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Dr. Kiviluoma is actively developing semi-empirical calculation models and wind-tunnel testing techniques. His calculations and expertise have so far been used on 20 big bridges, tall buildings, and other notable structures internationally. He works in close cooperation with major wind-tunnel laboratories and participates in European Union research projects.

A member of IABSE and CTBUH, Dr. Kiviluoma frequently disseminates research results in international forums and journals. Major recognitions include the 1st Nordic Bridge and Tunnel Prize by the Nordic Road Association and the best civil engineering dissertation award by the Oskari Vilamo fund in Finland.

Aeroelastic Wind-Tunnel Testing Technique Revisited

Architectural shaping and optimized stiffening systems of many new high-rise buildings offer increased challenges to dynamic wind response analysis. Mass unbalance due to asymmetric plans yields vibration mode shapes complicated with impeded torsion components. Narrower elevations raise susceptibility to across-wind vibration due to vortex shedding. Acceleration comfort criteria is recognized as one of the key issues in optimization of stiffening system and dampers, which then make wake buffeting due to other nearby tall buildings a specific concern. These general reasons are why aeroelastic wind-tunnel testing offers great possibilities and justification in aerodynamic studies of modern structures.

This presentation is based on a paper with the following objectives:

- Address reasons why and when aeroelastic wind-tunnel testing technique is worth using;
- Propose a new construction principle of scale models borrowed from bridge engineering; and
- Give examples of how automated manufacturing could be utilized to speed up testing and reduce design costs.

This presentation will highlight two specific issues — wake buffeting and wind-induced fatigue — which the renewing and redevelopment of urban landscape may bring into wind-resistant design of structures.

Tallinn Tornimäe is a project comprising dynamically and aerodynamically coupled twin high-rise towers. Slated to be the tallest building in Estonia and now under construction, the project is in a redeveloping city center with five existing high-rise buildings. Another case study to be discussed is the completed new roof structure of Helsinki Olympic Stadium in Finland.

AEROELASTIC WIND-TUNNEL TESTING TECHNIQUE REVISITED

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Abstract

Objectives of this paper are to address some reasons why and when aeroelastic wind-tunnel testing technique is worth using; propose a new construction principle of scale models borrowed from bridge engineering; and give examples how automated manufacturing could be utilized to speed up testing and reduce design costs. The paper highlights two specific issues, wake buffeting and wind-induced fatigue, which the renewing and redevelopment of urban landscape may bring into wind-resistant design of structures. Tallinn Tornimäe high-rise building, comprising dynamically and aerodynamically coupled twin towers, is used as a demonstrator. This building will the tallest in Estonia, and is currently under construction. It is located in redeveloping city centre comprising five existing high-rise buildings. Another dealt case study is completed new roof structure of the Helsinki Olympic Stadium, Finland, in which the architecture plays important role due to demanding old environment.

Keywords

tall buildings, wind load, aeroelasticity, wind-tunnel tests, wake buffeting, wind-induced fatigue

INTRODUCTION

Due to the developments in the 60'st in buffeting theory and boundary-layer wind-tunnel testing, the tallest or otherwise challenging buildings are frequently tested in wind tunnels. Various testing techniques are used to study wind load, acceleration comfort criteria, local pressures for cladding design and wind comfort at pedestrian level. To these, Council's monograph CTBUH (1980) gives comprehensive and yet many aspect up-to-date catalogue. Aeroelastic wind-tunnel testing technique is the one, in which the scale model is prepared respecting both aerodynamic and structural dynamics scaling laws, resulting model to vibrate in flow as the real structure in wind. In it, special issues in the wind-structure interaction are accounted for, including aerodynamic damping, aeroelastic stiffness and fluid virtual mass. Also important aspects are load correlation effect and its dependence on vibration amplitude in across-wind vibration due to vortex shedding and amplitude effects in galloping.

