Wind Engineering Joint Usage/Research Center
FY2019 Research Result Report

Research Field: Structural Wind Engineering
Research Year: FY2019
Research Number: No. 192008
Research Theme: Effective static wind-induced forces estimation for connection design of multi-story 3D modular structures

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Budget [FY2019]: 400000Yen

1. Research Aim

The multi-story 3D modular building is a type of structure formed by an assembly of 3D modular units with preselected building functions. Due to the assembly of a single module unit, the overall performance of the structure depends on the horizontal and vertical connections among the module units for transferring internal forces. Because of the independence of modular units with fixed and limited surfaces, the wind-induced deformation of multi-story 3D modular building structures may be different from that of traditional structures under strong wind loads[1]. The connection among modules in multi-story modular structures purely stacked by 3D modules are critical in structural engineering, usually taken as pin-connections , need to bear tension and shear forces due to bending and shearing deflections of 3D modular buildings. Under a strong wind load, it is obviously different from traditional building that a modular unit usually has fixed and limited local surfaces, and the corresponding length scale usually much smaller than that of the length scale of air, which means that the wind-induced forces among modules are in correlating with close units.
At present, the practice of multi-story 3D modular buildings has taken precedence over theoretical research, but the current codes still lack an accurate calculation theory and method for wind-induced internal forces in joint connections considering the time and special relationship of the fluctuating characteristics of wind. Up to know, limited work can be found for reference.
For this reason, establishing an effective static wind-induced forces estimation method for connection design among modules in multi-story modular structures purely stacked by 3D modules is a key issue and a challenges for the new structural buildings.

2. Research Method

This research method is: (1) To get the wind pressure distribution by wind tunnel test with rigid models of typical multi-story 3D modular building structures; (2) To understand the internal force distribution of connections among modules in typical multi-story 3D modular building structures by test and numerical analysis; (3) To establish suitable calculation method of wind-induced internal forces of connections among modules in multi-story 3D modular structure based on the effective static wind load method .

3. Research Result

3.1 Experimental set-up of wind tunnel tests

The wind tunnel tests were carried out in the 1.8m (height) ×2.2m (width) ×19m (length) Boundary Layer Wind Tunnel (BLWT) at Wind Engineering Research Center (WERC), Tokyo Polytechnic University (TPU). There are 4 test models composed of modules as shown in Fig. 3.1, which can be combined with each other by attaching them together on the lateral or vertical surface, in order to obtain the wind pressure data on the structure surfaces of the rigid models with height to breadth *H/B*=1:1 (M1), 2:1 (M2), 3:1 (M3) and 4:1 (M4). In each module, there are totally 96 measurement points including 72 points on vertical surfaces and 24 points on roof surface as shown in Fig. 3.2. The relevant parameters of 4 models are listed in Tab. 3.1, and the test procedure includes 4 cases, as shown in Tab. 3.2.

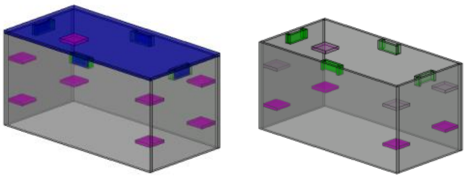


Fig. 3.1 Axonometric Diagram of Modules

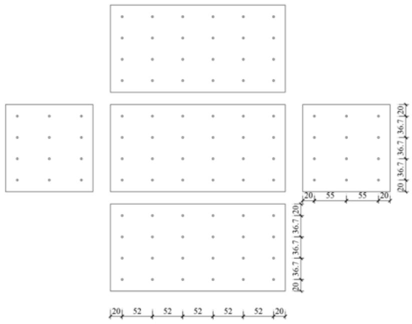
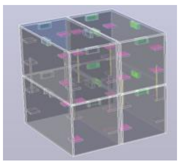
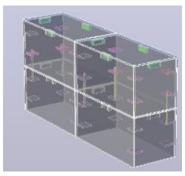
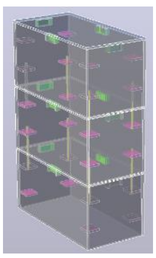


Fig. 3.2 The Measurement Points of Module

Tab. 3.1 Relevant Parameters of 4 Models

Model No.	Geometric Scale	Height (*H*, mm)	Length (*L*, mm)	Breadth (*B*, mm)	*H/B*	*L/B*	Number of Measurement Points
M1	1/20	300	300	300	1.00	1.00	240
M2	1/20	300	600	150	2.00	4.00	288
M3	1/20	450	300	150	3.00	2.00	240
M4	1/20	600	300	150	4.00	2.00	312

Tab. 3.2 Details of Test Procedure

Case No.	Model Construction	Modules	Aim
1		Composed of 4 modules, form a cube with 2 storeys	To obtain the data of the rigid model with *H/B* = 1:1.
2		Composed of 4 modules, form a cuboid with 2 storeys	To obtain the data of the rigid model with *H/B* = 2:1.
3		Composed of 3 modules, form a cuboid with 3 storeys	To obtain the data of the rigid model with *H/B* = 3:1.

4		Composed of 4 modules, form a cuboid with 4 storeys	To obtain the data of the rigid model with *H/B* = 4:1.

For terrain type, Category II defined in Japanese code (AIJ-2004)[2] was applied in the tests. The wind speed profile provided in the code and measured during the tests are compared in Fig. 3.3. The scale factors, including geometric scale, wind speed scale, time scale, as well as blockage ratio, are listed in Tab. 3.3. As for wind direction, 11 direction cases were considered, including 0˚, 10˚, 20˚, 30˚, 40˚, 45˚, 50˚, 60˚, 70˚, 80˚ and 90˚(Fig. 3.4).

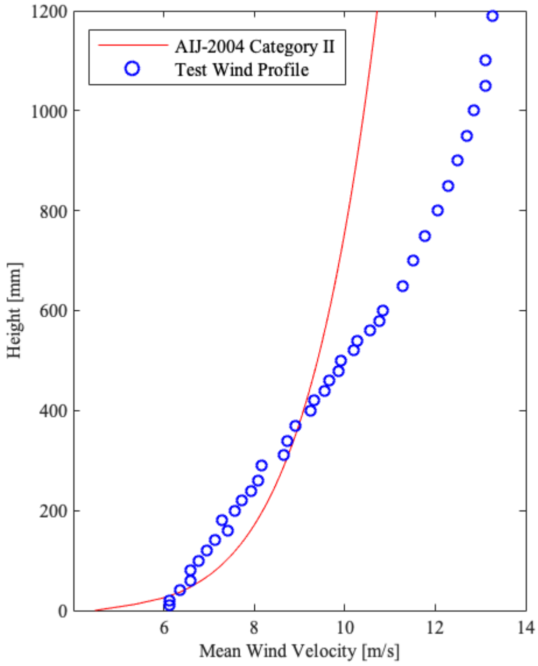


Fig. 3.3 Wind Speed Profile in the Tests

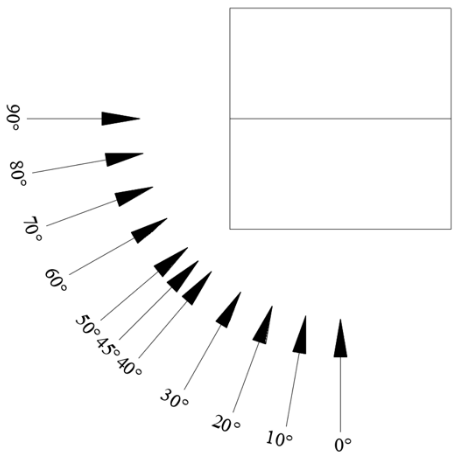


Fig. 3.4 Wind Direction Cases

Tab. 3.3 Scale Factors in 4 Cases

Factors	Case No.1	Case No.2	Case No.3	Case No.4
Geometric Scale	1/20	1/20	1/20	1/20
Wind Speed Scale	1/3	1/3	1/3	1/3
Time Scale	3/20	3/20	3/20	3/20
Blockage Ratio (< 5.00%)	2.27%	4.55%	3.41%	4.55%

3.2 Measured pressure distribution

Due to the symmetry of the models and conciseness, the distribution of average wind pressure coefficient and fluctuating wind pressure coefficient of M1, M2, M3 and M4 under the three wind direction angles of 0°, 45°, and 90° can be obtained. The specified pressure is defined as positive when the direction of wind pressure is directed to the roof surface, and vice versa. The average wind pressure coefficient, $\overline{C}_{pc}$, and the fluctuating wind pressure coefficient, C_{pc}, are defined as follow:

$$\overline{C}_{pc} = \frac{\overline{P}}{q_h}, \quad C_{pc} = \frac{\sigma}{q_h} \tag{3.1}$$

where, $\overline{P}$, σ, and q_h are the average value of wind pressure, the standard deviation of wind pressure, and the reference wind speed pressure, respectively [3].

The surface number and wind direction are shown in Fig.3.5, and the average wind pressure coefficient and the fluctuating wind pressure coefficient of M1, M2, M3 and M4 measured in this test are as shown in Fig.3.6-3.13.

According to Fig. 3.6, it can be concluded that: under wind direction angle 0°, the upward surface is under positive pressure and the absolute value increases along the height of the model. The airflow separates at the junction between the upward wall and the roof, and a "separation bubble" is formed within a certain range. Therefore, a large negative pressure is generated at the eaves and the corner of the upward roof, whose absolute value gradually decreases along the direction of the wind. The roof surface, side surfaces and backward surfaces are under negative pressure. Under wind direction angle 45°, the airflow separates at the corner of the roof, where a small area of separation is formed and a pair of "conical vortex" are formed on the sides of the separation area, so that the area around the "conical vortex" is subjected to a large negative pressure, whose absolute value gradually decreases along the direction of the wind. The whole roof surface is under negative pressure. Under wind direction angle 90°, the average wind pressure coefficient is symmetrically distributed on the roof surface, and the airflow is separated at the junction between the edge of the mountain wall and the roof. A “separation bubble” is formed within a certain range, so that a large negative pressure appears on the front edge of the roof, and the absolute value decreases gradually along the direction of the wind. The whole roof surface is under negative pressure. Similar conclusions can be drawn in M2, M3 and M4 according to Fig. 3.7-3.13.

The distribution of the average wind pressure coefficient and the fluctuating wind pressure coefficient in this paper is similar to that of J. D. Holmes’s research [4], which proves the rationality of the test data for dynamic time history analysis.

