Proceedings of the 4th UJNR Panel on Wind and Seismic Effects Workshop on Wind Engineering, July 20-21, Tsukuba, Tokyo

Modeling and Simulation of Transient Wind Load Effects

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ABSTRACT

Notwithstanding the developments made in recent decades in wind effects on structures, there is a need to revisit the current paradigms and to look for improved understanding concerning the nature of wind field, associated aerodynamics and the resulting load effects in light of the emerging themes: non-stationarity/non-homogeneity/transient wind events; mechanical/convective turbulence; unsteady/transient aerodynamics. This paper discusses these issues and illustrates their significance as the next frontiers in wind engineering, current progress and activities at the NatHaz Modeling Laboratory to address this challenge. The "Gust Front Factor" is introduced that follows codes and standards based description of wind loads and it accounts for the following features: variation in the velocity profile; dynamics effects introduced by the sudden rise in wind speed (pulse effect); non-stationarity (amplitude/frequency modulations) of turbulence in gust fronts; transient aerodynamics.

1.0 INTRODUCTION

The assurance of structural safety and reliability under wind loads requires accurate modeling of wind load effects. Significant work has been done to quantify and codify the effects of synoptic winds. However, not all wind events fit neatly into this classification, e.g., thunderstorms, hurricanes, and gust fronts. Various new experimental techniques and simulation methods are being developed to help establish a framework for incorporating the effects of transient events into the design of modern structures. As more full scale measurements are collected regarding severe wind events, new approaches to modeling are being created and improved, and these approaches extend into both physical models and computer simulations. With these new tools, the establishment of a new framework for studying transient, non-stationary wind events will be developed to account for effects that could significantly impact structural response, from what has already been accounted for in the case of synoptic winds. The aim of this work is the codification of new information, needed for the design of wind resistant structures.

2.0 STATIONARY VERSUS NONSTATIONARY/TRANSIENT WINDS

Most extreme wind events are non-stationary in nature and are often highly transient, e.g., wind fields in hurricanes, tornadoes, downbursts and gust fronts. Therefore, the most critical issue in wind field characteristics concerns the transient wind events, e.g., gust-fronts generated by downdrafts associated with thunderstorms. The significance of these transient wind events and their load effects can be readily surmised from an analysis of thunderstorm databases both in the U.S. and around the world, which suggests that these winds actually represent the design wind speed for many locations (Twisdale and Vickery, 1992; Brooks et al., 2001).

The mechanics of gusts associated with convective gust-fronts differs significantly from conventional turbulence (driven by momentum) both in its kinematics and dynamics. A survey of full-scale studies in the meteorological field suggests that winds spawned by thunderstorms, both on the updraft side as tornadoes and on the downdraft side as a downburst, fundamentally differ from the synoptic winds in neutrally stable atmospheric boundary layer flows. The key distinguishing attributes are the contrasting velocity profile with height and the statistical nature of the wind field. In gust-fronts, the traditional velocity profile does not exist; rather it bears an inverted velocity profile with maxima near

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the ground potentially exposing low- to mid-rise structures to higher wind loads (e.g., Wood and Kwok, 1998; Holmes and Oliver, 2000; Letchford and Chay 2002). Furthermore, such a change in the approach flow profile/kinematics, even in a steady state flow, would introduce a major change in the flow-structure interaction that may differ significantly from the corresponding boundary layer flow case. This is compounded by the inherent transient nature of energetic convective gusts that rapidly increase in amplitude and direction raising serious questions regarding the applicability of conventional aerodynamic loading theories. Although the size of gust-fronts may be relatively small and their effects rather local, the fact remains that they can produce significantly damaging winds. The famous Andrews Air force base downburst of 1983 clocked peak gusts of 67 m/s, whereas, ASCE Standard provisions list 50-year recurrence winds of 40-45 m/s (ASCE 7 Standard) in this region (Fujita, 1985).

