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TECHNICAL REPORT

Review of Wind Resistant Design for Tiled Roofs and Publication of New CFD Guidebook for Urban Wind Environment: Japan Country Report 2021

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ABSTRACT – This paper introduces recent activities related to the structural and environmental engineering in Japan. Part 1 in this paper illustrates outline of recent research and standardization related to ensuring wind resistant performance of tiled roofs. We introduce the results of damage survey on tiled roofs caused by Typhoon Faxai in 2019, which was conducted by National Institute for Land and Infrastructure Management and Building Research Institute in collaboration with clay roof tile industry organization. Then, the outline of the wind load calculation method stipulated in the Building Standards Law and the amended Notification for roof tiles is illustrated. In addition, "Guideline for Standard Structural Design/Construction for Tiled Roof" was revised in July 2021 as a supplement to the law. The outline of monotonous pull-up test and the standard specifications, both of which are newly added to the revised version of the Guideline, are also introduced. These activities are aimed to reduce structural vulnerability of tiled roofs, based on the lessons learned from the damage caused by the typhoon. In Part 2, we introduce activities to promote the appropriate use of computational fluid dynamics (CFD) in wind environment prediction. A working group within the Architectural Institute of Japan compiled a new CFD guidebook and guidelines for urban wind environment prediction, mainly aiming to include the application of large-eddy simulation to pedestrian-level wind problems or dispersion problems relating to concentration and temperature in cities. Reflecting the latest domestic and international research trends and the WG's validation works, achievements of their activities were published as "Guidebook for CFD Predictions of Urban Wind Environment" (2020, in Japanese), papers in international journals, and an extended experimental database for verification and validation of analysis codes.

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PART 1: RESEARCH AND STANDARDIZATION RELATED TO ENSURING WIND RESISTANT PERFORMANCE OF TILED ROOFS

INTRODUCTION

Recently, Japan has experienced devastating wind or flood-induced damage almost every year. For example, in the Typhoon Faxai (Reiwa 1st Year Boso Peninsula Typhoon in Japanese), observed maximum wind speed and maximum instantaneous wind speed were updated at many observation points in Japan. And these record storms caused great damage to buildings and other constructions. Vulnerability of exterior materials and wooden roof components to high wind has become apparent through damage investigations, and their significant damage situation has a great impact on society. Based on the actual situation of these high wind disasters, Ministry of Land, Infrastructure, Transport and Tourism (MLIT) conducted a survey and examination on the wind-induced damage caused by the Typhoon Faxai. In addition, the Ministry of Construction Notification No.109 of 1971 (hereinafter referred to as Notification No.109) was amended in December 2020, and from January 2022, the roof tiles of all new buildings will be required to be fixed based on the notification standard.

Part 1 of this paper introduces results of the survey on the damage to roof tiles caused by the typhoon, which was conducted by National Institute for Land and Infrastructure Management (NILIM) and Building Research Institute (BRI) in collaboration with MLIT. Then, the outline of the wind load calculation method for exterior claddings stipulated in the Building Standards Law and the amended notification standard for roof tiles is illustrated. In addition, "Guideline for Standard Structural Design/Construction for Tiled Roof" (hereinafter referred to as the Guideline) was revised in July 2021 as a supplement to the law. The outline of monotonous pull-up test and the standard specifications, both of which are newly added to the revised version of the Guideline, are also introduced.

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OUTLINE OF BUILDING DAMAGE CAUSED BY THE TYPHOON FAXAI, 2019

On September 9, 2019, the Typhoon Faxai landed on Chiba Prefecture with high wind. The central pressure at the time of landing was estimated to be 960hPa. As the typhoon approached and passed, it became a record storm that observed the highest maximum wind speed and maximum instantaneous wind speed in the history of observation at many observation points. For example, the maximum wind speed of 35.9m/s and the maximum instantaneous wind speed of 57.5m/s were observed in Chiba City.

NILIM and BRI carried out damage surveys on buildings at severe damage areas in Chiba Prefecture. As for the damage to houses, breakage of window glass, falling of roofing materials (including clay roof tiles and slates), scattering of timber roof components, and partial falling of exterior wall finishing materials were observed. Among them, those that appeared to be relatively old, those that had suffered significant decay or termite damage to components, and those that had deteriorated joint parts were significantly damaged. Houses that appeared to be relatively new were generally less damaged. But relatively new houses located along the coast were also damaged in the roof, where the windward opening was damaged and the timber roof components were scattered.

