Preliminary analysis of the Shanghai World Financial Center Incorporating Fluid Viscous Dampers

A.S. Gilani, PhD. PE., and H.K Miyamoto, MS. SE.
Marr, Shaffer, and Miyamoto Inc.
Sacramento CA, USA

Objectives, scope, and limitations

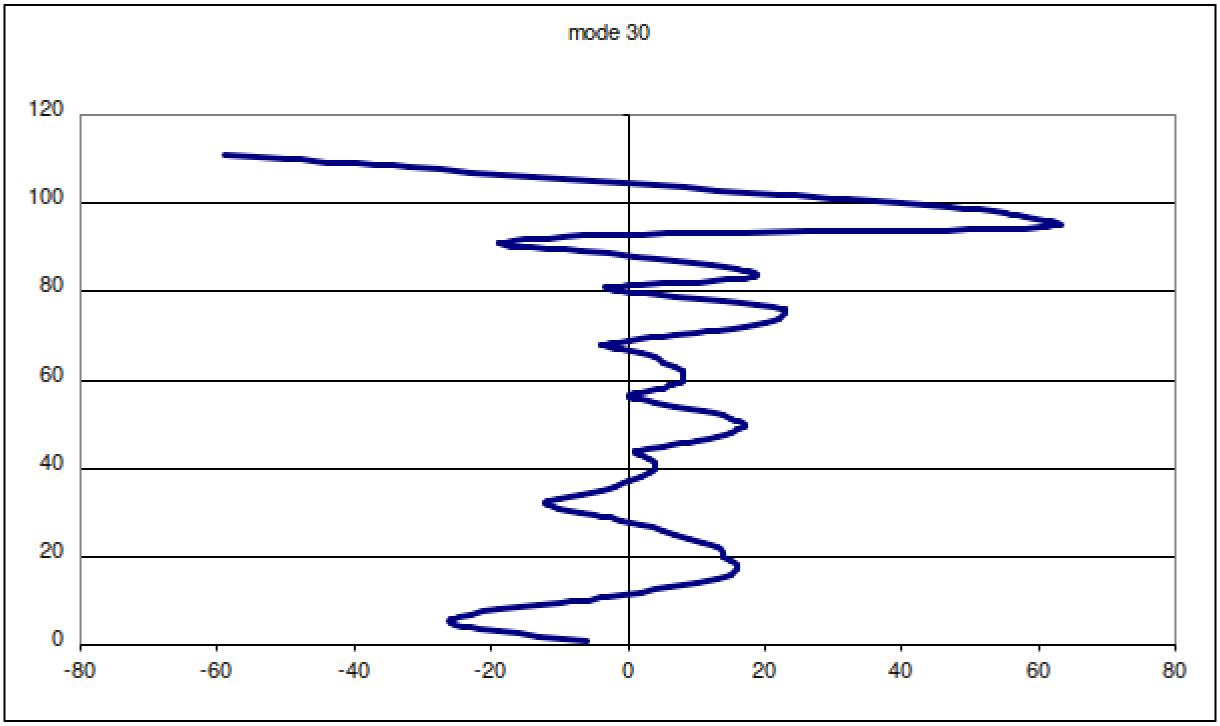
The Shanghai World Financial Center (WFC) is a 106- story building that is scheduled for construction in the near future. The structure, designed by KFP Associates, consists of office buildings, and a 10-story hotel segment located between floors 78 and 87. The structure is designed to be robust in resisting lateral loading due to wind and seismic effects. In addition, of concern to the owner and engineers is the level of perceptible vibrations for the future hotel occupants. The International Organization of Standardization (ISO) has recommended a general accepted criterion of 15 mg floor acceleration for residential occupancy.. It is usually not cost-effective to reach this limitation without incorporating energy dissipation devices. Such hardware has been successfully incorporated in the design of many high-rise buildings [1 and 3]. For the purpose of studies reported herein, the authors propose to use fluid viscous dampers (FVD) to achieve the floor acceleration limits. Such an approach has been shown to be very effective and economical for both high-rise buildings and many other structures [2]. In addition, since the forces in VFD are proportional to velocity and not displacement, (i) they do not amplify the axial force in the adjacent vertical members, and (ii) they will not significantly affect the stiffness and modal properties of the structure [4].

