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Structural Design of Double Skin Facades as Damping Devices for Tall Buildings

KYOUNG SUN MOON[a]

School of Architecture, Yale University, USA

Abstract

Double skin façade (DSF) systems are more effective environmental mediators than conventional single skin façade systems, and, due to this reason, their use for tall buildings has increased despite their higher initial costs. While many studies have been carried out on the environmental performance of the DSF system, research on its structural capability has been very rare. In tall buildings, excessive movement/acceleration can cause serious human discomfort problem. This paper investigates the potential of the DSF system as a structural motion control device in tall buildings. Two design strategies are investigated. In the first scheme, the connectors between the inner and outer skins of the DSF system is designed to have very low axial stiffness with a damping mechanism. Through this design, the dynamic motion of the primary building structure can be substantially reduced. However, the excessive vibration of the DSF outer skins is a serious design limitation. The second scheme is investigated to overcome this challenge. While DSF outer skins are fixed like those in conventional DSF systems, additional small masses are inserted into the DSF cavity and act as distributed tuned mass dampers (TMDs). Compared to the conventional TMD system, usually located in the occupiable space near the top of the building, the second scheme has the substantial benefit of saving this valuable occupiable space.

Keywords: Tall buildings, double skin facades, damping.

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1. INTRODUCTION

Tall buildings, which emerged in the late 19th century in the U.S, were a so-called "American Building Type", meaning that most important modern tall buildings were built in the U.S. Today, however, they are a worldwide architectural phenomenon. Many tall buildings have been built, especially in Asian and Middle Eastern countries, such as China, Korea, Japan, Malaysia, and the UAE. There has always been

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[a] Corresponding author: Email: kyoung.moon@yale.edu

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some skepticism regarding constructing tall buildings, especially since September 11, 2001. Moreover, today's severe global economic downturn has halted many tall building projects worldwide. Nonetheless, due to their significant economic benefits in dense urban land use, tall buildings are and will be built continuously all around the world.

Various façade systems, such as glass/metal curtain-walls, stone panels and precast concrete panels, are used to clad tall buildings. Generally, most façade systems are composed of several layers. In conventional cases, there are no substantial gaps between the facade layers. The double skin façade (DSF) system, which has a substantial cavity space between the façade layers, has been obtaining increased interest due to its energy efficiency by enhanced performance as an environmental mediator. While many studies have been carried out regarding environmental/energy aspects of the DSF system, no substantial research has been performed on the structural capability of the DSF system. In tall buildings, especially at their upper levels, excessive movement and acceleration can cause serious human discomfort problems. This paper investigates tall building dynamic motion control by introducing energy dissipating mechanisms within the DSF cavities.

2. DESIGN STRATEGIES

2.1. Low Axial Stiffness DSF Connectors

Two schemes have been studied producing promising outputs. The first one introduces low axial stiffness connectors in the DSF system. The concept is designing very flexible connectors between the DSF outer skin and the building's primary structure in the direction perpendicular to the building facades so that the transmissibility of the dynamic wind load can be reduced through them. The stiffness of the connectors in the other two directions parallel to the building facades is as large as that of other normal façade systems. As a result, the DSF outer skin moves back and forth, but the vibration of the primary structure, which is enclosed by the inner skin and contains occupants within it, is reduced significantly (Figure 1). Dynamic motion control for tall buildings is achieved through this mechanism. However, one challenge in this scheme is how to minimize the outer skin's vibration, which may involve serious constructional, visual and psychological concerns, without sacrificing effectiveness of the system.

