Wind Effects

Wind Effects on Buildings and Urban Environment

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Graduate School of Engineering
Tokyo Polytechnic University

INDEX

Report on 4th International Symposium on Computational Wind Engineering (CWE2006)

Date: July 16-19, 2006
Venue: PACIFICO YOKOHAMA, Yokohama, Japan

Pacifico Yokohama International Conference Center from July 16 to 19, 2006 under the joint auspices of the Japan Association for Wind Engineering, the 21st Century Center of Excellence Program at Tokyo Polytechnic University, and the International Association for Wind Engineering. Patronage was received from the Architectural Institute of Japan, the Japan Society for Natural Disaster Science, the Japan Society for Snow Engineering, the Japan Society of Civil Engineers, the Japan Society of Fluid Mechanics, the Japan Structural Consultants Association, the Japan Wind Energy Association, the Meteorological Society of Japan, the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, and the Visualization Society of Japan. Support was also received from the Maeda Engineering Foundation, the Kajima Foundation, the Yokohama Convention and Visitors Bureau, and the Japan Steel Bridge Engineering Association.

The 1st symposium was held at the Sanjo Conference Hall, the University of Tokyo in 1992, the 2nd at Colorado State University (U.S.A.) in 1996, and the 3rd at Birmingham University (U.K.) in 2000. The governing body of the 4th International Symposium on Computational Wind Engineering (CWE2006) consists of three committees: the Advisory Committee (Chairperson: Shuzo Murakami), the Scientific Committee (Chairperson: Masaru Matsumoto), and the Organizing Committee (Chairperson: Yukio Tamura).

Pacifico Yokohama, the symposium venue, is a complex with three facilities: an exhibition hall, an international conference center, and a hotel. It was built in the Minato Mirai district at the port of Yokohama for international and cultural exchanges. The 4th symposium was held on the entire 3rd floor of the International Conference Center.

The symposium comprised six invited lectures, nine organized sessions, and 27 general sessions, collectively encompassing 214 registrations. There were 259 participants/registrants (excluding 10 accompanying persons) from 24 countries.

During the Icebreaking Party, held on July 16, all the participants greatly enjoyed talking with each other, and viewing a fireworks display in front of Yamashita Park for the Yokohama International Fireworks Festival.

The opening ceremony of the symposium was held on July 17, Prof. Shuzo Murakami, Chairperson of the Advisory Committee, and Prof. Giovanni Solari, President of the International Association for Wind Engineering (IAWE) made speeches as the background to the symposium, which was then declared open.

The invited lectures and organized sessions are outlined below:

Invited Lectures

K. Ayotte, Windlab Systems Canberra, Australia
Computational Methods for the Wind Energy Industry

K. Hanjalic, Delft University of Technology, The Netherlands
Some Developments in Turbulence Modeling of Environmental Flows

A. Kareem, University of Notre Dame, USA
Numerical simulation of wind effects: a probabilistic perspective

A. Mochida, Tohoku University, Japan
Prediction of wind environment and thermal comfort at pedestrian level within urbanized area

K. D. Squires, Arizona State University, USA
Prediction of Turbulent Flows at High Reynolds Numbers using Detached-Eddy Simulation

T. Tamura, Tokyo Institute of Technology, Japan
Towards practical use of LES in wind engineering

Organized Sessions

Y. Ge (China): Computational aerodynamics for bridge flutter


T. Tamura


A. Kareem


A. Mochida


K. D. Squires


K. Hanjalic


K. W. Ayotte

M. Gu (China): Computation of wind loads and responses of buildings
A. Kareem (USA): Simulation of Transient Wind Effects
H. Kobayashi (Japan): Computer- controlled wind tunnel
A. Larsen (Denmark): Computational assessment of flutter wind speeds for bridges
A. Mochida (Japan): Assessment and design of pedestrian thermal and wind environment
T. Stathopoulos (Canada): Commercial CFD software and CWE applications
T. Tamura (Japan): Current feasibility and future sophisticated technique of CFD on wind-resistant structural problems
R. Yoshie (Japan): Assessment of urban wind environment

At the reception lobby of the venue, a Desktop Exhibition was held by four companies related to wind engineering. Demonstrations and exhibitions featuring wind velocity measurement systems and CFD codes attracted the attention of participants.

On July 18, a banquet started with a speech delivered by Prof. Yukio Tamura, and a toast made by Prof. Robert Meroney, Colorado State University. To introduce Japanese culture, the koto and shakuhachi were played, and classical Japanese dance was performed.