This report presents the results of the preliminary analysis of the structure including addition of FVD. It is noted that the current study has many significant limitations. Most importantly, no wind tunnel testing of the scaled model of the structure has been completed to date. As such, the assumed loading for the analytical studies is only at best an approximation. Furthermore, the effect of adjacent tall structure on the dynamic loading is not included. Typically nearby buildings have a significant effect in re-shaping the angle and direction of wind attach and might introduce additional aerodynamic: for example, fluttering or shedding of vortices [5]. As a result, the objective of this study has not been to size the FVD or to obtain exact effect of inclusion of the devices on the building response. The more refined analysis will be conducted at a later time. Rather, it is intended to show that the concept of using FVD is sound and that the devices can be effectively used as a mitigation strategy to limit the floor accelerations. The owner generously provided the ETABS model used in this study and only minor modifications were undertaken to the model. The basic geometry, material properties, sections, and structural systems were unchanged.

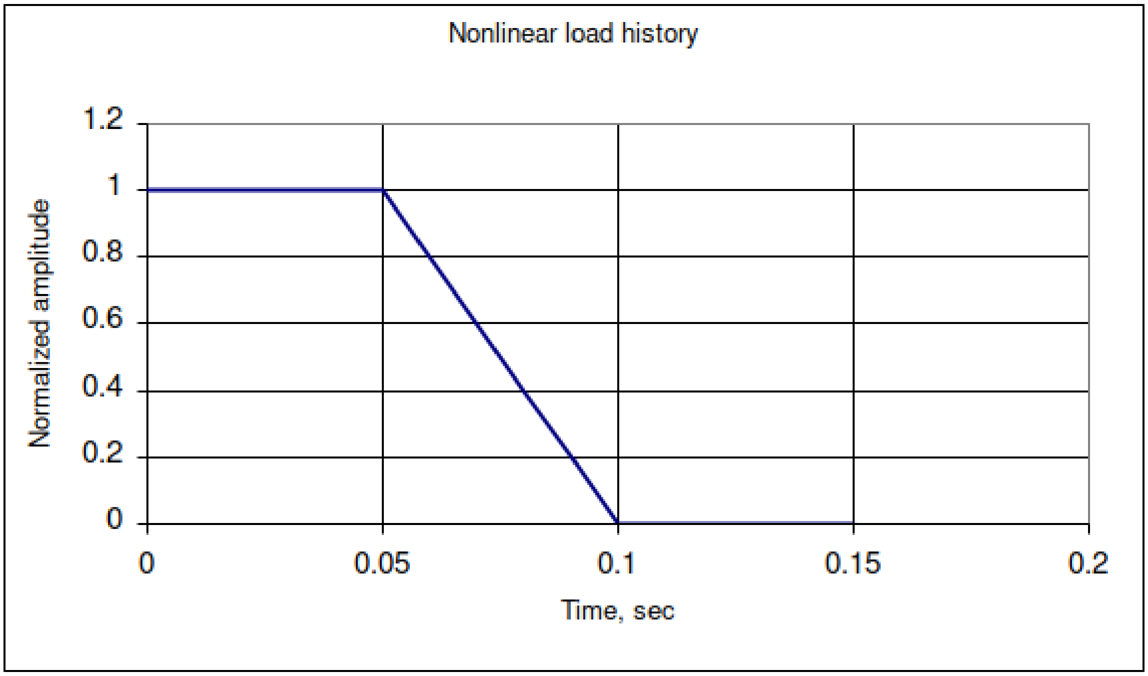
Overview

Typically the noise vibrations at the upper stories are caused by contribution from the higher modes of high-rise buildings. In order to mitigate such effects, modal analysis was expanded to include the first 30 Ritz vectors of the building rather than the first 15 modes included in the original model. It was noted that the last three modes (i.e., modes 28 through 30) had modal frequencies of 6.5 to 7.5 Hz In addition, these modes had relatively large modal mass participation factors for the principal (x- and y-) directions of the building. As such, these modes excited the building along the longitudinal and transverse directions; their high frequencies would likely cause noticeable accelerations even for low levels of inter-story displacement and are likely to have significant effect on the higher stories in the building. For these reasons, these modes would be desirable for investigating the effect of supplemental dampers in reducing floor accelerations. For the purpose of studies presented here mode number 30 was selected for further investigation. The modal amplitude and the displaced shape for this mode are shown below. The modal frequency for this mode is 7.5 Hz. Note that the modal amplitudes are normalized by the program ETABS in such a way that the effective modal mass equal unity. In the graph below, the x-ordinate designates the amplitude of motion along the transverse direction of the building, whereas, the y-ordinates are the story numbers. Note that the largest components of modal displacements occur near the top of the building. As such, it is proposed that the dampers be located between floors 68 and 98.

