


Review

Full-Scale/Model Test Comparisons to Validate the Traditional Atmospheric Boundary Layer Wind Tunnel Tests: Literature Review and Personal Perspectives

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Abstract: For this paper, full-scale/model test comparisons to validate the traditional atmospheric boundary layer (ABL) wind-tunnel simulation technique performed until now by the wind engineering community are systematically reviewed. The engineering background includes some benchmark low-rise buildings specifically established for use in wind engineering research (the Aylesbury experimental buildings, the Texas Tech University experimental building, the Silsoe buildings, etc.), several high-rise buildings in North America and East Asia, long-span bridges, large-span structures, and cooling towers. These structures are of different geometries, are located in different wind environments, and are equipped with various transducers and anemometers. By summarizing the different articles in the literature, it is evident that notable discrepancies between the full-scale measurement and the model test results were observed in most full-scale/model test comparisons, which usually took certain forms: the mean and/or the peak negative pressures at the flow separation regions on buildings were underestimated in the wind tunnel; differences in the root-mean-square (rms) values of the acceleration samples between the full-scale measurements and the force balance model tests were non-negligible; the vertical vortex-induced vibration amplitudes of bridges measured using section models and aero-elastic models were much lower than those observed on the prototypes, etc. Most scholars subjectively inferred that inherent technical issues with the ABL wind tunnel simulation technique could be responsible for the observed full-scale/model test discrepancies, including the Reynolds number effects, the turbulent flow characteristics effects, and the non-stationarity effects. However, based on the authors' years of experience and after discussion with experienced researchers, it was found that some of the full-scale measurements performed in earlier research were inherently less accurate and deterministic than the wind tunnel experiments they were supposed to validate, which could also be a significant cause of the full-scale/model test discrepancies observed. It is suggested herein that future studies in this field should regard full-scale measurements only as benchmarks, and that future works should focus on synthesizing the results from different schools of physical experiments and formulating universal empirical models of high theoretical significance to properly validate future wind tunnel tests.

Keywords: comparison study; full-scale measurement; wind tunnel test; Reynolds number effect; turbulent flow characteristics effect; non-stationarity effect; future perspectives



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1. Introduction

A mature technique now widely applied in the aviation industry, the wind tunnel test was introduced into the field of wind engineering research and design in the 1960s. After Jensen [1] proposed that the flow field simulated in a wind tunnel could be similar to the actual atmospheric boundary layer (ABL) employed in wind engineering model tests, simulating the ABL has become an indispensable test procedure. To fulfill the task

of simulating realistic ABL turbulent flow fields in the wind tunnel, passive simulation devices, including spires, roughness elements, grids, and barriers, can jointly be used [2,3]. It has been proved that the target flow field can be obtained by adjusting the position and the number of passive devices placed at the beginning of the wind tunnel work section. During the past 50 years, most scientific research and engineering practices undertaken by the wind engineering community have utilized the traditional ABL wind tunnel simulation technique. With this technique, on the one hand, theoretical achievements were made, while, on the other hand, the safety of numerous engineering structures in strong winds was ensured.

As a widely employed simulation technique, the reliability of ABL wind tunnel tests has attracted the attention of the wind-engineering community. Since the traditional ABL wind tunnel simulation technique came into being, hundreds of studies have been devoted to the validation of this simulation technique by comparing the model test and the full-scale measurement data, and all types of engineering structures were involved in those comparisons. It is, thus, implied that the full-scale/model test comparison has been recognized by the whole wind engineering community as a reliable validation method, although opposition exists [4]. Until today, most of the performed full-scale/model test comparisons have been disseminated among those in the profession by the literature. After summarizing these studies in terms of their engineering backgrounds, the research purposes, setups, the implementation of the research, and the various authors' interpretations of their results, via incorporation of the authors' own experiences, profound insights will be gained along with a thorough understanding of the related matters of science for guiding future works. This will eventually lead to fruitful endeavors by the wind engineering community to advance the traditional ABL wind tunnel simulation technique. Dalglish [4] has reviewed the full-scale/model test comparisons of wind effects on tall buildings undertaken by his group before 1980. However, except for this endeavor, the literature concerning full-scale/model test comparisons has not been systematically reviewed by others, to the writers' knowledge.

In this article, a literature review of the performed full-scale/model test comparisons is presented, following a brief introduction to the traditional ABL wind tunnel simulation technique. The literature review focuses on summarizing the full-scale/model test discrepancies observed by different researchers and also their explanations for those discrepancies. Finally, the authors' own opinions on the matter of science are put forward, which are supported by research based on their own full-scale measurement campaign.

2. Traditional ABL Wind Tunnel Simulation Technique

According to Dyrbye and Hansen [5], before the mid-1950s, the wind tunnels used for research were aeronautical tunnels with short working sections. They were converted for civil engineering applications by adding passive devices, such as grids, barriers, fences, and spires, to the test section entrance in order to generate turbulence. However, the turbulence generated in these tunnels usually did not meet the basic similarity requirements necessary to obtain realistic test results for structures situated in the ABL.

Jensen's model law [1] changed wind tunnel construction practice fundamentally. After the model law was published, ABL wind tunnels with long working sections were constructed. According to Simiu and Scanlan [6], in long wind tunnels, a boundary layer with a typical depth of 0.5 to 1 m develops naturally over a floor to the order of 20 to 30 m in length, which is covered with rough elements. Atmospheric turbulence simulations in long wind tunnels are probably the best scenarios that can be achieved at present. However, in long wind tunnels, the similarity between the turbulence in the laboratory flow and in the realistic ABL is still not generally as strong as Jensen had conceived.

