Structural Damages Caused by Tatsumaki

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Abstract

A Tatsumaki struck the south-east part of Tokyo in the evening of February 28th 1978. We made a survey immediately after the occurence of the Tatsumaki. The damages caused by the Tatsumaki were distributed in a straight belt area which had the length of 40 km and the width of 0.4 km. The most remarkable damages of all were that a train was turned over on a bridge over a river in Tokyo and that a prefabricated one-story school building, which had a floor area of 539 m^2 was lifted about 5 m up and flown over the next building and crashed down on to a third building. Structural damages caused by the Tatsumaki are the special theme of research in this paper.

1. Introduction

Severe local storms include down bursts, gust fronts, tornadoes, waterspouts and dust devils. Tornadoes, waterspouts and dust devils among severe local storms are particularly characterized by the rotational flow field. The "Tatsumaki" is a violently rotating column of air, pendent from the base of a convective cloud and nearly always observable as a funnel cloud, and occurs in Japan. The Tatsumaki is usually accompanied by damaging winds. The structure of the Tatsumaki is similar to that of the tornado.

There are several studies on the Tatsumaki in Japan.[1,2] According to these studies, the occurrence of the Tatsumaki is more than 10 per year and on the average one person is killed, sixteen are wounded and 62 houses are damaged per year by the Tatsumaki.[1] The maximum peak gust of the Tatsumaki has never been actually measured, however near the path of the Tatsumaki a maximum peak gust of above 60 m/sec has been recorded. The maximum peak gust estimated from the damages is considered to be about 100 m/sec. Of tornadoes in the United States, the maximum peak gust of 125 m/sec has been observed by a Doppler radar and 250 m/sec has been estimated from the analysis of the damages to structures. The occurrence probability of Tatsumaki at a certain place in Japan is estimated to be of the order of 10^{-6} per year whereas that of a tornado in the United States to be about 10^{-4} per year.[1]

From these results described above, it may safely be said that the Japanese Tatsumaki is less severe and less frequent than the American tornado. But more detailed knowledge of its characteristics, especially its maximum peak gust estimate, is required for the purpose of disaster prevention, because the structures such as an atomic power plant which need great protection from damage are increasing. A Tatsumaki hit the southeastern part of Tokyo near the coast of Tokyo Bay and caused severe damages including a train accident and a school building collapsed in the evening of February 28th, 1978, which showed the danger of the Tatsumaki in highly populated areas.

In this paper we will especially deal with the maximum peak gust estimate analyzed from the damages actually caused by the Tatsumaki.

2. Meteorological information on Feb. 28th, 1978

On that day a developed low atmospheric pressure cyclone was passing northeastward along the Japan Sea. The Tatsumaki appeared in the warm section between the warm and cold front. Fortunately, around the damaged area of this Tatsumaki, there were distributed a number of meteorological instruments installed for the purpose of disaster prevention and environmental protection which are shown in **Fig. 1.** The numbers in this figure indicate the maximum peak gust obtained at the observation points and the oblique line shows the damaged area.

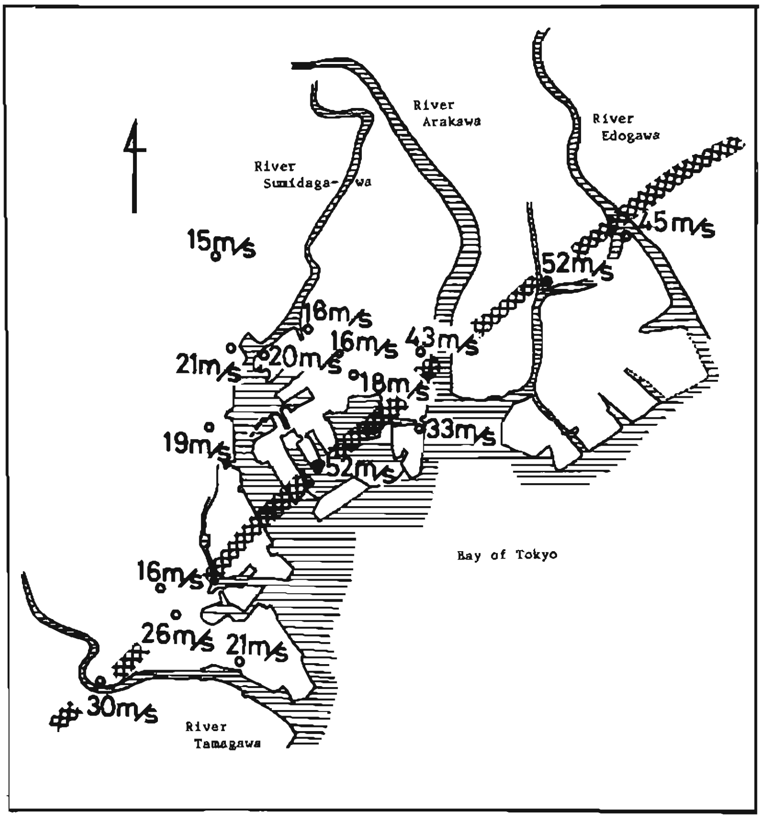

Fig. 1. The distribution of the maximum peak gusts due to the Tatusmaki observed at meteorological stations.

