Efficiency of the motion amplification device with viscous dampers and its application in high-rise buildings

Henry C. Huang

WSP Asia Ltd., Beijing, China

Abstract: After nearly a decade of application and investigation, a motion amplification device with viscous dampers for energy dissipation has been recognized as an effective solution to mitigate wind or seismic excitation, especially for stiff structural systems. As a result of compensation of amplified motion, it has been proved that the efficiency of viscous damper largely depends on the motion amplification device configuration, particularly for device stiffness. In this paper, a “scissor-jack” type of motion amplification device, called a “toggle brace damper” system, is studied. It is demonstrated that the efficiency of such a device reflected by its amplification factor is not merely a function of its geometric configuration, but is highly dependent on the support elements’ stiffness as well, similar to the mechanism of a leverage arm. Accordingly, a mathematical model in terms of complex modulus of the viscous damper with consideration of the support brace’s stiffness is established. The results indicate that the efficiency of the motion amplification device with viscous dampers significantly depends on the stiffness of the support elements. Other parameters, such as toggle brace configuration and damping values of the viscous damper, are studied and compared. As an application example, numerical analyses are conducted to study the dynamic performance of a 39-story office tower installed with toggle brace dampers constructed on soft soil in a reclaimed area, under a combined effect of the vortex shedding of an adjacent existing 52-story building and earthquakes. The results show that viscous dampers with a motion amplification system using a properly designed toggle brace device proved to be an effective solution to alleviate the external excitations.

Keywords: motion amplification device; vibration mitigation; viscous damper; energy dissipation; toggle brace damper

1 Introduction

Viscous dampers have proved to be one of the most efficient devices to absorb and dissipate large amounts of energy from earthquakes or wind to maintain the response of a given structure within acceptable limits. These devices are ideally suitable for flexible structures. Recent efforts have been dedicated to finding methods to improve the efficiency of the dampers of less flexible structures. Various motion amplification devices have been discussed by Hanson and Soong (2001) to overcome small deflections associated with small velocities which may render viscous damping devices ineffective. The “scissor-jack” type of motion amplification devices, called a “Toggle-Brace-Damper” (TBD), was proposed and patented by Taylor in 1999. Constantinou et al. (2001) demonstrated that the TBD system improved the efficiency of this energy dissipation device by magnifying the damper displacement and also verified its ability to enhance the efficiency of the TBD system through both cyclic loading tests and shaking table tests with a single-degree-of-freedom (SDOF) steel frame. McNamara and Huang (2000) adopted this concept and applied the TBD system to a 39-story office building in Boston, which was completed in 2000. Their computer analysis showed that the stiffness of the toggle braces played a very important role for enhancing the effectiveness of the overall system damper. Therefore, they revised the attachment of the lower brace proposed by Constantinou et al. (2001) and installed it directly into the beam-column joints, which eliminated the deflection from the beam. Hwang et al. (2005) proved that this modification was necessary to improve the effectiveness of the TBD system from his theoretical analysis and laboratory tests. DeSimone and Bongiorno (2002) used the same scheme and applied their viscous dampers on upper placed toggle brace for a 40 story high Four Season Hotel in San Francisco which were also primarily used to reduce wind load. Shao and Miyamoto (2002) applied the TBD to retrofit the torsional irregularity for stiff concrete shear wall structures to achieve the Enhanced Rehabilitation Objective of FEMA 356. Berton and Bolander (2005) proposed the displacement amplification device constructed using a combination of two rack and pinion mechanisms. From the labor tests, no discussion of the effectiveness of the damper was made. The amplification factors in both papers used the
2 Toggle brace damper (TBD) system geometric configuration

The revised lower TBD configuration proposed by McNamara and Huang (2000) is illustrated in Fig. 1. The damper in the TBD system is directly connected to the beam-column joint rather than to the beam, because the deformation of the beam due to damper force exerted on will reduce the effective damping contributed by the damper. Further, it will significantly affect the design of the floor beam.

The geometric relationship between the deformed elongated braces and the undeformed frame was established by Huang (2004) according to the horizontal and vertical direction geometric relationships below,

$$L_a(1 + \varepsilon_a) \cos(\alpha'_a) + L_b(1 + \varepsilon_b) \cos(\alpha'_b) = L + \Delta$$  \hspace{1cm} (1)

$$L_a(1 + \varepsilon_a) \sin(\alpha'_a) + L_b(1 + \varepsilon_b) \sin(\alpha'_b) = \tan(\alpha)L$$  \hspace{1cm} (2)

where $\Delta$ is the story drift, $L$ is the frame bay length and $H$ is the inter-story height. The ratio of the story height and frame bay length can be defined by $\alpha = \arctan(H/L)$. $L_a$ and $L_b$ are the length of lower and upper toggle braces. $\varepsilon_a$ and $\varepsilon_b$ are the strains of lower and upper brace members with elongation ($\varepsilon = \Delta L/L$). $\alpha_a$ and $\alpha_b$ are the horizontal angles of lower and upper braces after frame distortion with prime symbol. The equilibrium equations at the pivot joint can be written according to horizontal and vertical directions

$$EA_a \varepsilon_a \cos(\alpha'_a) - EA_b \varepsilon_b \cos(\alpha'_b) = F_d \cos(\alpha'_b)$$

$$-EA_a \varepsilon_a \sin(\alpha'_a) + EA_b \varepsilon_b \sin(\alpha'_b) = F_d \sin(\alpha'_b)$$

where the damper force ($F_d$) can be defined as the linear function of the velocity $F_d = c \nu$ and $c$ is the damper coefficient, $\nu$ is the relative velocity of the damper. $A_a$ and $A_b$ are the cross section areas of lower and upper brace members and $E$ is the modulus of elasticity of brace members. $\alpha'_b$ is the angle of the damper to the horizontal beam after the frame deformed. To simplify the equation, the simple geometric relationship is shown as

$$\frac{L_a(1 + \varepsilon_a)}{\sin(\alpha'_a)} = \frac{L}{\sin(\alpha'_a + \alpha'_b)}$$

Relative displacement ($\delta$) or the deformation of the damper is calculated by the difference of the damper displacement before and after the frame deformation

$$\delta = \sqrt{(L_a(1 + \varepsilon_a))^2 + L^2 - 2L_a(1 + \varepsilon_a)L \cos(\alpha'_a) - \sqrt{L_a^2 + L^2 - 2L_aL \cos(\alpha'_a)}}$$

where $\alpha_a$ and $\alpha_b$ are the horizontal angles of the lower brace and upper brace angle before the frame deformation. The relative velocity ($\nu$) of the damper can be calculated,

$$\frac{d\delta}{dt}(\Delta) = \frac{d\delta}{d\Delta} \frac{d\Delta}{dt}$$

Assume a steady harmonic excitation with radial frequency ($\omega$) is applied at the floor level, the relative velocity of the viscous damper in Eq. (7) can be simplified by $\nu = A_m(\Delta)\omega \Delta$, where the amplification factor $A_m(\Delta) = d\delta(\Delta)/d\Delta$. The damper forces $F_d = c A_m(\Delta)\omega \Delta$ for linear velocity related type damper are achieved.

For the given frame bay length ($L$), story height ($H$), the lengths of the lower and upper brace members ($L_a$, $L_b$, $E$).