Post-Disaster Survey and Analysis of Glass Curtain Wall under Influence of Super Typhoon “Meranti”

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Abstract. Typhoon “Meranti” made landfall in the city of Xiamen in Fujian province with the maximum wind speed 60 m/s in the center of the typhoon. It caused large economic losses in Xiamen with the severe damages in the glass curtain walls of high-rise buildings. Survey of damaged glass curtain walls was conducted right after the typhoon, including damage amount, damage type and damage level of glass curtain walls. Experimental structural experiments and numerical simulations of wind environment were performed to investigate the failure patterns of glass curtain walls. The causes of damage are analyzed with respect to design criterion, construction, and material. Finally, improvements on the criterion of glass curtain wall design, optimization of wind environment and construction method are proposed to reduce typhoon damage effectively in future.

Keywords: Glass Curtain Wall, Typhoon Disaster, Damage, Wind Pressure.

1. Introduction
Super typhoon Meranti landed Xiamen on 15 September in 2016. It is one of the strongest typhoons in the meteorological records [1], with the maximum instantaneous wind speed of 64.2 m/s recorded on Wuyuan Bridge in Xiamen, the lowest pressure of 915 hPa at the center, 120-180 km radius of wind speed of 25m/s, and 80-100km radius of wind speed of 35 m/s. The Nephogram and landing path can be seen in the Figure 1 and Figure 2, respectively. The maximum wind speed in Xiang-an district of Xiamen was 48 m/s for about two hours starting at 3:05am [2]. The gust wind was as high as 60 m/s in Wuyuan Bay and Xinlin Bay, 50 m/s in nearby urban area. The maximum 2-minute average wind speed reached 32.8m/s, while the maximum 10-minute average wind speed was 31.8 m/s (Figure 3). Figure 4 was taken after Meranti passed the area. The damage of Meranti in Xiamen was more than 1 billion RMB [2]. A recent assessment report showed that 7.04 million people from 79 counties in Fujian province were affected by “Meranti”.

As a prosperous coastal city in south east of China, Xiamen has numerous high-rise and super high-rise buildings. Glass curtain walls are the main envelope structure type for most high-rise buildings. This paper first presents the post-Meranti survey of glass curtain walls in Xiamen, then shows the results of experiments, simulations and numerical modeling of survey results, and finally provides some suggestions to improve the wind-resistance of glass curtain walls in Xiamen.
2. Outline of Survey of Glass Curtain Walls in Xiamen

2.1. Overview of Glass Curtain Walls in Xiamen

As a symbol of modern architecture, glass curtain walls have attracted a lot of attentions from architects. In Xiamen, glass curtain walls account for about 70 percent of 3,500,000 m² curtain structures, moreover, their usage in high-rise buildings is in increasing trend. Unfortunately, glass curtain walls are prone to be damaged by typhoons due to their elasticity, brittleness and viscoelasticity. Supported by Xiamen Municipal Construction Bureau, the post-disaster survey started 6 days after Meranti landed, was primarily focused on glass curtain walls in Xiamen. A team of 30 people from Xiamen University of Technology was divided into four groups and surveyed administrative areas in Xiamen comprehensively (Figure 5). The survey results are analyzed in the following sections.
2.2. Survey Results of Glass Curtain Wall in Xiamen

To obtain a comprehensive understanding of the influence of super typhoon “Meranti” on Xiamen, the survey was conducted in all four administrative regions. About 4,000 m² glass curtain walls were destroyed, mostly in Wuyuan Bay and Xinglin Bay where the typhoon vortex was. Even though main structure of curtain walls was rarely damaged, the failure of glasses occurred in some areas, such as Tefang Portman Fortune Center, Xiamen First Square, and Xiamen Exhibition Center. In the typhoon vortex area, Wuyuan Bay and Xinglin Bay, a large number of glass curtain walls were destroyed as indicated in the figure 6b and figure 7b. Table 1 lists selected typical survey results of failure types and area of damaged glasses. It shows that shedding of open fan and large wind pressure are the main failure types of glass curtain walls. Almost 50% damage of open pan was caused by mismatch of the lock and hardware accessories. The analyses of these failures are presented in the following sections.