According to the records of barograph in the vicinity of the damaged area, there existed a depression of about 2 mb for about 10 minutes around the hour of the Tatsumaki occurrence, which indicated the existence of a tornado cyclone of about 15 km in diameter. The movements of this low pressure system could be traced on detailed local weather maps and radar scope cine-records. The Tatsumaki was thought to travel with this cyclone.

The maximum peak gust observed by anemometers was 52 m/sec. This value was obtained at two locations on the severely damaged belt, both of which are indicated by black points in **Fig. 1**. The recorded maximum peak gust hyperbolically decreased as the distance of the observation point from the center line of the damaged area increased. The true maximum peak gust was not measured because the center of the damaged area does not necessarily mean the path of the center of the Tatsumaki and the center of the damaged area was somewhat uncertain in some areas.

3. Damages

The Tatsumaki hit the southeastern part of Tokyo and severe damage was caused along a line from the coast of Tokyo Bay near Haneda Airport running northeastward. The total amount of damage is indicated in **Table 1**. These statistics indicate that this Tatsumaki was not an extraordinarily severe one compared to the average Tatsumaki. The distribution of the damage to houses (including completely, partially and slightly damaged houses), the damage to the electric facilities (electric poles and power transmission lines) and some other remarkable damage are indicated in **Fig. 2**.

The damaged area around Kawasaki and that around Ichikawa seem to be connected approximately by one straight narrow belt. The length of the damaged area was about 40 km and the width was at most 0.4 km. Even though the total damage was not so serious, we have to note that there were two cases which could have been serious disasters if they had occurred at during the day. A detailed discussion will be found later.

Table 1. The statistics of the damages caused by the Tatsumaki

Item	Quantity
Number of Wounded	34
Number of Damaged Houses	
Totally destroyed	27
Badly damaged	249
Slightly damaged	904
Number of Derailments	3
Number of Afflicted Houses	1515

4. The translation velocity of the Tatsumaki

As the hours on the strip charts were not sufficiently accurate, the hours at which the strong gusts appeared on the charts do not always match the hours of the power failures recorded at the switching stations. The most reliable determination of the hour of the damage occurrence or Tatsumaki passage can be done by the hours of the power failure, which are recorded with an accuracy of one minute and the hour of the train accident, which is probably accurate within an order of ten seconds. The hours of the damage occurrence thus determined are indicated in **Fig. 2.**

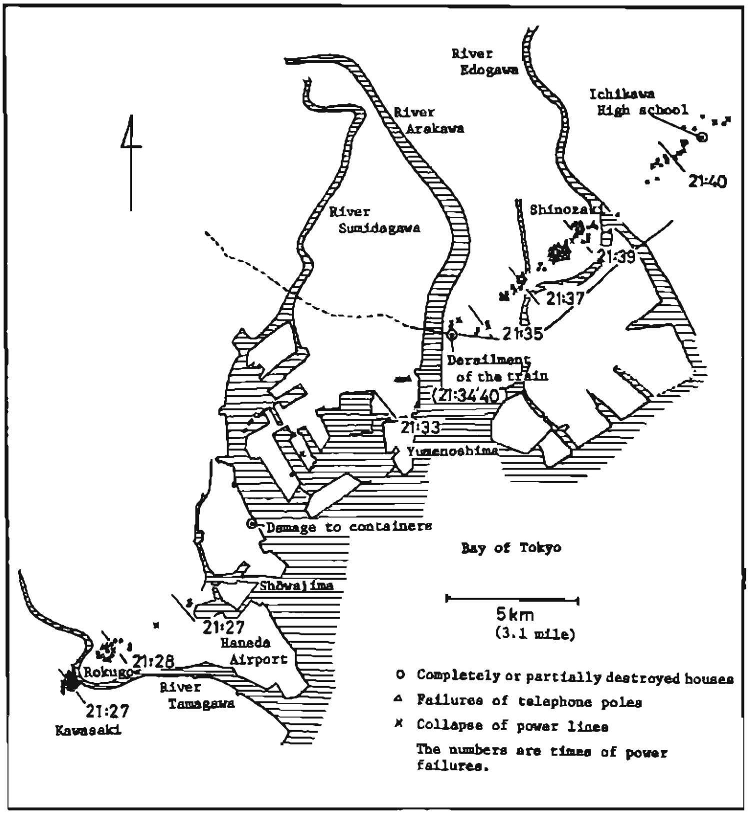

Fig. 2. The distribution of damage to houses (○), electric facilities (×) and other remarkable damages (◎). The numbers are the hours of the power failures and the hour of the train derailment.

