Wind Effects

Wind Effects on Buildings and Urban Environment

Bulletin

Vol.6 August 2006

Wind Engineering Research Center
Graduate School of Engineering
Tokyo Polytechnic University

INDEX

Annual Report of COE Research Projects

Project 1: Wind Hazard Mitigation

The objective of research project 1 was to promote and develop wind engineering technologies to mitigate wind disasters. The following researches were conducted in 2005FY.

Universal equivalent static wind load distribution

This paper describes a method for calculating the largest load effect (i.e., maximum and minimum load effect) on all structural members from a time history response analysis, and proposes a universal equivalent static wind load that reproduces the largest overall load effect. The method is then used to determine the maximum load effects for several actual cases. The goal is to provide a database of universal equivalent static wind load distributions and to develop a wind resistant design method. In practice, as the design wind load should be combined with dead load or snow load, either the maximum or minimum load effect is required to estimate the equivalent static wind load. In this discussion, the mean component is excluded from the wind load and the load effect. As the load effect can be positive and negative in the same member, all 2-powered N combinations of load effect can be considered in numbers of member N. Two combinations of largest load effects are required to determine the equivalent static wind load. One simple combination yields only positive or negative load effect. However, the equivalent static wind load reproduced by these combinations may be shown to be quite an unrealistic distribution. The largest load effect with the same sign as the mean load effect is not always shown to be a realistic load distribution. Here, a method for obtaining a more realistic universal equivalent static wind load distribution is developed. For the cantilevered truss roof shown in Figure 1, which consists of 336 members, the wind direction is parallel to the ridge. A POD analysis is applied to the fluctuating axial force calculated by time history response analysis. The sign of the largest load effect is consistent with the 1st eigen mode of the fluctuating axial force. As shown in Figure 2, the universal equivalent static wind load shows a realistic and smooth distribution.

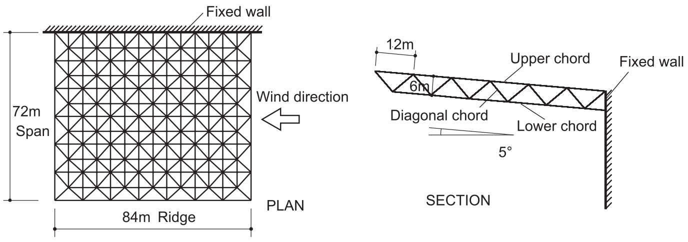


Figure 1: Large span cantilevered truss roof model

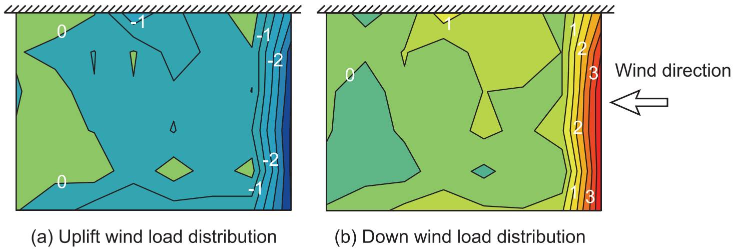


Figure 2: Universal equivalent static wind load distribution that reproduces maximum and minimum axial stress for all structural members of cantilevered truss roof

Wind disaster investigation and design wind speed

This study investigated the interaction of wind climates and structures including characteristics of extreme winds not only in Japan but also in other countries, and damage propagation processes of buildings.

There were 23 typhoons in 2005 and 3 of them made landfall in Japan. Typhoon 0511(MAWAR) caused damage from the Tokai to Kanto districts on August 25. Post-disaster investigation was conducted for a gymnasium of a junior high-school in Hakone, Kanagawa-prefecture. Typhoon 0514 (NABI) landed at Kyushu on September 6th, passed over the Sea of Japan and landed again at Hokkaido on September 7th. According to the General Insurance Association of Japan, losses due to damage amounted to at least 65.8-billion yen. Tornadoes accompanied the typhoon in two areas in Miyazaki-prefecture. This investigation showed considerable damage due to flying debris.

The most serious damage caused by winds occurs under the climates of typhoons, tornadoes and downbursts. However, in 2005 extra-tropical depressions developed in winter over the Sea of Japan and caused serious wind damage on the north-west coast of Japan. This type of wind climate had not been previously recognized

Photo 1: Damaged roof of gymnasium (T0511)

Photo 2: Damaged roof tiles at ridge (Yamagata prefecture)

Photo 3: Damaged snow fence (Yamagata prefecture)

as a cause of extreme winds. Especially in Yamagata-prefecture, considerable damage occurred in which a limited express derailed and overturned on the JR Uetsu-line. An urgent meeting was held by the Japan Association for Wind Engineering (JAWE), and it made recommendations for immediate intensive research. These recommendations stressed the necessity for an observation system network such as a doppler radar and establishment of an enhanced nowcast technique. They were submitted to the Minister of Land, Infrastructure and Transport of Japan via JAWE.

In the United States, hurricane Katrina caused serious damage, and a post-disaster investigation was conducted. This revealed damage to walls and windowpanes.

Design wind speeds

The design wind is important in evaluating the wind load of structures. Wind speed analysis should consider meteorological characteristics. One extreme wind climate is typhoons. Track data of typhoons in the north-western Pacific region were collected as well as extreme wind data in Asian countries (wind data in Vietnam in 2005).

Differences between basic wind speeds in countries bordering Japan have been studied. The necessity of future cooperation with neighboring countries is emphasized to get more consistent basic wind speed maps in the APEC area.

Wind resistant design of tiled roofs

Instantaneous wind force distributions were examined to determine the loading modes on roof tiles from wind tunnel test results. A negative peak force occurs only on one tile. That is, relatively large negative forces act on 2x2 or fewer tiles simultaneously. Thus, the restraint effect caused by overlapping of adjacent tiles prevents tiles from lifting during strong wind.

Static loading tests were carried out to clarify the fixing effects of tiles with overlaps. It was found that the load-displacement relationship can be reduced to the gravity effects and fixing effects.

Details of houses in Asian countries and in the Japanese islands were investigated. Some typical details were revealed that are relevant to wind resistant design.

Usability of high-rise buildings under high wind

Visual perception of vibrations was studied. As a preliminary study, visual objects and their observed durations were measured in an office and in a house. From this measurement, the probability of visual perception will be studied.

Wind response monitoring, system identification and urban hazard mitigation system

The accuracies of RTK-GPS and EEA-GPS were compared. Multi-GPS antennas were installed on buildings in different places to measure the responses. To transmit the structure response information, a system was constructed by which the acceleration records were uploaded to the website.

To validate the accuracy of damping estimation methods, numerical simulations were performed and the results from the frequency domain decomposition method

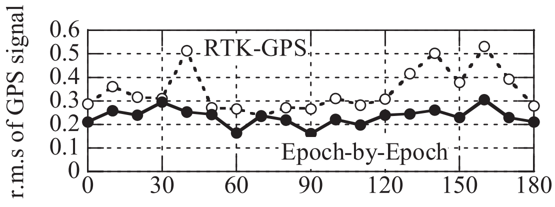


Figure 3: RMS value of GPS signal at stationary point

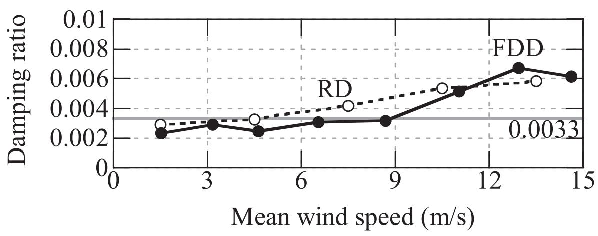


Figure 4: Damping ratio of high-rise steel tower for across wind direction

and the multi-random decrement technique showed good agreement with the actual values.

