Behavior of mechanically anchored waterproofing membrane exposed during typhoon
- Part 2: Relationship between wind force and membrane -

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ABSTRACT

A study was conducted on the island of Miyako, in 2007, to measure the response of a mechanically anchored waterproofing membrane system installed on the roof of a test building when subjected to strong winds from a typhoon. A relationship was found between wind pressure and the behavior of the waterproofing membrane system from the field test data collected during the typhoon. The billowing of the membrane was observed visually, and the wind speed, wind direction, wind pressure and strain-billowing height of waterproofing membrane were measured during the field test. At the maximum recorded wind speed of 16.8 m/s, during Typhoon No.12, the mean and maximum billowing height were 38 mm and 57mm, respectively, on the windward side of roof. Visual observation also confirmed that the billowing height of the waterproofing membrane on the windward side was higher than that of leeward side. The strain in the membrane was high on the windward side and the membrane strain was greatest along a 45° diagonal to the direction of the minimum fastener span. A correlation between wind pressure and billowing height of the waterproofing membrane was evident, and indicates that increases in negative pressure on the roof correspond to increases in the membrane billowing height. The relationship between wind pressure and the billowing height of membrane was almost the same as the frequency characteristics. Since both wind pressure and billowing height can be determined from this field test, it is very useful to use both these relationships as a basis for designing mechanically anchored waterproofing membrane systems with wind resistance.
1. INTRODUCTION

In 2004, the passage of Typhoons Nos. 18 and 22 over Japan damaged several mechanically anchored waterproofing membrane systems. The authors undertook a survey of damage to these systems, reviewed the wind resistance design of the membrane systems, and published results of this survey as part of the technical papers offered by the Architectural Institute of Japan. Although wind tunnel testing has also been conducted by different researchers to gain an understanding of the behavior of mechanically anchored waterproofing membrane systems, the data obtained from these tests are limited because the membranes were subjected to constant-wind load conditions. In response, a study was conducted on the island of Miyako, in 2007, to investigate the behavior of a mechanically anchored waterproofing membrane system installed on the roof of a test building when subjected to strong winds from a typhoon.

In the present study, the behavior of the membrane was observed visually, and the strain-billowing height of the waterproofing membrane was measured during a field test. The relationship between wind pressure and the strain-billowing height of the waterproofing membrane was investigated.

2. CHARACTERISTICS OF WATERPROOFING MEMBRANE

2.1 Testing of waterproofing membrane properties

The waterproofing membrane, of 1.5-mm thickness, was made of polyvinyl chloride (PVC) reinforced with polyester fiber. The polyester fibers, of thickness 556 dtex, were mixed with 1.5 filaments/cm densities in both directions of the sheet. The relationship between the elongation and the tensile stress of a dumbbell shaped PVC membrane specimen is shown in Fig. 1. The tensile stress of the PVC membrane decreased at an elongation of 16% because the polyester fibers ruptured at that strain. However, the relationship between the tensile stress and strain is approximately linear up to an elongation of 4 to 5%.

![Figure 1: mechanical property of PVC membrane in longitudinal direction.](image)

2.2 Frequency characteristics

It was thought that the characteristic frequency influences the billowing condition of this membrane system when subjected to elevated wind speeds, so the characteristic frequency of the PVC membrane was investigated. The test method used to determine the characteristic frequency in relation to the tensile stresses induced in the membrane is shown in Fig. 2. Initially, a strain gauge was affixed to the end of the specimen (50 mm × 1.5 mm × 60 mm; width, thickness, length, respectively) and then the specimen was placed in a test jig. The test was carried out at a temperature of 20 ± 2°C,
and the characteristic frequency of the PVC membrane was examined by artificially vibrating the center portion of the membrane. The range of tensile stresses to which the membrane was subjected varied between 0 and 1.0 N/mm². An example of the wave profile derived from vibration tests on the PVC membrane is shown in Fig. 3, and the frequency of the PVC membrane was constant at first and then attenuated with time. The relationship between the characteristic frequency and the tensile stress is shown in Fig. 4, and, in general, the higher the tensile stress, the greater the characteristic frequency of the PVC membrane. For example, the characteristic frequency of the PVC membrane is approximately 12 Hz at a tensile stress of 0 N/mm² and 40 Hz at a tensile stress of 1.0 N/mm².

