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Performance of structures and infrastructure facilities during an EF4 Tornado in Yancheng

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Abstract. Heavy damages to properties with attendant losses were frequently caused by tornadoes in recent years. This natural hazard is one of the most destructive wind events that must be fully studied and well understood in order to keep the safety of structures and infrastructure facilities. On June 23, 2016, a severe tornado, which is an Enhanced Fujita (EF) 4 storm, occurred in the rim of a coastal city named as Yancheng in China. Numerous low-rise buildings as well as facilities (e.g., transmission towers) were destroyed or damaged. In this paper, damages to structures and infrastructure facilities by the severe tornado are reviewed. The collapses of residential buildings, industrial structures and other infrastructure facilities are described. With an overview of the damages, various possible mechanisms of the collapse are then discussed and utilized to reveal the initiation of the damage to various facilities. It is hoped that this paper can provide a concise but comprehensive reference for the researchers and engineers to help understand the tornado effects on structures and expose the vulnerabilities that need to be improved in current wind-resistant design practices.

Keywords: tornado; damage; residential buildings; industrial structure; infrastructure facility; mechanism

1. Introduction

Tornado is a rapidly swirling mass of air that extends from a cumulonimbus cloud, often known as a thunderstorm, to the surface of earth. It is often visible as a condensation funnel developed from the base of the thunderstorm with rotating debris and dust (Haan *et al*. 2010). Due to its special physical structure, the tornado is known as one of the most violent and destructive natural disasters that causes tremendous damages to properties with attendant economic losses. Like earthquake, this disaster is prominent for low-occurrence but high-consequence. It always results in severe direct and indirect damages during a single event, and continues to threaten the life safety in many regions (Jauernic and Van Den Broeke 2016, Masoomi and van de Lindt 2016). Hence, tornado often draws more than ordinary attention from the society and engineering communities.

Studies in recent years have reported an upward trend in the outbreak of tornadoes and an increase of tornadoes occurred in one day (Brooks *et al*. 2014, Elsner *et al*. 2015, Tippett and Cohen 2016, Moore 2017). Tornadoes can happen at any time but most frequently in the late afternoon, when convective activities are more likely to occur because of the accumulated solar heating in a day (Kelly *et al*. 1978, Holzer 2000, Nikolai 2001). Then, it forms the favorable environment with atmospheric instability and thermal conditions to generate thunderstorms, which can evolve into vigorous and highly organized units of convection known as supercells (Davies-Jones 2015). The supercells are potentially responsible for almost all strong tornadoes.

As the tornado is so violent that causes instantaneous damages to the ground objects, the intensity is not always easy to be determined except by recently developed in-situ or remote sensing measurements. However, these methods are impractical for a wide-scale use. Thus the intensity of the tornado is usually rated via proxies, such as the damage. Fujita (1971) developed the Fujita scale to provide a method to rate the intensity of tornadoes based on damages. However, the tornado winds were often overestimated by the Fujita scale, especially for significant and violent tornadoes. To better standardize and elucidate what was previously subjective and ambiguous, more types of structures and vegetation are added, and degrees of damage are expanded, forming the Enhanced Fujita (EF) scale (McDonald 2006). The EF scale of tornado intensity and corresponding damage patterns are given in Table 1 in which the 3-s wind gusts estimated for each case are also presented.

Tornado events were observed and documented on all continents except Antarctica (Peterson 1998). Most of them occur on both hemispheres between the latitude 20° and 60° but predominantly over the territory of the USA (Goliger and Milford 1998). These extreme events are also prominent in the Asian continent. For example, it was counted that in China there would happen 10~100 tornadoes per year (Golden and Snow 1991). Due to the geographical location of Jiangsu Province in China, the open terrain accompanied with high temperature, low-level humidity and atmospheric instability in summer facilitates the development of strong convective climates and provides a beneficial condition for the emergence of tornadoes.