Figures 1 to 4 show typical damage states among the survey results [1]. Vulnerability of exterior materials such as clay roof tiles and timber roof components to high winds has become apparent through the survey. This result is consistent with the recent tendency of high wind damage in Japan. For details of the survey results including damage examples, see Reference [1].

Figure 1. Damage to clay roof tiles (1).

Figure 2. Damage to clay roof tiles (2).

Figure 3. Damage to timber roof components (1).

Figure 4. Damage to timber roof components (2).

DAMAGE SURVEY AND ANALYSIS OF ROOF TILES

Survey outline

NILIM and BRI, in collaboration with the clay roof tile industry organization, carried out field surveys three times from January to February 2020 in the areas affected by the typhoon. In these surveys, appearances of each building were visually inspected to confirm the structural type, number of floors, the type of exterior claddings, the estimated year of construction, and the damage situation. Interviews with residents were also conducted, if possible.

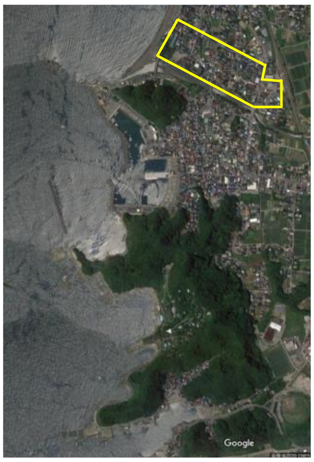
In the case of a tiled roof, it was also grasped from the appearance whether or not construction methods are based on those provided in the Guideline (hereinafter referred to as “Guideline construction method”). This guideline issued by an industry organization in 2001 is not legally enforceable, but specifications such as a method for fastening tiles that can be expected to have high wind resistance are provided on the premise of carrying out structural calculations and load tests based on stipulates of the Building Standard Law referred to the later section.

Survey areas

The surveys were carried out on residential areas around the city (171 buildings in Tomiura, Minamiboso City, 170 buildings in Ryushima, Kyonan Town) and coastal areas (150 buildings in Nishikawana, Tateyama City). All of them are located on the southwest side of the Boso Peninsula. Figure 5 shows each area of the survey. The area surrounded by the yellow framework indicates the main survey area. Yellow-colored framework is not illustrated in Figure 5(d), since the area where houses are scattered was also surveyed extensively.

(a) Location of Boso Peninsula

(b) Tomiura, Minamiboso City



(c) Ryushima, Kyonan Town

(d) Nishikawana, Tateyama City

Figure 5. Survey areas in the Boso Peninsula (adding characters and figures to Google Map).

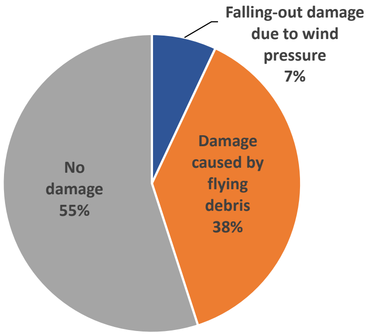
SURVEY RESULTS

Table 1 shows the damage rate (number of damages confirmed), and Figure 6 shows the cause of damage to flat portion of the roof according to the difference in construction method. In Figure 6, "Falling-out damage due to wind pressure" means that the ratio of the damage area to the total one is about 25% or more, and "Damage caused by flying debris" means that the ratio is smaller. In both Table 1 and Figure 6, construction method other than the Guideline construction method is described as “non-Guideline construction method”.

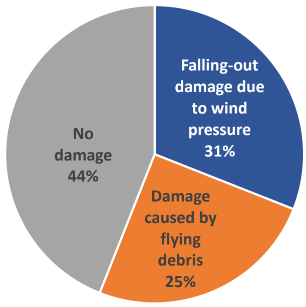
Lots of damages caused by flying debris occurred regardless of the construction method. Lots of roof tiles with non-Guideline construction methods were found to have fallen off due to wind pressure, and the damage was particularly frequent in roof tiles on flat portion that were not subject to fastening under the notification standard before the amendment. On the other hand, it was clarified that roof tiles by the Guideline construction method have very little falling or scattering damage due to wind pressure, and the wind resistance performance above a certain level was confirmed. However, for some clay roof tiles in the coastal area, damage caused by wind pressure was observed even if its connection was considered to be under the Guideline construction method. In addition, no damage was caused to some old houses whose clay roof tiles were replaced by the Guideline construction method.