Accordingly, one should question the appropriateness of a design based on conventional analysis frameworks in codes and standards, which generically treat these fundamentally different phenomena in the same manner. Extreme loads on structures are potentially sensitive to the influence of transient flows, i.e., the load coefficients may be enhanced by the form of gust and the associated rapid changes in the local flow and the load effects are likely to be correlated over larger areas than in conventional flows. These aerodynamic consequences clearly point to potentially higher loads on structures than would be predicted by the present codes and standards, thus calling for a careful examination of traditional design procedures.

The major challenge in this area is at least twofold, i.e., first the nature of flow field in rain bands, the eye wall of hurricanes, downdrafts and gust fronts need to be better quantified and secondly, analysis and modeling tools to capture these features need to be established. Design loads are based on the mean wind speed for a given site and direction and rely on the assumption that the fluctuations in the mean are characterized by a statistically stationary process, which has led to useful and practical simplifications. However, the gust-fronts generated in thunderstorms/downdrafts differ from the large-scale (extratropical/ depressional) storms as the mean wind speed exhibits sharp changes and in some cases changes in wind direction. This leaves the assumption of stationarity open to serious criticism.

Besides, this departure in statistical attributes of the wind field, gust-fronts are likely to be associated with rapid and substantial changes in the local flow around structures and will likely be correlated over a larger area. These changes in the kinematics and dynamics of the flow field would potentially result in higher aerodynamic loads. These attributes further complicate the concept of "gust factors," which in some forms are central to most assessments of wind loads. The gust factor concept, used for extratropical winds, must be revisited as the period used to evaluate average wind speeds for thunderstorm winds must be shortened to obtain meaningful results. The use of longer periods, like one hour, for thunderstorm winds may result in values of the gust factor almost 2-3 times the corresponding values in extratropical winds (e.g., Choi and Hidayat, 2002; Masters et al., 2005; Wang and Kareem, 2004). Current efforts toward gleaning information regarding the thunderstorm outflow characteristics would certainly aid in better defining the wind fields associated with these transient wind events (Gast et al., 2003). Also, new approaches towards modeling non-stationary winds would aid in better capturing the salient features of winds in transient events (Wang and Kareem, 2004; Chen and Letchford, 2005). In a recent study, Kwon and Kareem (2006) evaluated the efficacy of variable averaging intervals for characterizing nonstationary winds and recasting the gust factor as the storm evolved over time.

3.0 MECHANICAL/CONVECTIVE TURBULENCE

The origin of atmospheric turbulence can be broadly classified into two broad categories, i.e., mechanical and convective. While the former results from the shearing action of flow field by the protuberances from ground surface such as urban developments, vegetation and, in the case of oceans, sea surface roughness. This is the most common type of turbulence studied in the area of wind effects on structures as it manifests different levels of turbulence structure depending on the terrain topographical and surface features. The level of turbulence is characterized by the turbulence structure: intensity; length scale; spectral and correlation structure. The other type of turbulence results from convective origin resulting from atmospheric instabilities associated with atmospheric dynamics. One is more familiar with this type of turbulence while going through cloud cover or around thunderstorm in a plane. In contrast with the boundary layer type flows in these storms, the convectively driven flow fields have their own unique character and structure. Thunderstorm winds, downbursts and hurricane winds have a significant component that results from convective effects. Often the mechanical component is dwarfed by the convective effects due to the transient nature of these flows which do not have time to evolve into well developed flows and may not always reflect the terrain characteristics of the boundary.

The main challenge in this area is the structure of turbulence in extreme wind events like hurricanes, tornadoes, downdrafts and gust fronts. Questions remain as to the profiles of the mean flow and structure of these events which may play a major role in quantifying wind load effects on structures. Discerning the role of convective turbulence may become equally important as we obtain a better understanding of the overall turbulent structure in these extreme wind events and its ramification on the established loading models that rely on the structure of mechanical turbulence only.