Although the path of the center of the Tatsumaki has not been finally determined yet, it is likely that the damage mentioned above were caused by a single Tatsumaki spawned in a tornado cyclone which travelled from southwest to northeast. The translation velocity of the Tatsumaki determined from the hours of the power failures is 110–130 km/hr (30–35 m/sec) and the direction from southwest to northeast. This translation velocity approximately agrees with that of the tornado cyclone analyzed by the map and by the radar echoes observed at the aerological station at Takeno, about 60 km to the NNE of Tokyo.

5. Damage rates

The relationship between the damage rates of houses and the maximum peak gust due to typhoons in Japan as obtained through the wind damage surveys by the authors is shown in **Table 2**. The damage rates, Rc, Rp, and Rs are defined as

Rc = (completely damaged houses/total houses) × 100 (%)

Rp = (completely damaged houses + partially damaged houses/total houses) × 100 (%)

Rs = (completely damaged houses + partially damaged houses + slightly damaged houses/total houses) $\times$ 100 (%)

where completely damaged houses mean more than the roofs completely blown off; partially damaged houses mean some parts of roots broken or most of the roof tiles blown off; and slightly damaged houses mean some of roof tiles blown off or some window glass broken.

Table 2. The relationship between the damage rates of houses and the maximum peak gusts due to typhoons in Japan

Typhoon	Maximum Peak Gust	Rc	Rp	Rs
Isewan Typhoon	64 m/sec (143 mph)	3.5	17.5	
2nd. Miyako (Typhoon 6618)	85 m/sec (191 mph)	17.6	31.1	
3rd. Miyako (Typhoon 6816)	80 m/sec (179 mph)	7.0	33.5	
Typhoon 7513	68 m/sec (152 mph)	8.0	22.3	57
Typhoon 7709	60 m/sec (135 mph)	24.4	50.0	77.4

While the damage rates of the present Tatsumaki in the Edogawa District which is between the Arakawa River and the Edogawa River, where the Tatsumaki was in a mature state, the damage rates within the damaged zone of the Tatsumaki were Rc=0%, Rp=2.5% and Rs=5.2% respectively (see **Fig. 3**). These rates were obtained by dividing the number of damaged houses by the total number of houses in the area inflicted by the Tatsumaki, that is the area with a width of 0.4 km and a length of 5.7 km along the contour line of the damaged zone which is indicated by oblique lines in **Fig. 3**. The recorded maximum peak gust of the Tatsumaki was 52 m/sec at two observation points. The observation points were a short distance away from the center of the path and the true maximum peak gust is likely somewhat higher than this value. If the wind exceeds 52 m/sec in a typhoon, the damage rates of Rc, Rp, and Rs will be above 5%, 20% and 50% respectively as shown in **Table 2**. The present Tatsumaki damage is far less than those of typhoons of the same wind speed. The difference of the damage rates between Tatsumaki and typhoons is due to the short duration of the maximum peak gust. A high wind of a typhoon continues for several hours whereas in the case of a Tatsumaki it continues only for a few seconds. Furthermore, the area afflicted by the peak gusts in a typhoon is 10–15 km wide, while it is only about a hundred meters in the case of a Tatsumaki. With respect to the structural aspects, horizontal forces are mainly dominant in typhoon winds, whereas up lift forces are as strong as horizontal forces in Tatsumaki winds.

It is inappropriate to underestimate the force of Tatsumaki even if the damage rates of a Tatsumaki is low compared to those of typhoons. In an open area such as a plain or a river, a train was turned over and a prefabricated one-story school building was flown away by the Tatsumaki as described in the next section. These damages indicate the existence of strong up-drafts of the Tatsumaki. In a built-up urban area crowded with buildings, these structures are substituted for roughness