Ambient vibrations and wind-induced responses were measured for a high-rise steel tower to identify its dynamic characteristics and to evaluate the amplitude-dependent damping including the effects of aerodynamic damping using frequency domain decomposition and a multi-random decrement technique.

Wind pressure database and wind resistant design of large span structure

Wind pressure data on kinds of low rise buildings were obtained from wind tunnel experiments and opened to the community through the internet.

Wind pressure on large-span spherical shells was measured. Correlation between the dominant structure mode and the POD mode was examined.

CFD research

A CFD solver for predicting the wind pressure field on structures immersed in an atmospheric boundary layer is being developed. Numerical experiments of channel flow, cavity flow and flow around bluff bodies were conducted to check the accuracy of this solver.

Wind tunnel study of unsteady flow

Abrupt wind speed change ($30m/s^2$) was achieved in the wind tunnel. The aerodynamic forces on a rectangular cylinder in unsteady flow are being studied. In addition, a flow with a vertical mean velocity profile similar to a gust front was simulated in the wind tunnel.

Project 2: Design Method for Natural/ Cross-Ventilation

The aim of research project 2 is to develop a guideline for a cross-ventilation design method and to hold a workshop on the guideline in the final year of the COE project. The main works in this research in 2005 were as follows.

High-precision ventilation model for ventilation flow rates

The proposed local dynamic similarity model for ventilation flow rates expresses the relative pressure balance between the cross-ventilation driving pressure and the interfering cross-flow dynamic pressure in the vicinity of an opening. In the past several years, previous work has indicated that, for an isolated building model, the model improves the prediction accuracy of ventilation flow rates compared to that of the conventional orifice flow model even when the discharge coefficient greatly decreases with change in wind direction.

In 2005 we obtained the following research results from wind tunnel experiments. For outflow openings, the relations between discharge coefficient and dimensionless room pressure P_R* are similar even when the wind directions and opening positions are varied. It is possible to estimate the discharge coefficient by a single parameter P_R*. The tangential dynamic pressure P_t at the outflow openings was not constant, but it could be substituted by P_t measured close to the wall of a sealed building. When porosity is 16% or lower, the validity of the local dynamic similarity model is established regardless of porosity and approaching flow angle. The local dynamic similarity model coupled with a simple network model indicated better prediction accuracy of ventilation flow rates in two rooms than the conventional orifice model, as shown Figure 5.

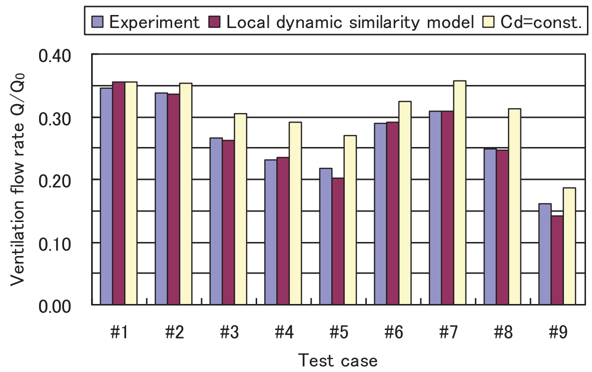


Figure 5: Measured and predicted ventilation flow rates

Analysis of airflow structure in cross-ventilated building by RANS turbulence model

Cross-ventilation is a phenomenon of very complicated turbulence flow because of the interaction of internal flow with envelope flow. The pressures near the opening exhibit reversible and irreversible changes of energy between dynamic pressure and static pressure associated with extreme deformation of airflows. Project 2 has successfully identified the mechanism of the interaction between inside and outside airflows in an isolated building model through simultaneous use of experiments and CFD. The modified k-ε model incorporating Durbin's limiter greatly improved the prediction accuracy of wind pressure distribution on a bluff body when compared with the standard k-ε model. The relatively poor prediction of the pressure distribution on an inclined roof surface may originate from the poor quality of the mesh system used to represent the actual shape of the flow domain near the roof. Further research is needed to handle complicated flow geometry using more sophisticated mesh systems.

Evaluation of thermal comfort in cross-ventilated environments

It is important not only to evaluate the wind-driven ventilation environment quantitatively but also to evaluate the thermal comfort of occupants from the qualitative aspect of the airflow and from the thermal viewpoint. The project aims at a new target, i.e., to evaluate the thermal comfort of occupants in wind-driven ventilation environment from the qualitative aspect of airflow. A preliminary field experiment on thermal comfort was conducted in a condominium in August, 2005, as shown in Figure 6. The convective heat transfer coefficients on the human body and the thermal comfort of occupants in a cross-ventilation environment were investigated with two adult persons and a thermal mannequin in sitting positions on chairs. The occupants voted their feelings on airflow, warmth and chilliness and how they felt about their thermal comfort during the experiment.

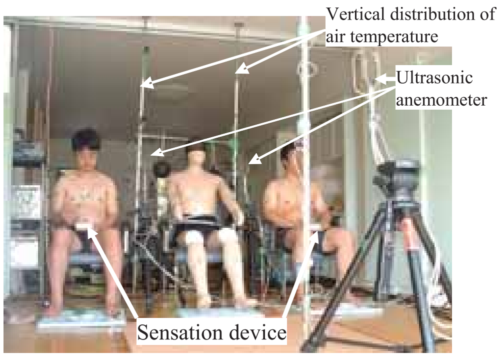


Figure 6: Field experiment on thermal comfort

International workshop

The 2nd International Workshop on Natural Ventilation was held at the AIJ Hall in Tokyo on 1st/2nd December, 2005. 7 foreign speakers and 11 Japanese speakers presented forefront studies on natural ventilation. In the 2nd session, a panel discussion entitled “Natural Ventilation for Passive Cooling and Its Regional Feasibility” was held. Each panelist presented standards on natural ventilation design for his country and introduced various case study buildings. Active discussion took place on the following subjects: appropriate design methods for opening sizes for natural ventilation, how to link users to natural ventilation, and the cost of natural ventilation. In the two-days' sessions nearly 200 persons participated in the workshop. The workshop offered the opportunity to exchange frontier technologies and perspectives on wind-induced natural ventilation and to introduce attractive features of ventilation study to the participants

Project 3: Indoor/Outdoor Air Pollution

Air pollution in urban areas poses a serious threat to human beings. Dispersion of pollutants in city areas, street canyon and residential areas is an important area of research. Although various regulations have been put in force, the problem is still acute. Indoor air pollution is another area that needs to be addressed. Indoor air pollution, such as sick house syndrome, sick building syndrome and damp building syndrome are very common problems. Hence, there is need for immediate measures and policy to control the air pollution menace, in both the inside and outside air environments.

The aim of Project 3 is to provide new knowledge for reducing air pollution and to propose risk assessment systems. This will contribute much to safe and healthy life, especially to environmental deterioration in developing countries where a large amount of pollutant is exhausted into the atmosphere.

The project is categorized in two areas: (i) outdoor air environment and (ii) indoor air environment.