4.0 CHANGING DYNAMICS OF AERODYNAMICS

The subject of aerodynamics has been treated traditionally by invoking the quasi-steady and strip theories and has been extended to unsteady aerodynamic theories for loads originating from wake aeroelastic effects. The current challenges are to address the aerodynamics in transient flows.

4.1 Transient Aerodynamics

Earlier and recent studies in fluid dynamics have pointed out an overshoot in aerodynamic/hydrodynamics loads on cylinders in unsteady flows (Sarpakaya, 1963; Okajima, 1997). It has also been noted that for the analysis of structures in non-stationary atmospheric turbulence, the traditional stationary analysis fails to account for possible transient overloads, e.g., the sharp changes in gusts were found to cause a transient aerodynamic force on a bridge model, which cannot be explained by a stationary statistical analysis (Kitigawa et al., 1982). The exposure of trains/trucks suddenly emerging from a tunnel to the energetics of gust-fronts can lead to drastic aerodynamic modifications, i.e., force sign reversal, which have led to serious concerns for their operational safety. As another example, a recent study by Yalla and Kareem (www.nd.edu/~nathaz) concerning pressure distributions on a wall exposed to periodic waves, large overshoots in pressure were noted due to sudden action of a wave slamming on the wall, which subsequently settled to normal hydrodynamic pressure levels. This trend is further confirmed in recent experiments involving a simulated downburst utilizing a translating wall jet, which suggests that surface pressures over a cube exceed the quasi-steady estimates (Letchford and Chay, 2002). This clearly points at the need to critically assess the impact of abrupt changes in the wind field magnitudes and associated modifications in aerodynamics of structures and supports the need for refining the current load descriptions. Efforts to explore these issues in transient aerodynamics are in place currently at several research establishments.

5.0 ANALYSIS, COMPUTATIONAL, IDENTIFICATION AND MODELING TOOLS AND FRAMEWORKS

The simulation of stationary Gaussian processes can be accomplished using spectral, time series and other techniques, such as state space modeling. A summary of these techniques can be found in Kareem (1999). Simulation of non-stationary events like gust fronts and hurricane wind fields can be accomplished by the generic summation of trigonometric time series, but it is computationally inefficient, since, due to lack of ergodicity, ensemble averaging requires simulation of a large number of time series. The POD based approach offers computational expediency, but thus far it has been explored to account for the amplitude modulations (Chen and Letchford, 2005a). The wavelet-based simulation offers an attractive approach, which may better capture both time and frequency modulations essential to describing complex events like downbursts. (Wang and Kareem, 2004, 2004a and 2005). An example of such a simulation in the time-frequency framework based on the measurements in a thunderstorm outflow (Gast et al., 2003) are presented in Fig. 1. The efficacy of the simulation scheme is demonstrated in Wang and Kareem (2005) utilizing comparison of the time-frequency attributes of the simulated and target time series. This simulation scheme has been extended to conditionally simulate time histories of wind at locations where data was not observed, or was missing due to malfunctioning of instruments (Kareem, 2006)

As computers increase in both computational speed and data storage capacity, computational fluid dynamics (CFD) is becoming a more attractive alternative to quickly simulating wind effects. Recent work into simulating transient events utilizing FLUENT, a popular commercial CFD package, has demonstrated its ability to model particular aspects of the flow field. Kim et al. (2005) utilized FLUENT to model downburst winds and their effects on a structures, indicating a wide variety of responses and other avenues for investigation. Chay et al. (2006) modeled a downburst characteristics using FLUENT, verifying its usefulness in simulating non-turbulent wind fields. The area of CFD modeling presents many new opportunities, but there are still challenges that limit its widespread use.

