

Chain Reaction Risk Analysis Under Typhoon Influence

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Abstract. In typhoon weather, the wind-born debris caused by the rupture of the glass curtain wall is the main reason for the large-scale damage to the glass curtain wall. This paper mainly discusses the accurate mathematical model of glass curtain wall damage rate under the probability of a typhoon attack, as well as the potential and expected value of losses caused by the typhoon of a skyscraper in Hong Kong. Results show that the output of the mathematical model is roughly normally distributed around the actual values which can approximately reflect the potential loss of a skyscraper in a strong typhoon. Discussion of the correlation of wind speed and height, the influence of the surrounding low-rise buildings, and the material of glass enhance the applicability of the results. Meanwhile, it is difficult to fully consider the complexity of the surrounding environment, which is the limitation of this study. However, this study can still benefit urban planning, architectural engineering, and insurance companies.

Keywords: Typhoon, Glass Curtain Wall, Wind-Born Debris, Mathematical Model, Risk..

1. Introduction

The southeast coastal areas of China are rich in economy and densely populated with towns, but also suffer from typhoon disasters for a long time. Hong Kong, as a representative of the region, has a maritime subtropical monsoon climate. It is prone to typhoons from July to September, and maybe hit by tropical cyclones of different intensities from May to November. The glass curtain wall is a non-load-bearing building envelope with a certain displacement capacity relative to the main structure. It is a distinctive feature of the era of modernist high-rise buildings. The records of disasters caused by wind show that wind-induced debris is the main reason for the damage to urban glass curtain walls, and other envelope structures.

To estimate the disaster of a typhoon, especially the expected value of the damage caused by wind-born debris, it is necessary to pave a way for evaluating the risk. Numerical and scenario modeling is the main means of evaluating the risk. Scenario modeling could analyze the windborne debris risk of the affected area. Lin and Vanmarcke (2009) used the numerical wind tunnel method to discuss the distribution law of wind-induced internal pressure. They also simulated the motion process of wind-induced debris and analyze impact probability [1]. However, current research about the large-scale damage to the outer glass curtain wall caused by the chain reaction of windborne debris of skyscrapers is insufficient.

This study takes the damage of Revenue Tower after severe tropical storm York as an example, focuses on the damage of glass curtain wall under typhoon attack, uses numerical methods to simulate the real situation, and calculates the expected loss in a typhoon with a certain cost of glass curtain walls. In addition, the practical application of this research is analyzed.

2. Methods

This study firstly collects the data on the probability of a strong typhoon hitting Hong Kong from the Hong Kong Observatory website. Next, a chain-like glass broken model is built by using the built-in function of Excel to calculate the damage rate of the glass curtain wall. Finally, a good foundation for explaining the potential loss and expected loss with the total probability rule is established.

2.1 Data of typhoon

Table 1 shows the average monthly number of tropical cyclone warning signals from 1961 to 2020 issued by the Hong Kong Observatory. According to the wind speed and pressure corresponding to wind level, the probability of typhoons in grades 9 and 10 is used as a reference, which is 0.43 per year. Here is a record when typhoon York landed in Hong Kong, the average wind speed was 21m/s and the Maximum wind speed was 45m/s. The design basic wind pressure in Hong Kong is 0.9kN/m² and the corresponding wind speed is 37.9m/s. After considering the load combination coefficient, it is 53.1m/s, which can meet the wind resistance requirements in the case of a typhoon.

Table. 1. Average monthly number of tropical cyclone warning signals

Month	Grade 1 and above	Grade 3 and above	Grade 8 and above	Grade 9 and 10
Jan.	-	-	-	-
Feb.	-	-	-	-
Mar.	-	-	-	-
Apr.	0.18	0.07	-	-
May.	0.48	0.32	0.08	0.02
Jun.	1.98	0.97	0.20	0.02
Jul.	3.85	2.23	0.60	0.08
Aug.	3.75	1.80	0.67	0.17
Spt.	4.17	2.18	0.62	0.10
Oct.	2.53	1.57	0.22	0.05
Nov.	0.53	0.22	0.03	-
Dec.	0.03	0.03	-	-
Annual value	17.52	9.38	2.42	0.43

2.2 A chain-like glass broken model

This study chose the severe tropical Storm York and a building called Revenue Tower whose glass curtain wall suffered severe damage under the typhoon as an example.