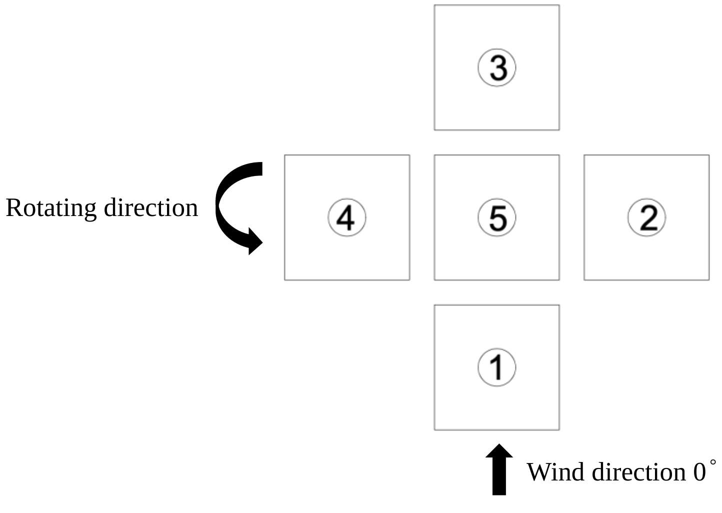
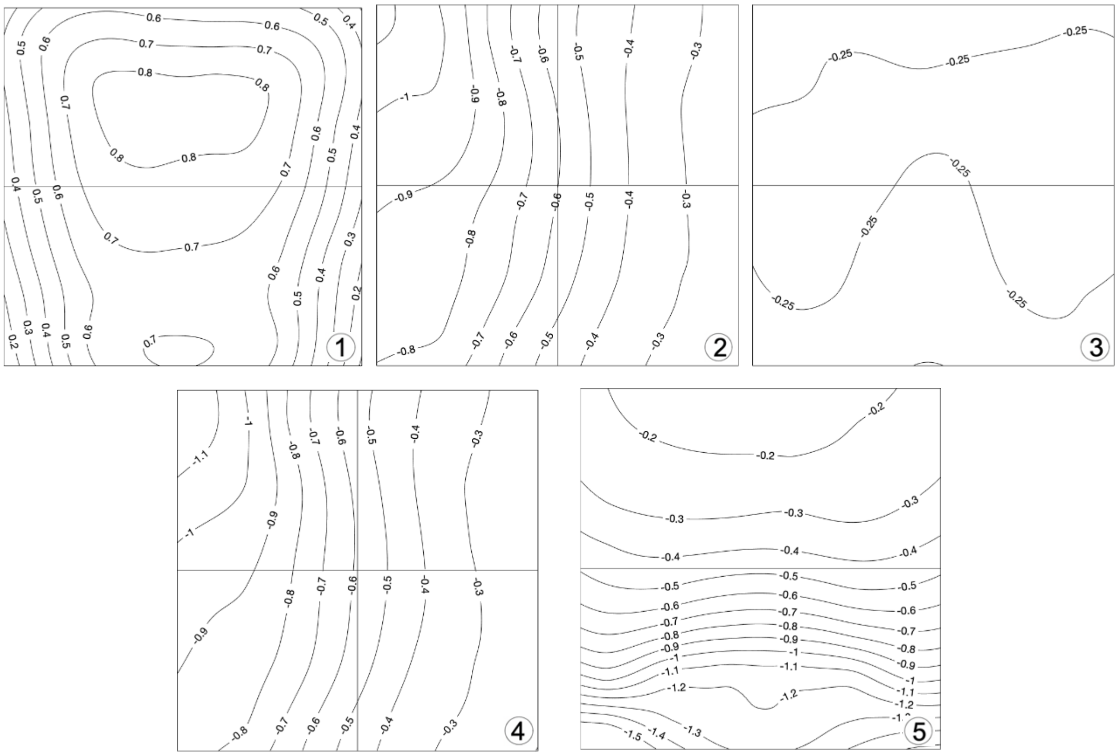
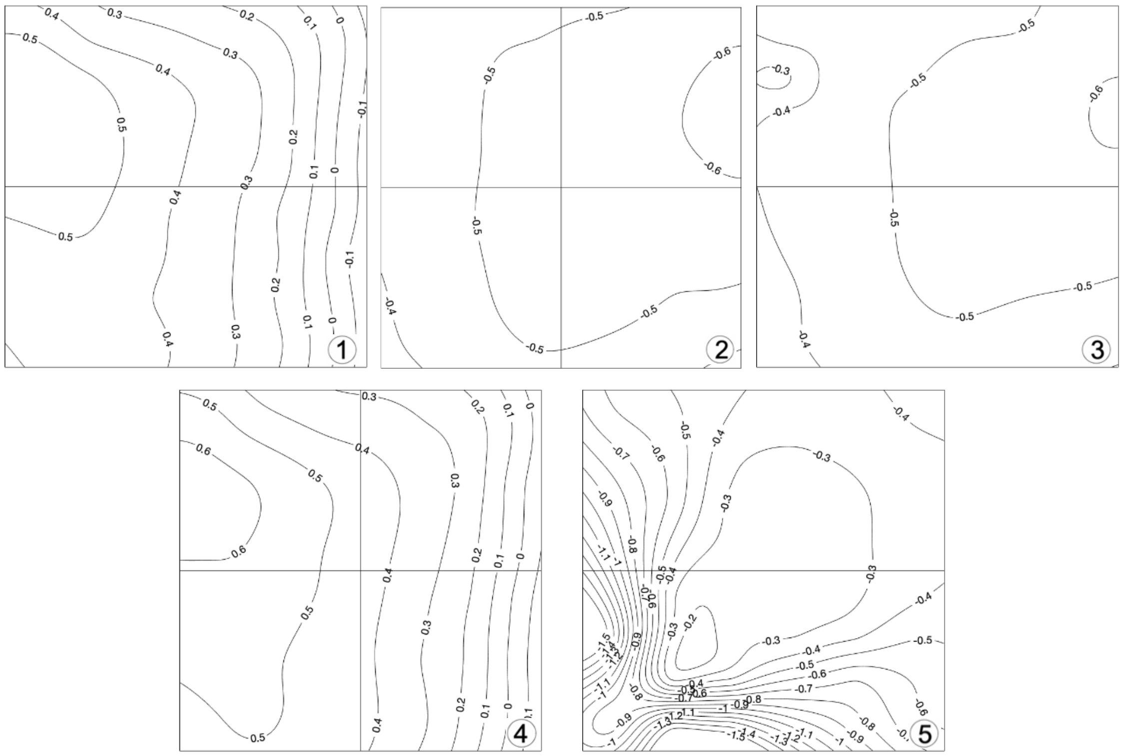


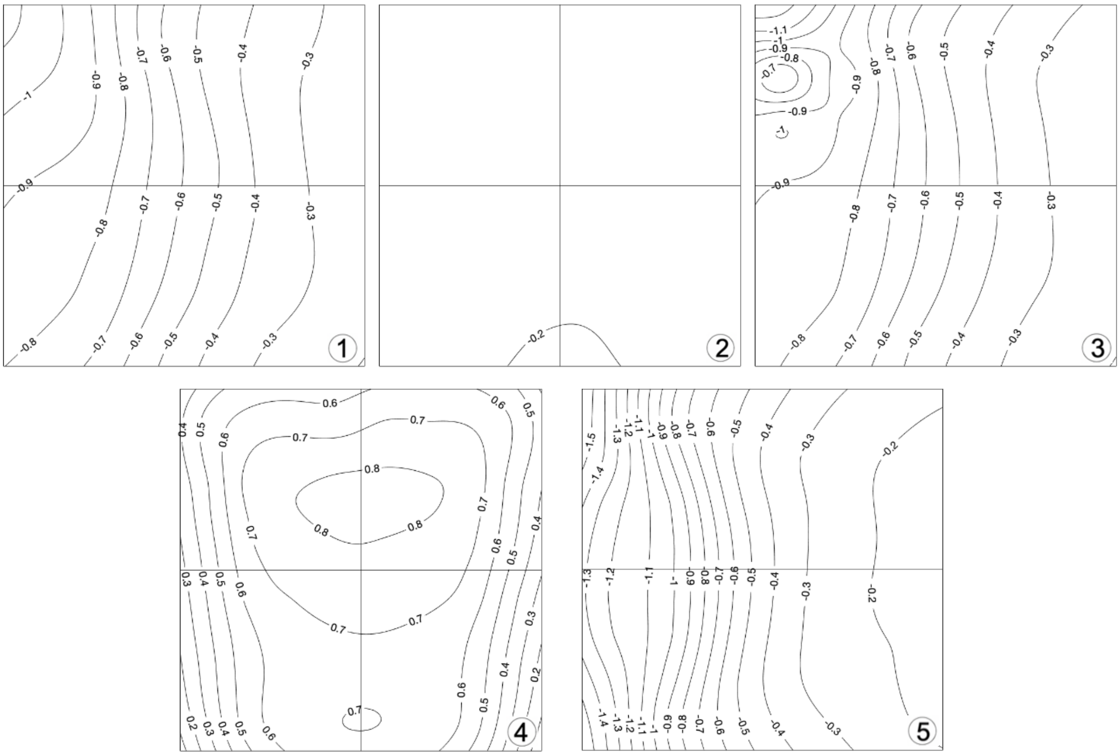
Fig. 3.5 Surface Numbers and Wind Rotating Direction