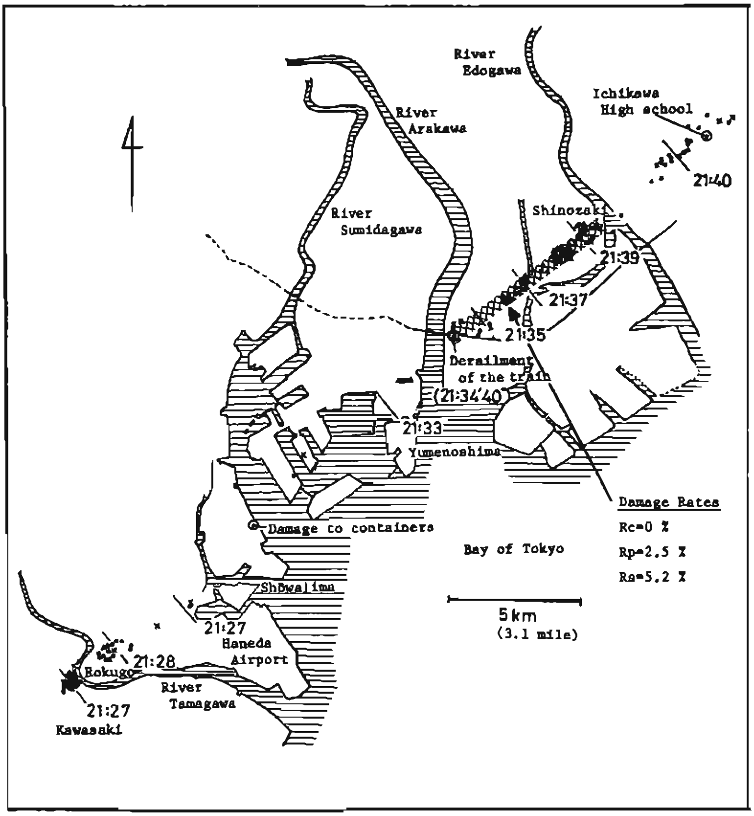

Fig. 3. The damaged zone caused by the Tatsumaki in a mature state.

blocks so that the boundary layer of the Tatsumaki increased in thickness and a high wind does not reach down near to the ground. These results explain that the damage to low houses of one or two stories in a build-up urban area are not so large as compared to those of an open area.

6. Two special cases of damages

The two last cars of a 10 car train travelling to Nakano at the speed of 78 km/hr were turned over on the rails of the other lane near the bridge entrance over the Arakawa River at 21: 34′40″ by a strong wind blowing off from south (see **Fig. 4** and **Photo. 1** offered by Tokyo Express). The height of the bridge was about 15 m above the water level and the external form is indicated in **Photo. 2**. Weights of the last and second last cars were 27.5 tons and 36 tons respectively. Fortunately only 21 people were injured because there were not many passengers on the train. The driver in the lead car was not aware of anything unusual and did not slow the train down until he felt the train derail and lean to the right. He found the cars in the rear had turned over after the train stopped completely. Although the two derailed cars had a total of 8 wheels, only one trace of the wheel crossing on the rail was found in the subsequent investigation. Two cars are assumed to have been first lifted up and then turned over by the wind.

A prefabricated one-story school building situated the north of Ichikawa City was lifted up approximately 5 m, flown over and crashed down on the other side of

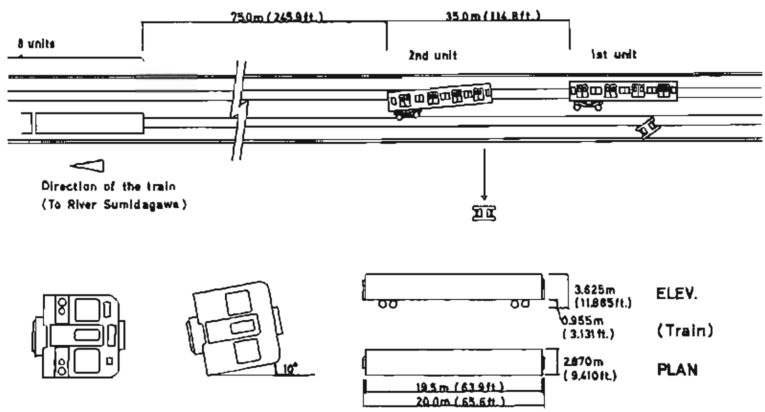

Fig. 4. The derailment of a train on a bridge over the Arakawa River.

