The evaluation of collapse probability of low-rise buildings based on Monte Carlo simulation

Beier Hu[1, †], Han Liu[2, *, †], Xiaoyu Tan[3, †], Yun Zhang[4, †]

[1]Department of Construction Engineering, Dalian University of Technology, Dalian, China

[2]School of Civil Engineering, University of Leeds, Leeds, United Kingdom

[3]Department of Project Cost, Jingzhou University, Hubei, China

[4]Department of Civil Engineering, North China University of Technology, Beijing, China

*Corresponding author: cn20hl@leeds.ac.uk

†These authors contributed equally

Abstract. Over recent years, wind-caused activities such as typhoons, hurricanes, and tornadoes have happened frequently in coastal areas, causing damage or even the collapse of many buildings. This study designs a three-story teaching building located in Dalian to discuss the influence of different wind speeds on the stability of this building and propose some measurements. This study firstly uses Monte Carlo simulation to analyze the probability of collapse of the beam. Results show that the probability of frame collapse on windy days is 0.399%. It indicates that the wind speed could affect the stability of the structure. Higher wind speed could cause a higher internal force and structure displacement, leading to structural disability. The study also provides some wind-resistant designs to increase structural stability. The first is to choose a wind-resistant location, making reasonable site selection. The second is to select a suitable roof to resist heavy wind, and to increase the safety factor of the roof wind load design. The third is to increase the cross-section reinforcement method to reduce the dynamic wind load effect of the structure effectively. The externally bonded steel from the reinforcement method should be checked to avoid shear damage to the members after the bending bearing capacity increase.

Keywords: Frame Structure; Low-Rise Building; Monte Carlo Simulation.

1. Introduction

Nowadays, with the continuous development of social economy, people's quality of life is also constantly improved, and people's understanding of life and humanistic living environment are also increasingly high. Therefore, the public has higher requirements for architectural design closely related to life and work. The stability of the building, a particularly key part of the design of the building structure, has become the dominant factor that determines the quality of the building. It is related to the safety of life and property of the masses, and also affect the harmony and stability of the society.

Natural disasters such as snow and wind have occurred frequently in recent years. Wind effects on ground buildings tend to bring different damage and disaster. Statistics show that all natural disasters, the disaster caused by the loss of a variety of disasters, cyclone in large quantities in the lower house of damaged or collapsed, and the resulting casualties are caused by cyclone as the main reason for the huge losses. Over recent years, typhoons, hurricanes, tornadoes and other activities in coastal areas of the world are frequent, especially typhoons often cause damage or even collapse of a large number of buildings. For example, Dalian City, China's Jinzhou area experienced strong wind and low temperature on March 9, 2013. The instantaneous maximum wind speed measured by the national general meteorological station in Jinzhou area was 24.6m/s (wind force 10). According to the automatic regional station, the instantaneous maximum wind speed in Shengli Street is 30m/s (wind level 11), and the maximum wind speed in Liangjiadian street is 34.1m/s (wind level 12). Affected by it, farmland, fruit trees, vegetable greenhouses in many areas were seriously damaged, thousands of square meters of light steel roof were blown off, many light steels color plate houses collapsed, and the loss is expected to exceed 10 million yuan [1].

Because of the disasters, the country has higher requirements for the stability of housing. Currently, frame structure is a common structural form widely used in various multi-storey industrial and civil buildings. Frame structure has a simple system composed of beams, columns and foundations. The frame structure is a flexible structure that can have good ductility performance. Therefore, it is essential to pay more attention to the performance of frame structure.

This study designs a three-story teaching building located in Dalian, a coastal city in China, and discusses the influence of different wind speeds on the stability of this building, and propose some measurements.

2. Background

In China, the low-level building is a widespread building type. It generally refers to 7 floors or lower than 7 floors, height is less than 24 meters of all kinds of buildings, including residential, factory, commercial and public buildings, etc. Such houses are often severely damaged by frequent typhoons in coastal areas. As for commercial and teaching buildings, three-story are more common. This study explores the risk of collapse when this three-story teaching building is subjected to different wind loads.