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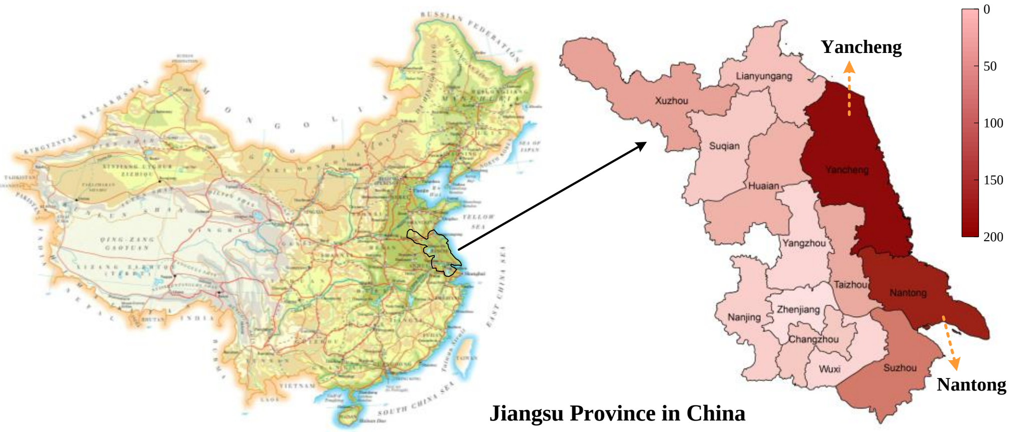


Fig. 1 Spatial distribution and occurrence of tornadoes in the Jiangsu Province of China

Table 1 The Enhanced Fujita (EF) scale of tornado intensity

Intensity	Wind speed range (km/h)	Damage patterns
EF0	105-137	Surface peeled off some roofs; some damages to gutters or siding; branches broken off trees; shallow-rooted trees pushed over.
EF1	138-177	Roofs severely stripped; mobile homes overturned or badly damaged; loss of exterior doors; windows and other glass broken.
EF2	178-217	Roofs torn off well-constructed houses; foundations of frame homes shifted; mobile homes completely destroyed; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.
EF3	218-266	Entire stories of well-constructed houses destroyed; severe damage to large buildings such as shopping malls; trains overturned; trees debarked; heavy cars lifted off the ground and thrown; structures with weak foundations are badly damaged.
EF4	267-322	Well-constructed and whole frame houses completely leveled; cars and other large objects thrown and small missiles generated.
EF5	>322	Strong-framed, well-built houses leveled off; foundations are swept away; steel-reinforced concrete structures are critically damaged; tall buildings collapse or have severe structural deformations; some cars, trucks and train cars can be thrown approximately 1 mile.

Hence, tornado is always reported as a severe disaster by public media in the Jiangsu Province of China.

According to incomplete statistics (Chen *et al*. 1999), there were 907 tornadoes ever occurred in the 13 cities of Jiangsu Province, China from 1960 to 1996. Among them, 98.9% of the tornadoes are rated below F3. At that time, the tornado was still rated with the Fujita scale. According to the 3-s gust wind velocity, the F3 scale in Fujita scale is approximately equivalent to the EF4 scale in the Enhanced Fujita scale. The spatial distribution of tornadoes in different cities of Jiangsu Province is shown in Fig. 1. It is observed that Yancheng and Nantong, which are located beside the yellow sea, are two most affected cities by tornado. Among them, the disaster in Yancheng is much more frequent and severe, and accounts for 22% of all the tornado events captured. However, fewer tornadoes happened in cities away from the ocean. Thus, a distinct phenomenon observed in Jiangsu Province indicates that the tornado is more likely to be developed in coastal areas.

On June 23, 2016, a severe EF4 tornado occurred in the rim of the coastal city Yancheng in China. Numerous low-rise buildings as well as facilities were destroyed or damaged. In this paper, damages to several specific structures and infrastructure facilities by the severe tornado are reviewed. The collapses of residential buildings, industrial structures and other infrastructure facilities are described. The possible mechanisms of the collapse are discussed, which may provide a better understanding of the wind-induced failures from destroyed structures and facilities. Suggestions are thus made to help enhance the design and building technology employed to mitigate the effects of tornadoes.