A closing session was held on the afternoon of July 19 Prof. Yukio Tamura stated that the symposium had been successfully completed, and expressed his thanks to the participants. Professors Robert Meroney and Giovanni Solari also expressed their gratitude to Prof. Yukio Tamura for organizing the symposium as the Chairperson of the Organizing Committee.

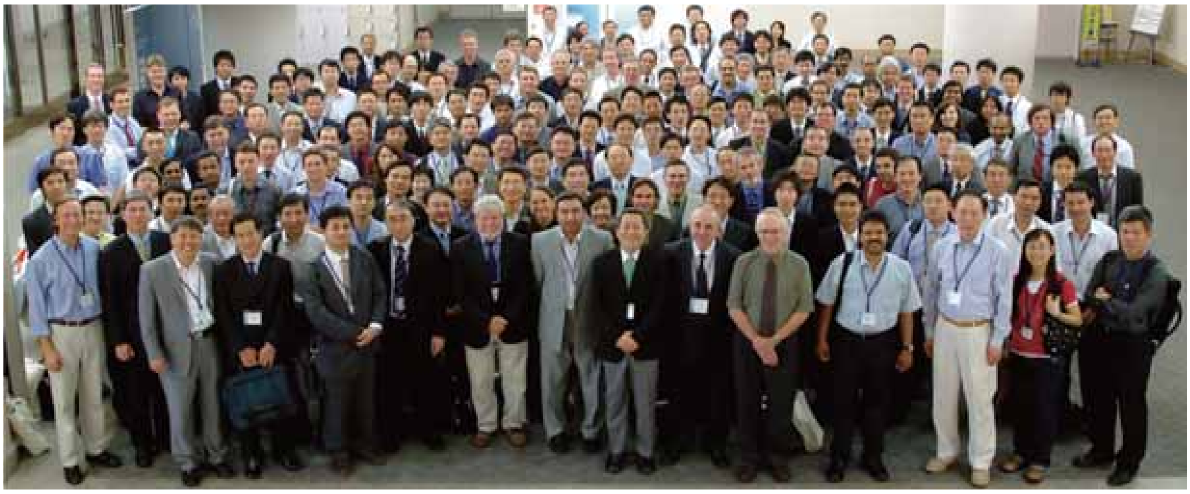
On a technical tour conducted on July 20, a visit was made to the Yokohama Institute of the Japan Agency for Marine-Earth Science and Technology, and its Yokosuka Headquarters. At the Yokohama Institute, participants observed the Earth Simulator supercomputer, which recorded an effective performance of 35.86TFLOPS during the LINPACK benchmark test. It was formerly the world's fastest advanced supercomputer before being superseded by Blue Gene, developed by IBM from 2002 to November 2004. A presentation concerning the simulation of air and ocean currents on a global scale was given by researchers specializing in marine meteorology, and a meaningful discussion ensued among researchers specializing in wind engineering. At the Yokosuka Headquarters, the participants were shown research findings, and visited research facilities.

Many more participants than expected attended the CWE2006, and this greatly contributed to its success.

(Masahiro Matsui)

Symposium venue: PACIFIO YOKOHAMA

A scene of symposium



Group photo session

Report on the 3rd Workshop on Regional Harmonization of Wind Loading and Wind Environmental Specifications in Asia-Pacific Economies (APEC-WW2006)

Date: November 2-3, 2006
Venue: India International Centre, New Delhi, India

The 3rd workshop on Regional Harmonization of Wind Loading and Wind Environmental Specifications in Asia-Pacific Economies (APEC-WW2006) was held at the India International Centre, New Delhi, India on November 2nd and 3rd, 2006. It was co-hosted by the Wind Engineering Research Group, Centre of Excellence in Disaster Mitigation Management, Indian Institute of Technology Roorkee & the 21st Century Center of Excellence (COE) program of Tokyo Polytechnic University. The 3rd APEC-WW followed the spirit set in the 1st APEC-WW and 2nd APEC-WW, which were held at TPU in Japan in 2004 and HKUST in Hong Kong in 2005, respectively. The purpose of the APEC-WW was to harmonize structural loading standards/codes and bylaws/specifications on wind environmental problems in the APEC area. The workshop participants comprised 26 delegates from 13 APEC countries, including American delegates who were newcomers to this workshop, and they all contributed to the discussions.