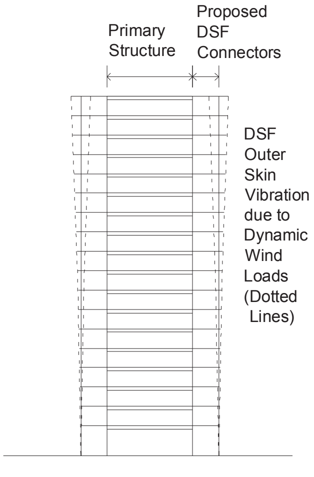

Figure 1: Concept diagram of low axial stiffness DSF connectors

2.2. Distributed Multiple Tuned Mass Dampers within DSF Cavities

The second scheme is investigated to overcome the challenges confronted in the first scheme. In this scheme, DSF outer skins are fixed like those in conventional DSF systems. While DSF outer skin mass itself attached to the low axial stiffness connectors is used as a counteracting inertia force generator in the first scheme, additional small masses are inserted into the DSF cavity in this scheme in order to act as distributed tuned mass dampers (TMDs), which effectively control tall building vibration under dynamic wind loads (Figure 2).

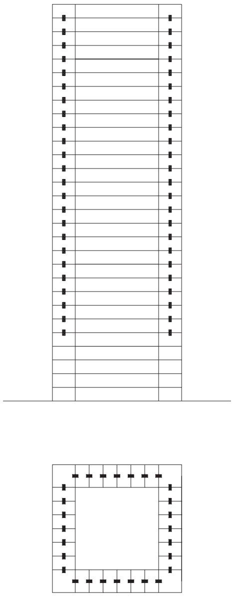

Figure 2: Concept diagram of distributed TMDs with the DSF cavities

3. LOW AXIAL STIFFNESS DOUBLE SKIN FACADE CONNECTORS

Wind loads are initially applied to the building facades and then transmitted to the structures. Considering this fact, a new approach to control tall building vibration through design integration between structures and DSFs is investigated in this section.

The idea is designing very flexible connectors between the DSF outer skin and the building's primary structure in the direction perpendicular to the building facades so that the transmissibility of the dynamic wind load can be reduced through them. In order to understand the behavioral characteristics of the proposed system clearly, the primary structure and the DSF outer skin are simplified and modeled as a two degrees of freedom system shown in Figure 3.

The system is composed of the primary mass (m), which corresponds to the primary building structure including the inner skin of the DSF system, and the secondary mass (md), which corresponds to the outer skin of the DSF system. The two masses are connected by low-axial-stiffness spring and damper components. Sinusoidal load, which represents simplified dynamic wind load, especially the vortex-shedding induced lock-in condition, is applied to the secondary mass to anticipate the system performance.

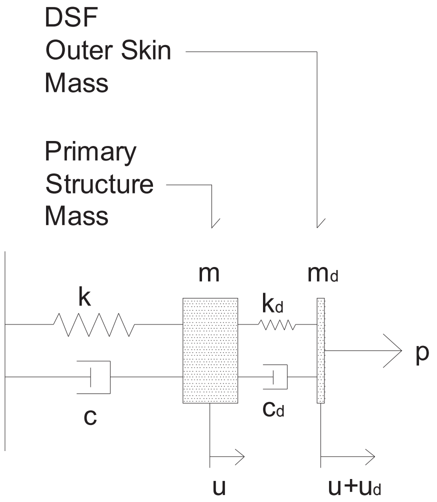

Figure 3: Simplified structural model of tall building vibration control using DSFs

Then, the solutions can be expressed as

$$\bar{u} = \frac{\hat{p}}{k} H e^{i\delta_1} \tag{1}$$

$$\bar{u}_d = \frac{\hat{p}}{k} H_d e^{i\delta_2} \tag{2}$$

Here, 'H' is the dynamic amplification factor of the primary structure, 'H_d' is that of the DSF outer skin, and δ's are the phase angles between the response and the excitation. The DSF outer skin mass is assumed to be 1% of the primary structure mass in this study. The primary structure's damping ratio is assumed to be 1%. With this 1% structural damping ratio, the maximum dynamic amplification factor, H, of the primary structure without the proposed DSF system is about 50 for a damped single degree of freedom system subjected to a harmonic load.

Figure 4 shows the simulation results of the case when the natural frequency of the DSF connector is half that of the primary structure. With this very low axial stiffness of the DSF connectors, the proposed system substantially reduces the transmissibility of the applied dynamic loads from the DSF outer skin to the primary structure as intended. The maximum dynamic amplification factors of the primary structure, H, occurring when the forcing frequency is almost the same as the primary structure frequency are about 18 and 22 when the connector damping ratio ξ_d = 20% and 40%, respectively, less than half of the maximum H value of 50 in the case without the proposed DSF system.