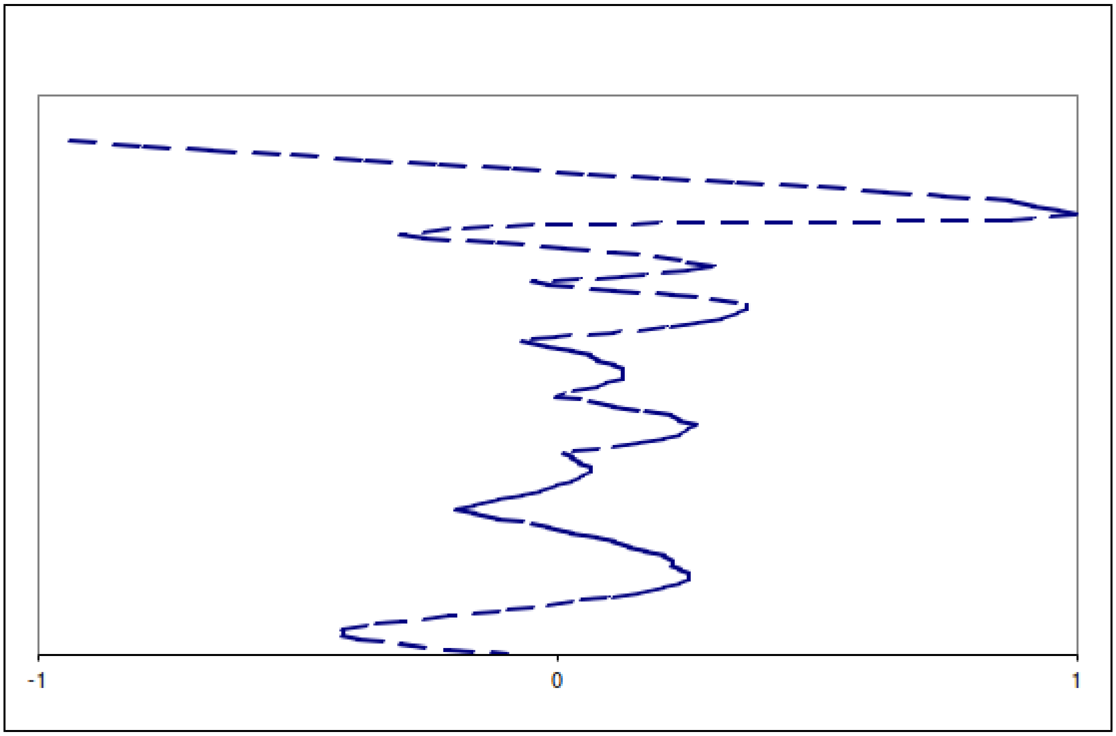
Loading history



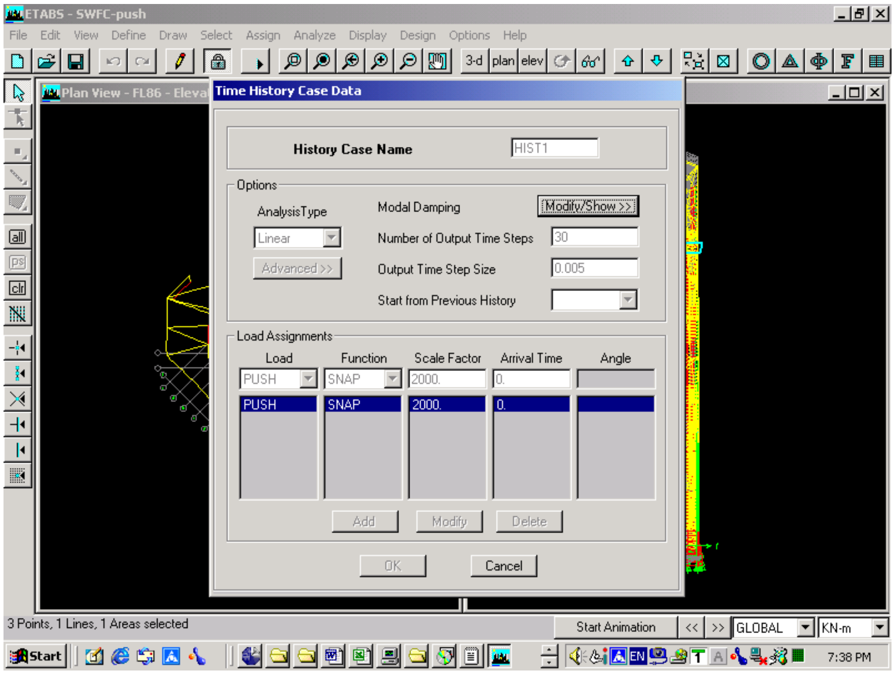
A loading history compatible with the 30th mode was developed. The nonlinear history was used to simulate the effect of snap back testing. The loading consisted of a constant segment followed by a descending branch.