According to Simiu and Scanlan [6], wind tunnel tests occur at reduced geometric scales for obvious reasons of economy and convenience. Due to scaling, the similarities of a set of dimensionless numbers (the Strouhal number, Rossby number, Reynolds number, Froude number, Prandtl number, Eckert number, and Richardson number) are jeopardized as the flow events are different for different values of dimensionless numbers. Therefore, the

question of scaling opens up the whole area of physical similitude. To meet the similarity criteria for wind tunnel experiments, researchers have paid attention to the dimensionless numbers mentioned above; they believed that when these dimensionless numbers in the model test and the full scale agreed well, the similarity issue with the wind tunnel test was effectively addressed. With the characteristics of the target flow and the scale factors for similitude established, it became apparent that some of the criteria established for similarity cannot, in fact, be satisfied under typical everyday test conditions. The researchers thus launched upon a series of inevitable compromises that rendered their task complex. Wind tunnel experiments vary widely, depending on the particular objectives and available resources, and some of the commonly used tests are described below [5].

(1) Tests of local pressures using scaled static models with pressure taps: Typical scales for these tests are in the order of 1:100 to 1:500. Mean and fluctuating pressures are often measured by connecting the pressure taps on the model with pressure transducers using thin vinyl tubing. The distortion of pressure fluctuations caused by the long tubes may be corrected using Fourier transform techniques. The fluctuating pressures measured in the wind tunnel are used to calculate the characteristic pressure and suction at each point of the structure.

(2) Direct measurements of overall wind loads: Typical scales for these tests are in the order of 1:100 to 1:500. The model is fixed to a base balance to measure the overall wind load acting on the model. Some balances measure all six load components (the three forces and the three moments); other balances measure only some of the load components. Specifically designed high-frequency base balances may be used to measure the fluctuating overall wind load on the model without significant distortion from natural model vibrations. The models used in these tests should have a natural frequency in excess of the most significant wind loading frequencies.

(3) Section model tests: Typical scales for these tests are in the order of 1:50 to 1:100. Section model tests are used to determine the aerodynamic data, e.g., the aerodynamic derivatives and the flutter parameters of the bridge deck. Preliminary investigations of the geometric shape of a bridge deck using section model tests can be conducted in the uniform flow.

(4) Aero-elastic tests using dynamically scaled models: Typical scales for these tests are in the order of 1:100 to 1:300. In aero-elastic tests, the model's movements should reflect those of the full-scale structure. Therefore, the actual natural frequencies and structural damping should be simulated in the test. The construction of aero-elastic models is often time-consuming due to the demand for accurate scaling of the many significant modes contributing to wind-induced structural behavior.

3. Performed Full-Scale/Model Test Comparisons

Since the traditional ABL wind tunnel simulation technique came into being, hundreds of studies have validated this technique by comparing the model test and the full-scale measurement results, the engineering backgrounds of which included low-rise buildings, high-rise buildings, bridges, large-span structures, and cooling towers. These studies are respectively reviewed in this portion of the study.

3.1. Low-Rise Buildings

According to Ref. [7], many full-scale measurement campaigns have been launched for researching wind effects on some benchmark low-rise buildings in the last four decades. In the early 1970s, the Building Research Establishment (BRE) in the UK began a full-scale measurement program on an experimental building of two stories in Aylesbury, England. In the late 1980s, a full-scale experiment on a low-rise building was conducted by the Texas Tech University in Lubbock, TX, USA. At the same time, a full-scale experiment was conducted in Silsoe, UK, which utilized a steel frame building with changeable eaves. At the beginning of the twenty-first century, a 6 m cube was constructed at the Silsoe Research Institute in open-country terrain. These full-scale measurement campaigns were followed

by the corresponding wind tunnel tests, which allowed researchers to validate the modeling technique via full-scale/model test comparisons.

3.1.1. Aylesbury Full-Scale Measurement Program

A pressure measurement campaign was conducted on a two-storey house on the outskirts of Aylesbury, England in the 1970s. As the building adjoined open country that extended uninterruptedly for about 15 km to the southwest, no interference effects existed for the upcoming flow from that direction. Wind-induced pressures were recorded at 72 positions on both the walls and roofs of the experimental building, using pressure taps. In addition, load cells were installed in the building to record the total overall loads and the total roof loads. Measurements of the velocity were also made using cup anemometers mounted at 3 m, 5 m, and 10 m on a mast in the vicinity of the experimental building. Multi-channel magnetic tape recorders recorded data in an analog form that was subsequently digitized.

To compare the results with the full-scale measurement results, Apperley et al. [8] modeled a two-storey house at a 1:500 scale in an ABL wind tunnel. The surface pressures measured in the wind tunnel were compared with full-scale data on the walls and the roof. The results suggested that the agreement was good, provided that the full-scale terrain was modeled accurately in the wind tunnel. For example, for normal winds coming into contact with a facet of the building, the agreement between the wind tunnel and the full-scale data was as good as that between two similar full-scale runs obtained on different days. However, it was also found that the model test results were sensitive to the simulated roughness length of the local upstream terrain. It was inferred that the roughness length that was simulated in the wind tunnel for Ref. [8] was obviously limited in order to characterize the local roughness near the measuring site.

3.1.2. Texas Tech University's Full-Scale Measurement Program

In the 1980s, a set of full-scale experimental facilities were created at Texas Tech University's Wind Engineering Research Field Laboratory in Lubbock, TX, USA, including a 9.1 m × 13.7 m × 4.0 m experimental building, a 49 m meteorological tower, and a pressure measurement system. The site location was carefully selected as the surrounding terrain was flat, with changes in elevation at less than a rate of 0.5%. The experimental building was fully instrumented with pressure taps. As the building was able to rotate on a concrete foundation, the instrumented portion of the building that was of interest could be oriented according to the ambient wind for data collection without losing any valid strong-wind scenario.

Tieleman [9] reported the measurements for both the full-scale building and wind tunnel model of that building. The wind tunnel measurements were shown to be acceptable for the wall pressures but quite inadequate for the roof corner pressures. Tieleman [10] believed that the inaccuracy could be associated with the incorrect simulation of the ABL turbulence near the model. It was found that a considerable improvement of the wind tunnel modeling of roof corner pressures can be achieved by placing the small spires directly upstream of the model to correctly simulate the turbulence intensities and the spectral densities.