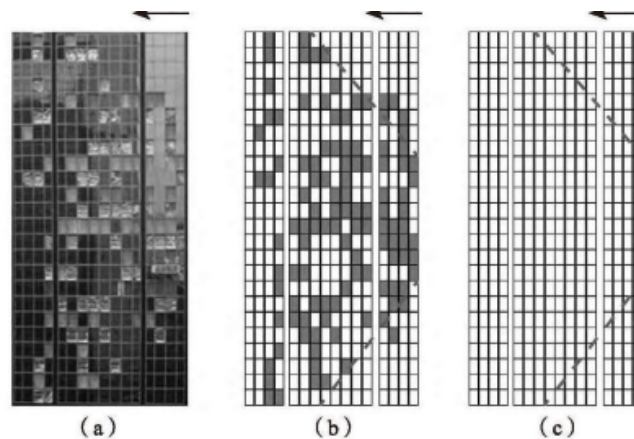


Figure 2. Failure analysis of partial glass curtain wall in East façade [3]

According to the results of typhoon damage to the glass curtain wall of Revenue Tower, it shows that the broken glass is in a trapezoidal pattern. The fragments spread downwind and caused damage to the downwind glass curtain wall after there are first five windows broken for uncertain reasons. There is great uncertainty and randomness in the whole process.

Considering the spread of debris, it is assumed that the damage to any one glass curtain wall will affect the three adjacent glass curtain walls downwind. When the sum of the damage indexes of the three windward glasses reaches the threshold, the glass they act on together has the possibility of breaking (Figure 3).

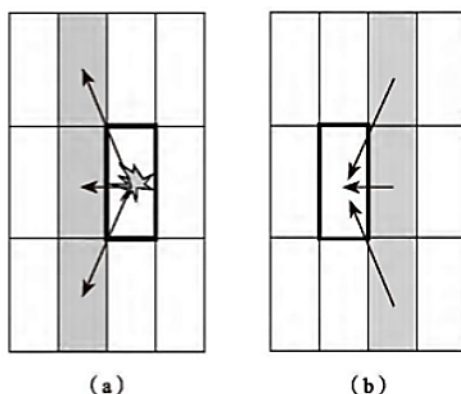


Figure 3. Schematic diagram of the chain-like glass broken model

The damage situation of the glass curtain wall is simulated through Excel build-in program, and the damage process at that time can be restored as follows by using the process.

$$P_{ij} = P_{i-1j-1} + P_{ij-1} + P_{i+1j-1} \rightarrow P_{ij} \in [0,100] \begin{cases} \text{If } P_{ij} \geq 50, \text{ then } P_{ij,adj} = \text{random}(0,100) \\ \text{If } P_{ij} \leq 50, \text{ then } P_{ij,adj} = 0 \end{cases} \quad (1)$$

Reproduce the original mathematical model of glass failure, and the construction process includes 4 steps:

- (1) Choose the first 5 broken windows and incept different numbers;
- (2) Insert logical statements into each remaining column. let all blocks calculate the sum of three adjacent grids on the right;
- (3) Calculate the sum of each number at the bottom;
- (4) Let the sum of broken windows be divided by the total number to get the percentage of failure windows.

2.3 Cost of glass replacement

In this stage, the cost of replacing a glass curtain wall is considered for dealing with expected loss. Table 2 shows the relevant price parameters of the single glass. It is noted that since all staff have been forced to stop work before the typhoon and the cleaning task undertaken by the health bureau is not considered, personnel compensation and environmental cleaning costs are not considered in this study.

