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Wind Load Study on High-Rise Buildings with multi-directional Mode Shapes in Complex Terrain

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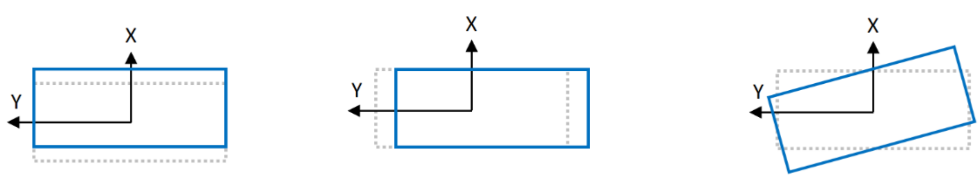
SUMMARY:
Structural response of high-rise buildings to wind loading is for the most part described by their reaction to the mean load as static response and to the fluctuating loading process by dynamic response. The latter is usually reflected by the motion of the building in its three fundamental modes, i.e. bending along the principal axes in the x-y ground plane and torsion around their vertical axis. With a symmetrical building system, these modes are uniaxial and associated to the symmetry axes of the building's façade footprint. For buildings with an eccentric structural system, the modal motion becomes more complex and modes may activate both translational and rotational motion. In this sense, a single fundamental mode is described by sub-modes relating to the geometric footprint usually with one sub-mode dominating the response process. This paper discusses the implications to derive floor-by-floor wind loading for structural design on the example of the Hassan Centenary Terraces Complex at the base of the Rock of Gibraltar. This complex consists of 6 high-rise building between 67 and 100m tall with eccentric structural systems. Apart from the particularity of the dynamic response, the consideration of the extreme topography at the Rock of Gibraltar is presented.

Keywords: High-rise buildings, eccentric modal motion, complex terrain

1. INTRODUCTION

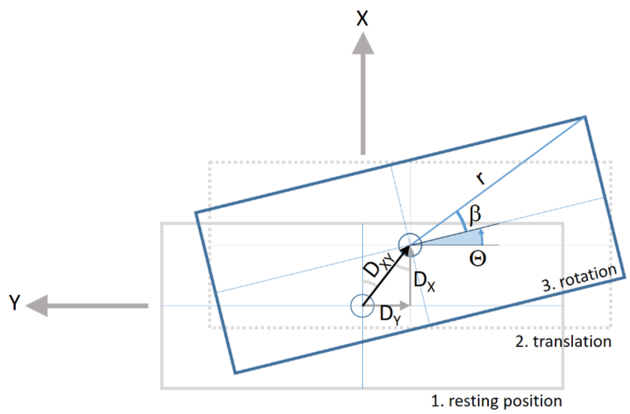
Most tall buildings exhibit mode shapes along the principal axes of the structure rigidity resulting in typical modal motions as illustrated in Figure 1. Such clear distinction and association of modal response to main structural coordinate system is usually the result of a symmetric arrangement of the lateral load carrying system.



1st Mode: Sway in X-direction | 2nd Mode: Sway in Y-direction | 3rd Mode: Torsion around vertical axis

Figure 1. Orientation of mono-directional mode shapes along principal axes of horizontal structural rigidity (no eccentricity).

In case of an asymmetric distribution of the lateral stiffening system, a main or dominant vibration can be accompanied with smaller contributions of motion in the off-directions. This means, that for the calculation of the modal loading, these extra contributions have to be treated in the same manner as contributions in a mono-directional shape. Figure 2 (left) illustrates the principle of a multi-directional mode shape of a building with unsymmetrical lateral stiffness distribution.



