

Field measurement of wind loads on low-rise building with adjustable roof pitch

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ABSTRACT: A low-rise building and a tower were constructed near Shanghai Pudong International Airport by East China Sea to study the characteristics of wind field and wind pressure on the roof of the building. The remarkable feature of the test building is that the roof pitch can be adjusted range from 0° to 30° , so that the wind pressure for different roof pitches can be analyzed. In this paper, the time-histories of three pieces of ten-minute wind pressures were analyzed with different roof pitches at 0° , 10° and 20° respectively, and then comparison was done with a wind tunnel test on a rigid model of 1:30 scale. It indicates that distributions of the mean and fluctuating pressure agree well with those of the wind tunnel test results. The non-Gaussian feature of the pressure is investigated. It is shown that there exists a linear relation between the skewness and kurtosis, and the fitting formulae are presented at 0, 10, and 20 pitches.

KEYWORDS: field measurement, test building with adjustable roof pitch, low-rise building, pressure coefficient, wind tunnel test, non-Gaussian.

1 INTRODUCTION

Wind is a part of our daily lives. While wind can be beneficial to humankind's enterprises, it can also be extremely destructive to buildings and other structures we build on the earth[1]. According to the survey of wind hazard, the main reason results in casualties and property losses is the damage and collapse of the low-rise buildings at villages and small towns, especially in China. So it is necessary to improve wind resistance capacity of low-rise buildings based on field measurement and thus reduce property losses attacked by severe wind.

The last three decades of the twentieth century were notable for a number of full-scale studies of wind loads on low-rise buildings. In these studies, advantage was taken of the considerable developments that had taken place in electronic instrumentation, and provided a vast body of data which challenged wind tunnel modeling techniques. In the early 1970s, the BRE(Building Research Establishment) in the UK commenced a program of full-scale measurements on a special constructed experimental building with two stories at Aylesbury, England[2]. The building had the unique feature of a roof pitch which was adjustable between 5° and 45° . In the late 1980s, another famous full-scale experiment on low-rise building was set up in Lubbock, Texas, USA[3,4]. The building had a small steel shed of height, 4.0m, and plan dimensions, 9.1 and 13.7m and a near-flat roof. The building had the unique feature of being mounted on a turntable, thus enabling control of the building orientation relative to mean wind direction. Almost at the same time, a new full-scale experiment was commenced in Silsoe, UK[5,6]. The building was a larger steel portal-framed structure, 24m long, 12.9m span, and 4m to the eaves, with a 10 degrees roof pitch, located in open country. The building had unique capacity of being fitted with both curved and sharp eaves. At the beginning of twentieth century, a 6m cube has been constructed at Silsoe Research Institute in an open country exposed position in order to provide a facility for fundamental studies of the interactions between the wind and a structure[7,8]. The building had the feature of the changes in roof pressure brought about by pitching the cube for-

wards by 2.5° and 5° . At the late of 2000s, the researchers from Hunan University in China put forward the idea of removable building and successfully developed field measurement of wind loads on that building[9,10]. The main feature is that the building can be moved to the typhoon landed areas, which makes more opportunities to carry out field measurement during typhoon. The building for field measurement in this paper is built near Shanghai Pudong International Airport by East China Sea. The size of the plane of the building is $10\text{m} \times 6\text{m}$ and the height of the eave is 8m. The feature of this building is that the pitch of roof can be changed. The roof pitch can be adjusted between 0° and 30° by using the lifting device. The architectural appearance of the pitch-changed building is designed according to the common characteristics of the low-rise buildings at villages in Southern China. Therefore, the research results have important significances to the wind resistance study of low-rise buildings in China.

2 THE FULL-SCALE FACILITY

2.1 Introduction of full-scale building

Pudong district in Shanghai is the area where strong wind, especially strong typhoons, frequently occurs each year. So a field laboratory had been set up by State Key Laboratory of Disaster Reduction in Civil Engineering of Tongji University to study the turbulence characteristics near ground and wind effects on low-rise buildings in the field. The field laboratory is located on flat area close to the Yangtze river estuary, and in the vicinity of Shanghai Pudong International Airport(see Figure 1). It consists of a test building and a meteorological tower(see Figure 2). This laboratory features many capabilities not found in past full-scale experiments. The notable feature of the test building is that its roof pitch can adjust from 0° to 30° . Figure 3 shows the full-scale building respectively with 0° and 30° roof pitch.



Figure 1. Location of test building



Figure 2. Landform around test building



(a) 0°



(b) 30°

Figure 3. Full-scale low-rise experimental building

Figure 4 shows the essentials of the design. The hinged design method was used for the connections of the roof and the girder of ridge. With the lifting of girder by two sets of worm and worm wheel, the roof pitch will change correspondingly.