2. General structure of a tornado

According to the radar observations, the tornado near the ground is spawned from a supercell, which is often evolved by a thunderstorm in environments with convective available potential energy and ground-relative winds that turn and increase prominently with the height (Burgess and Lemon 1990, Davies-Jones 2015). A classic supercell always contains a rotating updraft, known as a mid-altitude mesocyclone, and a downdraft that coexists symbiotically in an almost steady state. The updraft tilts the environmental horizontal vorticity in the mesocyclone upwards, allowing the updraft itself to start spinning if the vorticity is streamwise in the updrafts' reference frame. After a narrower vortex developed near the ground, which builds a rotating column that from the ground to a level aloft, a tornado will be finally formed from the contraction of the near-ground cyclone with spinning air.

Many models supported by lab experiments, numerical simulations and field measurements were developed to characterize the tornadic structure and the corresponding physical mechanism for the inherent motions of tornadoes (Golden 1971, 1974, Hsu and Fattahi 1976, Davies-Jones 1995, Ben-Amots 2016). In this paper, the conceptual model with additional consideration of downflow and motions of droplets by Ben-Amots (2016) is presented to briefly introduce the general structure of tornadoes. The schematic structure of the tornado is shown in Fig. 2.

As shown in Fig. 2, the tornado is constituted by a vertical or slanted fast spinning pipe (also known as a funnel), which is surrounded by a fast rotating torus of winds, descending from the cloud of the supercell. The pipe is filled with a mixture of air, water vapor and water droplets. These components from the cloud are continuously sucked into the pipe by the reduced pressure caused by centrifugal forces.

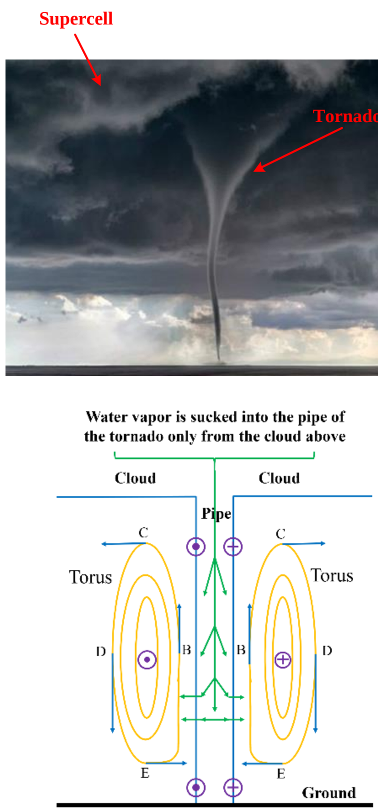


Fig. 2 Schematic diagram of the structure representing tornado

During this procedure, a condensation of vapor to droplets exists, making the pipe of the tornado opaque due to the appearance of water droplets. While rotating together with the pipe, the mixture of air, water vapor and water droplets sinks towards the ground. The water vapor then continues to condense and reaches a relatively cooler low altitude in the funnel. At a position where the water droplets are accumulated with the highest specific weight, the latent heat released by condensation heats up the water droplets prominently. Then the relatively hot water droplets are driven outward through the circumference of the pipe by the centrifugal forces of the fast rotating funnel. It is a circulation between the reduced pressure and the condensation of vapor, as the reduced pressure inside the pipe intensifies the condensation of water vapor, which leads to a further decrease of pressure due to the smaller volume of liquid water than water vapor. The driven-out hot water droplets join the ascending flow of the torus and add additional buoyancy to boost the air upward. The air from the bottom of the torus is simultaneously sucked in with additional strength. More details on the motions of air, water vapor and water droplets can be found in Ben-Amots (2016).