On November 2, Prof. A.K. Ghosh, the president of Indian Society for Wind Engineering, welcomed the participants and emphasized the significance of collaboration, harmonization, and exchange of information on wind loading and wind environment related codes and recommendations in APEC countries. Then, in accordance with the concept of this workshop, reports from 13 countries were presented by the delegates and active discussions took place. On November 3, semi-closed workshops were held to promote more detailed discussions. Participants were separated into two special sessions: wind loadings and wind environment. In the session on wind loading, design wind loads for three example buildings (Example 1 - A steel-framed warehouse in an urban area, Example 2 – A medium-height office building in a tropical city, Example 3 – A tall building in a city centre) based on the structural loading code of each country were compared and discussed. In the session on wind environment, the participants exchanged information on the current status of outdoor air quality, environmental quality standards, and emission standards for each country. As a result of the two-day workshop, resolutions for wind loading and wind environment were made and approved. The next workshop will be held in Shanghai, China.

During the visit, I fully realized the seriousness of outdoor air pollution in India because the cityscape was always blurred with dust and car exhaust, and I was surprised by the number of cattle resting in the middle of roadways. (Ryuichiro Yoshie)

Participants

A scene of workshop

A roadway in New Delhi

Tornado Damage in Nobeoka

Masahiro Matsui, Shuyang Cao, Yukio Tamura (Tokyo Polytechnic University)
Hiromori Miyagi (Miyazaki University)
Hironori Kikugawa (Oita National College of Technology)

Typhoon Shanshan (T0613) formed in the east Philippine Sea and moved to the north-west. It changed its course to the north on September 15th and landed on Kyushu on September 17th. A little before it landing, at 1400 JST, it caused gust damage in Nobeoka City, Miyazaki Prefecture. Three people died, ninety-four buildings were completely destroyed, and the limited express 'Nichirin' was derailed and overturned. From the interviews with people affected by it, the Japanese Meteorological Agency judged that the damages were caused by tornado. Our site investigation started on September 18th. It was found that damage was distributed in a line running from south to north through Nobeoka City.

The average wind speed at Nobeoka City before the tornado struck was about 15 m/s and the gust speed was about 25m/s. At about 1405 JST, a sudden and damaging gust occurred. At that time the cumulonimbus that formed a part of the rain-band of Typhoon Shanshan arrived at the city and the tornado seemed to be caused by the typhoon (Figure 1).

The tornado seemed to move across the coast at Midorigaoka where the sand break fence was damaged, as shown in Figure 2.

At Hama-cho, the roofing material of a large-span building that was right in the tornado's path was broken (Figure 3).

On the Japanese National Railroad, the first and the second cars of an express 'Nichirin' were overturned (Figure 4). The motorman reduced speed and tried to stop the train when he saw some flying debris, and the two carriages suddenly overturned just at that time. The site of this accident was right in the linear damaged area. Around the site there was a lot of damage to dwellings and trees (Figure 5).

At Nakajima-cho, flying objects (part of a corrugated slate plate) hit the wall of a dwelling, causing the roof to be blown off (Figure 6).

The damaged area was in a line 7.5 km long by 100 to 150m wide (Figure 7). Tornadoes often leave their footprints at some points or confined areas. However, this tornado caused continuous damage in a line. Tremendous damage was caused by flying objects. Not only outer walls but also inside walls were damaged by them.

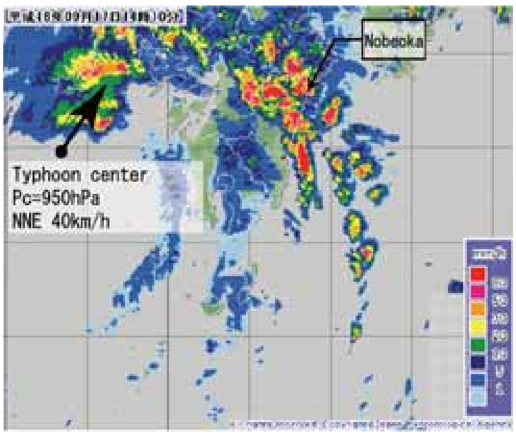


Figure 1 Radar echo 1400 JST, September 17, 2006 (JMA)

Figure 2 Broken sand break fence

Figure 3 Damage to large-span building
(Photo courtesy of Nobeoka City)

Figure 4 Overturned limited express 'Nichirin'