Development of aeroelastic testing techniques in civil engineering may be counted to start from the Tacoma Narrows Bridge collapse in 1940, and the extensive testing for suspension bridges in the US and the UK few years later (Scanlan 1982). The wind excitation mechanisms receiving the most attention are torsion flutter of bridge decks and vortex-induced vibration. For the longest span bridges, two types of testing have become as a standard, aeroelastic section model tests of bridge decks and confirmatory full aeroelastic tests of entire bridges. In the context of tall buildings, aeroelastic testing is recognized, but applications have been few. For many notable buildings designed in the past, there have been perhaps no practical reason to conduct aeroelastic testing, as wind-induced vibration is in control due to conventional structural schemes and high mass and stiffness. In some cases, it has been sufficient to model only first fundamental vibration mode of building, approximated by straight line, by using elastic spring support at the base.

Architectural shaping and optimized stiffening systems of many new high-rise buildings lay increased challenges to dynamic wind response analysis. Mass unbalance due to asymmetric plans yields vibration mode shapes to be complicated with impeded torsion components. Narrower elevations rise susceptibility to across-wind vibration due to vortex shedding. Acceleration comfort criteria is recognized to be one of the key issues in optimization of stiffening system and dampers, which then leave wake buffeting due to other nearby tall buildings as a specific concern. Implications of other nearby and future tall buildings are one of the aspects, which lay challenge to wind analysis in urban context.

One of the prominent drawbacks of aeroelastic testing is the time and special skills needed to built the scale model and the complexity of modifying it due to design changes. Although the testing itself is conducted in few days, typical model may take 1-3 months to build. This situation is about to change due to emerging techniques like rapid prototyping, automated milling of topography models (CAD/CAM) and simulation with combined parametric Finite Element Method (FEM) & 3D CAD software. By learning and investing to use these tools, wind engineer can basically design the scale model on his computer desktop by increasing productivity and quality.

This paper revisits aeroelastic testing by virtue of these key aspects: technical needs due to ever increasing structural challenges in tall buildings; and practical reasons on pushing technique's cost and schedule attractive respect to other techniques.

DISTINGUISHING ASPECTS OF WIND IN REDEVELOPING CITY CENTRES

City centres are continuously changing and developing areas, where new buildings are built while other may be renovated or dismantled. Many times, new buildings built to old areas are exceptionally tall or have architecturally impressed unforeseen geometries. While the service life of the building may be 50 to 100 yrs and more, one have obvious difficulties to think how the city would look like in later period of building's life. Big portion of the building may lie in wind shield of neighbouring buildings, while upper part may be prone to wake of other tall buildings. For wind engineering, local turbulence conditions in such circumstances are hard or impossible to assess without modelling the exact topography and obstacles in the building vicinity in wind tunnel tests. Additional uncertainty is due to roughness change, when wind blows from smoother terrain to city centre. Atmospheric boundary layer may take about 30 km distance to be in equilibrium, which means that turbulence at city centre, even in biggest towns, evidently deviates from that calculated from nominal surface roughness length.

When designing a new tall building into the city centre, one typically consider issues like:

1. how existing buildings affects the wind at the site
2. how the new building affects wind comfort at pedestrian level
3. how future development needs to be considered in design
4. how the new building affects design cladding pressures of nearby buildings
5. how the new building affects acceleration comfort of existing tall buildings in distance radius up to around 500 m

Issues 1 to 2 are generally inspected in detail while others have received minor attention. It may be postulated that certain extra conservatism is needed in structural and aerodynamic optimization.

The wake buffeting issues is illustrated in Fig. 1 and is of special interest in design. For example, the European prestandard Eurocode 1 (ENV 1994) recognizes the wake buffeting in the context of tall buildings. It recommends wind-tunnel testing and expert advice, but implies that, in the phenomena, along-wind building acceleration may be up to three times the original value. Such action evidently spoils most optimization efforts of building stiffening system for acceleration comfort, unless the phenomena is taken into account beforehand by conducting, e.g. aeroelastic testing.

