Wind Induced Damage to Roofs and Mitigations: A Comparative Study on Roofs in Bhutan and Japan

A final research report presented

by

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to

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ABSTRACT

Windstorms have become more frequent and widespread hazards in recent years in Bhutan. During 2011 and 2013 windstorms, 2424 and 1017 rural home roofs were damaged respectively and caused huge economy loss to the government. The past windstorm damages reveal that the rural home roofs are more vulnerable to strong winds given the nature of rural home construction in Bhutan.

In this study, the rural home roofs in Bhutan and Japan is studied based on the roofs; configuration, shape, slope, size, overhang, connection, support and roofing material used. The study is mainly carried out to assess the windstorm damage on the rural home roofs in Bhutan based on the above mentioned category comparing with the Japanese roof structures.

In this study, roof type, roof overhang, anchorage, roof-to-wall connection and support string vs damage is assessed using the survey data of four districts in Bhutan and reports of the roof damages.

From this study, it is concluded that most of the rural home roofs in Bhutan failed due to poor connections between roof-to-wall and pull through failure during the strong wind. This study proposes a few mitigation suggestion and recommendation to reduce the future damages by providing the strong support string and proving sand bags on the roof to prevent the uplift.

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LIST OF ABBREVIATIONS

AAWE	American Association for Wind Engineering
ADRC	Asian Disaster Reduction Center
ASCE	American Society of Civil Engineers
BAG	Bhutanese Architecture Guidelines
BHU	Basic Health Unit
CFD	Computational Fluid Dynamic
CGI	Corrugated Galvanized Iron
CIT	Chiba Institute of Technology
DCA	Department of Civil Aviation
DDM	Department of Disaster Management
DES	Department of Engineering Services
DHS	Department of Human Settlement
DoC	Department of Culture
DSE	Department of School Education
ESWL	Equivalent Static Wind Load
GI	Galvanized Iron
GLOF	Glacial Lake Outburst Flood
kN	Kilo Newton
N	Newton
NAPA	National Adaptation Programme of Action
NFE	Non-Formal Education
NSB	National Statistical Bureau

ORC	Outreach Clinic
RGoB	Royal Government of Bhutan
RNR	Renewable Natural Resource
RBP	Royal Bhutan Police
TAG	Traditional Architecture Guidelines
UNDP	United Nations Development Programme
VR	Visiting Researcher

GLOSSARY

Chorten	Stupa
Dzong	Fortress
Dzongkhag	District
Dungkhag	Sub-district
Jamthok	Elevated roof like monitor roofs
Lhakhang	Temple
Thromde	Municipal
Gewog	Administrative Block consisting of a number of villages under a District

CHAPTER 1: INTRODUCTION

1.1 Background

In the recent years, wind induced disaster is increasing and causing huge damages to rural home roofs in Bhutan. In 2011 and 2013 windstorms, 2424 and 1017 rural home roofs were damaged respectively causing the huge losses to the government and livelihood of the rural people. The rural people are very much concerned of the wind induced disaster but however the people involved in the windstorm activities in Bhutan is very less due to the lack of wind engineering capacity.

The rural home roofs in Bhutan are constructed by the carpenters based on their indigenous knowledge. Therefore, rural home in Bhutan is non-engineered construction. Till the early 1960's when Bhutan is not open the other world, people are using the wooden shingle or other local materials as roofing materials which is more eco-friendly and wind resistant. The people at the time were clever to use of the natural surrounding and wisdom to live in harmony with the environment. Therefore, there were no records of severe windstorm damage to roof in Bhutan. As per the Lotay's study paper (2013), in the early 1980s the roofing materials started changing from the wooden shingles to the corrugated galvanized iron (CGI) sheets. The most of the roof configuration are not changed even though the roofing materials are changed.

The change from wooden shingles to CGI sheets as a roofing materials are getting popular in Bhutan due to its durability and affordability for the rural people. Also government encourages the rural people to use the CGI sheets by giving the tax exemption to reduce the pressure on the timber use. Without the proper study on the wind effect on the CGI sheets as a roofing material for the rural home in Bhutan, it is causing huge damage during the windstorm.

As per the Lotay (2013), most of the Bhutan houses fall under the low rise building and low rise building suffered huge damages due to the lower aerodynamic boundary layer on the ground surfaces with high turbulence intensity.

In case of Japan, Japan has also lot of old houses like Bhutan. Most the traditional Japanese roofs are constructed based on the climate, culture and customs characteristics of each locality. Similar to past Bhutan, most of the roofing materials used was straw and eco-friendly materials from the surrounding natural during the Edo period (17-19th century).

1.2 Problem Statement

Bhutan is located in the Himalayan Range and strong seasonal wind causes huge damages to the structures and crops in Bhutan. Among the damages, roofs are mostly damaged during the windstorms. In 2011 and 2013 windstorm, 2424 and 1017 rural home roofs are damaged respectively. More than 60 per cent of the population of Bhutan lives in the rural homes and people depends on agriculture for their livelihoods.

Almost all the rural home construction in Bhutan was non-engineered. The roof is constructed using the timber or bamboo circular rafters and purlins with new replaced roofing material called corrugated galvanized iron (CGI) sheet metal. The houses are built by the local carpenters, who do not have much knowledge on the new roofing materials, even though carpenters are experts in the use of local roofing materials like wooden shingles. The changing of roofing materials from the wooden shingles to the light CGI sheets started in the early 1980s in Bhutan (Lotay, 2013). As of now, most of the rural home roofing materials are changed to light roofing materials like CGI sheets due to affordable, durable and less maintenance but no one has carried out any study on the change of the roofing materials in Bhutan environment. Local people do not understand the wind phenomena of the new roofing materials.

Most of the roofs are roofed with CGI sheets without changing the roof configurations; instead carpenters or people themselves invented or created their own ideas in closing the attics with ply board or timber planks and providing the support strings to hold down the roofs. But all these ideas are not assessed or tested by any one. In the master thesis report of Lotay, 2013 he conducted the Computational Fluid Dynamic (CFD) simulations on the attic opening and closing parameters but he did not study much on the roof configurations, overhang effect and connections details failure.

1.3 Scope and Objective

The scope of this study is to assess the rural home roofs in Bhutan based on the roofs; configuration, shape, slope, size, overhang, support string, connections, overhangs and roofing materials and comparing with the Japanese traditional roof.

The main objective of this study is to assess the rural home roofs failure based on the existing roof configuration during the windstorm based on the literature review. This study aim is to identify ways to mitigate or improve the existing roof structures to reduce the future windstorm damage, taking good examples of Japanese traditional roof construction technique.

This study does not recommend the change of Bhutanese architecture of roof and mitigation using the high and costly technique especially for the rural home roofs. Rather it recommends the simple mitigation measure to be incorporated during the construction and reconstruction of the roof to reduce the future damages.

CHAPTER 2: LITERTURE REVIEW

2.1 Bhutanese Traditional Roof Types, Material and Configuration

2.1.1 Types of Bhutanese Roofs

A Bhutanese roof has a distinct character of the Bhutanese architecture in the eastern Himalayan region with the large overhang and simply supported on the rammed earth wall or attic floors. The traditional Bhutanese roof plays an extremely significant part in the characterization of traditional Bhutanese architecture, which is one of the most important elements in the traditional Bhutanese architecture (BAG, 2014).

The traditional Bhutanese houses are mostly constructed by rammed earth wall in the western part and stone masonry in the eastern part of Bhutan. The houses are of two or three storeyed with a ground floor room mainly used for livestock, second floor is use for storage and third floor is used for living and shrine room.

Most of the traditional roofs are relatively high with large attic space between the roof and attic floor. This huge space under the roof is used for storing and drying fodders, vegetables and other farm products in old days but nowadays many houses keep empty. It was observed during the data collection survey that the rural home roof overhang is very large as compared to urban roof in Bhutan, the roof overhang range between 1.0m and 2.5m which protect the walls from sun and rainstorm.

As per the Bhutanese Architecture Guidelines, the Bhutanese roof plays an important role in protecting the building from external environmental elements. Also it played an important role in defining the hierarchy and significance of buildings and their status.

According to Bhutan Building Code 2002, roof slopes should be maintained in the range of 12 and 15 degree, since Bhutan lies in 27 degree north, which is almost like Okinawa in Japan. Since, Bhutan has heavy rainfall from late June to September, but steeper roof slopes are not possible for traditional Bhutanese roof. Since, traditional Bhutanese roofs were using wooden shingles as roofing materials before changing to CGI sheets roofing. As it is difficult to maintain steeper roof slope because of the stones that fix the shingles would roll off the roof. Therefore, to protect attic spaces and building earthen walls from rain and direct sunlight, traditional Bhutanese roofs have large roof overhang.

According to the survey and research report on traditional Bhutanese houses prepared by Chiba Institute of Technology (CIT), Japan in collaboration with Ministry of Works and Human Settlement (MoWHS), Bhutan mentioned, that traditional Bhutanese roof has wide eaves to protect the rammed earth wall from rain. The wide over hang roof blocks direct sunlight and cool down the room in summer. Traditional Bhutanese roofs are constructed on top of rammed earth walls, like Japanese traditional store houses. The open space between attic floor and roof sheathing are used for dying cow fodders and grains. It acts as ventilation for the roof.

The report stated that there are two common roofs; gable roof and monitor roof between Japan and Bhutan. This report mentioned that traditional Bhutanese roof has not changed a lot and as compared to China and Japan, whereby they need to adapt with the climate ranging from sub-tropical to sub-arctic. Therefore, a roof in China and Japan has a strong connection with climate-based cultures.

As per the Bhutanese Architecture Guidelines, (2014) there are four types of roofs in Bhutanese architecture i.e are Jabzhi roof, Jamthok roof, Drangim roof and Chenkhep roof. The

Jabzhi roof is a square hipped roof with four corners and this roof is used in the high status building like Dzong (fortress) and palaces in Bhutan as shown in Figure 1. The hip and gable roof, Jamthok, Drangim, Gung-nim (gable) and Chenkhep (lean-to roof) roofs are used for the residential roofs in Bhutan as shown in Figure 2 to Figure 8.

Figure 1: Jabzhi roof with CGI sheet roofing

Figure 2: Traditional Bhutanese gable roof with shingle roofing

Figure 3: Gable roof with corrugated galvanized iron (CGI) sheet

Figure 4: Hip + gable roof with CGI sheet roofing

Figure 5: Drangim roof with CGI sheet roofing

Figure 6: Jamthok roof with CGI sheet roofing

Figure 7: Ura Village with Jamthok roof

Figure 8 : Lean-to roof with shingle roofing (L) and CGI sheet roofing (R)

2.1.2 Types of Bhutanese Roof Materials

Bhutanese traditional roofing materials were mostly the wooden shingles and slates (figure 9) in the eastern, central and western part of Bhutan until the early 1960s. Some parts of central and southern part were roofed with bamboo mat, leaves or straw. Based on the surrounding environment and climatic condition of the region, the roofing materials were selected.

As mentioned in the Lotay (2013) master thesis report, the change of the roofing materials started from early 1980s in the rural places in Bhutan.

As of now, most of the rural home roofing materials are changed to light roofing materials like CGI sheets due to affordable, durable and less maintenance. Also government encourages the rural people to use the CGI sheets by giving the tax exemption to reduce the pressure on the timber use. Without the proper research on the use of CGI sheet metal as roofing materials for the rural home roofs in Bhutan. Rural home roofs suffering the huge damages during the windstorm.

Figure 9 : Wooden shingles (L) and slate roofing (R)

Figure 10 : Thatched roofing (L) and bamboo mat (R)

Figure 11: Banana leaves roofing (source: DoC, 2010)

Figure 12: Corrugated galvanized iron (CGI) sheet metal roofing

2.1.3 Bhutanese Traditional Roof Configurations

As per the Lotay, (2013) research, he mentioned that the common Bhutan rural house roofs are gable roofs, which consist of heavy tie beam heavy tie beams supported with series of vertical struts below and above the beam. Purlins are laid parallel to the roof ridge and perpendicular to the rafters. The circular or square battens are laid over the rafters with a 200mm-300mm interval and the battens are tightened or fastened to the rafters using toe-nails or wires. Then, CGI sheets are laid over the battens and CGI sheets are nailed or screwed to prevent uplift. The weight from CGI sheets and purlins are supported by a series of vertical struts and transferred to attic floor or end walls. By varying the height of the struts and adjusting the battens, purlins and rafters, roof angles are created.