Table 1. Selected Typical Survey results of glass curtain wall in Xiamen under influence of super typhoon “Meranti”.

| Project                   | Completed time | Type of Main structure | Area of glass curtain wall (m²) | Area of damaged glass curtain wall (m²) | Failure type                                                                 | Failure condition of whole structures |
|---------------------------|----------------|------------------------|---------------------------------|----------------------------------------|-------------------------------------------------------------------------------|---------------------------------------|
| Jinyuan Building          | 1995           | Frame                  | 32690                           | 3                                      | Damage by impact of shedding open fan; Damage by impact of shedding open fan; Most damage are external glass with granular debris; higher floor suffer more damage; deformation and shedding of open fan | √                                     |
| Yujing Yuan               | 2000           | Frame                  | 3000                            | 70                                     | Most damage of open pan; Damage of open fan.                                   | ★                                     |
| Huli Building             | 2009           | Frame                  | 31028                           | 500                                    | Most damage are external glass with granular debris; higher floor suffer more damage; deformation and shedding of open fan. Serious damage of east of #1 and north of #2. | ★★                                    |
| Tongan commercial building| 2009           | Frame                  | 40000                           | 2000                                   | 80% of northern glass curtain wall was damaged.                               | ★★★                                   |
| Xiamen Software center III| In construction| Frame                  | 30000                           | 900                                     |                                                                               | ★★                                    |
3. Analyses of Survey Results

In this section, the failure types of the survey results, the causes of glass curtain walls damages were analyzed from various perspectives including experiments, simulation and numerical calculations.

3.1. Wind Pressure Test and Analysis of Glass Curtain Walls

Wind pressure resistance performance of a curtain wall is the pressure that induces acceptable deformation without failures in the structure, and failures occur when wind pressure is higher. Wind resistance performance level is classified by the pressure difference $P_3$ under which the deflection of the relative surface normal reaches to allowed deflection. Table lists the Chinese standard classifications [3] of wind pressure performance of architecture curtain wall.

| Grading No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Grading index ($P_3$/kPa) | 1.0 $\leq P_3 < 1.5$ | 1.5 $\leq P_3 < 2.0$ | 2.0 $\leq P_3 < 2.5$ | 2.5 $\leq P_3 < 3.0$ | 3.0 $\leq P_3 < 3.5$ | 3.5 $\leq P_3 < 4.0$ | 4.0 $\leq P_3 < 4.5$ | 4.5 $\leq P_3 < 5.0$ | $P_3 \geq 5.0$ |

To test the wind pressure performance grading in Xiamen, wind pressure experiments were conducted in Xiamen Engineering Test Center accredited by China Metrology. To simulate the glass curtain wall damaged by the typhoon, a glass curtain wall specimen with three columns and a modular was selected as a testing sample. Its external size is 2541 mm by 4950 mm. A 6-support linkage window lock is on the open fan. Bearing span is 4150 mm. The column thickness is 3.0 mm and the beam thickness 25 mm. The arrangement of test points is shown in Figure 6.
The physical performance of curtain wall testing equipment JN-MQ2120 was utilized in this experiment with tested wind pressure range ±20 kPa, displacement measurement 0-100 mm, range of plan deformation ±100 mm. Four digital displacement sensors KJCS-50/TP64 were used for wind pressure testing. The test range and tolerance of the sensors are 50 mm and 0.1%, respectively. Deformations and displacements of all the points under different wind loads were obtained from the tests (Table 3. and Table 4.). According to Chinese Code GB/T 21086-2007 [4], the test sample is of wind pressure performance grading 8 (Table 2) with wind load standard value of 4620 Pa. Table 5. and Table 6. show the displacements when the wind load is 4620 Pa and figure 9 provides an overview of the relationship between middle displacement and wind pressure.