Table. 2. Price parameters of the single glass

Serial number	Engineering project	Specification	Quantity	Units	Quantities	Total cost comprehensive unit price (CNY)	The composition of the comprehensive unit price of the total cost					sum (CNY)
							Cost of labor	main material fee	Vice materials fee	administration, measure and profit fee (10%)	taxes (3%)	
1	HS6+1.14PVB+HS6 (LOW-E) +12A+TP6 Single silver hollow Laminated glass+HS6+1.14PVB +HS6Coated laminated glass	2625*1515	1.00	m ²	3.98	2022.96	1140.90	551.43	93.16	178.55	58.92	8045.07
2	HS6+1.14PVB+HS6 (LOW-E) +12A+TP6 Single silver hollow Laminated glass+HS6+	2625*1480	4.00	m ²	15.54	2023.54	1140.00	551.00	95.00	178.60	58.94	31445.78

	1.14PVB +HS6Coated laminated glass												
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2.4 Fundamental formula

A good foundation is built for explaining the potential loss and expected loss with the total probability rule.

Mathematical expectation equals the sum of the product of the value of the discrete random variable and the probability of the corresponding value of X.

$$E(X) = \sum_{k=1}^n x_k p_k \quad (2)$$

Where $E(X)$ is an expectation; x_k is the value of the discrete random variable; p_k is the probability of the corresponding value of X.

Potential loss $P(L)$ in this study is the product of the expected value and probability of a strong typhoon hitting Hong Kong.

$$P(L) = E(P) \times P(T) \quad (3)$$

Where $P(L)$ is potential loss; $P(T)$ is the probability of a strong typhoon hitting Hong Kong.

The expected loss $E(L)$ is the percentage of potential loss times the cost of changing the single glass curtain window and the expectation.

$$E(L) = \text{Cost} \times P(L) \quad (4)$$

Where Cost is the rough price of replacing a single curtain wall.

3. Result

In Excel, all blocks represent a window on the Revenue Tower, and every red block indicates this glass curtain wall is falling (Figure 4).

N12			=IF(011+012+013>50, RANDBETWEEN(0, 100), 0)												
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1															
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	91	62	36	41	0	0	0	0	0	0	0	0	0	0	0
8	35	49	38	81	83	0	15	44	0	0	0	0	0	0	0
9	55	63	26	97	88	80	11	71	66	0	0	0	0	0	0
10	51	27	60	69	42	48	56	93	85	73	46	0	0	0	0
11	58	79	19	69	41	29	29	25	85	52	33	56	35	48	
12	66	1	64	83	99	37	18	88	81	94	2	52	51	66	100
13	75	1	70	24	94	96	18	75	86	45	48	86	10	68	100
14	42	95	7	21	79	12	71	60	31	10	50	90	52	12	
15	49	33	45	50	15	87	36	33	27	50	21	75	0	54	
16	0	1	58	11	11	27	31	10	97	61	100	59	12	93	100
17	8	13	0	0	32	30	72	87	33	98	81	28	59	1	100
18	23	62	0	0	5	46	11	78	3	34	82	65	5	97	100
19	70	77	58	22	85	53	94	84	76	92	100	59	3	67	
20	50	13	15	95	12	12	89	4	35	55	82	54	54	0	
21	90	84	57	0	4	65	41	48	19	78	73	83	0	0	
22	42	23	46	0	33	32	18	72	100	91	53	0	0	0	
23	49	15	64	89	2	0	16	36	56	35	0	0	0	0	
24	57	71	12	38	30	50	15	65	0	0	0	0	0	0	
25	60	0	22	37	27	100	68	0	0	0	0	0	0	0	

Figure 4. Excel simulation diagram of the hit glass curtain wall

A total of 85 experiments is conducted and each experiment is numbered. The percentage of each glass failure is marked on the scatter chart (Figures 5,6). It can be seen that the data are roughly normally distributed, which proves that the simulation results can reflect the actual damage situation.



