Typhoon Damage Analysis of Typical Vulnerable Structures

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Abstract. Typhoon, as one of the most devastating natural hazards, has brought billions of property losses and threaten the safety of people around the world, and meanwhile, damage and collapse of various urban structures are the main components of direct losses caused by typhoon. Therefore, the review focus on the introduction on the impact and poster researches about three kinds of typhoon action, external wind pressure, internal wind pressure and wind-borne debris, on the structures at first, and then summarize the failure modes for three kinds of vulnerable structures, including bungalows, light steel industrial buildings and advertisement boards, respectively. Based on the data and field investigations on several severe or super typhoon, the failure modes of those structure start with the places where the elements are lack of potent connection and integrality, such as enclosure members, or the place where the stress concentration appears. This paper is looking forward to giving a assisting the engineers and scientists to improve the typhoon resistance measure or regulate the design of structures to prevent or alleviate the property loss and life security in typhoon in the field of structural analysis. This paper gives the summary on failure mechanism of vulnerable structures, and recommend the reinforcement trend on this field of structures.

Keywords: Typhoon; vulnerable structure; bungalow; light steel structures; advertisement boards.

1. Introduction

Tropical cyclone, as a kind of storm formulating in the tropical and subtropical ocean, mainly appears in the Western Pacific, the Atlantic, the Indian Ocean and Southern Pacific, and when the wind speed of the center of a tropical cyclone surpass 8 level, it would be called a typhoon or hurricane. As the most common area for tropical cyclone, the northwestern Pacific, there are almost 30% tropical cyclones every year around the world, and about 80% of them can reach to the typhoon status. For almost thirty years, typhoons have brought billions of damages and loss of property and threaten large amount of people's life security. Taking Guangdong Province, China as an example, from 1994 to 2018, there had been nearly 216 million population suffering in typhoon and even more than 1200 people died in this natural hazard, and meanwhile, almost 12 million hectares of farmland were affected and about 1 million buildings collapsed resulting from typhoon. According to the data for the annual variation of the number of the damage and loss of property coursed by typhoon between 1994 and 2018, it has an increasing tendency and the number of direct financial loss occupied the 64% of the total loss [1].

Previous researches and reviews on tropical cyclone are focused on the field of meteorology, including the variation of the typhoon structure, the variation of strength and the movement locus. Another discussing point of tropical cyclone is combined with the whole system of city, which mainly emphasis on integral assessment of the hazard brought by tropical hazard. However, the structure as a single building, like bungalow, single-storey workshops and advertisement boards, needs to be discussed and evaluated through different fields, because of their different architectural and structural features. Although there have been a certain number of research of the numerical simulation of various building recently, a thorough discussion on the failure mechanism of different kinds of buildings and discover the generality of damage between different structures is needed.

This paper mainly focuses on two parts, which are the failure mechanism of buildings in typhoon and common damage and analysis for typical vulnerable structures in typhoon. Firstly, the main factors for structure damage of typhoon will be discussed. Secondly, the failure modes and corresponding structural analysis of three typical kinds of buildings, bungalow, light steel industrial building and advertisement boards which are the most unsafe during the typhoon affected period will introduced to assist the engineers and researchers to improve the reinforcement method for vulnerable structures in the future work.

2. The Failure Mechanism of Buildings in Typhoon

After the formulation and landfall of the typhoon, the influence of typhoon on buildings and structures included two sections: one is the direct effect, the both external and internal wind pressure on the structures or buildings; the other is that the wind-borne debris. And according to information on post-hazard field investigation statistics and the features of the devastation of the structures and buildings. The factors for the structure damage can be classified in 4 groups: (i) The average speed of typhoon surpass the wind speed for structural design. (ii) The maximum instantaneous wind speed surpasses the wind speed for structural design, which is the primary cause for the damage happened in building envelopes. (iii) The damage caused by the wind-borne debris. The debris such as sand or stone in building's surrounding area and parts of elements of building envelopes against the gravity and force of friction having high speed with the strong wind are easy to cause the damage of the fragile members of building envelopes such as windows and doors. (iv) The damage caused by the instant increase of the wind-induced internal pressure. It is the most common reason for the collapse of the roof and exterior wall, when the completely enclosed structure became a semi-open structure [2].

Therefore, it is obvious whether the reliability of the buildings in typhoon affected area determined by three factors, external wind pressure, internal wind pressure, wind-borne debris. In this part, the paper will introduce them respectively in following words.