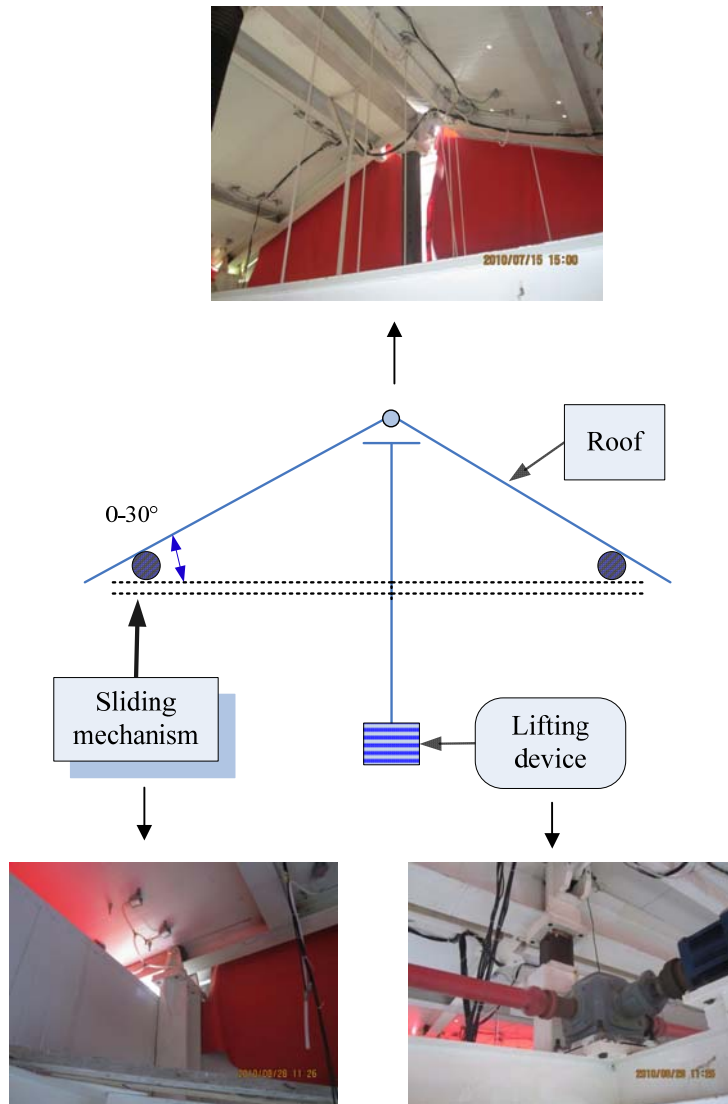


Figure 4. Elevating system

2.2 Field instruments

According to the demand of the field experiment, the anemometers type of R.M. Young 81000, R.M. Young 85106, R.M. Young 05305V are installed respectively at the level of 10m, 20m, 30m and 40m, see Figure 5. The sample frequency of R.M. Young 85106 is 1Hz, and those of the other two types are 20Hz. Micro differential pressure sensors supplied by Shuangqiao Sensor measurement and control technology Co. Ltd are installed on the roof of the test building to study local wind pressure in the field. Figure 6 shows the photo of the pressure sensors.