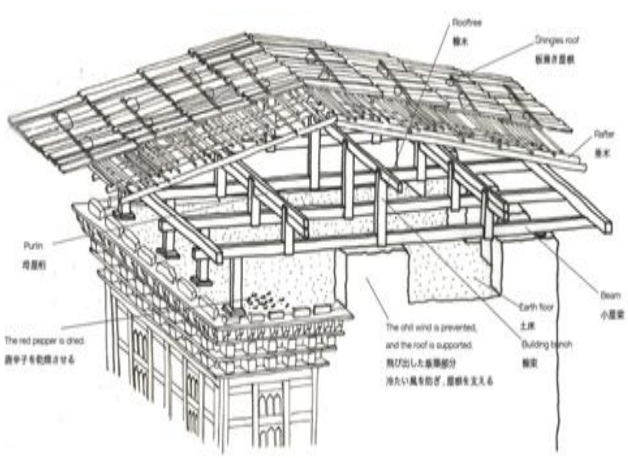


Figure 13: Bhutanese traditional roof configuration (source: CIT, 2010)

As per the Bhutanese Architecture Guidelines (2014), it described the Jamthok roof in Bhutanese traditional roof consists of a smaller gable which is litter raised above the larger and longer gable roof as shown in figure 14. The upper layer at the central part of the roof gives the more space area under the roof to store or to give more ventilation. Also the Jamthok roof with open space without window is called Lung-go, which means wind passage.

It was observed that these types of roofs are used in the region where they experiences very strong wind.

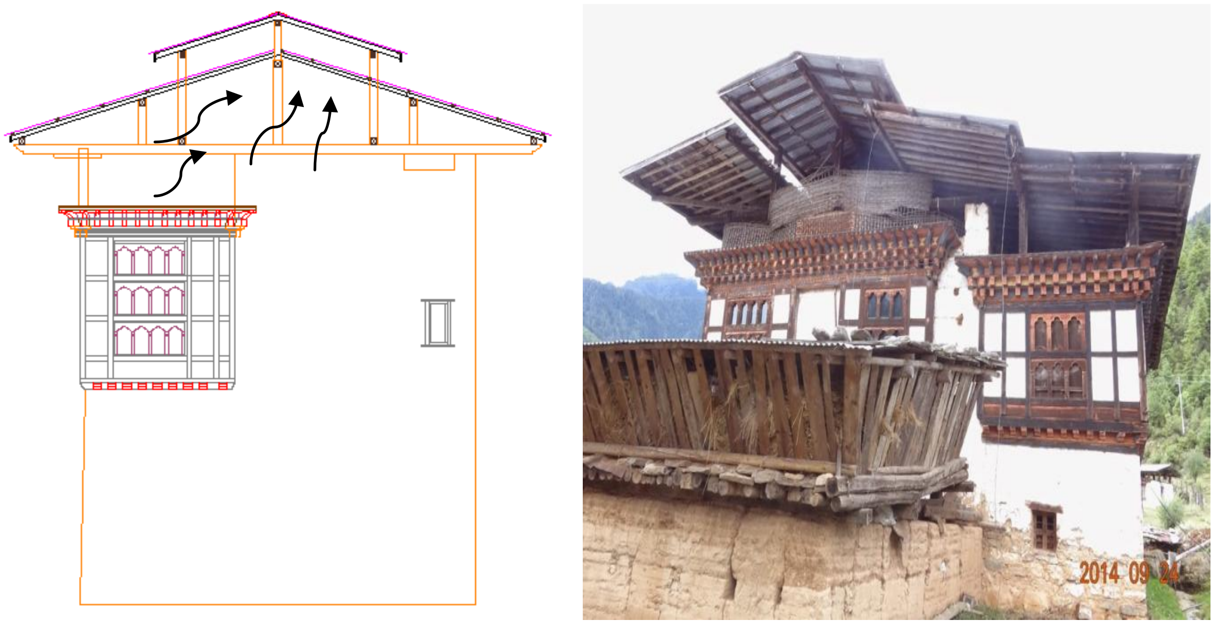


Figure 14: Jamthok roof configuration

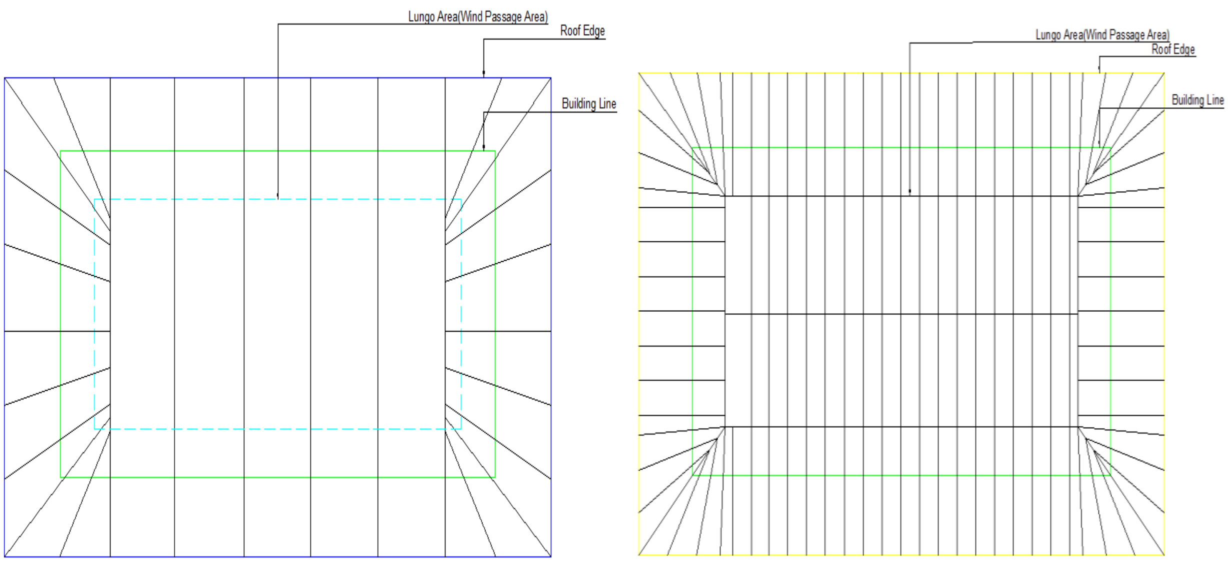


Figure 15: Hip + gable roof tie beam (left) and rafter (right) layout

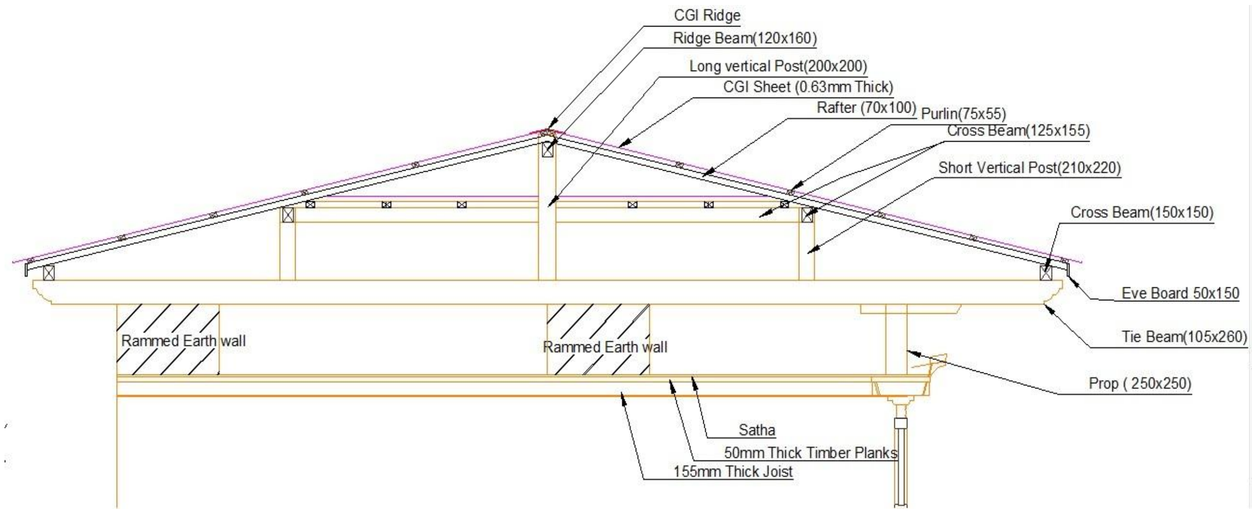


Figure 16 : Hip + gable roof configuration with CGI roofing

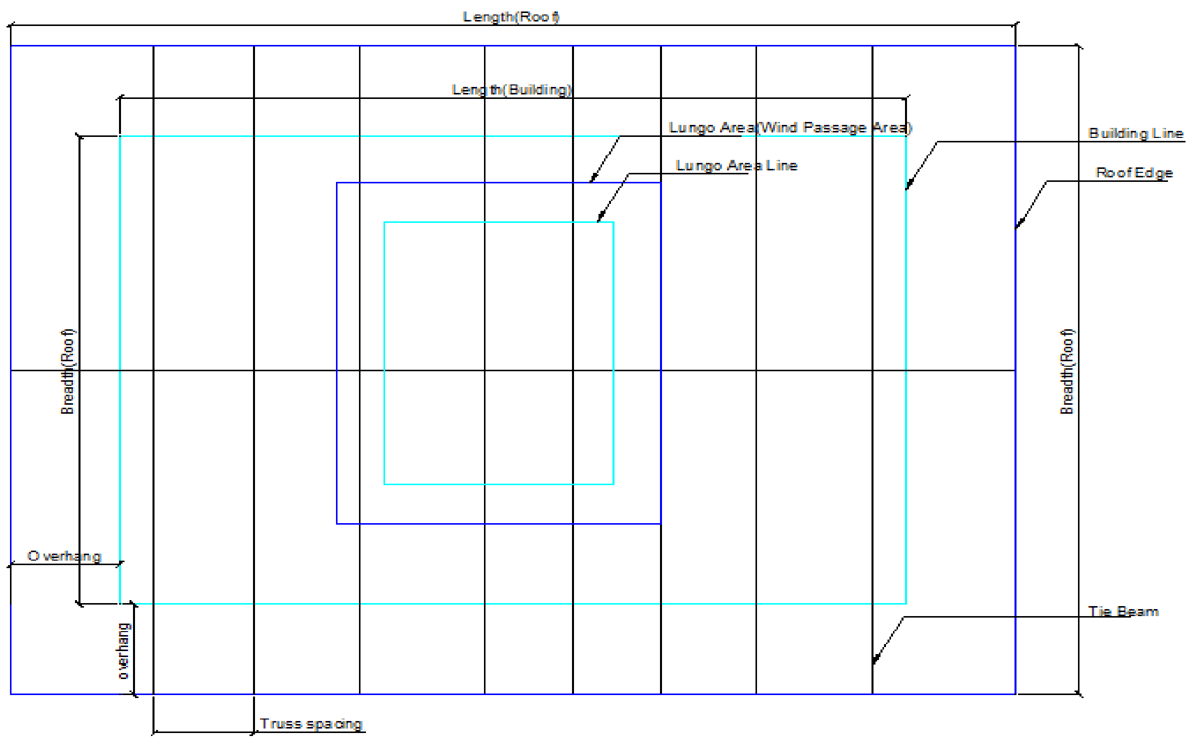


Figure 17: Jamthok roof tie beam layout

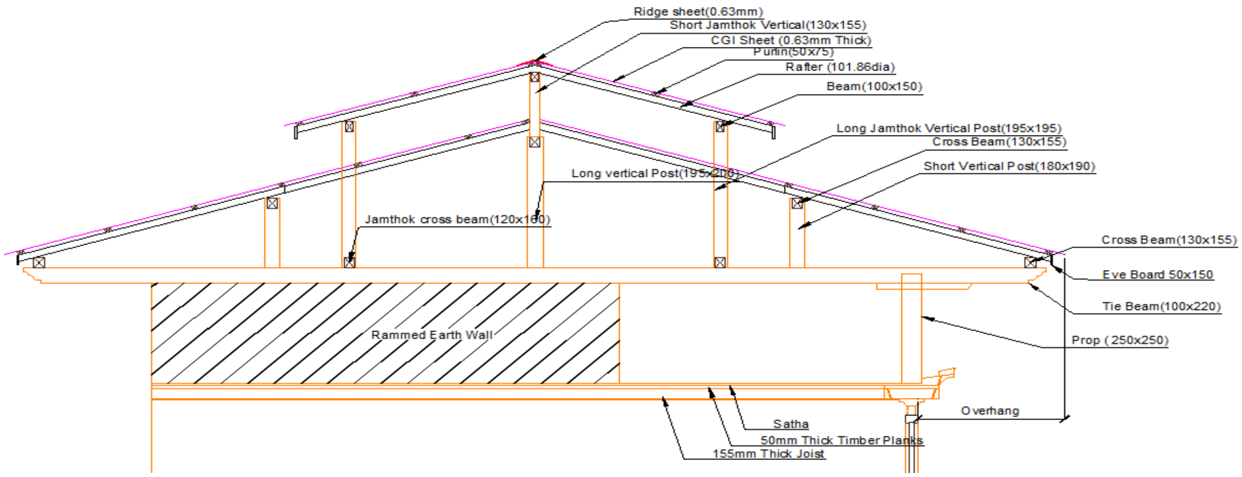


Figure 18 : Jamthok roof configuration with CGI sheet roofing

2.2 Japanese Traditional Roof Types, Material and Configurations

2.2.1 Types of Japanese Traditional Roofs

Japanese traditional architecture is well known for having an interesting roof design and very complex roof form in the Japanese architecture. Japanese traditional houses are built mostly by erecting the wooden columns on the flat packed earth ground or flat stones.