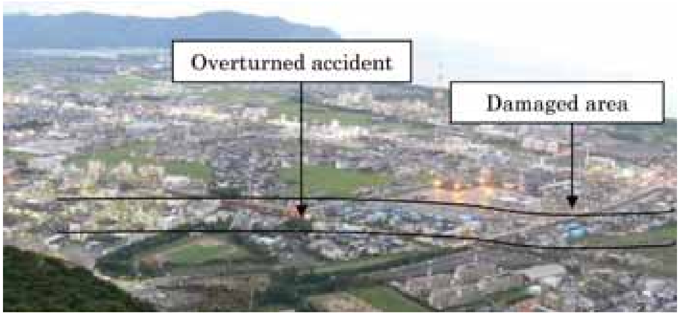


Figure 5 Damage around overturned carriages

Figure 6 Damage to wall and roof

Figure 7 Damaged area

Tornado Damage in Saroma

Shuyang Cao, Akihito Yoshida, Masahiro Matsui,
Yukio Tamura (Tokyo Polytechnic University)
Fumiaki Kobayashi (National Defense Academy of Japan)
Hirotoshi Kikuchi (Shimizu Research Institute)
Kouji Sassa (Kochi University)

On November 7, an F3-level tornado struck the Wakasa area of Saroma town in Hokkaido, causing severe human and property damage. Nine people died and 26 people were injured. Over 30 buildings, including a dwelling, warehouses and temporary structures were completely or partly destroyed. The TPU COE Program, together with a number of meteorologists, carried out a site survey from November 8-9. Some characteristics of the wind damage to the structures are described briefly in the following.

An area of roughly 200m*1500m located in a valley with 100m-high undulations suffered tornado damage, as shown in Photo 1 and Figure 1. The most severe damage occurred in almost a straight line on the right side of the tornado, because its moving speed was high (about 80km/h) so the wind speed was very high on its right side. Part of a temporary 2-storey building (length: 37.56m, width: 9m, height: 7m), which served as an office as well as a dormitory, was blown 60-90m, hitting the ground and other buildings, and nine people working on the second floor of this building died. The roof structures and roofing materials of the dwellings suffered severe damage, but the dependence of damages on the roof inclination was not clear because the roofs of all the buildings on the tornado route were damaged. Windborne flying debris caused damage to other buildings, cars and so on. Roof materials were found even on the sea 20km to the north. Figure 2 shows the moving direction of flying debris, showing that the tornado rotated counterclockwise.

Photo 1 Overview of the damage
(Photographed by F. Kobayashi)

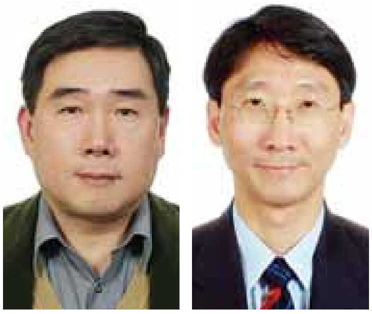
Figure 1 Distribution of the damage

Figure 2 Moving direction of the flying debris

Invited Article

The Applications of Information and Web Technologies on Wind Engineering: e-wind

Chii-Ming Cheng and Jenmu Wang
Wind Engineering Research Center, Tamkang University



1. INTRODUCTION

There are two common practices on the wind resistant design of tall buildings. For the majority of residential and commercial buildings, building wind codes are used to provide design wind loads. In most building wind codes, the aerodynamic assumptions of isolated, regular shaped (rectangular) buildings coupled with the simplified structural model were adopted to evaluate building design wind loads. Nevertheless, it is difficult for an average structural engineer to understand and properly utilize the building wind code. It is quite often to find various degrees of errors in wind resistant design practice. For a tall building with irregular shape and/or structural properties, wind tunnel tests are used to evaluate design wind loads. However, in many cases, building geometry and structural system are decided based on the wind code prior to the wind tunnel test. Therefore, an alternative approach is needed to provide an economic yet reasonably accurate solution for the wind resistant design of tall buildings; at least at the stage of preliminary design. The authors believe that "e-wind" could be the answer to it.

2. DEFINITION OF E-WIND

Generally speaking, e-wind means a scheme to promote wind engineering applications. To realize this goal, the latest information and web technologies are adopted to facilitate the user friendliness and easy accessibility. In this sense, e-wind could be defined as "the technology, processing and operation which provide wind engineering analysis, calculation and service on the Internet". E-wind implies that wind engineering components, such as wind code, aerodynamic database, analytical models and CFD, should be digitized, integrated, and accessible online. In the proposed flow chart of e-wind, shown in Figure 1, the wind code, aerodynamic database, the analytical wind engineering procedures and CFD are the essential ingredients of e-wind; whereas case-based reasoning, expert system, artificial neural network and web technology are the IT keys to e-wind.