The results of this study show that dynamic motion of tall buildings can be substantially reduced. However, there exists a design challenge: the excessive motion of the DSF outer skins. The maximum dynamic amplification factor of the DSF outer skin, H_d, shown in Figure 4, is about 1000 and 500 with ξ_d = 20% and 40%, respectively, when the forcing frequency is almost the same as the DSF connector frequency. Even though these excessive movements can be reduced somewhat by increasing connector damping ratio and DSF outer skin mass ratio or by introducing an active control system, further research is required for the practical application of the system.

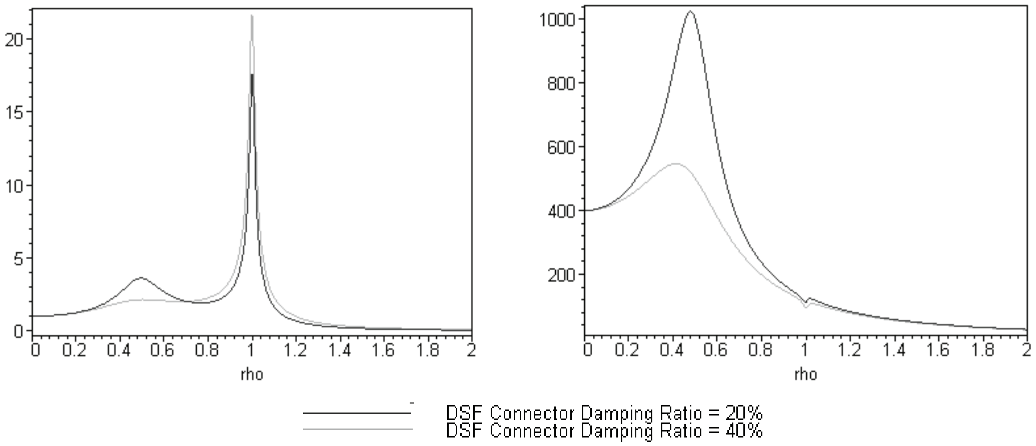

Figure 4: H (left) and Hd (right) plots

4. DISTRIBUTED MULTIPLE TUNED MASS DAMPERS WITHIN DSF CAVITIES

This section investigates the potential of vertically distributed multiple small TMDs within the DSF cavities, compared to the conventional systems composed of one or two large TMDs near the top of the building. The idea is to install relatively small multiple TMDs within the DSF cavities on multiple levels. By distributing multiple small TMDs over the building height, valuable space near the top can be saved for more desirable functions which can maximize the advantage of great views. In addition, by distributing multiple small TMDs horizontally on each level as well as vertically along the building height, greater reliability can be obtained in case some of them do not function properly or have some tuning errors. Further, not only the first mode but also higher mode responses can be effectively controlled if necessary.

A 240m tall 60-story structure in New York is modeled as a 60-degree-of-freedom system and comparatively studied with a conventional large TMD located at the top as well as with vertically distributed multiple TMDs within the DSF cavities. The building's plan dimension is 40m x 40m, story height is 4m typical, and mass density is 190 kg / cubic meter. The stiffness is configured for the building to have a fundamental period of about 6.3 seconds. This is achieved using quasi-parabolic stiffness with 2,200,000,000 N/m at the base. A relatively low inherent damping ratio of 0.5% regarding the first mode is assumed for the structure. This low inherent damping ratio results in the need for structural motion control not only for the first mode but also for the second mode response to meet the lateral displacement and acceleration design parameters. This paper focuses more on the study results of the first mode vibration control. A sinusoidal load, having peak value of 20,000 N and a period of about 6.3 seconds, is applied to each node of the 60-degree-of-freedom system model to simulate a vortex-shedding induced lock-in condition.

