THE JAPANESE ENHANCED FUJITA SCALE: ITS DEVELOPMENT AND IMPLEMENTATION

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1. INTRODUCTION

Tornadoes are small-scale phenomena whose development is difficult to identify with ordinary surface weather observation networks. It is necessary to investigate the tornado damage in order to estimate the gusty-wind phenomenon type and its intensity.

In Japan, the Fujita Scale (Fujita, 1971; referred to here as F Scale), which is used to estimate wind speed ranges based on tornado damage (e.g., the state of the buildings), has conventionally been used to rate tornado intensity. It is used for such classification in the United States, Japan and a variety of other countries for its simplicity. However, a number of factors (e.g., F Scale was developed in consideration of damage to buildings and other structures in the US.) limit the scale's effectiveness for accurate intensity rating in Japan.

The annual frequency of confirmed tornadoes in Japan is about 25 (year 2007-2015 average, Fig.1) and no record of F4 or F5 tornado has been observed. Fig.2 shows numbers of recent confirmed tornadoes in Japan by F Scale class. In 2006, hazardous tornadoes occurred in Nobeoka City in Miyazaki Pref. (F2) and in Saroma in Hokkaido Pref. (F3). The number of fatalities from these two tornadoes reached 12 in total. In response, Japan Meteorological Agency (JMA) started enhanced damage survey at the disaster sites in 2007.

Moreover, after the tornado on May 2012 which caused severe damage in several cities (such as Tsukuba in Ibaraki Pref.), the Director-level Conference for Measures against Tornadoes was held. It was recommended that JMA formulate a new set of guidelines to be applied to buildings and other structures in Japan in consideration of the F Scale issues. The formulation of a new set of guidelines includes:

- Organization of an advisory committee
- Consideration of expertise in wind engineering
- Ensurance of statistical continuity with F Scale

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2. FORMULATION OF THE JAPANESE ENHANCED FUJITA SCALE

2.1 *ISSUES FOR THE FUJITA SCALE AND THE ENHANCED FUJITA SCALE*

F Scale rating, which has conventionally been applied in Japan, is based on evaluation of a tornado's destructiveness. F Scale class is determined by matching the destructiveness to the "damage descriptions" in the F Scale guidelines. It is easy to be applied but it has some issues as outlined below:

(1) Correspondence between damage descriptions and wind speeds has not been adequately verified. Based on related studies, Minor et al. (1977) and Phan and Simiu (1998) proposed that wind speeds corresponding to F4 and F5 were overestimated.

(2) Only nine types of items can be used as damage indicators: residences, non-residences, greenhouses, chimneys, antennae, automobiles, trains, objects weighing several tons, and trees.

In response, the Enhanced Fujita Scale (referred to here as EF Scale) was developed in 2006 (McDonald and Mehta, 2006), and was adopted by the National Weather Service in the United States in 2007. In the EF Scale, Damage Indicators (i.e., damaged items, referred to here as DIs) and Degrees of Damage (i.e., damage severity, referred to here as DODs) are defined instead of "damage descriptions" in the F Scale. Each DI has several DODs, and wind speeds corresponding to each combination of DI and DOD are defined. This enables wind speed estimation of individual damage cases and more accurate evaluation than with the previous F Scale rating.

Since damage to buildings and other structures in the damage descriptions of the F Scale and the EF Scale are for the US and Canada, consideration of local architectural characteristics is required for a more accurate wind speed estimation in other countries. In response to these issues, JMA developed the Japanese Enhanced Fujita Scale (referred to here as JEF Scale) as an improvement on the conventional Fujita Scale for correspondence to buildings and other structures in Japan with reference to the EF Scale.

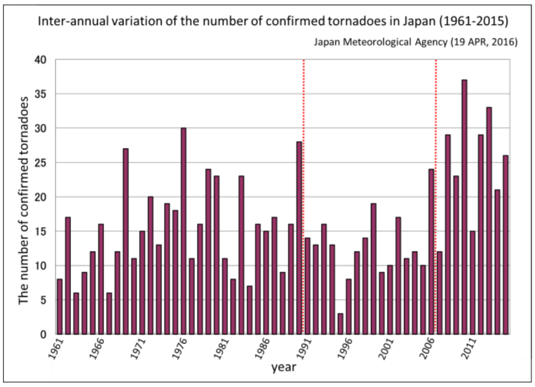

Fig.1: Inter-annual variation of the number of confirmed tornadoes in Japan (1961-2015, waterspouts excluded, JMA). No systematic rating system was applied before 1991. Fujita Scale rating started in 1991. Enhanced damage surveys started in 2007.