One of the unique characteristics of Japanese traditional houses is the houses have tremendous variety of roof styles, depending on the locality and the occupation of the owner. Also houses have large roof and deep eaves to protect the house from the hot summer sun and rainstorm. As mentioned in the open-air museum of old Japanese farmhouses, there are many types of Japanese roof types and farmhouse from Yamato Tosukawa, Nara has the large eaves to protect the house from strong wind and rain (Figure 19).

Figure 19: Farmhouse from Yamato Totsukawa, Nara with large eaves

The Japanese traditional roofs are classified into three types (**Figure 20**, **Figure 21** & **Figure 22**) as follows:

1. Yosemune (hip roof)
2. Kirizuma (gable roof)
3. Irimoya (hip and gable roof)

In the Japanese architecture of roofs, the gable roof (kirizuma) and hip roof (yosemune) are the two basic form of roof. The gable roof is composed of two inclined planes, parallel to the ridge of the roof. The hip roof is composed of four inclined planes, two inclined are parallel to the ridge of the roof and other two inclined planes are perpendicular to the ridge of roof forming the triangular shape.

Figure 20: Hip roof (yosemune)

Figure 21 : Gable roof (kirizuma) with thatched roofing (L) and cryptomeria bark roofing (R)

Figure 22 : Hip and gable roof (irimoya)

2.2.2 Japanese Traditional Roof Materials

Japanese traditional roofing materials are classified under four main types as follows:

1. Tile
2. Thatch
3. Plank or shingle
4. Bark

As per the Piccinini, (2003) the thatch, planks, shingles, barks and clay or copper tiles, a rich variety of roofing materials that has been used in the Japanese traditional architecture. It stated that tile has long history in Japan, the concave and convex tile (hongawara) was introduced in Japan around 538 AD along with Buddhism (Figure 23). Tiles in Japan were introduced based on the example of bamboo roofing in Indian and China (Figure 23). As per the Piccinini, (2003) planks, shingle and bark are the main three types of wood roofing materials in Japan. The sizes of the planks are 450 to 600mm long and 90 to 150mm wide with the thickness of 6 to 18mm. The slope of the roof are maintained about 20 degrees to prevent the stones rolling down from the roof.

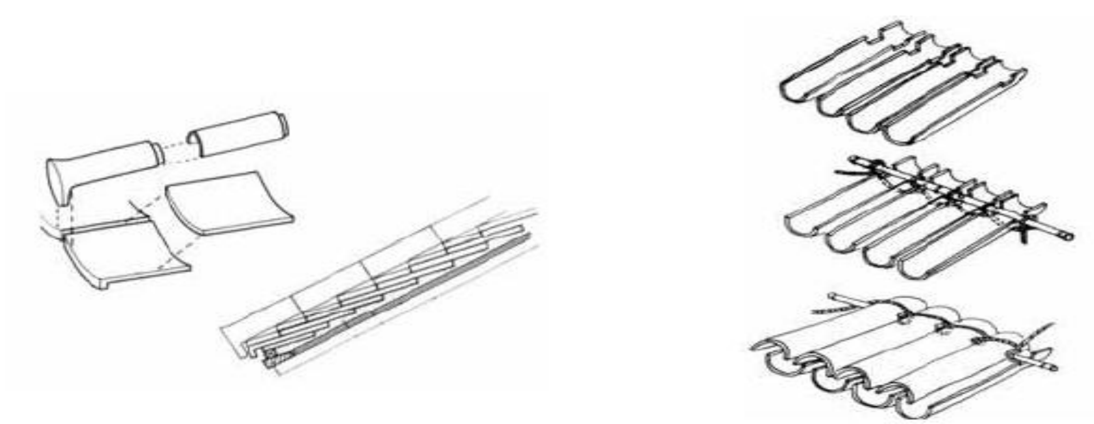


Figure 23: Concave and convex tile (L) and bamboo roofing (R) (Source: Piccinini, 2000)

The base tiles (hiragawara) are laid with the concave side facing up and semicircular tiles (marugawara) are placed over the concave tile. Tile roofing is heavy and need strong support the loads from the roof. There are also different types of tiles called kawara (Figure 24).

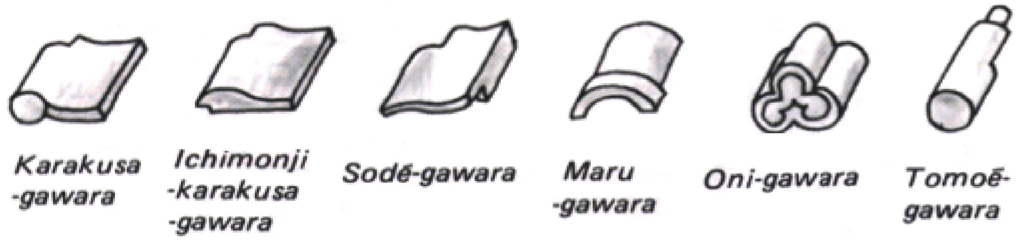


Figure 24: Types of kawara

In 17th century, the Kyoto pan tile (sangawara) was developed in the S shape, which gives good function for combination between base tile and cover tile. The S shape tile (Figure 25) requires less clay to prepare as compared to concave and convex tile. Therefore, S shape tile was much lighter than concave and convex tile. Also house with shingled roofing can be replaced using the S shape tile without changing the roof framework.

As per the Tsuruga Co. Ltd about 50% of Japanese houses used kawara as a roofing materials, which is made from natural materials and use of ceramic roofing tiles on Japanese houses since ancients times around 1400 years ago. It described that kawara have continuously evolved to possess with new additional features with the time change. In the recent time, the new features were incorporated in the kawara to withstand earthquakes, typhoons and heat insulation.

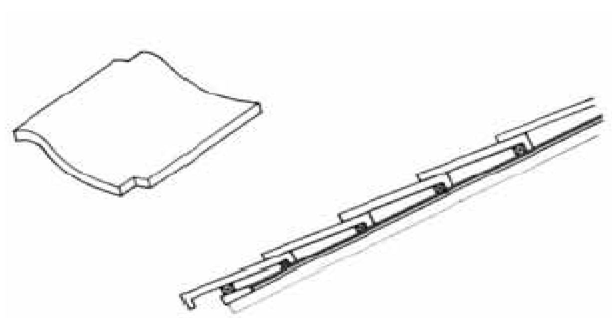


Figure 25: Pan tiles (sangawara) and its layout

One of the widespread roofing materials in Japan is thatch roof (Figure 26). It is light and does not require heavy truss framework to support, which became most economic roofing materials in Japan as compared to tiles roofing.

Figure 26: Thatch roofing

In the Sado Island of Niigata, people still used the wooden shingles with the stone over it to protect from the strong winds blowing in off the Sea of Japan (Figure 27).

Figure 27: Shingle or plank roofing in Sado Island Niigata (photo courtesy: Brian Southwick)

Figure 28: Bark roofing

2.2.3 Japanese Traditional Roof Configurations

The Japanese traditional roof has a unique roof configurations and they used all different lengths of members which can be spanned with equal-sized members (Engel, 1985). There are four main types of roof trusses in the Japanese traditional roofs (Figure 29 & Figure 30): Wagoya-gumi, Sasu-gumi, Shintsua-gumi and Noboribari-gumi. The Japanese truss (Wagoya-gumi) uses the series of vertical posts and mainly used for shingled or tiled roofing materials, which provides maximum supports along the slope and prevents from sagging. The brace truss (Sasu-gumi) is the triangular in shape and used for thatched roofs. The trusses are braces cross and the ridgepole is rest on the fork. The king post truss (Shintsuka-gumi) uses king posts which are vertical below the ridgepole and these types of trusses are used for shingled and tiled roofs. The rising beam truss (Noboribari-gumi) has the transverse beams below the purlins which eliminate many vertical posts which creates large space below the roof. These types of truss are used for shingled and tiled roofs.

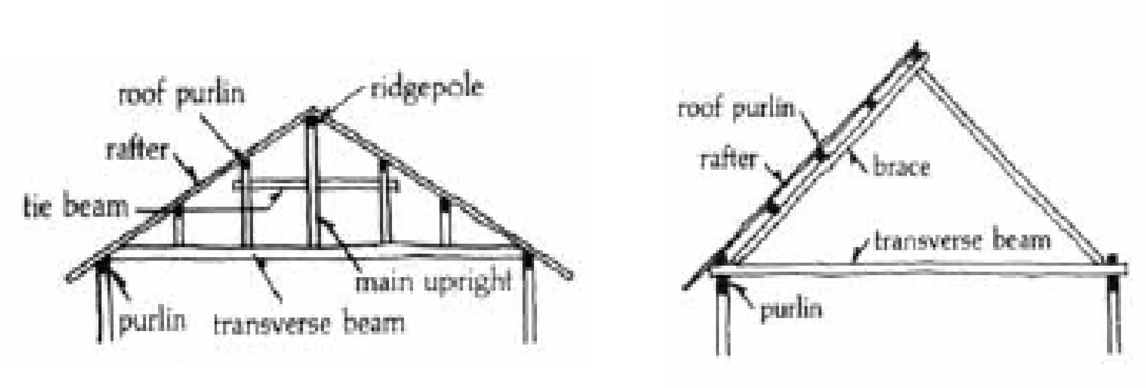


Figure 29: Japanese truss (Wagoya-gumi) (left) and brace truss (Sasu-gumi) (right) (Source: Piccinini, 2003)

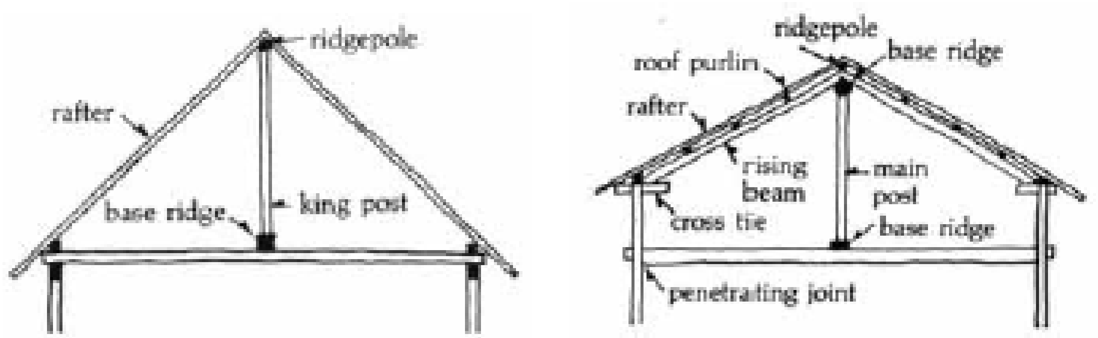


Figure 30: King post truss (Shintsuka-gumi) (left) and rising beam truss (Noboribari-gumi) (right) (Source: Piccinini, 2003)

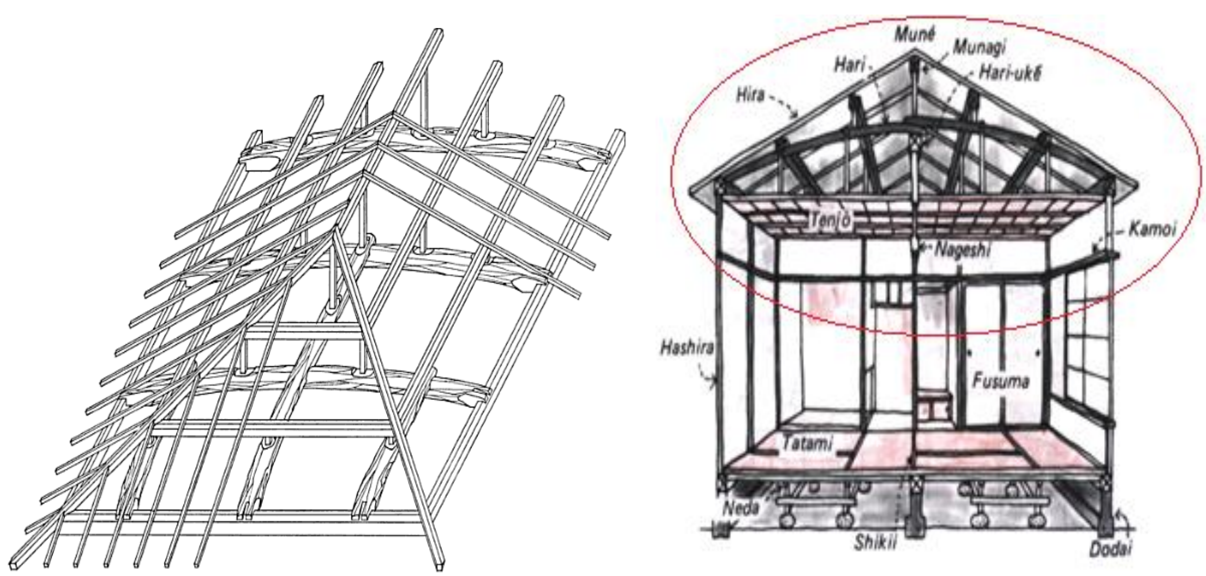


Figure 31 : Hip roof (light) and gable roof configuration (right) (Source: Engel, 1985)