**Table 3.** Horizontal lever deformation of test points.

| Test items   | Theoretical calculation (Pa) | Test (Pa) | Residual deformation of test points (mm) | Residual deformation of middle point (mm) | Failure phenomenon |
|--------------|------------------------------|-----------|-----------------------------------------|------------------------------------------|--------------------|
| Cyclic load  | 11754 ± 2760                 | -0.39     | -0.98                                   | -1.21                                    | -0.18              | No                 |
| Safety test  | 19590 ± 4602                 | -0.28     | -0.19                                   | -0.06                                    | -0.02              | No                 |

**Table 4.** Horizontal lever displacement of test points.

| Wind load standard value (Pa) | Displacement of test points (mm) | Deflection of middle point (mm) |
|-------------------------------|-----------------------------------|---------------------------------|
| 4602                          | Point X: 5.25, Point Y: 17.14     | 24.18                           |
| -4602                         | Point X: -5.99, Point Y: -18.59   | 25.36                           |

**Table 5.** Vertical lever deformation of test points.

| Test items | Theoretical calculation (Pa) | Test (Pa) | Residual deformation of test points (mm) | Residual deformation of middle point (mm) | Failure phenomenon |
|------------|------------------------------|-----------|-----------------------------------------|------------------------------------------|--------------------|
| Cyclic load| 11754 ± 2760                 | -1.14     | -1.79                                   | -0.88                                    | No                 |
| Safety test| 19590 ± 4602                 | -0.43     | -0.85                                   | -0.16                                    | -0.56              | No                 |
Table 6. Vertical lever displacement of test points.

| Wind load standard value (Pa) | Displacement of test points (mm) | Deflection of middle point (mm) |
|-----------------------------|---------------------------------|-------------------------------|
| 4602                        | 20.32                           | 11.47                         |
| -4602                       | -20.58                          | -10.46                        |

Figure 7 and Figure 8 show that the deflections of middle point of both horizontal lever and vertical lever rise with the increase of wind pressure. During the test, when the wind load reaches -6286 Pa, structure failures (lock points slip and glass broken) occur. Based on the experiments, the maximum wind speed 64.2 m/s of Meranti would correspond to a wind pressure of -8000 - 6600 Pa on the surface of structures. It suggests that the design criterion of open fan is of importance in the improvement of local regulations.

3.2. Wind Environment Simulation

Strong wind is an important factor in designing high-rise building in typhoon prone regions. Intensive urban buildings may change the local wind fields [5-10]. The survey revealed that grouped high-rise buildings suffered the most severe damages from the typhoon. In the section, a group of office buildings was selected to investigate the local wind fields.

3.2.1. Numerical Model

Numerical simulations have been widely used in wind environmental investigations. The commercial software ANSYS/Fluent was applied to model the buildings of Xinglin Bay commercial center (Figure 11, #12 in Table 1) and their structural model (Figure 12). The height of building #1-#6 is 110 m (27 stories), 118 m (29 stories), 110 m (29 stories), 101 m (29 stories), 80 m (20 stories), and 82 m (20 stories), respectively. Both recorded instant wind speed of 55 m/s during Meranti, and projected wind speed of 39.87 m/s in the area by the Wind Pressure Regulation of Building Structure in Fujian Province [11] were used to simulate the local wind fields. Five different wind angles (-45°, 0°, 45°, 90°, 135°) for those two wind speeds resulted 10 simulation conditions in ANSYS, as listed in Table 7.
To obtain accurate turbulent wind fields around the buildings, the Reynolds Averaged Navier-Stokes equation (RANS) was used with the assumption of incompressible wind flow. The Reynolds averaged continuity and momentum equations are:

\[
\frac{\partial \bar{u}_i}{\partial x_j} = 0, \quad \frac{\partial \bar{u}_j}{\partial x_i} = -\frac{1}{p} \frac{\partial p}{\partial x_i} + \frac{\mu}{p} \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} (\bar{u}_i u_j)
\]

where \( \bar{u}_i \) is the time averaged velocity, \( \bar{p} \) is the time averaged pressure, \( \mu \) is the air dynamic viscosity, \(-\bar{u}_i u_j\) is the Reynolds stress, \( x_i \) is the space coordinate \((x, y, z)\), \( i \) and \( j \) are positive coordinates. Compared to standard \( k-\varepsilon \) turbulence model has a better performance towards the flow around the building [12].