The original structure, which has an assumed inherent first mode damping ratio of 0.5%, does not meet the acceleration requirement of 0.02g and the maximum displacement parameter, a five hundredth of the building height, usually employed in practice. Studies suggest that 6.3% and 3.2% equivalent damping ratios are required to meet the both displacement and acceleration design parameters for the first and second mode resonance conditions respectively.

In conventional TMD design, a large single TMD with a modal mass ratio of 2.5% is to be located at the top of the structure and tuned to the first mode. By installing this TMD at the 60th node, both maximum displacement and acceleration meet the design requirements. However, when the TMD is tuned for the first mode and the building's second mode is primarily excited, the structure does not meet the acceleration criteria.

TMDs are now distributed from node 60 to node 31 for the fundamental mode control (Figure 5). In order to meet the design parameters, this configuration requires a total 67% more mass compared to the conventional system that has a single TMD at the 60th floor. However, compared to the conventional system, only 5.6% TMD mass is required for each level with this distribution. Furthermore, the total required TMD mass for each level represents multiple small TMDs manufactured possibly as DSF unit packages for easier installation. If the TMD mass for each level is distributed to 50 small TMDs, for example, each TMD mass is only about 0.1% of the conventional huge single TMD located near the top of the building.

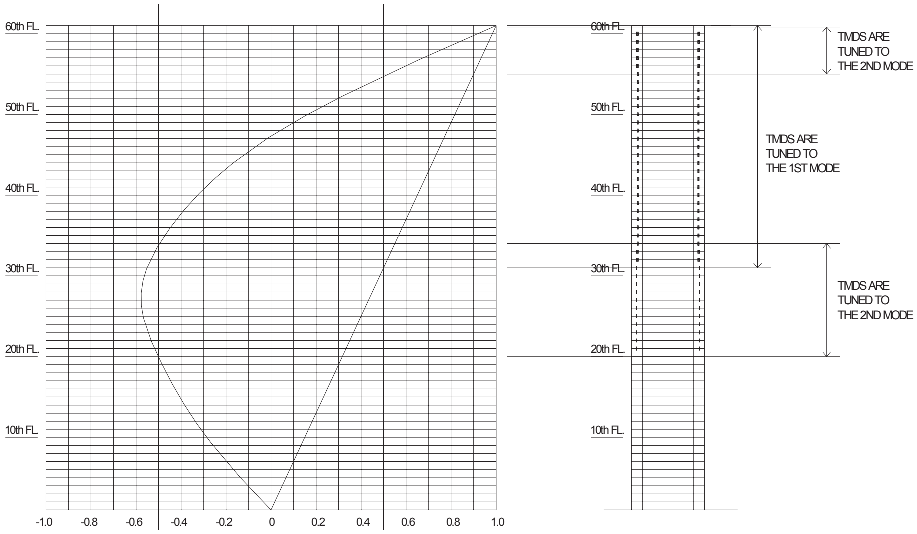

Figure 5: Example of vertically distributed multiple TMDs within the DSF cavities for the 60-story building based on its first and second mode shapes.

Figures 6 shows time history of the nodal and damper displacement at node 60 and the maximum inter-nodal displacement of TMDs installed from node 60 to node 31 and tuned to the first mode in the first mode resonance condition. Small TMDs can also be distributed according to the mode shapes for the second mode control. An example distribution is also shown in Figure 5. The analysis results for this case are omitted here.

In the distributed TMD system presented here, multiple small TMDs are installed within the DSF cavity space, the depth of which typically ranges from 0.3 to 1.5 meters. When the TMDs are designed to move in the direction perpendicular to the façade plane, the motion of TMDs should be accommodated within the depth of the DSF cavity, or the depth of the DSF cavity must be wide enough to allow TMD motion for optimal performance. One way to reduce TMD motion is to increase TMD damping ratio over optimal value. This strategy is examined using the distributed TMD model shown in Figure 5.