2.3 Wind Characteristics and Wind Direction in the South Asia Region

As per the Tamura & Cao (2010), "*wind is fundamentally caused by the temperature gradient of the atmosphere due variable solar heating of the earth's surface. It is initiated, in a more immediate sense, by density difference or pressure gradient between points of equal elevation. Large-scale air flows are so-called global atmospheric circulations, and generation of strong winds is closely related to these circulations and also to smaller scale temperature differences*." The paper also stated that there are several causes to the strong wind due wind climates, e.g. monsoons, frontal depressions, tropical cyclones, gust-front, downburst, tornadoes and so on. Even in the south Asian region, the summer monsoons and winter monsoons which are seasonal wind movement causing sometimes cyclone or windstorm in the region Figure 32. Wind always flow from the high to low pressure zone. During the change of the season, Bhutan suffers from strong wind due to the pressure different in the north and south zones. In winter the high pressure zone is created in the northern Himalayan region and low pressure created in Indian Ocean, which bring cold strong wind from north to south and vice-versa in summer as shown in figure 32.

Tropical cyclones are intense cyclonic storms which occur in the tropical ocean areas, mostly in summer and early autumn. It is caused due to the severe low pressure systems. As per the FM Global, (2001) stated that they are called different names based on the location of incidents. "*In the Caribbean, the Gulf of Mexico and the United States, these storms are called hurricanes, but in the West Pacific (China, Hong Kong, Japan, Korea, the Philippines, Taiwan), they are known as typhoons. And, in the South Pacific (Australia, Fiji, Samoa) and Indian Ocean, they are called cyclones.*" In the case of windstorm, it is caused by the pressure different causing strong, violent winds without precipitation.

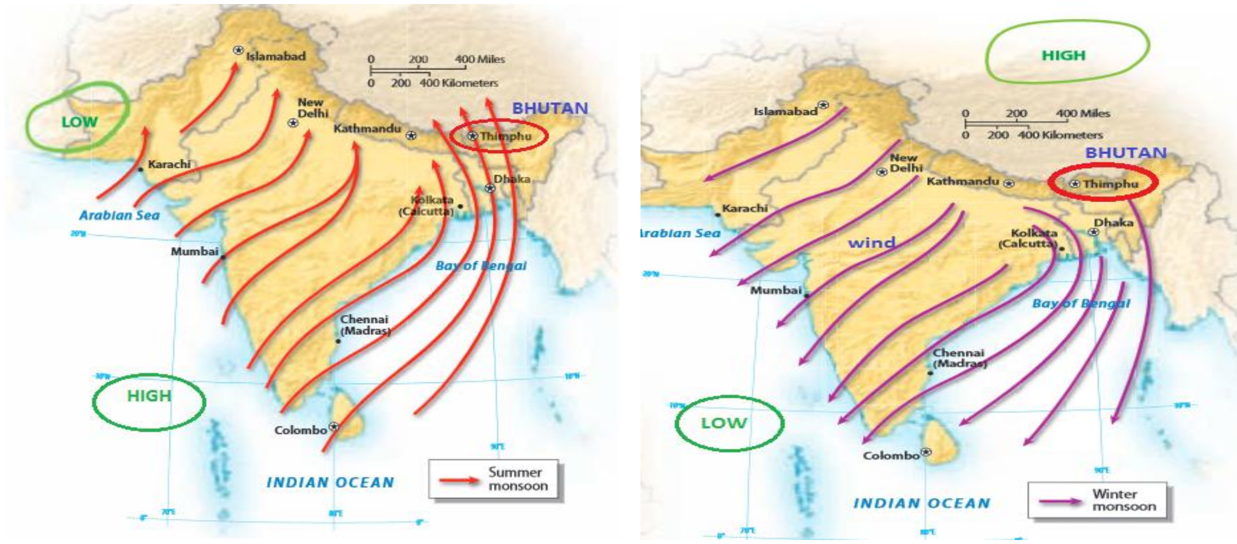


Figure 32: Summer (L) and winter monsoon (R) in the South Asia region (Source: www.pearsonhighered.com)

2.4 Different Scales of Windstorms

As per the Bhandari, Krishna, Kumar, & Gupta, (2005) there are various scale to measure the windstorm depending on the wind speed as shown in Table 1. During the 2011 & 2013 windstorm in Bhutan, the maximum gust wind speed of 22.0m/s and 24.4m/s was recorded respectively at the 10m above ground level as per the Department of Civil Aviation. Therefore, it is also important to check the Bhutan windstorm effect with other scale around the region.

Table 1: Various scales for measuring windstorms (Source: IS 875 (part 3))

Windstorm : Scales and Effects										
Beaufort Scale						Saffir–Simpson Hurricane Scale				
Bft	Descriptive term	Mean wind speed at 10 m above surface			Wind pressure	SS	Descriptive term	Mean wind speed		
		m/s	Km/h	knots	Kg/m²			m/s	Km/h	knots
0	Calm	0–0.2	0–1	0–1	0	1	Weak	32.7–42.6	118–153	64–82
1	Light air	0.3–1.5	1–5	1–3	0–0.1	2	Moderate	42.7–49.5	154–177	83–96
2	Light breeze	1.6–3.3	6–11	4–6	2.0–0.6	3	Strong	49.6–58.5	178–209	97–113
3	Gentle breeze	3.4–5.4	12–19	7–10	0.7–1.8	4	Very strong	58.6–69.4	210–249	114–134
4	Moderate breeze	5.5–7.9	20–28	11–15	1.9–3.9	5	Devastating	≥ 69.5	≥ 250	≥ 135
5	Fresh breeze	8.0–10.7	29–38	16–21	4.0–7.2	Fujita Tornado Scale				
6	Strong breeze	10.8–13.8	39–49	22–27	7.3–11.9	F	Descriptive term	m/s	Km/h	Knots
7	Near gale	13.9–17.1	50–61	28–33	12.0–18.3	0	Weak	17.2–32.6	62–117	34–63
8	Gale	17.2–20.7	62–74	34–40	18.4–26.8	1	Moderate	32.7–50.1	118–180	64–97
9	Strong gale	20.8–24.4	75–88	41–47	26.9–37.3	2	Strong	50.2–70.2	181–253	98–136
10	Storm	24.5–28.4	89–102	48–55	37.4–50.5	3	Devastating	70.3–92.1	254–332	137–179
11	Violent storm	28.5–32.6	103–117	56–63	50.6–66.5	4	Annihilating	92.2–116.2	333–418	180–226
12	Hurricane	> 32.7	> 118	> 64	> 66.6	5	Disaster	116.3–136.9	419–493	227–266

As per the IS 875 (part 3) the various scales for measuring wind storms are tabulated in Table 1, which shows 2011 & 2013 windstorm of Bhutan falls under the strong gale as per the Beaufort scale but as per the Saffir-Simpson Hurricane Scale and Fujita Tornado Scale, it fall under weak wind speed.

According to the Tamura, (2005) the damage not only depends on the wind speed but also the quality and strength of the structures. Therefore, various phenomena and damage occurred on the structures due to strong winds based on the wind speed as tabulated in Table 2. The 2011 & 2013 windstorm fall under the 30m/s of 3s gust wind speed, which described the damage to garage shutters and falling down of pedestrians. As per the Fujita scale, Bhutan windstorm fall under the F0 category, which described that there will be some damages to chimneys and breaks twigs off trees, pushes with shallow roots trees. Therefore, damages Bhutan faced during the windstorm falls under the F1 & F2 as per the Fujita scale (Table 3), which described the wind speed as 33-50m/s and 51-71m/s respectively.

Table 2: Various damages based on wind speed (Tamura, 2005)

Wind speed (10m above ground) 10min-mean	3s gust	Phenomena/Damage
5m/s	7～10m/s	- Vortex resonance/fatigue damage of truss members
10～15m/s	15～20m/s	- Handrail vibration/wind-induced noise - Vortex resonance of steel chimneys - Vibration perception in flexible high-rise buildings
20m/s	30m/s	- Seasickness and discomfort in high-rise buildings - Damage to garage shutters - Falling down of pedestrians
25m/s	40m/s	- Damage to roof tiles - Damage to window panes due to wind-borne debris
30m/s	45m/s	- Collapse of RC block fences - Damage to steel sheet roofing - Overall roof lift-off - Collapse of wooden houses - Falling down of gravestones
35m/s	50m/s	- Damage to window panes due to wind pressure of high-rise buildings - Blown over of heavy tombstones
40m/ s	60m/s	- Damage to cladding of high-rise buildings - Limit of allowable distortion of external sealing compounds
45m/s	70m/s	- Main frame stresses in high-rise buildings exceed elastic limit

Table 3: Fujita scale of wind speed and various damages originally formulated by Fujita in 1971(Doswell III, 2003)

F-Scale	Windspeed (mph)	Damage description
F0	40-72	Some damage to chimneys and TV antennae; breaks twigs off trees, pushes over shallow-rooted trees
F1	73-112	Peels surfaces off roofs; windows broken; light trailer houses pushed over or overturned; some trees uprooted or snapped; moving automobiles pushed off road
F2	113-157	Roofs torn off frame houses leaving strong upright walls; weak buildings in rural areas demolished; trailer houses destroyed; large trees snapped or uprooted; railroad boxcars pushed over; light object missiles generated; cars blown off highway
F3	158-206	Roofs and some walls torn off frame houses; some rural building completely demolished; trains overturned; steel-framed hangar-warehouse type structures torn; cars lifted off the ground; most trees in a forest uprooted, snapped, or leveled
F4	207-260	Whole frame houses leveled, leaving piles of debris; steel structures badly damaged; trees debarked by small flying debris; cars and trains thrown some distance or rolled considerable distances; large missiles generated
F5	261-318	Whole frame houses tossed off foundations; steel-reinforced concrete structures badly damaged; automobile -sized missiles generated; incredible phenomena can occur

2.5 History of Wind-Related Disasters around the World

According to Munich Reinsurance, (2013) study stated that out of 905 documented loss events, 840 events were weather-related i.e storms, floods and climatological events covering 93% and remaining 7% was caused by the earthquake. As shown in the Figure 34, the number of natural disaster around the world between 1980 and 2011, the average of 86% were weather-related and 14 geo-physical events. As shown in the Figure 33, one of the most economic loss contributors is the windstorm causing around 59% of overall losses (Re, 2013).