The spatial distribution of the loading matched the 30th mode shape. The normalized loading distribution is shown below.



The amplitude of the loading function was selected in such a way to cause a maximum drift ration of 0.3 percent. For the purpose of this study, a uniform story height of 4.2 m (that is the typical height for most of the floors) was assumed in computing the desired loading amplitude. This maximum drift occurred between the roof and 106th floor. For the hotel floors the drift was approximately one half of the target value of the highest floor. The 0.3 percent value was selected to match the drift value for which the building has been designed when subject to wind loading. The amplitude of the loading function was then adjusted, as seen in the picture below, to match the desired drift level.



History Case Name: HIST1

Options

Analysis Type: Linear

Number of Output Time Steps: 30

Output Time Step Size: 0.005

Start from Previous History:

Load Assignments

Load	Function	Scale Factor	Arrival Time	Angle
PUSH	SNAP	2000.	0.	
PUSH	SNAP	2000.	0.	

3 Points, 1 Lines, 1 Areas selected

For each mode, a modal damping of 1 percent of critical was specified. Since the spatial distribution of the applied loading matched the 30th mode shape, it was expected that the response would be primarily in this mode since the loading is mass orthogonal to all the other modes.

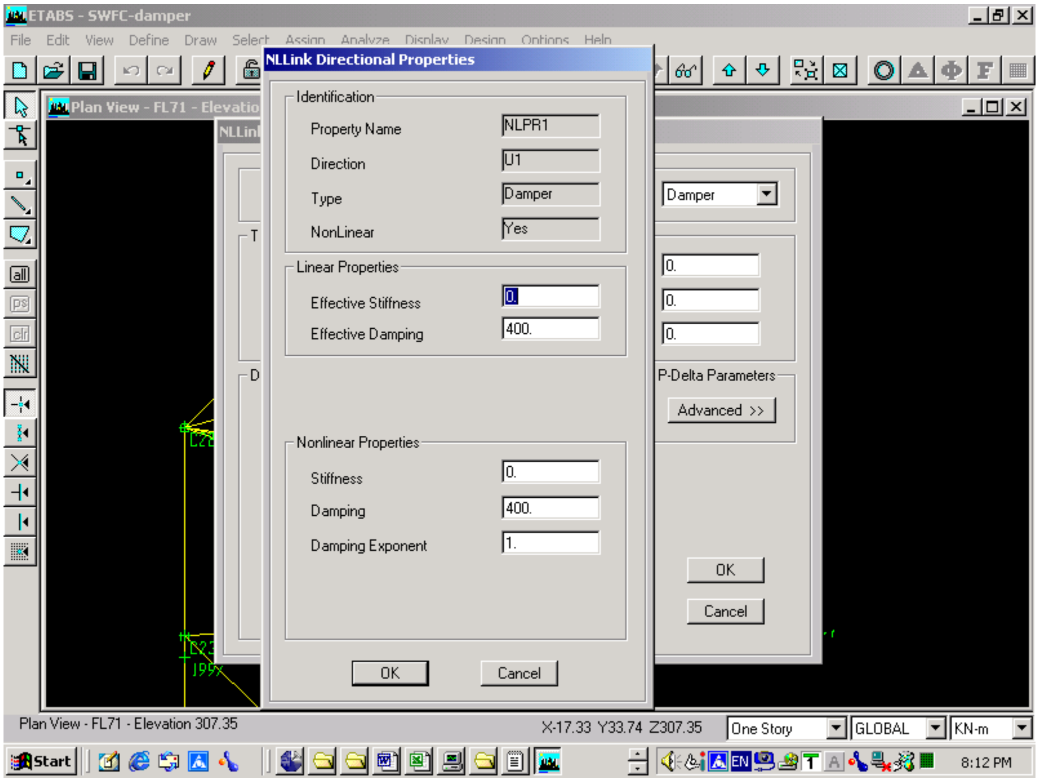
Analysis results

The resulting floor displacements for the 79th to 87th floor (the proposed hotel floors) are shown below. Note that the displacement responses of all floors are in-phase and the drift ratios are about approximately 0.14 percent.

Story	UX, m	UY, m	Elev.	drift x	drift y
FL87	0.084	0.102	381.15	%	%
				0.02	0.05
FL86	0.083	0.1	376.95		
				0.05	0.08
FL85	0.081	0.096	372.75		
				0.09	0.11
FL84	0.077	0.092	368.55		
				0.12	0.14
FL83	0.072	0.086	364.35		
				0.14	0.16
FL82	0.066	0.079	360.15		
				0.14	0.15
FL81	0.057	0.069	353.85		
