Practical Experience with Wind-Tunnel Predicted Tall Building Motions

Peter Irwin
Chairman
RWDI
Guelph, ON, Canada
Peter.Irwin@rwdi.com

Peter Irwin received an aeronautical degree from the University of Southampton and a doctorate in mechanical engineering from McGill University. His experience in wind engineering dates back to 1974 and includes extensive research and consulting in wind loading, aeroelastic response of structures, wind tunnel methods and instrumentation. He is world known for his expertise on very tall buildings.

Bujar Myslimaj
Senior Specialist
RWDI
Guelph, ON, Canada
Bujar.Myslimaj@rwdi.com

Bujar Myslimaj received a civil engineering degree from the University of Tirana and a doctorate in applied structural dynamics from the University of Tsukuba, Japan. After more than a decade in structural design, earthquake engineering and structural response control, he joined RWDI where he has been working as Senior Specialist in wind-induced response of structures and supplemental damping systems.

Summary

Predictions of peak accelerations from wind tunnel studies of 19 tall buildings are described and compared with full-scale reported experience. All buildings considered in this study were tested and built prior to 2000. More than a third of them have been occupied for more than twenty years. In the early years of this period the target criterion used by RWDI for residential buildings was for the 10-year return period peak acceleration not to exceed 15 milli-g. However, in some cases this proved difficult to achieve structurally, and after the structural designer had done all that was practically possible in terms of adding stiffness and mass, the results came in as high as 18 milli-g. The remaining measure that could be taken was to add a supplementary damping system. Space was set aside for the damping system but, in view of the subjective uncertainties in the 15 milli-g criterion, it was decided only to install such a system if experience proved that it was necessary. While there were rare reports of occupants noticing motion, no major complaints materialized and in those buildings in the 15 to 18 milli-g range no damping system has been installed. Therefore this range was subsequently treated by RWDI as acceptable on other projects. Wind tunnel studies for fourteen of the buildings discussed here predicted peak resultant 10-year accelerations within the 15-18 milli-g range, with no supplementary damping system. For the remaining five buildings, wind tunnel studies predicted peak resultant accelerations in the range of 23-28 milli-g, and supplemental damping systems (SDS) were installed to reduce acceleration responses to the 15 to 18 milli-g range. The only adverse experience we are aware of occurred on one of the buildings with a damping system when the system had inadvertently been immobilized when a windstorm arrived. Therefore our experience indicates that a 10-year criterion in the 15 to 18 milli-g range works in practice. More recent criteria are tending to be couched in terms of the 1-year return period acceleration and we agree with this approach, but the abovementioned experience still serves as a useful benchmark, provided the accelerations are appropriately scaled to compensate for the change in return period.

Keywords: wind-induced motion, tall building design, human comfort criteria, wind tunnel testing, supplemental damping system, building performance.

1. Introduction

The design of tall, slender buildings can be strongly influenced by the need to keep the wind-induced motions within levels that are acceptable to the occupants. Perception of building motions under the action of wind can be described by various physical quantities including maximum values of velocity, acceleration, and the rate of change of acceleration. Human response to motion in buildings is a complex phenomenon involving several psychological and physiological factors. It is unlikely that human beings are directly sensitive to velocity if isolated from visual effects because, once in motion at constant velocity, no forces act on the human body to keep it in such motion. Acceleration, on the other hand, requires a force to act that stimulates various body organs and senses. This changing acceleration is an important component of motion perception in tall, slender buildings and has become the widely used parameter for the evaluation of motion perception in buildings. It has become the standard for comparison and establishment of motion perception guidelines of various countries and international organizations.

From motion simulator studies and full-scale experience with wind-induced motions in tall buildings criteria are defined as limits that should not be exceeded more than once in a particular return period. The Council on Tall Buildings and Urban Habitat (CTBUH) recommends 10-year peak resultant accelerations of 10-15 milli-g for residential buildings, 15-20 milli-g for hotels and 20-25 milli-g for office buildings [1]. Generally, more stringent requirements are suggested for residential buildings [2,3], which would have continuous occupancy in comparison to office buildings usually occupied only part of the time and whose occupants have the option of leaving the building in advance of a storm.