(i) Outdoor air environment

In the outdoor air environment field, we are developing an accurate CFD model for predicting pollution levels in urban locations, and carrying out wind tunnel experiments to verify its applicability. In fiscal 2005, we developed a calibrator for a hot wire probe with different temperature and a system for simultaneously measuring fluctuating concentration, velocity and temperature (Figure 7, 8). By using these systems, we also carried out an accurate wind tunnel experiment for measuring concentration diffusion in nonisothermal flow. This experiment is providing data such as average wind velocity, temperature, concentration, various turbulence intensity data, shear stress, heat flux, concentration flux, etc., which are necessary for CFD verification (Figure 9). We are reducing measurement inaccuracies in this experiment and improving the reliability of data for CFD verifications. Steady RANS could cause us to over estimate a pollutant gas's concentration in weak wind regions behind buildings

Figure 7: Calibrator for hot wire probe with different temperature

Figure 8: System for simultaneously measuring fluctuating concentration, velocity and temperature

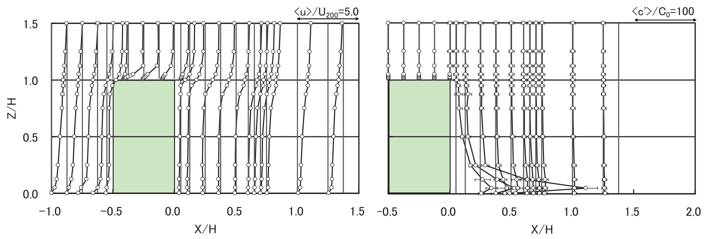


Figure 9: Measurement examples

Figure 10: Modeling region of Mong Kok in Hong Kong

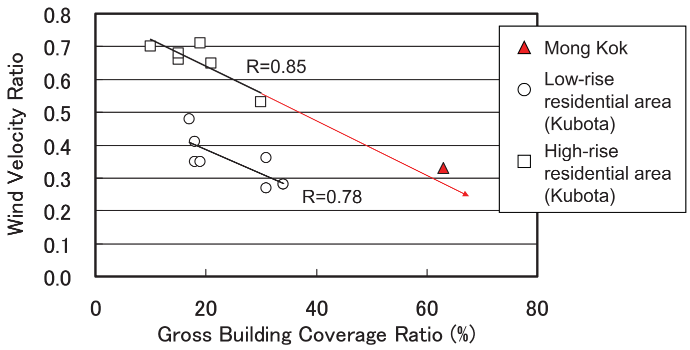


Figure 11: Relation between gross building coverage and wind velocity ratio

when we compare it experimental results. However, it is clear that prediction accuracy would progress substantially if we could reproduce periodic vortex shedding in Unsteady RANS. Thus, we placed a guard at CFD simulations by LES and DES since it is difficult to reproduce periodic vortex shedding in a RANS model. We developed a parallel LES program in fiscal 2005, and are carrying out calculations based on the above experiments.

Furthermore, at the start of fiscal 2005, as a new research topic, we added a wind tunnel experiment for setting up a cross-ventilation assessment system in Hong Kong and CFD simulations. As a first step, we made a model of the cityscape of Mong Kok with closely-packed high-rises (Figure 10), and carried out a wind tunnel experiment to determine street ventilation and pollutant diffusion. In Hong Kong, where the building density is much higher than in Japan, urban areas are very poorly ventilated compared to our country, and the average wind velocity ratio would be organized by gross building coverage ratio as in past researches of Kubota (Figure11).

(ii) Indoor air environment

The "quality" problem regarding the overall indoor environment is called IEQ (Indoor Environmental Quality). This area has been attracting increasing attention with the increasing health consciousness of residents. The research project 'Indoor Air Environment' will be based on the analysis of the flow field that is formed indoors and will deal with IEQ control totally. Key words of our research project are Contamination Control and Public Health Engineering.

This research focuses on indoor air pollution issues that have a large influence on the health risk of indoor residents. The research fields are physical environmental factors such as indoor airflow, temperature field, humidity field, etc.; microbial contamination due to molds, fungi, etc.; and chemical compound contamination due to volatile organic compounds. Comprehensive research will be carried out on IEQ control from the physical, biological and chemical standpoints focusing on these areas.

Indoor air chemistry

Recently, theoretical analysis and investigations have begun to verify that some free radicals are generated by chemical reactions. The free radicals and other products of reactions are often more irritating than their precursors. In particular, the products of ozone / terpene reactions cause greater airway irritation in mice than would be predicted from the known response of mice to ozone or terpenes.

We analyzed chemically reactive pollutants in indoor air. We used a computational fluid dynamics (CFD) technique to simulate bimolecular reactions occurring indoors. Various chemical reaction models have been proposed. The fundamental model uses a Rate Constant. In this research, the Second Order Rate Constant model, which is a simple model reproducing bimolecular reaction, is adopted. In order to demonstrate the performance of the Second Order Rate Constant models of ozone and limonene, CFD simulations are carried out for a 2D test room. The results predicted by CFD simulation were consistent with the experimental results.

Indoor air biology

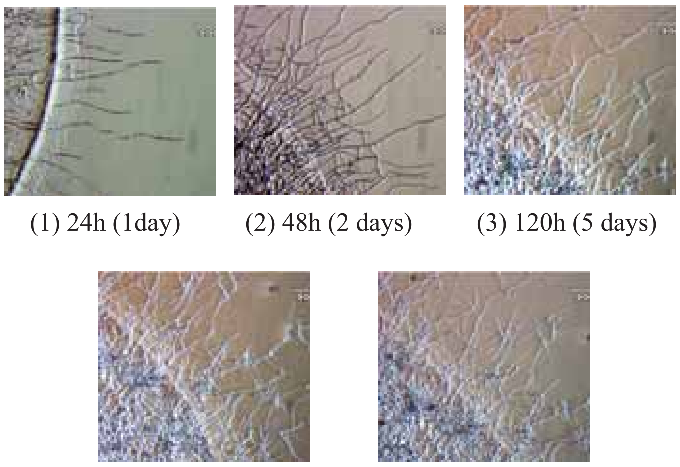
Fungal growth and infestation are deeply associated with indoor air humidity, temperature, building materials and ventilation rate. The final goal of this study is to develop a numerical model that predicts microorganism growth and MVOC emission by taking into account the influence of moisture, temperature and building materials.

In this projext, the micro cell type test chamber was developed and measurements of MVOC emission rate from various fungi (*Alternaria alternata* (NBRC 31805), *Eurotium herbariorum* (NBRC 33235), *Aspergillus penicillioides* (NBRC 33024), *Penicillium critrinum* (NBRC7784) and *Aspergillus niger* (NBRC31628)) were conducted by taking into account the influence of moisture and temperature.

Furthermore, the growth responses of fungi were measured for various building materials, taking into account the influence of nutriment, moisture and temperature.

Indoor air physics

Indoor environment studies are currently focusing on phenomena around the human body at the microclimate level, and this has identified the need for more realistic and detailed human body models. Numerical models closely representing the actual shape of the human body have already been proposed for seated female models (or androgynous models based on female body shapes), and are available for indoor environment analysis applications. However, other human body shapes have not been modeled. In addition, since existing models use coarse meshes, insufficient detailed data on various parts of the human body have been gathered. This study aims to develop virtual manikins that represent human body scales for adult males and females as well as children (mostly seven-year-olds). These virtual manikins are of two postures. The virtual manikin is divided into 17 parts for the control of the thermal manikin, allowing the control and analysis of radiation heat transfer, surface temperature, and other factors in each part. We examined the accuracy of the indoor environment prediction by conducting a coupled convection and radiation analysis on a simple room. As a result, we confirmed that the thermal environment could be predicted with sufficient accuracy for the analysis of microclimates around the human body.