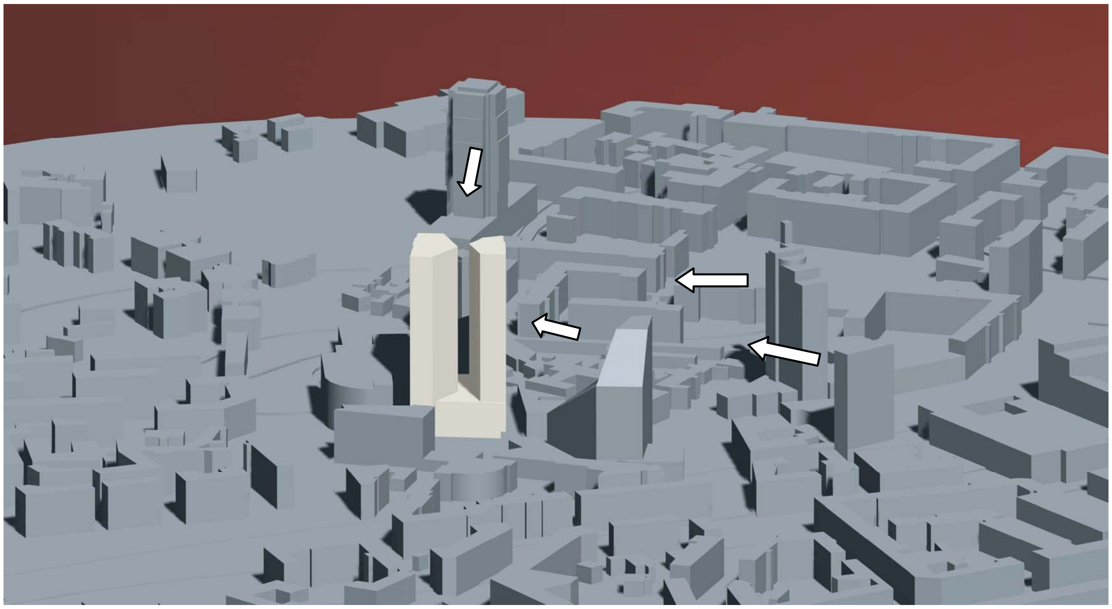


Fig. 1: Wake buffeting issue as illustrated in the context of the Tornimäe Twin Tower laying among sparsely built tall buildings in Tallinn, Estonia. Arrows are indicating possible problematic wind directions for the new building.

SCOPE OF AEROELASTIC TESTING

Aeroelastic testing is most suitable and theoretically the best technique for detailed study of overall building vibration response. By modelling 3D vibration mode shapes of the building, one is able to assess all excitation mechanisms of wind, including buffeting, wake buffeting, vortex-induced vibration and galloping. Regardless dominant excitation mechanism, with extracted modal peak acceleration, one is able to compose equivalent static wind load for design purposes, which takes into account inertia loads associated to acceleration (Fig. 2). As long as the building is prone to dynamic actions, it may postulated that equivalent static wind load approach results in more realistic presentation of the phenomena than the typical design code approach. Drift and base shear may be about equal, but base moment is different due to disparity of load distribution. In practise, one may always make conservative assumptions in application of wind load design standards so that meaning of typical disparity is perhaps insignificant. One significant expectation is the torsion load due to mass unbalance in stories of the building. In modern tall buildings, architectural demands may results in that plan shapes and stiffening system are not symmetrical ones. Any vibration of the building results in torsion inertia component, which results in additional forces. Here, the trend seems that torsion component of wind loading in design codes like ASCE-7 (ASCE 2002) increases respect to earlier revisions. Another expectation is transverse wind vibration due to vortex shedding, where inertial load component always exists, while the conventional across-wind load component is zero for symmetric plan buildings.