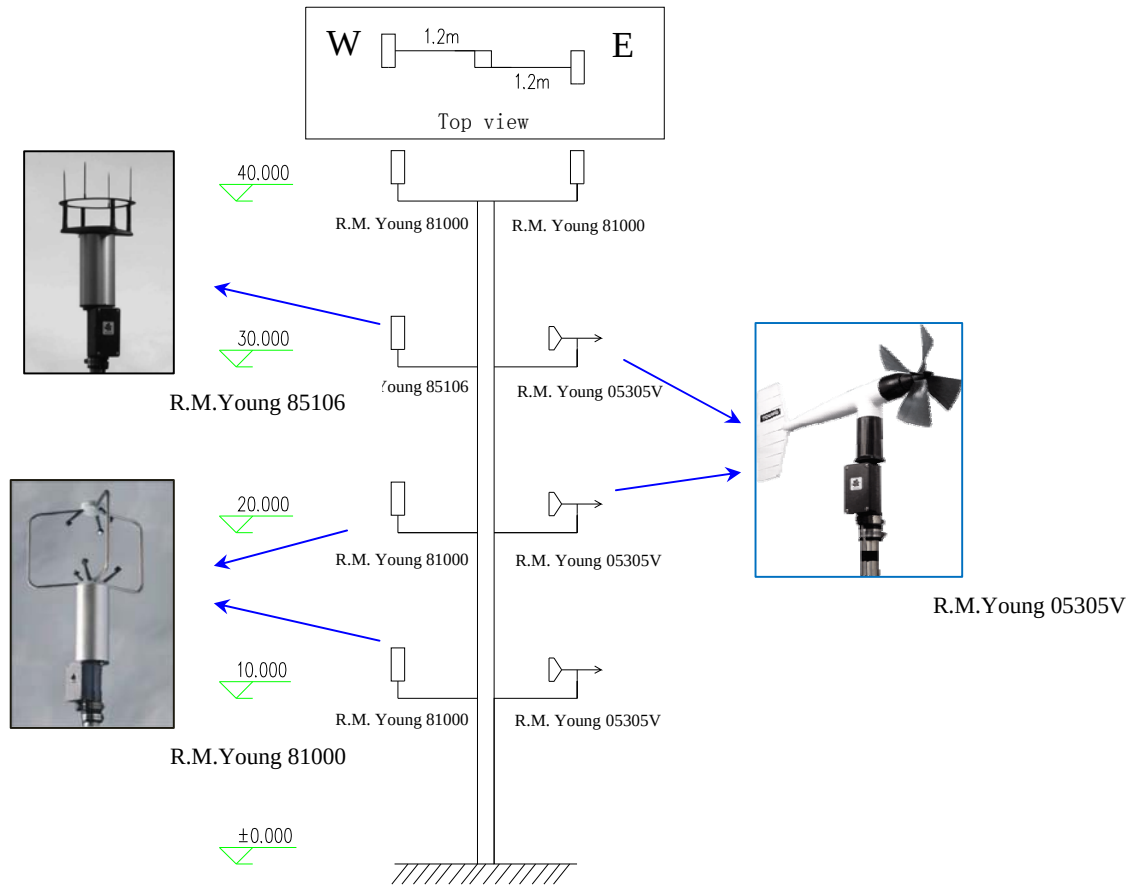


Figure 5. The arrangements of anemometers

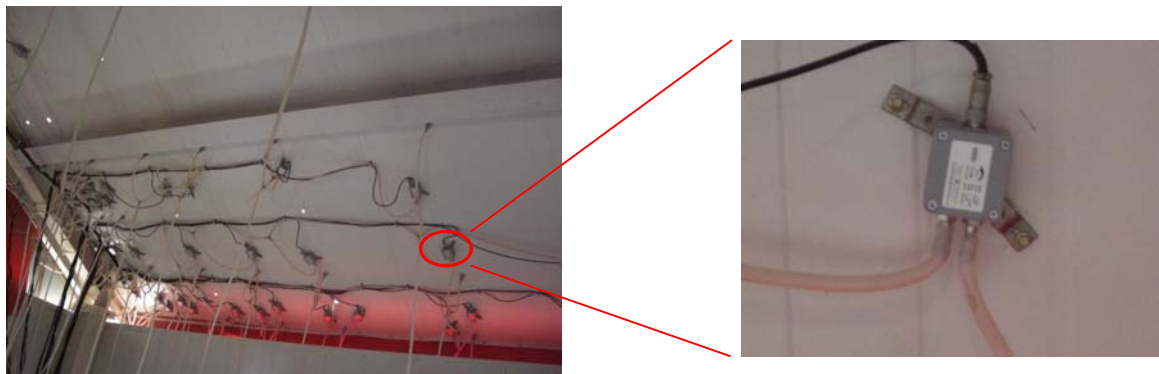


Figure 6. Micro differential pressure sensors

Figure 7 shows the pressure measurement system of field experiment in this paper. A valve is added to prevent rainwater from damaging the sensors.

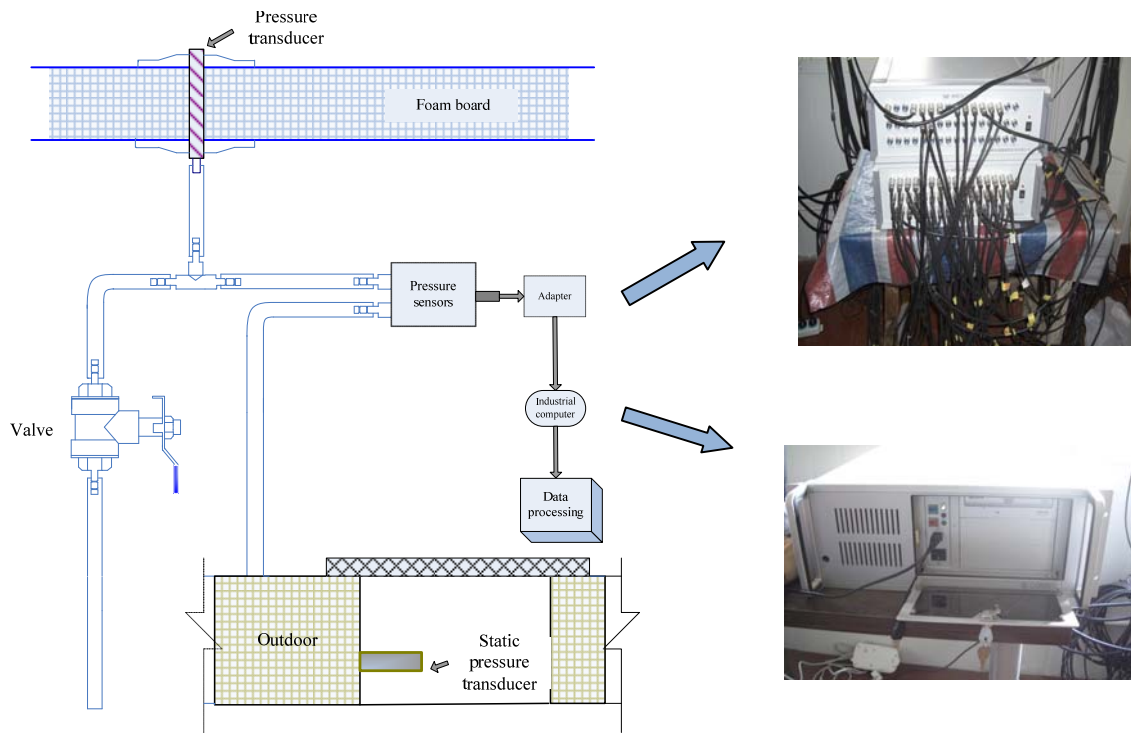


Figure 7. Pressure measurement system

2.3 Layout of pressure measurements

Figure 8 shows the positions of pressure transducers, there are ninety-four taps on the roof. There are more pressure transducers installed at north-east corner of the roof than other regions because of the frequently emerge of southeast wind in Shanghai.

