Wind-Induced Damages on Roofs: Sri Lankan Case

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Abstract

Although many studies have focused on identifying the single factors that cause wind-induced damages on roofs, the studies carried out in the Sri Lankan context mainly focus on the wind patterns in Sri Lanka and the damages to people and property. Therefore, there is a need for pooling of expertise to identify the wind-induced damages to roof, strategies to mitigate them and challenges encountered to systematically adopting avenues in the Sri Lankan context. This study administered a qualitative approach. The extensive literature review was followed by semi structured interviews with 07 subject matter experts and data was analysed using manual content analysis. The findings revealed that roof is the most vulnerable building element to wind disaster, even in the Sri Lankan context. It also proved that location and topography, structures and vegetation around the building, proximity and the height of neighbouring buildings or structures, shape, elevation and height of the building, choice of roofing material and workmanship are the factors contributing to wind-induced damages on roof. Strategies should be adopted considering these factors. Reluctance to adhered to current standards and guidelines is the major challenge.

Keywords
Roof, Winds, Disasters and Mitigations

1. Introduction

Extreme winds are regarded as one of the severe disasters, causing massive losses of life and possessions across the globe (Jin and Yan 2009). The phenomena resulted from the combined effects of strong wind due to heavy rain and storm surge have created damages of severe nature to buildings and structures (Tamura and Cao 2009). Wind is caused by the temperature gradient of the atmosphere due to variable solar heating of the earth's surface (Tamura 2005). Majority of wind-induced damages create adverse impact on residential houses and low-rise commercial buildings, which are all non-engineered structures. This is because the sophisticated design methods developed and adopted in building standards/codes are not very often reflected in the construction technologies for those buildings (Baker, 2004; Holmes et al. 2006; Tamura and Cao 2009). In addition, damage to openings such as windowpanes and steel shutters is also significant since they can trigger the complete destruction of the main frames and develop damage to downstream buildings as wind-borne debris (Holmes et al. 2006; Tamura and Cao 2009). According to Tamura (2005), most wind-induced damages have been concentrated on roofs and particularly in their cladding around eaves, ridges and corners. In the Sri Lankan context, wind events seem to be most prevalent in the latter parts of the year and are most likely to occur in the months of June and November (Disaster Information Management System 2018). In addition to cyclones, Sri Lanka is often affected by other wind events throughout the year causing destructions to the country. The disastrous circumstances triggered by wind has surged an interest to research on wind-induced disasters.

Within the global context, number of studies have been carried out to identify the factors that cause damages on roofs due to wind (Evans and Mandt 2003; Caufield et al. 2012; WBDG 2018). However, these studies are based on identifying single factors that cause wind-induced damages on roofs. The studies carried out in the Sri Lankan context mainly focus on the wind patterns in Sri Lanka and the damages to people and property (Srisangeerthanan et al. 2015). Therefore, there is a paucity of literature in this area both in the global and the Sri Lankan context. Thus, there is a pressing need for pooling of expertise to identify the wind-induced damages to roof and strategies to mitigate them in the Sri Lankan context. Thus, this paper investigates the causes of wind-induced damages on roofs in Sri Lanka and appropriate strategies to mitigate them. Accordingly, the paper is structured as follows. First, literature review is provided by discussing why roofs are highly subjected to wind-induced damages, factors that influence wind-induced damages on roofs. Context specific information related to wind-induced damages in Sri Lanka and the current standards and practices adopted in Sri Lanka also provided within the literature review. Following the literature review, the research methodology of the study has been discussed. Analysis and discussion are provided thereafter, evaluating the empirical evidence gathered from the study together with key literature related to them. Header should have numbering

2. Literature Review

2.1 Wind-induced disasters

Wind is initiated by the density difference or pressure gradient between points of equal elevation. There are several wind climates that might result in strong wind, to name a few; monsoons, frontal depressions, tropical cyclones, gust-front, downburst, tornadoes, devils, gravity winds and lee waves (Tamura 2005; Tamura and Cao 2009). High winds can have other indirect effects as areas along the cyclone path may receive very heavy and widespread rainfall that leads to flash floods and landslides (Jin and Yan 2009). Extreme wind conditions can cause fatalities and injuries due to falling, flying or collapsing objects and direct damage to property and the economy by disrupting transportation and communication systems and services due to falling trees or damage to power transmission lines (Tamura and Cao 2009). According to Tamura (2005), most wind-induced damages have been concentrated on roofs and particularly in their cladding around eaves, ridges and corners.