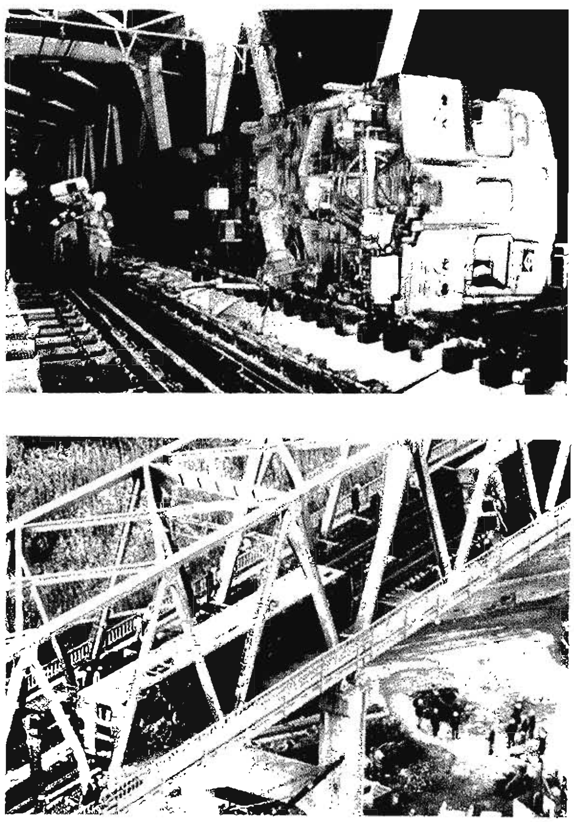

Photo. 1. The derailment of a train (offered by Tokyo Express).

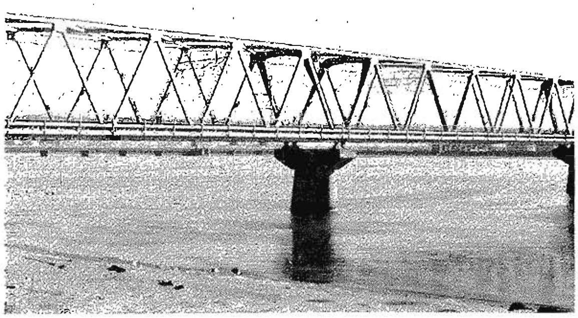

Photo. 2. The external form of the bridge.

a neighbouring building which was 4.8 m in height (see **Photo. 3** and **Fig. 5**). The school building had 7 rooms and a floor area of 9.1 m $\times$ 59.2 m. The distance between the two buildings was 37 m. The floor boards of the school building remained intact and the desks in the rooms also remained as they were. The weight of the uplifted building including the side walls and roofs was about 82 kg·w/m^2. It was found that the side walls were not sufficiently fixed to the floor boards or to the foundation of the building, therefore the building could be lifted up only by an up-lift force equivalent to the weight of the building.

These two special cases indicate that damage was caused by up-lift forces of short duration and therefore there were strong up-drafts.

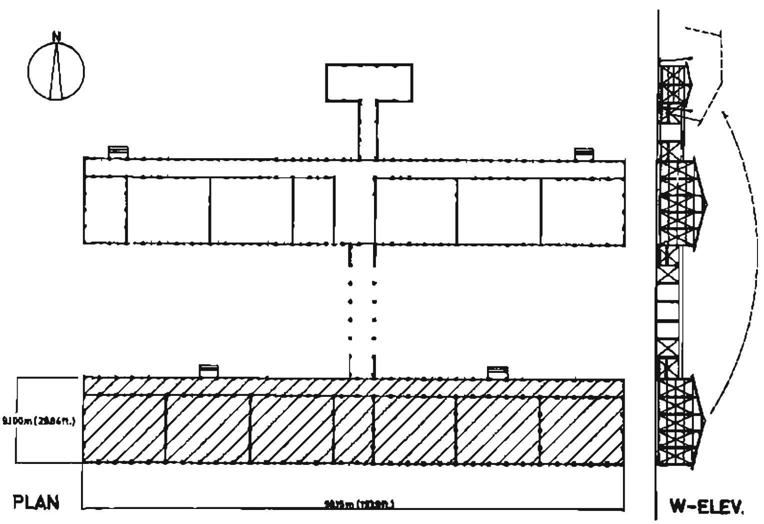

Fig. 5. The damage of a prefabricated school building caused by strong up-draft.

