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THREE IMPORTANT WIND-RESISTANT DESIGN LESSONS FROM TWO VISITS TO AREAS DEVASTATED BY ONE SUPER TYPHOON

Aquino, Ronwaldo Emmanuel[1,3], and Tamura, Yukio[2]
[1] RWDI, Canada
[2] Beijing Jaotong University, Canada
[3] ron.aquino@rwdi.com

Abstract: Typhoon Haiyan made landfall in the central part of the Philippines on November 8, 2013, and was said to be the strongest tropical cyclone ever recorded as of that time, based on a peak 1-minute sustained wind speed as high as 315 km/h, estimated by the US Joint Typhoon Warning Center. In December 2013, a joint survey team from the Philippine Institute of Civil Engineers (PICE) and the Japan Society of Civil Engineers (JSCE) visited the Haiyan-devastated areas to inspect wind-related damages and to investigate actual storm surge levels. Another team whose formation was initiated by the Japan International Cooperation Agency (JICA) visited the affected areas in January 2014. The first author led the wind damage survey subgroup of the December 2013 survey team, while the second author was the primary wind engineering specialist on the January 2014 survey team. This paper is intended to be a summary of lessons learned from the observations during the two surveys, specifically in the field of wind-resistant design of low- to medium-rise buildings and whole communities. The paper groups these lessons learned into three topics. The first is on the forensic determination of peak typhoon wind speed without any direct measurements. The second is on holistic design being good design practice, specifically emphasizing the importance of design and maintenance of components and cladding. The last topic is on the need for more public education on wind-resistant design principles and standards.

1 INTRODUCTION

Typhoon Haiyan, known as Super Typhoon Yolanda locally, made landfall in the central part of the Philippines on November 8, 2013 (Fig. 1a), and was said to be the strongest tropical storm ever recorded as of that time, based on a peak 1-minute sustained wind speed as high as 315 km/h (87 m/s), estimated by the US Joint Typhoon Warning Center. The meteorological stations at the hardest hit areas were damaged due to storm surge and so there were no direction measurements of the maximum wind speeds. Meanwhile, the highest recorded gust speed but not at the peak of the storm and not at the hardest hit areas is 205 km/h (57 m/s), and the estimated gust speed based on the lowest recorded pressure is around 280 km/h (78 m/s).

In December 2013, a joint survey team from the Philippine Institute of Civil Engineers (PICE) and the Japan Society of Civil Engineers (JSCE) visited the Haiyan-devastated areas to inspect wind-related damage and to investigate actual storm surge levels (Tajima et al. 2014). Another team whose formation was initiated by the Japan International Cooperation Agency (JICA) visited the affected areas in January 2014 (Tamura et al. 2014). The first author led the wind damage survey subgroup of the December 2013 survey team, while the second author was the primary wind engineering specialist on the January 2014 survey team. This paper is intended to be a compilation of lessons learned from the observations during the survey, specifically in the field of wind-resistant design of low- to medium-rise buildings and whole communities.