3.2.2. Boundary Condition
Software ICEM CFD was applied to modeling and meshing the full-scale model of the building group. Speed entrance boundary was applied in windward surface during calculation and the wind speed distribution at entrance was obtained by UDF. With the assumption that wind fields can be fully extended in the area, the regional export boundary was treated as pressure-out boundary. The ground and building surface was a non-slip wall boundary with the effects of the boundary layer, and the side and the upper part of the building was assumed to be symmetrical boundary. Based on the Regulations, class A surface roughness [13,14] was used to obtain wind profile with:

\[
u = u_{10} \left( \frac{z}{z_{10}} \right) ^{\alpha}
\]
where \( \alpha \) is the ground roughness (\( \alpha = 0.12 \) for class A surface), \( u_{10} \) is the wind speed at 10 m, \( z_{10} \) indicates height of 10 m, \( z \) is height. And the turbulence intensity profile of approaching flow was calculated by:

\[
I_a = 0.1 \left( \frac{z}{z_{10}} \right)^\alpha
\]

(3)

### 3.2.3. CFD Solution Settings

The equations are solved by pressure-based solver using a finite control volume discretization method. A semi-implicit method for pressure-linked equation consistent (SIMPLEC) was applied for velocity-pressure coupling. Standard pressure interpolation is used. Convergence is obtained when all scaled residuals have leveled off. To compare with the survey results, qualitative results of local wind fields and wind pressure distributions of the building surface are shown in Figure 11-Figure 21. Wind speed vector of condition.

Wind speed vector (Height :50m) | Wind pressure distribution
---|---

**Figure 11.** Simulation result of condition 1.

Wind speed vector (Height :50m) | Wind pressure distribution
---|---

**Figure 12.** Simulation result of condition 2.
Wind speed vector (Height: 50m) \hspace{0.5cm} Wind pressure distribution

**Figure 13.** Simulation result of condition 3.

Wind speed vector (Height: 50m) \hspace{0.5cm} Wind pressure distribution

**Figure 14.** Simulation result of condition 4.

Wind speed vector (Height: 50m) \hspace{0.5cm} Wind pressure distribution

**Figure 15.** Simulation result of condition 5.
Figure 16. Simulation result of condition 6.

Figure 17. Simulation result of condition 7.

Figure 18. Simulation result of condition 8.
Wind speed vector (Height :50m)  Wind pressure distribution

Figure 19. Simulation result of condition 9.

Wind speed vector (Height :50m)  Wind pressure distribution

Figure 20. Simulation result of condition 10.

Wind speed vector (Height :10m)  Wind speed vector (Height :100m)

Figure 21. Wind speed vector of condition 4.

It can be seen in Figure 11-Figure 21. Wind speed vector of condition , wind pressure distribution was influenced by wind attack angles. When the wind attack angle is at -45°, the wind pressure on the south of #2 and #3 building is high. When the wind attack angle is at 0°, the wind pressure on the south-east of #3 and #6 building is high. Using the positive wind pressure as the base for wind load calculation, the maximum wind pressure on each building for five wind attack angles and two wind speeds is tabulated in table 8. The simulation shows that majority of positive pressure is within bearing capacity of glasses tested by the experiment in section 3.1. Comparing the two different wind speeds,
in some conditions, such as the wind attack at 0°, large difference between wind pressures from the simulation and the experiment can be found in #2 and #3 buildings, which agrees with the survey results. Figure 16 and figure 21 shows the wind speed vectors of 10 m, 50 m, 100 m of condition 4. It can be concluded that the size of the wind vortex decreases with the rise of structural height. With the increase of height, the vortex was progressively developed from concentrated to disperse until homogeneous. (The heights of the simulated building are different, therefore at the height of 100m, there are only 4 buildings’ wind speed vector as shown in the figure 21.)