For this design, this study chooses Dalian as a research goal as it is a coastal city with four distinct seasons in the northern hemisphere's warm temperate region. Dalian area is located at the southern tip of Liaodong Peninsula, bordering the Bohai Sea and the Yellow Sea. The region is located in the middle latitude region of the Northern hemisphere, and the annual average wind speed is between 3-6.0 m/s. It is one of the regions with the highest wind speed in northeast China.

3. Methods and results

This study collected the wind speed data of Dalian over the past ten years. In recent 10 years, the average annual wind speed in Dalian has shown an obvious downward trend. The variation characteristics of wind speed were analysed based on the data of monthly average wind speed and daily maximum wind speed of seven meteorological stations in Dalian from 2010 to 2021.

The collected data mainly includes the windy weather in Dalian. It shows apparent seasonal variation, with the windiest weather in winter and spring, followed by autumn and the least windy weather in summer.

3.1. Components rigidity calculation by internal force method

About calculating the internal force, first of all, some formulas were used to figure out the cross-section moment of inertial, which were based on the Chinese code for the design of concrete structure GB50010-2015.

For beams, the rigidity of each part of the frame can be worked out using the result of the cross-section moment of inertial, Ec of the material, and the span of the frame. But the rigidities need to be adjusted because of the different positions, which can make the subsequent calculations closer to reality. So the rigidity of mid-span times 2.0, the rigidity of side-span times 1.5. For columns, the height of the column could be used instead of the span of the frame, and then the calculations of rigidities don’t need to adjust (Table 1).

Table 1. The parameters of the modeling

Linear rigidity of frame beam							
Beam span	Ec (N/mm2)	b×h (mm)	calculation span lb（mm）	cross section I0 (mm4)	midspan ib	side span ib (1.5)	Ralative linear stiffness
BD	32500	500*500	5000	5400000000		52650000000	1
DE	32500	500*500	5000	5400000000	70200000000	52650000000	1.33
EG	32500	500*500	5000	5400000000		52650000000	1
column line stiffness							
floor	Hi (mm)	Ec (N/mm2)	b×h (mm)	Ic (mm4)	ic		
1-3th	4000	32500	500x500	10800000000	8.78E+10	1.666666667	
				0.91c	7.90E+10	1.125	

3.2. Maximum Moment calculation by moment distribution method

The moment distribution method is used to get the internal force of the frame under the constant vertical load. The distribution coefficient is calculated by comparing the rigidities of different parts at one point. Those coefficients represent how much bending moment can be obtained for each part of the frame structure. According the code and text book, the moment would transmit between columns and beams. Between columns, one third of the first distribution from the up column or column below could transmit. But between beams, one second of the first distribution from left beam or right beam could transmit. When calculating the second distribution, all the carry-over moments of one point need to be added together, and then the result times the coefficient again. At last, the first distribution adds a carry-over moment and the second distribution, the final moment of each part could be figured out. For calculating the internal force using the distribution moment method, software, such as ftool and MATLAB, is also used as a help to get more accurate data.

3.3. Bearing capacity limit

According the code and the guild book, the formula was chosen from three formulas below (Formulas 1,2,3, Figure 1) which fit the situation.

Bearing capacity limit:

$$\text{If } \xi_b h_0 \geq x \geq 2a',\ M_u = a_1 f_c b x\,(h_0-0.5x)+f_y A_s(h_0 - a') \tag{1}$$

$$\text{If } x \leq 2a',\ M_u = f_y A_s(h_0 - a') \tag{2}$$

$$\text{If } \xi_b h_0 < x,\ M_u = a_1 f_c b (h_0)^2 \xi_b (1-0.5\xi_b)+f_y A_s(h_0 - a') \tag{3}$$