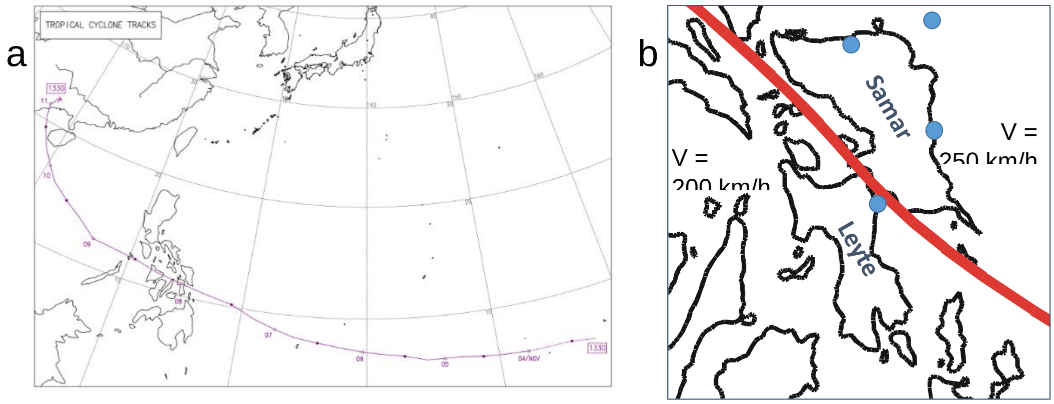

Figure 1: (a) Track of Typhoon Haiyan (from Japan Meteorological Agency website, retrieved February 8, 2017), and (b) code wind speeds in areas hardest hit by Typhoon Haiyan showing location of meteorological stations and boundary line (in red) between two code wind zones (200 km/h and 250 km/h zones).

2 ON THE FORENSIC DETERMINATION OF PEAK TYPHOON SPEEDS

As in any wind engineering application, the first thing that needs to be established to determine wind effects on structures is the wind climate, specifically the wind speed. In the wind-resistant design of new buildings, the wind speed is based on a statistical analysis of wind speeds from decades and years of recording, representing a windstorm of a certain probability following a certain code of practice. When evaluating a building damaged by an actual windstorm with an actual peak wind speed, the wind speed used in the evaluation is ideally based on direct measurements from the same meteorological stations used for the code wind speed.

2.1 Different wind speed estimates by different groups or methodologies

Unfortunately, in the case of a very severe storm such as Typhoon Haiyan, meteorological stations in the hardest hit areas were severely damaged by storm surge such that there were no direct measurements of wind speed. Instead, it is usually only based on estimates of storm central pressure from satellite imagery and the like. Even then, as illustrated earlier, there could be different estimates from different groups; e.g. 315 vs 280 km/h (or 87 vs 78 m/s). That alone is a difference of more than 10% - which could mean a difference of at least 25% in estimated wind loads since wind loading is proportional to the square of wind speed.

There were on-ground forensic investigations led by the authors as mentioned, which led to very different conclusions. Aquino et al.'s (2014) preliminary estimate was that the peak 3-second gust speed at 10m height was at least 315 km/h (87 m/s) in flat, open country terrain (or simply open terrain). Tamura et al.'s (2014) estimate, also documented in Sanada et al. (2015), was that the gust speed at 5m height in light suburban terrain was about 250 km/h (70 m/s), or a peak 3-second gust speed of just under 300 km/h (83 m/s). Meanwhile, a study by Agar (2015) and referenced by Hernandez et al. (2015) estimated that the 1-minute sustained wind speed was about 350 km/h (97 m/s) at 10m height in open terrain, suggesting that its peak 3-second gust speed is about 425 km/h (118 m/s).

In any case, contrast these all to the code (Association of Structural Engineers of the Philippines or ASEP 2010) wind speed prevailing at the time, defined as a 50-year return period 3-second gust speed at 10m height in open terrain, which is 200 km/h (55 m/s) for Leyte Province and 250 km/h (70 m/s) for Samar Province (see Fig. 1b). With a code wind load factor of 1.6 for ultimate wind loading, the corresponding equivalent wind speeds at these sites ($V_{ultimate}$) can be estimated considering that wind loads are proportional to the square of wind speed. $V_{ultimate}$ can then be taken as sqrt(1.6)*V_{50year}, or about 250 km/h (70 m/s) and 315 km/h (88 m/s) for Leyte and Samar, respectively.