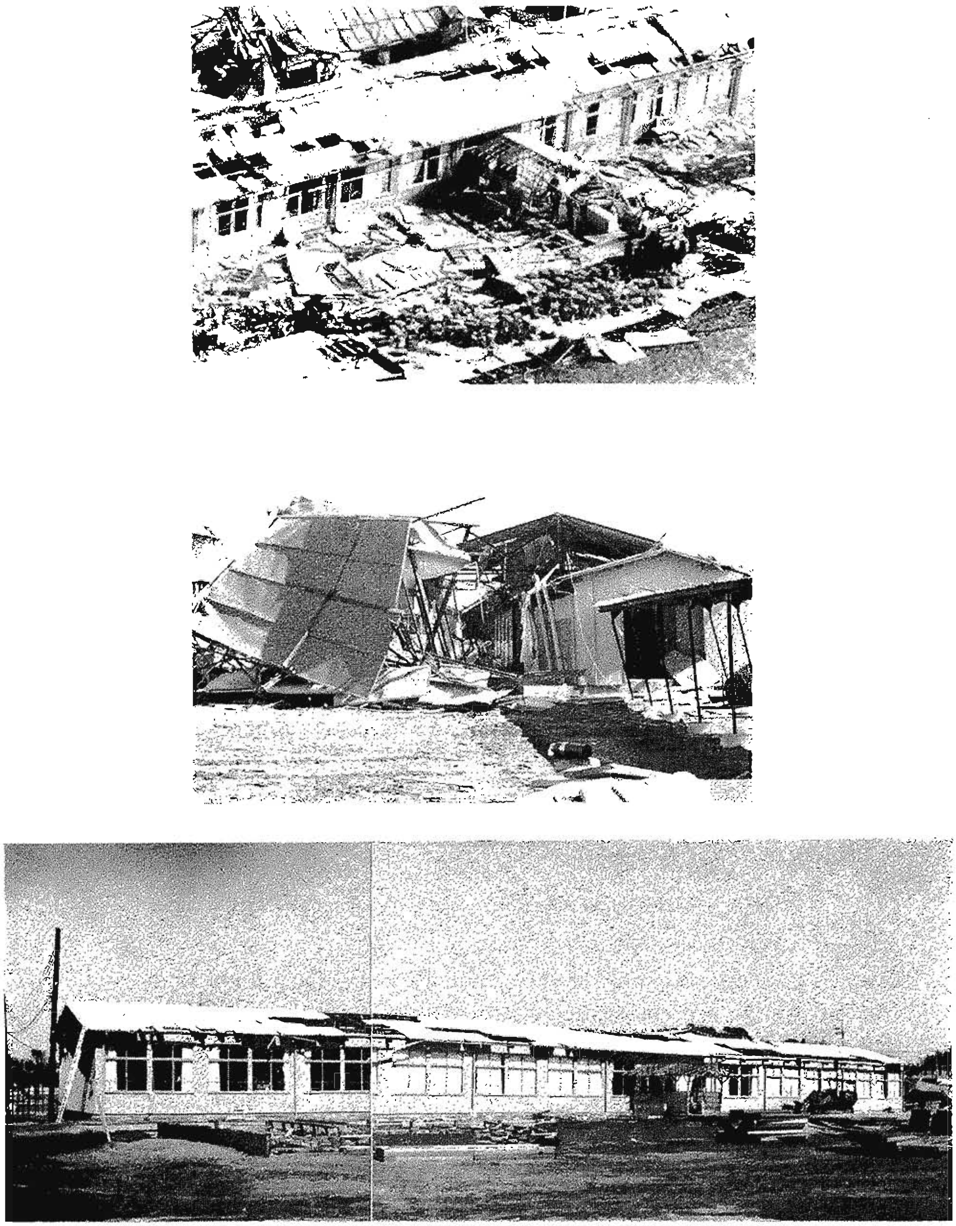

Photo. 3. The damage to a prefabricated school building.

7. Maximum peak gust estimated from damages

We assumed this Tatsumaki to be an axisymmetric structures without suction vortices when estimating the maximum peak gust. As shown in Chapter 2, the distribution of the maximum peak gust associated with this Tatsumaki was plotted as a function of the distance from the center line of the damaged area. The measured maximum peak gust was 52 m/sec and the maximum tangential velocity of 17 m/sec was obtained by subtracting the translation velocity of 35 m/sec given in Chapter 4. The true maximum peak gust was not measured because the path of the Tatsumaki center was not so close to the observation points. The shortest distance between them is estimated to be about two or three times of the radius of the Tatsumaki, therefore the true maximum peak gust is supposed to be 75 m/sec by adding the translation velocity of 35 m/sec and the maximum tangential velocity of 40 m/sec as shown in **Fig. 6**. The maximum vertical velocity is supposed to be of the same order as the maximum tangential velocity (C. A. Wan and C. C. Chang).[5]

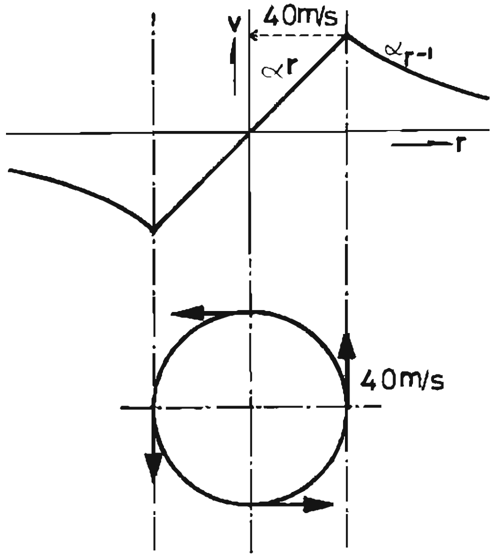

Fig. 6. The hyperbolic function of the tangential velocity.