2.2 Wind-induced damages on the roof

When the damages caused by wind-induced disasters are concerned, the studies have shown that most damage occurs because various building elements have limited wind resistance due to inadequate design, application, material deterioration, or roof system abuse (Badiu and Bratucu 2014). When high winds affect a building, it is well established that the highest forces occur along the building edges. On the roof, these locations are near the eaves, ridges, hips and rakes. Hence damage initiated on these edges can lead to progressive failure of the rest of the roofing (Tamura 2005; Badiu and Bratucu 2014). Hence most wind-induced damages have been concentrated on roofs and particularly in their cladding around eaves, ridges and corners (Tamura 2005).

2.3 Factors that influence wind-induced damages on roofs

There are number of factors, which cause wind-induced damages to roof of the building. When wind interacts with roof both positive and negative pressures occur simultaneously. The magnitude of the pressures is a function of the following primary factors which could influence wind-induced damages on roofs (American Society of Civil Engineers [ASCE] 2017; Whole Building Design Guide [WBDG] 2018).

- **Exposure:** The characteristics of the ground roughness and surface irregularities in the vicinity of a building influence the wind loading. ASCE 7 (2017) has defined 03 types of exposures as Exposures B, C, and D. Exposure B includes urban, suburban, and wooded areas. Exposure C includes flat open terrain with scattered obstructions and areas adjacent to oceans in hurricane-prone regions. Exposure D includes areas adjacent to large water surfaces outside hurricane-prone regions, mud flats, salt flats, and unbroken ice. The smoother the terrain, the greater the wind load
- **Basic wind speed:** ASCE 7 defines the basic wind speed as the wind speed with a 50–year mean recurrence interval (2% annual probability), measured at 33 feet above grade in Exposure C.

- **Topography:** Abrupt changes in topography, such as isolated hills, ridges, and escarpments, cause wind speed-up (WBDG 2018)
- **Building height:** Wind speed increases with height above the ground. Therefore, the taller the building, the greater the speed and, hence, the greater the wind loads (ASCE 7 2017)
- **Internal pressure:** Wind striking a building can cause either an increase in the pressure within the building (i.e., positive pressure), or it can cause a decrease in the pressure (i.e., negative pressure). Internal pressure changes occur because of the porosity of the building envelope. When a building is pressurized, the internal pressure pushes up on the roof. This push from below the roof is combined with the suction above the roof, resulting in an increased wind load on the roof (WBDG 2018)
- **Aerodynamic pressure:** Because of building aerodynamics (i.e., the interaction between the wind and the building), the highest uplift loads occur at roof corners.
- **Roof design and shape:** The shape and angle of a roof affect the building's lift in high winds (Dean and Frei 2008)
- **The types of roofing materials:** Among roof materials, asphalt, shingles, tile, metal wood, shakes must be installed properly to protect a building from high winds (Caufield et al. 2012). The way these materials are installed can also increase the chances for failure (Evans and Mandt 2003). The mortar or adhesive placed under the roofing material also important in supporting the structure and protecting it (Caufield et al. 2012)
- **Roof connections:** For a building to be safe in high winds or cyclones, its structural integrity is extremely important. Structural integrity depends on the provision of Anchorage, Bracing and Continuity (A, B and C) right throughout the structure (Hazard Resilient Housing Construction Manual 2015)