2.2 Complex nature of (typhoon) wind and high uncertainty in civil engineering structures

One other thing that makes forensic determination of typhoon wind speeds challenging is the complex nature of wind itself. It may be viewed simply in terms of one quantity, e.g. a wind speed, but wind has a velocity that changes with position (spatially uncorrelated), time (dynamic), direction, intensity, and lastly, with surroundings including both nearby and distant structures and topographic features. For example, in Samar, the wind damage survey teams found two examples of very similar buildings side-by-side (Figs. 2a & 2b), but one would have more damage than the other. Figs. 2c & 2d shows another example of two very different lattice towers, one newer, and the other more slender and on top of a hill just under a kilometer away from the newer one. Between the two, it is the newer one that is damaged. These similar structures experienced different levels of damage likely due to different immediate surrounding conditions and terrain. The damaged tower was closer to water (thus stronger overall local wind speed) while the adjacent buildings are not necessarily on flat, open land with uniform surroundings.

There is more behind these damages of course, such as how the structures were designed, and whether they were properly designed to code. There is also the matter of whether the construction followed the design, and there is also the matter of small structural or architectural details such as at roof ends (as studied by Tamura et al. 2014 and Sanada et al. 2015) which could impact performance under wind.

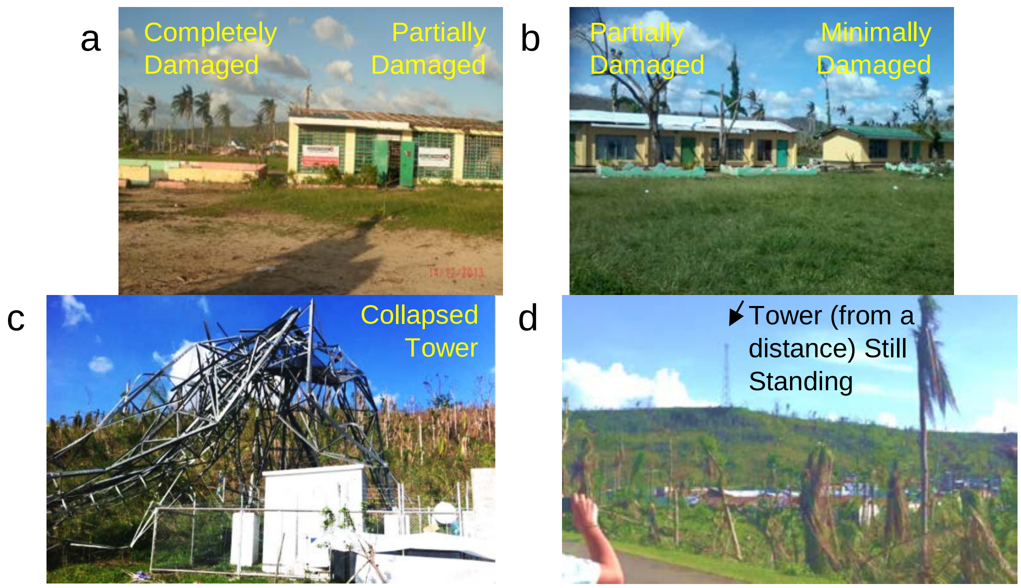

Figure 2: Examples in Samar of (a and b) two side-by-side buildings with different levels of damage, and (c and d) two lattice towers within a kilometer of each experiencing different levels of damage as well.

Figure 3: Simple structures investigated by (a) Aquino et al. (2014) and Agar (2015), and (b) Tamura et al (2014) and Sanada et al (2015).

The complex nature of wind makes forensic investigation of these damages more difficult. For example, Aquino et al.'s (2014) preliminary wind speed estimate was based on the assumption that the wind velocity profile (distribution with height) followed the code suburban profile, but the aerodynamics due to surrounding buildings near the damaged structure (Fig. 3a) probably played a more crucial role. Wind tunnel modelling and testing would be able to capture the unique details of the building, but it is highly impractical for these very simple applications.

Even if uncertainty behind the wind parameters is low, there is still uncertainty in the structural wind response, mainly due to uncertainty in material properties but also in structural dynamic properties, especially the inherent damping. The study by Sanada et al. (2015), however, did well to eliminate one uncertainty by taking a sample from the structure they were investigating (i.e. a sample of the steel rebar shown in Fig. 3b) and testing it in the laboratory to obtain its material property.