				0.14	0.15
FL80	0.048	0.06	347.55		
				0.13	0.13
FL79	0.040	0.052	341.25		

Supplementary dampers

In order to improve (reduce) the response of the hotel-occupied floors to lateral wind loading, it is proposed that supplementary energy dissipation devices (dampers) be installed between the 68 and 88th floors of the structure in both the x- and y- directions. To facilitate installment of devices, it is proposed that the dampers be placed along the inner core of the building. In design it is assumed that the modal properties and stiffness of the structure are unchanged after the addition of dampers. As such, the damper stiffness was assumed to be small and negligible. For the preliminary studies described here, it is proposed that the dampers have an equivalent modal damping of 4% of critical. This damping ratio provides a conservative estimate of the anticipated energy dissipation properties of the FVDs. It is further assumed that stiffness-proportional damping is assumed. Then the damping to be specified for the dampers is computed from: $C=\frac{2K\xi}{\omega}$. In this equation, $\omega=2\pi$ f and f is the modal frequency or 7.5 Hz. K designates the lateral stiffness of the floors along which the dampers are situated. Since the dampers are inclined diagonally at an angle θ to the horizontal, a factor of $Cos^2\theta$ has to be applied to the story stiffness of the building to obtain the property along the longitudinal axis of the damper. The story stiffness of the floors can be computed from the nonlinear time history analysis of the previous section of the report. Since a set of two dampers are used in each direction, K=0 and C=200 was specified for each nonlinear FVD in each direction.



NLLink Directional Properties

Identification

Property Name NLPR1

Direction U1

Type Damper

NonLinear Yes

Linear Properties

Effective Stiffness 0.

Effective Damping 400.

Nonlinear Properties

Stiffness 0.

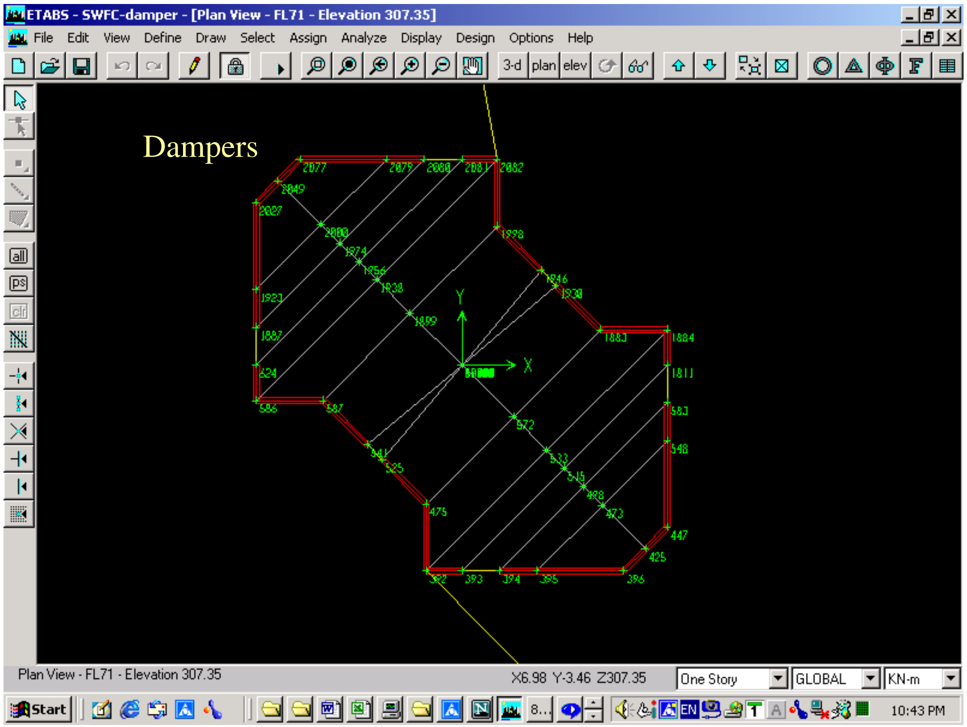
Damping 400.