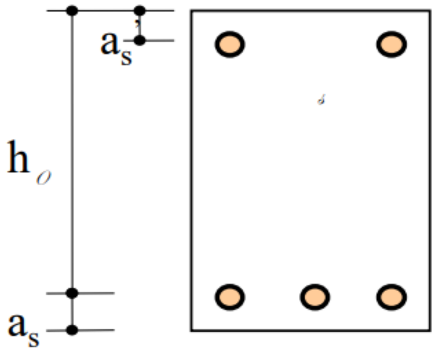

Fig. 1 Diagram of reinforced concrete

By looking up the exact data of the material, the bending moment limit can be figured out easily. After getting the bending moment limit, the other two formulas (Formulas 4,5) were used to figure out the displacement limit by using the bending moment limit.

$$\sigma = \frac{M_u}{I_x} \tag{4}$$

$$\delta = \frac{5wL^4}{384EI} \tag{5}$$

By calculation, this model load-displacement limit is 791.977mm

3.4. Probability model

For this frame structure, there are many uncertainties, the final load applied to the beam can be controlled between 13.5KN~16KN due to factors such as cement density, adhesive strength, humidity, etc., and this range is also consistent with the local standard load value. The cross-section of the cement beam could also change according to the construction process [2]. This study sets a range on the depth to simulate the difference of the cross-section. Similarly, the elastic modulus of reinforced concrete beams continues to fluctuate over time. Regarding wind strength, this report determines the threshold based on the observed local wind value in the past ten years and creates 10,000 wind value samples in the range of Level 1 to 10 to serve as the wind uncertainty (Table 2) [3].

Table 2. The threshold based on the observed local wind value

Level	Speed(m/s)	Code
0~1	0~0.2	RANDBETWEEN(0,20)/100
1~2	0.3~1.5	RANDBETWEEN(30,150)/100
2~3	1.6~3.3	RANDBETWEEN(160,330)/100
3~4	3.4~5.4	RANDBETWEEN(340,540)/100
4~5	5.5~7.9	RANDBETWEEN(550,790)/100
5~6	8.0~10.7	RANDBETWEEN(800,1070)/100
6~7	10.8~13.8	RANDBETWEEN(1080,1380)/100
7~8	13.9~17.1	RANDBETWEEN(1390,1710)/100
8~9	17.2~20.7	RANDBETWEEN(1720,2070)/100
9~10	20.8~24.4	RANDBETWEEN(2080,2440)/100

Through the structural stress simulation of ftool software, it is found that the load-bearing moment of a beam in the structure is always the largest, so the load limit of the beam is calculated, and the Monte Carlo simulation is used to obtain the probability of collapse of the beam [4].

To increase the modeling accuracy, 1,000,000 samples are used for Monte Carlo simulation in MATLAB, combined with all the above uncertainties. A probability histogram is obtained from modeling. It shows that the horizontal axis is the displacement of the concrete beam, and the vertical axis is the number of displacements of this value (Figure 2). Then export the 1,000,000 displacement samples, arrange them in ascending order, and compare them with our previously calculated load-displacement limits (791.977mm).

Modeling results show that a total of 996015 samples meet the standard, and the probability is 0.399%.

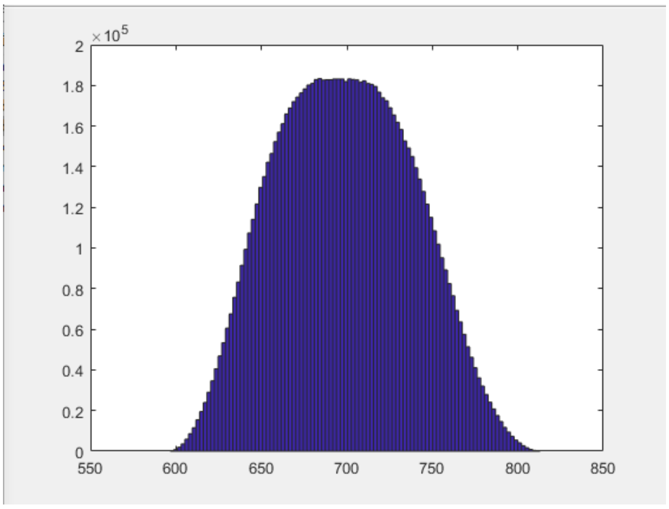

Fig.2 Probability histogram

4. Discussion

4.1. The effect of wind speed on structure stability

Different wind speeds cause different levels of internal forces, and from the internal forces, the displacement of the structure could be figured out step by step, and the displacement can show the stability of the structure directly. According to the reference study, with the increase in building height, wind load gradually becomes the dominant factor of building structure stability [5]. Unlike general buildings, offshore buildings are often subjected to greater wind, a greater probability of encountering typhoons, and require better wind resistance design, such as the Burj Khalifa Hotel in Dubai.