(1) 24h (1day) (2) 48h (2 days) (3) 120h (5 days)

(4) 144h (6 days) (5) 168h (7 days)

Figure12: Fungal spore growth of *Penicillium critrinum* (4% of PDA)

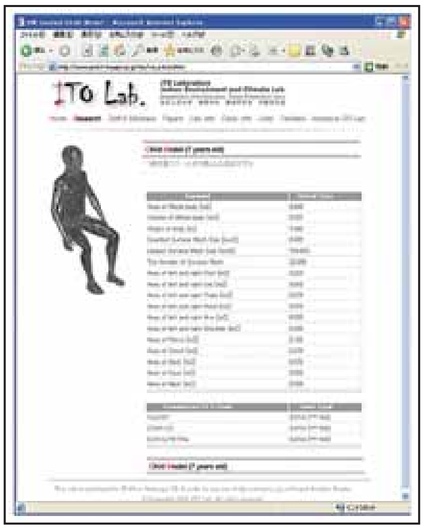


Figure 13: Download Site of Virtual Manikin [http://www.arch.t-kougei.ac.jp/ito/]

Prompt Report of "The Fourth International Symposium on Computational Wind Engineering (CWE 2006)"

Date: July 16-19, 2006
Venue: PACIFIO YOKOHAMA, Yokohama, Japan
Co-convened by: The Japan Association for Wind Engineering, The 21st Century COE Program at Tokyo Polytechnic University, The International Association for Wind Engineering

From July 16 to 19, 2006, "The Fourth International Symposium on Computational Wind Engineering (CWE 2006) was held at Yokohama, Japan. It was co-convened by the Japan Association for Wind Engineering, the 21st Century COE Program at Tokyo Polytechnic University, and the International Association for Wind Engineering. 271 people participated in this symposium, and it was very successful. The coming bulletin will report on it in detail.

Symposium venue: PACIFIO YOKOHAMA

The symposium site

Report of COE International Advanced School on "Computational Wind Engineering"

Date: July 14-15, 2006
Venue: Atsugi Royal Park Hotel, Atsugi, Japan
Hosted by: The 21st Century COE Program at Tokyo Polytechnic University

The International Advanced School on "Computational Wind Engineering", hosted by the COE program, was held from July 14 to 15, 2006 at Atsugi-city where TPU is located.

Prof. Robert N. Meroney (Colorado State University) and Prof. Siva Parameswaran (Texas Tech University) provided a two-day CFD course on CFD principals and applications in wind engineering. Over 40 people attended the lectures and enjoyed discussions with the lecturers.

Prof. Robert N. Meroney (Colorado State University)

Prof. Siva Parameswaran (Texas Tech University)

Invited Article
Performance of Glass/Cladding of High-Rise Buildings in Hurricane Katrina

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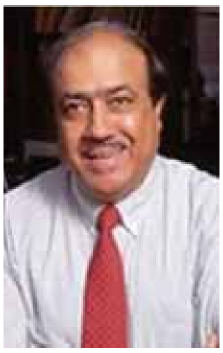
University of Notre Dame




Introduction

On August 29, 2005, Hurricane Katrina made landfall on the coast of Louisiana as a Category 4 hurricane. The center of the storm passed approximately 30 miles to the east of New Orleans, Louisiana around 9 AM CDT. In an effort to understand and improve the performance of glass and cladding on tall buildings in urban areas to extreme winds associated with hurricanes, the NatHaz Modeling Laboratory at the University of Notre Dame conducted a field reconnaissance study to assess the damage to the glass and cladding of a number of tall buildings in the Central Business District of New Orleans and surrounding areas. An additional focus of this study was to investigate the effectiveness of vertical evacuation – allowing citizens to escape the flood waters of hurricanes by seeking shelter at higher elevations in engineered structures.

Research Team and Objectives

The Research Team included Dr. Ahsan Kareem and Rachel Bashor from the NatHaz Modeling Laboratory and Dr. Elizabeth English from Louisiana State University. The team members visited New Orleans several times for field surveys and to conduct interviews of building owners, managers and maintenance personnel as well as both residents and visitors who remained in New Orleans during the hurricane. The objectives of the study included: correlating wind induced damage to observed winds; examining the performance of glass and cladding on tall buildings; determining the causes of poor performance; and assessing the performance of the buildings for vertical evacuation and the effectiveness of this type of escape route.

Description of Hurricane Winds

Determining the actual wind speed in New Orleans throughout the storm is somewhat challenging due to the lack of available data. The Florida Coastal Monitoring Program (FCMP) at the University of Florida collected wind data at several locations during the passage of the hurricane through the use of deployable monitoring systems. Their initial estimates of the maximum 3-second wind speeds for the region were 102 mph (46 m/s). Measurements by Texas Tech University for this region estimated the maximum 3-second wind speeds to be 82 mph (36 m/s). From these two sources, the maximum 3-second wind speed in the Central Business District of New Orleans is estimated to be somewhere between 82 mph and 102 mph, considerably under ASCE 7-05 (2005) design winds of 130 mph (58 m/s).

Observation of Building Damage

The damage to the glass and cladding of tall buildings varied significantly throughout the Central Business District. Many buildings only suffered minor damage – perhaps a few broken windows. However, several buildings suffered heavy damage to the glass and cladding, especially to the North and West faces. This damage pattern correlated with the prevailing wind directions as the hurricane passed by the city. In New Orleans, the research team documented the condition of the exterior faces of twenty tall buildings in the area and toured the damaged areas and rooftops of several buildings including the Hyatt Regency Hotel, the Amoco Building, and the 1250 Poydras Building. These buildings, located near the Superdome (See Figure 1), sustained significant glass and cladding damage as well as damage to roofs and rooftop structures and appurtenances.

Hyatt Regency Hotel

The Hyatt Regency Hotel, located near the Superdome, suffered significant glass and cladding damage, especially on the North face of the hotel (See Figure 2). Nearly every window on the North face of the hotel was broken as it experienced not only high winds during the storm, but wind with debris accelerating through the canyon formed by the upwind buildings. In addition, the inside of the hotel was heavily damaged: walls were torn down and room contents were scattered everywhere. Along with the glass damage, the roof was also significantly damaged. Large portions of the roof were torn up and missing. There was evidence of abrasions on certain faces of the various roof structures, including the round center tower, and evidence of façade elements ripped off at several corners. The debris found on the property included gravel, fasteners, and large pieces of glass debris likely from other buildings upwind.

Amoco Building

The Amoco Building sustained a large amount of glass and cladding damage as well as damage to the rooftop penthouse (See Figure 2 and 3). A large percentage of the windows were broken and were boarded up with plywood. Of the windows that were not covered, many of them showed pitting where a missile had impacted the window. The roof of the Amoco Building originally had a layer of loose pea gravel several inches thick that covered the tar surface completely. The wind blew off much of the gravel, piling some up along the South parapet and exposing sections of tar. The penthouse structures on the roof suffered considerable damage, as some of the large beams had been blown off supports and torn out of the cinder block wall. The four columns that supported the penthouse had all been pushed away from the supports – one was missing from the rooftop. It appeared that the four bolts that held the steel column to its concrete base had been sheared off. Most of the penthouse cladding had been blown off; some large components were found on an adjoining low-rise building south of the Amoco Building.

1250 Poydras

The building known as 1250 Poydras also suffered damage to the glass and cladding, especially on the North face. The old gravel roof of this building had been replaced two years ago; however, the roof had bubbled up in the Northeast corner. Additionally, a roof drain had been pulled up. The penthouse was in good condition – it only lost one door. Overall the roof of 1250 Poydras performed satisfactorily. On an adjoining structure, the team found glass on the roof, which was consistent with spandrel glass in the Hyatt along with vision glass that was likely from 1250 Poydras. In addition, various other items were found on the roof including: large gravel, pea gravel, insulation, and sand from the roofing material of 1250 Poydras.

Possible Damage Scenarios

The gathered evidence suggests that the majority of the damage was likely caused by wind-borne debris. The wind-borne debris included pea gravel, rooftop

Figure 1: Location of select buildings investigated by the research team

Figure 2: Damage to Hyatt Regency Hotel and Amoco Building as seen from the roof of City Hall

Figure 3: Rooftop penthouse on Amoco Building was nearly destroyed

Figure 4: Broken window on North face of Hyatt Regency Hotel, likely caused by missile impact

appurtenances, siding, and penthouse structures which became airborne and caused significant damage to the glass and cladding of the surrounding buildings. The finding of gravel, glass shards, pitted glass and other debris on or inside buildings supports the scenario that the majority of the damage was caused by wind-borne debris. The breakage patterns to the spandrel glass supports the missile impact theory due to the appearance of impact holes with cracks that spread from the impact point (See Figure 4). Given the orientation of the buildings in relation to the damaged areas and the presence of gravel, it is likely that the main debris source was the gravel roofs and appurtenances of upwind buildings.