Table 1. Damage rate (number of damages confirmed) of the tiled roof.

Damaged portion in roof	Guideline construction method	non-Guideline construction method
Gutter and eaves	11% (3)	43% (88)
Ridge	27% (7)	68% (146)
Flat portion excluding gutter and eaves	45% (13)	57% (120)



(a) Guildeline construction method



(b) non-Guideline construction method

Figure 6. The cause of damage to flat portion of the tiled roof.

OUTLINE OF WIND RESISTANT DESIGN OF ROOF TILES

Wind load for exterior claddings including roof tiles

The Building Standard Law of Japan stipulates wind loads for structural frames and exterior claddings, respectively. In the following, the outline of wind load for exterior claddings including roof tiles is summarized. The Ministry of Construction Notification No.1458 of 2000 (hereinafter referred to as Notification No.1458) based on the Building Standards Law stipulates the calculation method of wind load for exterior claddings. The wind load shall be calculated by the following formula to confirm the structural safety of the exterior claddings.

$$W = \bar{q}\,\hat{C}_f \tag{1}$$

$$\bar{q} = 0.6{E_r}^2{V_0}^2 \tag{2}$$

$$E_r = 1.7\left(\frac{H}{Z_G}\right)^{\alpha} \tag{3}$$

where,

W: Wind load (N/m^2)

$\bar{q}$: Average velocity pressure (N/m^2)

$\hat{C}_f$: Peak wind force coefficient

E_r: Coefficient representing the vertival distribution of wind speed

H: Average roof height (m) (H=Z_b in case of $H \leq Z_b$)

α, Z_b, Z_G: Values related to the roughness terrain category listed in Table 2

V_0: Standard wind speed (m/s)

Table 2. Roughness terrain category and related values of α, Z_b, Z_G.

Roughness terrain category	$\boldsymbol{\alpha}$	$\boldsymbol{Z_b}$ (m)	$\boldsymbol{Z_G}$ (m)
I	0.10	5	250
II	0.15	5	350
III	0.20	5	450
IV	0.27	10	550

The standard wind speed, which is the basis of wind pressure, is divided into nine categories in the range of 30 m/s to 46m/s, and each administrative unit is indicated in a table of the Ministry of Construction Notification No.1454 of 2000 (hereinafter referred to as Notification No.1454).

In addition, the roughness terrain category required for the calculation of velocity pressure is also specified in Notification No.1454. Category I is an area that is extremely flat and has no obstacles, and Category IV is an area that is extremely urbanized, respectively. Both categories are defined by the regulations of a specific administrative agency. As shown in Figure 7, Categories Ⅱ and Ⅲ are classified according to the building height and the distance from the coastline or lakeshore line. In addition to the conditions shown in Figure 7, Category II also includes areas that are extremely flat and have obstacles scattered around, as defined by the rules of the specified administrative agency. Though the above provisions follow the concept of roughness terrain classification stipulated in the AIJ Recommendations for Loads on Buildings [3], the description is such that there is no significant difference in the judgment results in building confirmation. The rules related to the category were partially amended in December 2020 and will come into effect in January 2022.

Peak wind force coefficient is calculated as the difference between peak external pressure coefficient and peak internal pressure coefficient. It is important to set the negative peak external pressure coefficient appropriately according to the slope and the roof portion in order to design the wind resistance of the roof tile. From this point of view, the notification standard stipulates the coefficients for each portion as shown in Table 3. When the peak wind force coefficients are adopted other than those stipulated in the standard, the value evaluated in the wind tunnel experiment shall be used.