It is distinct in the torus that the components constituting the torus rotate around the axis of the funnel. Due to the angular momentum conservation, the wind rotates faster when it gets closer to the pipe. This is why the tornado has violent tangential velocities and makes destructive damages. A general dimensionless tornado-vortex tangential velocity profile can be seen in Fig. 3(a), and it is often analytically defined as Eq. (1) (Strasser and Selvam 2015). It is shown that the tangential velocity is around zero at the center of tornado as a hollow exists in the structure. Thus the pressure deficits increase along the augment of the radius and finally become stable (Refan and Hangan). For the vertical tangential velocity profile of the tornado, it is different from the boundary layer wind profile as a maximum occurs near the ground, which is similar to those observed in downbursts or hurricanes (Hamada *et al*. 2010, Holmes and Oliver 2000, Kwon and Kareem 2009, Letchford and Chay 2002). Fig. 3(b) summaries the vertical profiles of a typical EF4 tornado at different radiuses (El Damatty and Hamada 2016). The height where the maximum appears is observed to rise with the increase of the radius ranging from 50 m to 200 m. This height differs from 5 m to 60 m, further enhancing the power of tornadoes to destroy engineering structures. In addition, the angular momentum is transferred to the funnel through viscosity and turbulence, thus sustaining the rotation of the funnel against dissipation (Ben-Amots 2016). In such a case, the vapor from the cloud will continue to give tornadoes formidable strengths. Apart from the great power of tornado itself, the debris on the ground or from damaged building structures will be rolled up by tornado and further form physical missiles, which have great kinetic energy as they are equipped with a large velocity. The physical missiles thrown by the tornado are big threats and will cause additional damages and injuries.

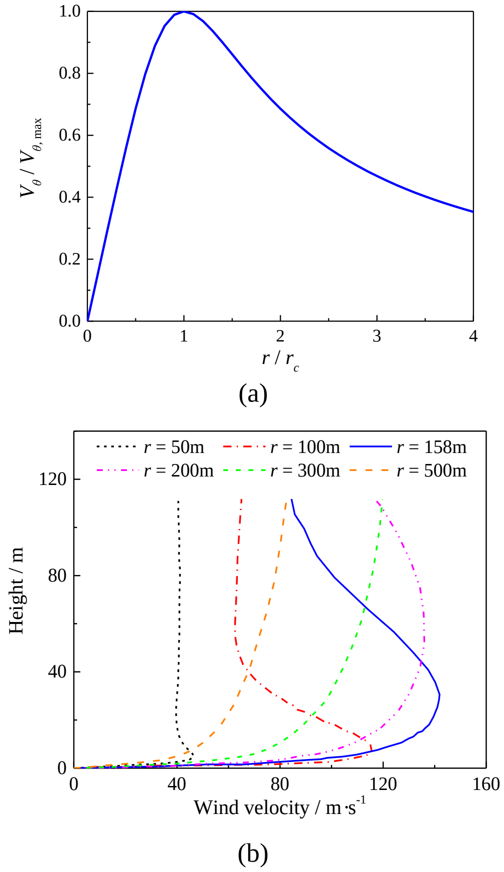


Fig. 3 Tangential velocity profiles of the tornado

$$V_\theta(r) = \alpha \cdot r \cdot \left[\frac{2}{(r/r_c)^{2n}+1}\right]^{1/n} \tag{1}$$

where $V_\theta(r)$ is the tangential velocity of the tornado; α and n are general constants; r is the radius away from the funnel axis; r_c is the radius indicating the position where the tangential velocity achieves maximum $V_{\theta,\max}$ and equals to $\alpha \cdot r_c$.

3. Description of the tornado in Yancheng and overall losses

On the afternoon of June 23th, 2016, a tornado accompanied with frequent lightning and heavy hail occurred in the countryside of Yancheng in Jiangsu Province. According to the damages to constructed facilities, it was rated as an EF4 tornado that caused 99 fatalities and 846 people injured. More than 1962 residential buildings and 8 industrial structures were ruined, and over 3200 hectares of crops were destroyed. A general view of tornado-induced damages is shown in Fig. 4.