In the early 1980's the target criterion used by RWDI for residential buildings was for the 10-year return period peak acceleration not to exceed 15 milli-g. However, on some of the extremely slender towers that were starting to be designed in New York this proved difficult to achieve structurally, and after the structural designer had done all that was practically possible in terms of adding stiffness and mass, the results came in as high as 18 milli-g. The remaining measure that could be taken was to install a supplementary damping system. Space was set aside for the damping system but, in view of the subjective uncertainties in the 15 milli-g criterion, it was decided only to install such a system if experience proved that it was necessary. While there were rare reports of occupants noticing motion, no major complaints materialized and in those buildings in the 15 to 18 milli-g range no damping system has been installed. Therefore this range was subsequently treated by RWDI as acceptable on other projects. The limiting 10-year peak acceleration is indicated as a range in recognition of the subjective nature and uncertainty in any such a criterion involving human response.

This paper summarizes the experience of the performance of 19 tall buildings originally designed to satisfy the 15 - 18 milli-g criterion for occupancy comfort in residential buildings. It also provides evidence on the satisfactory performance of those buildings where wind tunnel studies predicted peak resultant accelerations in the range of 23-28 milli-g and a supplementary damping system (SDS) was installed to keep building motions during 10-year wind events within the 15-18 milli-g range.

2. Tall buildings considered

The selection of 19 tall residential buildings discussed here were all tested in RWDI's wind tunnels. Their heights vary from 94m up to 260m, while the natural frequencies of first order sway and torsional modes cover a range of 0.12-0.44 Hz. A brief summary of the information on the buildings is given in Table 1.

Table 1: Building Heights, Natural Frequencies and Damping Ratios Used in Wind-Induced Response Studies

Building Number	Building Height (m)	First Order Modes Frequencies (Hz)			Assumed Damping Ratio (% of critical)
		f_x	f_y	f_{tor}	
1*	249.4	0.193	0.199	0.295	2.0
2	163.4	0.176	0.224	0.250	2.0
3	198.1	0.189	0.184	0.300	1.5
4	137.2	0.185	0.135	0.323	2.0
5	236.2	0.154	0.169	0.400	2.0
6	178.0	0.244	0.250	0.400	2.0
7	215.0	0.177	0.149	0.331	1.5
8	110.9	0.192	0.164	0.250	2.0
9	163.0	0.195	0.208	0.224	1.5
10	124.4	0.170	0.224	0.204	2.0
11*	207.8	0.147	0.171	0.250	1.5
12*	145.2	0.411	0.213	0.440	2.0
13	94.0	0.278	0.243	0.139	2.0
14	141.2	0.370	0.216	0.356	2.0
15	143.3	0.135	0.180	0.333	2.0
16	259.4	0.131	0.125	0.263	1.25
17	175.4	0.201	0.157	0.200	1.5
18*	247.8	0.131	0.154	0.211	2.0
19*	259.4	0.179	0.159	0.236	2.0

* For these buildings, wind tunnel studies predicted peak resultant accelerations above the 15 –18 milli-g range.

The relation between building height and the sway frequencies of the building is shown in Figure 1. Although the plotted data is limited in number, the general trend of frequency decrease with the increase of building height reported in the technical literature [4, 5], is followed.

It should be noted that all buildings listed in Table 1 were tested and built prior to 2000. More than a third of them have been occupied for more than twenty years. Wind tunnel studies for fourteen of the buildings investigated predicted peak resultant accelerations within the 15-18 milli-g range (see Figure 2). For the remaining five buildings, wind tunnel studies predicted peak resultant accelerations in the range of 23-28 milli-g (see Figure 2) and therefore SDS systems such as Tuned Mass Dampers (TMD) and Tuned Liquid Column Dampers (TLCD) were designed and installed to reduce acceleration responses to the 15 – 18 milli-g range. Table 2 summarizes the information for the five buildings where the installation of SDS was found to be the most effective remedial measure for acceleration reduction. It is worth mentioning that the recommendation for implementing an SDS in the buildings where wind tunnel predicted peak accelerations higher than the RWDI's recommended design criteria for occupancy comfort in residential buildings is consistent (see Figure 3) with the recently proposed limits of acceptable motion for the comfort of occupants and users of buildings and structures [6]. Note that the limits of acceptable motion for occupant comfort proposed by Melbourne [6] are dependent on the return period and the predominant frequency of the building. Results presented in Figure 3 correspond to an hour of maximum wind in a return period of 10-years.