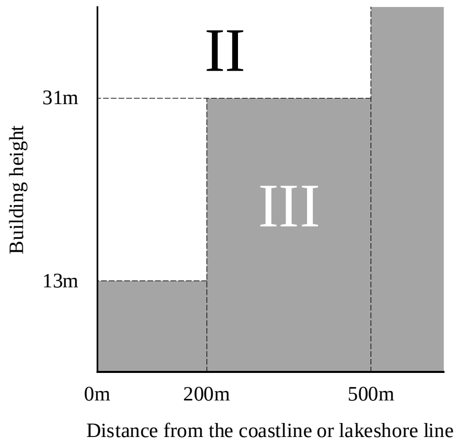
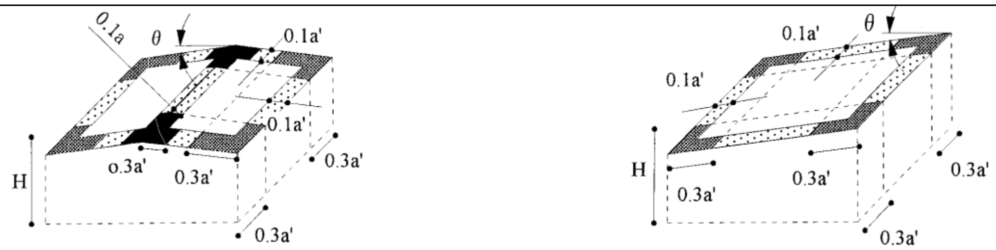


Figure 7. Application of roughness terrain categories of II and III.

Table 3. Negative peak external pressure coefficient on gable roof and one-sided roof.

portion \ roof pitch, θ	10deg. or less	20deg.	30deg. or more
	−2.5	−2.5	−2.5
	−3.2	−3.2	−3.2
	−4.3	−3.2	−3.2
	−3.2	−5.4	−3.2

Table 3. Negative peak external pressure coefficient on gable roof and one-sided roof. (cont.)



In this table, the positions of the portions shall be as specified in the above figure. In addition, the peak external pressure coefficient corresponding to θ other than the values of θ listed in the table shall be the values obtained by linearly interpolating the values listed in the table. For a gable roof surface with θ of 10 degrees or less, the value of the one-sided roof surface at the value of θ shall be used.

In the above figure, H, θ and a' represent the following values, respectively.

H Average of building height and eaves height (m)

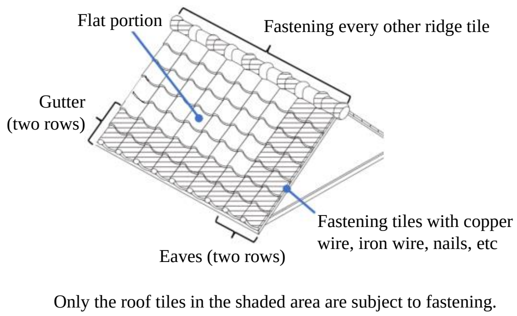
θ Roof pitch (deg.)

a' Whichever of the short side length of the plane and twice the value of H is smaller (if it exceeds 30, it shall be 30) (m)

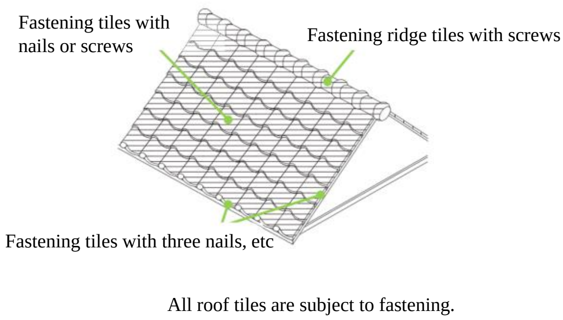
Amendment of notification standard for the construction methods of roof tile

Regarding roof tiles, the above-mentioned results of damage surveys suggest that the guideline construction method which reflects the results of structural calculations or tests is effective in terms of structural strength against high wind. Based on this result, MLIT decided to position the guideline construction method as a notification standard, and from January 2022, it will be mandatory for new construction of buildings with tiled roofs. Figure 8 shows a comparison of the fastening standards before and after the amendment of the Notification No.109 in 2020. Before the revision, only the shaded area in Figure 8(a) was subject to fastening, but after the amendment, all tiles will be required to be fastened as shown in Figure 8(b).

Since the wind resistant performance of roof tiles differs depending on the fastening method, the number of nails or screws for fastening tiles in flat portion is specified according to the shape of the roof tile and the standard wind speed as shown in Figure 9. The nails are limited to those whose shafts are processed so that they do not easily come out, such as screw nails and ring nails. Table 4 shows the stipulated fastening method according to the standard wind speed. In areas where the wind speed is 38 m/s or more, use disaster-proof tiles (tiles that are laid so that adjacent tiles mesh with each other due to hookes for the improvement of wind resistant performance) and fasten them with one or more nails or screws. In addition to these fastening methods, it is also possible to construct roof tiles by a method that has an allowable strength equal to or higher than the revised notification and a method whose structural safety has been confirmed by structural calculation in accordance with Notification No.1458.