3. OUTLINE OF TEST SPECIMENS AND MEASUREMENT

3.1 Test specimens

The waterproofing membrane was fixed using a prefabricated technique, whereby the membrane is mechanically fastened using circular fixing plates. After drilling holes into the concrete substrate for fixing, the plates (ext. diam.: 75 mm; thickness: 1.7 mm) are fixed by means of anchors (stainless steel screws of diam. 6 mm and nylon plugs) and non-styrene epoxy acrylate resin adhesive. The PVC sheet is then adhered to the fixing plates. These fasteners were positioned at a spacing of 0.6 m (a typical value), as shown in Fig. 5, resulting in a total of 81 points over the surface of the roof.

3.2 Outline of measurements

The measurement method is the same as that described in Part 1 of this study. The following parameters were measured directly: wind direction and wind speed, wind pressure, billowing of the waterproofing membrane (as shown in Fig. 6), the strain of the waterproofing membrane around the fixing plates, and the surface temperature of the waterproofing membrane. At the same time, we used a video camera to record the behavior of the waterproofing membrane when exposed to strong wind.

4. MEASUREMENT RESULTS: WIND CHARACTERISTICS OF TYPHOOON NO.12

The wind direction and wind speed during the approach of Typhoon No. 12 are shown in Fig. 7. Between September 17 and 18, the wind direction changed from ENE to E, and then to ESE. Note that 0° corresponds to due north from the test building; 90° is due east. The highest mean wind speed over 10 min was 16.8 m/s, recorded between 00:20 and 00:30 on September 18.
5. BILLOWING OF WATERPROOFING MEMBRANE

5.1 Billowing conditions

The billowing conditions of the waterproofing membrane during Typhoon No. 12 are shown in Fig. 8. By visual inspection of the billowing height and video observation, we found that waterproofing membranes were sucked up by wind pressure, and that the billowing was high on the windward side but relatively low on the leeward side. Moreover, in response to strong wind, the waterproofing membrane appeared to exhibit a combination of two behaviors, a percussive quivering during constant billowing, and an intermittent flapping in the direction of the wind.
The time history waveform of the billowing height of the waterproofing membrane is shown in Fig. 9. On the windward side, the membrane billows constantly and the fluctuation in billowing is minimal. On the other hand, the fluctuation in billowing is large on the leeward side. We suggest the reason for this is that the membrane tends to billow easily, with only a slight amount of slackness; however, as billowing continues beyond this point the membrane becomes constantly stretched, resulting in only a small degree of fluctuation in the billowing.

The results for the billowing height of the waterproofing membrane are shown in Fig. 10. The maximum mean billowing height was 38 mm at measurement point H3. The maximum billowing height is higher on the windward side, with a value of 57 mm at H3. Here, if we focus on the fixed position (P5) in the middle of the four measurement points (H1 to H4), we can see that the billowing height of the membrane is different at each measurement point. If we consider the impact on fastener parts implied by this result, we can conclude that the horizontal force is considerably high, due to the fact that fasteners are subject to sudden abrupt motions due to the difference in billowing behavior in the four directions (back/forth/left/right).

![Fixed position of the waterproofing membrane](image)

Figure 8: Billowing condition of waterproofing membrane on roof during Typhoon No.12.