Damping Exponent 1.

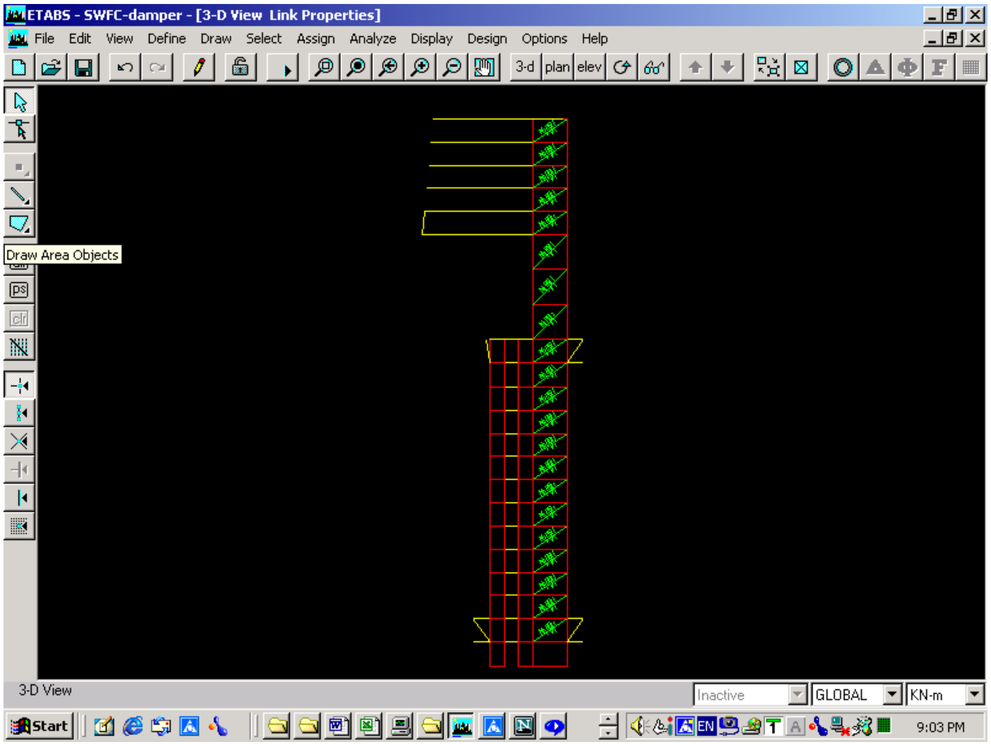
OK Cancel

Plan View - FL71 - Elevation 307.35 X-17.33 Y33.74 Z307.35 One Story GLOBAL KN-m

Dampers were placed along the four sides of the inner core between the 68th and 88th floor as shown in the figure below. Please note that in this view only a portion of the building cross section around the core is shown. Although the hotel floors only extend from the 79th to 87th floor, it is expected that the response of the first ten or so floors will affect the acceleration of the hotel floors. Similarly, in the next phase of the analysis, additional dampers will be situated at floors above the 87th level. This spatial arrangement will attempt to mitigate the large modal amplitudes of the upper stories due to the 30th mode.