2.4 Impacts of wind-induced disasters in Sri Lanka

During the years of 1978, 1992, 2000, 2003 and 2010, 2014, 2016 massive losses and damages have been caused due to cyclones in Sri Lanka (Srisangeerthanan et al. 2015; Disaster Information Management System 2018). Strong winds in the order of 50m/s can be expected in the coastal zone (Hazard Resilient Housing Construction Manual, 2015). Mostly, the east and northeast coastal areas of the island suffer from highly destructive winds during the cyclone season and the monsoon seasons annually (Srisangeerthanan et al. 2015). The houses located in the districts of Anuradhapura, Trincomalee, Polonnaruwa, Colombo and Batticaloa appear to have been most affected due to wind events (Disaster Information Management System 2018). In July 2018, severe winds have caused damages to 262 houses and 05 commercial properties in the areas of Homagama, Moratuwa, Kesbewa, Padukka, Ratmalana and Dehiwala and 849 individuals from 263 families got affected as a result (Disaster Management Centre 2018).

2.5 Currently practicing codes and standards in Sri Lanka

As a result of the cyclone which severely affected eastern and north eastern coastal areas in 1978, Sri Lankan Government introduced "Design of Buildings for High Winds, Sri Lanka" (1980) to be followed when designing buildings for high winds. This was based on CP-3 Chapter-V, part-2:1972 and the document is more suitable to be applied for design of low-rise buildings (Chaturanga et al. 2016; Weerasuriya et al. 2016). According to the Design of Buildings for High Winds, Sri Lanka (1980), wind loading zones has been established by dividing Sri Lanka into three (3) wind loading zones for the purpose of design of buildings and structures. The basic wind speed considered for the design of residential houses in each zone are Zone 1 – 49.0m/s, Zone 2 – 42.5m/s and Zone 3 – 33.5m/s. Severity of wind effects is highest in Zone 1, an approximately 50km wide belt along the North East Coastline and reduces in the order, Zone 2 and Zone 3. Figure 1 illustrates the wind loading zones of Sri Lanka.

The design manual "Design building for high winds – Sri Lanka" is the only mandatory document available for wind load design in Sri Lanka, although it extensively covers the design and construction of low-rise buildings (Weerasuriya et al. 2016). However, the evolution of tall building construction requires advances for Sri Lankan wind loading standards, which cannot be prepared yet due to lack of available data and technology. Therefore, designers have used different international standards such as CP 3 Chapter V – Part 2:1972, BS 6399.2:1997, AS 1170.2:1989, AS/NZS 1170.2:2002 and EN 1991-1-4:2005 for wind design for medium and high-rise buildings (Chaturanga et al. 2016).

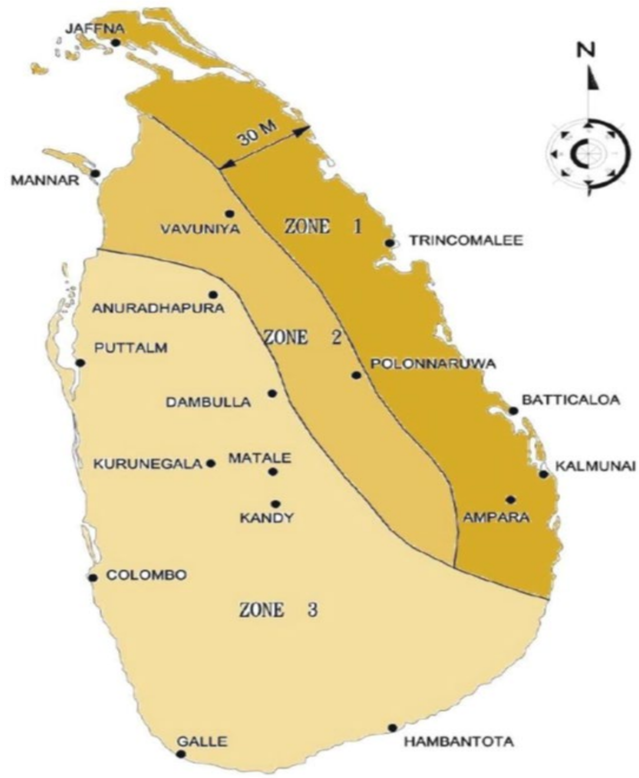

Figure 1.Wind loading zones of Sri Lanka (Source: Hazard Resilient Housing Construction Manual 2015)

The literature review identified the existing standards and codes currently published in Sri Lanka as Hazard Resilient Housing Construction Manual (2015)-Hazard Resilient Construction Series No. 1 by NBRO, Design of Buildings for High Winds in Sri Lanka by Ministry of Local Government Housing and Construction (April 1980) and Technical Guideline for Resilient Construction (2018) by NBRO and UNDP.