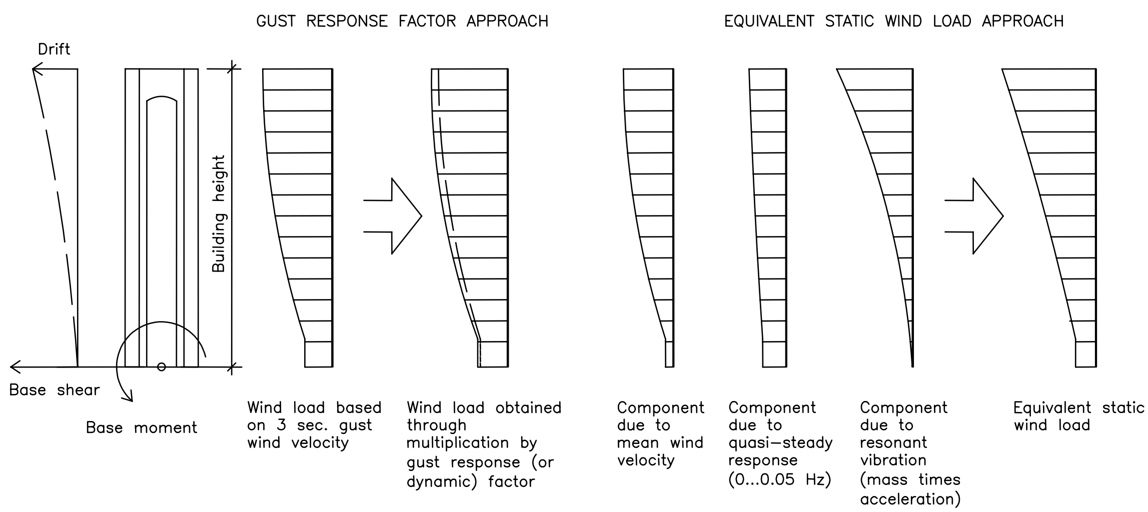


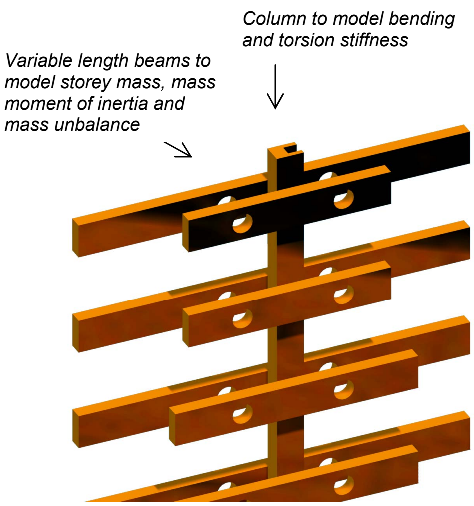
Fig. 2: Comparison of typical design code approach vs. equivalent static wind load approach.

Obviously, the most important benefit of aeroelastic testing from design point of view, is its capability to make highest quality estimate of acceleration comfort criteria. For such criteria, several recommendations have been postulated for office and residential buildings. Among these, ISO 6897 (ISO 1984) standard may be among the most rigorous ones. In the case of tall buildings, the wind-induced vibration is most often multimodal occurring at dominant discrete frequencies, to which this standard propose usage of standardized 1/3-octave frequency bands in assessment. If acceleration recommendations are followed, it may be encountered in practise that application of conventional drift criteria alone may not lead to acceptable design.

Due to the fact that acceleration comfort criteria is one of the key design criteria in modern tall buildings, and it may lead to development of novel and expensive damper systems, the benefits of earoelastic testing preserve attention. As in the present state-of-the-art, there might be possible risk, as aeroelastic testing is not commonly used in standardized wind-tunnel test programs, that unusual wind excitation mechanisms results in design errors in the tallest and the most slender buildings. For example, it is well known from bridge aerodynamics that turbulence mitigates drastically vortex-induced vibration. While the height of the record tallest buildings increases steadily and the wind will be less turbulent in high altitudes, these buildings will be especially prone to across-wind vibration. Aeroelastic testing is more or less obligatory in study of across-wind vibration, as e.g. vortex shedding lock-in and load correlation is strongly dependant on vibration amplitude and fluid-structure interaction.