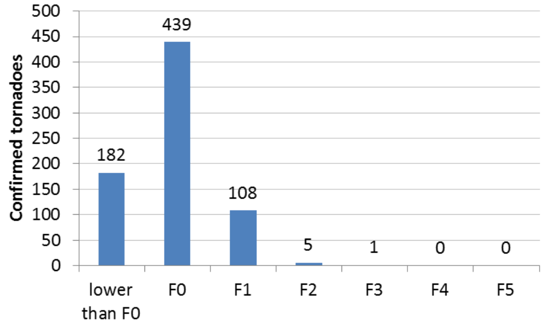

Fig. 2: The number of recent confirmed tornadoes in Japan by F Scale (2007-2015, JMA). No record of F4 or F5 tornado has been observed.

2.2 ORGANIZATION OF THE ADVISORY COMMITTEE FOR TORNADO INTENSITY RATING

Between 2013 and 2015, JMA hosted six meetings of the Advisory Committee for Tornado Intensity Rating (chair: Yukio Tamura, professor emeritus, Tokyo Polytechnic University; Table 1 shows the list of the committee's members.) consisting of wind engineering, architecture, forestry and meteorology experts to examine and formulate JEF Scale. This committee examined the determination of buildings and other structures to be used for DIs and DODs in JEF Scale and the research plans for estimation of corresponding wind speeds. A special research project titled "Cooperative Study on a New Scale for Rating Tornadoes in Japan" conducted by the Wind Engineering Joint Usage/Research Center made a significant contribution to the establishment of correspondence between DIs/DODs and wind speeds. This research project consists of 24 experts in wind engineering, architecture, and in other related matters.

As a result of these research and examination, JEF Scale was formulated in DEC 2015 and JMA implemented it in APR 2016.

Members of the Advisory Committee of Tornado Intensity Rating

ITO, Masaru	Permanent Technical Advisor, Structural Engineering Division, Nihon Sekkei, Inc.
KIKITSU, Hitomitsu	Senior Researcher, Department of Structural Engineering, Building Research Institute
MAEDA, Junji	Professor, Division of Architecture and Urban Design, Faculty of Human-Environment Studies, Kyushu University
NIINO, Hiroshi**	Professor, Atmosphere and Ocean Research Institute, The University of Tokyo
OKUDA, Yasuo	Research Managing Coordinator for Advanced Building Technology, Building Department, National Institute for Land and Infrastructure Management
SAKATA, Hiroyasu	Professor, Department of Architecture and Building Engineering, Tokyo Institute of Technology
SHOJI, Yoshinori	Laboratory Head, Meteorological Satellite and Observation System Research Department, Meteorological Research Institute
SUZUKI, Satoru	Laboratory Chief, Meteorological Environment Department, Forestry and Forest Products Research Institute
TAMURA, Yukio*	Professor emeritus, Tokyo Polytechnic University

*Chair **Vice-Chair

Table 1: The list of the members of the Advisory Committee of Tornado Intensity Rating (as of DEC, 2015). The committee consists of wind engineering, architecture, forestry, and meteorological experts.

3. DETAILS OF THE JAPANESE ENHANCED FUJITA SCALE

3.1 THE CHARACTERISTICS AND RATING PROCEDURE OF THE JAPANESE ENHANCED FUJITA SCALE

DIs and DODs for JEF Scale are based on buildings and other structures commonly found in Japan. Each DI/DOD combination has corresponding wind speeds (rounded to multiples of 5m/s (3-sec. average)) calculated by wind engineering expertise. 30 types of buildings and other structures, such as wooden houses, non-residences, warehouses, greenhouses, vending machines, vehicles, sign boards, fences and trees, are used as DIs (Table 2). Multiple DODs are defined for each DI, and each DOD has three corresponding wind speed values (referred to here as DOD-Levels), such as Representative (Rep.), Lower Bound (LB) and Upper Bound (UB) wind speed values, in consideration of structural and material differences.