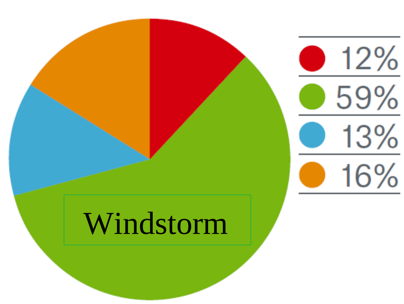


Figure 33: Overall Losses due natural disaster around the world (Munich Reinsurance, 2013)

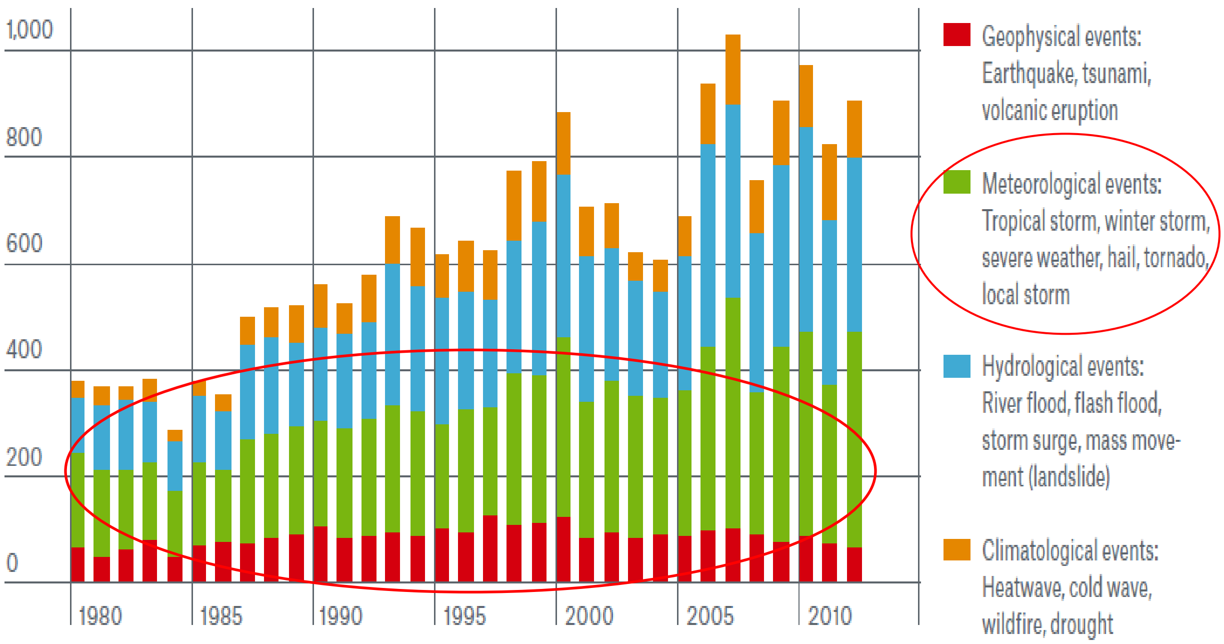


Figure 34: Graph showing the number of natural disaster around the world between 1980 and 2012 (Re, 2013)

The trend of windstorm disaster is also increasing in Bhutan from 2011(Figure 35) but there was no data record of windstorm till 2011. Therefore, it is difficult to say whether windstorm trend is really increasing in Bhutan or not due to lack of past windstorms data. During the 2011 and 2013 the windstorm thousands of rural homes roof were damaged in Bhutan causing huge loss to the government for the insurance compensation.

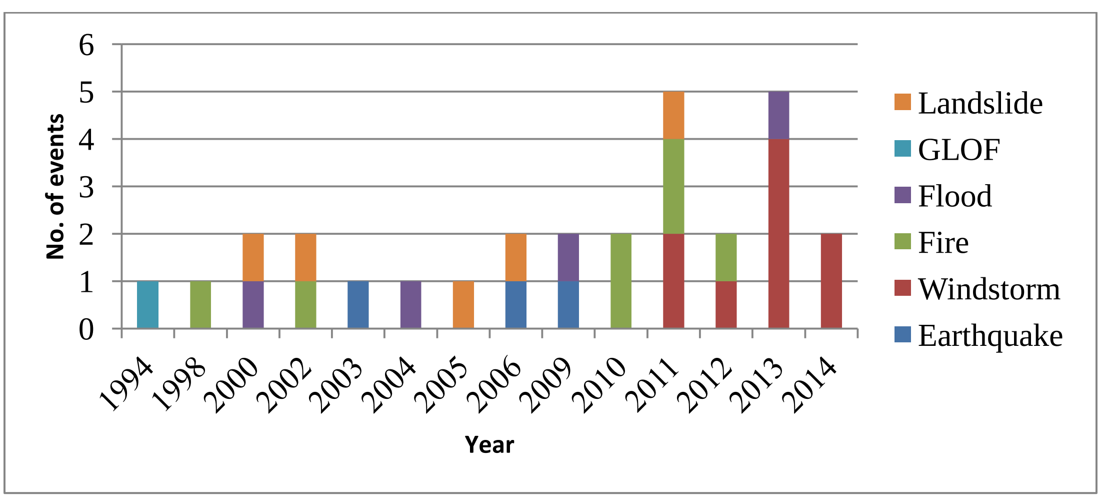


Figure 35: Graph showing the natural disasters in Bhutan from 1994-2014

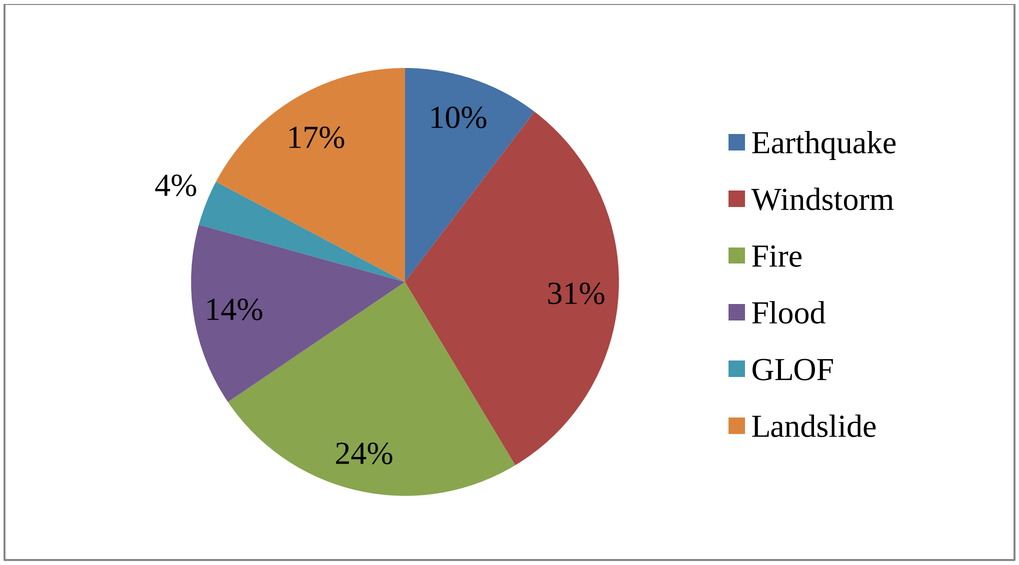


Figure 36: Showing the percentage of natural disaster occurred till 2014

As described in the Figure 36, one of the most natural disasters in the Bhutan is windstorm covering around 31% of the events followed by the structure fire with 24%.

2.6 Wind Effects on the Roofing System

According to Morrison, (2010) the severe windstorm can cause significant damage to the infrastructure. The wooden structures and roofs of residential are most vulnerable to windstorm failure. The loads applied on the per roof connection are significantly larger than the mean maximum capacity of individual connection, which indicates the significant load sharing in the roof. The failure of the roof will not initiate at the single connection. According to Mahaarachchi & Mahendran, (2009) from their field and laboratory investigations have shown that damage of CGI sheet metal roofs occurred due to the failure of their connections during the strong wind. In the rural home roofs in Bhutan, most of the connections between the CGI sheet metal and purlin are connected by galvanized iron (GI) screw of 4-6 inches long and connection between purlin and rafters are mostly connected by using toe – nails of 4 – 6 inches long of single nail. The single nail connection can withstand the force up to 0.71 kN (Lee, 2008).

Wind damages have historically been dramatic causing losses of life and property around the World and roof failure is one of the major wind induced failure during causing the major insurance claims (AAWE, 1997).

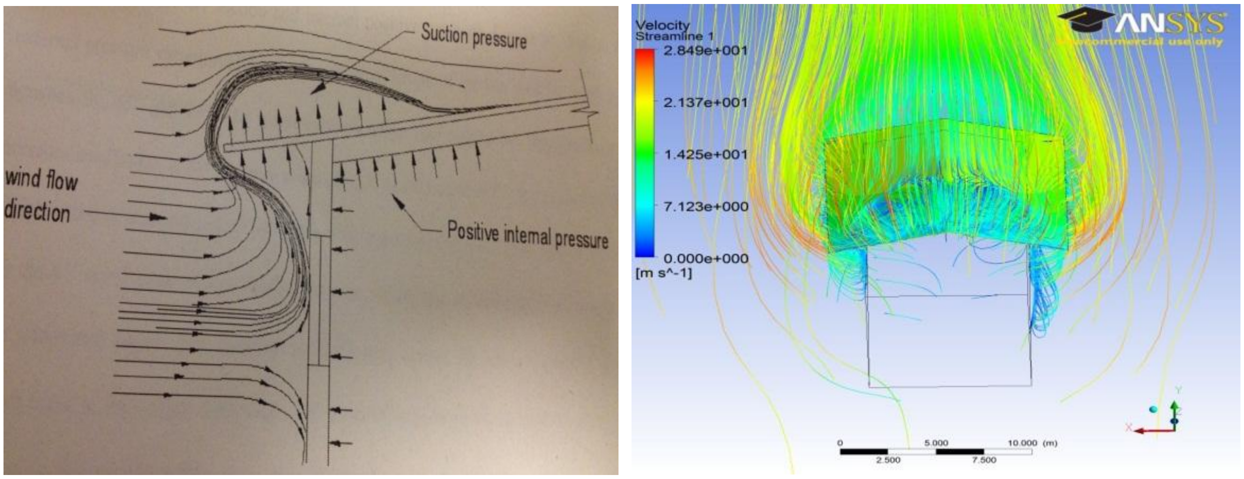


Figure 37: Positive and negative wind pressure on roof (Lotay, 2013)

The wind flow around buildings creates both negative and positive fluctuations over a roof system and wind pressure distribution varies over the roof. The high suction pressure are occurred at the corner and perimeter due to the flow separations and vortex formation (Baskaran, Eng, Molleti, Yew, & Eng, 2008).

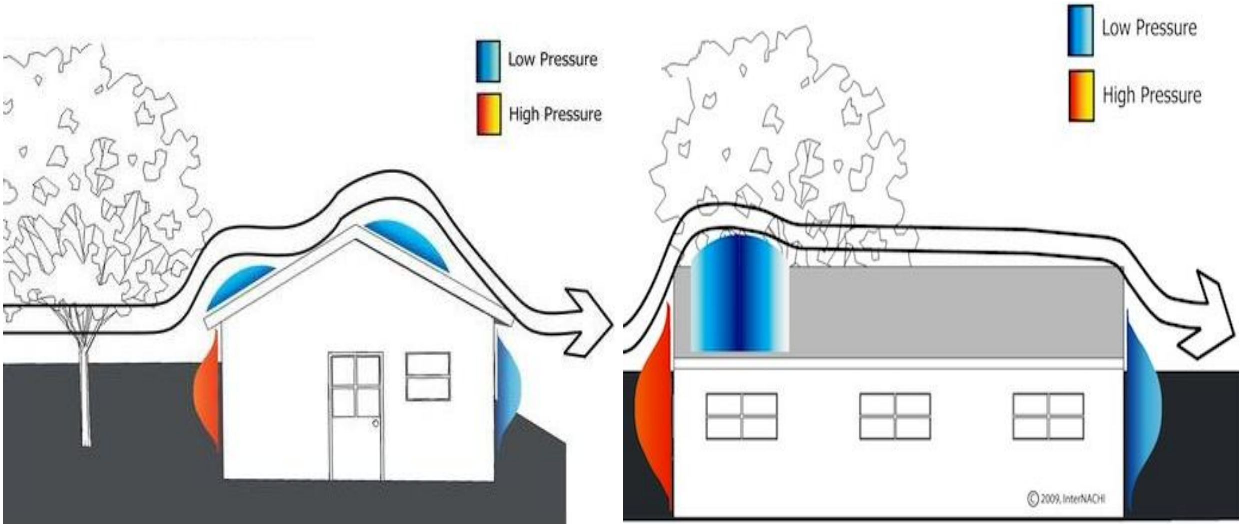


Figure 38: External wind pressure pattern roof (source: www.nachi.org)

As described in the Figure 38, wind creates positive pressure at the windward side and suction (-ve) pressure at the leeward side of the building. Also, the suction pressure is created on the cladding which can cause the uplift of the roof claddings.

As per the Walker, (1975) the wind pressure on the low-rise buildings roof cladding fluctuate very heavily due to the natural turbulence of wind near the ground and turbulence induced by flow-building interaction. Therefore, he stated that the strong wind can cause the severe fatigue damage to light-gauge steel roofing.

In a number of post disaster investigations on wind damages to low-rise buildings have revealed that hip roofs performed better than gable roof during the strong wind events. The performance of hip roof as compared to gable roof was due to the reduced aerodynamic loads and spatial distribution and stated that peak wind induced pressure can be reduced approximately 50% as compared to gable roofs (Meecham, 1992).

As per the study carried out by Xu, Reardon, Mahlberg, & Henderson, (1996) on the comparison of wind pressure, fatigue loading and fatigue damage to roof claddings on the hip and gable roof. They stated that gable roof suffered the worst suction pressure at the gable/ridge junction, while the hip roof experiences the worst suction pressure at the ridge but hip roof experiences less severe as compared to the gable roof. Regarding the fatigue damage to roof cladding, they mentioned that it not only depends on the roof configuration but also the type of sheeting. The hip roof experiences the less fatigue damage as compared to gable roof.