2.1. External Wind Pressure

Although the calculation measure of the external wind pressure on the surfaces of the building under the action of typhoon has common theoretical basis with measure of it under the *National Standard of People's Republic of China* (hereinafter referred in '*Standard*'), there are still some differences between typhoon action and normal wind action as the aim of calculation.

Firstly, for the calculation of the fundamental wind pressure, according to *Standard*, it is a single constant value for a certain city, while it is necessary to use data for time-histories about the wind speed and direction of typhoon because the degree of the structural damage not only depend on the maximum value of the wind speed, also based on the variation of the wind speed. For example, after part of vulnerable structure damaged by local pressure beyond the limit, the internal forced for the rest of elements will redistribute with the variation of the speed and direction of the wind. Therefore, the path and degree of the structural damage are strongly related with wind speed, wind direction and wind pressure distribution coefficient.

Secondly, under the *Standard*, the figure coefficient of wind load is a surface average value, and ignore the differences between the value in different wind direction. Because the wind direction keep changing during the period of typhoon, so researchers mainly applied the tunnel test with the model of structures or use simulation software to identify the distribution of the coefficient and classify the different zones on the surface of structures [2].

According to the data and results from the simulation and tunnel tests, the location of the maximum value of the pressure always is in the place where the geometry of buildings change dramatically, so the principle of the structural damage always start from the place, and then the hole taking place in vulnerable members of the building envelop make the structure became partially unenclosed construction, increasing the probability of the risk for whole building.

2.2. Internal Wind Pressure

Compared with external wind pressure, when building is enclosed structures, the values of internal wind pressure are so small that can be ignored. However, if a door, window or element of building envelopes were broken by the strong wind, the internal wind pressure and pressure difference between internal and external wind pressure would rise abruptly and create potential threaten to the element of the structure. This chapter would focus on the research status and the modes about how the internal wind pressure influence the buildings would describe in 3.1.2.

To simulate and identify the influence on internal wind pressure, from 1970s to 1980s, after the studies and tunnel tests of Stathopoulos, Surry, Holemes and other scientists, specialists identified that the dominant frequency of the internal pressure vibration could be solved by the formula proposed by Helmholz, and with deeply research with the resonance effort of buildings, scientist thought synchronous vibration could be explain by the movement of air drought contained by perforation, in other words, the external pressure of perforation make air drought move inside and compress the air in the building until the intensity of the pressure up to a certain level, which force the air drought goes back. Up to now, the scholars have a consensus on the internal pressure response equation, applying a second-order ordinary differential equation to describe the response of internal pressure on abrupt-disclosed structure [3,4]. After assuming power spectrum of internal pressure would represent large value of resonance if frequency of vortex shedding and Helmholtz were similar, Liu and Rhee studied the effect of the hole size and location on resonance amplitude, not only verify the assumption, also finding the size of the hole has the positive relation with the amplitude of resonance as well as the rule of the power spectrum of internal pressure on laminar flow wind situation [5]. W. Pearce and D.M. Sykes tested the problem of pressure vibration for building having flexible roof with single hole, discovering the frequency of Helmholtz was correlated reciprocally with flexibility causing the increase of air damping. According to the results from tunnel tests, a single hole on the leeward also triggers the resonance of buildings, and has the influence on fatigue loading [6]. B.J. Vickery, C. Bloxham and P.N. Georgiou did the researches about the problem of wind-induced internal pressure dynamic response for structures with opening, and summarize the relation on between the parameter of internal air and openings size of the structures with different size openings as well as the flexibility of roof [7-9]. R.I. Harris did the research on propagation of pulsating internal pressures in buildings with compartments and define the characteristic response time of internal pressure [10]. A.R. Woods and P.A. Blackmore focused on the effect of dominant openings and porosity on internal pressures both steady state or not, but didn't consider the influence on wind direction [11]. J.D. Ginger, C.W. Letchford and other scientists carried out the theoretical analyses, numerical simulation, full scale measurement and tunnel tests of full-scale test building models and low-rise buildings from Wind Engineering Research Field Laboratory, and studied the characteristics of the intensity of the pressure on different geometry and flexibility of the structures [12,13]. R.N. Sharma and P.J. Richards established the theoretical formula about the interaction between external pressure, internal pressure and roof, the researches represent that the flexibility of the roof produce two resonances, and Helmholtz frequency decreases to low frequency where load can energy are concentrated, which is one of reasons for building being damaged in typhoon or hurricane [14].