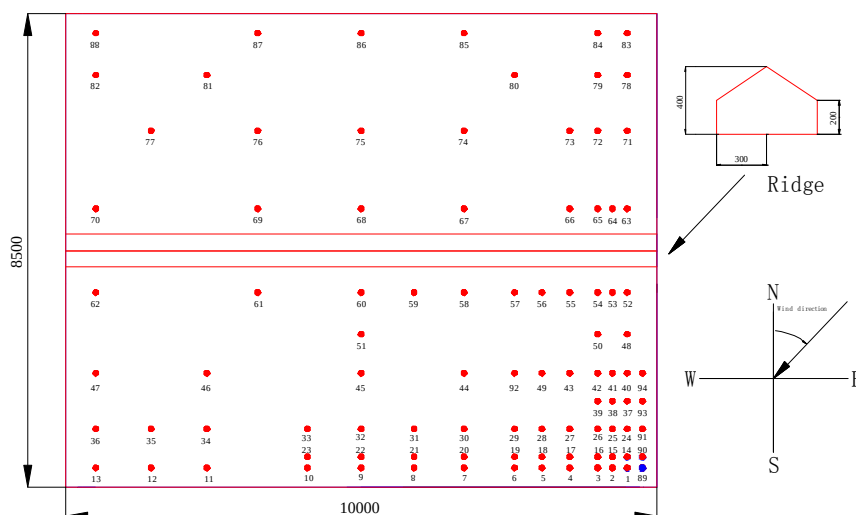


Figure 8. Layout of pressure measurements on test building

3 TEST RESULTS

In order to compare the wind pressure on the roof between full-scale experiment and wind tunnel test, wind tunnel test was made with a rigid model of 1:30 scale based on full-scale test building. The test is carried out in TJ-2 Boundary Layer Wind Tunnel in Tongji University, whose working section is 3m in width, 2.5m in height and 15m in length. Wind condition corresponding to roughness exposure B in the Chinese code [11] is simulated in the wind tunnel at a length scale of 1/50. Table 1 shows the parameters of field measurement and wind tunnel test.

Table 1. Cases of field measurement and wind tunnel test

Parameters	FS1	FS2	FS3	WT1	WT2	WT3
Test type	Full-scale	Full-scale	Full-scale	Wind tunnel	Wind tunnel	Wind tunnel
Scale proportion	1:1	1:1	1:1	1:30	1:30	1:30
Roof pitch	0°	10°	20°	0°	10°	20°
Mean wind speed at eave	8.58 m/s	9.95m/s	9.97m/s	9.02m/s	9.02m/s	9.02m/s
Mean wind direction	41°	34°	43°	40°	35°	45°
Turbulence intensity	0.233	0.158	0.221	0.247	0.245	0.241
Frequency (Hz)	20	20	20	312.5	312.5	312.5
Sample time and data length	10min 12000	10min 12000	10min 12000	38.4s 12000	38.4s 12000	38.4s 12000

The surface pressure on the body is usually expressed in the form a non-dimensional pressure coefficient [12]. A general time-varying pressure coefficient C_{p_i} is as follows:

$$C_{p_i} = \frac{p_i - p_{\infty}}{p_0 - p_{\infty}} \quad (1)$$

where p_i is the pressure of tap i; p_0 is a total reference pressure; p_{∞} is a static reference pressure. In this paper, the mean wind speed was measured at height of the eave of test building.

3.1 Pressure distribution on roof surface

In order to compare the results, Figure 9 shows the contour graph of mean wind pressure on the roof based on two types of experiments, and Figure 10 shows the contour graph of fluctuating wind pressure. It indicates that the distributions of mean and fluctuating pressure agree well with those of the wind tunnel test results. No matter field or wind tunnel experiment, we can see there are two pairs of conical vortices occurred at the windward of roof as well as the backside of ridge. In these regions, negative pressure is larger than that in other regions.