3. Research Methodology

This research administered a qualitative approach. Qualitative approach directs to capture in depth opinion and understanding of the respondents by exploring their experiences, attitudes and behaviour (Dawson 2007). Having considered the exploratory nature of the study, this research was then subjected to a qualitative research approach using semi structured interviews with seven subject matter experts. These subject matter experts are specialized in disaster management of wind-induced disasters. The number of experts were limited to seven (07) due to the data saturation. Semi structured interviews were employed since they are flexible and allow a researcher to ask questions that are not that structured and explore spontaneous issues raised by the interviewees (Berg 2009). The profile of the subject matter experts is summarized in Table 1.

Table 1. Profile of the respondents

Respondents code	Designation	Work experience (years)
R1	Director, Human Settlements Planning and Training Division, National Building Research Organization (NBRO)	20-25
R2	Senior Scientist, NBRO	15-20
R3	Disaster Risk Reduction Advisor- United Nations Development Program (UNDP)	10-15

R4	Professor, University of Moratuwa	15-20
R5	Deputy Director , Department of Meteorology	20-25
R6	Engineering Consultant	10-15
R7	Technical Specialist, Disaster Management Center (DMC)	20-25

According to Hsieh and Shannon (2005), content analysis provides subjective interpretation of texts in a qualitative research using systematic coding and patterns. Hence the data was analysed using manual content analysis.

4. Research Findings and Discussion

4.1 Reasons for considering roof as the most critical element affected by wind

Extreme winds can cause fatalities due to falling, flying or collapsing objects and direct damage to buildings. The mainstream literature revealed that amongst the building elements affected by wind, the roof is the most vulnerable. According to the respondents, since Sri Lanka is located near the confluence of the Arabian Sea, Indian Ocean, the Bay of Bengal and the tropical cyclone path, cyclonic storms and gale force winds are associated with monsoon activity or severe weather changes in the Bay of Bengal. Hence winds are becoming a common disastrous situation in Sri Lanka. All the respondents endorsed the view that even in the Sri Lankan context, roof is the most critical element affected by wind. R1 stated; *"blowing off of roofs of buildings along the cyclone path is a typical damage caused by extreme high winds"*. As pointed out by R3, the roofs are vulnerable to significant wind forces because of their higher elevation from the ground and lighter weight. As a result, roofs are damaged by falling trees at higher elevation. R4 commented; *"having sharp corners and protruding eaves make the roof vulnerable to wind forces"*. As highlighted by R7, *"compared to other elements of the building, when the roof lacks in proper bearing and anchoring to the superstructure, it can easily be blown away and this is commonly observed in the Sri Lankan context"*. He further asserted that local wind flow separation at the building causes high negative pressures near roof edges, especially at the eaves, gables, ridges and hips.

As a result of the impact of winds, the roof sustains damages severely, compared to other elements of the building. These findings corroborated the findings of Tamura (2005) as he claimed that most wind-induced damages have been concentrated on roofs and particularly in their cladding around eaves, ridges and corners. R2 pointed out; *"lifting the roof cladding at eaves or gable end and lifting of reepers from rafter are commonly observed in Sri Lankan houses affected by wind"*. In addition, R3 claimed that breakage of cantilever rafter at eaves and collapsing of roof truss have been recorded during the recent wind disaster situations. Among roof materials, asphalt, shingles, tile, metal wood, shakes must be installed properly to protect a building from high winds (Caufield et al. 2012). The way these materials are installed can also increase the chances for failure (Evans and Mandt 2003). The mortar or adhesive placed under the roofing material also important in supporting the structure and protecting it (Caufield et al. 2012). These findings support the claims of Badiu and Bratucu (2014) and Tamura (2005) of the roof system abuse leading to wind-induced damages to buildings.