It indicates that the wind speed could affect the stability of the structure. Higher wind speed could cause a higher internal force, and the displacement of the structure increase, which shows the downward trend of stability.

4.2. Means to increase stability

4.2.1 Wind-resistant design method of structure

(1) Make reasonable site selection

Based on the construction plan, choose a wind-resistant favorable location. It is suggested to avoid choose the wind-resistant unfavorable location, such as wind outlets, mountain passes, and estuary because these unfavorable locations would cause a drastic change in wind speed.

(2) Choose a suitable roof

A suitable roof could resist heavy wind. It is suggested to give priority to four slope roofs, take cast-in-place reinforced concrete roofing, and strengthen the geometric mutation parts.

(3) Increase the safety factor of the roof wind load design

It is advisable to increase the safety factor of the roof wind load design by 20% to 30%. The strong suction caused by the strong wind and its pulsation effect and the wind vibration caused by the flexibility of the roof structure under the wind load often damage the roof. At present, the domestic research results in this respect are less.

4.2.2 Methods of strengthening building structures against wind

(1) Increase the cross-section reinforcement method.

It is suggested to increase the cross-section reinforcement method. This method is to increase the plate surface or the bottom of the plate is not less than 40mm thick reinforced concrete post-pouring layer, in order to facilitate the construction of the plate surface pouring to form a rigid floor and roof. If the overlapping layer must be poured on the bottom, the bottom should be excavated by injection. The reinforcement shall be hot rolled, and the diameter of the plate shall not be less than 8mm [6].

(2) Reinforcement method of externally bonded steel

The steel plate effect is certainly not as good as thickening a layer of reinforced concrete, but the texture is certainly light, and the steel plate effect is also stronger than the carbon fiber cloth, but the flexibility is not high. Therefore, for this method, the following requirements shall be met:

When considering the secondary force influence, the lag strain effect of the steel plate shall be determined according to the initial force situation of the component reinforcement. Before reaching the limit state of bending bearing capacity, the external adhesive steel plate cannot be bonded with the concrete stripping damage. After the reinforced concrete structural members are reinforced, the increase range of the positive section bending bearing capacity should not exceed 40%, and the shear bearing capacity should be checked to avoid the shear damage of the members after the bending bearing capacity increases.

4.2.3 The control of the wind vibration

(1) Passive control

The method of resisting dynamic load is developed as the structure's seismic risk control system to control the structure's dynamic response actively. The main idea of passive control is to improve the vibration resistance and comfort of the building by increasing the damping of the structure, improving the ductility of the components and using additional energy dissipation system. For the steel structure, the weight is light and the damping is small, so it is easier to adopt the structural vibration control measures to improve the wind and seismic resistance of the structure [7].

(2) Active control

In recent years, civil engineering has used active control to reduce the motion under environmental loads. More and more attention has been paid to force response. Since the real-time control force of active control can change with the excitation input, the control effect does not depend on the characteristics of external load, so it is obviously better than passive control. Recently, the theoretical research of active structural control takes various control algorithms as the main line, and adopts computational analysis and simulation methods to study the feasibility of structural active control, the delay effect and delay compensation of control system, and the influence of control parameters on the control effect. The adaptive control scheme has the idea of bionics. A new control scheme mimics the adaptive process in nature. The adaptive control scheme has the idea of bionics. A new control scheme mimics the adaptive process in nature. In high-rise buildings, the application and development of adaptive control are mainly parameter estimation adaptive wind-resistant and earthquake-resistant control. Adaptive wind resistance is to automatically adjust and correct the control action of the system online according to the input and output of the whole and observed measured data of the structure by online identification method so as to achieve the purpose of wind resistance. However, it is not feasible to measure the whole state of the structure, so only the structure's first few displacements or velocities are measured in the adaptive anti-risk control system [8-13].