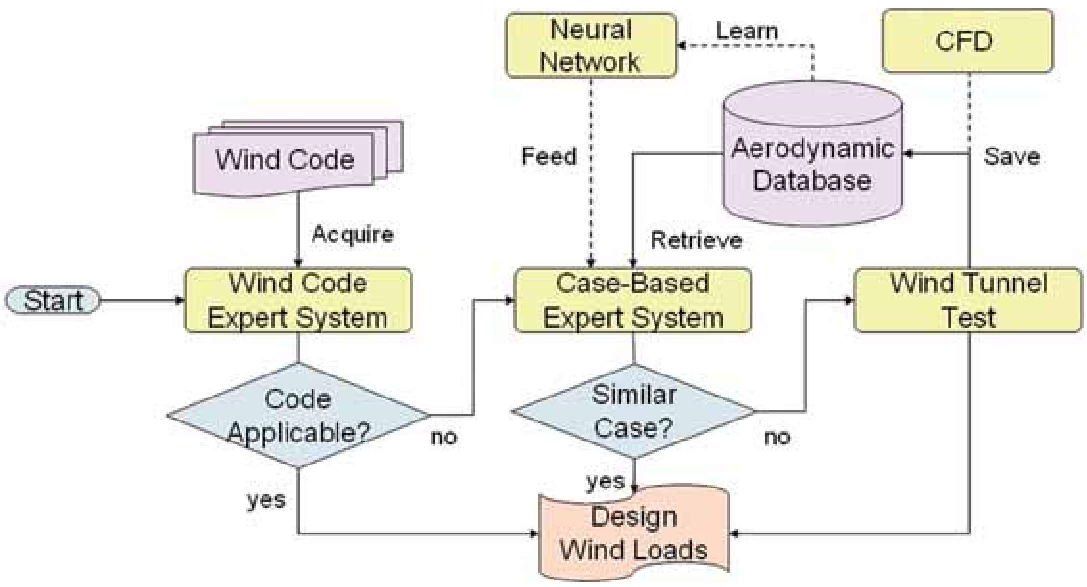


Figure 1 Flow chart of e-wind

3. CURRENT STATUS OF E-WIND

In the past few years, the Wind Engineering Research Center at Tamkang University (WERC-TKU) has chosen “e-wind” as one of its primary research project. Currently, two aerodynamic databases have been established and two prototype expert systems on the wind resistant design of buildings have been built. Brief summaries of these “e-wind” components are listed as follows.

3.1 Aerodynamic database for isolated tall buildings

Wind tunnel measurements and their analysis of various generic building shapes have been systematically performed to establish the case base of the expert system. Total of 60-plus building shapes were studied so far. Most the building models were tested in both open terrain and city environment flow fields (α=0.15, 0.32), some models were tested in suburban and coast environments (α=0.25, 0.10). The database can be categorized into two sets of models. The first part called the core database, it consists of various generic building shapes, which include: (i) rectangular with different cross sectional side ratio, (ii) polygons (circular, triangular and rectangular), (iii) L shaped cross-sections and (iv) some irregular shapes. The second part called the auxiliary database, which concentrates on effects of buildings with basic square cross-section shapes plus minor cross sectional modifications, including aspect ratio changes, corner chamfering, and two types of recess sections. The wind force coefficients and reduced force spectra in the alongwind, acrosswind and tortional directions were measured through HFFB.

3.2 Aerodynamic database for building interference

Aerodynamic database for building interference can be divided into three parts. The first part is focused on the interference of a pair of identical square shaped prisms. In the second part of the database, rectangular prisms with side ratio, B/D=0.5 & 2.0 and circular cylindrical models were used as the principle building, while the interfering building remains to be the square shaped prism. The third part considers the interference effect of a square shaped principal building under the influence of another rectangular shaped building with width ratio R_B= 0.75, 1.0, 1.5, and height ratio R_H= 0.75, 1.0, 1.25. All three parts of wind tunnel tests were repeated for the three turbulent boundary layers, BLA (α =0.32), BLB (α =0.25) and BLC (α=0.15). The alongwind, acrosswind and torsional wind loads of the principal building were measured when the interfering building were placed at different locations that covers an area of x:(-3B,13B) × y:(-6B, 6B).