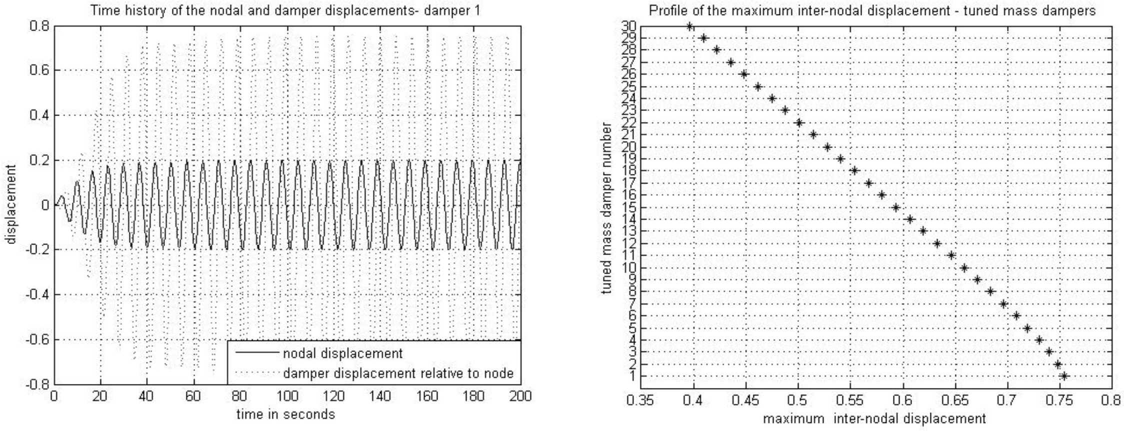

Figure 6: Time history of the nodal and damper displacement at node 60 (left) and profile of the maximum inter-nodal displacement of TMDs (right).

When the first mode of the primary structure is excited, the motions of the TMDs tuned to the first mode range from ± 0.4 to ± 0.75 meters, and the TMD damping ratios from 10.8% to 11.5% for optimal performance. Suppose that the motion of the TMDs should be limited to maximum ± 0.5 meters due to the limitation of the DSF cavity space. This limited motion can be achieved by increasing the TMD damping ratios ranging from 15.5% at the mid-height to 29.5% at the top, which is much higher than the previous case. Figure 7 shows the maximum inter-nodal displacement of TMDs installed from node 60 to node 31 with these increased damping ratios. In this case, however, the system's performance is reduced.

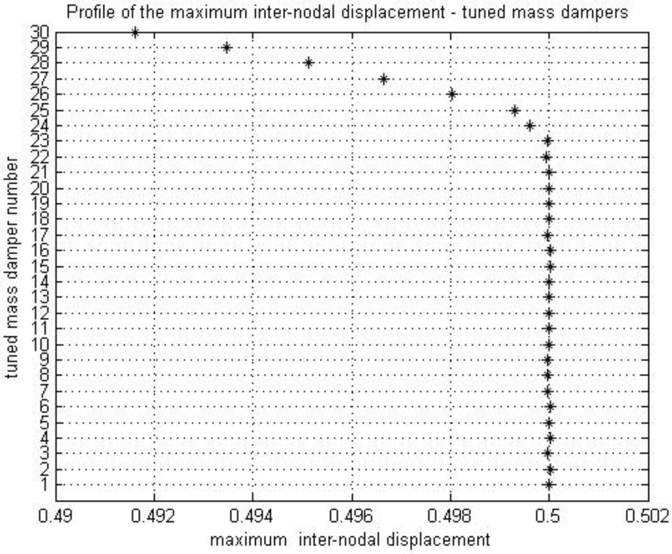

Figure 7. Profile of the maximum inter-nodal displacement of TMDs within the DSF cavities with increased TMD damping ratio to limit the TMD motion

5. CONCLUSIONS

Through the study of low axial stiffness DSF connectors and vertically distributed multiple TMDs within DSF cavities, new design strategies for solving the motion problem of tall buildings were introduced. Building envelopes have traditionally been designed as an environmental mediator in terms of their functional performance. With the development of new façade technologies, investigation on more integrated ways of design is crucial to produce better performing buildings. The presented design strategies require further studies for practical applications. More rigorous investigative work on these and other new technologies will eventually produce higher quality built environments.

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