4.2 Factors influencing wind-induced damages on roofs in Sri Lanka

The wind loads acting on the roof are decided upon many factors, since the wind speed and thus atmospheric pressure causes various impacts on the roof. The underlying factors have been pointed out by the respondents. All the respondents claimed that location and topography around the building is the main factor, since it determines the level of building exposure to winds. R3 explained; *"Wind speed increases as it passes over or between hills, but it may slow down as it passes over rougher terrain"* R1 stated; *"wind speed accelerates over open and flat large expanses of land or water"*. This mirrored the findings of the impact of exposure (ASCE 7 2007) and topography (WBDG 2018). R4, R5 and R6 pointed out that structures and vegetation around the building has an impact on the wind load acting on the roof. According to R5, *"wind load can be slowed by trees and vegetation around the building"*. R6 added; *"certain species of trees act as barriers to blowing and hence reduce the effect on the structure"*. Another factor highlighted by the respondents is the proximity and the height of neighboring buildings or structures. R4 explained; *"wind forces decrease when a site is surrounded by taller buildings but increase where it funnels around or between buildings"*. Hence the higher the building, the more exposed it will be to higher winds particularly as proven in ASCE 7 (2017).

The shape of the building has a major effect on wind separation and hence the magnitude, nature and distribution of wind forces acting upon them. Dean and Frei (2008) also pointed out that the shape and angle of a roof affect the building's lift in high winds. Elevation and height of the building above ground is also a factor affecting wind impact. R3 explained; *"tall buildings and buildings on higher elevation are more vulnerable to wind forces"*. Accordingly, poor workmanship leads to create disastrous impact on the roof during high windy situations. R6 and R7 pointed out that Sri Lankan houses and low-rise noncommercial buildings are still being constructed with clay tiles and in the rural areas, thatched roofs are still visible. Hence the choice of roofing material also leads to create adverse impacts on roofs due to winds. Caufield et al. (2012) also argued that some roofing materials are not effective to resist high winds. R7 stated his opinions on workmanship; *"design and construction of roofs are done so carelessly, so that roofs with poor connections are blown away during high winds".* Therefore, poor workmanship is arguably causing damages to roof.

Although certain guidelines are in place to design building structures to mitigate wind-induced damages, there are number of factors that prevent the adoption of these guidelines. All the respondents claimed that people are reluctant to adopt the guidelines. R1 explained; *"From the high-end building contractor to the carpenter in the village, reluctance to change is evidence. They are quite used to practice the ad-hoc methods, they have been using for years and thus do not like the technical guidelines".* Certain guidelines are too technical and difficult to be convinced and understood. According to R2, *"technical details in the guidelines are not well understood especially by construction workers".* Despite the fact that certain areas have been identified to be mostly vulnerable to wind disasters, lack of real time monitoring systems to predict wind-induced damages in the zones is challenging. R7 asserted; *"As a country, we are still lagging behind in novel technological applications to mitigate wind-induced damages".*

According to the respondents, Design of Buildings for High Winds in Sri Lanka by Ministry of Local Government Housing and Construction (April 1980) is the widely followed guideline and it corroborated the findings of Weerasuriya et al. (2016), although the stakeholders are not solely dependent on it. The Technical Guideline for Resilient Construction (2018) by NBRO and UNDP is not being used yet since it is relatively new. Hazard Resilient Housing Construction Manual (2015) - Hazard Resilient Construction Series No. 1 by NBRO is widely used for post disaster reconstruction of sites affected by landslides. Lack of financial support to practically implement the strategies among beneficiaries is highlighted and R3, R4 and R7 opined that the government lacks the interest in facilitating funding. Lack of coordination among the stakeholder organisations to implement awareness programs among contractors, technical officers, supervisors, construction workers is also a significant challenge. In addition, R4 highlighted; *"since the disaster resilient model houses are constructed focusing mainly on landslides and floods, potential damages induced by winds are overlooked".* Scarcity of material in the local market to construct resilient roofing has been highlighted with the less availability of resilient roofing material at affordable prices.