(a) 0°

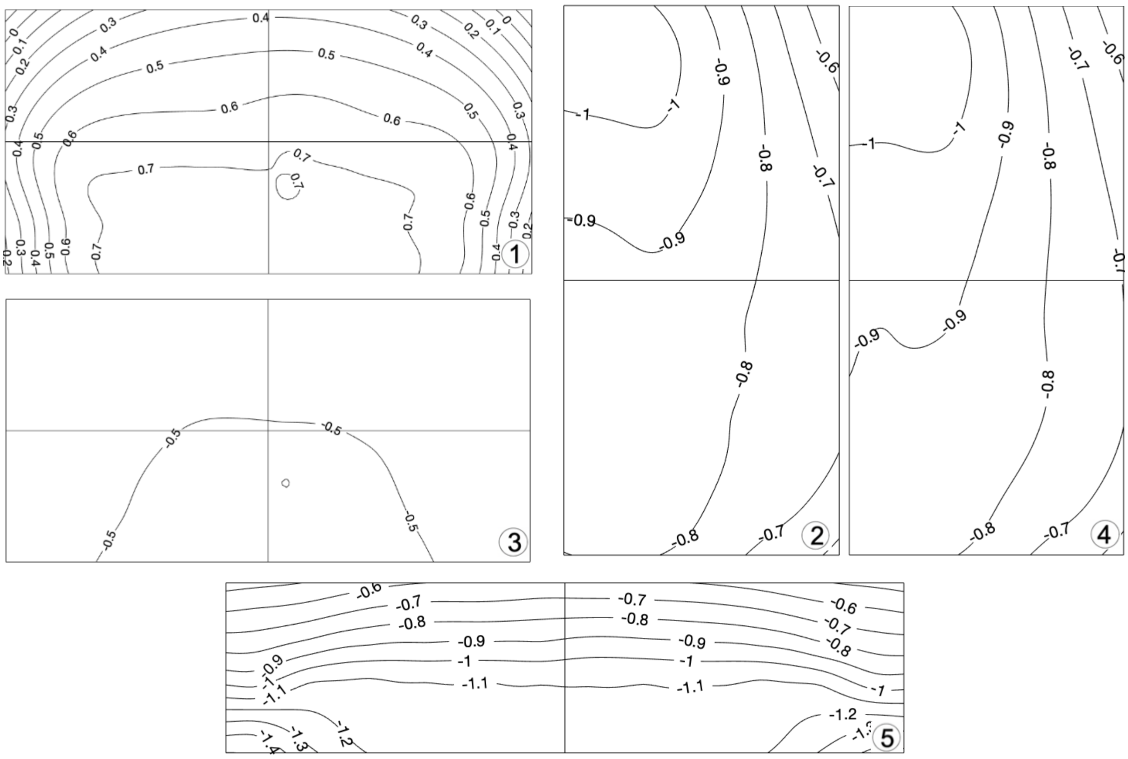


(b) 45°

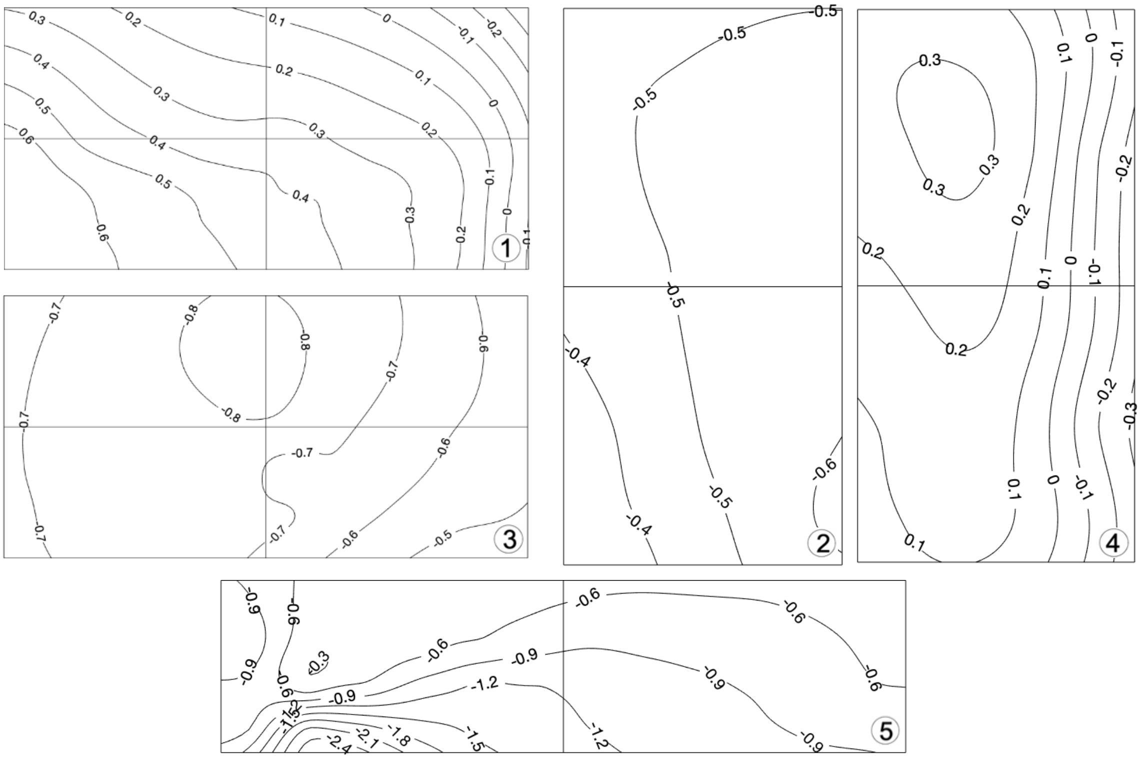


(c) 90˚

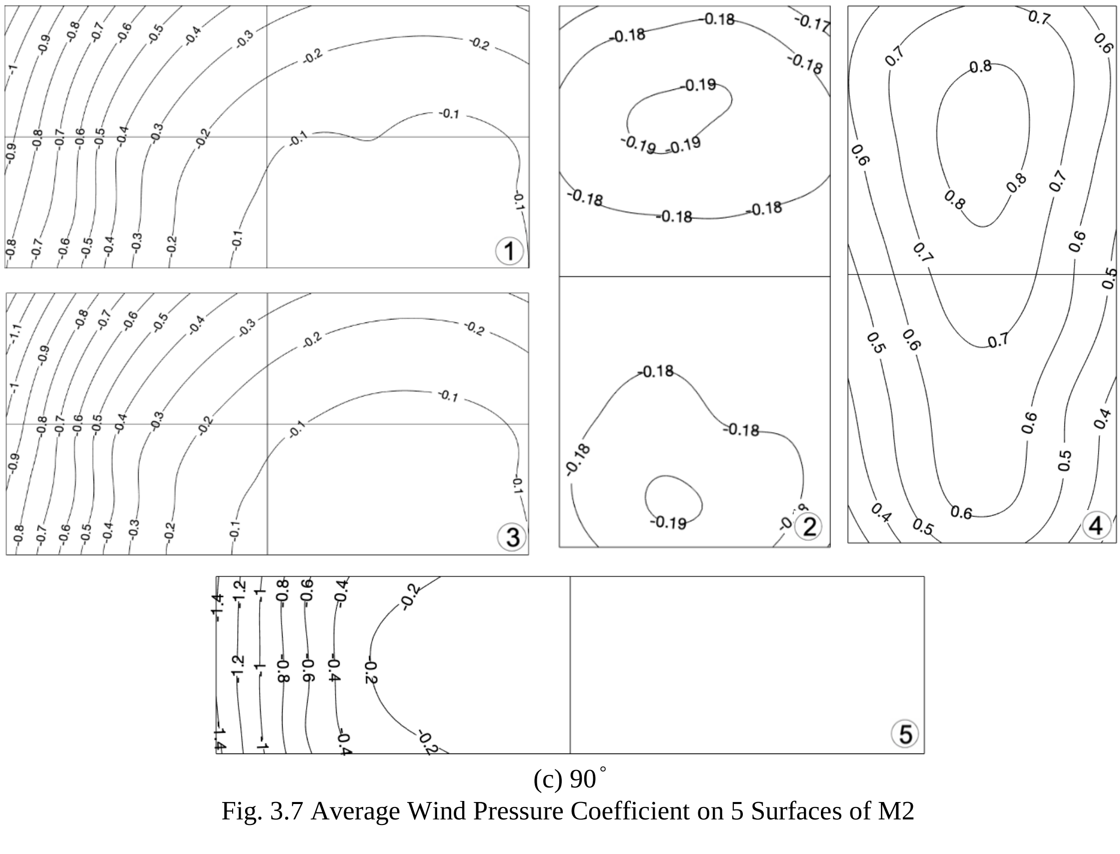
Fig. 3.6 Average Wind Pressure Coefficient on 5 Surfaces of M1



(a) 0˚

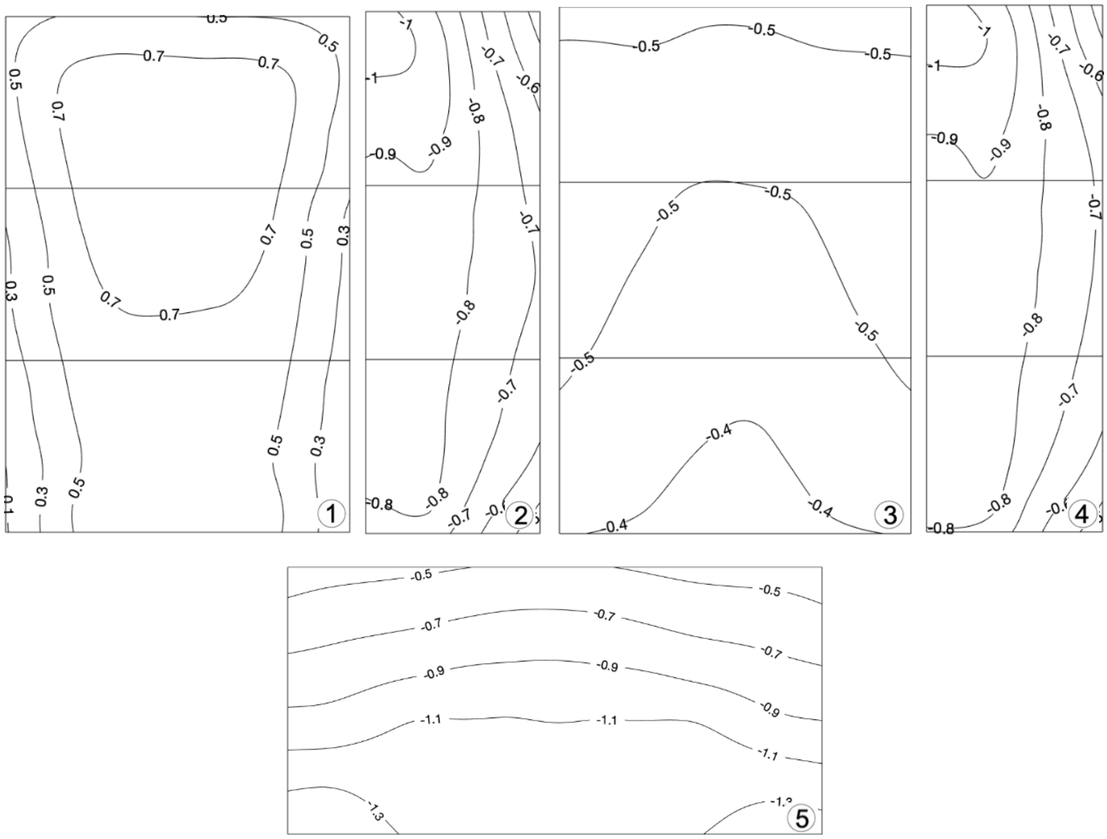


(b) 45°



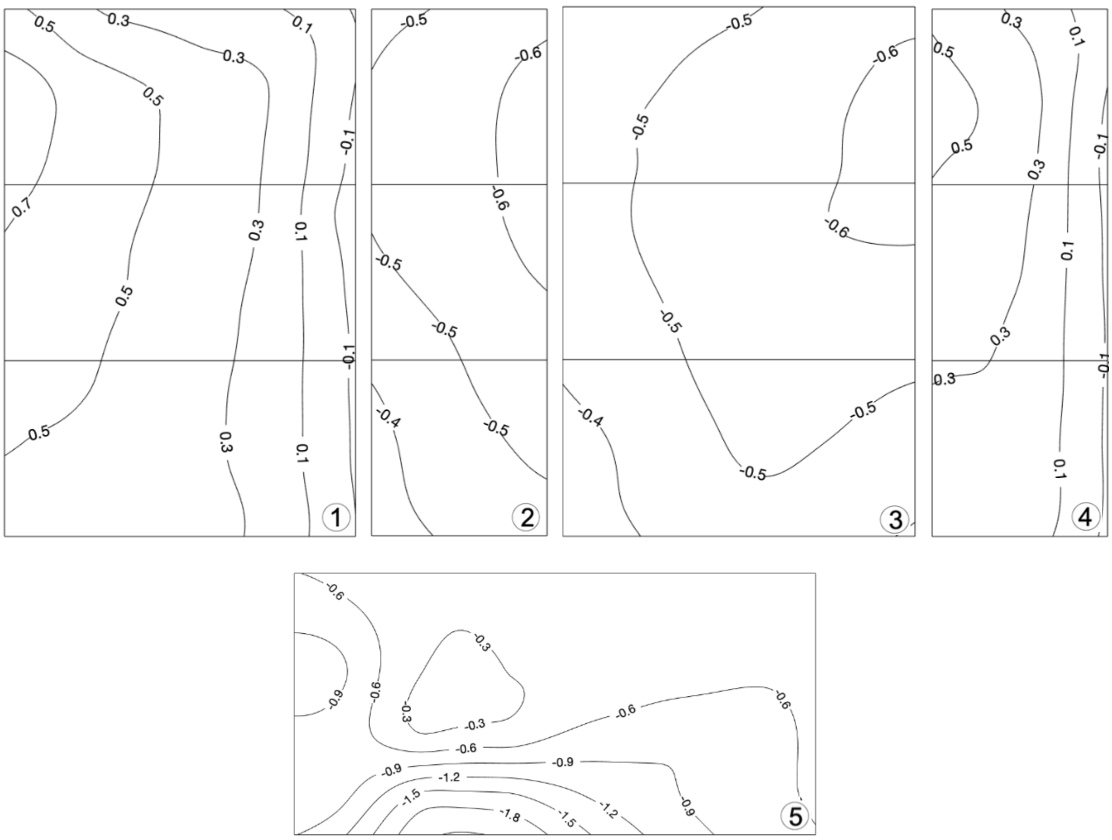
(c) 90°

Fig. 3.7 Average Wind Pressure Coefficient on 5 Surfaces of M2



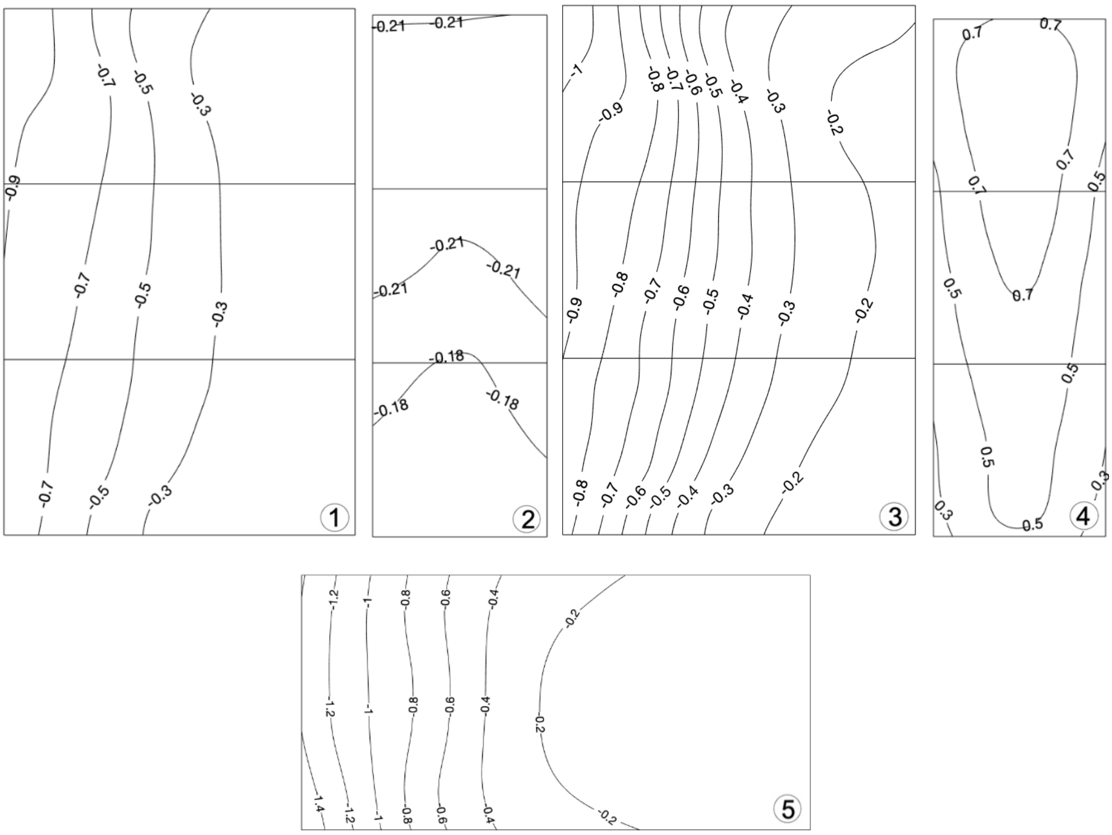
0.5
0.7
0.3
0.1
1
-1
-0.9
-0.8
-0.7
-0.6
2
-0.5
-0.4
3
4
-1.1
-1.3
5