Now we take up two cases of the damage by the Tatsumaki under discussion, one is the damage to a prefabricated school building and the other is the derailment of a train.

The damage to the prefabricated school building (see **Fig. 7**); If the maximum peak gust is assumed to be 75 m/sec, the up-lift force per square meter is given as follows.

$$F_L=\frac{1}{2}\rho V^2 C_L \qquad (\mathrm{kg{\cdot}w/m^2}) \tag{1}$$

where the up-lift coefficient C_L is calculated to be 0.45 by DIN. Putting $\rho=0.124$ ($\mathrm{kg{\cdot}w{\cdot}sec^2/m^4}$) (at 10°C, 984 mb) and $V=75$ m/sec in Eq. 1. We have

$$F_L=157\ \mathrm{kg{\cdot}w/m^2}>82\ \mathrm{kg{\cdot}w/m^2}$$

As the weight of the prefabricated school building was only 82 $\mathrm{kg{\cdot}w/m^2}$, the up-lift force per square meter could exceed the weight per square meter of the prefabricated school building.

The drag force per square meter is also calculated to be 450 kg·w/m^2 by DIN. The total force acting on the school building is 477 kg·w/m^2 obtained by the vectoral summation of the drag force and the up-lift force. The rising angle to the horizontal is considered to be about 20 degrees. If the total force F_t of 477 kg·w/m^2 acting on the building with the rising angle of 20 degrees continues for only a half second, the initial velocity V_0 is given as follows;

$$Ft\cdot g\cdot \Delta t = M\cdot V_0 \qquad (2)$$

Putting F_t=477 (kg·w/m^2), g=9.8 (m/sec^2), Δt=0.5 (sec) and M=82 (kg/m^2) into Eq. (2). We have

$$V_0 = 29 \text{ m/sec}$$

The distance flown over by the building is roughly calculated to be about 53 m in the case where the building was carried over with an initial velocity of 29 m/sec and a rising angle of 20 degrees. The distance flown over measured on the spot was about 40 m, which is almost the same as the calculated value of 53 m. Furthermore, the height of the orbit above the next building that was 24 m distance from the building which flew is also calculated to be about 5 m, which slightly exceeds the next building of 4.8 m in height.

From the results mentioned above it may safely be said that the assumption of the maximum peak gust of 75 m/sec is reasonable.

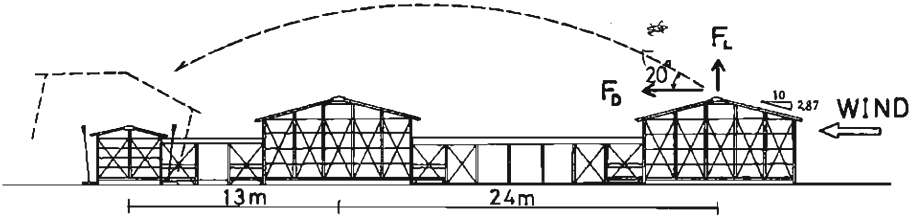

Fig. 7. The orbit of the building which flew.

The damage to a train (see **Fig. 8**); In most cases of Tatsumaki, the increasing rate of wind velocity is not so small that it may be neglected. The force acting on the train was obtained by the summation of the resultant wind force and the accelerating force of the increasing velocity of winds. Thus the lift force per square mteer of the reference area of the train can be shown by

$$F_L = \frac{1}{2}\rho V^2 C_L + \rho 1 \frac{\partial V}{\partial t} C_V \qquad (\text{kg}\cdot\text{w/m}^2) \qquad (3)$$

where the resultant wind velocity V equals the square root of the horizontal wind velocity of 75 m/sec plus the vertical wind velocity of 40 m/sec. The attack angle of the resultant wind to the horizontal wind is about 30 degrees. If the section of a car of the train is supposed to be square, the vertical lift coefficient C_L acting on the square prism with the attack angle of 30 degrees is assumed to be 1.3 according to wind tunnel experiments. The virtual mass coefficient C_V is not known. The value is roughly decided to be 1.0 as it is assumed to be of the same order of C_L. And the acceleration $\frac{\partial V}{\partial t}$ is considered to be of the order of 10 m/sec^2 which was roughly calculated from the anemometer records. Putting $\rho=0.124$ (kg·w·sec^2/m^4), $V=\sqrt{75^2+40^2}=85$ (m/sec), $C_L=1.3$, $C_V=1.0$, $\frac{\partial V}{\partial t}=10$ (m/sec^2) and $l=3$ m (the approximate width of the train) into Eq. 3, we obtain

$$F_L=586\ (\text{kg}\cdot\text{w/m}^2)\simeq 640\ (\text{kg}\cdot\text{w/m}^2)\,,$$

where 640 kg·w/m^2 is the averaged weight of a car of the train and is almost the same as the estimated lift force of 586 kg·w/m^2. The train would be derailed by the joint action of the overturning moment due to the horizontal force and the lift force estimated above.