4.3 Strategies to mitigate wind-induced damages on roofs

Certain strategies to mitigate wind-induced damages on roofs were proposed by the respondents. According to all the respondents, land selection, orientation of the building and shape of the structure are of grave importance. R1 commented; *"selecting a location where the wind does not blow direct on to the structure from any direction can be reasonable precaution"*. R2 advised; "*avoid exposed locations as practicable as possible. In unavoidable situations, the building should be properly sheltered".* Selecting a sheltered location with permanent shelter is another measure. In hilly terrains, whenever possible, locating the building in a valley, but away from any strong wind paths. According to R5, *"orientation of the house should be such that the wind force is minimum".* The respondents opined that the shape or the design profile of a building has a major effect on wind separation and hence the magnitude, nature and distribution of wind forces acting upon them. R6 suggested; *"rectangular structures should be planned to have their shorter sides facing the most critical wind direction in a wind tunnel situation"*. It was the opinion of the all the respondents that avoiding irregular shapes as far as possible is beneficial because simple symmetrical shapes offer better stability under wind loads. According to R7, "*square or rectangular shapes are preferable. Although a circular or even an octagonal floor plan may ideally streamline the wind flow from any direction, they pose functional difficulties"*.

Roof type and its slope can play a major role in the event of a wind. R3 explained; "*suction forces on low-pitched roofs cause lifting off of the roof cover. Suction can be substantially reduced by having a pitch of 45°. If this is not practical, slopes less than 30° should be avoided as far as possible"*. As explained by the respondents, hipped roofs are better than gable roofs in withstanding wind forces. However, to be effective, any overhangs should be kept as small as possible. Best practices for spacing and sizing of members of timber roof structure should be adhered to. R1, R2, and R6 advised that specifications of timber roof structure for sheet and tiled roofs should be obtained from Hazard Resilient Housing Construction Manual (2015) - Hazard Resilient Construction Series No. 1 by NBRO. They further advised on the use of installing corrugated asbestos cement sheets as per the Hazard Resilient Housing Construction Manual (2015), i.e. gable end area and overhangs should be 3 hook bolts and washer and the general roof area should be 2 hook bolts and washers. R7 asserted that reinforced concrete flat roofs can be utilized to provide greater resilience to high winds. Roof connections play an important role in mitigating wind impacts. R1, R6 and R7 quoted the Hazard Resilient Housing Construction Manual (2015). R6 commented; *"In terms of anchorage, every part of the structure must be tied back to some secure point to resist all the applied forces and bracing should be designed as such every part of the structure must be held rigid so it cannot tilt, slide or rotate"*. R1 opined that every part of the structure must be property connected to every other member in the ''strength chain" from the cladding to the ground for ensuring continuity. He explained that strength chain is a continuous load path carrying the wind loads acting on the roof and walls down through the structure to the foundation.

The above discussed findings have been mapped in as shown in Figure 2.