(a) 0°



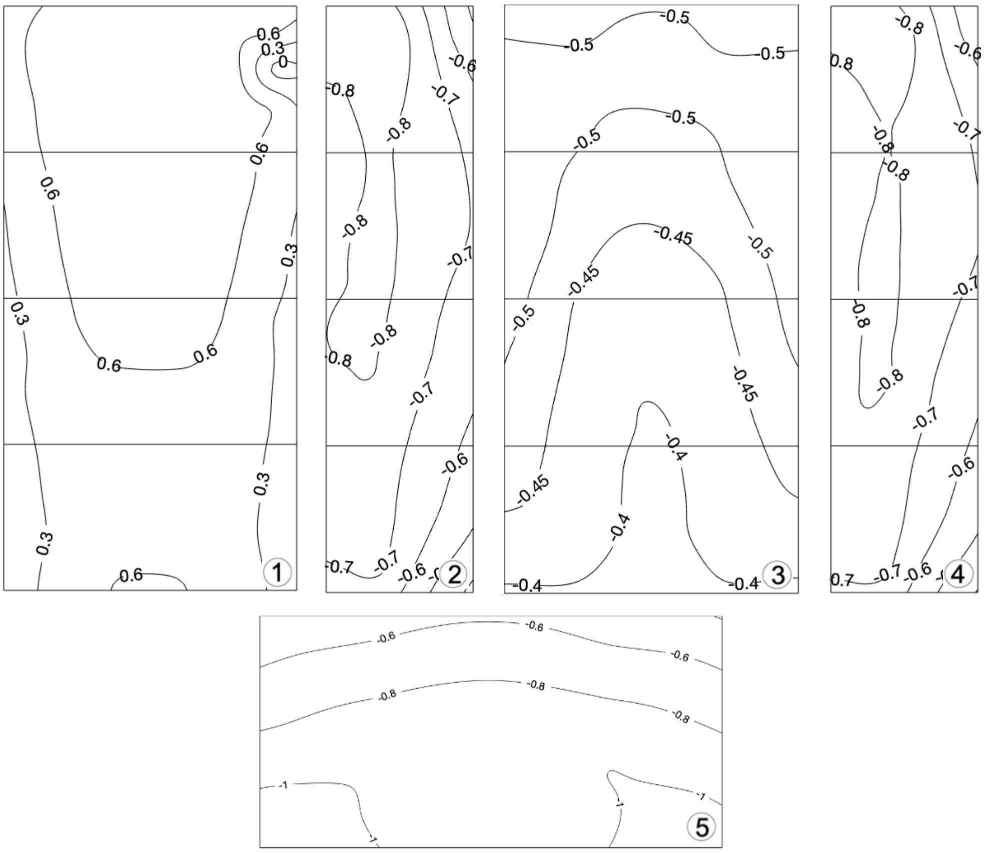
0.5
0.3
0.1
-0.1
0.7
1
-0.5
-0.6
-0.4
2
3
4
-0.3
-0.9
-1.2
-1.5
-1.8
5

(b) 45°

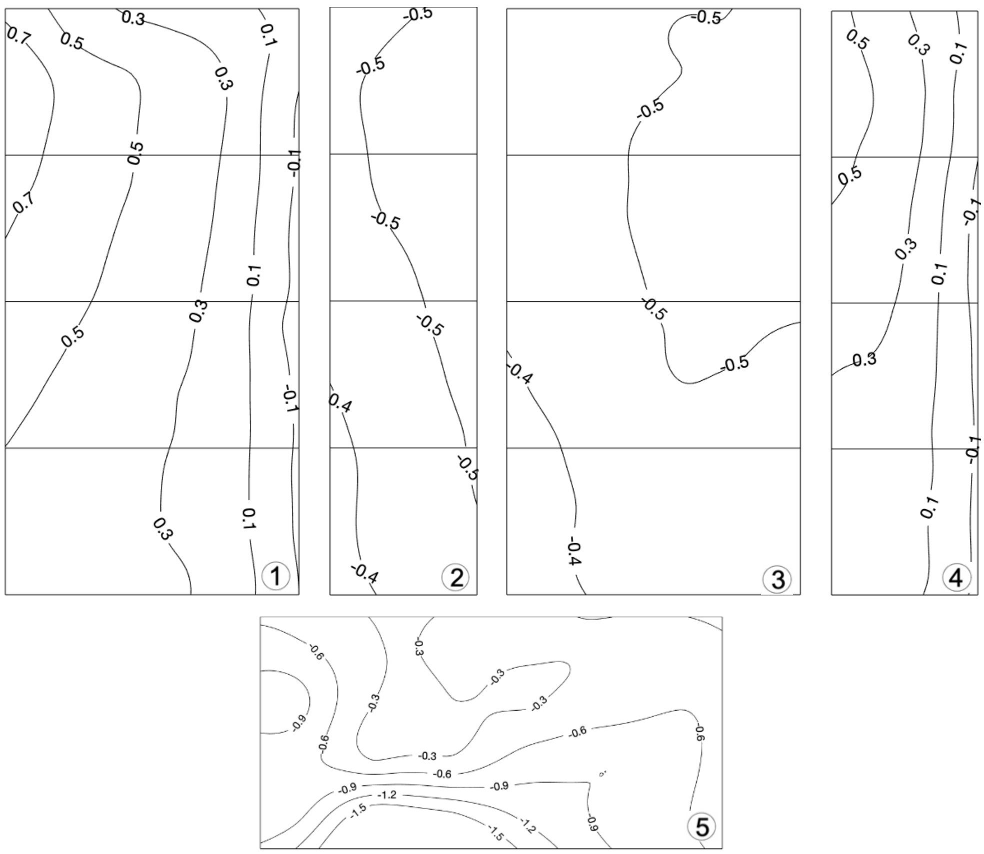


(c) 90°

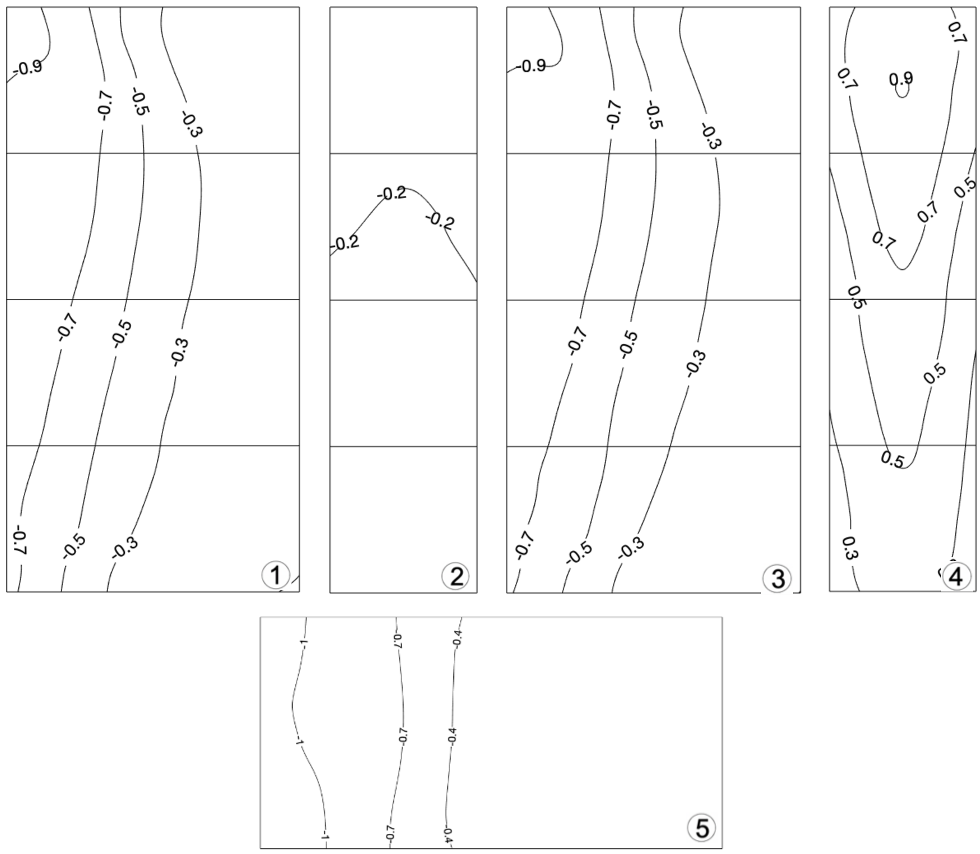
Fig. 3.8 Average Wind Pressure Coefficient on 5 Surfaces of M3