3.1.3. Silsoe Full-Scale Measurement Program 1: The Steel-Framed Building

The Silsoe Structures Building was a steel-framed building with a 10° duo-pitch roof, constructed from 1986 to 1987 for taking full-scale wind pressure measurements. It was 24 m long, by 12.9 m in span, and by 5.3 m ridge height, and was located on an open-country site at the Silsoe Research Institute. The building had changeable eave geometry, offering either a traditional sharp eave or a curved eave of 635 mm in radius.

A lot of studies have been undertaken by researchers based on the resulting full-scale measurements and the subsequent model tests. Richardson and Blackmore [11] compared the model-scale wind pressures for the Silsoe Structures Building to the full-scale data

and found that the two sets of data compared well for transverse winds; however, model tests were likely to underestimate the mean wind pressure coefficients for cornered winds. Dalley [12] also conducted full-scale/wind tunnel surface pressure comparisons on the Silsoe Structures Building, which suggested that differences between the model and full-scale surface pressure spectra at two taps were notable. Hoxey et al. [13] conducted detailed wind pressure comparisons and found differences at the separated flow region of the windward roof slope. Richardson et al. [14] compared the wind pressures obtained on the full-scale Silsoe Structures Building with those from two 1:100 scaled models. The results suggested that when certain wind tunnel procedures were implemented, good predictions of the full-scale mean wind pressure coefficients could be obtained. However, high negative pressures still tended to be underestimated in the wind tunnel. Comparisons of the surface pressures measured on the Silsoe Structures Building at both full-scale and model scale were undertaken by Hoxey et al. [15], who observed differences in the separated flow at the windward eaves of the building, and the smoke technique for full-scale flow visualization was then utilized to reveal the related flow mechanics.

3.1.4. Silsoe Full-Scale Measurement Program 2: The 6 m Cube

In order to provide a facility for comparisons between the full-scale and the previously published model test data, a full-scale 6 m cube was constructed at Silsoe Research Institute in open-country terrain. Surface pressure measurements were made on the vertical and horizontal central-line sections, with additional taps on one-quarter of the roof. Measurements of wind velocity were also made in the region around the cube, using ultrasonic anemometers.

Based on the full-scale measurement campaign, Richards et al. [16] compared the mean pressure coefficients, measured on location, with published wind tunnel data. The results suggested that when the wind was perpendicular to one face, there was good agreement between the full-scale and the wind tunnel's windward wall pressures. However, the full-scale and the wind tunnel's wind pressures, as measured on the roof and leeward wall, appeared to be different. Richards and Hoxey [17] studied the effects of reattachment length on pressure distribution on the 6 m cube and found that the effects could not account for the differences between the full-scale and the typical wind-tunnel data. According to Kasperski and Hoxey [18], some wind tunnel experiment studies showed that the extreme values of some local pressures and global forces followed a type III distribution; a type III distribution could be fitted to the full-scale data from the 6 m Silsoe cube.

3.1.5. Eindhoven University of Technology's Full-Scale Measurement Program

With the goal of investigating the consistency between building pressures in full-scale and wind tunnel experiments, a field measurement campaign was launched at the Eindhoven University of Technology [19,20]. The test building had the dimensions of 44 m in height, 167 m in width, and 20 m in depth. The facade of the building was made of steel columns, with steel parapets and glass windows. The surroundings of the building were flat. For meteorological wind measurements, a 30-meter-high guyed mast was established 130 m westward of the main building. The top of the mast was at the roof height of the test building. Temperature sensors and cup anemometers were mounted at three levels on the mast. In addition, a direction vane and a sonic anemometer were placed on top of the mast.

After taking measurements, Geurts [21] compared the full-scale and the wind-tunnel wind-induced pressures on the windward and leeward sides of the test building; they found that the wind velocity spectra in the wind tunnel were shifted toward higher frequencies compared to the full-scale data. It was also noted that the full-scale pressure spectra attenuated faster than the full-scale velocity spectra, but this was not observed in the wind tunnel. The coherence of the pressures was identical for both the full-scale model and the wind tunnel in many cases.

3.1.6. Tongji University's Full-Scale Measurement Program

In recent years, researchers from Tongji University constructed a wind engineering research field laboratory in Shanghai, China, which consisted of a low-rise building and two anemometer towers. The full-scale building was 10 m in length, 6 m in width, and 8 m in eave height. Its roof pitch could be adjusted from 0° to 30°.

Two wind pressure samples of ten minutes in length, respectively obtained at 0-degree and 20-degree roof pitches, were compared with those measured on a 1:30 scaled rigid model in a wind tunnel by Huang et al. [7]. It was shown that the mean and the fluctuating wind pressure distributions were similar for the two experiments, but that there was a notable difference in the magnitudes of the mean and the fluctuating wind pressure coefficients between the two experiments.

3.1.7. Other Full-Scale Measurement Programs

Besides the aforementioned full-scale/model test comparisons concerning the well-known benchmark low-rise buildings, other researchers have also conducted related studies [22–24], and it is interesting to learn that all these works suggest that the negative pressure coefficients measured on the roofs of low-rise buildings were underestimated in wind tunnels.

In 1975, Marshall [22] compared the wind pressures measured on a single-family dwelling with data measured on a 1:50 scale model that was placed in a turbulent boundary layer. The results showed that the pressure spectra and the coherence of surface pressures obtained from the full-scale and the model-scale experiments agreed well with each other, but the fluctuating wind pressure coefficients obtained from the model tests were consistently low.

In 1991, Richardson and Surry [23] compared the full-scale surface pressures measured from several agricultural buildings with data from 1:100 scale models. Mean wind pressure distributions at mid-building length obtained from the two experiments, recorded under the wind perpendicular to the ridge line, were compared. It was shown that a very good agreement between results was possible, but, in local regions where separation and recirculation occurred on the windward roof slope, the model-scale experiments tended to significantly underestimate the suction data. This observation appeared to be dependent on roof pitch.