2.3. Wind-borne Debris

According to the statistical data in post-damage investigations on tropical cyclones, wind-borne debris are one of the most significant reasons for destruction of structural envelopes. For example, many glass curtain walls of super high-rise buildings were destructed by severe tropical storm York, and some glass curtain walls of high-rise building in Hong Kong also was broken by super typhoon Mangkhut. The Fig. 1 has shown the destruction of the glass curtain walls in two storm respectively [15]. Meanwhile, once destruction happened in part of structural envelopes, internal wind pressure would rise intensely, causing failure of rest of elements of structures envelopes and creating more and more debris to make a chain reaction.

(a) (b)

Fig 1. The damage of glass curtain wall of buildings in Hong Kong in 1999 (a) and 2018 (b) [15].

In conclusion, the researches existed for wind-borne debris could classify in two groups, initial flight condition for wind-borne debris and trajectories of wind-borne debris, both of which are involve in the analysis of aerodynamics. About the former, the surveys include the location of the debris sources and the restriction condition of the debris, and the coefficient of aerodynamics for the debris in stationary state could gain by the conventional wind tunnel experiment.

For initial flight condition, the wind-borne debris come from the surrounding environment. Therefore, in order to simplify the calculation, the debris could be classified in four groups based on the area of the building and the number of potential debris and distribution, and each group have a corresponding value of the density of the debris. However, because lack of the statistical investigation, the research only gives the description about classification of the environment. Table 2. has shown the details of classification [16].

Table 2. Classification of wind-borne debris sources environment [16].

Group	Description
A	CBD, with high building density and dominated by high-rise building with glass curtain walls
B	Urban area, with relatively high building density and dominated by multi-storey residence.
C	Residential suburb, dominated by masonry residential structures and with relatively more trees.
D	Industrial suburb, dominated by industrial building and open area with a bit of trees.

For the calculation of the trajectories of the debris, Wills and other scientists classified the debris into three groups, compact, plate-like and rod-like, which makes scientists using different parameter of geometry to describe the different kinds of wind-borne debris. Based on the geometry of the debris, Wills and other scientists studied the initial take-off condition, they defined new parameters I to represent the degree of fixation of debris, and obtain the formula to calculate the critical value of the wind speed to take off (equation (1)) [17].

$$U^2 = \frac{2\rho_m hgI}{\rho_a C_F} \tag{1}$$

And then, they studied the initial take-off condition for wind-borne debris in the shape of cubes-like and plate-like by tunnel tests, obtaining the conclusion that the line relation between critical value of the wind speed to take off U and parameters of characteristics of the debris $\sqrt{\frac{2\rho_m hg}{\rho_a}}$, and the slope is $\sqrt{\frac{I}{C_F}}$,which is a constant of the debris. Wang and Letchford proved the models in Wills article in different wind tunnels when they studied the debris characteristic of rectangle slabs [18]. And because from the research of Holmes the flight time of wind-borne debris is about 1-2 seconds [19], the value of wind speed during that period could be regard as a constant value. Therefore, the critical value of wind speed could be utilized to calculate the trajectories of the debris if the geometry, material and condition of fixation is clear. However, considering the complexity of initial condition, it is more reliable to use the initial wind speed as the impact velocity of the debris to design the buildings or structures.

In addition, about the field of trajectories, based on different assumption on aerodynamics in different degrees of complexity, there are a series of models to describe the trajectories of wind-borne debris. McDonald etc., Lee, Simiu and Cordes, Redmann et al., Twisdale and other scholars started to establish from a simple model which only considered the resistance effect of spherical debris to a 6-dimensional trajectory model that comprehensively considers lift, drag, lateral force, pitch moment, rolling moment and deflection moment coefficients [16]. And then Tachikawa was the first scholar combined the simulation with tunnel tests to study the trajectories of plate-like shape wind-borne debris and proposed the function expressions whose independent variables are all angle velocity to represent the coefficient of drag, lift force and pitch moment [20]. After that, Tachikawa also calculated the 2-dimension trajectory of rob-like and board-like debris in the situation that the coefficient of drag and lift are constant values [21]. Utilizing coefficient of average drag in flight period, Holmes calculate the trajectory of compact debris and study the influence on vertical air resistance and small range turbulence, and also calculate the trajectory of rectangle board-like debris with the usage of quasi-stable state assumption and the coefficient of drag, lift, and pitch moment regarded as the function about striking angle of incidence [22]. Baker propose dimensionless numerical solution of the trajectory of debris in compact, plate-like and rod-like respectively, and Fu A. generalized the aerodynamic equation of the plate-like debris to three dimension space, proposing the six degrees of freedom model for plate-like debris in three dimensional space based on Euler equation and utilizing quartarnion to describe the rotation of flying plate-like debris to solve the problem of locking rotation angle matrix in Euler equation [23, 24].