Figure 5. Statistics of failure results of glass curtain wall

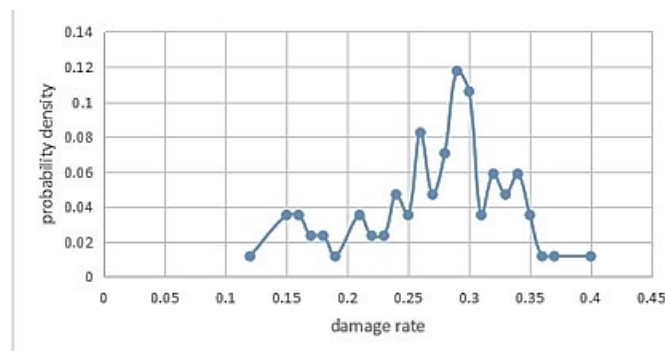


Figure 6. PDF of statistics of failure windows

In order to facilitate calculation, Excel built-in program is used to fit the data, compile the cumulative distribution function and draw a more precise normal distribution graph of glass failure rate (Figure 7).

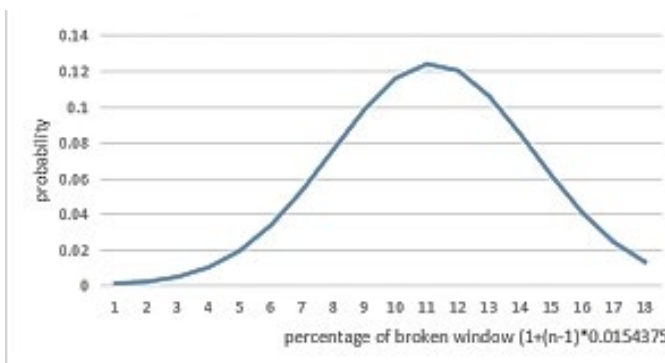


Figure 7. Probability of percentage of broken window

Through analyzing the mechanism of continuous damage induced by secondary debris between glass curtain wall units, and reproducing the continuous damage scenario of glass curtain wall under the action of typhoon through computer simulation. Through the above analysis, it can be seen clearly that the Excel built-in program can simulate the data under typhoon conditions roughly.

After obtaining the approximately normal distribution of glass failure rate, we can calculate the mathematical expectation of glass curtain wall's failure is $E(X)=98.161$, round up to 99. and the probability of expected $E(P)$ is about 27.266596%. The potential loss got from the total probability rule is 0.11724636, the percentage of potential loss of the glass curtain window of the typhoon in a year. Therefore, the final result of the expected loss $E(L)$ is 337,669 CNY.

4. Discussion

4.1 Accuracy and rationality of the model

Figures 5 and 6 show that each failure rate takes the actual failure rate of 28.9% as the center and roughly presents a normal distribution, which proves that the simulation results roughly reflect the real situation. Figure 8 shows the damage to the glass curtain wall during another hurricane that happened in Lake Charles, Louisiana. It is consistent with the study result, which shows that this research has a certain practical scope.



Figure 8. The damage to the glass curtain wall during the hurricane happened in Lake Charles, Louisiana

4.2 Adjustable parameters of the model

To set the model's initial value and enhance the applicability of results, this study can be combined with the study of the variation of wind speed with height. Obtaining the atmospheric boundary layer state according to the Z/L judgment method, aerodynamic parameter and surface roughness coefficient by calculation of measured wind profile under the specific scene, the exponential law gives the correlation of wind speed and height [6].

Taking Hong Kong as an example, the parameters of Revenue Tower and severe tropical storm York, which attacked Hong Kong, have a significant impact on the damage to glass curtain walls. For example, the two parameters of the typhoon, formation/duration, and intensity, magnitude, are the points that need to be considered, because typhoons usually form on the sea surface (such as in the South and North Pacific, North Atlantic, and Indian Ocean) 3-5 latitudes away from the equator in the tropical region. The initial stage is a tropical depression. From the initial low-pressure circulation to the maximum average wind force near the center, it usually takes about 2 days, three or four days slow and only a few hours fast, In the development stage, the typhoon continuously absorbs energy until the central pressure reaches the lowest value and the wind speed reaches the maximum value. After the typhoon lands on the land, it will weaken and disappear rapidly under the joint influence of ground friction and insufficient energy supply. In other words, typhoons are mainly formed in summer rather than winter, and their intensity and destructive power are determined by the actual natural conditions and their subsequent development. In this paper, the frequency of typhoons hitting Hong Kong is determined by the past data statistics, and the average value is found from the data. There are insufficient considerations for extreme cases and problems divorced from reality.