TECHNIQUES TO INCREASE PRODUCTIVITY IN AEROELASTIC TESTING

Aeroelastic scale models generally comprise a metallic spine to model stiffness and mass; and light weight cladding elements to model building geometry. The complexity of the model construction is proportional how this scheme is implemented. The proposed scheme (Fig. 3) is a direct extension of aeroelastic models used in bridge engineering. This scheme comprises brass spine and balsa cladding elements. Column in the spine is made by joining generally available miniature profiles, and it essentially models stiffness in two principal directions and torsion stiffness. Cladding elements are separated to avoid modal damping to exceed target values.



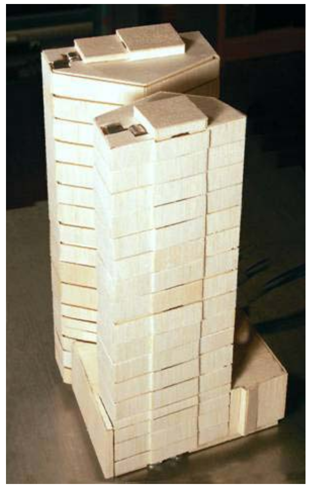


Fig. 3: Proposed spine-cladding system for aeroelastic model of tall building; 1:500 model for the Tallinn Tornimäe Twin Tower by the author.

Due to challenge of constructing and tuning aeroelastic scale models, the design is most often assisted by FE-modelling of the scale model itself. Recently, combined parametric FEM and 3D CAD software have gained popularity among mechanical engineers. By making parametric 3D CAD model of the scale model, one can optimize the parameters (natural frequencies and mode shapes) in FEM portion, which then are automatically updated back to CAD. Once completed, one is able to automatically generate needed workshop drawings.

Rapid prototyping is nowadays used by some advanced wind tunnel laboratories. In the technique, small objects from plastic like material, of any shape, could be automatically constructed by means of 3D CAD. Evidently, cladding elements, like those shown in Fig. 3, could be quickly and accurately manufactured using this technique.

In the case of developed areas, the nearby buildings need to be modelled in topography. Such topography models could be automatically milled using CAD/CAM techniques commonly available in the last decades. Engineer in most cases has necessary maps available, and can prepare CAD/CAM model of the site vicinity with relatively small effort. The automated milling itself is conducted in one to several working days depending on size of the topography model.

Above mentioned techniques may not be all what its available to increase productivity, but illustrate some tools which have not been available in the past, when wind-tunnel testing techniques have got their most extensive development.

EXAMPLES

Tornimäe Twin Tower

Tornimäe Twin Tower (Fig. 4) is a cast-in-citu concrete building currently under construction in Tallinn, Estonia. The building complex facilitates shopping centre, hotel tower and residential tower, having 6, 28 and 30 stories, respectively. By its height 115 m, it will be the tallest building in Estonia, if the spire of historic St. Olav's Church is leaved out in this comparison. Client of the building is AS EKE Invest; developer is Lemcon Ltd; and construction is conducted by Estonian companies. Architect and structural engineer are also local, AS Nord Projekt. Wind engineering and proof engineering are conducted by WSP ConsultingKORTES Ltd.

Towers are realized by the conventional core stiffening system and are dynamically and aerodynamically coupled each other. Vibration mode shapes are relatively complicated and about 6 modes are in minimum needed to satisfactorily model dynamics. Fundamental natural frequency of the tower is of order 0.3 Hz. From wind engineering point of view, acceleration comfort criteria and cladding design pressures are of main interest. Towers' plan geometry implies funnelling effect between the towers, which may increase local pressures and cause aerodynamic coupling.