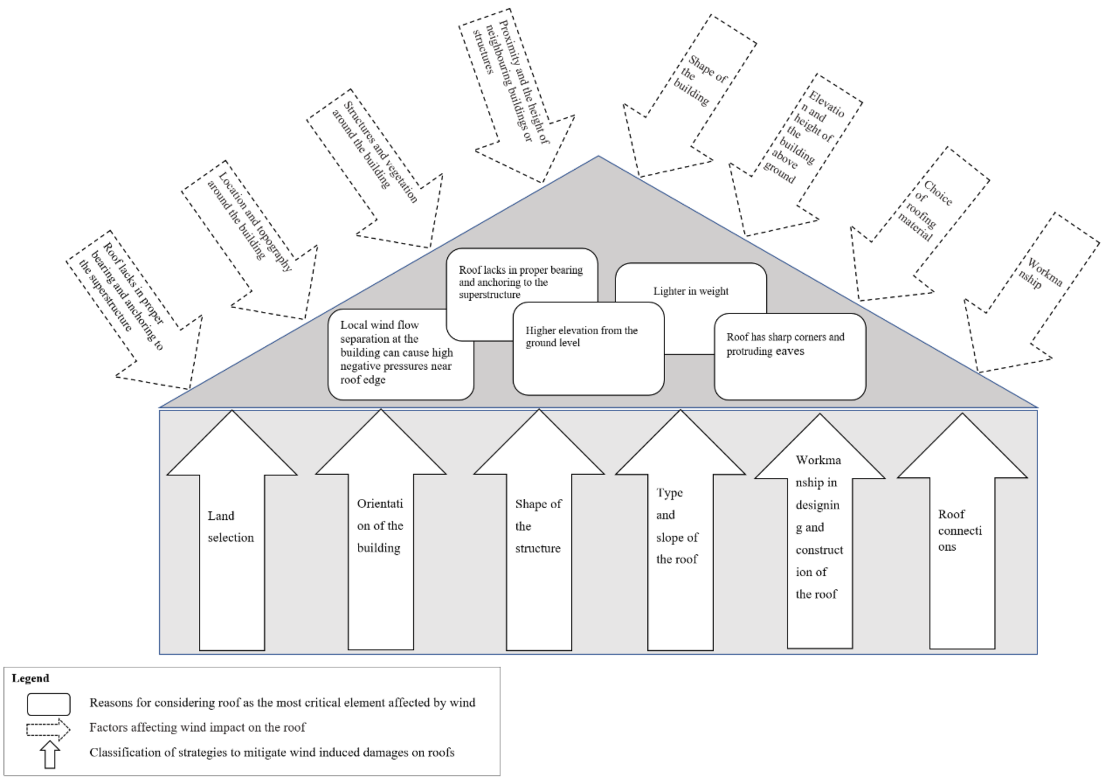

Figure 2: Mapping of the Findings

Based on this mapping, it can be argued that, wind-induced damages on roof has two main origins, namely environmental related and human related. Environmental related factors include the location of the building, topography of the land, and presence of vegetation in the surrounding area. Human related factors can be further divided into design (orientation of the building, shape and slope of the roof, type of roofing material used, roof bearings) and workmanship (poor workmanship, use of inferior roofing material and connections) related factors. Based on this analysis, it can be seen that minimizing damages on roofs due to wind can be done through two approaches. First approach is proper land selection by avoiding high-wind susceptible areas. The second approach includes proper design and workmanship of roofs, which impost responsibility on the construction workforce, both skilled and unskilled. Due to the scarcity of the lands and other prevailing socio-economic reasons, selecting a low-wind prone area could be challenging. Therefore, both designers and workers who are engaged in the construction industry has a huge role in minimising the impact of wind-induced damages on roofs. Further, it can be argued that some of the triggering conditions of strong wind could also be minimised up to some extent by growing vegetation and by adhering to proper landscaping practices. Placing greater responsibility on the construction workforce further strengthen the argument that there are no disasters created by nature, but they are man-made.

5. Conclusions and Recommendations

Roof has been identified as the most critical element vulnerable to wind-induced damages. Previous studies were more focused on identifying the factors, which determine the magnitude of the pressure acts on the roof due to wind forces. This study, which has adopted a qualitative approach contributes to the existing body of knowledge by identifying key factors that influence wind-induced damages on roofs due to wind speed and thus atmospheric pressure and additionally human related factors. These factors affirm why roof is the most critical element in the event of a wind related disaster.

The study categorised the wind-induced damages on roof in to two main origins, namely environmental related and human related. Accordingly, it was also deduced that minimising damages on roofs due to wind can be done through proper land selection by avoiding high-wind susceptible areas and proper design and workmanship of roofs. Thus, the study reconfirms that both designers and workers have a greater role in minimising the impact of wind-induced damages on roofs. Further, in terms of the impact on the practice, the study would assist the building designers to consider appropriate measures when designing roofs.

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