CHAPTER 3: METHODOLGY

3.1 Recent Windstorm Damages in Bhutan

In the present study qualitative and quantitative methods are used. The damage assessment for the 2011 and 2013 windstorm damages are carried out based on the damage pictures and report collected after the windstorm. The comparison was done between the 2011 windstorm and 2013 windstorm based on the data collected. The data used in this assessment is primary data collected from the Department of Disaster Management and survey carried out in December 2014 and January 2015 in four districts. In this study assessment is carried out based on the failure modes of the rural home roofs and roofing features such as roof overhang, anchorage, type of roof, connections, support string and roofing materials used based on the survey carried out in four districts in Bhutan. The survey was carried out in four districts in Bhutan to assess the mitigation incorporation during the reconstruction. In each districts, 15 households were interviewed based on the questionnaire prepared (Annex 1). The four districts (

Figure 39) out of twenty districts were selected based on the location and 2011 and 2013 windstorm damages.

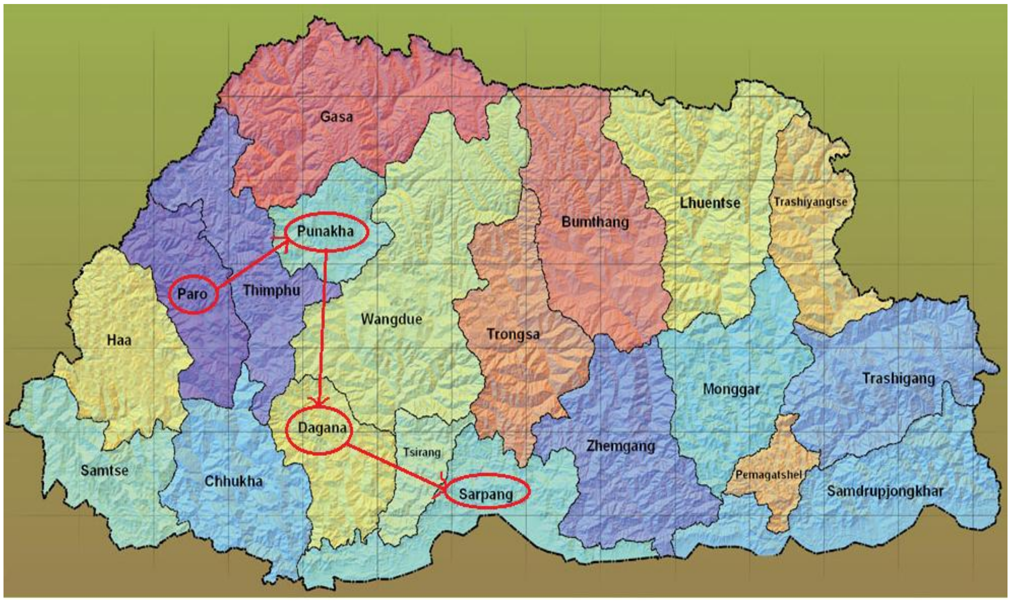


Figure 39: Map showing the four districts

In the comparison study of roof connection between Bhutan and Japan, qualitative methods is used based on the joinery, roof configurations, overhang, roofing materials and anchorage.

3.2 Wind load Calculation and Pull-through Force per Connection of CGI Sheet Metal

As described in the Chapter 2, one of the common failures in rural home roofs in Bhutan is due to the pull-through failure of connections. In the study conducted by Ramli, Majid, Chik, Muhammad, & Deraman, (2014) on the pull-through failure of nail connection, they calculated the equivalent static wind load using the Newton first law and hydrodynamic equations.

In this study to find the pull through force per connection is adopted based on the (Ramli et al., 2014) experiments. Based on the Ramli et al., (2014) experiments, the pull through force per connection for the CGI sheet metal is calculated for the 2011 and 2013 windstorm. As mentioned above the gust wind speed during the 2011 & 2013 is 22m/s and 24.4m/s respectively. Static pressure from basic wind speed is calculated using the following equation.

$q = 0.613 * V_s^2$ (N/m^2)

where,

V_z wind speed (m/s)

CHAPTER 4: DATA ANALYSIS AND RESULTS

4.1 Recent Windstorm Damages to Rural Home Roofs in Bhutan

The 2011 windstorm affected the seventeen districts (Lotay, 2013) and the 2013 December windstorm affected the thirteen districts out of twenty districts in Bhutan. Both the windstorm damage data is collected from the Department of Disaster Management (DDM).

Table 4: 2011 windstorm damages on rural home roofs in the seventeen districts in Bhutan

Sl. No.	Name of district	Rural Home Roof	Monastery Roof	Stupa	School/NFE Roof	BHU/ORC Roof	RNR Centre Roof	Village head office	RBP Outpost Roof	Grand Total
1	Gasa	3								
2	Thimphu	11	3		1	1				
3	Paro	137	6	1	1					
4	Haa	28	4	1	1	1				
5	Wangdue Phodrang	17	3							
6	Chukha	59	3		4					
7	Tsirang	34								
8	Dagana	170	4		7	1	1	2		
9	Trongsa	2								
10	Zhemgang	300	21		9	5	3	1		
11	Mongar	378	6		8	4	1	1		
12	Trashigang	401	7		13	2				
13	Trashi Yangtse	200	5	1	1	1			3	
14	Pema gatshel	433	9		6	5	1			
15	Sarpang	161	2	1	5					
16	Samtse	1	1		1					
17	Samdrup Jongkhar	89	3		2	1				
	Total	**2424**	77	4	59	21	6	4	3	**2598**

Table 5: 2013 windstorm damages on rural home roofs in the thirteen districts in Bhutan

Sl. No.	Name of Districts	Rural Home Roof	Monestary Roof	Stupa	School/NFE Roof	BHU/ORC Roof	RNR Centre Roof	Village Head Office	RBP Outpost	Grand Total
1	Gasa	72	3		1	1				
2	Thimphu	13								
3	Paro	310	25		4	2				
4	Haa	229	8		4	2		1		
5	Wangdue Phodrang	12	3			1				
6	Chukha	37			2					
7	Dagana	31								
8	Trashigang	46	2							
9	Trashi Yangtse	2								
10	Samtse	15								
11	Bumthang	15	4							
12	Lhuentse	5								
13	Punakha	230	8		1	2		2		
	Total	**1017**	53		12	8		3		**1093**

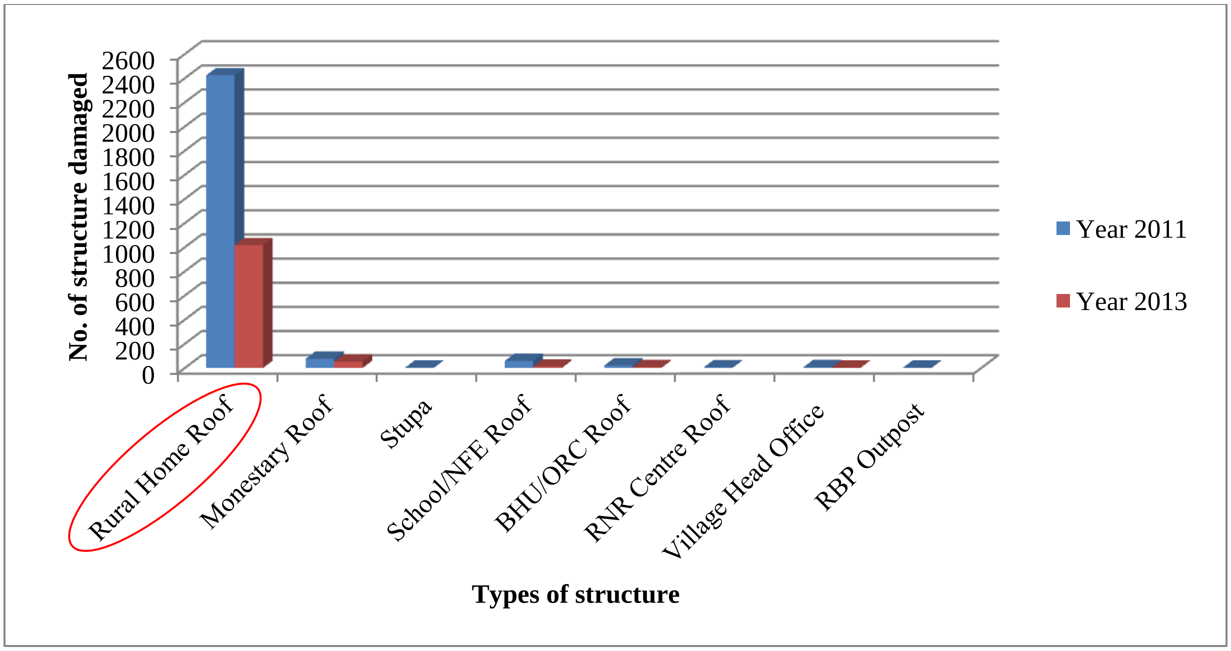


Figure 40: Graph showing the 2011 and 2013 windstorm damage on different roof structures

The 2011 windstorm was the epoch-making turning-point for most of the Bhutanese community to learn on the wind induced disaster. The windstorm damaged 2424 rural home roofs in seventeen districts out of total damage of 2598 structures. As per the Department of Civil Aviation (DCA), Bhutan wind record, the maximum gust wind speed was 22m/s at the 10m height from the ground surface with one second time interval of recording. As shown in the Table 4, during the 2011 windstorm the eastern region of Bhutan was affected more as compared to the western region. In the case of December 2013 windstorm, western region was affected more as compared to eastern region as shown in Table 5. The 2013 windstorm damaged 1017 rural home roofs in thirteen districts in Bhutan out of total damage of 1093 structures. The maximum gust wind speed was 24.4m/s at the 10m height from the ground surface with one second time interval of recording.

In the both the windstorms, the maximum damages were observed on the rural home roofs. Even though the gust wind speed of 2013 windstorm was higher than 2011 windstorm but the damages was comparatively less during the 2013 windstorm.

In the case of 2011 and 2013 windstorm, different mode failure of rural home roofs as shown in Figure 41 & Figure 42, it was observed that the common failure of the rural home roofs in Bhutan was due to the poor connections, lack of anchorage system, roof-to-wall connection, large overhang and inadequate timber sections. The failure mostly occurred at the gable roof ends and roof ridge as you can see in the Figure 43.

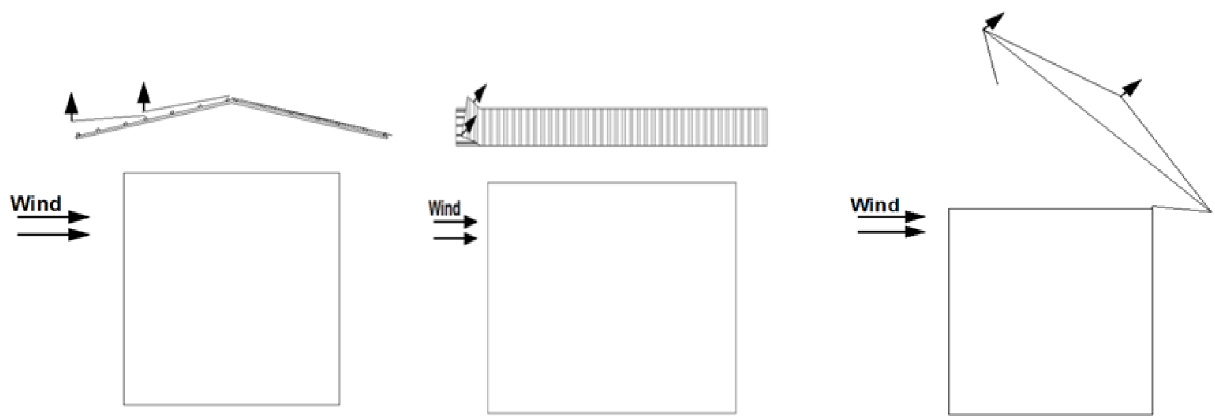


Figure 41: Gable end and roof edge failure

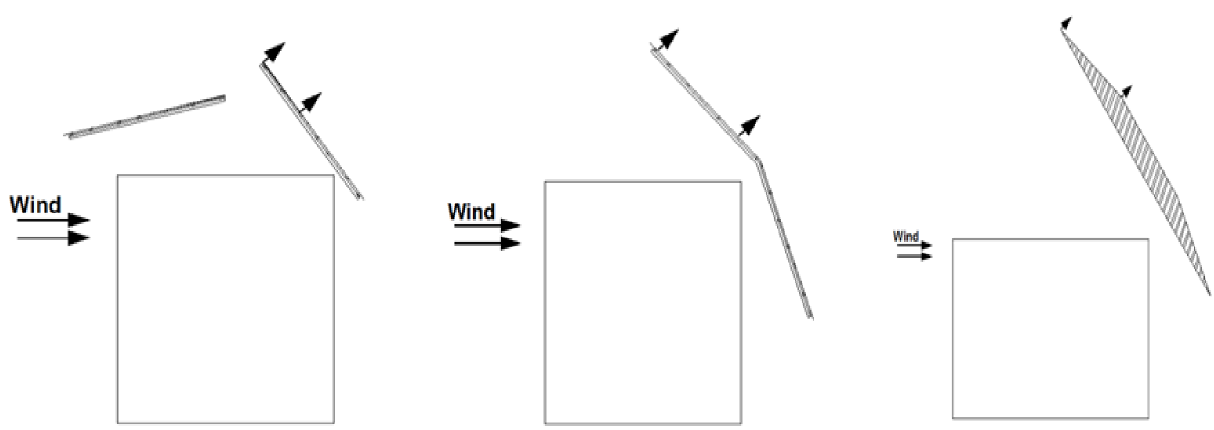


Figure 42: Roof failure at roof ridge and over turning failure mode

Figure 43: Roof ridge failure during 2011 windstorm

During the 2011 and 2013 windstorms, one of the common failures in the rural home roofs was observed at the roof ridge in the eastern part of Bhutan. It was observed that most of the purlins and rafter was irregular circular timber, whereby the connection at the roof ridge is not good. It was observed that the connection at the roof ridge is a simple lap joint with single toe-nail connection but generally the roof ridge connection is done by the bamboo strap or string. The irregular circular timber rafter makes difficult to secure tight connection at the roof ridge and also the groove made in the circular rafter makes the timber section weak during the strong wind to fail at the roof ridge as shown in Figure 44.