5. Conclusion

This study designs a three-story teaching building located in Dalian to discuss the influence of different wind speeds on the stability of this building and propose some measurements.

The Monte Carlo simulation method can obtain the probability of collapse of the beam. The influence of different wind speeds on stability is discussed, and some measures are proposed. To increase the accuracy of this study, this study used wind condition from level 0 to level 10. And speed of the wind was from 0 to 24.4m/s. Then in this study, 1,000,000 samples are used for Monte Carlo simulation in MATLAB, combined with all the above uncertainties. Using the outcome of the displacement equation compared with the previously calculated limit displacement value, the probability of frame collapse on windy days is 0.399%.

According to the means to increase stability can clear some points:

The construction plan should consider choosing a favorable wind-resistant location and suggest avoiding the wind-resistant unfavorable site, such as wind outlet, mountain pass, and estuary.

A suitable roof can resist heavy wind. Priority choice is four slope roof, cast-in-place reinforced concrete roof, and geometric mutation parts to take local strengthening measures.

The safety factor of the roof wind load design is around 20% to 30%. Resonance is one of the important reasons for the damage to flexible roofs. In typhoon-prone areas, roof structure often occurs. The strong suction caused by the strong wind and its pulsation effect and the wind vibration caused by the flexibility of the roof structure under the wind load power effect often makes the roof suffer damage.

The cross-section reinforcement method is advised. It can not only improve the carrying capacity of the reinforced components, but also increase the cross-section stiffness, change its self-vibration frequency, so that the performance of the normal use stage can be improved to some extent, and can effectively reduce the dynamic wind load effect of the structure.

Externally bonded steel is suggested in the reinforcement method. The increased range of the positive section bending bearing capacity should not exceed 40% and should be checked to avoid shear damage of the members after the bending bearing capacity increase.

The control of the wind vibration has both passive and active aspects. For passive, it is easier to adopt structural vibration control measures to improve the wind and seismic resistance of the structure. For active, only the first few displacements or velocities of the structure are measured in the adaptive anti-risk control system.

References

[1] Hang Cheng. Trend of mean wind speed in Dalian area in recent 40 years. 2019.

[2] Simiu, E. and Scanlan, R.H. Wind effects on structures: fundamentals and applications to design (Vol. 688). New York: John Wiley. 1996.

[3] De Wit, S. and Augenbroe, G. Analysis of uncertainty in building design evaluations and its implications. Energy and buildings, 2002, 34(9), pp.951-958.

[4] Rubinstein, R.Y. and Kroese, D.P., 2016. Simulation and the Monte Carlo method. John Wiley & Sons.

[5] Guo Gang. Study on wind-resistant reinforcement method of building structure. Science&Technology Information [J]. 2008.14.99

[6] Zhang Xiangting. Calculation of wind-resistant and seismic design of high-rise building structure [m]. Tongji University Press, 1997.

[7] Yang Tuanjie. A brief talk on wind-resistant design of high-rise buildings and effective control method of wind-induced vibration [J]. Science and Technology Information, 2012(12)

[8] Fu Jiyang, Wu Jiurong, Xu An. Study on wind-resistant optimum design and wind-induced vibration control of high-rise buildings [J]. Engineering mechanics, 2022, 39(5): 22.

[9] Li Junjie. Analysis of the optimization of wind-resistant design of high-rise building based on wind-induced vibration performance [J]. Building materials development orientation, 2018,16(21): 1.

[10] Wong Mingfung. Optimization of wind-resistant design of high-rise buildings based on wind-induced vibration [J]. Engineering mechanics, 2013,30(2): 8.

[11] Sun Qingli. On Stability Analysis in Building Structure Design[J]. China's new technologies and new products, 2012.

[12] Wang Guoan. Study on the overall stability of high-rise building structures[J]. Building Structures, 2012, 42(06):127-131

[13] Weng Yun. Considering the influence of shear deformation frame and the giant frame stabilization theory [D]. Zhejiang University, 2009.