3. Failure modes and analysis of damage for vulnerable structures in typhoon

The devastation and losses for cities hit by typhoon has strong relation with building damage. According to field investigation on Severe Typhoon Hagupit (No.0814) by Song, researcher focuses on the structures on Maoming and Zhanjiang Cities, which were two of the worst cities affected by the typhoon, finding that most of devastation concentrated on architectures such as bungalows and adobes in civil architectures and light steel industrial building and wood or bamboo frames in industrial architectures, as well as structures such as outdoor advertisement boards, telegraph poles, scaffolds and enclosures. In this part, the article would divide to three parts, including civil architectures, industrial architectures and advertisement boards, to describe the failure modes and analysis of typhoon damage for three kinds of structures with typical architectures respectively.

3.1. Civil architectures

3.1.1. Failure modes of civil architectures

According the field investigation on Super Typhoon Saomai(No.0608) and Severe Typhoon Hagupit (No.0814), in the field of civil architectures, although most of civil buildings are multistory masonry buildings and some other more stable buildings in recent year, there are still some single story masonry buildings and adobes which are vulnerable to damage by strong winds. For single story masonry buildings, the failure mostly happened from the vulnerable element on the roof, including eave, ridge, corner of roof and etc, while the masonry walls are seldom damaged. The damaging situations are shown in Fig. 2. For adobes, because of the invasion from the environment, the capacity of various elements is decreased, causing the collapse of buildings. The damaging situations are shown in Fig. 3 [25, 26].

Fig 2. The damaging situation of single storey masonry building [25].

Fig 3. The damaging situation of adobe [25].

3.1.2. Analysis of damage

From failure modes of vulnerable building, it is obvious that one of the crucial reasons for damage is blamed on the low value of structural stiffness and unreasonable structural design of the structure. Based on the structure of low-rise buildings and taking gable roof as an instance, when typhoon passed over, vortex effect would appear in surrounding the houses and on the roof respectively. It is shown on Fig. 4. After windward side carrying the vortex action of typhoon directly, the wall on this side would carry the wind pressure, which makes great vibration on whole house, and then, the air strikes the eaves from underside and generates upper suction of the wind vortex along the eaves of the house, meanwhile, along the both sides and leeward of the house are also subjected to the outward suction of the wind suction vortex. If the house is sealed, the compressive stress or suction could be resisted by the whole house. However, if the windward or leeward wall of the house were opened or the door and windows are broken by the airflow into the hole, the stress state of each part of the house will immediately produce significant changes that the roof of the house, the two sides and the back wall have been consistent with the same direction of building exterior surface wind suction can be superposition of thrust, Because of the hole house suddenly increase foreign strong airflow. And in this situation, the thrust with high value and various directions would strengthen and accelerate the process of the destruction of entire house. The stress direction on all situation are shown on Fig. 5 [27].

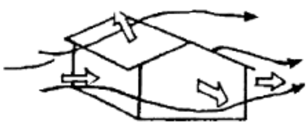


Fig 4. The stress condition of house in free stream air flow [27].

(a) **(b)** **(c)**

Fig 5. The stress condition of house in different situation.
(a)enclosure, hole opened in the (b)windward and (c)leeward [27].

3.2. Industrial architectures

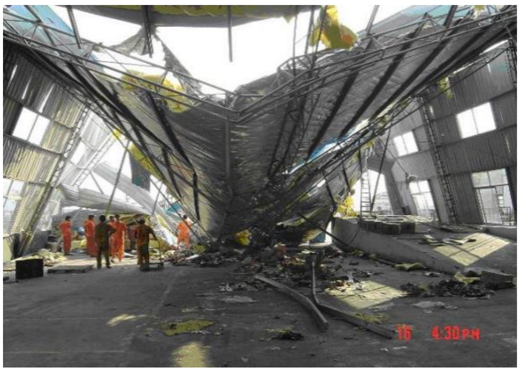
3.2.1. Failure modes of industrial architectures

Costal cities as one of the most significant engines of economics in China, especially in Guangdong, Zhejiang, Fujian Province, there are large number of industrial architectures in various industries. And because of some outstanding features of light steel industrial buildings, such as standardization produce, quick construction, low steel consumption and good protection of environment, it has been widely using in SMEs. However, those provinces also the worst area hit by typhoon in China, the destruction of light steel industrial buildings have brought severe damage on loss of property. Therefore, this part will focus on the analysis of typhoon damage in light steel industrial buildings [2].

