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Dynamic characteristics of high-rise buildings: In-situ measurements versus FEM calculations

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SUMMARY:
The natural frequency is an important dynamic characteristic in the estimation of wind-induced vibration levels in high-rise buildings. A comparison is made between the natural frequencies obtained with design level FEM calculations and in-situ measurements for three high-rise buildings in the Netherlands. The results corroborate earlier findings that the natural frequency is often underestimated in the design phase of high-rise buildings. Ongoing work is looking into the reasons for this underestimation, and aims to establish a basis for guidelines to setup a FEM model for the accurate estimation of the dynamic characteristics of high-rise buildings.

Keywords: High-rise buildings, wind-induced vibrations, dynamic characteristics

1. INTRODUCTION

Wind-induced vibrations are an important aspect in the design of high-rise buildings. The main dynamic characteristics of the building that influence these vibrations are the natural frequency and the damping. Ellis (1980) found that differences of 50% between computed and measured in-situ natural frequencies are common. Ellis furthermore noted that empirical relations often provide more accurate estimates for the fundamental natural frequency than computer based predictions. In current design practice, the natural frequencies are generally determined with a FEM model. More recent studies, e.g. Kijewski-Correa et al. (2006), Zhou et al. (2017) and Bronkhorst and Geurts (2020), observed that it is also quite difficult to make accurate FEM based predictions of the natural frequency in the design phase. This indicates there is a need for guidelines which specify how to setup a FEM model of a high-rise building to obtain an accurate estimate for the natural frequencies.

In the research project HiViBe (High-rise ViBrations in delta cities explored) measurements and calculations are performed on several Dutch high-rise buildings. The aim of this project is to improve current modelling approaches in engineering practice. This abstract presents results on the measurements and FEM calculations of four buildings studied within the HiViBe project. Section 2 provides some information of the buildings, the measurement setup, and the performed FEM calculations. Section 3 discusses results of the measured and computed natural frequencies of the buildings. This section furthermore presents an outlook on the work foreseen for these buildings, to determine what model setup is needed to obtain an accurate prediction of the natural frequencies.

2. METHODS

Table 1 gives information about the superstructure and the foundation of the studied high-rise buildings investigated in this study. Figure 1 shows a side view of the buildings, indicating the instrumented floors. The cross sections show the main load-bearing elements in each of the buildings and indicate the axis system.

Table 1. General information on the investigated high-rise buildings (RC = reinforced concrete).

High-rise (City)	New Orleans (Rotterdam)	JuBi tower (The Hague)	NEMC (Rotterdam)	Zalmhaven I (Rotterdam)
Superstructure				
Height	155 m	146 m	120 m	215 m
Width	28 m	50 m	45 m	35 m
Depth	28 m	38 m	21 m	35 m
Main load-bearing system	RC core and walls	RC cores (3)	RC walls	RC core and walls
Foundation				
Foundation	316 piles	521 piles	352 piles	163 piles
Pile section	0.45 m (circle)	0.45/0.4 m (square)	0.45 m (square)	0.76-0.95m (circle)
Pile length	21 m	8 m	18.5 m	64 m

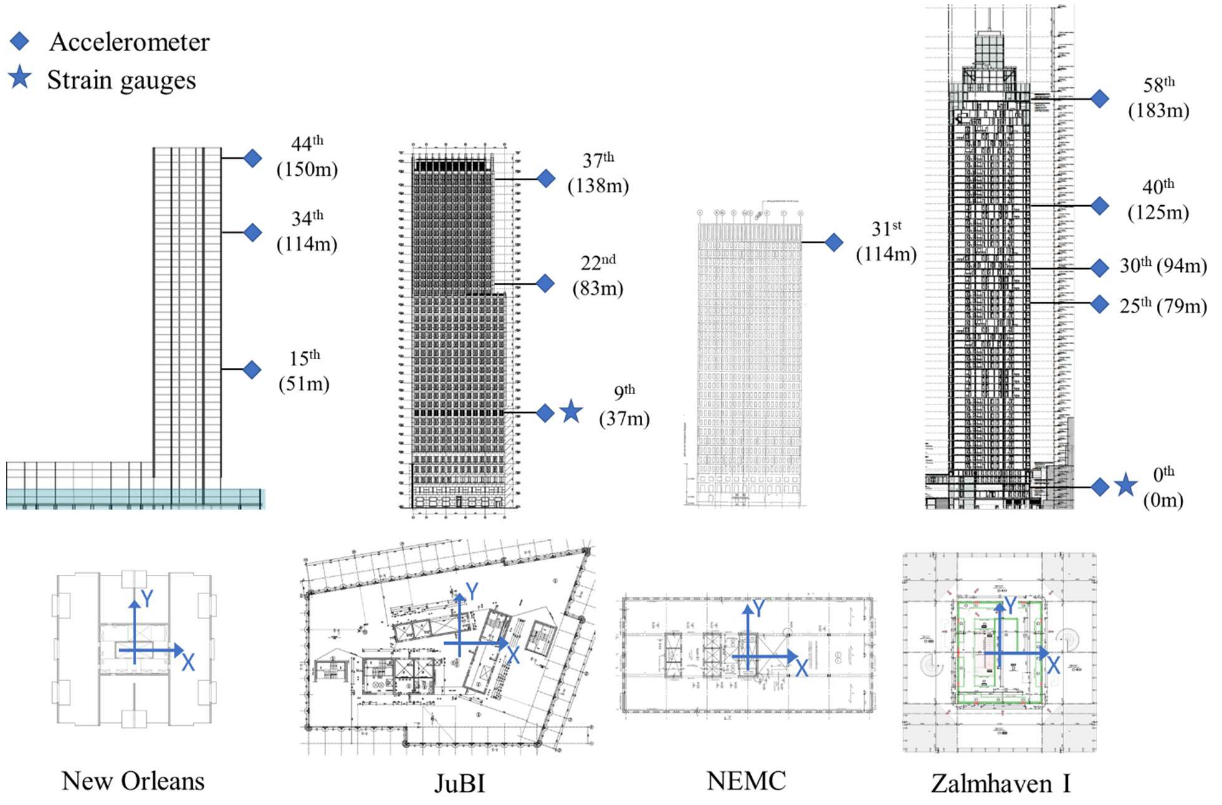

Figure 1. Side views and cross sections of the studied buildings indicating the instrumented floors and the building axis system.