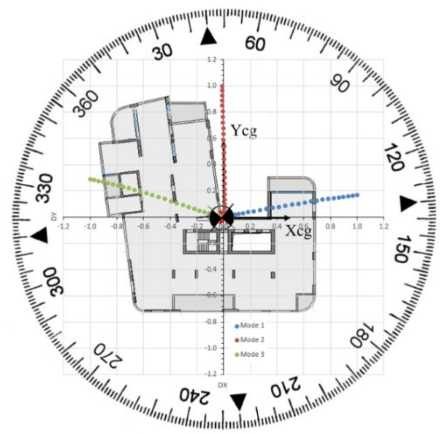


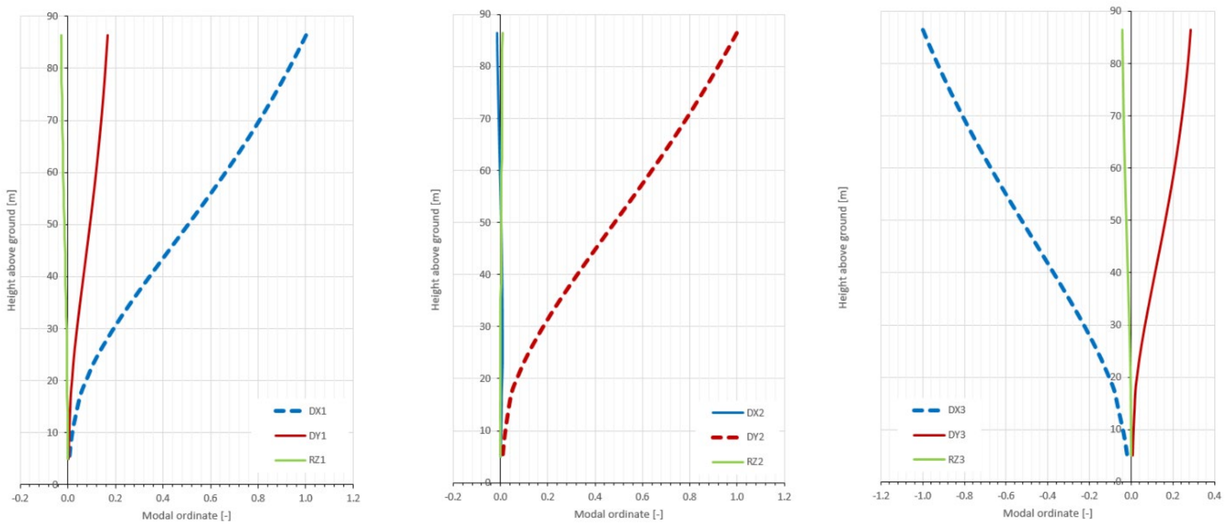
Figure 2. *Left:* illustration of different directional components of a single mode shape. *Right:* Mode shapes seen from above. The translational motion of the first three fundamental mode shapes is shown by plotting the components DX and DY pairwise over height for each mode (mode 1: blue; mode 2: red; mode 3: green).

The treatment of multi-directional mode shapes for the derivation of wind loads for structural design from wind tunnel testing is in the following described in the example of the Hassan Centenary Terraces Complex in Gibraltar (Figure 3).

Figure 3. Rendering of the Hassan Centenary Terraces Complex in Gibraltar (left picture: Copyright HM Government of Gibraltar). The buildings are numbered from the left to the right. To the right, the overall location and orientation of the development complex is shown in a rendering from an online news article in La Information published on 12.07.2019.

2. DYNAMIC PROPERTIES

The development complex consists of two types of buildings: the first comprises building 1 to 4, characterised by a relative slender design and more regular mono-directional mode shapes. The second type comprises building 5 and 6, which are lower than the other four, but exhibit a distinct multi-directional behaviour of the first three vibration modes.



Mode 1: 0.35Hz Mode 2: 0.39Hz Mode 3: 0.54Hz

Figure 4. Components DX, DY and RZ of the given three modes of building 6, indicating the dominant component by a dashed line. For presentation of modes in x-y plane (see Figure 3, right)

In case of a multi-directional mode shape as given in this case, the overall modal motion of the structure is calculated in its components. For that, we look at each component as an individual load-response case, where the response magnitude depends on the load magnitude. The modal structural parameters (mass, stiffness and damping), since evaluated individually for each component, are determined with sub-modal component shapes scaled to unity of the dominating component (Figure 4). Consequential, these mass and stiffness are referred to as individual sub-modal parameters. For calculating the global modal mass and the global modal loading, the global mode shapes are used consistently scaled for all directional components. Here, only the dominant component reaches unity.

3. RESPONSE ANALYSIS

The structural dynamic response was calculated in time and frequency domain. In both cases, the loading process was condensed to modal loading. For the frequency domain, the base moment method after Kijewski and Kareem (2003) was applied. The time domain analysis served to control the correctness of the approach to treat the overall response process in individual sub-modal processes and for the estimation of overall peak responses. Figure 5 shows a direct comparison of the results for peak horizontal acceleration from both response calculation methods. All sub-modal components exhibit a good similarity apart from the values of the dominant component DXPP. Here, the base-moment results reflect the minimum of the range of resulting values from the time domain analysis indicating hence an underestimation. The average of the time domain peaks is about $\pm 0.17 m/s^2$, which is about 26% higher than the result from spectral analysis. This difference may be due to background vibration.