Another cause of damage can be contributed to poor connections and lack of redundancy. This applies mostly to roof top structures. Nearly all of the damaged penthouses had missing siding at the corners associated with high levels of suction. For example, the round tower on the roof of the Hyatt was missing siding on the corners of the North face. Also, miscellaneous fasteners were found on the roof of the Hyatt among the debris. Another example of inadequate connections and bracings was the penthouse on the Amoco Building.

Vertical Evacuation

The team assessed the feasibility of vertical evacuation during a hurricane with building managers and occupants. Prior to visiting New Orleans, an interview was conducted with a guest of one of the tall hotels in the area who was stranded in New Orleans during the hurricane. The team also interviewed several different hotel managers as well as building engineers for hotels and office buildings, including the Hyatt Regency Hotel. Overall the hotels and office buildings that provided shelter were able to keep occupants safe, although the degree of comfort varied.

Concluding Remarks

In an effort to understand and improve the performance of glass and cladding on tall buildings to extreme winds associated with hurricanes, the research team conducted a field reconnaissance study to assess the damage to the glass and cladding of a number of tall buildings in New Orleans. The research team found considerable evidence that wind-borne debris from rooftops attributed to the glass and cladding damage of the buildings in New Orleans. In several cases, vertical evacuation was effective in providing a safe refuge from hurricane flood waters despite the significant glass and cladding damage sustained.

Acknowledgements

The research team wishes to gratefully acknowledge the support of the National Science Foundation through grant CMS 05-53060. The authors must also sincerely thank Dr. Elizabeth English and Mr. Tom Smith as well as the building owners, management, and occupants for their cooperation. The views and findings presented herein are those of the authors and do not necessarily reflect those of the sponsor.

Investigation Report of Damage Caused by Hurricane Katrina

Fumiaki Nagao The University of Tokushima
Hiroaki Nishimura General Building Research Cooperation of Japan

Introduction

Following the course shown in Figure 1[1)], Hurricane Katrina developed into a Category 5 hurricane in the Gulf of Mexico, and made landfall at around the mouth of the Mississippi River as a Category 4 hurricane. While losing strength, it moved almost northward through the east of New Orleans (around Louisiana – Mississippi border), depriving more than 1,000 people of their precious lives and causing extensive damage. To get an overview of this historical disaster and to help reduce typhoon damage in Japan, investigations on the damage caused by Katrina were conducted in New Orleans (Louisiana), Biloxi (Mississippi), and other areas. Some field investigations were conducted jointly with an investigation team of the JSCE Coastal Engineering Committee, headed by Tomoya Shibayama, professor at Yokohama National University, and attended by another 7 members.

Figure 1: Track of Hurricane Katrina[1)]

Investigation Schedule

Investigations were conducted from November 27, 2005, through December 4, 2005, according to the schedule shown in Figure 2. On November 30, 2005, we accompanied JSCE's investigation team on their investigation tour through the hurricane-stricken area on the Gulf of Mexico coast of Mississippi, and investigated the damage in some restricted areas under the guidance of FEMA and the USACE. On November 28, 2005, we also investigated the damage caused by Hurricane Rita around Highway I-10 near the Texas - Louisiana border.

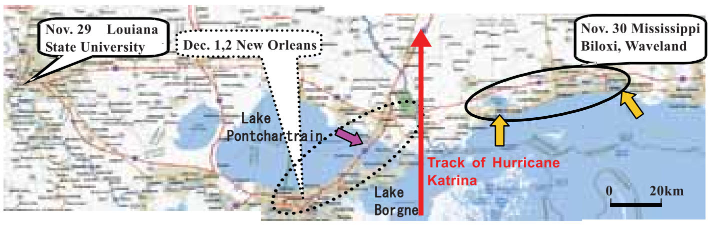


Figure 2: Hurricane Katrina investigation schedule (Maps from MapQuest[2)]) (Small arrows represent the directions in which PC bridges fell down due to storm surges.)

Damage Overview

Reported damage resulting from the hurricane as of the end of December 2005, included 1,313 deaths, 2.5 million affected families (those who asked for some relief), 527 thousand people made homeless, 71 thousand affected stores, more than 400 thousand unemployed people, 6,644 missing people (those whose whereabouts are unknown), and 5 million people affected by power outage. In addition, the hurricane caused extensive damage to forests, agricultural products, stock farm products, and facilities related to the oil industry. The physical damage is estimated at about $200 billion. Areas damaged by storm surges were still off-limits. In New Orleans, where 80 % of the city was flooded, residents were finally permitted to return home for a while, but only during daytime, on December 1, 2005, more than 3 months after the hurricane struck the city. In the city, however, many refugees still cannot return home, and hurricane-devastated buildings there remained untouched after emergency treatment or were completely untouched. Full-scale repair work had just started in some areas. Though traffic signals were partially recovered, about half of them were still not working, and a number of policemen were keeping a watch on road traffic.

Wind Damage

Damage to billboards and house roofs caused by strong winds was observed over a wide area through which Katrina passed. Following Katrina, 36 tornadoes have occurred in Mississippi, Alabama, Georgia, Virginia, and Pennsylvania, and damage caused by these tornadoes is reported.

Photo 1 is a satellite image taken on September 3, 2005, of a group of high-rise buildings in the business district of New Orleans that were extensively damaged by strong winds[3)]. The waterproof sheet on the roof of the Superdome, a building about 82 m high and 210 m in diameter, was stripped off by the wind, but had been repaired at the time of our investigation. We were told that the wind stripped the roof from the direction of the portion where the waterproof sheet was not stripped off (from the northwest). Photo 2 shows the windows of the 28-story, reinforced concrete Hyatt Regency Hotel damaged by the wind. The white panels in the picture are sheets fitted into the broken windows as a temporary protection measure. The north face of the building on the windward side was damaged, and about three fourths of it was affected, independently of height. The building was less heavily and only partially damaged in the side and back faces relative to the wind direction. According to an investigation by the University at Buffalo, the State University of New York[4)], it has been reported that small stones were found in all the rooms where glass was broken and that a large number of small stones that had been used to hold the roofing of the building next to the hotel to the north were missing. Photo 3 is an enlarged view of part of the damage, and shows that a balloon is projecting from a sheet as a temporary safety measure. This would have been installed to regulate flow rates on the exhaust side of a room dryer. After a lapse of 3 months, large dryers had been used to dry building rooms all over the city. Thus, the damage, including not only direct damage but also the costs of recovering building functions and operating losses for the recovery period, is considered to have a tremendous impact on the area.

Breakage of windows, probably due to windborne debris, was observed in a lot of buildings over a wide area. Photo 4 shows a window on the second floor of a building, showing traces of a windborne debris. Though a crack extends from a relatively small impact scar, the window did not fall out, probably because of a safety film. Photo 5 shows a building of about 15 stories taken from the 20th floor of a neighboring building. The photo indicates that cement plates laid for roof insulation were blown out by strong winds (these cement plates, which were laid on the roof slab, may not have been anchored or glued). If blown out by wind, cement plates, which may damage the building itself or other buildings, are very dangerous.

The rooftop panels of many high-rise buildings were also heavily damaged, as shown in Photo 6. If panels on a building top are subjected to positive pressure from the wind from the windward side, the applied load is about 2 to 2.5 times that applied to the same panels used to cover a room behind them. This is due to the strong negative pressure generated behind them. This should be taken into consideration in design.

Photo 7 shows a damaged soffit, and Photo 8 a damaged canopy. The glass canopy on the road side was also blown out by strong winds, as shown in Photo 8. Generally, the wind load on a soffit is often quite heavy, so care should be taken in design. However, in many cases, wind load on a soffit is not included in wind resistant design standards. Therefore, examples of wind force coefficients on soffits and other data should be provided.