(a) 0°

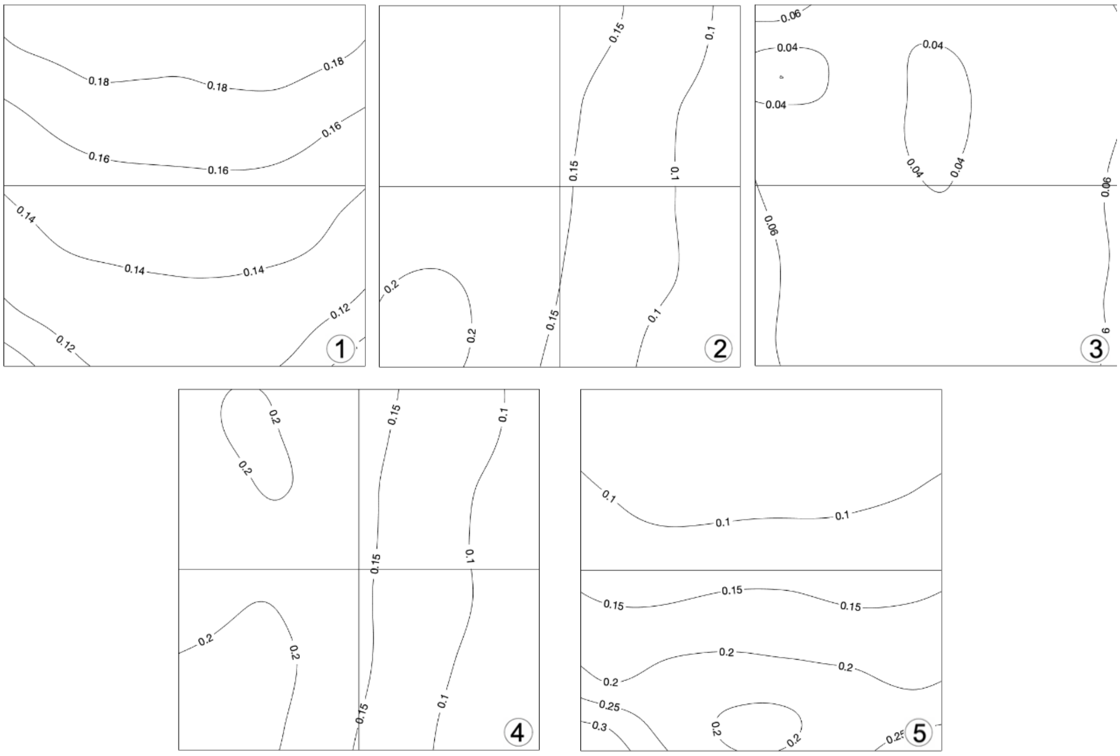


(b) 45°

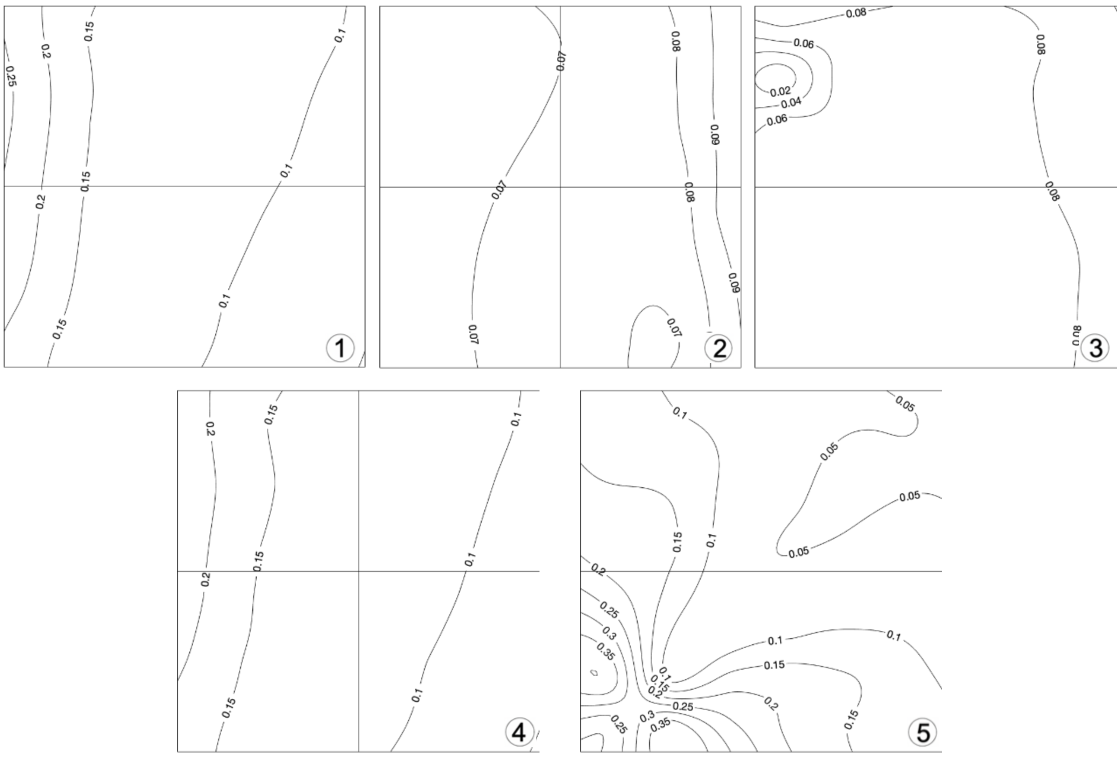


(c) 90°

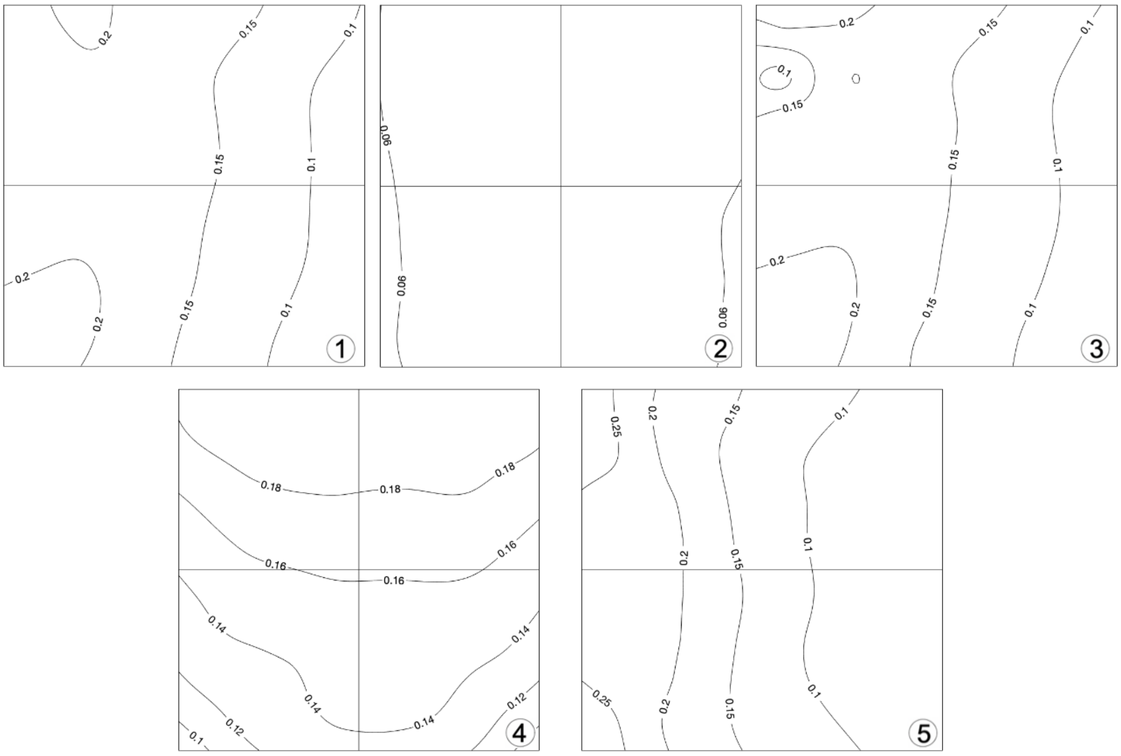
Fig. 3.9 Average Wind Pressure Coefficient on 5 Surfaces of M4



(a) 0°

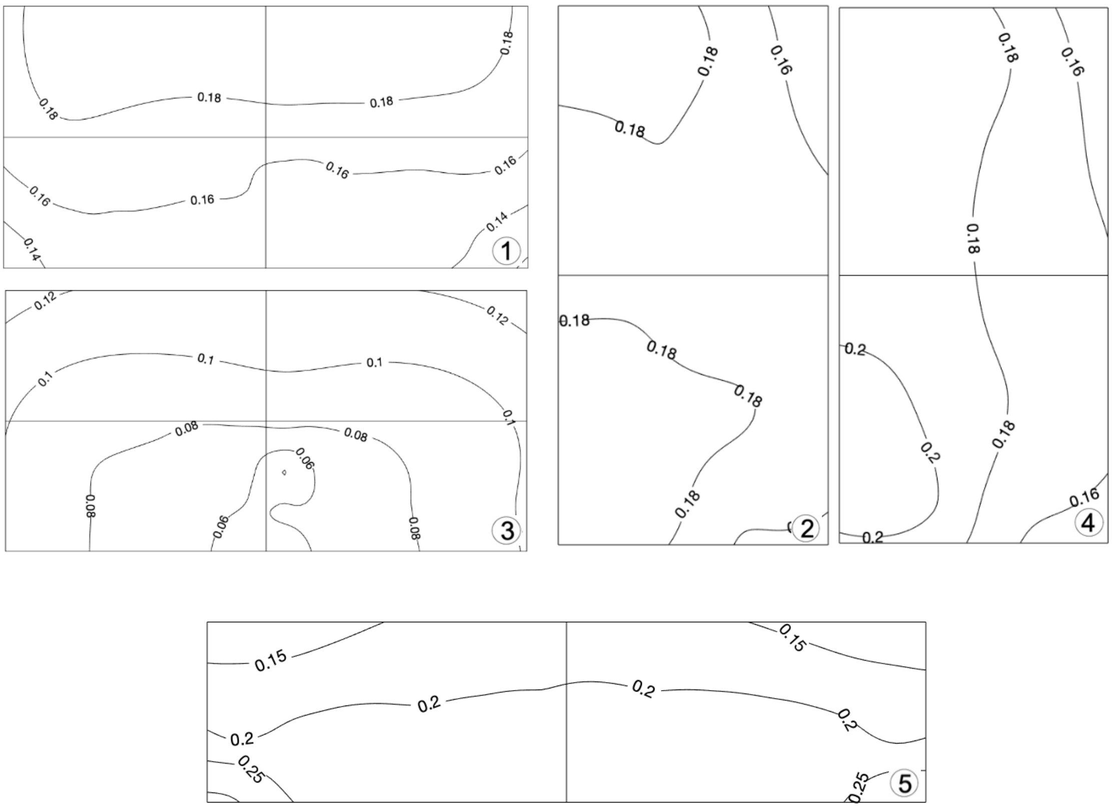


(b) 45°

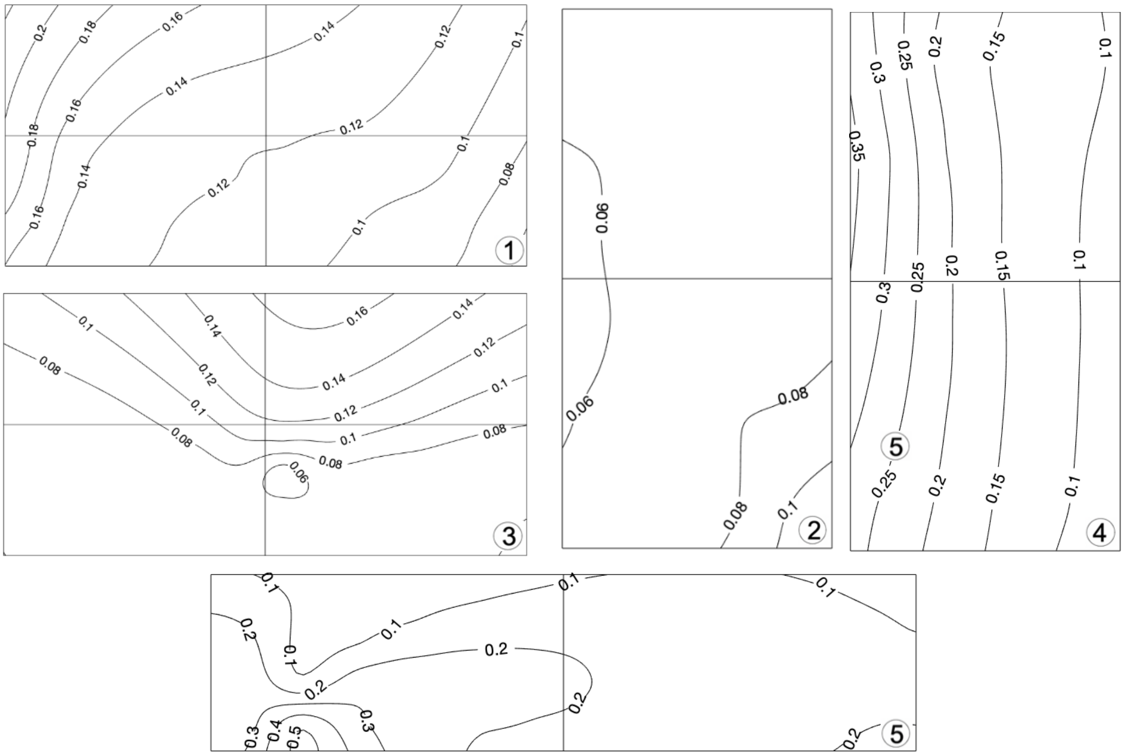


(c) 90˚

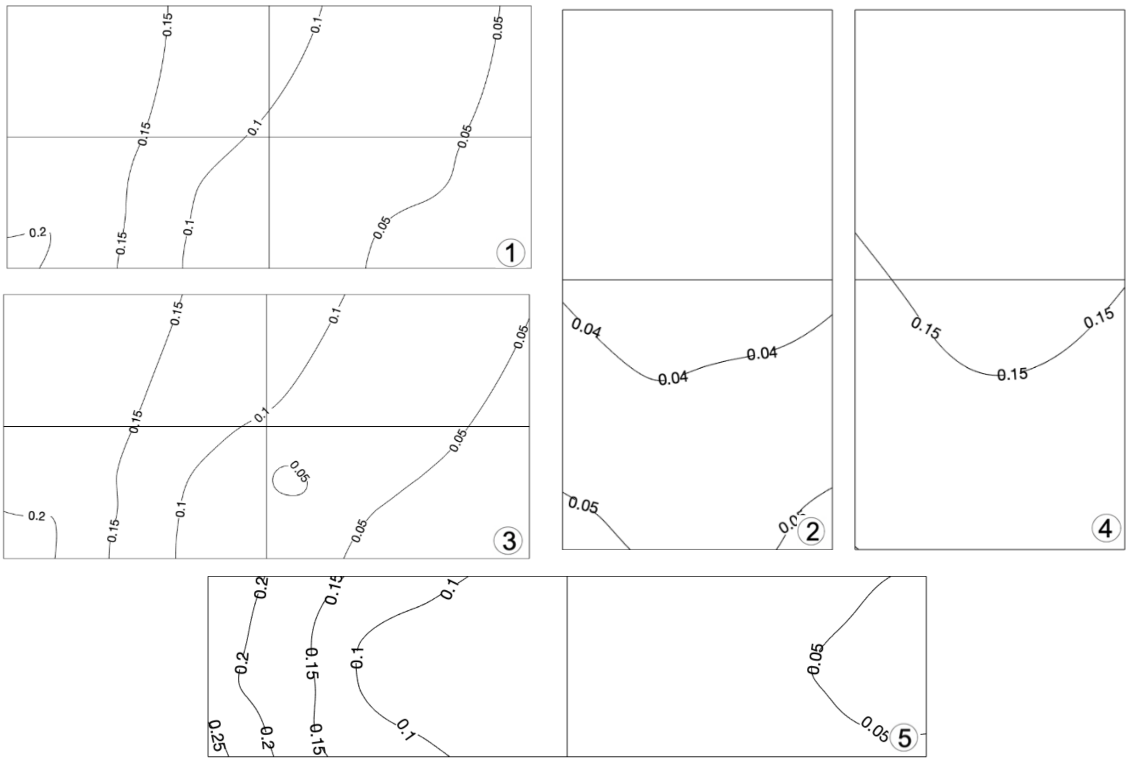
Fig. 3.10 Fluctuating Wind Pressure Coefficient on 5 Surfaces of M1