6.0 SCALE MODELS

6.1 Wind Tunnels and Beyond

Both active and passive devices have been used to generate turbulent boundary layer flows in shorter test sections. Active devices like air jets, flapping vanes, airfoils and individually controlled multiple fan facilities are capable of generating a wide range of turbulence parameters. More recent efforts are underway to generate vortical flows, like tornadoes, and impinging translatory jet type flows, like in thunderstorm outflows, and other transient features using active and passive devices, including moving or pulsating jets, computer controlled battery of multiple fans, special management of flow through bypassing of flow in the test section (Letchford and Chay, 2002; Cao et al. 2002; Haan et al. 2003).

The NatHaz Modeling Laboratory has developed a transient flow field simulator (TFFS) to generate sudden changes in wind speed to mimic gust-fronts utilizing a battery of low inertia, AC servomotor driven and individually computer-controlled fans in an open circuit wind tunnel-type test section with tailored transient flow features (Fig. 2). A similar wind tunnel (Fig. 3) has been earlier developed at Miyazaki University which employs 99 fans to generate effectively desired flow features (Cao et al. 2002). The NatHaz Laboratory, in collaboration with the Center of Excellence (COE) on Wind Effects in Urban Areas at the Tokyo Polytechnic University, is investigating the role of transient aerodynamics in the formation of loads on basic surface mounted prisms. Figure 4 shows interesting temporal variations in time histories of wind fluctuations at various heights in a simulated gust front.

The NatHaz Laboratory is also undertaking experiments utilizing established wind tunnel facilities. The addition of a controlled flat plate, operating at a high incidence to the flow, modifies the existing boundary layer in the tunnel to create a gust front wind speed profile. Figure 5 shows the initial setup of the inclined flat plate within a standard, modular low speed wind tunnel section. Figure 6 compares the results of measurements conducted in the low speed wind tunnel with those of laboratory and full scale experiments, demonstrating good agreement and the feasibility of the modification. Ongoing work is aimed at finding optimal orientations and flow conditions while investigating the effects of flow field modifications and subsequent transient behaviors on scale models. This type of setup provides an easily implemented method of conducting experiments in existing wind tunnel facilities.

7.0 CODES/STANDARDS AND DESIGN TOOL

Design loads are based on the mean wind speed for a given site and direction and rely on the assumption that the ratio of the fluctuations to the mean is a statistically stationary process, which has led to useful and practical simplifications. However, the gust-fronts generated in thunderstorms/downdrafts differ from the large-scale (extratropical/depressional) storms as the mean wind speed exhibits a departure from the boundary layer profiles, sharp changes, and in some cases changes in wind direction as alluded to in the earlier sections.

In spite of the preceding observations, one can argue that the current design codes are adequate, in general, and there is no overwhelming view that these are not. This is notwithstanding limitations due to reductive formats and simplifications in codes. Structures are vulnerable to the actions of extreme winds and may experience some level of failure in extreme winds, which can be attributed to an under-design lacking necessary redundancies, poor construction and deterioration due to aging rather than simply under specification of wind speeds. Aerodynamic studies in oscillatory flows and recent initial studies in impinging, translating or pulsating jets and actively controlled fan generated flows would provide sufficient evidence to implicate if indeed there is possible load enhancement.

7.1 Introduction of Gust Front Factor

One possible scenario to account for the changes in load effects in gust-fronts would be through quantifying wind speeds that would embody the effects associated with gust-fronts. It is proposed that this be accomplished through introduction of the “Gust-Front Factor” akin to the gust loading factor for buffeting effect currently widely accepted in codes and standards (Kareem, 2006). Such augmentation in wind loads nonetheless should not be to account for poor design or construction practice. Rather, it could be clearly defined as a practical step to account for load increase without changing the historic force/pressure database. Such changes may be warranted for all or limited cases depending on the findings of the research involving transient wind.