In the morning of the day, the local bureau of meteorology had issued alerts of thunderstorms and downpours. Unfortunately, the strong convective weather met the triggering condition of the tornado, leading to a

Fig. 4 Overview of the tornado-induced damages in Yancheng

severe heartrending disaster. Large numbers of well-constructed residential buildings were completely leveled, and cars as well as other large objects like debris were rolled up and thrown towards other facilities, which further generated missiles threatening the safety of other structures. The injuries and fatalities were caused by the tornado mainly in three ways: i) picking people up and hurling them towards the ground; ii) crushing people under debris; iii) impaling people with objects flying in the air with incredible force. Hence, the common practice of sheltering from the tornado is staying in an interior room under the ground of a residential building. This also raises a consideration to construct a reinforced basement or subterranean shelter for each residential building to provide safety against wind actions or debris attacks in tornado-prone areas.

4. Damages to residential buildings

Most of the residential buildings in this area attacked by the tornado are masonry structures, which belong to a common building type in the countryside of China. Along the moving path of the tornado, the masonry structures are all damaged partially or totally in the violent wind event. The most prominent damages mainly include cracks and collapse of the structure, roof partially or completely damaged or whirled away, and cladding components damaged or destroyed. This part will present a brief summary of the encountered damages to residential buildings during the EF4 tornado. Possible mechanisms about the damages are discussed, and some considerations against tornado are provided.

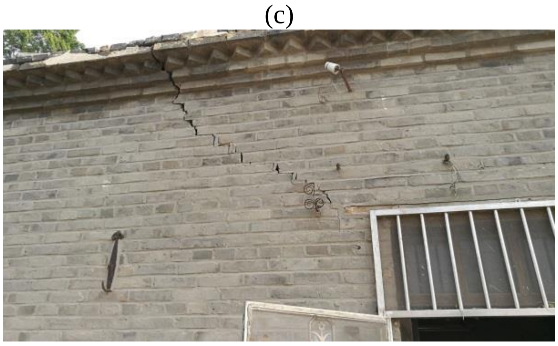
4.1 Cracks of the structure

There are two kinds of cracks observed in the tornado-induced damages to structures. One is the inclined crack, and the other is the vertical crack. The typical inclined and vertical cracks observed in residential buildings are shown in Figs. 5 and 6, respectively.

(a)

(b)

(c)



(d)

Fig. 5 Inclined cracks occurred near the top corner of the door

Fig. 6 Vertical cracks occurred in masonry walls

Actually, these cracks occurred in the masonry walls are characterized by the failure of mortar, while no penetrating cracks are observed in bricks. The masonry structure is a typical composite structure with the cooperation between bricks and mortar. The observation above is the most likely failure mode of masonry structures, as the tensile strength of mortar is far smaller than that of bricks. As a result, these mortar cracks are always what triggers the further collapse of structures. Improving the tensile strength of the mortar and the adhesive property between the mortar and bricks are therefore a direct measure that can mitigate cracks.

As shown in Fig. 5, two categories of inclined cracks are observed near the top corner of the door. One is the case that the inclined crack stretches towards the outside of the door, as illustrated in Figs. 5(b)-5(d). The other case shown in Fig. 5(a) is that the inclined crack is generated over the door and then bifurcated into two cracks towards the two corners of the door. In the view of the crack width, they both originate at the junction of the roof and the wall, and extend to the top corner of the door. This is because the largest peak pressures occur at the corners of the roof under tornado winds (Haan *et al*. 2010) and a significant stress concentration always exists at the blunt corner of the door where the geometric is discontinuous. In Fig. 5(a), the lintel is employed to alleviate the stress concentration. However, it cannot avoid the tornado-induced crack stemming from the corner of the roof. To alleviate this kind of inclined cracks, the cast-in-place concrete roof is thus suggested be utilized with the lintel employed over the door.