(a) 0˚

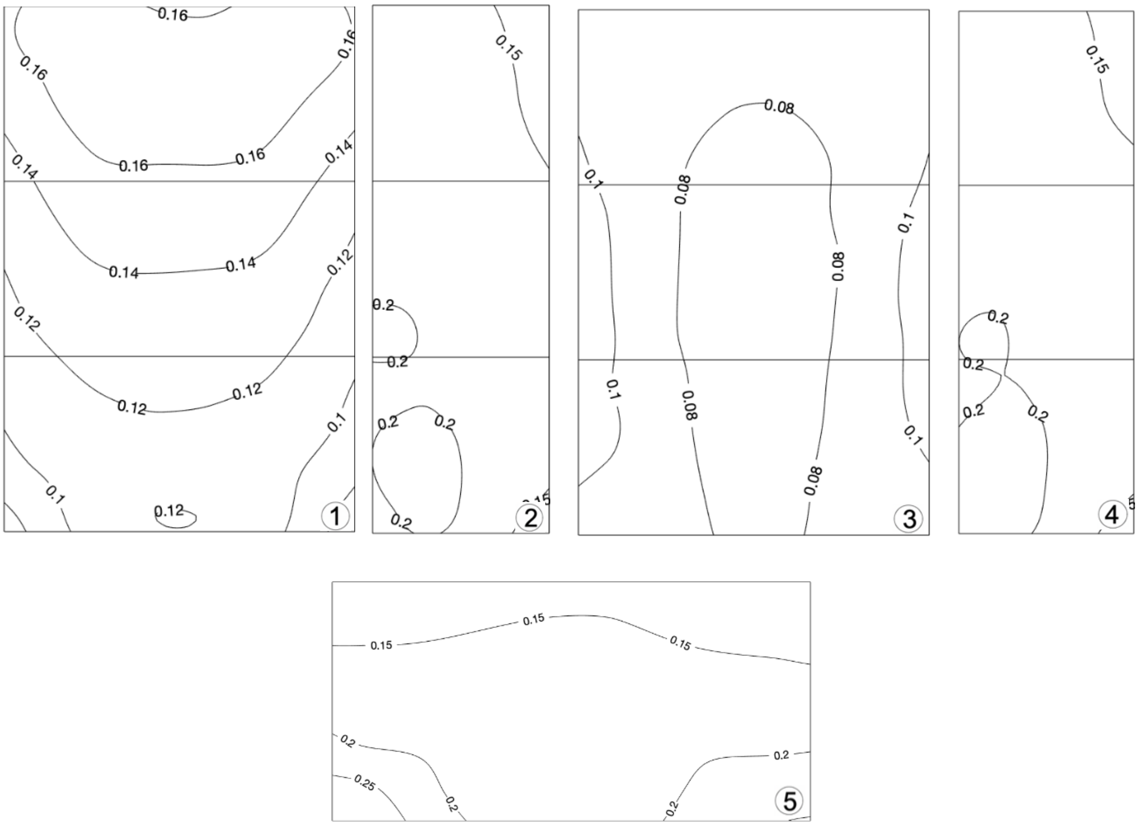


(b) 45°

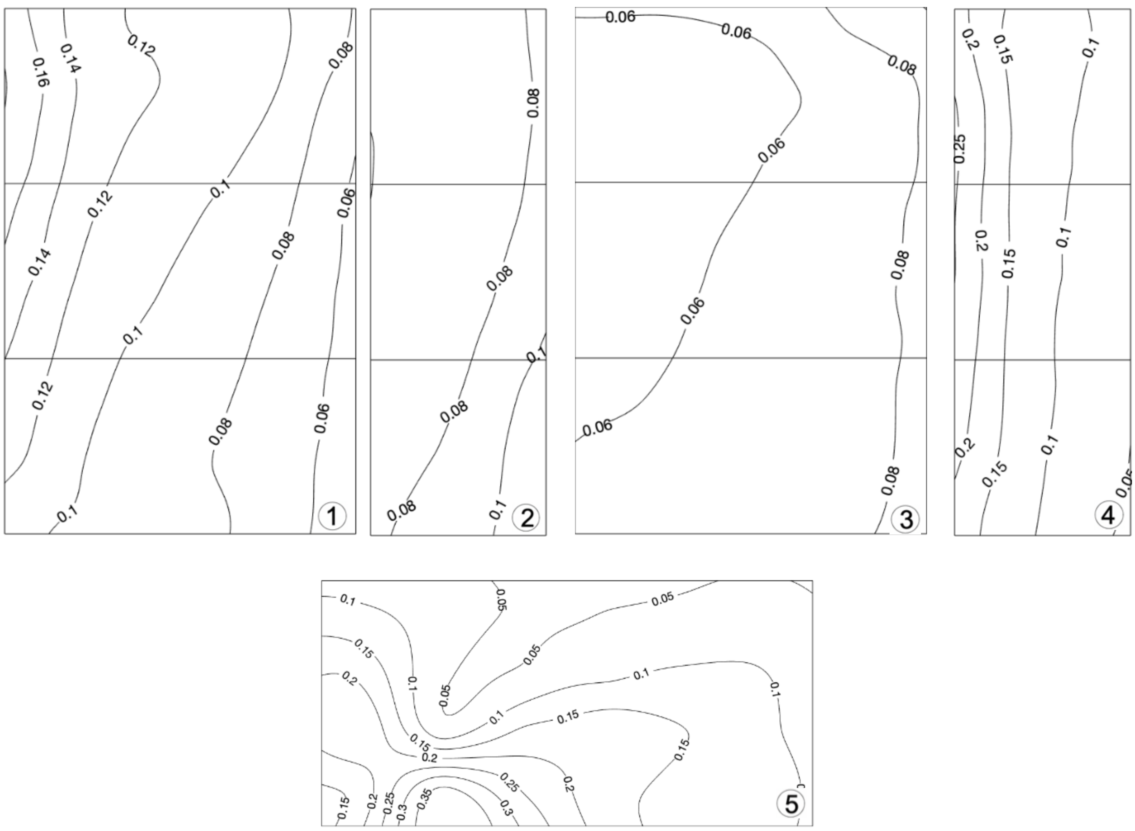


(c) 90°

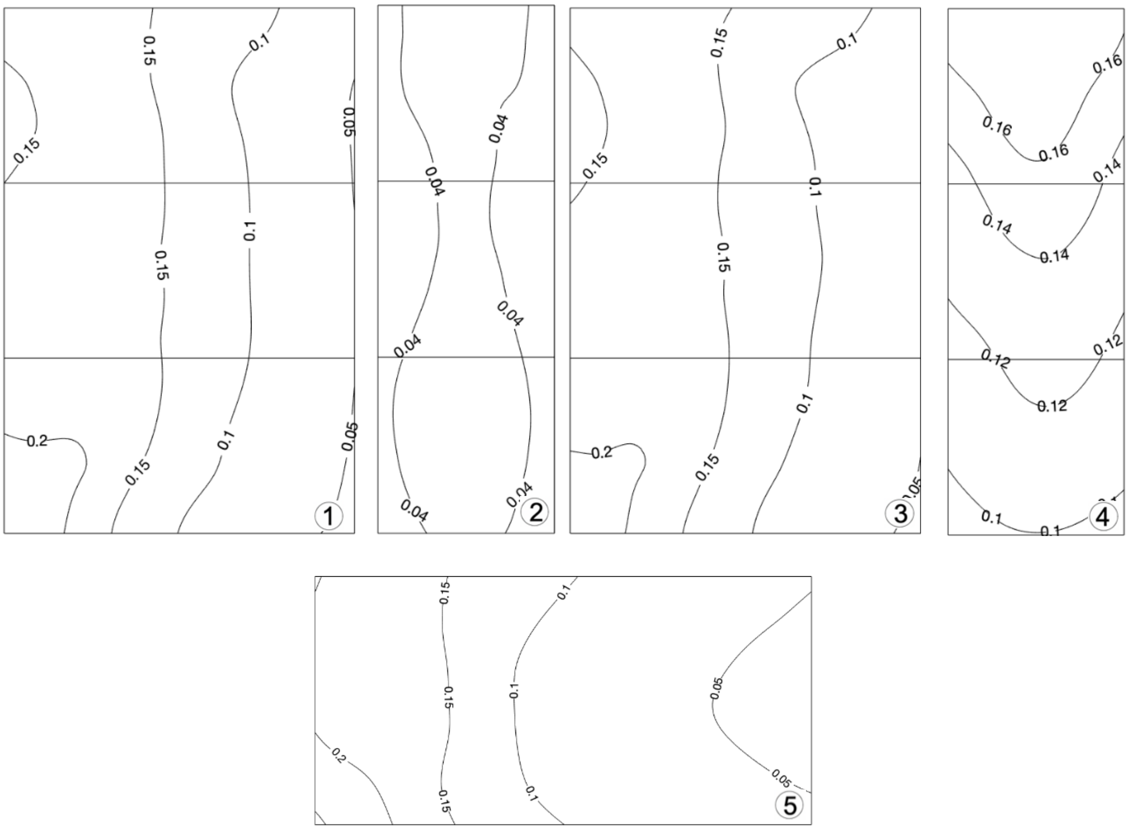
Fig. 3.11 Fluctuating Wind Pressure Coefficient on 5 Surfaces of M2