![Billowing height of waterproofing membrane at H1 to H4 positions](image)

Figure 9: Billowing height of waterproofing membrane at H1 to H4 positions (Evaluation time: 0.2 sec, measurement time: 2007.9.18 00:20 to 00:30).
5.2 Elongation of waterproofing membrane around fasteners

The wind force over 20 sec at four points (P1, P2, P4, P5) around the billowing of the waterproofing membrane and their mean (Pf1) waveform are shown in Fig. 11. Although there is some degree of variation in behaviors, it is possible to assess the mean wind force at the four points.

The maximum values for wind force, membrane billowing, and membrane elongation are shown

![Figure 10: the result of billowing height of waterproofing membrane (Maximum wind speed: 16.8 m/s).](image)

![Figure 11: comparison of wind pressure at each point and the mean wind pressure at these points.](image)

![Figure 12: the relationship between peak wind pressure and maximum strain-billowing height of waterproofing membrane.](image)
in Fig. 12. Note that the wind direction at this time was due east, as shown by the arrow in the figure. From the results of membrane elongation distribution around the fixed parts of the waterproofing membrane in the figure, we demonstrated that the elongation tends to be greater on the windward side, especially at an angle of 45° from the shortest distance between fastener fixing points. On the basis of this finding, we predicted that the horizontal force at fasteners operates in the direction in which membrane elongation increases.

5.3 Fluctuation of membrane billowing height

The fluctuation in mean wind pressure for the four surrounding points, along with the power spectrum density of the fluctuation in billowing is shown in Fig. 13. The fluctuation in billowing height of the membrane and power spectrum density of the fluctuation in wind force closely match, with two peaks, one at approximately 0.04 and the other at 1.0 Hz. These peaks may be due to wind speed fluctuations or eddies separated by eaves, but further and more detailed study is needed to clarify this.

![Figure 13: the relationship between wind pressure and the billowing height of PVC.](image)

5.4 Relationship between wind force and membrane billowing

The relationship between the wind force and the billowing of the waterproofing membrane is shown in Fig. 14. When the wind force is low, the membrane billowing tends to widely fluctuate, but when the wind force is high, the relationship between these two quantities tends to converge. In addition, as the height of the membrane billowing increases, the inclination of the billowing decreases. The relationship between the wind force and the billowing height is similar to the
relationship between stress and membrane billowing described by the authors in a previous study utilizing a wind resistance test method. By making the comparison to the wind resistance test method, we can apply the measurement data from this study as basic data in the test methods of future studies. In addition, since this relationship reveals the same tendencies for Pf1 to Pf4, the relationship between the wind force and the billowing height can be determined using the mean of the four wind force measurement points around the billowing height.

6. CONCLUSION

In order to evaluate the wind resistance of a mechanically anchored waterproofing membrane system, we constructed a test building on the island of Miyako and measured the behavior of a waterproofing membrane installed on the roof of the building. The results of tests conducted during Typhoon No. 12, which featured the maximum wind speed of 16.8 m/s, were as follows:

1) The waterproofing membrane was sucked up by the wind force, and billowing was high on the windward side. Also, in this state of billowing, the membrane quivered slightly, and it flapped intermittently in the same direction as the wind.
2) Based on the results of 10 min of data, during which maximum wind speed was observed (00:20 to 00:30 on Sept. 18, 2007, with evaluation time of 0.2 sec.), the maximum height of membrane billowing was 57 mm.
3) The wind force around the membrane fixing points becomes high on the windward side, and through the billowing of the membrane, elongation also increases on the windward side. As a result, a strong force arises at fasteners in the direction along which elongation is high. We showed that the membrane elongation tends to be particularly high at an angle of 45° from the shortest distance between fastener fixing points.
4) The waterproofing membrane was sucked up by the wind pressure, and billowing was high on the windward side. We also observed that the membrane exhibited slow quivering at approximately 0.04 Hz, and also faster, more percussive quivering at around 1 Hz.
5) As for the relationship between the wind force and the waterproofing membrane, we found that as the wind force increases, the height of membrane billowing also increases, but the angle of inclination of the billowing decreases.
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