In 2009, Liu et al. [24] presented a comparison of the wind pressure coefficients obtained from one full-scale single-family home that had experienced a sustained hurricane with the results of wind tunnel experiments on a 1:50 scale model of that home. They observed that the wind tunnel and the full-scale mean and fluctuating wind pressure coefficients matched well at almost every monitoring location on the roof, but the peak negative pressure coefficients obtained from the wind tunnel were generally smaller than the corresponding full-scale data.

3.2. High-Rise Buildings

3.2.1. Dalglish's Full-Scale/Model Test Comparisons

In the early 1960s, Dalglish et al. measured wind pressures and structural responses for several high-rise buildings located in downtown areas in Canada that experienced strong ABL winds and compared the full-scale measurement results with the corresponding model test data. The first full-scale measurement campaign was undertaken on a 34-storey office building in downtown Montreal. In 1967, Dalglish et al. [25] reported simultaneously recorded wind pressure samples, ranging from 15 min to 1 hour, taken from twelve wind pressure transducers arranged at two levels on that building. The mean pressures, pressure variances, spectra, and cross-spectra obtained from full-scale measurements were compared with the preliminary results from wind tunnel experiments in cooperation with the University of Western Ontario. It was found that the statistical properties of full-scale wind pressure fluctuations could be reproduced using model complexes placed in a boundary layer wind tunnel. In 1969, Dalglish [26] completed the wind pressure

measurements over a 4-year period on a 34-storey office building for the purposes of checking wind tunnel techniques. Comparisons were made on the mean and the fluctuating pressures, the power spectra, and the correlation between selected pairs of pressure values measured at various points on the building. Good agreements were found in general, but the comparisons showed some unsatisfactory correlations for certain wind directions.

Several years later, another field measurement campaign was launched on the 57-storey Commerce Court Tower in Toronto. Wind effects and the wind-induced structural responses of that building were measured using pressure transducers, strain gauges, accelerometers, and displacement transducers. In 1975, Dalgliesh [27] recorded simultaneous surface pressure measurements at 32 points on that building. The wind pressure samples were processed and compared with the corresponding model test data. The agreement between full-scale and model test mean wind pressures was satisfactory in general, but the level of agreement for fluctuating wind pressure coefficients was not very good. In 1978, Dalgliesh and Rainer [28] measured the wind-induced movements of the same 57-storey office tower. They found that the observed building movements and wind tunnel results correlated well once the model data had been adjusted for building frequencies. In 1979, Dalgliesh et al. [29] compared the full-scale wind pressure coefficients measured from that 57-storey building with the corresponding model test data. A good agreement was shown where sufficient full-scale data were employed. In 1982, Dalgliesh [4] reviewed the earlier comparisons made between the full-scale measurements and the wind tunnel tests undertaken for the 57-storey office tower and supplemented them with new examples of a comparison between the full-scale and the model test dynamic behaviors. The comparison suggested that there might be little hope of predicting the full-scale behaviors to within about 10 to 15 percent in terms of relative error, even when the input data on which the model was produced were accurate. This is due to the reason that the field observations were subjected to so many uncontrolled variables. In 1983, Dalgliesh et al. [30] presented the results from several years of observation on the accelerations of the 57-storey office tower under moderate to high winds. It was concluded that the full-scale and model-scale standard deviations of the structural acceleration correlated well for most wind directions. The details of Dalgliesh’s comparisons are briefly summarized in Table 1.

Table 1. Main features of Dalgliesh’s full-scale/model test comparisons.

Number	1	2	3	4	5	6
Time	1967, 1969	1975	1978	1979	1982	1983
Reference(s)	[25,26]	[27]	[28]	[29]	[4]	[30]
Building name	34-storey office building	Commerce Court Tower	Commerce Court Tower	Commerce Court Tower	Commerce Court Tower	Commerce Court Tower
Location	Montreal	Toronto	Toronto	Toronto	Toronto	Toronto
Height	440 feet	239 m	239 m	239 m	239 m	239 m
Surroundings	Surrounded by other buildings	Sheltered by building to the west	Sheltered by building to the west	Sheltered by building to the west	Sheltered by building to the west	Sheltered by building to the west
Type of wind event	Windstorm	Unknown	Unknown	Windstorm	Unknown	Moderate/high ABL winds
Meteorological measurements?	Yes	Yes	Yes	Yes	Yes	Yes
Measurement devices	Pressure transducers	Pressure transducers	Accelerometers, displacement sensors	Pressure transducers	Strain gauges, accelerometers, displacement sensors	Accelerometers
Height of measurement section	134 feet and 413 feet	Four heights	202 m and 234 m (accelerometers); -15 m (displacement sensor)	Four heights (102 m, 138 m, 166 m, 202 m)	11th floor (strain gauges); 202 m and 234 m (accelerometers)	202 m
Calculated results for comparison	Mean, variances, spectral functions, and cross-spectral functions of wind pressures	Mean and rms values of pressures, base shear coefficients, overturning moments	Mean deviation of along-wind displacements, standard deviation of across-wind displacements	Mean and rms values of pressures and probability densities of peak pressures	Acceleration spectra, mode shapes, and displacements	Standard deviation of accelerations against the dynamic reference pressure
Agreement with model test results	Good	Excellent for mean pressures; marginal for rms values of pressures	Good (conditionally)	Good (conditionally)	Poor	Good