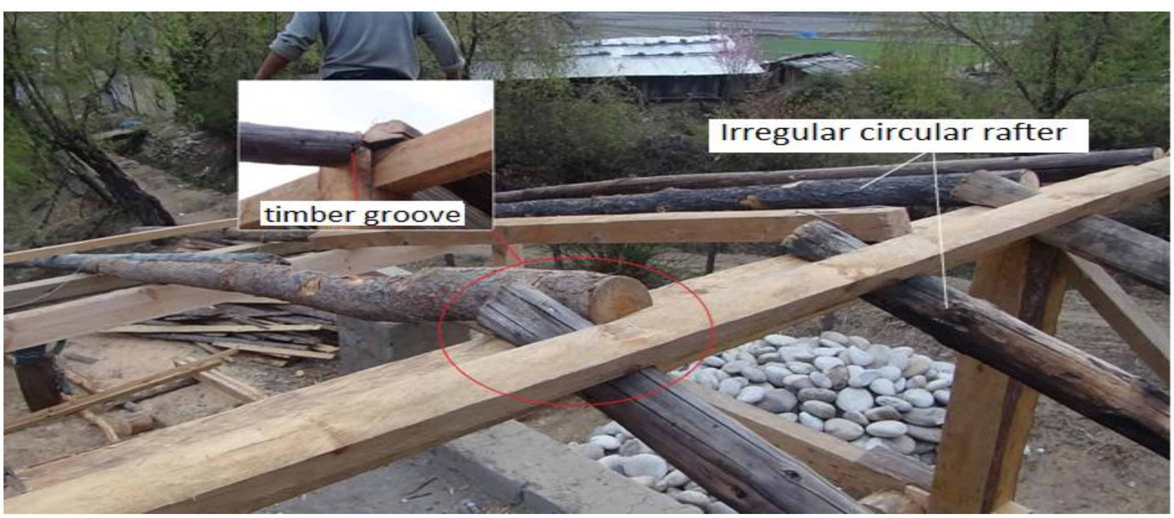


Figure 44: Roof ridge connection in rural home roof with deep groove and lap joint

In the case of 2013 windstorm damages, most of the failure was observed in the connection between rafter to the tie-beam and purlin to the rafter, whereby the damages were mostly full-blown off in the western region of Bhutan. The timber section used in the western part of Bhutan is much larger as compared to the eastern part of Bhutan roof. In the western part of Bhutan, roofs are constructed with circular timber rafters and square/rectangle timber for the purlins but in the eastern region roofs are constructed mostly with circular timber or bamboo rafter and circular timber or bamboo purlins. As you can see in Figure 45 &

Figure 46, failure of roof was observed due to the connection failure between the rafters and struts causing the full-blown off. The rural home roof of Bhutan is simply support on the attic floor, whereby there is no connection between the support and floor or wall. Therefore, it was observed that most of the failures are due to lack of rigid connection between the strut/support and attic floor and roof-to-wall connection.

Figure 45: Failure due the poor connection between rafters and struts causing full-blown off

Figure 46: Full-blown of rural home roof due to failure in the connections

One of the most failures in the 2011 and 2013 windstorm in the rural home roofs in Bhutan was observed in the purlin section failure at the weak section or at the joint. Also, it was observed that most of the purlins used are rectangular timber section with dimension between 50mm and 100mm. Since the available purlin length in sawmill were between 3000mm and 3700mm. Therefore, simple lap joint or inclined joint (

Figure 47) was used by the local carpenters, which is weak to resist the strong wind pressure.

Figure 47: Purlin section failure (L) and joint failure (R)

Figure 48: Weak lap joint at roof ridge (L) and purlin are not laid equally (R)

As described in the Figure 41, one of the most common roof damages occurred at the gable ends during the windstorm. It was observed that most of the gable end roof has weak connection especially between the purlins and rafters. The large roof overhang creates the high uplift pressure at the gable end. Since most of the rural home roofs of Bhutan has the roof overhang between 950mm and 2500mm. As described in the Figure 37, the positive pressure and suction pressure at the roof overhang; if the roof overhang is large the pressure at that point will certainly increase and cause the damage at the roof end.

Figure 49: Gable roof end failure (L) and large roof overhang (R)

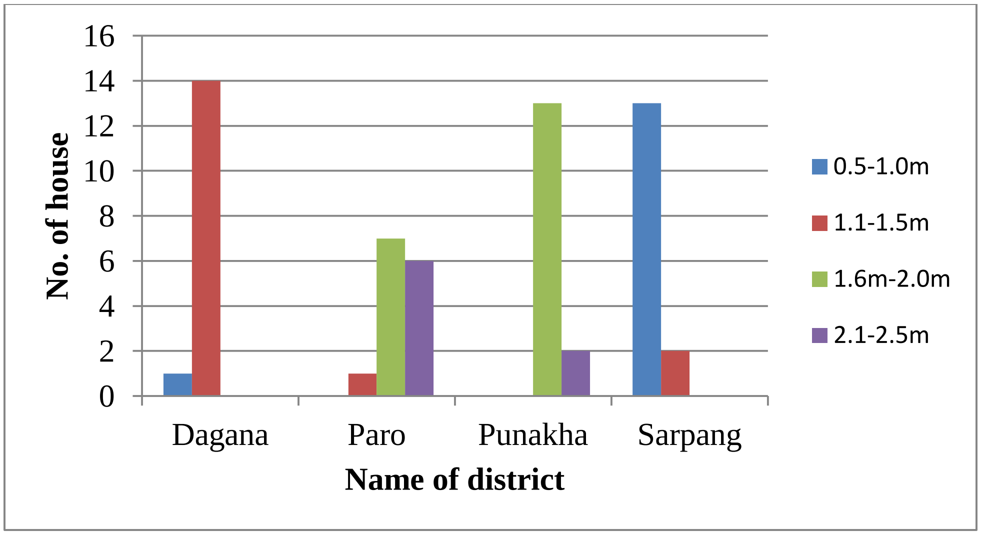


Figure 50: Graph showing the roof overhang in the four districts in Bhutan

Paro and Punakha is the district located in the western part of Bhutan, Dagana is located in the central part of Bhutan and Sarpang located in the southern part of Bhutan. It was observed that the large roof overhang (<1.5m) found in the western part of Bhutan as compared to the southern part of Bhutan. In Sarpang, roof overhang is between 0.5m – 1.0m as shown in

Figure 50.

The large roof overhang in the Bhutanese rural homes roof has many advantages and disadvantages. Since Bhutan experiences heavy rainfall from late June to September and steeper roof slopes are not possible for the Bhutanese rural home roof. Therefore, to protect attic spaces and walls from the rains and direct sunlight, the rural home roof have large roof overhang.

One of the common rural home roof failures was over-turning or sliding of roof cladding components as shown in Figure 51. It was observed that rural home roofs are simply supported on the attic roof and there is no rigid connect between roof-to-wall as shown in Figure 52. It was observed that the roof members are not connected rigidly with each other, instead each member acts independently. Therefore, integrity of the roof structure is lost during the windstorm and causing the roof damage. As described in the graph (Figure 53), most of the rural home roofs in the western and central part of Bhutan are simply supported

Figure 51: Sliding of roof (L) and over-turning of roof (R)

Figure 52: Roof supports/struts are simply supported on the attic roof or wall

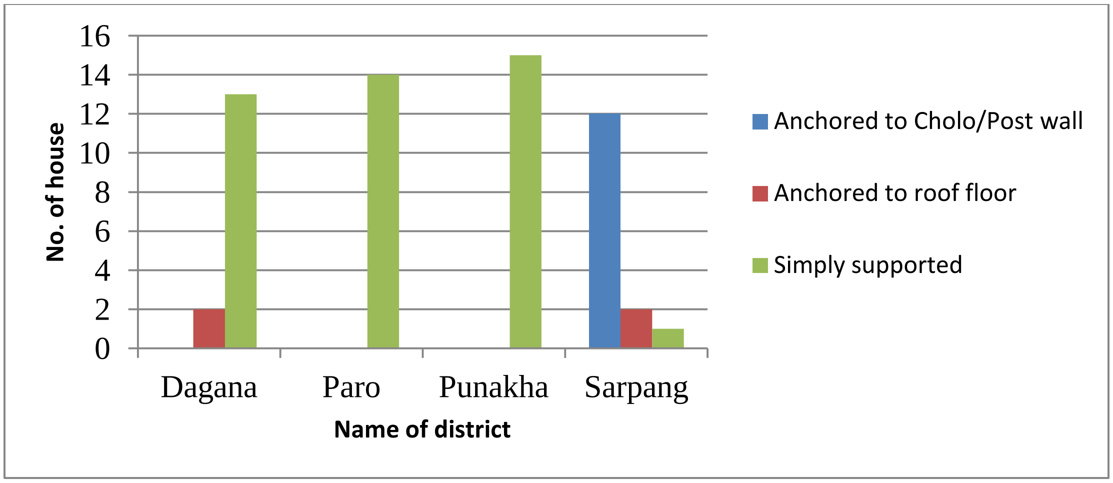


Figure 53: Graph showing the different type of roof-to-wall connection

4.2 Recent Survey on the Windstorm Damages in the four districts in Bhutan

The survey on the windstorm research was carried out mainly for the data collection on the damages in the four districts, organized by the Department of Disaster Management under National Adaptation Programme of Action (NAPA – II) project through UNDP support. The core working group was formed for the windstorm research. The core working members are from various agency; Department of Engineering Services (DES), Department of Human Settlement (DHS), Department of Culture (DoC), Department of School Education (DSE) and Department of Disaster Management (DDM). The Paro district was selected as a pilot district site for survey and data collections on the windstorm damages. Since, in the 2011 and 2013 windstorms, 137 and 310 rural home roofs were damaged respectively in Paro. Other three districts namely: Punakha, Dagana and Sarpang were selected based on the location and 2011 & 2013 windstorm damages, taking the consideration of all types of roof representation in the region. During the survey and data collections, it was observed that most of the failures of the rural home roofs occurred due to the poor connection, anchorage, opening effect and large overhang. The analysis of data was carried out for the four districts with the 15 households based on the roof types, anchorage, roof overhang, and support string and roof-to-wall connections.