Lastly, it should be emphasized that wind speeds estimated from damaged structures are just estimates that are only equivalent-stationary straight wind speed based only on the knowledge of aerodynamic actions on an isolated building model under, typically, synoptic (non-typhoon) wind. They may likely be different from the actual wind speed. Surrounding buildings and topographic features are typically irregular or non-uniform, unlike what has been effectively assumed in wind loading codes.

3 HOLISTIC DESIGN IS GOOD DESIGN

3.1 Wind-resistant design is not just structural design

For most buildings in the Philippines, it is typically the structural engineers who are responsible for determining the wind loading. They would typically design the roof frames of residential buildings, but there is little thought given to designing the roof sheets, doors and windows. If there is one thing that needs first to be emphasized, it is that wind-resistant design is not just structural design: it starts with protecting the building envelope. Performance and maintenance of components and cladding (C&C) is key, as it is part of the critical path in the so called "damage chain" under an extreme wind event (Fig. 4). Most of the observed buildings suffered damages to their C&C. In many cases, there is no damage to the primary structural system, but then there is water ingress and damage to contents within the building. Even then, the building would not be suitable for occupancy until the damage is repaired. If the building housed commercial activities, there would be business continuity issues.

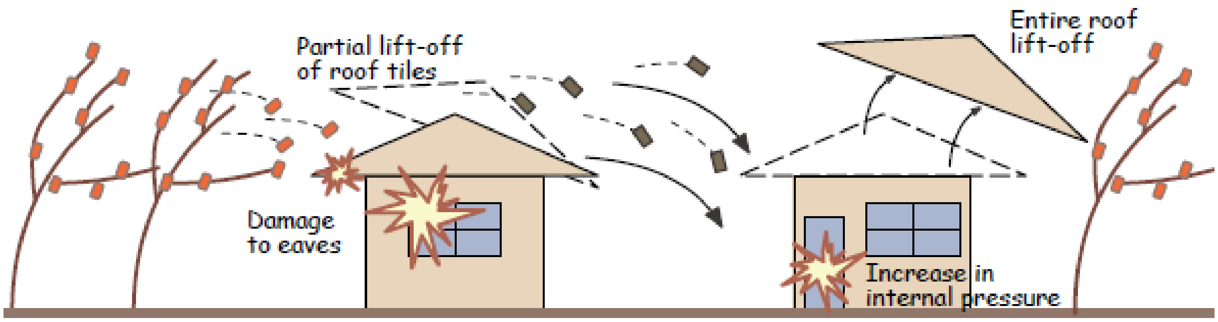

Figure 4: Damage chain due to extreme wind event.

3.2 Connection design is very important

Connection design, whether between C&C and main structural systems, or between different parts of the structural system, is very important. The importance of connection design between C&C and main structural systems is related to the above discussion on proper design of C&C. Good connections help prevent wind-borne debris being the cause of damage to neighbouring structures and property. It is most evident in older construction where timber was a primary structural material (Fig. 5). Figure 6 shows some examples of older timber construction damages, which typically used nails or inadequate bolted connections in the roof-structure connection detailing.

Figure 5: Older structures of timber construction with damaged secondary (cladding/roof) systems.

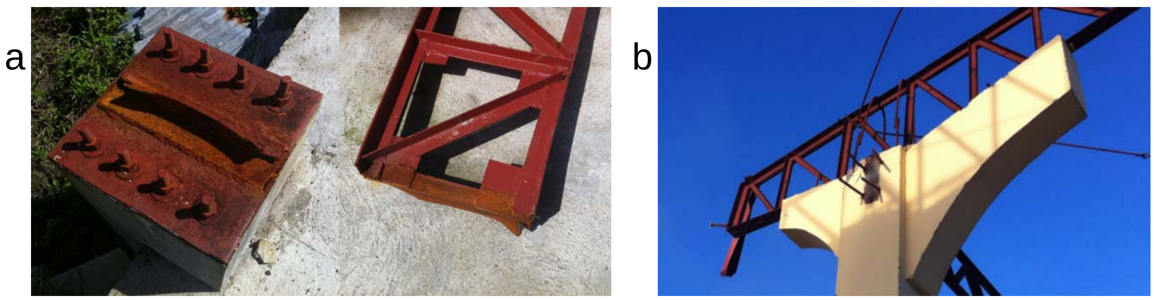

Figure 6: Newer structures with poor frame-roof connection detailing.