3.2.2. Full-Scale Measurement Campaigns Undertaken by Li

From the early 2000s, Li took advantage of the research opportunities offered by typhoons passing through south and southeast areas in China to measure typhoon characteristics and the typhoon-induced responses of typical high-rise buildings [31–35]. These full-scale measurements were then utilized to validate the prior model tests (mainly force balance model tests) conducted at the structural design stages. In 1996, Li et al. [31] continuously measured the accelerations of the Di Wang Tower during the passage of Typhoon Sally, and it was found that the root-mean-square (rms) values of acceleration samples measured on the prototype were consistent with those obtained from the force balance model test. In 2005, Li et al. [32] discussed the structural responses measured on Central Plaza Tower in Hong Kong and the Di Wang Tower in Shenzhen during the passage of Typhoon Sally. According to a full-scale/model test comparison, the differences in the rms values of the acceleration samples between the full-scale and model test data were found to be in the range of 4.0–12.5% for the two tall buildings. In 2006, Li et al. [33] compared the wind effects on the Jin Mao Tower obtained at the full scale and the model scale. In the wind tunnel, both the suburban and the urban boundary layers were simulated for the force balance model tests and the mean and fluctuating forces on the building model were measured using a high-frequency force balance. Full-scale measurements of the wind effects on the Jin Mao Tower were conducted under typhoons. The model test data were found to be in good agreement with the full-scale measurement results. In 2007, Li et al. [34] presented some full-scale measurement results of the wind effects on Jin Mao Tower during the passage of Typhoon Rananim. The wind tunnel data obtained from the force balance model test were compared with the full-scale measurement results. It was found that differences in the acceleration standard deviation between the two experiments were 11.8% and 19.1% for two wind direction scenarios. In 2008, Li et al. [35] systematically presented the full-scale measurement results for the wind characteristics and wind-induced structural responses of four tall buildings (the Center in Hong Kong, Di Wang Tower in Shenzhen, CITIC Plaza Tower in Guangzhou, and Jin Mao Tower in Shanghai) during the passages of three typhoons. By comparing the full-scale measurements and the wind tunnel results, it was shown that the rms values of the acceleration samples measured with the prototype were consistent with those obtained from the model tests in general. The differences in the rms values of the acceleration samples between the two experiments were in the range of 9.3–19.1%.

The details of Li's studies are summarized in Table 2. Comparing Table 1 with Table 2, the following differences between Dalglish's and Li's studies can be noted. (1) Due to the differences in meteorological conditions between inland areas in North America and coastal areas in East Asia, Dalglish paid more attention to strong ABL wind events, while Li focused more on typhoon events. (2) Most of the measured results were of surface wind pressures in Dalglish's work, while the results were structural accelerations in Li's work. Thus, Dalglish's studies and Li's studies should provide references to the pressure measurement model tests and the force balance model tests, respectively. (3) The buildings selected by Li for full-scale measurements were more slender. Since the stronger resonance might be induced for flexible buildings, Li generally focused on the occupants' comfort. (4) Dalglish's engineering background concerned buildings of comparatively greater rigidity. Thus, it was reasonable for him to compare data measured on the prototype to those obtained from rigid models, with regard to the fact that the self-excited forces measured on those full-scale buildings were limited.

Table 2. The main features of Li’s full-scale/model test comparisons.

Number	1	2	3	4	5
Time Reference	2004 [31]	2005 [32]	2006 [33]	2007 [34]	2008 [35]
Building name	Di Wang Tower	Central Plaza Tower (CPT); Di Wang Tower (DWT)	Jin Mao Tower	Jin Mao Tower	The Center; Di Wang Tower; CITIC Plaza Tower; Jin Mao Tower
Location	Shenzhen	Hong Kong; Shenzhen	Shanghai	Shanghai	Hong Kong; Shenzhen; Guangzhou; Shanghai
Height	384 m	374 m; 384 m	420.5 m	420.5 m	350 m; 384 m; 391 m; 420.5 m
Surroundings	Surrounded by a number of tall buildings	Both are surrounded by tall buildings	Surrounded by other buildings on one side	Surrounded by other buildings on one side	Unknown for the Center and CITIC Plaza Tower
Type of wind event	Typhoon Sally	Typhoon Sally	Typhoon Rananim	Typhoon Rananim	Three typhoons
Meteorological measurements?	Yes	Yes	Yes	Yes	Yes
Measurement devices	Accelerometers	Accelerometers	Accelerometers	Accelerometers	Accelerometers
Height of measurement section	298.34 m	73rd floor for CPT; 298 m for DWT	6th floor (about 300 m)	69th and 76th floors	Several selected floors in each instrumented tall building
Calculated results for comparison	Rms value of acceleration	Rms value of acceleration	Rms value of acceleration	Rms value of acceleration	Rms value of acceleration
Agreement with model test results	Good	4.0–12.5% differences	Good	11.8–19.1% differences	9.3–19.1% differences

Other researchers also conducted full-scale/model test comparisons similar to Li’s works. In 2008, Fu et al. [36] measured the ABL wind characteristics and the wind-induced responses of two prototype tall buildings. Comparing the full-scale rms values of the acceleration samples with the corresponding wind tunnel data, it was found that the force balance model tests were basically conservative when considered for use with the full-scale/model test relative differences in rms values of the acceleration samples, which were in the range of 12.4–16.5%. In 2010, Fu et al. [37] conducted field measurements for the wind effects on the Guangzhou West Tower from Typhoon Megi. Meteorological winds, structural accelerations, and surface pressures were simultaneously measured on that building. After full-scale/model test comparisons, it was found that the structural accelerations obtained from the force balance model tests were basically in good agreement with those obtained from field measurements. Slight differences were observed in the mean wind pressures between the two experiments. In 2015, Yi and Li [38] presented the results of full-scale measurements and force balance model tests to ascertain the wind-induced structural responses of a tall building with a height of 420 m in Hong Kong. After comparison, it was shown that the model test could provide reasonable predictions of the realistic resonant responses of the building, but it could not predict the realistic background responses very well.

3.2.3. Other Full-Scale/Model Test Comparisons

Different from the above-mentioned studies focusing on wind pressures on the studied buildings’ external surfaces and their wind-induced structural responses, Kato et al. [39] investigated the wind-induced internal pressures seen in a high-rise building. Full-scale measurements were undertaken using absolute pressure meters. The mean pressure coefficients measured inside the full-scale building were around -0.26 and were constant along the building’s height. The mean internal pressure coefficients estimated using the wind tunnel model were consistent with those obtained from the full-scale measurement process. It was, therefore, inferred that the mean wind pressure coefficient obtained from the model test was sufficient for examining the mean internal pressures in the building.