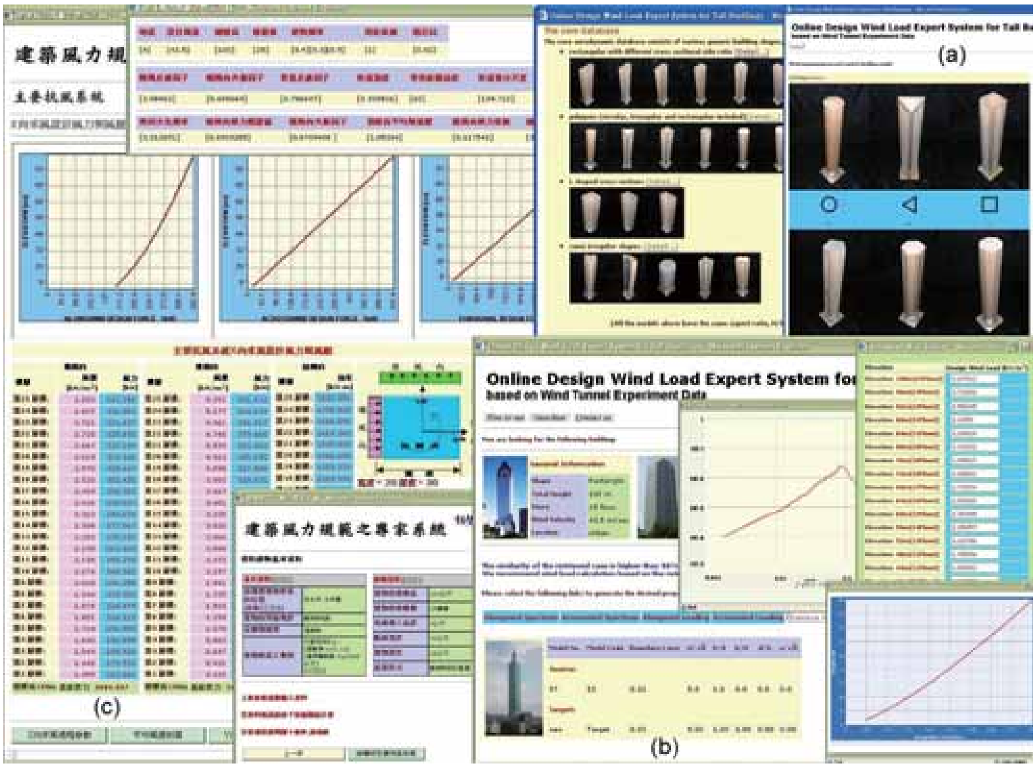


Figure 2 The user interfaces of the expert systems

3.3 Web-enabled design wind load expert system for tall buildings

A case-based expert system based on the above mentioned aerodynamic database (see Figure 2a) for isolated tall buildings was developed. The expert system incorporates not only the aerodynamic database but also analysis procedures of structural dynamics, wind load modification methods and heuristic knowledge of wind engineering. Case-based reasoning and web programming techniques were used to implement the system. Based on the client-server architecture, the user interface is built on Internet browsers using mostly Java Server Page (JSP). Similar cases can be selected, and design wind load modifications are performed using correction factors calculated by numerical programs written in Fortran. In addition, web-charting software is used to produce figures of wind spectra and loading distributions. Screen shots of the system are shown in Figure 2b. The system can be used at the preliminary design stage to get reasonably accurate design wind loads without performing costly and time-consuming wind tunnel tests.

3.4 A wind code based expert system for building wind resistant design

The design codes and standards for wind resistant design are usually complex and prone to misinterpretations. The comprehension of wind code and calculation of design wind loads are difficult and time-consuming for designers that have insufficient wind engineering training. Therefore, Taiwan's new wind code and the logic flow of calculation were coded in rules, and a rule-based online expert system was developed for generating design wind loads according to the design standards. The user interface is built on Internet browsers using mostly JSP, and the knowledge base and inference engine are on a MS IIS server. Engineers can go through a guided process to input building geometry, surroundings and structural properties step by step. The expert system finds the appropriate section of the code and calculates the necessary coefficients and parameters. Finally, it works out the wind load distributions for structural designs. The application areas of the system covers the evaluations of design wind loads for structural systems and design wind pressures for claddings. Screen shots of the system are shown in Figure 2c.

3.5 Application of CFD on building wind resistant design

The rapid developments in both computer hardware and software have created a possible environment for the practical applications of CFD to simulate flows within and around buildings and other structures in recent years. Recently, an isolated 85-story building was selected to investigate the appropriateness of the CFD simulation on the design wind loads of a tall building in the preliminary design stage. During the numerical simulation, the V2F turbulence model and commercial CFD software, STAR-CD, was used for the numerical simulation. In order to validate the CFD results, wind tunnel test was performed. Results indicate that, for the mean wind load, the CFD procedure tends to under-estimate the actual wind load by 13%. As for the building design wind load, the building wind code tends to over-estimate and the CFD gives a reasonable estimation. This investigation indicates that the CFD technique can be used to predict the mean wind load of an isolated tall building with reasonable accuracy, collaborated with gust response factor would then be suitable for the purpose of preliminary building design.