(a) Fastening standard before the amendment in 2020



(b) Fastening standard after the amendment in 2020

Figure 8. Comparison of the fastening standards before and after the amendment of the Notification No. 109. (Added to the figure illustrated in Reference [4])

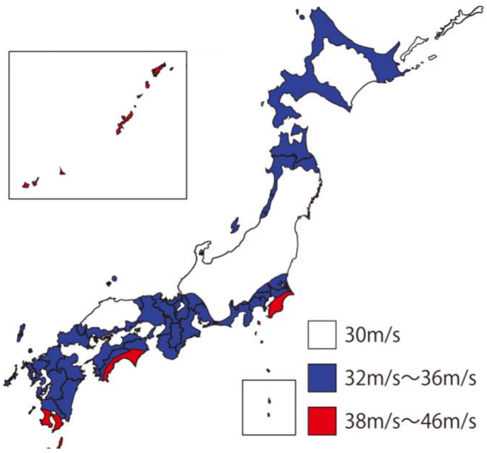
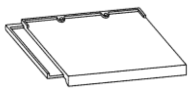


Figure 9. Standard wind speed stipulated in the Notification No.1454 [4].

Table 4. Fastening method of roof tile according to standard wind speed stipulated in the amended Notification No.109.

Type of roof tile \ Standard wind speed V_0		30m/s	32～36m/s	38～46m/s
F type 			Fastened with two nails or screws	Usage prohibited
J type 	S type 	Fastened with a single nail or screw		Usage prohibited
Disaster-proof tile (J type, S type, and F type)		Fastened with a single nail or screw		

(NOTE) Example of hook in the disaster-proof tile [5]

J type

F type

Revision of the Guideline

In parallel with the amendment of the notification standard, NILIM verified and reviewed the validity of the first edition of the Guideline and provided a draft revision of the Guideline. The revised edition shown in Figure 10 [5] was issued in July 2021 by roof tile-related and other organizations. In the revision, the following contents were newly added.

The first is the establishment of a monotonous pulling-up load test method for tiled roofs. Figure 11 shows the test of clay tiled roof. In the past, a load test was carried out in which a constant wind load was set and then raised (loaded) to the wind load level was repeated 150 times, but there was a problem in the test that the allowable load capacity was unclear. On the other hand, according to the newly provided monotonous pulling-up load test, it is possible to evaluate the allowable strength R by the following equation.

$$R = \frac{\bar{P}_{max}}{a\, A_e} \tag{4}$$

where,

$\bar{P}_{max}$: Mean value of maximum pulling-up load obtained in each test (N)

a : Safety ratio of 1.5 or more

A_e : Working area according to the number of effective roof tiles of the test piece (m^2)

In the case of the test results shown in Figure 12, based on Equation (4), it is evaluated that the allowable strength is approximately 1.8kN/m^2, while mean value of the maximum load is approximately 2.7kN/m^2.

Figure 10. "Guideline for Standard Design/Construction of Tiled Roof (Revised Edition)" [5].

Figure 11. Pulling-up load test of clay tiled roof.

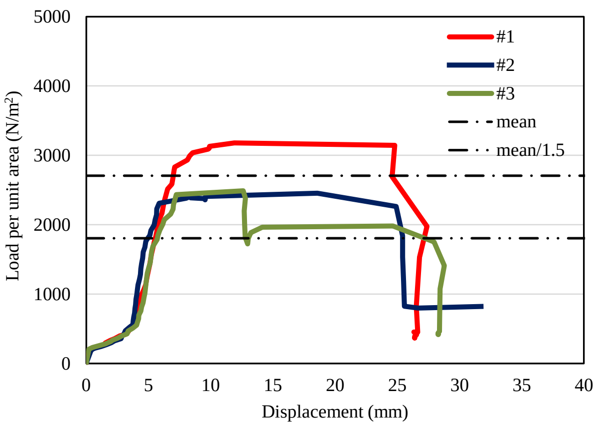


Figure 12. Example of load-displacement relationship obtained by monotonous pulling-up load test [5].

