case1)

Influence of Supplemental Dampers on Structural Response

To assess the performance of fluid dampers on the system, structural responses besides whipping effect index should be investigated. Fig.10 and Fig.11 (The two figures are abbreviated due to space limitation) depict the response ratios of B-Case3 to B-Case1 and B-Case3 to B-Case2 respectively. Compared with B-Case1, the displacement responses of model 2 and the second floor of model 1 are decreased generally but those of the first floor of model 1 are not always decreased in B-Case3. While compared with B-Case2, the displacement responses of the first and the second floor of model 1 are always mitigated and those of model 2 are generally increased except $T_{y1} = 0.8$. These denote that supplemental damping can mitigate responses of the system not only for B-Case1 but also for B-Case2 on most occasions.

Duing to the space limitation, the investigation on torsional response is abbrevited in this manuscript. The full content of the manuscript will be submitted to a journal soon later.

CONCLUSIONS

Whipping effect and torsional response of tower-podium system with and without fluid dampers connected have been investigated using a standardized method. The mechanism of whipping effect is simply analysed. A set of standardized model system is calibrated to simulate general high towers and their podium structures. The equations of motion of the system are derived and developed to facilitate the parametric analysis of tower-podium system. The effects of a series of key parameters on whipping effect and torsional response are investigated through solving the developed equations of motions for the system. The study on mechnism of whipping effect due to the stiffness change demonstrates that whipping effect is resulted from the sharp change of the first vibration mode other than the second vibration mode. The results of the comprehensive parametric analysis show that seismic responses and whipping effects are influenced by various parameters. In usual case (hereinafter the cases of stiffer podium are referred), compared with rigidly connected case, the vibration performance of a tower can be improved by using linking fluid dampers and accordingly whipping effects and seismic responses of the tower can both be effectively alleviated. In addition, the seismic responses of the podium can also be reduced. While compared with the case of without any connections, using linking fluid dampers can reduce seismic responses of the tower but at the same time possibly increase those of the podium. The deterioration of the seismic performance of the podium is owing to the limited energy-dissipated capability of the fluid dampers because the dampers can not be excited efficiently due to their low installing locations. In that case, the effect of direct mutual interaction between tower and podium predominates over the effect of dampers' energy dissipation. Therefore, although using linking fluid dampers can evidently alleviate whipping effect of tower, it is not always effective to reduce the seismic responses of both tower and podium by using this approach. Similar conclusions can be drawn for the cases which are relevant to torsinal responses of the systems.

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