**Table 8.** Maximum wind pressure on buildings with different wind attack angles (Pa).

| Wind attack angle | Wind speed (m/s) | Building  |
|------------------|-----------------|-----------|
|                  | No.1            | No.2      | No.3      | No.4      | No.5      | No.6      |
| -45°             | 2421.93         | 2330.45   | 3449.05   | 4051.25   | 2865.14   | 3758.98   |
| 0°               | 1052.63         | 4048.88   | 4194.4    | 994.76    | 2620.99   | 3020.09   |
| 45°              | 75.58           | 1402.14   | 2108.42   | 3243.94   | 2944.82   | 3061.15   |
| 90°              | 1824.02         | 3232.64   | 3826.64   | 3699.23   | 449.24    | 3286.12   |
| 135°             | 3953.04         | 610.4     | 4456.76   | 4008.61   | 833.23    | 3008.07   |
| -45°             | 1963.06         | 2153.4    | 1960.88   | 2413.85   | 1029.15   | 1957.82   |
| 0°               | 1221.79         | 1845      | 1132.52   | 1481.01   | 832.48    | 1571.56   |
| 45°              | 2004.96         | 1367.25   | 2028.66   | 2228.79   | 2011      | 2028.66   |
| 90°              | 1686.02         | 2127.8    | 1671.19   | 203.64    | 1949.27   | 233.204   |
| 135°             | 2049.5          | 1114.59   | 680.26    | 1312.37   | 2134.54   | 1605.62   |

The large difference of wind pressures between projected wind speed and recorded wind speed was only found in some situations. From the survey, the authors noticed that negative wind pressure played a significant role in the failure of structures. The peak values of negative pressure are more significant than those of positive pressure in most nephograms (Figure 13-20). Some of them are beyond the ultimate value of -6286 Pa obtained from tests presented in the section 3.2. Numerous glasses were damaged due to negative pressure, especially, the damage of south-north of #2 building and south-west of #6 building, which agrees well with the simulations for wind attack angle 0° and 45°. Moreover, “narrow tube effect” may occur due to the arrangement of buildings. For example, north-east of #1 building and south-west of #4 building may form narrow tube due to their close locations and orientation, which may contribute to negative wind pressure. Severe damages of glass curtain wall occurred in #1 building and #4 building, with 55 and 24 pieces of glasses broken respectively, conforming well to simulation results. The authors believe that the wind environment simulation is an important tool and should be used more during the design stage of buildings to avoid the wind disaster caused by improper layout of buildings.

The planning and layout of the buildings affect the wind environment of the building structures, which also plays a macroscopic role in the wind safety performance of the glass curtain wall. As indicated in the Table 8, in a building group, the building with the highest maximum wind pressure varies with the wind attack angle. "Narrow tube effect", negative pressure damages, unfavorable diversions and other damages caused by adverse wind environment were observed frequently in the survey. Therefore, the optimization of wind environment should be pay more attentions in the planning stage to reduce the risk of adverse wind fields. Glass curtain wall should follow the actual wind field parameter for building surfaces to be cost effective and ensure structural design of wind resistance performance.
4. Conclusions
A post-disaster survey of glass curtain walls in Xiamen was conducted after the super typhoon “Meranti”. Based on the analyses, the experimental tests and numerical simulations of the survey, the following conclusions can be obtained:

1) Regional wind environment plays a significant part on the wind pressure of buildings. The optimization and adjustment of the local winds should be emphasized at the planning stage of buildings, and the wind parameter should be selected based on local climate records.

2) Wind pressure on buildings is heterogeneous, therefore, the wind load on building should be chosen by subarea.

3) Experiment result shows that the glass curtain fails when wind pressure reach to 6286Pa, which is much lower than the maximum observed wind pressure in this typhoon. As a consequence, the improvement of designed standard wind load is highly recommended in Xiamen area.

4) Almost 50% damage of open fan was caused by mismatch of the lock and hardware accessories. The wind resistance of open fan may be designed independently.

5) According to the survey and analysis, in glass curtain wall design, the regional wind environment, wind pressure defaults for different areas, and hardware accessories design should be taken full considerations, to improve the construction and management methods and wind resistance performance of glass curtain walls.

Acknowledgement
This research is supported by the Engineering Project of Zhangjiangwan Bridge and the Connection Line.

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