The procedure for tornado intensity rating using these DIs, DODs and DOD-Levels is as follows (Fig.3):

(1) Determination of DI and DOD for each case of tornado-related damage

(2) Selection of DOD-Level defined for the combination of DI/DOD determined in (1) and establishment of wind speed corresponding to each damage case

(3) Selection of the maximum wind speed obtained from (2) to represent the phenomenon (referred to as "*wind speed for rating*")

(4) Application of the *wind speed for rating* to the wind speed range in Table 3 and subsequent determination of the JEF Scale class

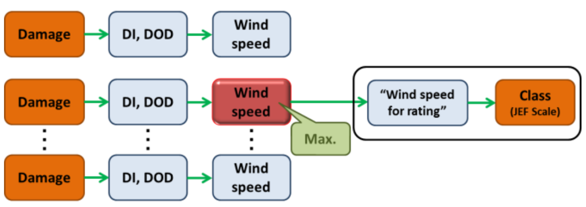

Fig. 3: The rating procedure of tornado intensity using JEF Scale. The maximum value among the wind speeds for individual damage cases is selected to represent the "wind speed for rating" of the phenomenon.

1	Wooden houses or stores
2	Industrialized steel-framed houses (prefabricated)
3	RC apartment buildings
4	Temporary buildings
5	Large eaves
6	Steel-framed warehouses
7	Small non-residential wooden buildings
8	Greenhouses, gardening facilities
9	Wooden livestock sheds
10	Small sheds
11	Shipping containers
12	Vending machines
13	Light vehicles
14	Ordinary vehicles
15	Large vehicles
16	Railway vehicles
17	RC utility poles
18	Ground-based billboards
19	Traffic signs
20	Carports
21	Hollow concrete block (HCB) walls
22	Wooden, plastic, aluminum or mesh fences
23	Windbreak or snowbreak fences for roads
24	Net fences
25	Broad-leaved trees
26	Coniferous trees
27	Gravestones
28	Road surfaces
29	Temporary scaffolding (with wall ties)
30	Gantry cranes

Table 2: The list of DIs for JEF Scale. 30 types of buildings and other structures commonly found in Japan were selected.

Class	Wind speed range (m/s) (3-sec. ave.)
JEF0	25 to 38
JEF1	39 to 52
JEF2	53 to 66
JEF3	67 to 80
JEF4	81 to 94
JEF5	Over 95

Table 3: The correspondence between wind speeds and JEF Scale classes. This correspondence was determined based on the estimated correlation between rating using F Scale and JEF Scale, and the wind speed ranges of F Scale classes.

Fig. 4: Example damage cases of each DOD in DI=1 "Wooden houses or stores." There is no photo for DOD=5 available.

3.2 EXAMPLES OF DOD AND DOD-LEVEL

"Guidelines for the Japanese Enhanced Fujita Scale" has a detailed description of structural and material conditions for each DI/DOD/DOD-Level. In damage surveys, wind speed for each damage case is established by selecting DI, DOD and the matching condition of DOD-Level with reference to the guidelines.

Suppose a wooden house collapse by a tornado (referred to as "damage case (A)"). The DI for damage case (A) is DI=1 "Wooden houses or stores." This DI has eight DODs (Fig.4 shows examples of damage corresponding to each DOD) and each DOD has three DOD-Levels (Table 4). The DOD for damage case (A) is DOD=8 "Major destruction/collapse of main structures and frames." DOD-Level in DOD=8 is selected in consideration of construction year. LB is selected for houses built before 1981, Rep. for 1981-2000 and UB for those built after 2000. If the house in damage case (A) was built in 1990, Rep. is selected and therefore, this damage case is rated as 75m/s.

3.3 ONE EXAMPLE OF WIND SPEED ESTIMATION METHOD OUTLINE BASED ON WIND ENGINEERING EXPERTISE

Wind speeds for each DOD were estimated using wind engineering expertise. This section describes the outline of wind speed estimation method for DOD=8 "Major destruction / collapse of main structures and frames" in DI=1 "Wooden houses or stores" as an example (Kikitsu et al., 2017).