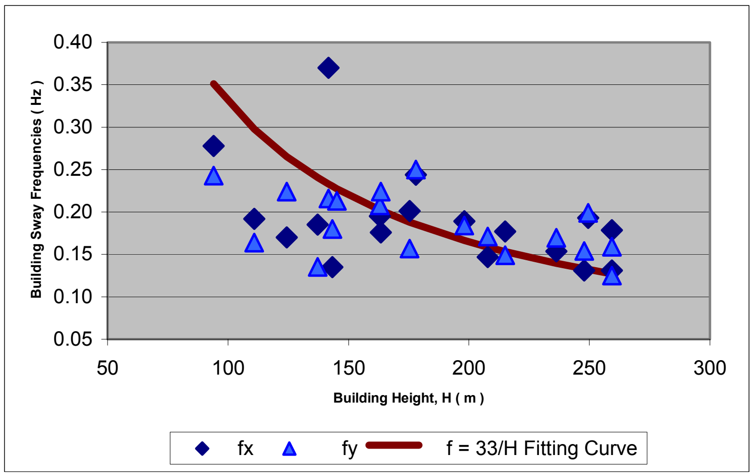

Fig. 1: Variation of Building Sway Frequencies with the Building Height

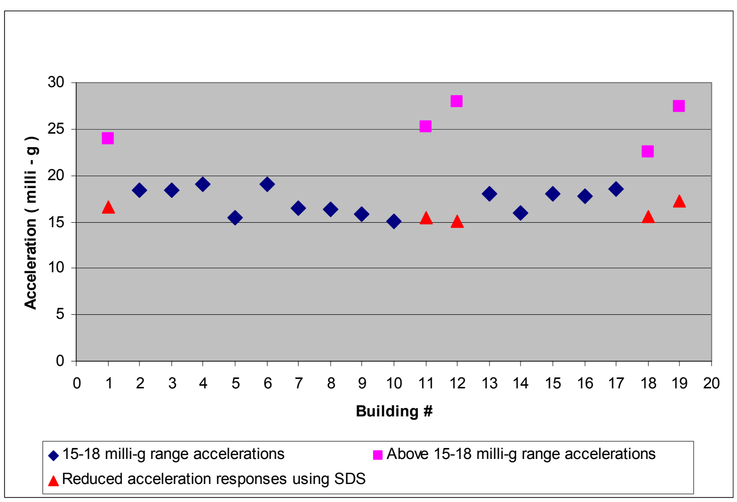

Fig. 2: Summary of Predicted and Improved Acceleration Responses

3. Buildings with supplemental damping system

As shown in Table 2, TMD-s were installed in buildings numbered 1, 18 and 19. For buildings 11 and 12, preliminary feasibility studies concluded that installation of TLCD-s would be the most effective solution in terms of cost and performance. Photos of the buildings with supplemental damping system are shown in Figures 4 through 8. Inserts are added in each building photo to show what type of supplemental damping system was designed and installed in the building.

At about 90% completion of the building, on-site frequency measurements were taken and based on those data final frequency tuning of the damper was performed. As part of the post-installation maintenance package of the SDS, annual inspections are performed at the site to make sure that all components of the SDS function properly and the performance of the damper is not compromised.

Table 2: Buildings with Supplemental Damping System

Building Number	Building Name and Location	SDS Type Installed	10-Year Peak Resultant Acceleration (milli – g)	
			Without SDS	With SDS
1	Park Tower, Chicago, IL	TMD	24.0	16.6
11	Random House, New York, NY	TLCD	25.3	15.4
12	Wall Centre, Vancouver, BC	TLCD	28.0	15.2
18	Bloomberg Tower, New York, NY	TMD	22.5	15.5
19	Trump World Tower, New York, NY	TMD	27.4	17.3

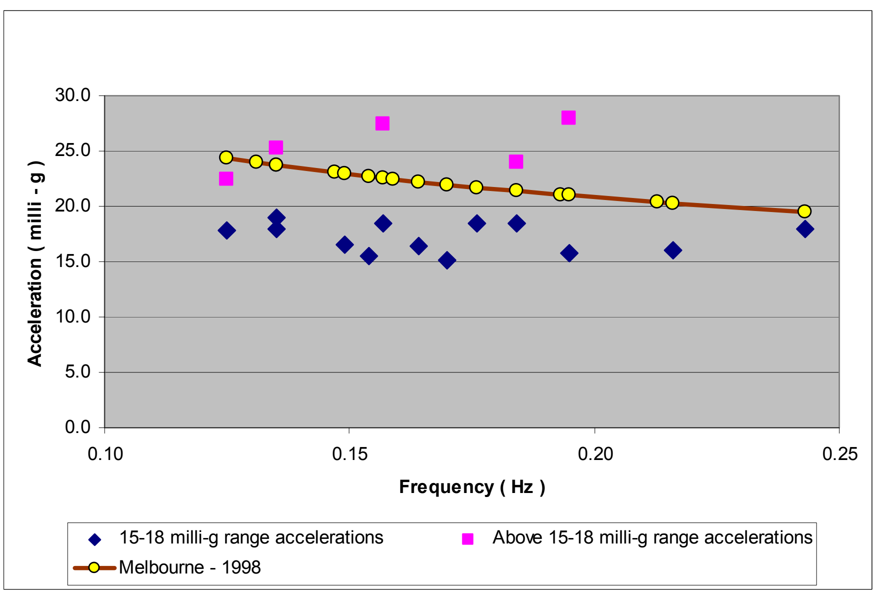

Fig. 3: Comparison of Predicted Acceleration Responses with the Motion Limits for Occupancy Comfort Proposed by Melbourne