While some low-rise buildings, including wooden houses, were damaged by storm surges and waves, other low-rise buildings were damaged by strong winds (Photo 9). In many cases, it was difficult to determine whether they were damaged by storm surges or by strong winds. Damage caused by strong winds was similar to damage caused by typhoons or tornadoes in Japan. For example, severe damage was observed in roof ridge tiles (see Photo 10, which shows a space under an eave with a flooding sign), and antennas, and some houses were damaged by fallen trees.

Damage caused by Storm Surges

Most deaths and damage caused by this hurricane are associated with storm surges, of which the highest was over 7 m. Considering that these surges are closely related to strong wind characteristics surrounding the hurricane, the due to storm surges is also damage cause by strong winds. This can be illustrated by the flooding resulting from broken levees in New Orleans (see Photos 11, 12, and 13). Louisiana State University[5] and other

Photo 1: Business district in New Orleans[3]

Photo 2: Hyatt Regency Hotel

Photo 3: Detailed picture of photo 2

Photo 4: Breakage of windows

Photo 5: Slating on the roof of a building blown out by the wind

Photo 6: Damaged rooftop panels

Photo 7: Damaged soffit

Photo 8: Damaged soffit and canopy

research institutes have reported that, as shown in Figure 1, seawater blown inland from the Gulf of Mexico by southeast to east winds in the front and right sides of the course of Katrina, combined with sea level rises due to the hurricane low pressure. Furthermore, storm surges that passed through Lake Borgne and struck New Orleans from the eastward, and storm surges from the north caused by north or northwest winds from Lake Pontchartrain, a blackish lake about the same size as Tokyo Bay, located in the left front of the course of Katrina, caused damage.

This is also clearly shown by the directions in which many prestressed concrete bridges over these lakes or the gulf fell or were moved (see Figure 1). For example, in Biloxi (see Photo 14) or Bay St Louis, located on the right side of the course of Katrina, bridge beams were carried to the northwest or the north, while in Lake Pontchartrain, located on the left side of the course of Katrina, bridge beams fell down or were moved to the east. This damage was probably due to tidal waves accompanying storm surges, or storm surges greatly exceeding the height of the bridge beams, which are usually 1.5 to several m above the water surface, but were submerged by the storm surges, combined with drag generated by the flow of seawater when the storm surges occurred. (The water level increased by about 1.5 m for 15 minutes in some areas, and that has been videotaped. The video footage shows that seawater crashed ashore at a fairly high flow rate. In local news reports, the term "tsunami" was used rather than "storm surges"). In a PC bridge on Highway I-10 in Louisiana, which is 12.2 m wide and 19.5 m long and employs simple beams, the liners were lifted off their supports (see Photo 15) in the southernmost substructure and some of them were swept several meters away, although the bridge beams were not prostrated. They were probably lifted by storm surges. However, a 3-span continuous reinforced concrete bridge neighboring Highway I-10, shown in Photo 16, was damaged by some fall prevention fences, but the bridge itself was not seriously damaged by storm surges.

Photo 17 shows how a floating casino moored in Biloxi was washed ashore and damaged by storm surges. Similar damage was observed in other areas, and a ship crashed


Photo 9: Houses damaged by storm surges and strong winds


Photo 10: Damaged roofing


Photo 11: Broken waterway levees


Photo 12: Private houses behind broken levees


Photo 13: Private houses washed out by storm surges


Photo 14: Damaged PC bridge in Biloxi


Photo 15: Escape of liners from the bridge support


Photo 16: 3-span continuous bridge


Photo 17: Floating casino washed ashore by storm surges


Photo 18: Damaged oceanfront elevated house


Photo 19: Trace of houses washed out by storm surges

into and damaged a building. Photo 18 shows how an oceanfront elevated house was damaged. This house was only a few meters from a sandy coast. The building site was only about 1 m above sea level and there was no levee. There is a building standard in place that requires that coastal houses be built with the floor above ground level to protect against storm surges. This standard assumes that storm surges may rise under floors. This house was destroyed by storm surges above the second floor level or by strong winds. The barge, stairs, and fences of this house were also missing. Similar damage was found around this area, and many houses disappeared without leaving any trace other than their concrete bases (see Photo 19).

Conclusion

Hurricane Katrina caused a lot of damage due to strong winds, in addition to severe damage due to storm surges. Many high-rise buildings were damaged by strong winds, and breakage of windows probably due to windborne debris was seen everywhere. The most effective way to avoid this kind of damage is to prevent such windborne debris from being produced. In Japan, the roofs of high-rise buildings must be inspected carefully.

Acknowledgement

I am grateful to members of the damage investigation team for their cooperation: Tomoya Shibayama, professor at Yokohama National University; Fuminori Kato, senior researcher at the National Institute for Land and Infrastructure Management; Haruyuki Kojima, professor at Kyushu Kyoritsu University; Yoshimitsu Tajima, assistant professor at the University of Tokyo; Katsumi Tamagawa, researcher at the Foundation of River & Watershed Environment Management; Hisamichi Nobuoka, assistant professor at Ibaraki University; Takashi Yasuda, executive director at Gifu University; and Tomohiro Yasuda, research associate at Kyoto University. I would also like to thank E. C. English, associate professor; S. C. S. Cai; and H. S. Mashriqui, assistant professors at Louisiana State University, for giving us a brief overview of the damage. My thanks also to Mr. John "Bud" Plisich and other staff at FEMA, and the staff at the USACE for guiding us around restricted areas. Also, let me thank Masaru Sakato, Consul General at the New Orleans Consulate-General of Japan, and Shigeaki Makanae, Deputy Consul at the Consulate-General, for helping our field investigations, and members of the Research Committee on Wind-induced Disaster, Japan Association for Wind Engineering, for giving us helpful information. Finally, special thanks to the 21st Century COE Program of Tokyo Polytechnic University for providing travel expenses.

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Wind Gusts Struck Northern Japan from December 25 through 26, 2005

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High winds caused by a low-pressure system were observed along the northern coast of the Japan Sea from 25th to 26th in December, 2005. These winds caused gust damage in Sakata, Yamagata Prefecture and Minehama, Akita Prefecture.

Meteorological Conditions on Day of Wind Gusts

From December 25 through 26, 2005, a synoptic scale low developed above the Japan Sea as a cold air mass moved down. A weather map at 21:00 JST on December 25, 2005 shows a cold front extending from the 990 hPa low to the San'in region, indicating that the pressure dropped by about 20 hPa in one day, and the low developed rapidly. A rapidly developing low often seen around Japan in winter is referred to as a "bomb". Convection around this cold front was active, and the damage caused to the Sakata region by a wind gust (around 19:00 JST on December 25, 2005) corresponded to a band of cumulonimbus clouds formed on the south of the cold front (see the left picture of Figure 1). The right picture of Figure 1 shows that the damage caused to Akita by another wind gust (around 12:00 JST on December 26, 2005) was associated with a northwest monsoon following the passage of the cold front. In these meteorological satellite images, distinctive white clouds whose tops are extremely high are observed over these wind-gust-stricken areas (see the circled portions in the pictures). In the radar echo images shown in Figure 2, echoes with a top height of over 8 km corresponding to a precipitation intensity of over 64 mm/h, which is large for winter, are observed for the wind gusts.