7.2 The Gust Front Factor

With the success of a gust loading factor for capturing the dynamic effects introduced by buffeting and its popularity in design standards and codes have led us to introduce a “Gust Front factor” which can be used in conjunction with the existing design standards (Davenport 1967; Zhou and Kareem, 2001). The Gust Front Factor is introduced that follows codes and standards based description of wind loads and it accounts for the following features: variation in the velocity profile; dynamics effects introduced by the sudden rise in wind speed (pulse effect); non-stationarity (amplitude/frequency modulations) of turbulence in gust fronts; transient aerodynamics. The design load is described as:

$$F_{Design} = F_{ASCE\text{-}7}\, G_{G\text{-}F} \tag{1}$$

where F_{Design} is the design load, $F_{ASCE\text{-}7}$ is the current recommendation of ASCE 7 and $\mathrm{G}_{\mathrm{G\text{-}F}}$ is the Gust Front Factor (GFF). In case of normal boundary layer case the $G_{G\text{-}F}$ reduces to unity and the design load would be equal to the ASCE 7 recommendations. The details concerning the formulation of the GFF are quite involved and would be addressed in a subsequent publication. In view of the complexity of the problem, we are introducing a web-based portal to assess the GFF in an e-design format used earlier (Kwon et al., 2005). It should be emphasized that this is the first time such a concept has been advanced and, like its counterpart gust loading factor, it is expected that it will over years advance in its sophistication in modeling and ease of computation so that it eventually finds a home in ASCE 7, other design standards and design office practice.

8.0 CONCLUDING REMARKS

This paper reflects on one of the critical issues in wind effects on structures concerning transient/nonstationary effects. Various new avenues for investigating and quantifying these effects are presented. Advances in the overall body of knowledge have been made as a result of full scale measurements, aided by new analysis, computational and modeling techniques. However, there are still many avenues to be explored regarding the effects of non-stationary severe wind events on structural loading and response. The "Gust Front Factor" is introduced that follows codes and standards based description of wind loads and it accounts for the following features: variation in the velocity profile; dynamics effects introduced by the sudden rise in wind speed (pulse effect); non-stationarity (amplitude/frequency modulations) of turbulence in gust fronts; transient aerodynamics.

9.0 ACKNOWLEDGMENTS

The authors acknowledge the support provided in part by NSF Grant CMS 03-24331. The authors are also very grateful to Prof. Yukio Tamura, Director COE, Tokyo Polytechnic University, and Profs. S. Cao and A. Nishi for their counsel and support of the experiments at Miyazaki University.

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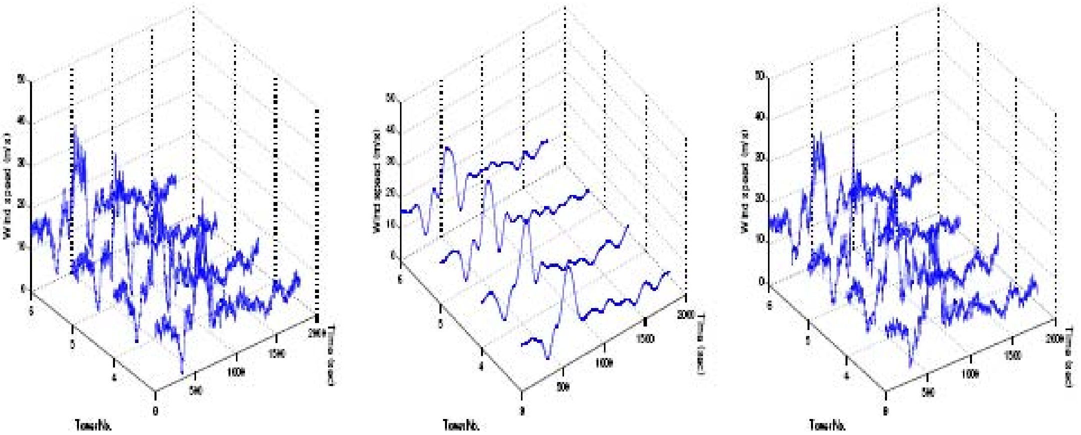

a) Measurements b) Time-dependent means c) Simulations

Fig. 1 Example simulation of a gust front (Wang and Kareem, 2005)