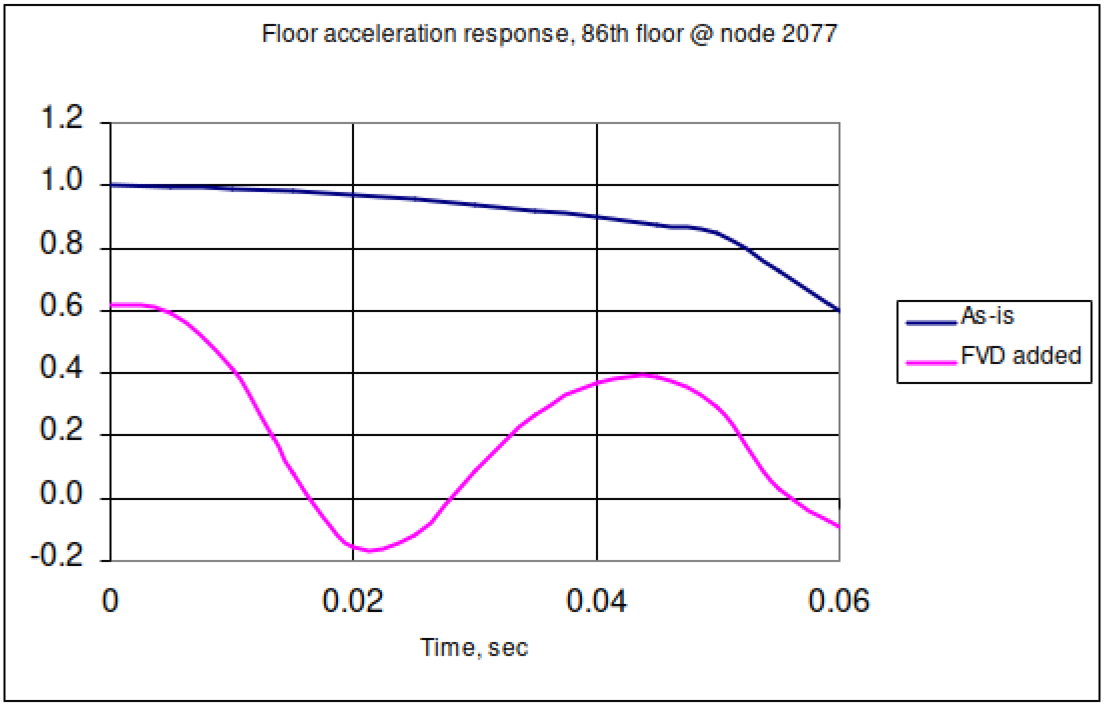


Distribution of FVD along the perimeter of the building core

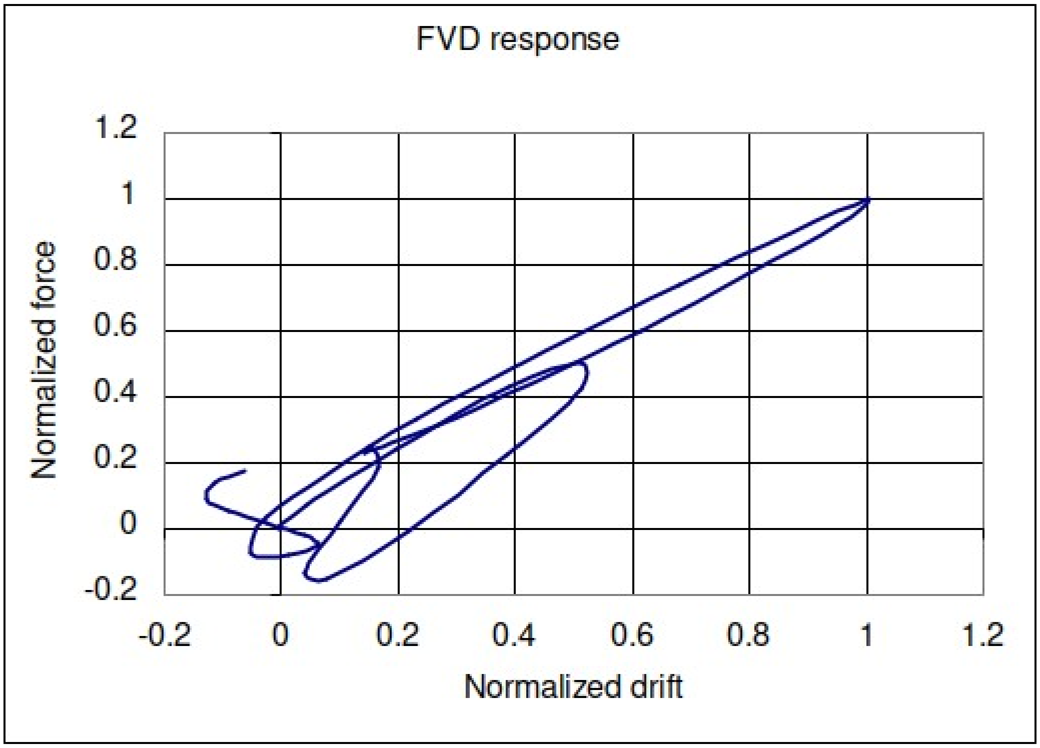


Distribution of FVD between floors 68 and 87 (One of four is shown)

To evaluate the effectiveness of the adding FVD to the structure, floor acceleration response for a typical node of the 86th floor was studied. A 0.06-second initial segment of the acceleration response is shown in the figure below. The data was normalized with respect to the maximum computed response of the undamped structure for comparison purposes. It is noted that the addition of the VFD devices has reduced the floor acceleration by approximately 40 percent. Similar reductions in accelerations were computed for other floors as well. Note that the addition of the damper has introduced a high-frequency component to the response as indicated by the oscillations in the response of the unit with the FVD. This local mode is neglected as its frequency is much larger than the building frequency and is likely a consequence of the specific type of loading that is used in this study.



To further examine the response of the FVD devices, the behavior of a damper between floors 86 and 87 was investigated. The force response for the damper is directly available from the ETABS program. The displacement output was computed by subtracting the output displacement of the node at the bottom of the device from the output displacement at the top of the device. The computed displacement was then factored by $Cos\,\theta$ to obtain deformation along the axis of the damper. Finally both the force and deformation values were normalized to obtain typical response for any of the dampers. The force-deformation plot of the typical damper is shown below. The hysteretic nature of response resulting in the energy-dissipation is noted. Note that story drifts of 0.14 percent, a value obtained from the analysis of the building without the FVDs, translates to a displacement of approximately 4 mm along the axis of the FVD device. The addition of the damping devices further reduces this value. As such, in practice, motion amplification devices, such as toggle arrangement, will be designed and employed to amplify the damper deformations and engage the FVDs [2]. The design of the toggle brace dampers will be addressed in the next phase of the analysis.