In Fig. 6a, back-to-back welded connector angles are used although typically a bolted connection would be used. Additionally, there are no gusset plates or reinforcement plates to provide lateral support in the off-axis direction, which was probably the primary reason for the damage. In Fig. 6b, steel rebars are bent as hooks to anchor the roof truss-beam in place.

3.3 Design against wind is still important even in highly seismic regions

In the Philippines, a highly seismic region, there is some misconception that once you design for earthquakes, and since the seismic base shear is almost always larger than the wind base shear for most buildings, therefore there is no need to design for wind. When it comes to smaller buildings, typically the residential type, the philosophy is that the main frames need to be strong enough to resist earthquake and it is only the roof system that needs to resist wind loading. However, as shown in the observed buildings in Fig. 7, wind may still damage low-rise buildings designed to resist earthquakes. Unlike in seismic design, where the “maximum credible earthquake,” typically with a ~2,500-year return period, is deterministically established, such damaged buildings are not designed to any “maximum credible storm.” The Philippine wind-resistant design code effectively designs for approximately a 700-year return period wind speed (or 1,400 years for important structures), but storms with return periods longer than these are not unlikely. In some special cases, such as in nuclear applications, a very long return period wind speed (e.g. from a 10,000-year storm) may be considered, but such would be too impractical for most buildings in the Philippines.

Figure 7: Small reinforced concrete buildings damaged by typhoon Haiyan.

3.4 New design and new construction are not necessarily immune from damages

As mentioned above, typically the philosophy is that the main frames are designed to resist earthquakes and the roof system is designed to resist wind loading. However, the whole structure should be analyzed for simultaneous wind action, which is what the code requires (Fig. 8).

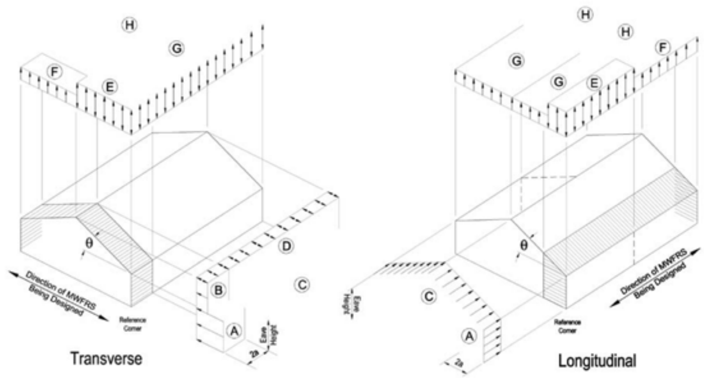

Figure 8. Example wind loading diagram from Philippine code provisions (ASEP 2010).

Figure 9. Large volume, newer reinforced concrete building with extensive damage.

Consider the building in Fig. 9 which was about 5 years old at the time Typhoon Haiyan made landfall. Because of its huge volume and large walls, the simultaneous wind action on walls and roofs should have been considered. It is possible that the roof, for example, and its connection to the main supporting structure was well designed, but the main frames were not. For example, the roof beam supporting system may have been inadequate for uplift. There may also have been poor consideration of the aerodynamic impacts of the ventilation openings along the wall (i.e. it is an open or partially open wall), poor connection design/detailing, and/or some lapse in construction implementation.