The second is the development of standard specifications for general construction methods whose wind-resistant performance has been confirmed by systematic load tests. The applicable range according to the standard wind speed is summarized in the form of a list using the combination of specifications such as the type of roof tile, the size of nails or screws. These standard specifications can be applied for general construction sites assuming roughness terrain category of III. In addition to the above standard specifications, other higher performance-level specifications that can be able to handle the wind load of the roughness terrain category II are also provided. Wind-resistant performance corresponding to these specifications can be considered higher than that in the standard specifications. Examples of these specifications are shown in Tables 5 and 6, respectively. Among the roof damage caused by the Typhoon Faxai, damage caused by wind pressure was observed in the coastal area facing the sea, even if the roof was designed and constructed according to the Guideline. It is recommended to adopt the specifications shown in Table 6 in coastal areas where such wind conditions are expected.

Table 5. Standard specifications of clay roof tile [5].

Type of roof tile	Type of fastening material	specification of fastening material		Standard wind speed (m/s)		
				30	32～36	38～46
				Load confirmed by load test (N/m^2)		
			number of fastening	738	1,063	1,735
J type tile	nail	Diameter(D) 2.7mm×Length(L) 65mm	1	✓	✓	
	screw	D4.2mm×L57mm	1	✓	✓	
		D3.8mm×L51mm	1	✓	✓	
Disaster-proof J type tile	nail	D2.4mm×L55mm	1	✓	✓	✓
		D2.4mm×L65mm	1	✓	✓	✓
	screw	D3.8mm×L45mm	1	✓	✓	✓
		D3.8mm×L51mm	1	✓	✓	✓

Table 6. Higher performance-level specifications of clay roof tile [5].

Type of roof tile	Type of fastening material	specification of fastening material		Standard wind speed (m/s)			
				30	32～36	38～40	42～46
				Load confirmed by load test (N/m2)			
			number of fastening	1,207	1,737	2,145	2,837
Disaster-proof J type tile	nail	Diameter(D) 2.4mm×Length(L) 55mm	1	✓	✓	✓	
		D2.4mm×L65mm	1	✓	✓	✓	
	screw	D3.8mm×L45mm	1	✓	✓	✓	✓
		D3.8mm×L51mm	1	✓	✓	✓	✓

✓: Applicable

CONCLUSION

Part 1 of this paper illustrated outline of recent research and standardization related to ensuring wind resistant performance of tiled roof on buildings. It is expected that the amendment of Notification No.109 and the revision of the Guideline, which aim to reduce structural vulnerability observed in damage surveys and clarify wind resistance performance of tiled roofs, will contribute to the improvement of structural safety against high wind for tiled roofs.

PART 2: COMPUTATIONAL FLUID DYNAMICS GUIDEBOOK FOR WIND ENVIRONMENT PREDICTION

Background of the guidebook

The wind environment of an urban area influences people's safety and comfort through pedestrian-level winds, urban ventilation, etc. For example, in the vicinity of a high-rise building, a large downdraft of wind can cause people to fall and objects to scatter. Also, in high-density urban spaces, the weakening of the wind can lead to the retention of pollutants.

Therefore, in order to design a safer and more comfortable urban space, it is necessary to predict the wind environment in the city. Wind tunnel experiments have been the mainstream prediction method. However, Computational Fluid

Dynamics (CFD) also has come to be used in various fields of engineering due to the increasing speed of computers, development in various numerical methods and the spread of fluid analysis software.

However, in the use of numerical simulations such as CFD, it is important to ensure the reliability of the results. In recent years, guidelines (best practice guidelines) have been developed for each field of application, and standardization of procedures for verification and validation has been promoted by academic societies and journals.

The Architectural Institute of Japan (AIJ) has been working on guidelines for the appropriate use of CFD to predict wind environments. In 2007, a guidebook was published in Japan explaining the considerations required for the appropriate use of CFD to predict wind environment in urban areas and how to validate the accuracy of the method. In 2016, an English version was published under the title "AIJ Benchmarks for Validation of CFD Simulations Applied to Pedestrian Wind Environment around Buildings" (Figure 13) [6].

The guidebook provides recommendations based on benchmark tests for various building geometries, as well as a database of wind tunnel experiments to validate the accuracy of CFD. The guidebook has had a great impact in Japan and abroad. The validation database has been accessed more than 10,000 times since its establishment and has been used to validate numerous domestic and international CFD studies. A report by Tominaga et al. (2008) [7] that summarizes the main points of the guidelines is one of the most cited articles in the Journal of Wind Engineering and Industrial Aerodynamics.