From a branch of the above parameter problem, that is, the wind speed problem and debris problem caused by the typhoon, there is another important factor affecting the total number of damage (XK) to the glass curtain wall around the building - the height of the surrounding floors. The height of the surrounding high-rise buildings is lower than that of the revenue tower, which has withstood the damage to a certain extent. The example that happened in Lake Charles, Louisiana, is another example of a glass curtain wall damaged by debris caused by a hurricane. It can be seen from the figure that the failure mode of its glass curtain wall follows the trapezoidal expansion, but the position of the whole trapezoid shifts downward compared with the revenue tower. It is speculated that the reason for this difference is that the building is close to the coast and surrounded by flat land and a single

bungalow, so the impact of debris is mainly concentrated below; This is slightly different from the example of Hong Kong.

Another important issue is the glass curtain wall. The damaged individual is a certain style of glass curtain wall, and the structural strength of glass curtain walls with different structures (such as frame glass curtain wall and unit curtain wall) is different to some extent; Apart from structural differences, there are also differences in the materials of the glass curtain wall itself. There are obvious differences between tempered glass and safety glass in combating wind-induced flying objects. Considering this difference, it is necessary to properly adjust the damage threshold in the face of different glass curtain walls to facilitate fitting. At the same time, different types of glass curtain walls and different structures require many kinds of maintenance funds. Therefore, it is necessary to adjust the cost required for the replacement of a single glass curtain wall, that is, a parameter in the formula for calculating the potential loss.

4.3 Model limitation

In this study, this paper only considers the influence of the sum of cumulative damage of three glasses in the upwind direction on one glass in the downwind direction, ignoring the influence of wind-born debris not from the Revenue Tower and wind-born internal and external pressure in strong typhoon weather. Variables such as the variation of wind speed with height, damage caused by surrounding debris, the material of glass, and the impact of low-rise buildings on the main building.

Moreover, this paper only uses the total probability rule without other more complex algorithms, which leads to the wide range in the failure rate of glass in this paper, and the accuracy can only roughly reflect the damage to glass curtain walls of skyscrapers.

4.4 Application of model

This article mainly focuses on calculating the possible damage rate of the glass of skyscrapers and the funds needed to repair skyscrapers in southeast coastal cities, mainly in Guangdong. Therefore, the mathematical model and the expected values of damage and compensation described in the article can be used by the holders of skyscrapers to calculate the expected annual loss of glass curtain walls in the case of a strong typhoon. Of course, this can also be used as a reference by insurance companies to determine the claim scope of typhoon-related insurance. This model can also be used by local governments, especially those troubled by typhoons, to provide a basis for part of the expected loss of typhoons, that is, the damage to the glass curtain wall of skyscrapers (as property damage). Urban planning can benefit from this study and architectural engineers can design stronger buildings based on this study as well.

5. Conclusion

This study predicts the expected probability of damage to the glass curtain wall of skyscrapers when there is a chance of typhoons hitting Hong Kong, and the potential loss in a year considering the probability of a strong typhoon hitting Hong Kong.

This study uses the built-in function of Excel to write a mathematical model that can simulate the large-scale damage to the glass curtain wall caused by wind-induced debris during the typhoon, and arrange the experimental values, to know that it is roughly normally distributed around the actual values. Then the full probability formula is used to include the typhoon attack probability, the conditional damage rate of glass within one year, and the expected loss.

The result is that the probability of glass failure rate roughly shows a normal distribution centered on the actual data, which proves that the adopted method has certain feasibility and accuracy. Though there are more variables, in reality, this study shows its reliability through the research of other similar cases.

According to the result, this mathematical model can be applied to estimate the expected loss of continuous failure of the glass curtain wall of the skyscraper, for example, the insurance company

can adopt this model to estimate the potential loss after a typhoon hit a city where their clients have skyscrapers. Meanwhile, based on this study and the local typhoon damage reality, the government can make better urban planning and optimization of high-rise buildings can go further.

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