(a) 0˚

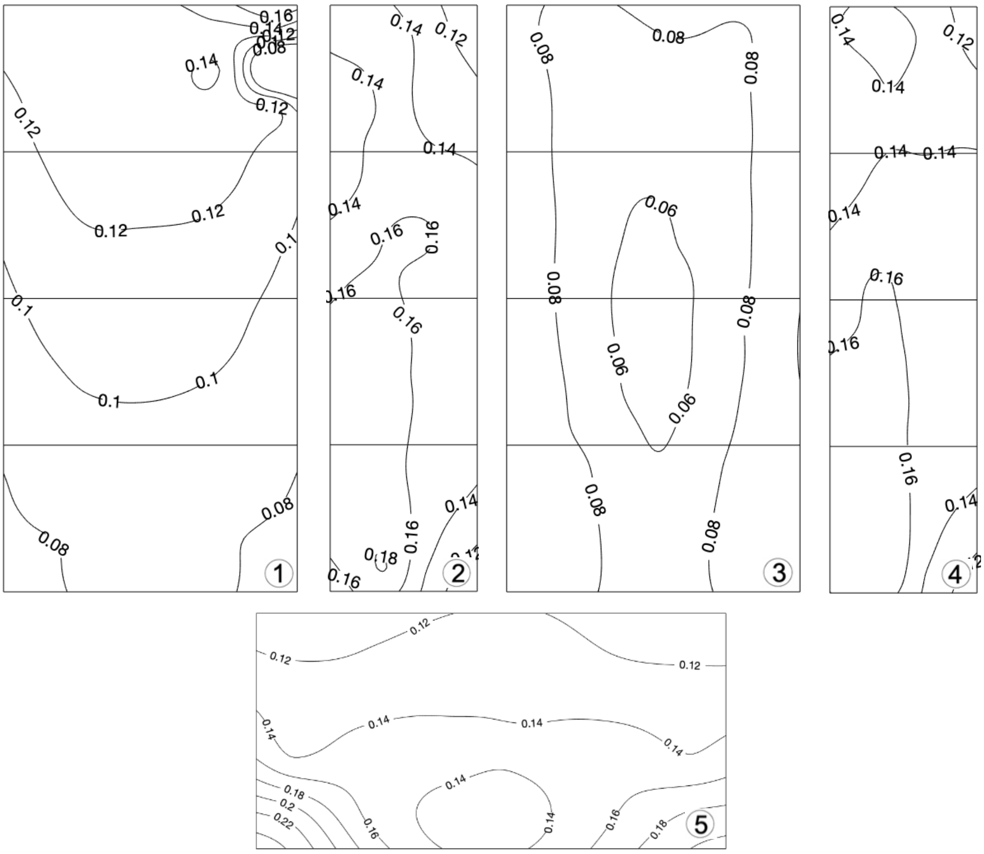


(b) 45˚

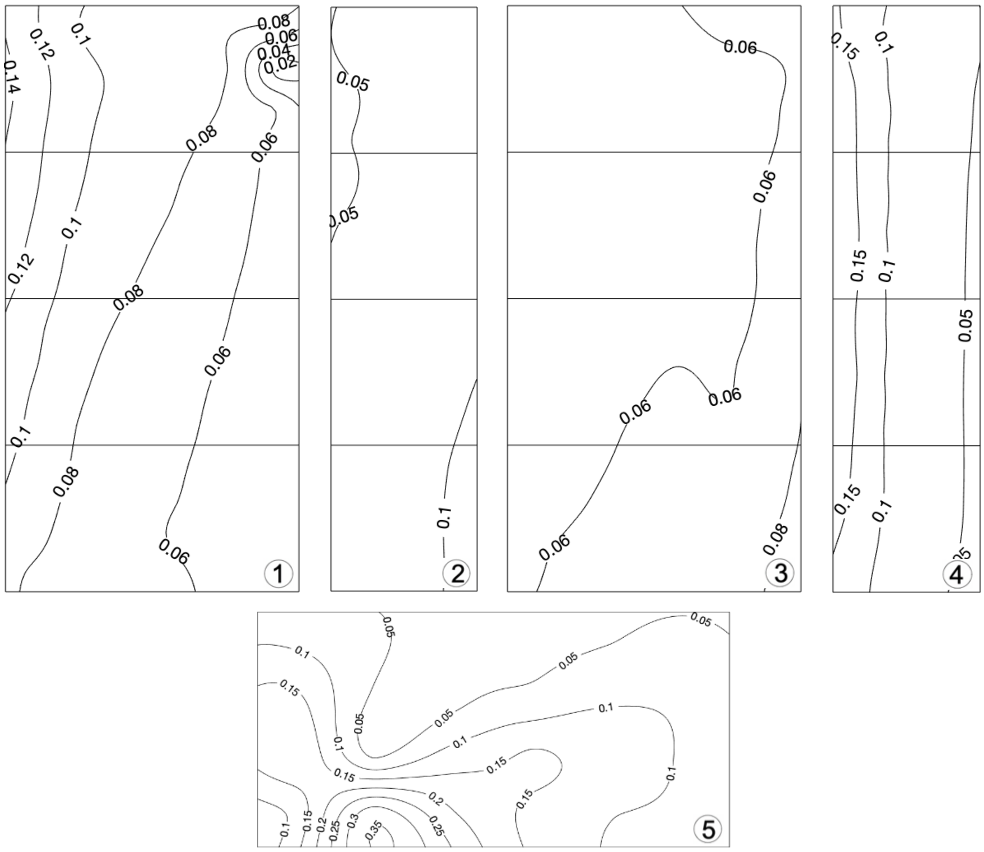


(c) 90˚

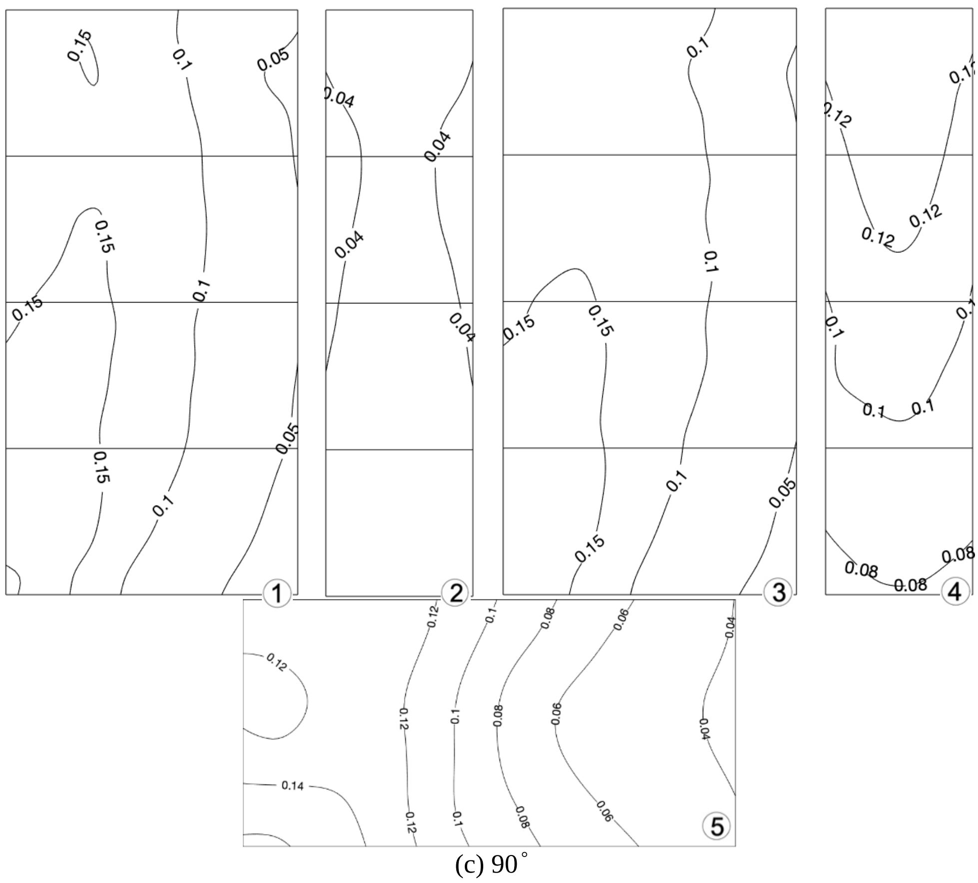
Fig. 3.12 Fluctuating Wind Pressure Coefficient on 5 Surfaces of M3



(a) 0˚



(b) 45°



(c) 90°

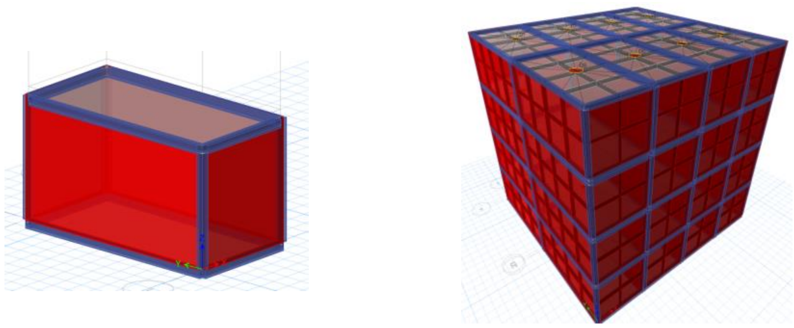
Fig. 3.13 Fluctuating Wind Pressure Coefficient on 5 Surfaces of M4

3.3 Finite element analysis

1) Finite element model

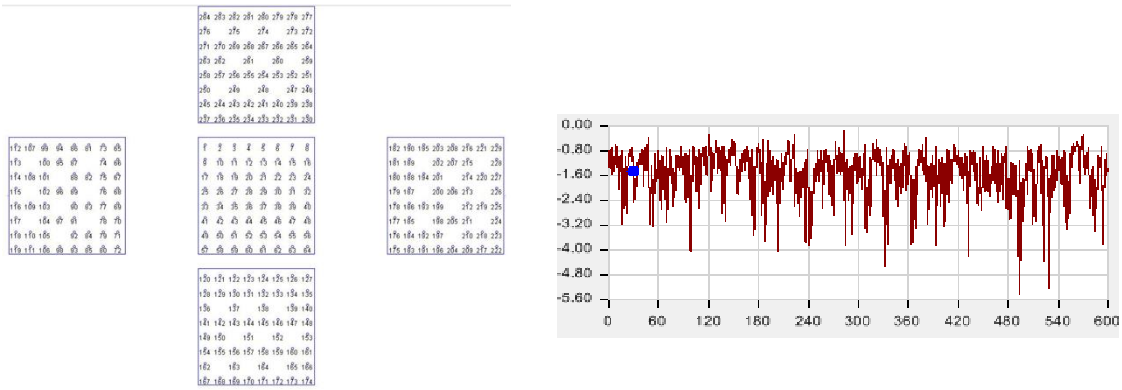
The ETABS finite element model of 3D modular structure was established in this paper. The size of the modular unit is 3m (height) × 3m (breadth) × 6m (length) and the size of the whole 3D modular structure model is 12.6m × 12.6m × 12.6m which is formed by 24 modular units in 4 storeys as shown in Fig. 3.14. The frame of the unit is made of box section of Q345 steel (f_y=345N/mm2, E_s=2 × 10^4N/mm^2) whose size is 200mm × 200mm × 10mm × 10mm. The wall and floor are made of the material which has equivalent stiffness to concrete (E_c=3 × 10^4N/mm^2) in order to ensure the stiffness of the modular unit and the thickness is 200mm. The inter-module connections play the role of load transfer elements in 3D modular structure and the section of them is same as the frame. The height of the inter-module connections is 200mm which makes interval between adjacent modules to transfer axial force, shear force and moment. All of the joints including intra-module connection, inter-module connection and module-to-foundation connection are rigid connected. The frames, walls, floors and connections are all simulated by 3D shell element. Since every part of the model component is in elastic state under wind load, the ideal elastic model is adopted as the constitutive model.
The time-domain method is applied in the calculation for the wind-induced response of 3D modular structure, and the relevant parameters are as follows: (1) Basic wind pressure: 0.55kPa (the return period is 50 years, considering Shanghai area); (2) Terrain roughness: $\boldsymbol{\alpha}$=0.15 (based on the *Load Code for the Design of Building Structures* (GB50009-2012) [5]); (3) Time period step: 0.067s (based on the sampling frequency of the wind pressure data); (4) Structural damping ratio: 0.02.

**Due to Coronavirus situation, the data of this year's wind tunnel test cannot be applied in the finite element analysis in time, so the analysis is based on the data in the database of Global COE Program in TPU as shown in Fig. 3.15.*



(a) Modular Unit Model (b) 3D Modular Structure Model

Fig. 3.14 ETABS Finite Element Model (Case 1)



(a) Measurement Point Distribution (b) Time History Wind Load

Fig. 3.15 Wind Load Data

2) Analysis method

The wind-induced internal forces in connections *Y* is a stochastic process, compare the results of time history analysis and code-based analysis. The internal force is evaluated as follows:

$$Y = \bar{Y} + g\sigma_Y \tag{3.2}$$

where, *Y* is the internal force, including axial force, shear force and moment. $\bar{Y}$ is average internal force. *g* is the gust factor, which can calculate the confidence ratio. σ_Y is the standard deviation.

3) Analysis result

Considering one selected connection in FEA model for wind-induced internal forces analysis as shown in Fig. 3.16, wind direction case 0° was analyzed in this paper. The time-history results of internal forces in the inter-module connection, including axial force ***N***, shear force parallel to wind direction $\boldsymbol{V}_2$, shear force perpendicular to wind direction $\boldsymbol{V}_3$, moment perpendicular to wind direction $\boldsymbol{M}_3$ and moment parallel to wind direction $\boldsymbol{M}_2$ are shown in Fig. 3.17- Fig. 3.21.
Tab. 3.4 gives the finite element calculation results of internal forces in different confidence ratios compared to the results based on Chinese code GB50009-2012 [5], and the calculated values in red are the results nearest to code-based results. It can be concluded that:

(1) For axial force ***N***, the code-based results can only guarantee less than 90% of the time history results as shown in Fig. 4.4, which may cause unsafety in connection design under current code.

(2) For shear force $\boldsymbol{V}_2$, the code-based results can guarantee 90-95% of the time history results. While in shear force $\boldsymbol{V}_3$, the code-based results can guarantee less than 85% of the time history results, because the average value is less than 0 and the deviation is high.