The actual damage caused to the Sakata region by the wind gust is compared with the meteorological data in order to find the causes. Figure 3, which is a map prepared by a 4-day field survey, shows that local damage was scattered linearly over a range of about 14 km. In area 1 in this figure, damage was limited to an area several meters wide by 500 to 600 m long. The most significant damage was observed in area 2, where the damaged area was about 20 m wide, as measured on the F1-scale, and was found to be in the range of about 500 m long by 100 m wide. When correlating the actual damage on the ground with the wind speed data and radar echo data over the area, strong echoes reflecting cumulonimbus are seen to develop to the south of the damaged area, and a wind gust of about 20 m/s surrounding the clouds was observed at 19:10 JST (Figure 4). These correspond to damaged areas 2 and 3, which were struck by the gust at 19:08 and 19:14 JST, respectively. It is assumed from the strong echoes on the ground that the gust observed at around 19:10 JST was generated by the divergence of a downward flow. However, an anemometer on the coastline (Shinkawa) near damaged area 1 registered another wind gust of 36.9 m/s at 19:06 JST, which differs from observations in other areas in absolute wind speed and time of occurrence. There is a high possibility that this wind speed reflects the wind gust that damaged the area. However, the figure also shows that damaged areas 1 and 2 were located in an area where echoes were relatively weak. It is believed that the echoes reflecting the cumulonimbus developed rapidly just before they made landfall, reached their peak between 19:10 and 19:20 JST, and that areas 1 and 3 correspond to the development stage and the peak stage of the echoes, respectively.

The wind gusts on weather maps appeared with a rapidly developing low (bomb). The damage caused

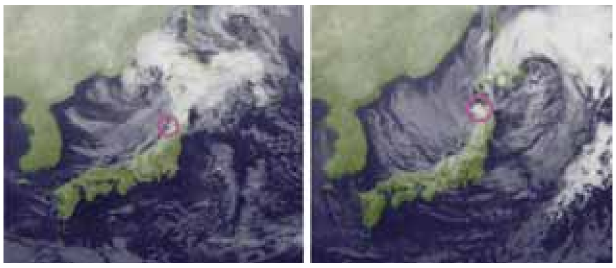

Figure 1: Meteorological satellite infrared images (Left: 19:00 JST on December 25, 2005; Right: 12:00 JST on December 26, 2005)

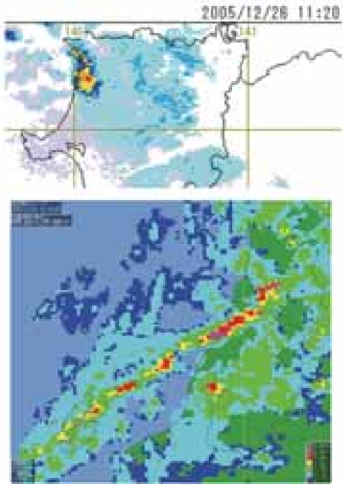

Figure 2: Radar echo patterns (Upper: 11:20 JST on December 26, 2005; Lower: 19:10 JST on December 25, 2005)

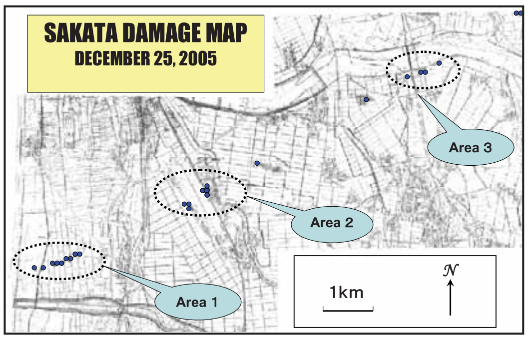

Figure 3: Damage map of Sakata region

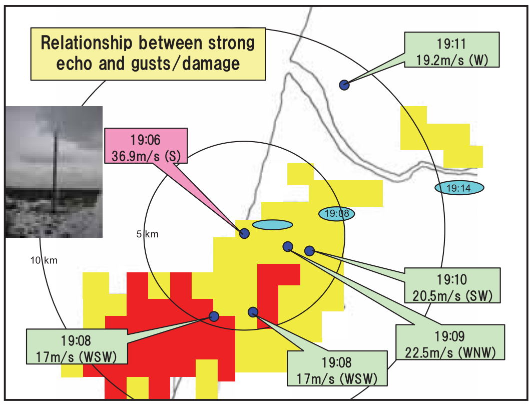

Figure 4: Strong echo area when gust attacked Sakata region at 19:10 JST, wind speed (gust) data, correspondence to damage on from the strong echoes on the ground

to the two areas, one under a cold front and the other under a northwest monsoon, appeared with developed cumulonimbus. Considering the damage on the ground and the meteorological conditions, the wind gust that struck the Sakata region is estimated to be a tornado or a local downburst (microburst) following the development of cumulonimbus.

Damage in Sakata, Yamagata Prefecture

Gust damage occurred around Sakata City from 19:00 to 19:20 on December 25th. A maximum instantaneous wind speed of 21.6m/s and a maximum wind speed of 10.6m/s, which were not remarkable values, were recorded at 19:12 at the Sakata meteorological observatory, while the anemometer on the Shinkawa coast recorded a peak gust speed of 36.9m/s at 19:06. The derailment accident, thought to be caused by this gust, occurred on the JR Uetsu-line at 19:14, causing 5 deaths and injuries to 32 people. The damage investigation started on January 2nd, 2006 on completion of rescue operations.

Figure 5 shows the main locations of damage occurrences. Damage was scattered in a straight line from the coast to the east-northeast for a distance of about 12km. Local flat terrain was covered with an even layer of snow and there was little roughness except in villages and wooded areas. Damage to roof tiles, agricultural warehouses, vinyl houses, etc. were seen near the site of the derailment accident, clearly indicating the influence of the gust.

Damage at Minehama, Akita Prefecture

A gust occurred in Minehama, Akita Prefecture, causing collapse of a wooden house, scattering of roofs

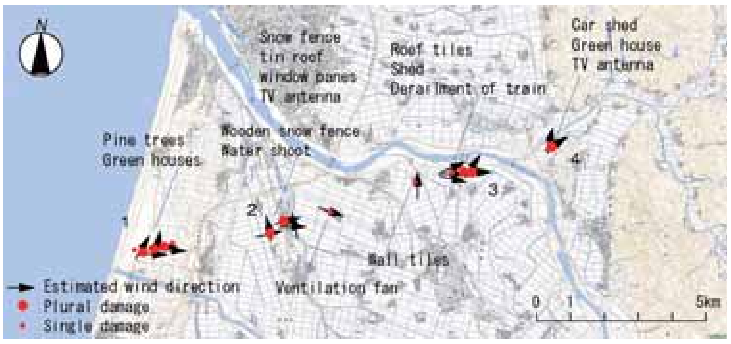

Figure 5: Location of the damaged area

Photo 1: Damaged pine trees in Kuromori-district

Photo 2: Damaged snow fences at Kouei-cho

Photo 3: Traces of a damaged ware house near the derailment accident site

Photo 4: Damaged ridge tiles Enoki-district

Photo 5: The damaged ridge tiles were conncted with metal wire

Photo 6: Damaged plastic greenhouse in Ishinazaka-district

and damage to agricultural facilities etc. from 11:10 to 11:20 on December 26th, 2005.

Wind speed records in Hachimori and Noshiro, the Automated Meteorological Data Acquisition System (AMEDAS) observation point, 7 to 8km from the damaged area, showed 8m/s and 16m/s, respectively,

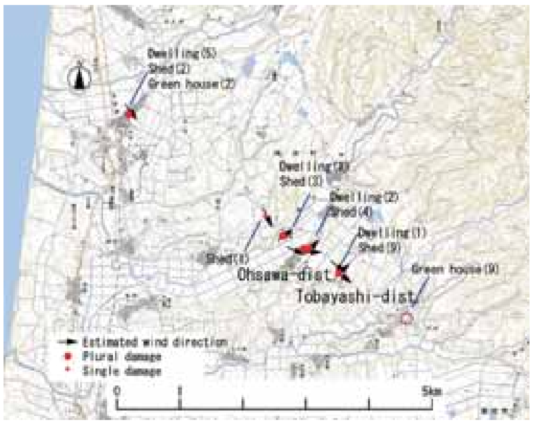

Figure 6: Location of the damaged area

which were not remarkable speeds.