Summarizing the damage action of the light steel industrial buildings on field investigations, there are classified in four groups: (i) Main body in good condition, but the enclosure of roof and walls are damaged partially, shown in Fig. 6a. (ii) Main body in good condition, but the enclosure of roof and wall are damage in large area and even blown off, shown in Fig. 6b. (iii) Whole roof structures were broken, including roof truss, shown in Fig. 6c. (iv) Whole industrial structures are collapsed, shown in Fig. 6d.

(a)

(b)



(c)

(d)

Fig 6. The different modes of light steel industrial buildings [2].

3.2.2. Analysis of damage

The main reason for damages of the structures are two parts, typhoon action and bearing capacity of structures. For typhoon action, because of the extensive value of fluctuating wind and abrupt change of geometry of structures, causing the value of fluctuating wind pressure surpass the value of design so that the enclosure of roof damage first, and then the new generation of the debris surrounding the building and the instant increasing internal pressure continue damaging the structures. For bearing capacity of structures, most of connection method between steel sheets used in enclosure structures in roof and walls belongs to lap type, resulting the low connection strength between each steel sheets or steel sheets and purlines, where it is easy be damage by wind. In addition, the simple lightweight steel workshops also collapse in severe typhoon blame on the low capacity to resist lateral wind loads.

3.3. Advertisement boards

Both in metropolis and rural area, there are still some vulnerable structures expecting the buildings, such as outdoor advertising boards, street lamps, telegraph poles and etc, which causing large part of debris potential to make secondary disaster in typhoon affected area, especially for advertisement boards. Therefore, in this part, the paper will focus on the failure modes of advertisement boards and conclude the most common reason for damage in typhoon.

3.3.1. Failure modes of advertisement boards

Based on investigation on Super Typhoon Hato(No.1713), for advertisement boards, the investigators conclude the main destruction form and features: (i) Curtain and iron sheet covering on advertisement boards layer fell off, as big part of components of wind-borne debris, shown in Fig. 7a. (ii) Part of the board panel purlins were damage, but beams and columns were intact; (iii) The beams and purlins of the panel were seriously deformed or broken, but the columns were intact, shown in Fig. 7b. (iv) The column was broken at the weld joint, but the connection with the foundation was intact, shown in Fig. 7c. (v) The independent billboard column was damaged at the foundation, and the whole structure was seriously tilted or overturned, shown in Fig. 7d [29].

(a)

(b)

(c)

(d)

Fig 7. The different failure modes of advertisement boards [29].

3.3.2. Analysis of damage

After doing researches on the investigation on Typhoon Zuri (No.0812) and Hagubi (No.0814), Song concluded the main reasons: (i) Curtain or iron sheet and other covering layer and panel steel structure connections are simple and crude, and connection strength is also insufficient. (ii) The type and geometry of the panel and support structure steel members are too small, and the strength is not enough to resist the wind load. (iii) The steel members are seriously corroded, so the strength is greatly weakened, appearing many weak parts in crucial location. (iv) Most of advertisement boards have not undergone formal wind resistance design. (v) Quality cannot be guaranteed, having problem like poor processing quality and lack of effective supervision [28].

And based on structural characteristics of advertising board, the problem on wind-induced internal pressure doesn’t exist. Therefore, the composition and vulnerable position of the advertisement boards concentrate on the place which is lack of connection, like curtain layer or the elements with unsteadiness, low stiffness and stress on concentration, like panel frame or joints between board and foundation.

4. Summary

Typhoon, as one of the most devastating natural hazards, has brought billions of property loss and threaten the safety of people, most of which also blamed on the vulnerable structures, including bungalow, light steel industrial buildings and advertisement board. The paper has introduced the failure mechanism of building in typhoon action, and discussed the impact and research status of external wind pressure, internal wind pressure and wind-borne debris on vulnerable building, and then, concluded the failure mechanism for three kinds of structures. For bungalow and light steel buildings, a large portion of damages were roof damage, which mostly are resulted from instant increasing internal wind pressure and low connection strength between elements. For advertisement boards, the vulnerable part also appeared in the place, where the elements connection strength keeps low level. Therefore, reinforcing the joint strength and the element which occurs stress concentration is one of the most efficient and effective measure to reduce the damage of vulnerable structures. However, there are still lack of researches on typhoon resistance measure or regulation focusing on these kinds of buildings. In the future, it is necessary to do the further research in the field of typhoon resistance to regulate the typhoon resistance design of vulnerable structures, bungalow, light steel structures, advertisement boards and so on. This paper gives the summary on failure mechanism of vulnerable structures, and recommend the reinforcement trend on this field of structures.

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