The critical wind speed for collapse of

DOD	Damage		Wind speed (m/s)		
			Rep.	LB	UB
1	Visible minor damage (breakage of glass)		30	25	35
2	Minor loss (detachment)/ displacement of roofing materials	Clay tile roofing	35	25	50
		Metal sheet roofing	40	30	55
3	Major loss (detachment) of roofing materials	Clay tile roofing	45	30	60
		Metal sheet roofing	50	40	65
4	Destruction/detachment of eaves or sheathing roof boards		50	40	65
5	Damage (deformation, cracking, etc.) to walls from deformation of main frames		55	40	65
6	Loss of metal wall cladding		60	45	70
7	Destruction/detachment of roof frames/components		65	50	75
8	Major destruction/collapse of main structures and frames		75	55	85

Table 4: DODs for DI=1 "Wooden houses or stores." Eight DODs and three corresponding wind speeds, Rep., LB and UB were defined for this DI.

wooden houses or stores is estimated in condition that horizontal resistant strength of upper structure R and wind loads against buildings w are balanced. The relationship between wind loads w (N/m^2) and instantaneous wind speed V(m/s) is given as following equation (1),

$$w = \frac{1}{2}\rho V^2 C_f \qquad (1)$$

where ρ is air density (1.2kg/m^3) and C_f is wind force coefficient. Engineering estimation from the typical shape of buildings indicates C_f = 1.2. Horizontal resistant strength per unit area R (N/m^2) is described using story shear coefficient C_0:

$$R = C_0 \frac{W}{A_w} \qquad (2)$$

where W(N) is building weight and A_w(m^2) is wind receiving area. C_0 is the maximum of the story shear coefficient model in consideration of the development of building standards for wooden houses in Japan (before 1981, 1981-2000 and after 2000) (Fig.5).

The typical value of horizontal resistant strength for each period of construction is obtained by evaluating building weight W and wind receiving area A_w as common values in Japan. Wind speed corresponding to DOD is evaluated as the minimum wind speed that satisfies $R \le w$. Wind speeds corresponding to the building standards before 1981, 1981-2000 and after 2000 give LB, Rep. and UB, respectively.

3.4 CORRESPONDENCE BETWEEN WIND SPEEDS AND THE JAPANESE ENHANCED FUJITA SCALE CLASS IN CONSIDERATION OF STATISTICAL CONTINUITY

The JEF Scale class corresponding to wind speed was determined to allow the categorization of phenomenon rating results in the same class for both F Scale and JEF Scale wherever possible in order to maintain statistical continuity (e.g., phenomena rated as F2 on F Scale would generally be rated as JEF2 on JEF Scale).

215 actual tornado-related damage cases were rated using both F Scale and JEF Scale to investigate their estimated correlation. The wind speeds in the F Scale were converted into three-second average values using Durst curve (Dregger, 2005; WMO, 2009; ANSI, 1996). The rating results of the damage cases using both scales were plotted on a scatter diagram and the correlation between wind speeds estimated using F Scale and

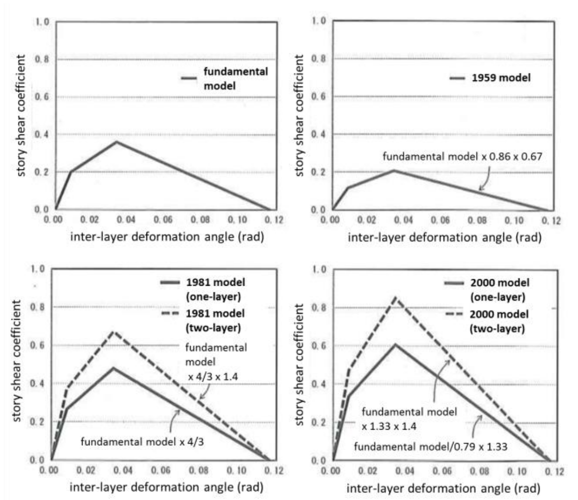

Fig.5: Story shear coefficient models for each construction period. The maximum of the story shear coefficient depends on the models. (Sakata, 2014)