The literature suggests that some advanced measuring techniques were utilized for full-scale experiments on tall buildings. For example, Lim et al. [40] examined the feasibility of using continuous-wave Doppler LiDAR for flow measurements around full-scale buildings, as opposed to traditional experimental instrumentation. The mean wind velocities and the turbulence intensities measured around a full-scale, nominally cuboid building in suburban terrain were compared to the results obtained from a 1:100 scale model. The turbulence

intensities obtained from the wind tunnel experiments were 2–6% higher than the nominal value of 14% measured in the full-scale testing.

3.3. Bridges

Many long-span bridges have been equipped with structural health monitoring systems in recent years, which has provided good opportunities for researchers to explore these bridges' real behaviors under strong winds. However, to the writers' knowledge, a limited number of researchers have employed structural health monitoring data to validate the corresponding model test predictions.

In 1998, Delaunay and Grillaud [41] carried out field measurements of the turbulent wind characteristics and the wind-induced response of a cable-stayed bridge to check the validity of the turbulence characteristics used for its design and the structural dynamic responses obtained by combining both theoretical computations and taut-strip model experiments. It was found that both the turbulent wind characteristics found in the wake of an upstream arch bridge measured on the site and the full-scale response of the cable-stayed bridge that was subjected to this particular excitation were in good agreement with the results of earlier estimations. Small discrepancies could be related to the fact that some full-scale responses concerning the vertical flexural modes of the cable-stayed bridge that were predicted were lower than those of the earlier estimations.

In 2001, Frandsen [42] carried out full-scale measurements on the Great Belt East suspension bridge. Pressures on the deck surface and structural accelerations were simultaneously measured for the first time. Large amplitudes due to vortex-induced oscillations were measured on location and lock-in phenomena were also observed. By comparing the full-scale measurements with the model test results, it was found that the limitations of conventional experiments for predicting the full-scale structural behavior were evident due to the scaling effects.

In 1999, the skew winds surrounding the Tsing Ma suspension bridge during Typhoon Sam, the modal damping ratios, and the structural acceleration of the bridge were measured on its prototype by Xu and Zhu [43]. The buffeting responses of the bridge were then computed using the measured results and the aerodynamic coefficients and flutter derivatives of the bridge deck and tower obtained from the wind tunnel test. By comparing the computed accelerations of the bridge deck and the cables to those measured on the prototype, it was found that the agreement was good in general.

In 2014, Li et al. [44] monitored the wind-induced vibrations of a full-scale suspension bridge with a central span of 1650 m. Thirty-seven vortex-induced vibration (VIV) events were observed. The VIVs from a section model test and those from the full-scale bridge were compared. It was shown that the vertical VIV amplitudes of the section model were much lower than those from the field measurements. Moreover, torsional VIVs appeared in the section model test, whereas they were not observed for the full-scale bridge.

Summarizing the above research, the common challenges across the different studies conducted on various bridges are identified as concerning the vertical VIV amplitudes of long-span bridges, measured using section models and aero-elastic models; these were much lower than those observed for the prototypes, and this is probably due to the scaling effects.

3.4. Large-Span Buildings

Some full-scale/model test comparisons have used large-span spatial structures as engineering backgrounds. For example, Chen et al. [45] presented the results of a combined study of full-scale measurements and wind tunnel tests for the Guangzhou International Convention and Exhibition Center. In the wind tunnel, wind-induced pressures were obtained on the roof of a 1:300 scale model under the suburban boundary layer flow. Full-scale measurements of the winds and wind-induced structural responses were conducted during the passage of Typhoon Nuri. In comparison, it was found that the accelerations measured on the prototype were in good agreement with those obtained from model tests.

Chen et al. [46] carried out full-scale measurements for the wind-induced responses of a large-span cable-supported roof. At selected locations, the power spectral densities of the structural responses from full-scale measurements agreed well, qualitatively speaking, with those computed via finite element analysis where the wind load input was obtained from pressure measurements in the wind tunnel, suggesting the validity of the predictive approach.

3.5. Cooling Towers

Pirner [47] compared the wind pressure fluctuations from a model test and in situ measurements on a cooling tower. Using the model, wind pressures were measured using two microphones with a Reynolds number (Re) = 5.04×10^5 , and in situ wind pressure values were obtained at $Re = 3.48 - 5.22 \times 10^7$. It was found that when certain conditions were preserved, the agreement between the two experiments was very good.

In 2009, a full-scale measurement campaign for wind effects on a 167-meter-high cooling tower was undertaken by the authors at Peng-cheng electric power station in Xu-zhou, China [48]. To the south of the tower, there was an adjacent cooling tower of the same size as this one for taking measurements, and there was an industrial complex to its west. However, to its north and east, there was no large building interfering with the wind effects. During its construction, 36 transducers were evenly installed around the tower's throat section at 130 m high. The whole full-scale measurement campaign lasted from 2010 to 2015 on the basis of 2–3 iterations of intensive tests per year. Each time, the occurrence of the strong wind scenario was predicted based on a local meteorological center's weather forecast. Equipment was set up before the arrival of the strong winds, and simultaneous 24-h recordings of wind and wind-induced pressures were then conducted, which usually continued for 1 to 2 weeks. Comparing the full-scale measurement data with the corresponding model test data, Cheng et al. [49] found that the agreement in terms of mean wind pressure distribution between the two experiments was good overall, but that in terms of dynamic wind effects, it was not satisfactory. In addition, Cheng et al. [50] found that the model test conducted at the cooling tower's design stage was conservative in use since comparing the results to the full-scale measurement results showed that unfavorable wind pressure spectra and coherence were likely to be measured in the wind tunnels. The Peng-cheng cooling tower full-scale measurement campaign will be revisited in Section 5.