Analysis started with analytical wind response calculation, which revealed the need of increasing torsion stiffness of the apartment tower. Improved structure was subjected to wind-tunnel testing using aeroelastic model (Fig. 5) and cladding pressure measurements. Topography model was made using automated milling from CAD/CAM model (Fig. 1). Aeroelastic part of the model (Fig. 3) is about 0.3 m in height, and was designed by FEM analysis. Accelerations were measured by 4 miniature accelerometers. With the model it was possible to model and identify responses of 11 lowest mode shapes. This gave possibility to study acceleration comfort related also to higher mode shapes, in frequency range around 1 Hz.

Results of the analysis basically confirms analytical wind response calculations, but at same time revealed wake buffeting issues. Example of check of ISO acceleration criteria is shown in Fig. 5. In the figure, shown is check of 3 separate 1/3-octave frequency bands. It could be observed that the existing high-rise building, Radisson Tower (103 m in height), boosts acceleration response by some 100% due to wake buffeting. Clearly, this leaves needs to augment analytical calculation models. To further study the phenomena, hot-wire measurements were conducted at position of the new building, with the building model removed. It turns out that wake buffeting does not affect peak gust wind velocity, but it retards mean wind velocity and increase turbulence intensity thereof. In terms of typical equivalent static wind load, in the onset of wake buffeting, mean wind component is reduced and resonant component is increased.

Fig. 4: Sketch of Tallinn skyline after completion of the Tornimäe Twin Tower.

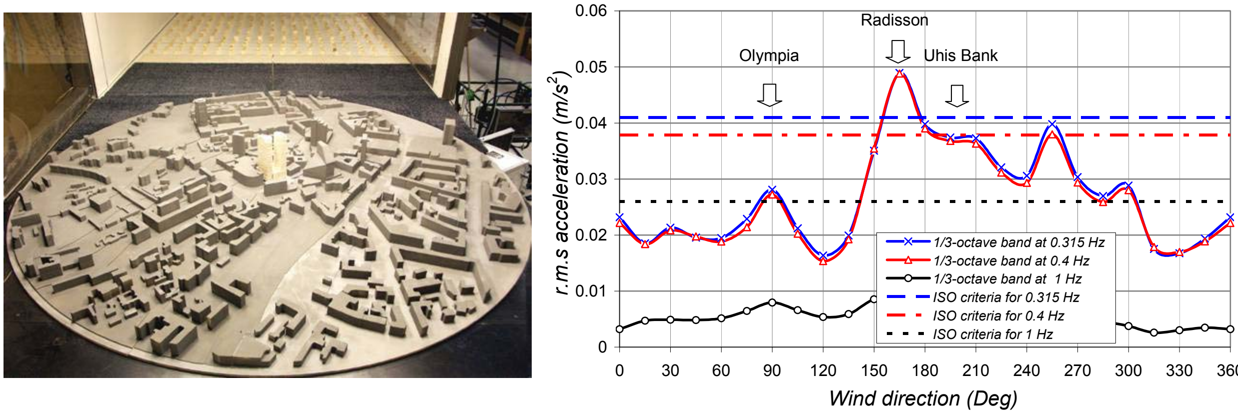


Fig. 5: Aeroelastic wind tunnel model of the Tornimäe Twin Tower and the resulting check of ISO acceleration comfort criteria in top floor of the residential tower (photo by the author).

Helsinki Olympic Stadium new roof structure

One of Finland's national landmarks, the Helsinki Olympic Stadium, recently received new roof structure (Fig. 6a) due to requirements for major sport events. K2S Architects Ltd won a competition to design the roof and the challenge for the structural engineers was to remain true to the aesthetic concept. Client of the project was Stadionsäätiö; developer HKR Rakennuttaja; contractor Naaraharju Ltd and structural engineer Turun Juva Ltd. WSP ConsultingKORTES Ltd was assigned to wind engineering. Size of the roof is 39 x 98 m^2 and fundamental natural frequency is 1.8 Hz and 1.0 Hz, without and with snow load, respectively.