Figure 2: Transient Flow Field Simulator (TFFS) at the NatHaz Laboratory

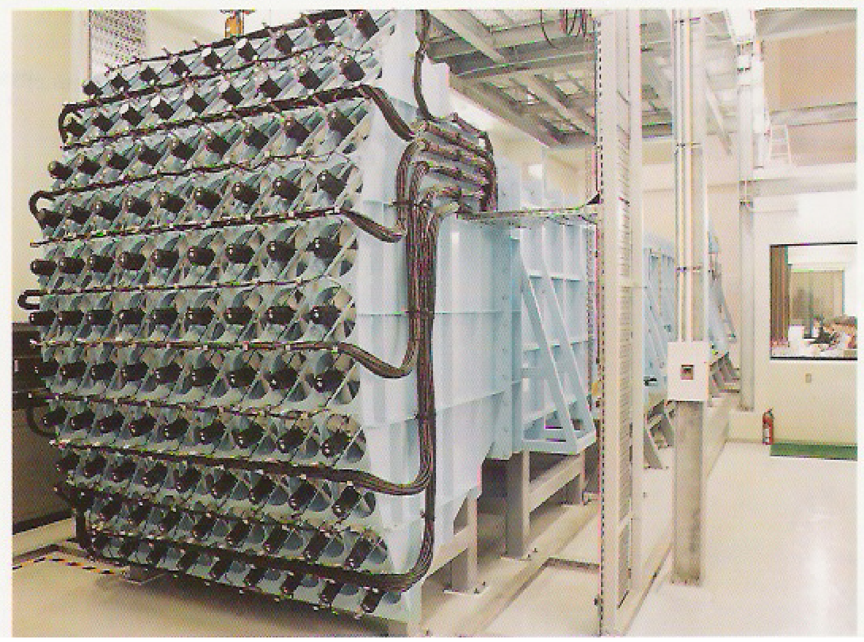

Figure 3: Actively controlled Miyazaki University wind tunnel

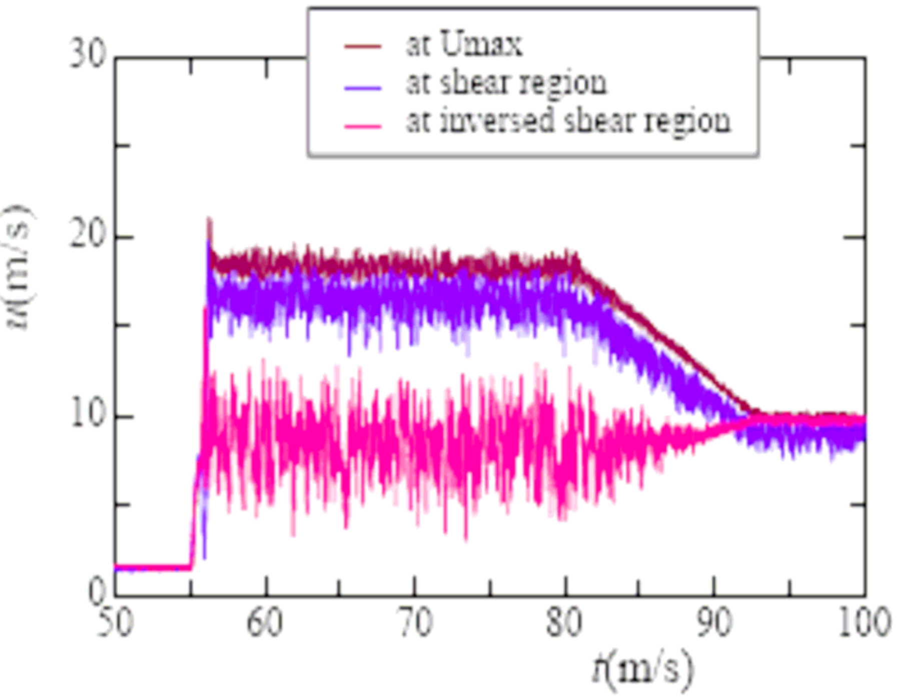

Fig. 4 Temporal velocity variations along the height of a simulated gust front flow field (Miyazaki Wind Tunnel)