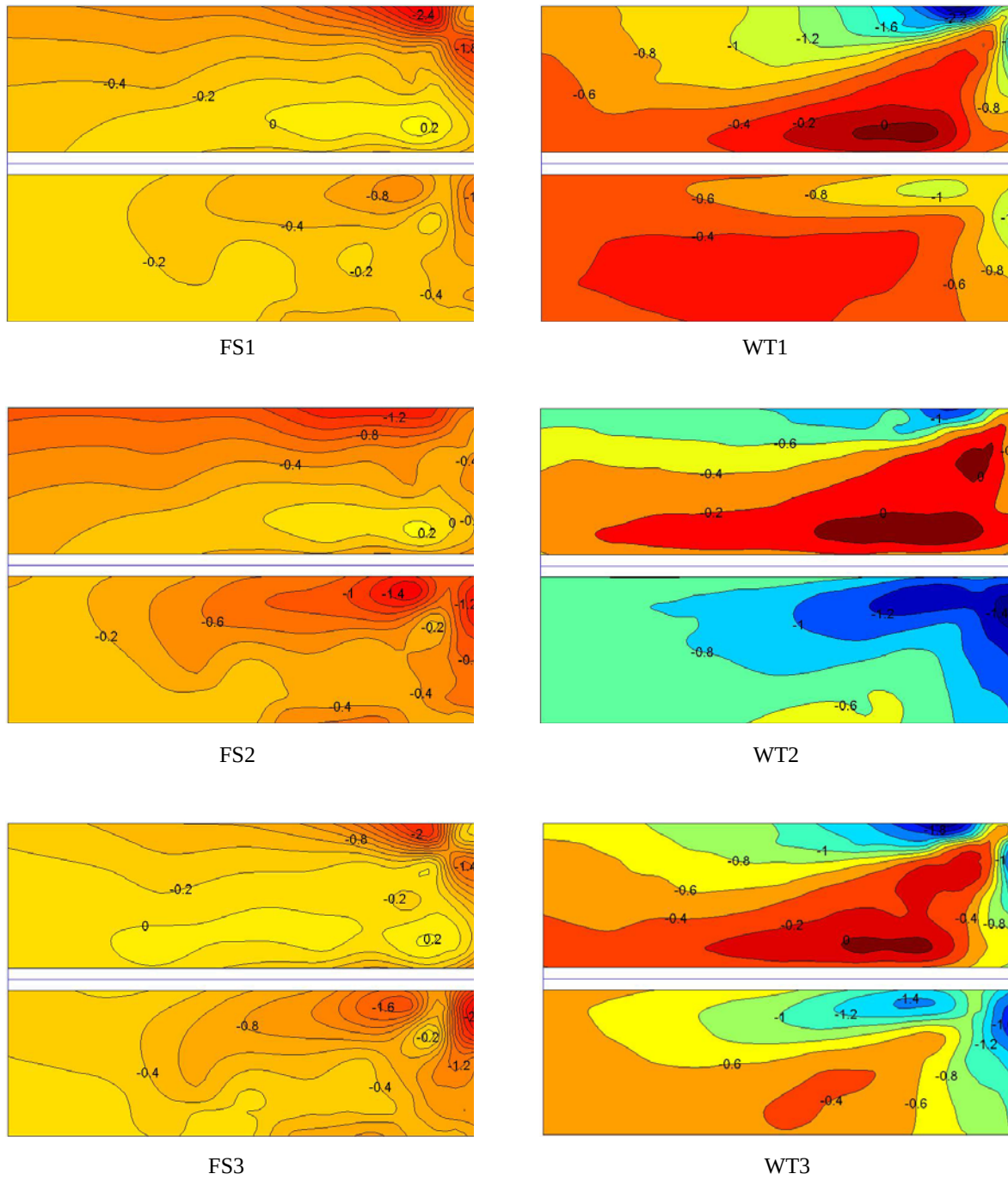


Figure 9. Contours of mean wind pressure coefficients

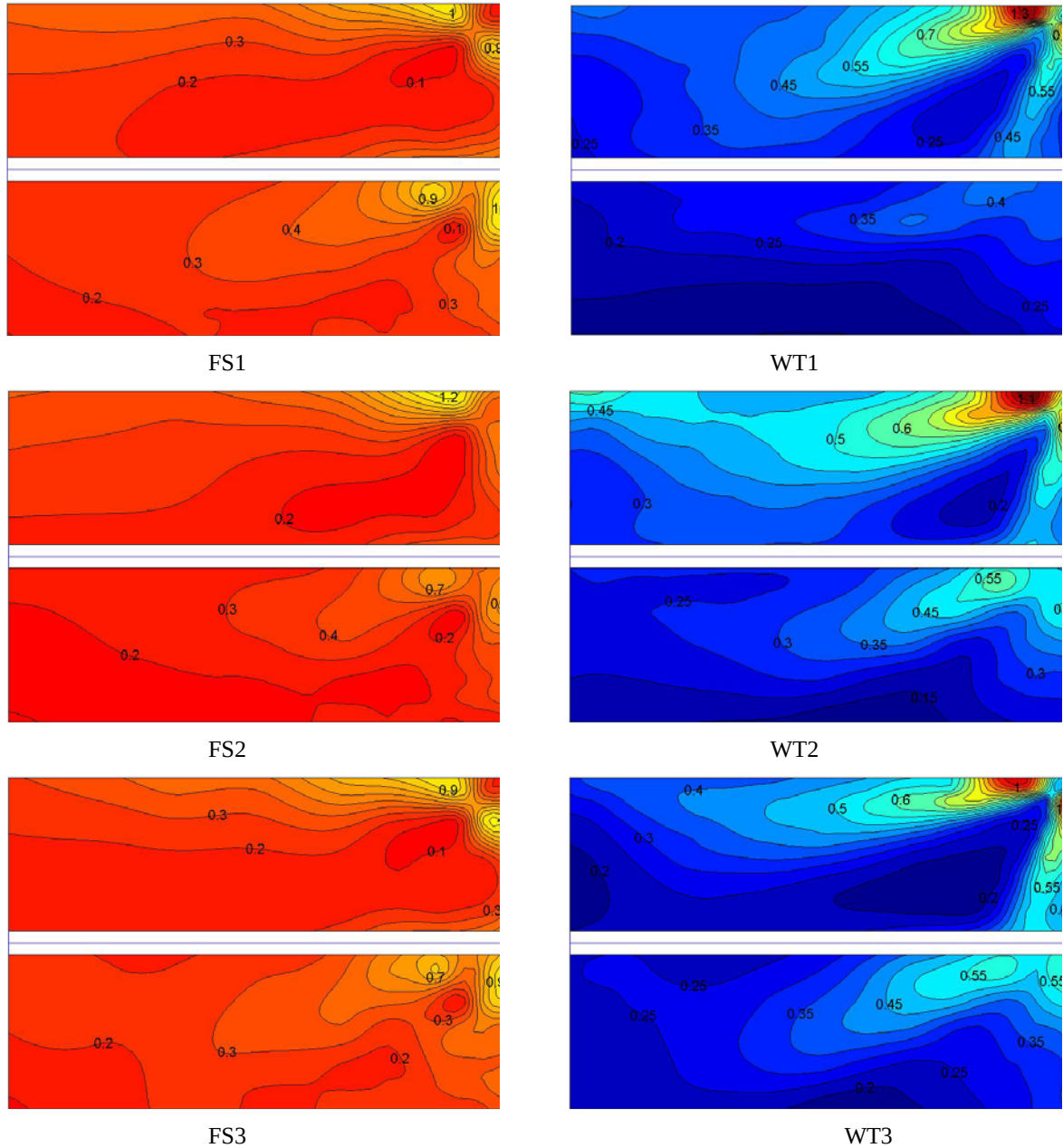


Figure 10. Contours of rms wind pressure coefficients

3.2 Mean and peak wind pressure coefficients along middle line

In order to study the influence of the roof pitch on the wind pressure, the pressure coefficients of the nine taps along the central line are analyzed, which are taken advantage of the field data FS1, FS2 and FS3 in Table 2. Figure 11 shows the mean, fluctuating and peak values of wind pressure along the middle line changing with the roof pitch. First of all, we can see from Figure 11(a), in the windward region, the mean negative pressure is maximum at the 0° and minimum at 20° , but contrary to the leeward area. The results in Figure 11 (b) is the same as Figure 11 (a), fluctuating wind pressure increases with the roof pitch decreases in the windward region, in contrast to

the leeward regional conclusions. It can be seen obviously from Figure 11(c), the maximum wind pressure at 20° is significantly smaller than these at the other two roof pitch, while Figure 11(d) shows the minimum value is at 0° . In summary, the roof pitch has a significant influence on the roof surface wind pressure, not only on the mean wind pressure, but also on the fluctuating and peak wind pressure. The wind pressure changes significantly because the air flow pattern and the internal structural properties of vortex on the roof surface vary with the roof pitch.