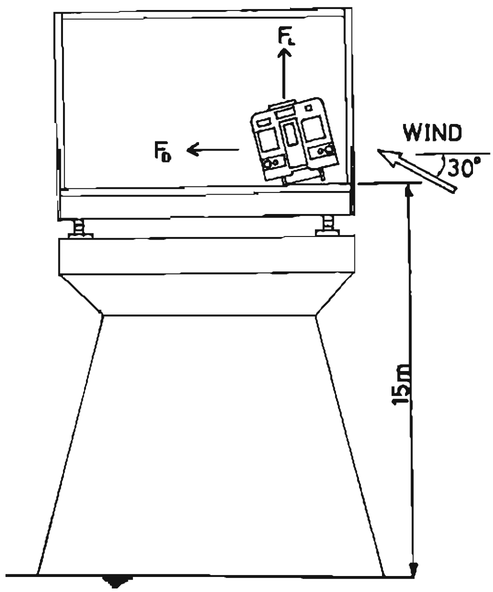

Fig. 8. The lift force acting on the train.

8. Conclusions

A Tatsumaki struck the area along the northwest coast of Tokyo Bay in the evening of February 28th, 1978. The damages were distributed in a straight belt area beginning at Kawasaki, Kanagawa ending at Kamagaya, Chiba. The length and the width of the damaged area were about 40 km and 0.4 km respectively. The most remarkable damage of all was that a train of Tozai-line was turned over on the bridge over the Arakawa River in Tokyo, and that a prefabricated one-story school building was lifted about 5 m up and flown over the next building and crashed down on to a third building.

There are dense meteorological observation networks in Tokyo and the wind fluctuations corresponding to the Tatsumaki movement were recorded on several stations. The maximum peak gust of 52 m/sec was recorded at two observation points. However the true maximum peak gust was not measured because the path of the Tatsumaki center was not so close to the observation points. We assumed the true maximum peak gust to be 75 m/sec from several anemometer records. From the analysis of the damages to structures, it may safely be said that the assumption of the maximum peak gust of 75 m/sec is reasonable.

The translation velocity of the Tatsumaki is estimated to be 30 or 35 m/sec from the hours of the power failures and the direction from southwest to northeast. This velocity approximately agrees with the upper wind velocity observed at the aerological station at Takeno.

Acknowledgements

The authors are greatly indebted to many persons and organizations that contributed to gathering data in field surveys of Tatsumaki damages. Special credit is due to Prof. Mitsuta and his colleagues of Kyoto University who have joined our surveys and spent much time and effort in field surveys of Tatsumaki damage, and it is also due to the Eidan Subway Company who sent us the details of the derailed cars.

References

1) Mitsuta, Y.: Wind Disasters Caused by Small Scale Disturbances, Annuals of Disaster Prevention Research Institute, Kyoto Univ., 1968, No. 11A. pp. 499–506, (in Japanese).
2) Ishizaki, H., Mitsuta, Y, et al.: Disaster Caused by Severe Local Storms in Japan. Annuals of Disaster Prevention Research Institute, Kyoto Univ., 1971, Vol. 20, pp. 227–243.
3) Tom, H. C. S.: Tornado Probabilities, Monthly Weather Review, Vol. 44, 1963, pp. 730–735.
4) Ishizaki, H. and Mitsuta, Y.: Studies of a Tatsumaki at Toyohashi, Dec. 7th, 1969, Annuals of Disaster Prevention Research Institute, Kyoto Univ., 1971, No. 14A. pp. 481–500, (in Japanese).
5) Wan, C. A. and Chang, C. C.: Measurement of the Velocity Field in a Simulated Tornado-Like Vortex Using a Three-Dimensional Velocity Probe, J. of the Atmospheric Sciences, 1972, Vol. 24, pp. 116–127.
6) Fujita, T. T.: Workbook of Tornadoes and High Winds, SMRP Research Paper 165, Sept. 1978.
7) Mitsuta, Y., et al.: Analysis of Tatsumaki in Tokyo in Feb. 28th, Annuals of Disaster Prevention Research Institute, Kyoto Univ., 1979, Vol. 22, pp. 385-406, (in Japanese).