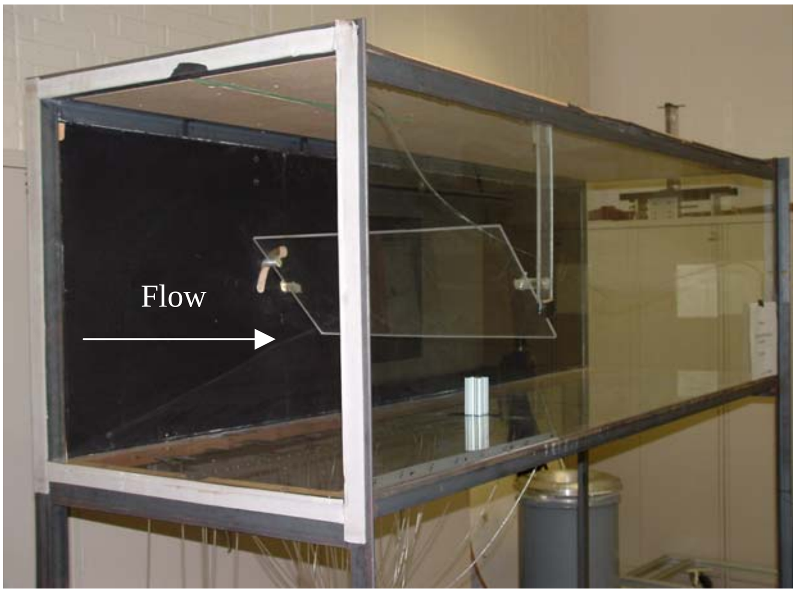

Figure 5: Downburst flap installed in a standard low speed wind tunnel section at the NatHaz Modeling Laboratory

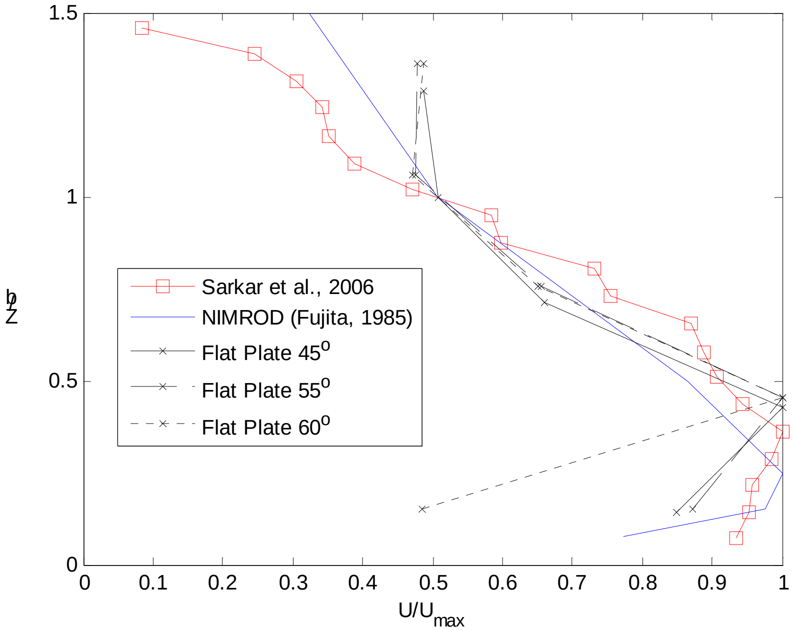

Figure 6: Downburst flap experiment results compared to laboratory and full-scale measurements