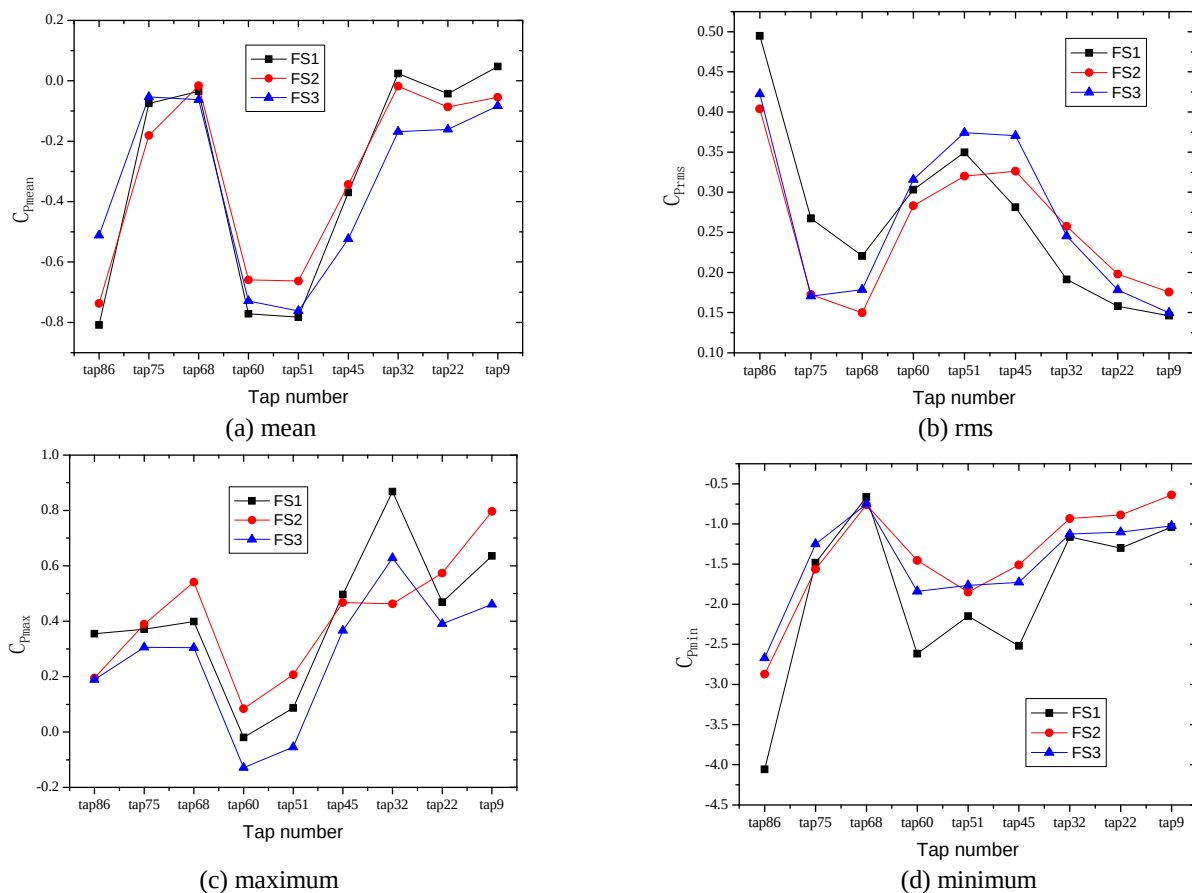


Figure 11. Mean and peak wind pressure coefficients along central line

3.3 Non-Gaussian features of fluctuating wind pressure

The assurance of safety and reliability of buildings requires estimation of the extremes of the applied load effects. If the statistical description in a system differs significantly from Gaussian, conventional methodologies with implicit assumption of Gaussian may no longer be valid requiring a non-Gaussian estimation framework. This is particularly important when considering the extremes, which are sensitive to the tail regions of the probabilistic description of non-Gaussian processes. For instance, the local pressure fluctuations measured at corners as well as other separation flow regions of roofs of low buildings are found to be highly non-Gaussian [13,14]. Thus, it is necessary to carry out the study on non-Gaussian features of fluctuating wind pressure.

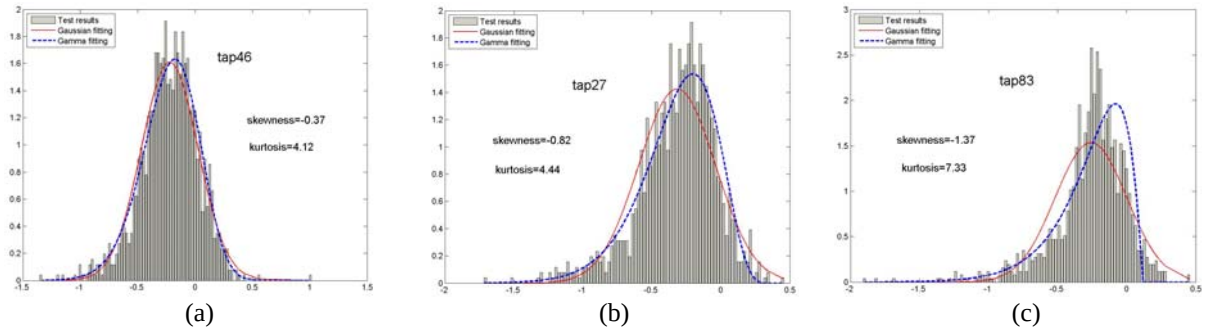
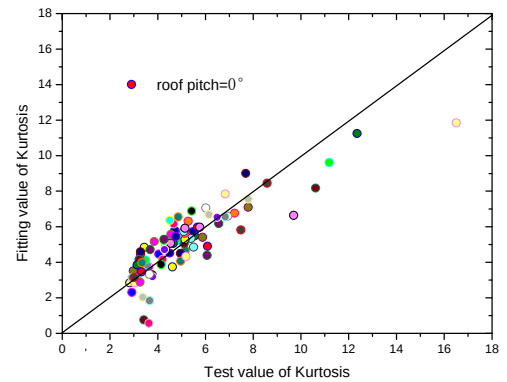
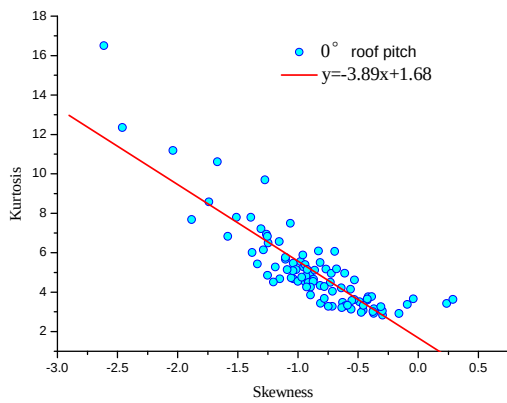