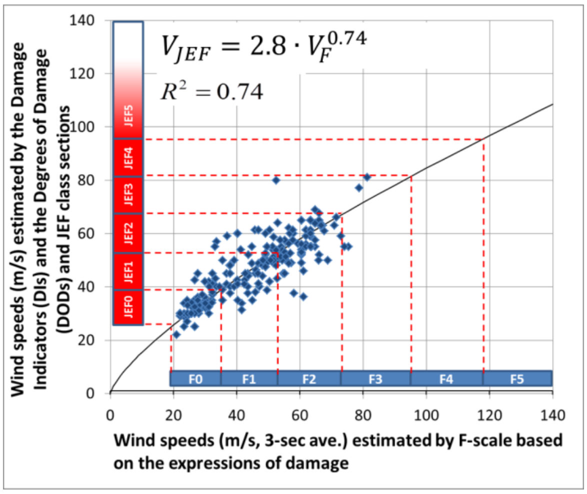

Fig. 6: 215 damage cases rated using both F Scale (horizontal) and JEF Scale (vertical) were plotted on a scatter diagram. Blue dots indicate the individual rating results of damage cases, and the black line indicates the regression curve.

JEF Scale was examined using regression analysis with a power function (Fig. 6). The regression curve is expressed by following equation (3),

$$V_{\mathrm{JEF}} = 2.8 \cdot V_{\mathrm{F}}{}^{0.74} \qquad (3)$$

where V_{F} and V_{JEF} are wind speeds in F Scale and JEF Scale, respectively. The coefficient of determination was 0.74. Based on the regression curve and the wind speed ranges of F Scale classes, the correspondence between JEF Scale classes and wind speeds was determined as shown on Table 3.

4. OPERATION OF THE JAPANESE ENHANCED FUJITA SCALE AND THE ACTUAL RATING CASES

JMA started to rate tornado intensity using JEF Scale on 1 APR, 2016. 44 gusty-wind phenomena were confirmed from 1 APR to 31 DEC in 2016, and 3 of them were rated as JEF2, 14 as JEF1, 20 as JEF0. The seven other cases could not be rated for reasons, such as no damage cases applicable to any DIs.

On 5 OCT, 2016, a tornado occurred in Kochi and Nangoku Cities (both in Kochi Pref.) and four persons were injured (as of 31 DEC, 2016). The damage case of a roofing material detachment on a factory (Fig. 7) were rated as DI=6 "Steel-framed warehouses," DOD=3 "Loss (removal, detachment) / distortion of roofing materials [With openings at windward wall]," and UB (60m/s) was selected because the detached roofing materials were made of metal sheet. Comparing with wind speeds for other damage cases, this wind speed was largest and determined as the *wind speed for rating* of the phenomenon and therefore, this tornado was rated as 60m/s, JEF2.

5. THE ENGLISH VERSION OF "GUIDELINES FOR THE JAPANESE ENHANCED FUJITA SCALE" AND TORNADO RATING IN THE FUTURE

JMA is now preparing the English version of "Guidelines for the Japanese Enhanced Fujita Scale," which gives a detailed description of DIs/DODs, the outlines of corresponding wind speed estimation methods and operational comments, and plans to upload it on the JMA Web site after APR, 2017 (URL: http://www.jma.go.jp/jma/en/Publications/publications.html)

Fig. 7: Detachment of metal sheet roofings on a factory rated as 60m/s (A tornado occurred in Kochi and Nangoku Cities in Kochi Pref. on 5 OCT, 2016).

"Advisory Committee for Tornado Intensity Rating" and the research project "Cooperative Study on a New Scale for Rating Tornadoes in Japan" will continue to be active to revise JEF Scale. To increase the ratable damage cases, addition of new DIs/DODs will be examined. Also, Unmanned Aerial Vehicles (UAVs) are being considered as a useful tool for a more detailed investigation of buildings and other structures from various angles in determining DI and DOD.

6. CONCLUSION

The Japanese Enhanced Fujita Scale (JEF Scale), which is based on buildings and other structures commonly found in Japan, was developed and implemented to rate tornado intensity more accurately than the conventional F Scale. In JEF Scale, tornado intensity is rated in wind speed rounded to multiples of 5m/s by applying damage cases to DIs/DODs, and the corresponding wind speeds were estimated using wind engineering expertise.

JEF Scale will contribute to the studies on the mechanism of tornado, improvement on its forecast, and disaster prevention through the accumulation of accurate tornado data including intensities, sizes, frequencies, geographical distribution and so on. We expect that JEF Scale provides a useful tool for comparing tornado intensities in Japan with those in the world.

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