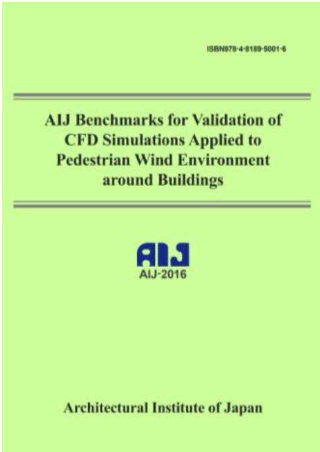


Figure 13. AIJ Benchmarks for Validation of CFD Simulations Applied to Pedestrian Wind Environment around Buildings (2016).

Revision of the guidebook

While previous versions of the guidebook (2007 and 2016) were successful, there is little mention of the application of large-eddy simulation (LES) to wind environment problems or dispersion problems relating to concentration and temperature. In light of increasing user interest, it has become necessary to enrich the contents of the guidebook and expand the scope of applications of the guidelines. With the spread of CFD commercial software and open source codes, there is also a growing demand for easy-to-understand guidebooks that explain the typical boundary conditions and the application of and theory behind other equations employed in this field.

Therefore, a working group within the AIJ compiled a new CFD guidebook and developed guidelines for urban wind environment prediction, reflecting the latest domestic and international research trends. They also conducted benchmark tests on the LES and other CFD simulations required for the guidebook. In 2020, "Guidebook for CFD Predictions of Urban Wind Environment" (translation, Figure 14) was published in Japanese [8]. The validation database was also expanded.

The guidebook consists of four main sections: Part 1: Basic knowledge for predicting urban wind environment, Part 2: CFD analysis techniques for predicting urban wind environment, Part 3: Guidelines for CFD application for predicting urban wind environment, and Part 4 (reference section): Experimental database for validating the accuracy of CFD analysis. Part 1 summarizes the fundamentals of CFD analysis of urban wind environments. Part 2 outlines the CFD analysis techniques required to predict and evaluate urban wind environments. Part 3 provides guidelines for the appropriate use of CFD analysis to predict and evaluate urban wind environments based on the results of benchmark tests conducted by the authors and results published elsewhere. In the reference section, an overview of experimental databases that can be used to validate the accuracy of the CFD analysis is provided.

The experimental database contains wind tunnel experiments and measurements for a total of 13 test cases, ranging from single buildings to simple building arrays and real urban areas, and addresses dispersion problems (Figure 15). In addition, data on inflow turbulence that can be used for LES analyses are also provided. These data were generated by LES analyses that reproduced the spires and roughness blocks in the wind tunnel where the experiments were conducted. These data are freely downloadable from the web page of the database (https://www.aij.or.jp/jpn/publish/cfdguide/index_e.htm), and can be used to verify the accuracy of the analysis code and the validity of the setting conditions.

Figure 14. Guidebook for CFD Predictions of Urban Wind Environment (2020).

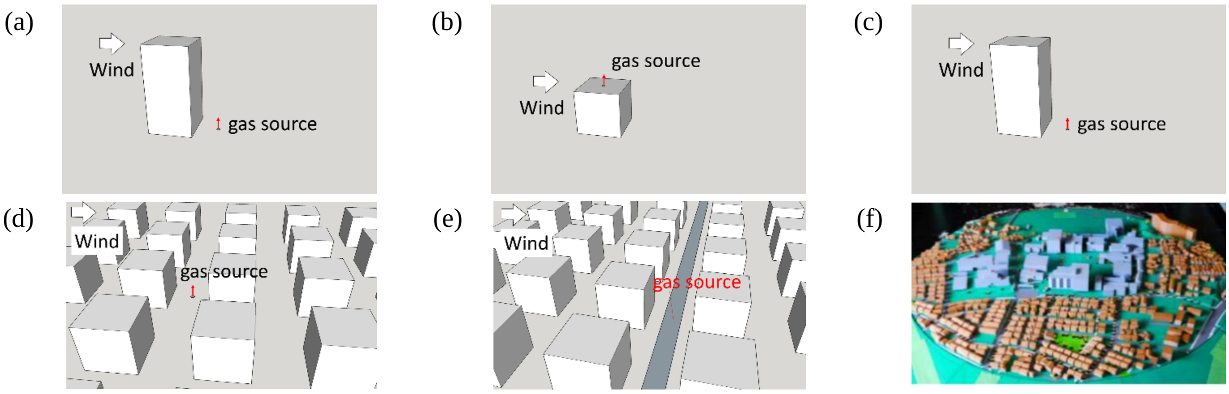
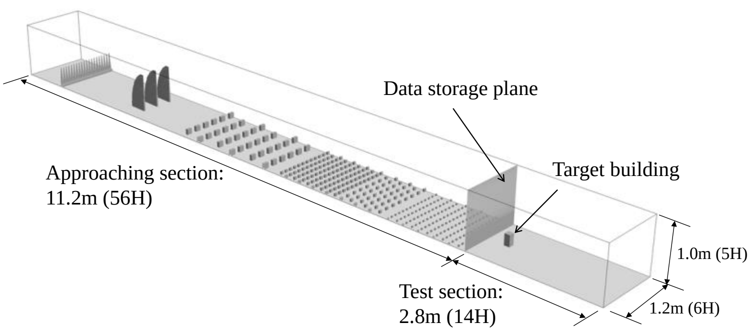