Figure 6 shows the damaged area. Damage was scattered in a straight line about 5km long. The most remarkable damage was the collapse of a two-story wooden office building in the Osawa district.

Conclusion

The developing low-pressure front was passing at that time, and development of cumulonimbus was observed from radar and other meteorological observations. In such meteorological conditions, there is a possibility of very local meteorological disturbances such as down bursts and tornadoes. However they are difficult to forecast. Moreover, it is impractical to avoid damage by installing anemometers, because these are very local and short-term phenomena. It will be necessary to advance understanding such localized phenomena, and research on a damage mitigating plan etc. in the future.

Photo 7: Collapsed wooden 2-stories office building in Osawa-district

Photo 8: Brown-off roofing material from the collapsed building

Photo 9: Damaged greenhouse in Tobayashi-district

Universal Wind Load Distribution on Large-Span Cantilevered Roof

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This study investigates a new concept for determining the universal equivalent static wind load (ESWL) distribution, based on a largest load effect calculated by time-domain response analysis. The universal ESWL reproduces the overall largest load effect on structural members simultaneously. The aim is to develop a wind resistant design method based on the universal ESWL.

The gust loading factor (GLF) method has recently been adopted in the building codes and laws of many countries for estimating the ESWL of a general roof structure. However, the GLF method is aimed at determining a specific load effect on a structural member, or a wind force. It does not guarantee an adequate design wind load except at the relevant largest load effect. As wind induced responses vary in time and space, the largest load effects do not occur on all structural members simultaneously. In practice, it is necessary to check all largest load effects, and determining an adequate ESWL has been very time consuming. Here, a universal ESWL that reproduces the largest load effect of all structural members on a cantilevered roof is introduced as an example.

Wind tunnel tests were carried out using a wind pressure model of the cantilevered roof, as shown in Figure 1. A total of 96 fluctuating wind pressures were measured simultaneously on both the inside and outside of the roof. Time-domain analyses of quasi-static responses of all members were carried out using the fluctuating wind force obtained from the wind tunnel test. The roof model consisted of 8 beams, each composed of 7 nodes and 6 line elements. Adjacent beams were assumed to be pin-jointed. The load effect of the shear force (SF) of all structural members was used in this analysis.

Figure 2 shows the represented ESWL distributions, (a) GLF method and (b) universal ESWL reproducing largest load effects. Large negative values at windward centre are shown and the absolute values of the ESWL rapidly decrease toward the leeward side for each ESWL. The universal ESWL distribution shows a comparatively uniform distribution in the longitudinal direction compared with the ESWL of the GLF method.

Figure 3 compares the actual largest SF estimated by the time-domain response analysis with that estimated by the representative ESWLs. In the figure, the member numbers are given in the order of the largest SFs estimated by the time-domain response analysis, as shown by the solid line. The white circles show the largest SFs estimated by representative ESWLs. The ESWLs estimated by the GLF method take account of the absolute largest value of all largest load effects. The largest SF estimated by the GLF method varies from the actual largest SF except for one given by a specific load effect. It is clear that many ESWLs have to be considered in the GLF method in this case. The largest SF estimated by the universal ESWL coincides with the actual largest SF.

The method for estimating the universal ESWL that reproduces the largest load effects on all structural members is discussed. It is necessary to apply it to various kinds of structural models to confirm of its general applicability. Construction of a database for the universal ESWL is a topic for future study.

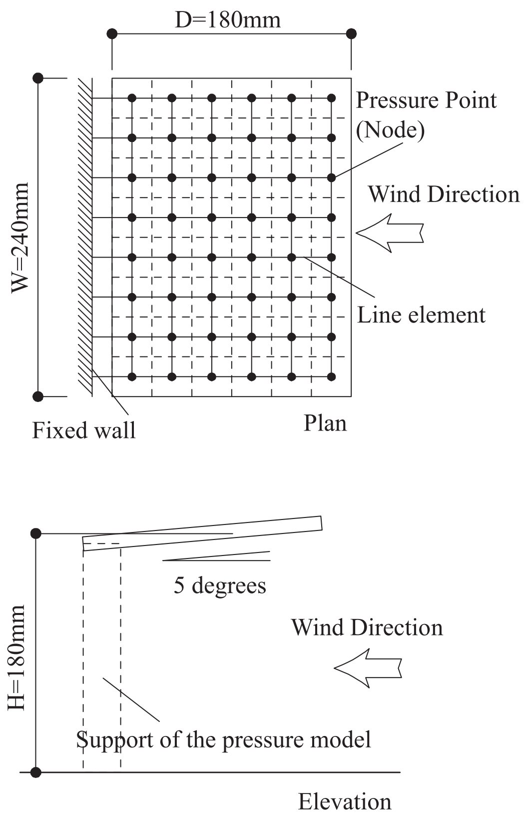
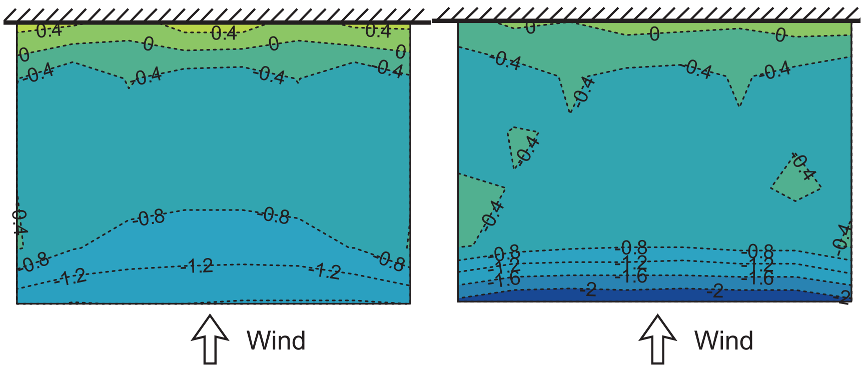
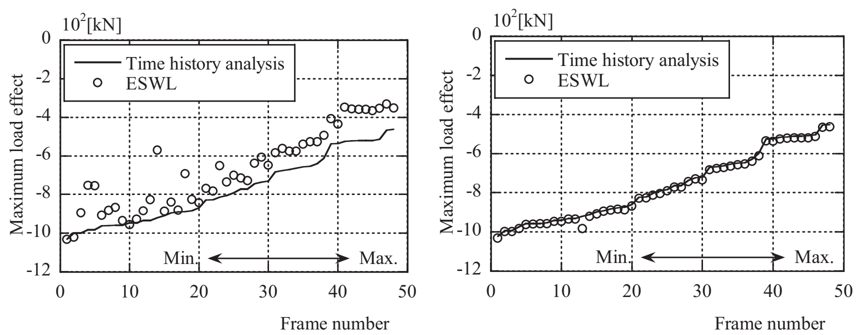


Figure 1: Large span cantilevered roof model



(a) GLF method (b) Universal ESWL

Figure 2: Equivalent static wind load distribution



(a) GLF method (b) Universal ESWL

Figure 3: Comparison of largest load effect

Announcement

COE International Advanced School on Wind Effects on Buildings and Urban Environment

Date: March 5-9, 2007
Venue: Tokyo International Forum

Lectures in the advanced school will deal with wind disaster, wind load, natural ventilation, indoor and outdoor air pollution, and airflows in buildings and cities. The lectures will provide the outline and latest knowledge as well. The advanced school will be of interest to students, engineers, and researchers who work in relevant scientific research or design topics.

For more details, please check: http://www.wind.arch.t-kougei.ac.jp/AS/

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ISBN 4-902713-18-7