3.6. Typical Full-Scale/Model Test Discrepancies

From the above literature reviews, it is clear that most full-scale/model test comparisons arrived at the conclusion that the discrepancies between the full-scale measurement results and the wind tunnel data were noticeable. The typical discrepancies can be summarized as below:

- (1) Mean and/or peak negative pressures at the flow separation regions on low-rise building roofs were usually underestimated in the wind tunnel [7,9,13–15,24];
- (2) The local fluctuating pressures attributable to vortex shedding on high-rise building models sometimes differed from those on the prototypes [27];
- (3) The aero-elastic model tests for high-rise buildings were found to underestimate the real dynamic structural responses in the intermediate-frequency range [4];
- (4) Differences in the rms values of the acceleration samples between the full-scale measurements and the force balance model tests were sometimes in the range of 4–25% for high-rise buildings [32,34–37];
- (5) The vertical VIV amplitudes of long-span bridges measured using section models and aero-elastic models were much lower than those observed with the prototypes [42,44];
- (6) The pressure fluctuations measured on the prototypes followed a non-Gaussian distribution, whereas the model test samples followed a Gaussian distribution [37,47,48,50];
- (7) Coherences between wind pressure samples at separated locations were stronger for model tests than for the full-scale measurements [21,50].

4. Researchers' Explanations of the Observed Full-Scale/Model Test Discrepancies

In the literature, many researchers gave their own explanations for their observed full-scale/model test discrepancies:

Low-rise buildings: Dalley [12] thought that the poor comparison between the full-scale and the model spectra recorded over the eaves of the Silsoe Structures Building indicated differences in the approaching flow between the two experiments. Hoxey et al. [13,15] believed that bluff-body aerodynamics were Re -sensitive, and the observed full-scale/model test discrepancies of wind pressures on the Silsoe Structures Building were Re effects, which were associated with the separated flow recorded on the windward roof slope of that building. Richardson et al. [14] suggested that the underestimation of high negative pressures on the roof of the Silsoe Structures Building in the wind tunnel tended to be related to the fact that viscous damping at the model scale attenuated the magnitude of pressure in the separated and vortex flow fields, which were fundamentally Re effects. Richards et al. [16] believed that the velocity profile, the turbulence, and Re could be responsible for the observed discrepancies in wind pressure on low-rise buildings. Richards and Hoxey [17] briefly considered the effects of reattachment length on the pressure distribution and found that the effects could not account for the differences in wind pressure between the two experiments on the 6 m cube benchmark model. They suggested that the full-scale/model test differences could be related to Re . Huang et al. [7] thought that the observed full-scale/model test discrepancies in their study were probably caused by the inadequate simulation of turbulence intensities in the wind tunnel, the small-scale turbulence content in the wind tunnel, the inaccurate details in the scaled model, the different stationary features of the oncoming flow between the two experiments, Re effects, and Jensen number effects.

High-rise buildings: According to Dalglish [26], the discrepancies observed by comparing the field measurement pressures on a 34-storey office building in downtown Montreal with the wind tunnel data were due to the difficulty of establishing a static reference pressure for full-scale measurements, the inadequacy of realistic wind velocity information, and the lack of stationarity and homogeneity of the full-scale velocity field. In addition, Dalglish [27] thought that the reasons for the discrepancy between full-scale measurement and model test results for Commerce Court Tower in Toronto were that: (1) the full-scale winds were not frequent enough or strong enough to provide sufficient reliable data, and (2) unsteadiness existed in the full-scale wind direction. Lim et al. [40] thought that the discrepancy between the full-scale measurement results and the model test data for the RMIT building 201 was related to the relatively low sampling frequency of the LiDAR and the spatial averaging of the data over a relatively large area in the field experiment.

Bridges: Delaunay and Grillaud [41] suggested that their full-scale/model test discrepancy for the Iroise cable-stayed bridge was a result of the improvement of the bridge between the early design stage and the final project. Frandsen [42] thought that the observed discrepancy was related to the scaling effects of the Great Belt East bridge model. Li et al. [44] attributed the full-scale/model test discrepancy of the suspension bridge to Re effects and the flow pattern difference.

Large-span structures: Chen et al. [46] suggested that the difference in the stadium's dynamic responses between the prototype measurements and the prediction utilizing model test data and finite element calculations might be attributed to inaccuracy in the full-scale measurements, the inaccurate modeling of wind loads on the roof of the stadium in the wind tunnel, the difference in wind direction, the mismatches of the turbulence intensity and the turbulence scale between the two experiments, the damping issue, and limitations in the finite element simulation.

Summarizing the researchers' explanations for the observed full-scale/model test discrepancies presented above, Richardson et al. [14], Hoxey et al. [13,15], and Richards and Hoxey [17] attributed the observed differences to Re effects. Marshall [22], Apperley et al. [8], and Dalley [12] proposed that the observed differences could be associated with the fact that the complete turbulent flow characteristics of a realistic ABL flow field can

hardly be truthfully simulated in a traditional, passive wind tunnel (hereinafter referred to as turbulent flow characteristic effects). Richards et al. [16], Li et al. [44], and Chen et al. [46] thought that both Re effects and turbulent flow characteristics effects existed. Dalgliesh [26] and Cheng et al. [48,50] attributed the observed differences to the fact that the non-stationary features of realistic ABL winds can hardly be truthfully simulated in a traditional passive wind tunnel (hereinafter referred to as non-stationarity effects). Huang et al. [7] believed that all the above adverse effects existed.

It is clear that the wind engineering community has arrived at the consistent conclusion that three main similarity problems adversely affect the reliability of the traditional ABL wind tunnel simulation technique. (1) Turbulent flow characteristics effects: Wind tunnel tests treat the empirical ABL flow characteristics presented in Codes of Practice and monographs as simulation targets. However, it was found that the turbulent flow characteristics simulated in the wind tunnel deviated from their simulation targets in many cases, causing significant negative effects. (2) Re effects: Basically, the flow separation location for flow around a bluff body without corners is sensitive to Re . Since the Re for model tests is usually two orders of magnitude smaller than the Re for the prototype flow event, significant distortions might be caused to the model test data. (3) Non-stationarity effects: Hurricanes, tornadoes, downbursts, and gust fronts are non-stationary in nature and are often highly transient. Being different from those extreme wind events, the common ABL strong winds were assumed to be stationary before. However, recent studies have indicated that the realistic ABL strong winds lack stationarity compared with the flow simulated in the passive ABL wind tunnel [26,48]. Although the non-stationarity of ABL strong winds may not be as significant as those of extreme wind events, this possibly makes the flow field harder to understand and has a significant influence on the wind effects on structures [50].