3.5 Wind-resistant design means having whole communities be aware of wind-resistant design principles

This ties in heavily to the message in the succeeding section of the paper, but the point here may be illustrated by this following scenario. Imagine a person who has done his due diligence to ensure that the house was engineered and built to standard. However, imagine that all his neighbours did not put as much care into their own homes. A storm like Typhoon Haiyan comes, and the properly engineered building gets damaged anyway due to wind-borne debris from neighbouring buildings (e.g. Fig. 4). In short, wind-resistant design, to be holistic, should not end with single individuals doing the right thing for themselves. It must involve education and involvement of whole communities.

a  b 

Figure 10. (a) Blown off roof rebuilt in the same way as before within a month of Typhoon Haiyan, and (b) an example non-engineered temporary structure being built.

Figure 11. Example of residential building in Japan with all glass windows (and doors) having shutters that can be closed shut to add protection during a wind storm.

4 ENFORCEMENT AND IMPLEMENTATION OF BUILDING CODES

Despite all that the world has learned from past storms, proper enforcement of building codes is still a pressing issue. Especially in developing countries, the proper implementation of the principle in codes and standards should be carried out so that there would be no need for enforcement. There may be a cultural aspect to this – e.g. certain groups of people may prefer strong enforcement due to inability to implement. But ultimately, it is a matter of educating the public – and also building officials, engineers, and construction professionals including those in specific trades such as carpenters, masons, and so on, and it must extend to the smaller towns and cities outside of large metropolitan areas such as the Philippine capital of Manila and business centres in Cebu and Davao. Unfortunately, it can be said that this has not happened enough. (Before and during Typhoon Haiyan, there was also confusion in the Philippines behind the concept of what is a "storm surge," but that is another matter). Very simple, easy-to-understand guidebooks with many drawings and figures rather than verbiage (typical of building codes), and frequent and continuous seminars in local cities and in the trades associations are necessary.

An example illustrating this are the examples shown in Fig. 10. Fig. 10a shows a case were the home owners appear to have rebuilt their blown off roof within a month of Typhoon Haiyan's landfall. However, these are not necessarily built in a way such that they better resist wind. Fig. 10b shows an example temporary shelter not engineered to be immune from strong storms; i.e. because another design storm could occur within the next year. There is a need of course to provide shelter especially immediately after an extreme storm such as Haiyan but also possibly one that might need to be used for weeks or months after the event. In that case, it should also be engineered so that its occupants are as safe as they would be in a permanent structure.

It cannot be emphasized further that wind-resistant design all starts with protecting the building envelope. All people need to be aware of this. In the Philippines, there is the National Structural Code of the Philippines or NSCP (e.g. ASEP 2010) which is the code basis for wind loads that can be applied to walls, windows, doors, and roofs. But there are no codes and standards of practice on how to make these wind-resistant in construction. For example, in Japan, window shutters are quite commonly part of residential building construction (e.g. Fig. 11). It is possibly for a different purpose (e.g. for privacy), but it does help to have them installed and closed shut when a storm is approaching. It could be one strategy in the Philippines, especially since large openings are typically used for ventilation almost year-round.

It was observed that new design and new construction generally fares better than older ones. (Figs. 5a and b, and Fig. 12a are examples of older construction; Fig. 12b is an example of newer construction.) Economics would make this issue not go away soon, but indeed, newer construction which is usually composed of reinforced concrete main frames and steel roof trusses fare better than older construction, which is usually composed of reinforced concrete masonry wall and timber roof framing. Perhaps citizens could use an incentive from the government to upgrade, such as tax breaks. In any case, there is always new knowledge in wind-resistant construction. The government may also either provide incentives to people or require them to maintain building cladding features; to repair them to address deterioration or damage and to keep them to a certain standard, if necessary, but also to upgrade them if there is new and better knowledge in wind-resistant designs.

And finally, and already mentioned earlier: wind-resistant design means having whole communities aware of and practicing wind-resistant design principles. People who know should do their part to spread the word, and it may well start with engineers.

a b

Figure 12. Example (a) older construction, and (b) newer construction.

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