4. Performance of the Buildings

For all buildings considered in this study, to our knowledge there have never been any serious complaints of building performance in terms of excessive motion, except on one building when the SDS had been inadvertently immobilized as discssued further below.

Fig. 4: Park Tower Building in Chicago and the TMD being Installed at the Top of the Tower

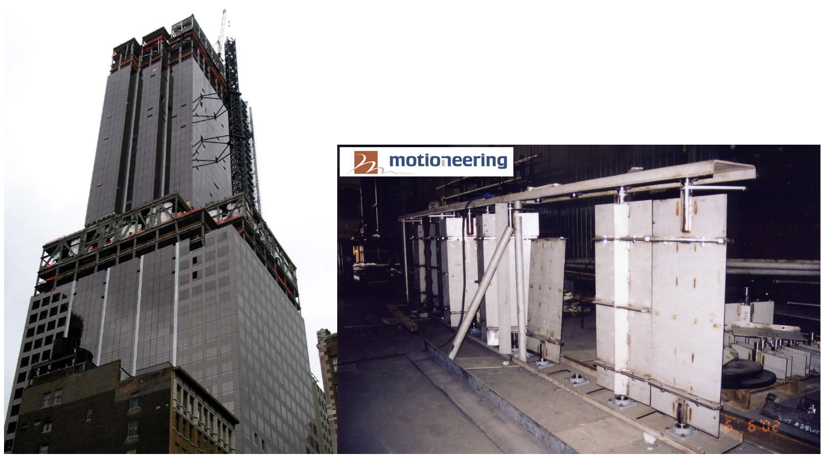

Fig. 5: Random House Tower in New York City with the Vanes of the TLCD Prior the Installation

Fig. 6: Wall Centre Tower in Vancouver with the TLCD during Construction

Fig. 7: Bloomberg Tower in New York City with its TMD at the Final Stage of Construction

Fig. 8: Trump World Tower in New York City with the TMD during Construction

Unfortunately, obtaining good quantitative evidence of a building's true behavior through instrumentation after construction is challenging, mainly because there is resistance from many of the owners to funding such monitoring programs. Also there is the perception that occupants may mistakenly take the presence of instrumentation and technicians in the building as a sign that all is not quite right with the structure, and owners are very conscious of the image of their projects. In this situation any anecdotal evidence certainly is of interest. Of particular interest is the anecdotal evidence on the Park Tower (Figure 4) that was outfitted with a TMD designed to reduce the wind tunnel predicted peak total acceleration of 24 milli-g (see Table 2) down to the 15-18 milli-g range. There were no recorded complaints of excessive building motions during windy days with the TMD working at the roof-top mechanical floor of the building. However, during one storm when the TMD had been inadvertently left locked up after maintenance of other equipment in the mechanical room, tenants started to complain to the building manager. The manager realized what had happened and unlocked the TMD mass. No further complaints of excessive building motion came in. This serves as a good indication that the building's behavior [10-year acceleration = 24 milli-g] without the TMD would have been unacceptable, and that with the TMD [10-year acceleration ≈17 milli-g] it was acceptable.

5. Concluding Remarks

Based on the experience with the 19 residential buildings considered in this study, it appears that if wind tunnel predictions of the 10-year peak resultant acceleration can be kept to within 15-18 milli-g, or lower, then the building performance will be satisfactory.

The prediction of peak accelerations for a given return period depends on not only wind tunnel data but also on the meteorological statistics and the way the two are combined. The process by which wind tunnel and meteorological data are combined is cirtical in arriving at meaningful results. For the studies discussed here the Upctrossing Method described by Irwin et al. [7] was used

There is a trend towards setting motion criteria in terms of the 1 rather than the 10 year-return-period. For example the recently published ISO criteria are in terms of the 1 year return period. The present authors are in favour of this trend since it appears that human comfort issues need to be assessed based on more common events than once in 10 years. However, the present results were obtained in a period when the 10 year return period was used as the standard in North America and therefore are expressed in those terms. The experience with these buildings can still serve as a useful benchmark when using criteria based on shorter return periods through appropriate rescaling of the results.

6. References

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