4. FUTURE DEVELOPMENT OF E-WIND

It can be certain that the aerodynamic database will become a powerful tool of building wind resistant design. Due to the versatile of building geometrical variations, currently the aerodynamic database should not be used at the detail design stage; unless the contents of database can be significantly enriched and better wind load adaptation scheme can be employed to account for the effects of minor shape variation on wind loads. CFD simulations and the Artificial Neural Networks are the most likely problem solvers and their effectiveness are currently understudy.

5. CONCLUDING REMARKS

E-wind, a combination of wind code, aerodynamic database, analytical analysis, CFD, ANN and web technology, is under construction at WERC-TKU to provide a building wind load solution package that is easily accessible via web browsers. The key elements of e-wind have been established or under construction. A simple version of e-wind is basically functional and can be accessed at http://windexpert.ce.tku.edu.tw/. More works on CFD and ANN branches are needed to enhance the capability of e-wind.

Evaluation Techniques for Damping in Buildings

Akihito Yoshida Tokyo Polytechnic University

This paper discusses the feasibility and efficiency of simple and user-friendly but accurate damping evaluation techniques. The technique, called the Multi-Mode Random Decrement technique (MRD), can be applied to ambient excitations such as wind, turbulence, traffic, and/or micro-seismic tremors, thus enabling easy handling of closely-spaced mode.

1. PRIMITIVE LABORATORY INVESTIGATION OF DYNAMIC PROPERTIES OF A BUILDING MODEL

To investigate the features of the various damping evaluation techniques, ambient response measurements of a 4-story building model were conducted using fifteen servo-type accelerometers. Figure 1 shows an elevation and plan of the tested 4-story model, which can oscillate with x, y and θ components. Three accelerometers were installed at each level for the x and y directions to be translated into equivalent motions (x, y and θ components) at the centroid. It is assumed that the floor was subject to lateral rigid body motion. The sampling rate was set at 100Hz, with a Nyquist frequency of 50Hz. The sampling length of the ambient vibration record was set at 12 hours.

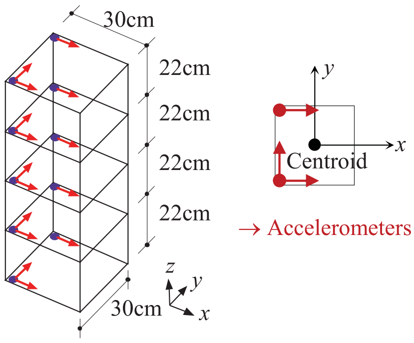


Figure 1 4-story building model

2. DAMPING EVALUATION TECHNIQUES USED FOR COMPARISON

Two different evaluation techniques in the time domain and five techniques in the frequency domain were used to evaluate damping based on the ambient vibration records as follows:

Techniques in Time Domain:
(1) Traditional random decrement technique (TRD);
(2) Multi-mode random decrement technique (MRD) .

Techniques in Frequency Domain:
(1) Half-power method (HP) based on power spectral density function of tip acceleration;
(2) $1/\sqrt{2}$ method ($1/\sqrt{2}$) based on transfer function of tip and base accelerations;
(3) Phase gradient method (PG) based on transfer function of tip and base accelerations;
(4) Curve fit of transfer function (TF) of tip and base accelerations;
(5) Frequency domain decomposition (FDD) based on the singular value decomposition of the cross-spectral density matrix of 12 vibration components of the 4-story model.

Additionally, damped free oscillation tests (DFO) were conducted for direct measurement of the first vibration modes in the x and y directions. The following sections describe the MRD and FDD techniques.

Multi-mode Random Decrement technique (MRD)

The TRD technique assuming a SDOF system can efficiently evaluate the damping ratios and the natural frequencies only for well-separated vibration modes. It is very efficient in evaluating the amplitude dependency of the dynamic characteristics of buildings. However, if there are closely spaced predominant frequency components, a beating phenomenon is observed in the Random Decrement signature (RD signature). In such case, TRD cannot be used to evaluate damping ratio. In order to evaluate multiple closely spaced vibration modes, the Multi-mode Random Decrement technique (MRD) has been proposed (Tamura et al., 2002), where multi-SDOF systems with different dynamic characteristics are superimposed. The RD signature with beating phenomenon is approximated by superimposing different damped free oscillations as follows:

$$R_i(t) = \frac{x_{0_i}}{\sqrt{1-h^2}} e^{-h_i\omega_i t} \cos\left(\sqrt{1-h_i^{\,2}}\,\omega_i t - \phi_i\right)$$

$$R(t) = \sum_{i=1}^{n} R_i(t) + m$$

where $R(t)$: original RD signature, $R_i(t)$: RD signature for the i-th mode component, x_{oi}: initial value of i-th mode component, h_i: i-th mode damping ratio, ω_i: i-th mode circular frequency, t: time, ϕ_i: phase shift, and m: mean value correction of original RD signature.