Conventional static and dynamic wind tunnel testing and initial equivalent static wind load revealed a need to constraint displacements of free corners. Strengthened structure was investigated by aeroelastic testing. The roof is subjected to wake buffeting from the wind blowing over structures at the opposite side of the stadium. The static resistance was relatively straightforward to control. However, visible oscillation of the roof, which could be feel annoying by spectators, as well as wind-induced fatigue, required further investigation by aeroelastic testing (Fig. 6b).

a) *b)*

Fig. 6: a) New roof structure of the Helsinki Olympic Stadium (photo K2S Architects Ltd) and b) aeroelastic wind tunnel model (photo by the author).

Base model was milled automatically from CAD/CAM model of the stadium and was the same in static, dynamic and aeroelastic tests. Aeroelastic model was manufactured from grillage made of thin aluminium plate, whose dimensions were calculated by parametric 3D CAD/FEM modelling. Thickness of the roof was modelled by balsa elements attached below the grillage. At the top, there was thin foil, which made model impermeable. One of the main challenges was to achieve the small mass of the model (0.1 kg) without increasing modal damping to exceed target value. Accelerations were measured at 4 points. In addition, for fatigue assessments, dynamic resultant forces were measured by force transducer at columns of the roof.

The model was prepared for similarity of lowest 3 fundamental mode shapes, which are enough to pick up essential dynamics. These were also extracted from measurement results. Results indicate that in design wind velocity, accelerations are big, of order 1 g. This reflects into equivalent static wind load as well as need of wind-induced fatigue assessment. From static point of view, load combination of full wind load and half show load was governing. Stress cycles were assessed by using Rainflow stress cycle counting from aeroelastic test results and local continuous 13 yrs wind record. A detailed analysis was made, which take into account wind direction effects and nominal months, in which snow load may act with wind. Analysis indicates that stress cycles are likely to cause fatigue problems in specific details, which were then assessed in detail.

As a result, the structure act as aeroplane wing, which is subjected to wake buffeting in prevailing wind directions, but whose structures can resist such actions. Furthermore, peak-to-peak oscillation amplitude is obtained to be of order 0.15 m in winds where the stadium could be assumed crowned. These are not likely to cause adverse comment. However, provisions were designed for dampers to reduce possible visual disturbance on demand.

CONCLUSIONS AND DISCUSSION

- Aeroelastic testing technique is technically demanding and may take time. Using some modern tools like CAD/CAM - based automated manufacturing and parametric CAD/FEM - link for design of the wind tunnel model, time line and costs may be kept on the same level than in conventional testing
- wake buffeting due to other nearby high-rises in sparsely built city centre can double the acceleration response. Same is true vice versa; one is not able to build a new tall building without possibly adversely affecting acceleration comfort in nearby old ones
- wake buffeting is mainly due to retardation of mean wind velocity and increase of turbulence intensity in a manner that peak pressures remains about invariant. Negligent post processing of pressure measurement results do not reveal the whole picture thereof, and aeroelastic testing is superior to study of the phenomena
- whenever new structures are constructed over built notable environment, architecture preserves special attention. This may challenge wind engineering to use aeroelastic testing even for structures to which it have not been often used before
- when wind-induced fatigue is about to be problematic, big number of stress cycles occur just around fatigue limit. Resonant vibration need to be analysed in special care, making aeroelastic testing and standard Rainflow stress-cycle counting indispensable
- ever increasing record heights of tallest buildings and increasing aspect ratios (height/width) expose upper part of the building to be in less turbulent wind and across-wind vibration due to vortex shedding lock-in may initiate. In these circumstances, aeroelastic testing could be considered to be obligatory in good wind engineering.

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