

INFLUENCE OF HIGHER MODES ON THE DYNAMIC RESPONSE OF IRREGULAR AND REGULAR TALL BUILDINGS

Seymour M. J. Spence^{*}, Massimiliano Giofrè[†] and Vittorio Gusella[†]

^{*} CRIACIV/Department of Civil and Environmental Engineering (DICeA)
University of Florence, via S. Marta, 3, 50139 Firenze, Italy
e-mail: spence@strutture.unipg.it (contact author)

[†] CRIACIV/Department of Civil and Environmental Engineering (DICA)
University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy
e-mails: mami@unipg.it, guse@unipg.it

Keywords: Tall Buildings, Structural Response, Time Domain Analysis, Modal Analysis.

ABSTRACT: In the present paper the effect of higher mode truncation on the response of tall buildings with both regular and irregular geometric shapes in elevation is investigated. Wind tunnel tests using Synchronous Multi-Pressure Sensing System (SMPSS) measurements on two tall buildings, one of irregular geometry and another of regular geometry in elevation, are performed. These measurements were carried out for wind directions covering 360° with 10° increments. The importance of considering higher modes and wind direction when estimating the dynamic response of irregular tall buildings possessing complex 3D modes shapes is investigated and compared to the case of tall buildings with a regular geometric profiles and uncoupled mode shapes.

1 INTRODUCTION

Recent trends in tall building design have seen an ever increasing number of proposals for buildings with geometrically irregular shapes. However the methods adopted for estimating their response are generally based on theories that were developed considering buildings with regular geometric profiles and uncoupled fundamental mode shapes. In particular, in estimating the dynamic response it is generally deemed sufficient to consider only the first three modes of vibration as any errors committed are generally considered to be known and acceptable [1,2,3]. However these studies are all concerned with alongwind and acrosswind response of regular tall buildings with rectangular cross sections impinged by wind blowing normal to a building face. In the case of irregular tall building, the presence of non-coincident centers of mass and stiffness lead to complex 3D mode shapes, which combined with an irregular geometric profile, can lead to a far greater sensitivity to wind direction. Indeed for irregular tall buildings it is often difficult and meaningless to distinguish between alongwind and acrosswind response.

In this paper the errors committed by mode truncation on the estimation of the response of irregular tall buildings is investigated and compared to that seen for a regular tall building.

2 ANALYSIS FRAMEWORK

Wind tunnel tests on two rigid 1:500 scale models, one of the Bank of China building and the other, a regular tall building of the same roof height and square footprint, were carried out at the Boundary layer wind tunnel of the CRIACIV (Inter-university Research centre on Buildings Aerodynamics and Wind Engineering) in Prato, Italy. Synchronous Multi-Pressure Sensing Systems (SMPSS) measurements were taken using 126 carefully positioned pressure taps located over the models various surfaces. These measurements were repeated with 10° increments from 0 to 360° for a total of 36 wind directions in the case of the Bank of China building while for the regular building only increments from 0 to 90° were considered due to the buildings symmetry. A sampling frequency of 250Hz was adopted and 30s of data was recorded for each wind direction.

Equivalent dynamic systems with 3 degrees of freedom per floor were used to model the response of the buildings. In the case of the Bank of China Building the system was carefully calibrated so as to attain the same 3D fundamental mode shapes and associated frequencies as experimentally reported in literature for the actual building [4]. The regular building was modeled with the same floor densities and fundamental frequencies as the Bank of China Building but with uncoupled mode shapes and so with mass and elastic centers placed on a single vertical axis. The response analysis was carried out in the time domain with direct integration of the generalized equations of motion.

3 RESULTS AND DISCUSSION

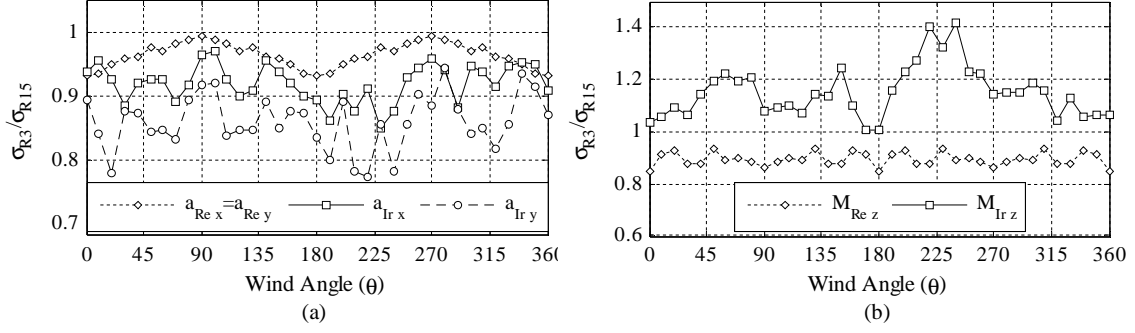
3.1 Effects of higher mode truncation

In order to investigate the effects of mode truncation on the dynamic response the following parameter was considered:

$$s_{R3}(q)/s_{R15}(q) \quad (1)$$

where $s_{R3}(q)$ is the Root Mean Square (RMS) of a particular response component R considering only the contribution of the first three modes for a wind direction θ while $s_{R15}(q)$ is its counterpart considering the contribution of 15 modes. This was chosen as the total response is considered to be adequately estimated by the first 15 modes of vibrations. The validity of this conclusion lays in the fact that the 15th vibration mode has a natural frequency of 2.2413Hz which is greater than 2Hz which is generally accepted as the upper limit after which the energy content of wind storms practically ceases.

The results of this study clearly show the importance of considering the contribution of higher modes to the dynamic response of tall buildings with an irregular geometric profile. Indeed, as can be seen in Fig. (1) for the top floor acceleration and base torque, the effects of mode truncation is far greater in the case of an irregular geometric profile (Ir) compared to a regular profile (Re). In the particular case of the top floor acceleration, errors of up to 23% can be seen which is over three times what is observed for the regular building. Similar results to those shown in Fig (1) are observed for all important response components. The unstable nature of the irregular building response components demonstrates the sensitivity of the effects of mode truncation to wind direction. Fig. (2) shows the variation with height of the maximum and minimum of $s_{R3}(q)/s_{R15}(q)$ for all wind directions for a component of the translational acceleration, bending moment and torque. In general the difference between the responses of the two buildings tends to decrease towards the base of the structures as can be seen for the translational acceleration in Fig. (2a), and bending moment in Fig. (2b).


 Figure 1: Dependency of $s_{R3}(q)/s_{R15}(q)$ on wind direction: (a) top floor acceleration (b) base torque.

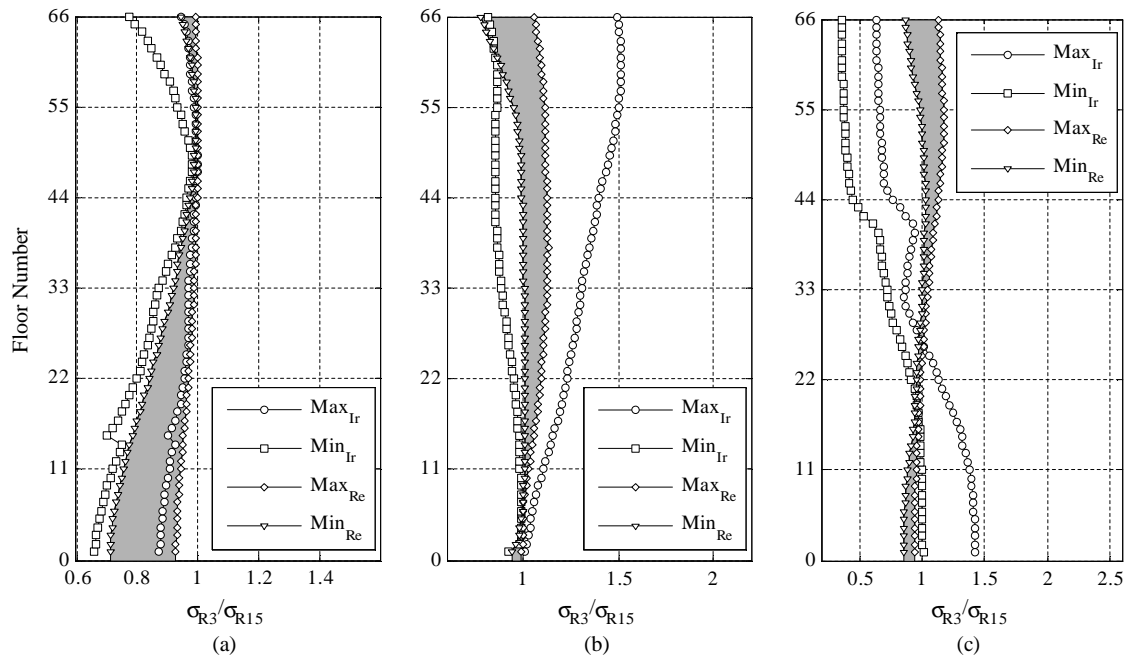
However, this is not seen for the torsion where far greater errors can be observed for all floors Fig. (2c). This phenomena is also seen for the rotational response. Indeed the sensitivity of the torsional response to mode truncation in the case of irregular geometry is significant where errors of up to 40% can be seen at the base and up to 70% towards the top. This is far greater than that seen for the regular building. It is also interesting to note that mode truncation will not necessarily underestimate a response component. The errors are clearly seen to depend on wind direction and floor location.