5. Personal Perspectives

Without field measurement experiences, the authors initially believed that a full-scale/model test comparison would be the most reliable approach to validate the traditional ABL wind tunnel test, and it was assumed that the majority, if not all, of the researchers who had not actually made full-scale measurements would endorse this contention. In view of the literature disseminated to those in the profession, Refs. [8–17,19–24,31–38,41–47,51–59] also directly or indirectly sustain this contention. The full-scale measurement campaign for wind pressures on the Peng-cheng cooling tower (see Section 3.5) was undertaken by the authors from 2009 to 2015; after completing the on-location practice, we have some different viewpoints.

Dalgliesh thought that full-scale measurements were inherently less accurate and deterministic than the wind tunnel experiments they were supposed to validate, so full-scale/model test comparisons have their limitations [4]. In fact, Dalgliesh's concerns regarding the inherent inaccuracies in full-scale measurements have not been dismissed by most full-scale measurement campaigns, although the real situations were usually not truthfully reported in the literature. For example, many full-scale pressure measurements were fatally compromised by the impossibility of obtaining reliable static pressure at a point that was situated close enough to the test building, but far enough away from neighboring obstructions, and providing a reliable backing pressure. The data from the BRE Aylesbury experiment (see Section 3.1.1) showed static pressure offsets on the different backing-pressure branches due to leaks through faulty pressure transducers. It was also extremely difficult to obtain a reliable dynamic pressure reference. In addition, the pressure and load transducers used in some field studies were notorious for their zero and calibration drift.

In the Peng-cheng cooling tower full-scale measurements, we directly arranged individual pressure transducers on the tower's external surface, instead of using pressure taps connected with pressure transducers via the tubing, to avoid the faulty pressure transducer's contamination of the whole measurement system. In addition, the static reference pressure was obtained using an innovative method of calculating the value from the total

wind pressure measured at a point with an invariant mean wind pressure coefficient, to address the issue that the reference static pressure traditionally established for pressure measurements on full-scale structures by using a pressure transducer arranged inside a cabin near the location cannot play the same role as static pressure in the wind tunnel [60]. Moreover, two anemometers were initially arranged near the Peng-cheng cooling tower at a height of 20 m for measuring the dynamic pressure reference, which is 110 m lower than the pressure measurement section. Therefore, the correlations between the measured wind velocity samples and the measured wind pressure samples were extremely low. To deal with this issue, wind velocity samples were extracted from the full-scale wind pressure samples measured in the quasi-steady region on the actual large cooling tower in order to calculate the dynamic pressure reference [61]. Finally, the zero-drift issue was effectively addressed by repeated and timely calibrations of the transducers when on location. However, even with these well-designed and correctly implemented field measurement practices, the data measured at the Peng-cheng cooling tower are still less deterministic and usually cannot clearly show any rule of physics. We suggest that this is associated with the non-stationarity and the non-uniformity of the realistic wind velocity field and the constantly changing wind direction at the location, which are hard to control. Now, we believe that besides the inherent technical issues with the ABL wind tunnel simulation technique introduced in Section 4, the inaccuracy and the non-deterministic nature of the full-scale measurement process also largely contribute to the full-scale/model test discrepancies observed.

To this end, some researchers have used other methodologies to validate wind tunnel tests, particularly parametric studies in wind tunnels (such as a variation of the Jensen number or of the turbulence length scale) or comparisons between different wind tunnels testing the same model. The Aylesbury comparative experiment (ACE) used “blind” testing, i.e., each laboratory had one of three identical models and test specifications but had no knowledge of the results from the other laboratories until the results were reported. The key finding of the ACE was that differences between the different tests were almost completely due to errors in the reference static and dynamic pressure values.

Finally, we suggest that future studies by the wind engineering community regard the full-scale measurement process as only a benchmark, and that works should focus on synthesizing the results from the full-scale measurements and the wind tunnel experiments to obtain universal empirical formulae that will be of high theoretical significance to properly validate future wind tunnel tests. A good example in history is the endeavors made by the wind engineering community to acquire a target for the high Re effects simulations on circular cylindrical models in wind tunnels. Since the 1970s, many researchers have measured the mean wind pressure distribution on several full-scale large cooling towers. However, the results are usually incomplete and scattered, and cannot meet researchers’ needs regarding the use of these results in wind tunnel tests at low Re . By supplementing these full-scale measurement results with sufficient wind tunnel data of low precision and via effective mathematical fitting, a formula using an eight-termed Fourier series to express the mean wind pressure distribution on large cooling towers at high Re has finally been obtained, which effectively provides the standard for validating the wind loads as simulated on circular cylindrical models in wind tunnels today. In addition, we and most of the authors of the reference articles suggest performing more accurate full-scale measurements in future research by addressing the uncertainty issue regarding the technique, which is usually associated with the nature of realistic wind events (the unsteady and the non-stationary features), the testing errors related to the equipment and the humans involved, the free choice of data processing practice, etc.

6. Conclusions

For this article, the authors performed full-scale/model test comparisons to validate the traditional ABL wind tunnel simulation techniques, which are systematically reviewed. The authors’ engineering backgrounds are in low-rise buildings, high-rise buildings, bridges, large-span structures, and towers. According to the literature review, most

comparisons supported the conclusion that notable differences existed between the full-scale measurement data and the model test results. Most scholars subjectively inferred that inherent technical issues with the ABL wind tunnel simulation technique could be responsible for the observed full-scale/model test discrepancies. However, based on the authors' years of experience, and after exchanging data with experienced researchers, it was found that some of the full-scale measurements performed in the literature were inherently less accurate and deterministic than the wind tunnel experiments they were supposed to validate, which could also be a significant cause of the full-scale/model test discrepancies observed.

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