3. DAMPING RATIOS FROM VARIOUS TECHNIQUES

Figure 2 shows the RD signature using the x component of the tip accelerations of the 4-story building model. The initial amplitude of the acceleration to get the RD signature was set at the standard deviation, σ_{acc}. The lowest natural frequency of the x component of the translational vibration mode of this model and that of the y component are closely located. Therefore, the RD signature with a beating phenomenon was observed as shown in Figure 2, although it was not clear. As described above, the TRD technique should not be used to evaluate the dynamic characteristics. The MRD technique is an appropriate approach in such a case to identifying the two different dynamic characteristics. However, when a beating phenomenon is not clear, as in this case, it is difficult to identify the two different dynamic characteristics by the MRD technique. Thus, coordinate transformation is needed to make the acceleration records, which have almost the same energy for the acceleration in the x and y directions, as shown in Figure 3.

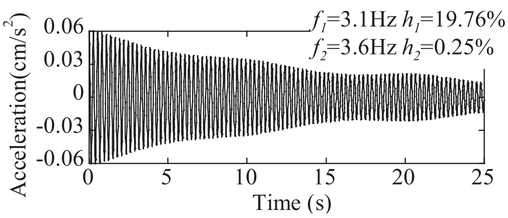
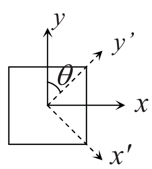


Figure 2 RD signature of tip acceleration (x' dir.)



$$x' = x\cos\theta - y\sin\theta$$
$$y' = x\sin\theta + y\cos\theta$$

Figure 3 Coordinates transformation to x', y' axes

Figure 4 shows the RD signature using the tip acceleration in the x' direction. It can be seen that the beating phenomenon is much clearer than that using the tip acceleration in the x direction as already shown in Figure 2. The natural frequency and the damping ratio evaluated by MRD for the RD signature using the tip acceleration in the x' direction are 3.6 Hz and 0.24% for the 1st mode, and 3.7 Hz and 0.37% for the 2nd mode.

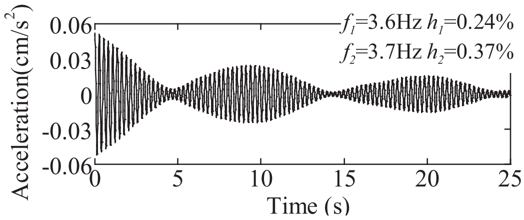


Figure 4 RD signature of tip acceleration (x' dir.)

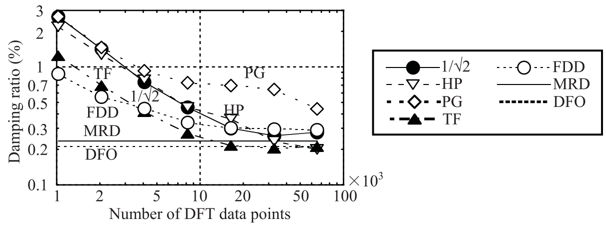


Figure 5 Variations of damping ratios with DFT data points

Figure 5 shows the variations of the damping ratio with the number of data points used for the Discrete Fourier Transform (DFT) calculation. In the frequency domain approaches, the power spectral density functions or the transfer function is calculated via DFT. It is well known that leakage error in PSD estimation always takes place due to data truncation of DFT. Leakage is a kind of bias error, which cannot be eliminated by windowing, e.g. by applying a Hanning window, and is harmful to the damping estimation accuracy, which relies on the PSD measurements. The bias error caused by leakage is proportional to the square of the frequency resolution (Bendat & Piersol, 1986). Therefore, increasing frequency resolution is a very effective way to reduce leakage error. As shown in Figure 5, the damping ratio evaluated by frequency domain approaches decreases with increasing number of data points used for the DFT calculation and converge to a constant value. It is noted that, to accurately identify the damping ratio, the number of data points used for the DFT calculation should be larger than 16,384 in this case, which is almost 600 times the natural frequency of the model. This means that the sample should be long enough. An ensemble averaging operation with a sufficient number of samples is also necessary to obtain a correct power spectral density function. Therefore, a very long record of ambient vibration is necessary to accurately evaluate the damping ratio using a sufficient number of long-enough samples.

COE Program TPU

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