The New Orleans is equipped since 2011 with a permanent monitoring system on the 34th floor, which was temporarily supplemented with additional acceleration sensors on the 15th and 44th (Bronkhorst et al., 2020 and 2021). The Zalmhaven I is instrumented with a permanent monitoring system on the 1st and 58th floor since January 2022; additional sensors were placed on the 20th, 25th and 30th floor for a few months (Bronkhorst et al., 2022). The JuBi tower was instrumented with accelerometers on the 9th, 22nd and 37th floor and strain gauges on the 9th floor (Gomez and Metrikine, 2019). The New Erasmus Medical Center (NEMC) was equipped with acceleration sensors on the top floor (Berg and Steenbergen, 2013).

FEM calculations were performed by HiViBe partners, to compute the modal properties of the studied buildings. The FE models were setup closely following the same approach as applied in design practice. Table 2 gives the overall mass and global bending stiffnesses of the superstructure in the building axis system. Table 2 also specifies the modelled structural components, and the stiffness properties applied for these components. The effect of the piles is accounted for through spring elements. The structural components were modelled using 1D and 2D elements; Table 2 indicates the components that were modelled with 1D elements. Limited information about the setup of the model was available for the JuBi tower at the time of writing this abstract; this information will be presented at the conference.

Table 2. Structural information on the investigated high-rise buildings.

	New Orleans	JuBi tower	NEMC	Zalmhaven I
Superstructure				
Bending stiffness X/Y ($Nm^2\cdot10^{12}$)	42.3/34.7	-	21.7/66.4	157/157
Mass ($kg\cdot10^6$)	57.9	74.8	52.4	87
Structural components				
Core(s) (MPa)	32.8/38.2	-	20	17/38
Shear walls (MPa)	32.8	-	20	19/38
Columns (MPa)	210 (steel) $^{+}$	-	-	19
Beams (MPa)	15^{+}	-	-	-
Floor (MPa)	10	-	20	1
Lintels (MPa)	15	-	-	15
Foundation				
Plate thickness (m)	2.5	-	2	2.5
Plate stiffness (MPa)	15	-	15	12
Pile stiffness (vert., MN/m)	500	-	69.6-108	500
Pile stiffness (hor., MN/m)	10	-	12.5-18	∞

$^{+}$ Modelled using beam (1D) elements

3. RESULTS AND OUTLOOK

The modal properties (natural frequencies and mode shapes) of the buildings were obtained from the acceleration measurements with Frequency Domain Decomposition (FDD), proposed by (Brincker et al., 2000). Table 3 gives the measured and estimated natural frequencies, as well as the dominant direction of the corresponding mode shapes. The results for the natural frequencies show that the numerical models of all buildings underpredict the measured values. This indicates that there is a mismatch between the applied properties in the FEM model (see Table 2) and the in-situ properties. Moretti et al. (2022) performed parameter identification to estimate the in-situ structural properties of the New Orleans tower from the measured ambient vibrations. The results of this study suggest that the underestimation for this building is mainly caused by an underestimation of the building and foundation stiffnesses. Additional FEM calculations by the

HiViBe partners will be performed to establish how the model properties should be changed to calibrate the simulated dynamic characteristics with the measurements. The results of these simulations will provide a first base for guidelines on the setup of FEM models for the prediction of the dynamic characteristics.

Table 3. Comparison of natural frequencies between FEM and measurements.

Mode	New Orleans		JuBi tower		NEMC		Zalmhaven I	
	FEM [Hz]	Measured [Hz]	FEM [Hz]	Measured [Hz]	FEM [Hz]	Measured [Hz]	FEM [Hz]	Measured [Hz]
1	0.20 (X)	0.28 (Y)	0.34 (Y)	0.39 | 0.46 (Y)	0.27 (Y)	0.54 (Y)	0.24 (X)	0.34 (X)
2	0.23 (Y)	0.29 (X)	0.47 (X)	0.56 | 0.63 (X)	0.44 (X)	0.68 (X)	0.25 (Y)	0.34 (Y)
3	0.50 (θ)	0.64 (θ)	0.76 (θ)	0.92 | 1.00 (θ)	0.74 (θ)	1.30 (θ)	0.52 (θ)	0.63 (θ)
4	1.02 (X)	1.33 (X)	1.27 (Y)	1.40 | 1.64 (Y)	1.19 (Y)	1.97 (X/θ)	1.23 (Y)	1.26 (Y)
5	1.25 (Y)	1.53 (Y)	1.65 (X)	2.05 (X)	1.64 (X)	2.17 (Y/θ)	1.25 (X)	1.44 (X)
6	1.55 (θ)	2.01 (θ)	2.14 (θ)	2.45 (θ)	2.26 (θ)	2.83 (θ)	1.51 (θ)	1.86 (θ)
7	2.14 (X)	2.77 (X)	2.59 (Y)	-	2.37 (X)	3.22 (-)	-	-
8	-	3.56 (Y\θ)	3.23 (X)	-	-	-	-	-

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