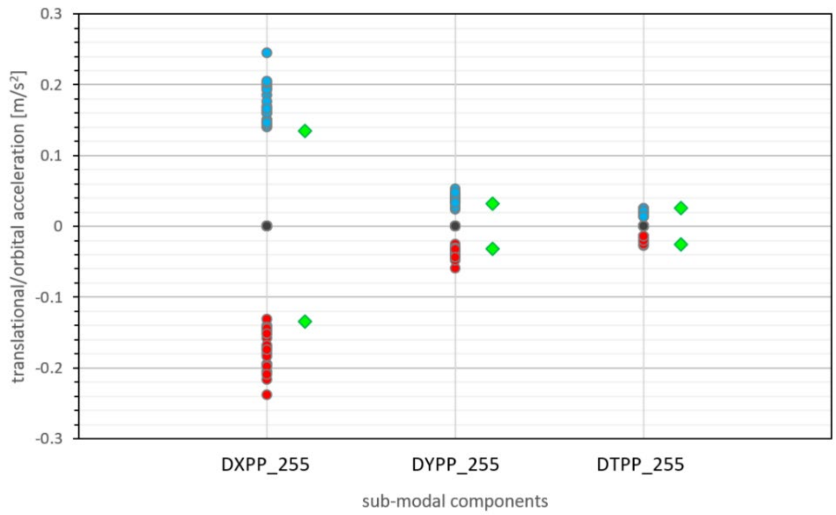


Figure 5. Comparison of results for horizontal acceleration from time domain response calculation and base-moment method. The values from time domain analysis are taken as peak values from 24 10-minutes sub-series and the results from base-moment (single value) is marked as green rhombus.

4. SUMMARY AND OUTLOOK

The paper demonstrates the application of sub-modal response calculation for building with an eccentric structural system in both time and frequency domain. Particular attention is directed towards the feasibility and correctness of this approach. Furthermore, the full-length paper will address further challenges in this example project resulting from the proximity of the Rock of Gibraltar. Here, CFD calculations regarding the blockage effect in the wind tunnel setup when including the rock were made. Some full-scale measurements at the base of the rock were available allowing some assessment of the validity of the experimental study.

REFERENCES (extended)

Kijewski, T., Kareem, A., 2003. *Aerodynamic Load on Tall Buildings: Interactive Database*. Journal of Structural Engineering, ASCE, March 2003

Liang, S., Li, Q.S., Liu, S., Zhang, L., Gu, M., 2004. *Torsional dynamic wind loads on rectangular tall buildings*. Engineering Structures, doi: 10.1016/j.engstruct.2003.09.004

Aly, A.M., 2013. *Pressure integration technique for predicting wind-induced response in high-rise buildings*. Alexandrian Engineering Journal. https://doi.org/10.1016/j.aej.2013.08.006

Kijewski –Correa. T., Kilpatrick, J., Kareem, A., Kwon, D-K., Bashor, R., Kochly, M., Young, B.S., Abdelrazaq, A., Galsworthy, J., Isyumov, N., Morrish, D., Sinn, R.C., Baker, W.F., 2006. *Validating Wind-Induced Response of Tall Buildings: Synopsis of the Chicago Full-Scale Monitoring Program*. Journal of Structural Engineering. DOI: 10.1061/(ASCE)0733-9445(2006)132:10(1509)

Clough, R.W., Penzien, J., 1993. Dynamic of Structures. McGraw-Hill, Inc., 2nd Edition. ISBN 0-07-113241-4

Tabatabaei, R., 2011. *Torsional Vibration of Eccentric Building Systems*. Chapter in "Recent Advances in Vibration Analysis", Baddour, N. (Ed.), InTech, ISBN 978-953-307-696-6

Figure 3, source1: "http://www.skyscrapercenter.com/building/hassan-centenary-terraces-block-6/34907", accessed on September 29, 2020

Figure 3, source 2: "https://www.lainformacion.com/economia-negocios-y-finanzas/gibraltar-boom-inmobiliario-pisos/6506387/", accessed on October 26, 2020