Figure 15. Extended benchmark cases: (a) test case H (1:1:2 isolated building with gas dispersion); (b) test case I (Cubic building with gas dispersion); (c) test case H (1:1:2 isolated building with gas dispersion under unstable boundary layer); (d) test case K (Simple cubic array with gas dispersion); (e) test case L. (Simple cubic array with gas dispersion under unstable boundary layer); (f) test case M (building complexes with complicated shapes and terrain in actual urban area with gas dispersion).

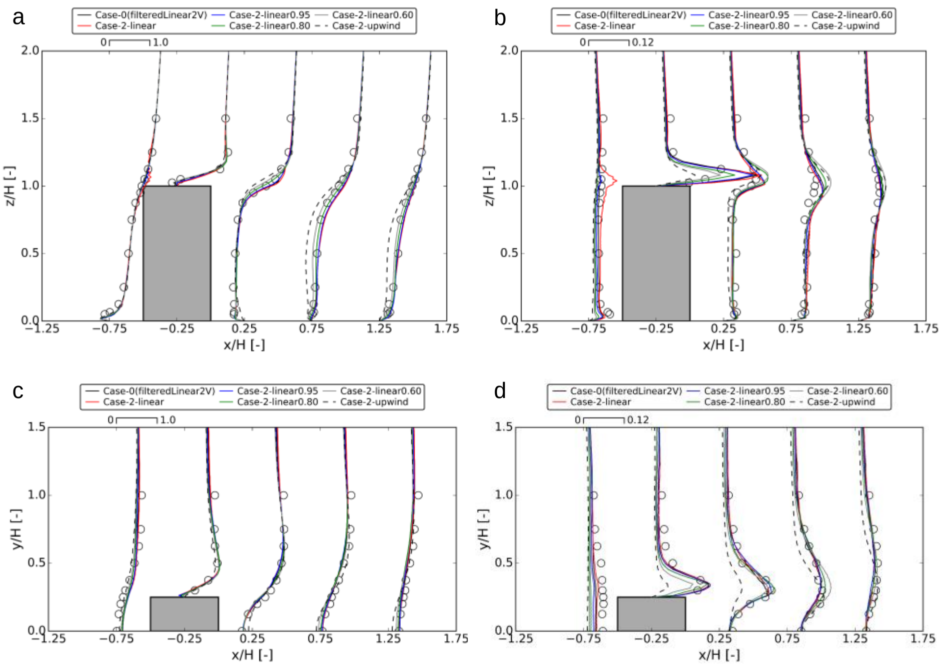
Related publications

Although the 2020 guidebook is in Japanese, the framework for the guidelines has been presented internationally, for example, by Okaze et al. (2019) at the 15th International Conference on Wind Engineering [9]. Furthermore, the results of major benchmark tests by LES have been published in journal articles such as Ikegaya et al. (2019) [10] and Okaze et al. (2021) [11].

In particular, Okaze et al. (2021) reported a representative benchmark test with LES conducted for airflow prediction around an isolated building model (Figure 16). In this study, the accuracy of predicting mean wind speed and second-order turbulence statistics around an isolated building model was systematically examined for sensitivity to grid configuration, discretization of advection term, subgrid-scale turbulence modelling, and convergence criteria [11].



i) Schematic of wind tunnel and LES set up



ii) Some LES validation results against wind tunnel data
(sensitivity to discretization scheme of advection term; a, c: mean velocity; b, d: velocity variance)

Figure 16. A benchmark test of LES of flow around an isolated building model (Okaze et al. (2021)) [11].

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