Proposed FVD devices.
It is proposed that 120 FVD devices be placed along the four orthogonal sides of the perimeter of the building core between floors 68 and 98. The actual size and stroke of the proposed dampers can not be determined with certainty at this time due to the lack of the actual loading function, However, past experience in the wind-control of high rise buildings for the purpose of reducing floor accelerations have utilized 500-750 kN dampers having a stroke of ± 10 to ± 50 mm. Similar type of dampers are proposed for the WFC.

Summary and conclusions
To examine the effectiveness of the FVDs in reducing the undesirable floor accelerations of the Shanghai WFC, FVD were added to the analytical model of the WFC. The purpose of this phase of analysis was conceptual and significant assumptions were made regarding the critical modes to be suppressed, the input wind loading, and the FVD properties. Nonetheless, the prepared model provided useful insights to the expected response of the structure. The analytical models with and without FVD were subjected to nonlinear loading whose spatial distribution approximately matched the critical mode of the building and whose amplitude approximately produced a maximum story drift of 0.3 percent. It was noted that the floor accelerations were reduced when FVD were incorporated in the model: it is clear that FVD are effective in limiting floor accelerations. It is noted that to excite FVD at such small level of inter-story drift, it is likely that displacement amplification setups such as toggle bracing would be required. Furthermore, to better utilize FVD devices, it is proposed that they extend approximately ten stories above and ten stories below the proposed hotel segment of the high-rise structure. These issues will be studied in more detail in the next phase of the analysis.

References

1. Klembczyk A. Structural control of high-rise building using a tuned mass with integral hermetically sealed, frictionless hydraulic dampers. 2002
2. Miyamoto H.K., and Scholl, R.E.: Performance based design of steel pyramid using viscous dampers. 1996
3. McNamara, R.J, Huang, C.D., and Wan V.: Viscous-Damper with motion amplification device for high rise building applications. 2002
4. Whittaker AA.S.: Passive control-analysis and design issues. 1995
5. Simiu, E. and Scanlan, R.H. : Wind effects on structures. 1997