(3) For moment $\boldsymbol{M}_3$, the code-based results can guarantee 97.5-99.5% of the time history results due to small values and low deviation. In moment $\boldsymbol{M}_2$, Chinese code can guarantee less than 85% of the time history results, because average value is less than 0 and the deviation is high, which is similar to V3.

Tab. 3.5 Comparison of Time History and Code-based Results

Internal Force	Code-based Results	Different Confidence Ratios					
		85%	90%	95%	97.5%	99.5%	100%
Axial Force-***N*** (kN)	-8.75	-8.05	-8.85	-10.08	-11.00	-12.70	-14.34
Shear Force-$\boldsymbol{V}_2$ (kN)	5.31	4.29	4.72	5.43	5.93	7.10	8.02
Shear Force-$\boldsymbol{V}_3$ (kN)	-1.20	-1.70	-2.00	-2.44	-2.86	-3.70	-5.34
Moment $\boldsymbol{M}_3$ (kN • m)	0.55	0.39	0.43	0.49	0.54	0.66	0.75
Moment $\boldsymbol{M}_2$ (kN • m)	-0.18	-0.24	-0.27	-0.33	-0.38	-0.48	-0.63

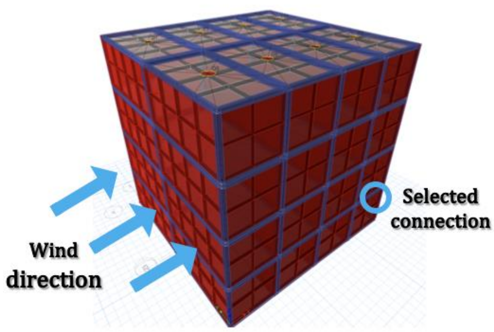


Fig. 3.16 Wind Direction 0° and Selected Connection

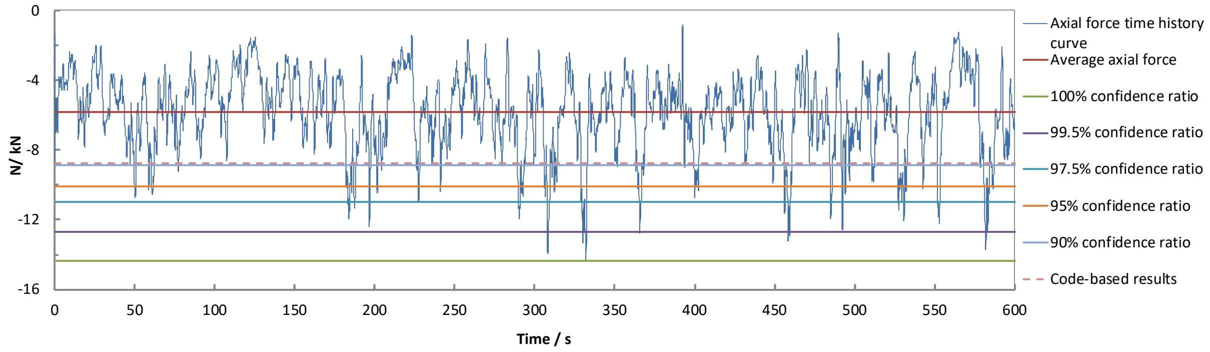


Fig. 3.17 Time History of Axial Force ***N*** Compared to Code-based Results

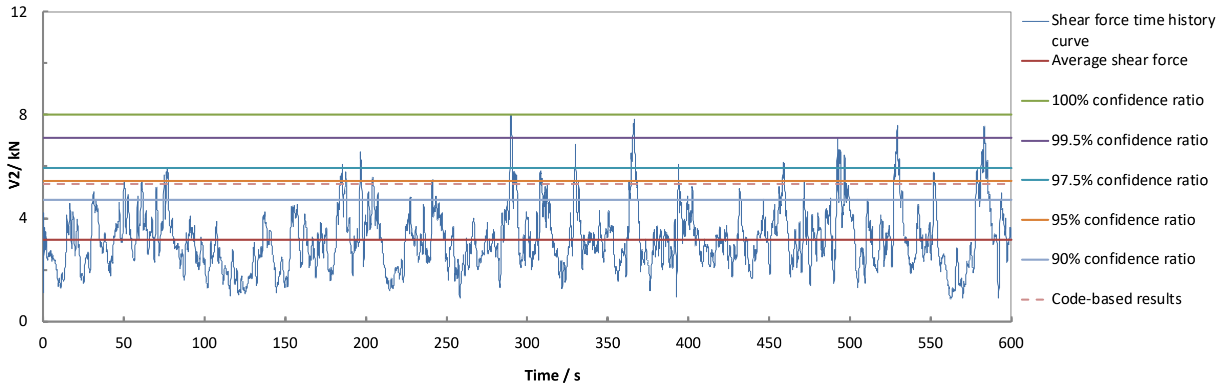


Fig. 3.18 Time History of Shear Force $\boldsymbol{V_2}$ Compared to Code-based Results

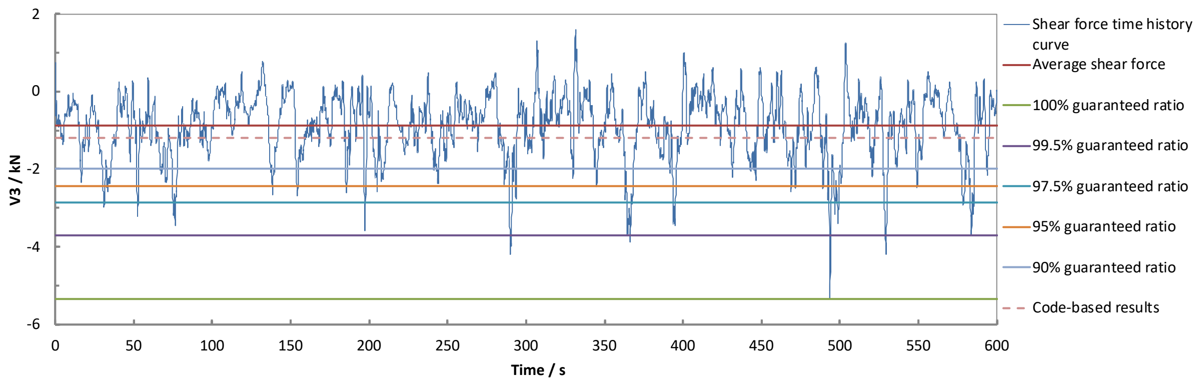


Fig. 3.19 Time History of Shear Force $\boldsymbol{V_3}$ Compared to Code-based Results

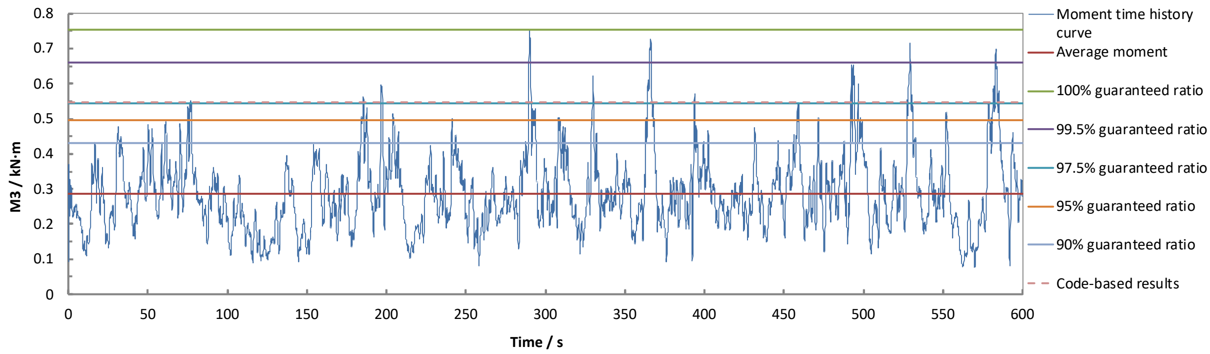


Fig. 3.20 Time History of Moment $\boldsymbol{M_3}$ Compared to Code-based Results

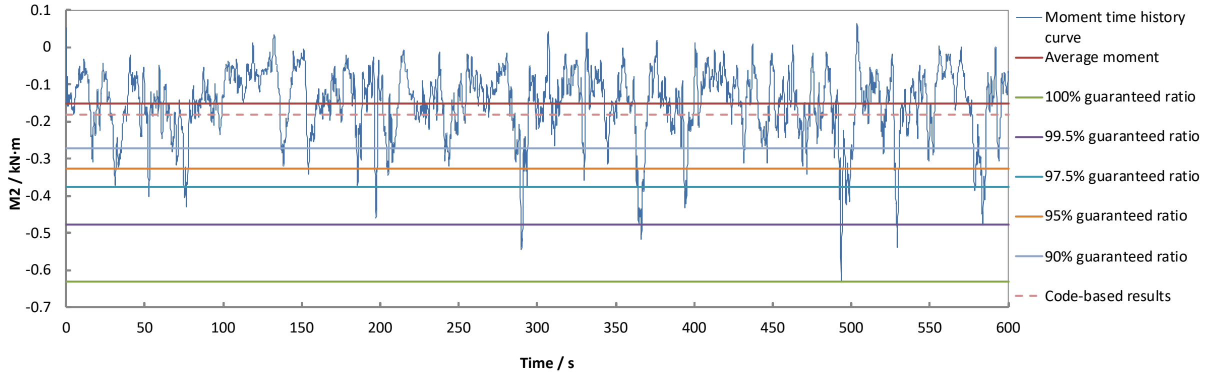


Fig. 3.21 Time History of Moment $\boldsymbol{M_2}$ Compared to Code-based Results

3.4 Conclusion

Considering the characteristics of spatial and time correlation of fluctuating wind for wind-induced internal forces in inter-module connections, an effective static estimation method will be proposed in the future using a modifying coefficient to reflect the extreme value in structural design. Based on the wind tunnel test data, the finite element model was established to obtain the dynamic time history analysis results. The calculation results of internal forces of inter-module connections based on Chinese code GB50009-2012 [5] was compared with the time history analysis results. As a result, the code-based results cannot guarantee enough confidence ratios in practical design and still lack in theoretical support. The following conclusions can be drawn based on above analysis:

(1) Wind-induced internal forces of inter-module connections have spatial and time characteristics due to the force transferring features of multi-story 3D modular structures.

(2) Current load code doesn't consider the spatial and time characteristics of multi-story 3D modular structure and may results in an unsafety estimation.

(3) The code-based results can only guarantee about 90% of internal forces in reality, and different types of internal forces have various confidence ratios under current load code, which indicates that different types of internal forces in inter-module connections should be adjusted differently considering the characteristics of spatial and time correlation of fluctuating wind.

(4) Based on current work, an effective static estimation method can be proposed in the future using a modifying coefficient to reflect the extreme value of internal forces in connection design under wind load.

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4. Published Paper etc.

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2) Presentations at academic societies
Yuan-Qi Li, Yu Zheng, Akihito Yoshida, Wind-induced load estimation for clips of standing seam metal roofing system considering dynamic characteristics, 2nd International Workshop on Wind Effects on Buildings and Urban Environment, Wind Engineering Joint Usage / Research Center, Tokyo Polytechnic University, Atsugi, Japan, March 10-12, 2019

5. Research Group

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6. Abstract (half page)

Effective Static Wind-induced forces Estimation for Connection Design of Multi-story 3D Modular Structures

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Keywords: Wind-induced internal force estimation, Inter-module connection, Multi-story 3D modular structure, Spatial and time correlationship

Abstract

This project mainly focuses on an effective static estimation method for wind-induced internal forces in inter-module connections of multi-story 3D modular structures considering the dynamic characteristics of wind and structure. Firstly, simultaneous wind pressure distribution was measured by rigid modular models mainly considering height-to-breadth ratio in the BLWT of Tokyo Polytechnic University, Japan, for obtaining a test database for the following research. Then, finite element modeling and numerical analysis for typical multi-story 3D modular structures was conducted to obtain the time-history internal forces of inter-module connections for further comparison analysis. The internal forces of inter-module connections were calculated based on current Chinese code, and compared to the finite element results based on different confidence ratios. Finally, an effective static estimation method can be proposed in the future using an equivalent modifying coefficient to reflect the extreme value of internal forces in connection design under wind load for multi-story 3D modular structures based above comparison analysis.