It can be seen from Fig. 6 that the vertical crack in the masonry walls also originates from the corner of the roof. Compared to inclined cracks observed at the door, this kind of crack is more serious as it may directly lead to the collapse of the structure. Several studies have shown that tornadoes produce greater pressure on structures than straight-line winds for the same reference wind velocity

(Sabareesh 2012, Masoomi and van de Lindt 2016). In respect to the gable-roof building, the general lateral force by tornado winds can be 50% greater than the standard provisions and the vertical uplift force is two to three times the value of provisions (Haan *et al*. 2010). This improves the possibility for masonry walls to suffer from cracks since the wind load is not a significant consideration in the design of these low-rise residential buildings. In such a case, the wind pressure coefficients in standards are suggested be defined in two categories according to buildings whether located in tornado-prone areas or not.

4.2 Damages of the roof

As one might expect, the houses experienced the EF4 tornado also sustained roof damages, which typically exhibited missing or partially damaged roofs and imposed the trusses above the buildings as shown in Fig. 7. The roof of a building in this area is always fabricated with clay tiles distributed over wooden beams. There is usually no connection between two adjacent tiles, which thus resist the wind-induced uplift forces only with gravity. In some houses, an enhancement is often employed over the clay tiles with large pieces of steel tiles connected by rivets. The damage pattern in Fig. 7(a) indicates the feasibility of the enhancement in protecting the inner roof from being further damaged by the tornado although the steel tiles are partially torn apart. For the roofs shown in Figs. 7(b)-7(d) with only tiles as cladding covers, the tiles are easily rolled up and swept away due to the strong uplift force caused by the low static pressure zone inside the vortex core of the tornado (Haan *et al*. 2010, Huang *et al*. 2015, van de Lindt *et al*. 2007, Yang *et al*. 2018). The damage of roof panels can be evaluated with the data-based probabilistic damage estimation method (He *et al*. 2015, Huang *et al*. 2016, Ji *et al*. 2018). In addition, it is very dangerous that the tiles may be rolled into the tornado as debris and then hit other infrastructure facilities like physical missiles. Hence, improving the wind-resistant performance of the roof against the strong uplift forces is an urgent problem in the tornado-prone areas. The concrete roof may obviously alleviate this problem, as it works with a higher strength and integrality.

(a) (b) (c) (d)

Fig. 7 Damages to the roofs of residential buildings

4.3 Damages to cladding structures

As shown in Fig. 8, the damages to cladding structures surveyed in this area mainly include the failures of windows and handrails. Numerous shattered glasses were observed, accompanied with the window frames out of surface deformation. The glass fragments caused many injuries to residents inside the building and people nearby. In respect to the handrails, they were found so forcibly hit that suffered from severe deformations, as shown in Fig. 8(d). The initiations for the damages to windows and handrails are possibly attributed to the physical missiles carried and thrown by the tornado.

4.4 Collapse of structures

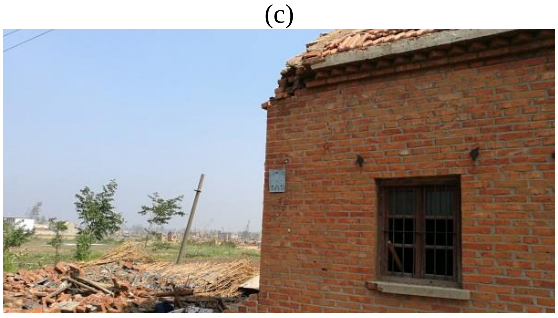
The most severe damage induced by the tornado is the collapse of structures. The residential buildings in this area are either single-storey or double-storey structures. As shown in Fig. 9, the prominent collapse failure of the single-storey structure is being totally toppled down with the walls broken into separate bricks. However, only the second storey of the double-storey structure is pushed over by the tornado and the main structure of the first floor is almost undamaged. It can be predicted that the collapse of the masonry structure originated from the roof damages which were easily caused by the aforementioned strong uplift forces. After the wooden beams were swept away from the roof, the walls lacked sufficient out-of-plane stiffness and were easily toppled down by the pressure. Meanwhile, the largest pressure occurred in the corner of the roof (Haan *et al.* 2010), which enhanced the bending moment imposed on each wall. In addition, the gust-front wind shown in Fig. 3(b) intensifies the wind pressure on buildings. These may explain what caused the collapse of residential buildings.