3.2 Influence of the background response

To study the importance of the background dynamic response the following parameter was considered:

$$\sqrt{s_{Rr3}^2(q) + s_{Rb15}^2(q)} / s_{R15}(q) \quad (2)$$

where $s_{Rr3}(q)$ is the RMS of a particular response component R considering only the resonant


 Figure 2: Extremes of $s_{R3}(q)/s_{R15}(q)$ on height: (a) translational acceleration (b) bending moment (c) torque.

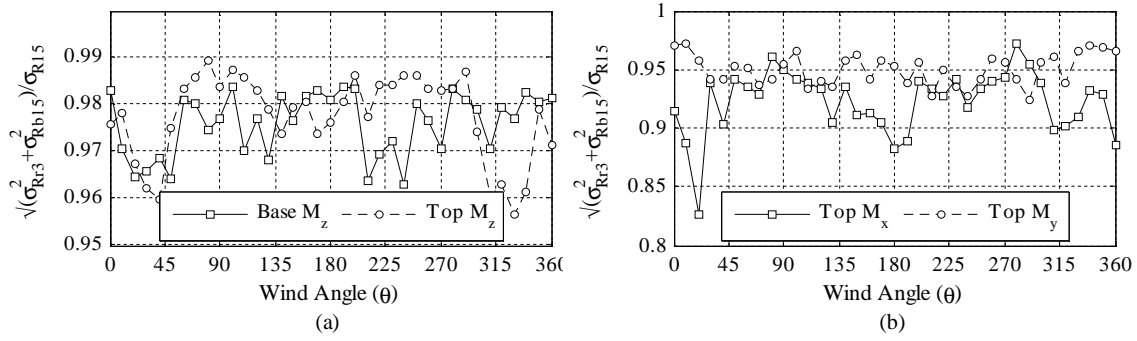


Figure 3: Dependency of $\sqrt{(s_{Rr3}^2(q) + s_{Rb15}^2(q))} / s_{R15}(q)$ on wind direction: (a) torque (b) bending moments.

response of the first three modes for a wind direction θ while $s_{Rb15}(q)$ is the background response considering the contribution of first 15 modes of vibration. The influence of the background response is significant. Indeed by considering a full background representation the errors in the estimation of the dynamic response are dramatically decreased for all response components except the acceleration which has a negligible background contribution. Examples of this behavior are shown in Fig. (3) for the top floor bending moments and top floor and base torque. As can be seen the errors are generally reduced to within 10% of the full response considering all 15 modes of vibration.

4 CONCLUSIONS

This study clearly demonstrated the susceptibility of irregular tall buildings to the influence of higher modes on their response. In particular the top floor acceleration was seen to be very sensitive where errors were tripled compared to the regular building. Also the importance of wind directionality on the errors committed by mode truncation was seen for all response components with the possible exception of the base bending moments. The important role played by the correlation of the modal response was observed by the presence of both over and underestimates sometimes accruing for the same response component by simply varying the incident wind direction or the floor at which the response was being calculated. The particular sensitivity of the torsional response to higher modes was significant with errors of up to 70% in the estimation of the top floor torque. The contribution of the higher modes seems to affect mainly the background response for all components, except the acceleration. In these cases, the error associated with resonant response truncation is found to be confined to within about 10% of the full response.

REFERENCES

- [1] E. Simiu, Equivalent static wind loads for tall building design. *ASCE Journal of Structural Division*, **104**, 719-737, 1976.
- [2] A. Kareem. Wind-excited response of buildings in higher modes. *ASCE Journal of Structural Division*, **107**, 701-706, 1981.
- [3] G. Huang, X. Chen. Wind loads effects and equivalent static wind loads of tall buildings based on synchronous pressure measurements. *Engineering Structures*, **29**, 2641-2653, 2007.
- [4] Q.S. Li, K. Yang, C.K. Wong, A.P. Jeary. The effect of amplitude-dependent damping on wind-induced vibrations of a super tall building. *Journal of Wind Engineering and Industrial Aerodynamics*, **91**, 1175-1198, 2003.