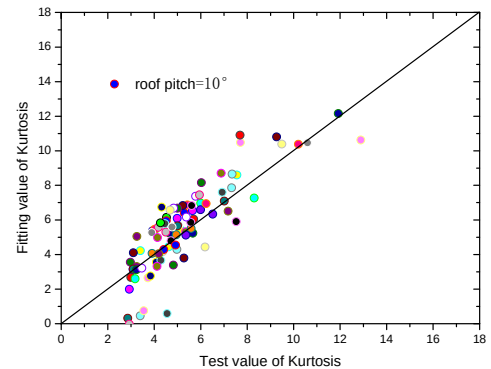
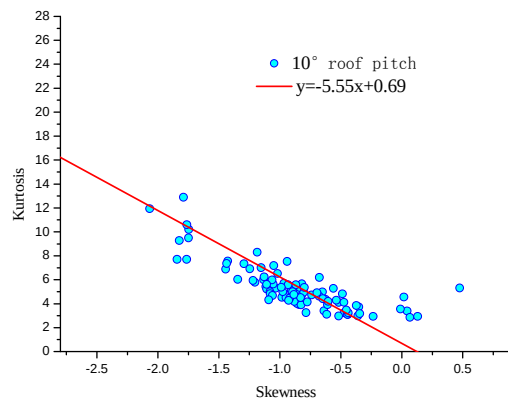
Figure 12. Probability distribution of wind pressure

Due to space limitation, only the probability distribution of fluctuating pressure for typical measured taps under working condition of FS1 has been given in Figure 12. We can see the local fluctuating pressure measured at the windward of the roof as well as the backside of the ridge is found to be highly non-Gaussian. The absolute value of skewness and kurtosis in these regions are obviously larger than that in other regions. The probability distribution of fluctuating pressure agrees well with Gaussian processes when skewness is larger than -0.5, and has better agreement with Gamma distribution when the value of skewness is between -1 and -0.5, nevertheless neither of the distributions is in accordance with the measured data.

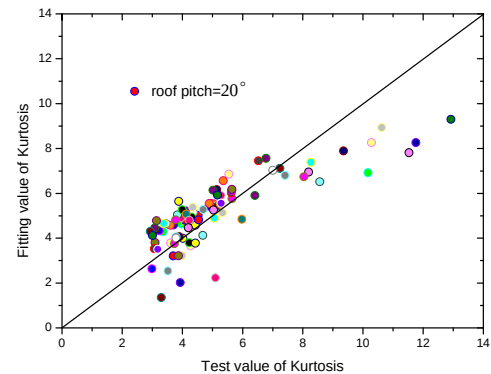
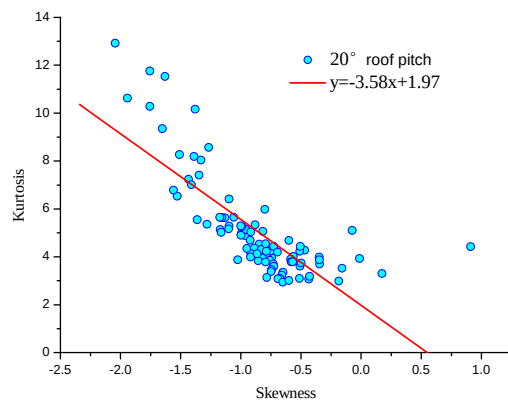
The value of skewness and kurtosis are sensitive to the tail regions of the probabilistic distribution of non-Gaussian processes, and the relation between skewness and kurtosis is very important for the study on the extremes of the applied load effects. Figure 13 shows the relation between the measured results. It shows that there is a linear relation between the skewness and kurtosis, and the fitting formulae are presented between skewness and kurtosis at 0° , 10° , and 30° pitches. To evaluate the precision of the fitting functions, the theoretically calculated and the fitted values of kurtosis in all work cases are also compared in Figure 13. It can be seen from Figure 13 that the fitted values can be reliably used for evaluating the theoretically calculated values.



(a) roof pitch= 0°



(b) roof pitch=10°



(c) roof pitch=20°

Figure 13. Variation of skewness with kurtosis

4 CONCLUSIONS

The characteristics of wind pressure on the roof of the test building are studied. The main results are as follows:

- (1) The trend of average and fluctuating wind pressure distribution tested by the filed measurement is consistent with that by wind tunnel test.
- (2) The probability distribution of fluctuating pressure agrees well with Gaussian processes when the skewness is larger than -0.5, while has better agreement with Gamma distribution when the value of skewness is between -1 and -0.5, nevertheless neither of the distributions are in accordance with the measured data.
- (3) There exists a linear relation between the skewness and kurtosis, and the fitting formulae are presented between skewness and kurtosis with 0, 10, and 30 pitches, which will be helpful to the calculation of the extreme of wind pressure.

5 ACKNOWLEDGEMENTS

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