For the double-storey structure, the aerodynamic shape was changed to a cube after the second storey was pushed over. Meanwhile, the tornado effect was transient due to the small-scale climate. The tornado might have moved to a place far from the double-storey building after the collapse of the second storey. With these considerations, the aerodynamic forces acting on the first storey of the double-storey structure are alleviated compared to the single-storey building. The difference in aerodynamic actions may account for the different failure modes in the two categories of structures.

(a)

(b)

(c)



(d)

Fig. 9 Tornado-induced collapses of residential buildings

In fact, the tornado loads are seldom considered in current design codes for buildings and other structures except nuclear facilities since a low occurrence rate is historically summarized (Masoomi and van de Lindt 2016). However, the tornado-induced damages to residential buildings are really severe and different from our knowledge to those caused by strong boundary winds. The tornado effects are generally more violent due to its physical structure and working mechanism that produce large wind velocities, gust-front winds, strong uplift forces, etc. Hence in standards, it is suggested to divide the areas into two categories, the tornado-prone area and ordinary area, in light of the historical statistics of tornadoes and local topographic features. The latter point on landform considers the potential places where tornadoes are more likely to happen.

It is widely reported that concrete structures sustain little visible damages to the main elements, and only windows and glass curtain walls are easily destroyed. Besides, for steel structures, the envelope system and roof frequently sustain significant damages (LaFave *et al.* 2016). In such a case, concrete structures, with a reinforced concrete room as a shelter, are suggested for residential buildings in tornado-prone areas.

5. Damages to industrial structures

In addition to the residential buildings described previously, the large-expanse industrial structures in the surveyed area were also seriously destroyed, as shown in Fig. 10. The arrow in Fig. 10(a) indicates the moving path of tornado. Similar to residential buildings, the large-span roof of the industrial structure was totally damaged. With the increase of the span length, the roof becomes more and more flexible and thus sensitive to wind actions, which facilitates the destruction of tornado wind effects. In Fig. 10(a), most of the light steel roof panels were swept away, but the beams were almost completely preserved. This means the connection between the roof panel and the beam is not tight enough. Moreover, the flying roof panels would cause secondary damages to structures and threaten the safety of the people nearby. For the outer walls, the concrete frames sustain very little damages while the claddings were pulled apart and blown everywhere in the regions nearby. Another distinct failure mode of the industrial structure with steel columns occurs at the column bases exhibiting both anchor rod pullout and fracture, which is similar to the observation of tornadoes in USA (LaFave *et al.* 2016). Fig. 10(c) presents a typical example of the anchor rod failure. It is found that there is no bending deflection in the column, but the anchor rod failure occurs earlier. This is a prohibited failure mode in the design of steel structures. Thus, these column bases were clearly not well designed as they were not able to bear prescribed moments from lateral loadings.

Generally, the tornado-induced damages to industrial structures concentrate on the roof and claddings. To protect these components from being damaged in tornado winds, the first step is to better understand the pressure distribution, especially for the static pressure, on such a large-expanse structure as existing studies still focus on small-size residential

(a)

(b)

(c)

Fig. 10 Tornado-induced damages to industrial structures

buildings. The connections between roof panels and beams, as well as those between cladding components and columns, should be enhanced in tornado-prone areas. More purlins are suggested to be placed at the roof like Fig. 10(a) to shorten the span length of roof panels.

6. Damages to infrastructure facilities

The EF4 tornado also caused severe damages to infrastructure facilities in Yancheng, such as the collapse of transmission lines, advertising boards, street lamps, trees and cars. Fig. 11 shows the typical damage patterns of transmission lines. The transmission tower for long-distance power transport and the utility pole for short-distance case are included in Figs. 11(a) and (b) and Figs. 11(c) and 11(d), respectively.

The failure mode of the transmission tower is the collapse due to buckling. The large tangent wind velocity and gust-front wind of the tornado account for this kind of destruction. However, there is a lack of procedures in the codes to guide the estimation of tornado effects on transmission line systems (El Dammatty and Hamada 2016). This calls for more studies focusing on the tornado forces on transmission line systems and the measures to mitigate the failures of transmission towers. In respect to the utility pole, it is often pushed over due to the shallow burial depth that cannot resist the tornado-induced moment. Hence, increasing the burial depth is a good solution to alleviate this problem.

Other tornado-induced damages to infrastructure facilities are presented in Fig. 12. For the advertising board being pushed over, there is a lack of resistance at the base against moment induced by the wind pressure, which highly depends on the wind velocity. Because of buckling, the failure pattern of the street lamp is similar to that of the transmission tower. Some of the trees are broken off at the same height, which is initiated by the gust-front wind velocity. Meanwhile, some other trees are directly pushed over, as the roots are too shallow. The damages to cars are caused in two manners. One is being directly rolled up by the tornado and thrown towards ground with a crash. The other is generated by the debris missiles smashing up cars or resulting in severe deformations.

(a)

(b)

(c)

(d)

Fig. 11 Tornado-induced damages to transmission lines

(a) Advertising board (b) Street lamp

(c) Trees

(d) Cars

Fig. 12 Tornado-induced damages to other infrastructure facilities

7. Conclusions

This paper presents a review on the damages to structures and infrastructure facilities by the EF4 tornado in Yancheng on June 23, 2016. The collapses of residential buildings, industrial structures and other infrastructure facilities are described with corresponding possible mechanisms discussed. The following conclusions can be drawn accordingly.

(1) Inclined and vertical cracks are observed in the masonry residential buildings after the tornado event. These cracks are developed from the corner of the roof where the largest peak pressures usually occur under tornado winds.

(2) The tiles on the roofs of both residential and industrial structures are easily rolled up and swept away by tornado due to the strong uplift force caused by the low static pressure zone inside the vortex core.

(3) The initiations for the damages to windows and handrails are possibly attributed to the physical missiles, including the debris from the damaged buildings, gravels on the ground, broken trees, etc., carried and thrown by the tornado.

(4) The collapse of the masonry structure possibly originates from the roof damages caused by strong uplift forces. After the wooden beams are swept away from the roof, the walls lack sufficient out-of-plane stiffness and are easily toppled down by the wind pressure.

(1) Concrete structures, with a reinforced concrete room as a shelter, are suggested for residential buildings in tornado-prone areas, since they are reported to experience little visible damages on the main frames.

(2) The failure mode of the transmission tower is the buckling-induced collapse, which is generated by the large tangent wind velocity and gust-front wind of the tornado. The utility pole is often pushed over due to the shallow burial depth that cannot resist the tornado-induced moment.

(3) The large tangent wind velocity and gust-front winds of the tornado account for most damages on advertising boards, street lamps, trees and cars. The debris missiles carried by the tornado also smash up cars and result in severe deformations.

Currently, the tornado loads are seldom considered in the design codes for buildings and other structures since a low occurrence rate is historically summarized. The design practice still employs the provisions in standards from traditional boundary layer winds, which cannot satisfy the requirement to guarantee the safety of both structures and residents. Hence, it is suggested to divide the areas into two categories, the tornado-prone area and ordinary area, in light of the historical statistics of tornadoes and local topographic features. In the ordinary area, it can still follow the previous provisions about wind loads. However, in the tornado-prone area, more details on the tornado loads should be supplemented for residential buildings, industrial structures and other related infrastructure facilities. This calls for more studies focusing on the tornado effects and measures to mitigate the encountered failures. Thus, it can realize the goal of deepening understanding of how structures respond to tornadoes and ensure the safety and robustness for buildings and other infrastructure facilities in tornado-prone areas.

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