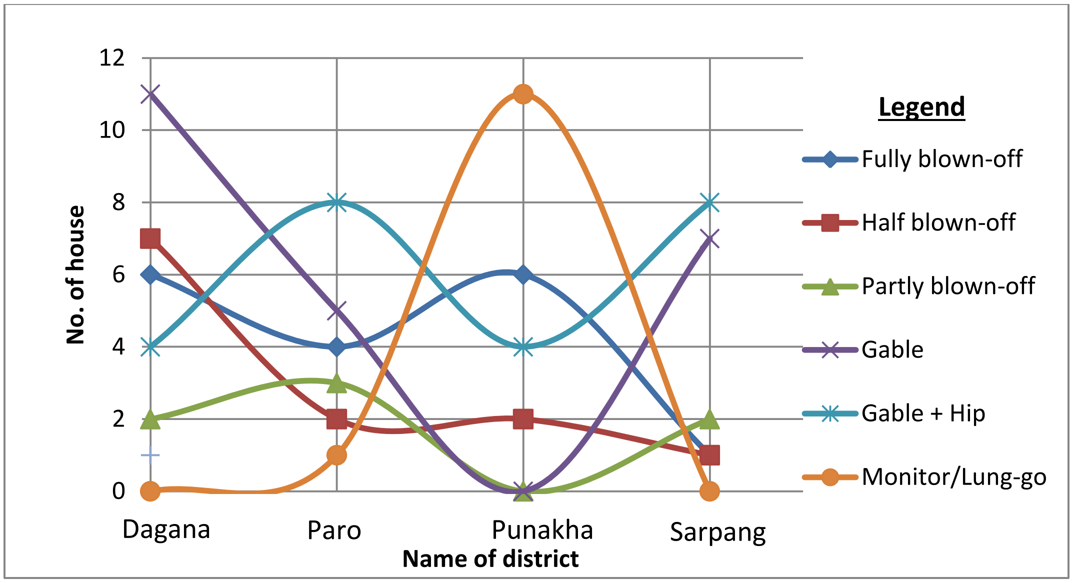


Figure 54: Graph showing the windstorm damage vs the type of roof in four districts

As described in the section 2.1.1, gable roof is one of the most common roofs in Bhutan, gable + hip combine (usually called hip in Bhutan) and lung-go roof. It was observed that lung-go roof and gable + hip roof were commonly used in the western part of Bhutan. The gable and gable + hip roof were commonly used in the western, central and southern part of Bhutan. In the case of roof damages during the 2011 & 2013 windstorm, it was observed that the most damage was observed in the Punakha district with maximum full blown-off damage followed by Dagana district as compared to other districts as shown in

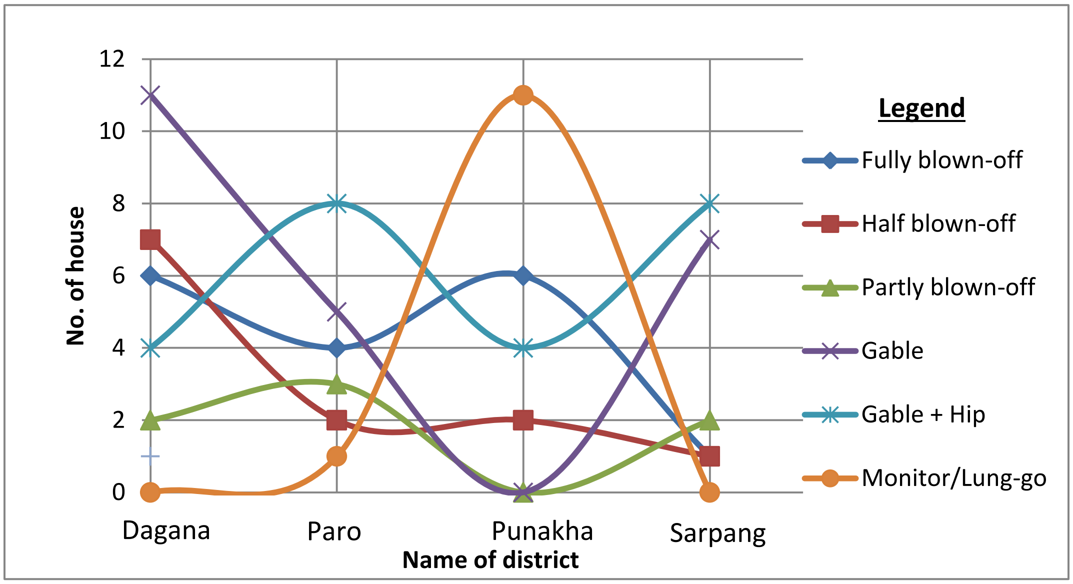
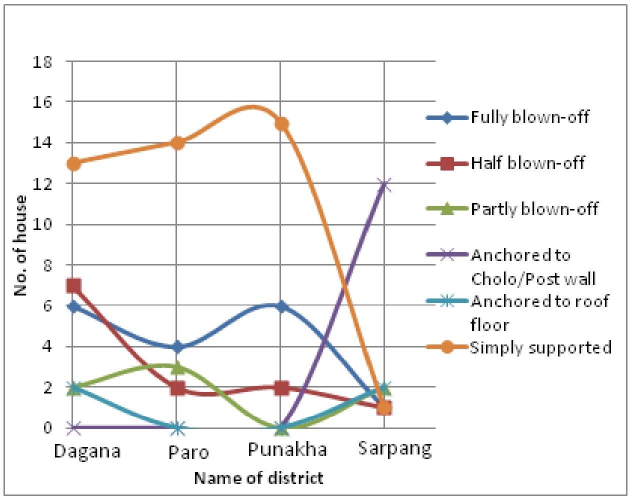


Figure 54. As shown in the Figure 55, Punakha district has maximum simply supported roof followed by Paro and Dagana district, which suffered full blown-off during the windstorm. Also, the large roof overhang create a huge uplift pressure at the roof edges, which lead to the failure of the roofs at the edges causing full blown-off or half blown-off in the rural home roof during the windstorm. Most of the western part of Bhutan rural homes have large roof overhang as compared to the central and southern part of Bhutan roofs.



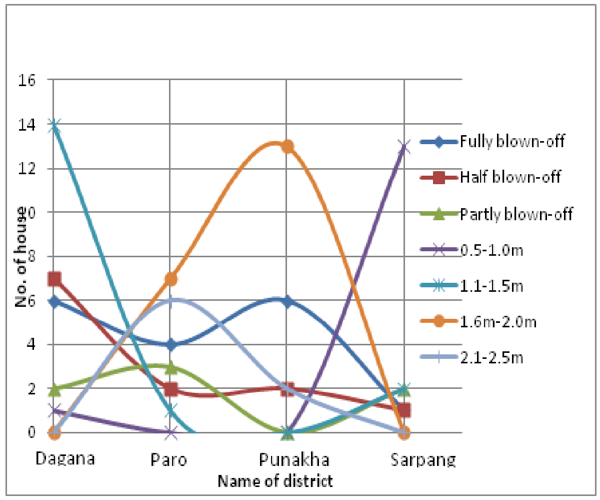


Figure 55: Graph showing damage vs anchorage (L) and damage vs roof overhang (R)

In the case of the use of support strings and different types of connection materials used in the rural home roofs. It was observed that most of the western and central part of Bhutan roofs used the support strings as compared to the southern part of Bhutan roofs. The roofs in the southern part of Bhutan were anchored to the wall or post, therefore there do not use the support strings as shown in Figure 56. Also most of the connection between the Corrugated Galvanized Iron (CGI) sheet metal and the purlin members are connected using galvanized iron (GI) screws. The connection between purlins and rafters are done by single toe-nails of 4 - 6 inches long and observed that most of the connections are not done properly as described in

Figure 47 & Figure 48.

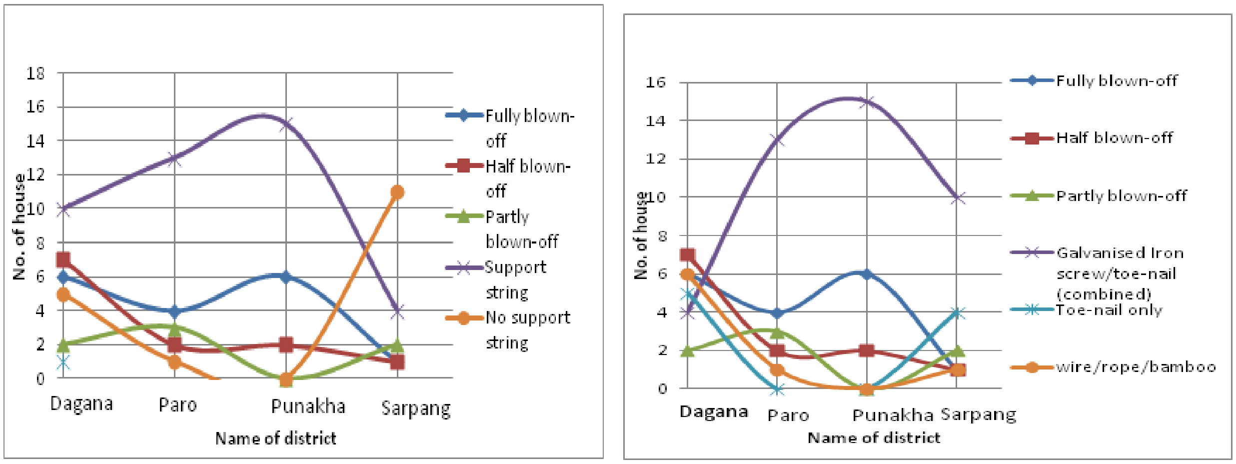


Figure 56: Graph showing the damage vs support string (L) and damage vs connection (R)

4.3 Static Wind Load and Pull through Load Calculation on the CGI Sheet Metal

As described in Chapter 2 and Chapter 3, most of the rural homes in Bhutan are considered as non-engineered structures and common roofing materials as a corrugated galvanized iron (CGI) sheet metal. However there is no construction manual or guidelines on how the CGI sheet metals are assemble in our Bhutanese traditional roofing system. Therefore, it was observed that in the 2011 & 2013 windstorm, most of the roof damages occurred due to the pull-through failure of the CGI sheet metals. Based on the Ramli et al., (2014) experiments, the pull through force per connection for the CGI sheet metal is calculated for the 2011 and 2013 windstorm. As mentioned above the gust wind speed during the 2011 & 2013 is 22m/s and 24.4m/s respectively.

Table 6: Pull through force per connection (Ramli et al., 2014)

Spacing between nail connection		0.3 m	0.45 m	0.6 m	0.9 m
Wind Speed (m/s)	ESWL (kN/m^2)	Force (kN)			
32.5	0.65	0.4	0.49	1.18	1.46
28	0.48	0.39	0.43	1.15	1.33
23	0.32	0.39	0.39	1.12	1.21
18	0.20	0.39	0.35	1.09	1.11
13	0.10	0.38	0.32	1.08	1.04

Static pressure from basic wind speed is calculated using the following equation.

$q = 0.613*V_s^2$ (N/m^2) ……………………………………………………………………..(2)

where,

V_z wind speed (m/s)

In this study wind speed of 22m/s & 24.4m/s is adopted as per the 2011 & 2013 windstorm respectively.

(i) $q = 0.613*(22)^2$ **= 296.69** N/m^2…………………..2011 windstorm

(ii) $q = 0.613*(24.4)^2$ **= 364.96** N/m^2…………………2013 windstorm

Table 7: Pull through force per connection (Ramli et al., 2014)

Wind speed (m/s)	Spacing between nail connection	0.3m	0.45m	0.6m	0.9m	Remarks
	ESWL (kN/m^2)	Force (kN)				
32.5	0.65	0.4	0.49	1.18	1.46	
28	0.48	0.39	0.43	1.15	1.33	
24.4	**0.36**	**0.39**	**0.4**	**1.13**	**1.17**	2013 windstorm
23	0.32	0.39	0.39	1.12	1.21	
22	**0.3**	**0.39**	**0.38**	**1.1**	**1.19**	2011 windstorm
17	0.2	0.39	0.35	1.09	1.11	
13	0.1	0.38	0.32	1.08	1.04	

As per the study conducted by Lee (2008) the maximum load before the pull through failure was recorded as 0.71kN. Also it was observed that with the increase of distance between the nail connections, the force acting on the connection increases as shown in the Ramli et al. (2014) experiment (Table 6). In most of the rural home roofs in Bhutan, the connections between the nails were observed at 600mm – 800mm for the CGI sheet width 1220mm and 500mm – 650mm for the CGI sheet width 910mm. It was also observed that most of the rural home roofs use the CGI sheet width of 1220mm. In the Ramli et al. (2014) study, they interpolated the Lee (2008) maximum load in their pull through force per connection and found that it occur at the spacing of 480mm of nail connection.

Therefore, most of the rural home roofs of Bhutan have the nail connection spacing greater than 500mm (Table 7) which is greater the Ramli et al. (2014) and Lee (2008) experiment result. Therefore, most the rural home roofs have chances of failure due to pull-through failure during the windstorm in the near future. Also, during the 2011 & 2013 windstorms the failure of the roof could be one of the pull-through failures.

4.4 Mitigations and Counter Measures for the Rural Home Roofs

4.4.1 Roof Type Selection

As described in the Chapter 2 section 2.1.1, most of the rural homes roofs in Bhutan are gable roof or hip + gable roof. Therefore, it is important to select the roof type during the construction. There is misunderstanding of hip roof in Bhutan, actually the hip roof in Bhutan are hip + gable combined. Therefore, the most suitable roof in Bhutan is hip roof with small overhang, if using CGI sheet metal as roofing materials. As per the windstorms, damage and guidelines for mitigation measures, the Bhandari, Krishna, & Kumar (2005) stated that hip roof gets the low uplift pressure, which performance good during strong wind as compared to other roof types as shown in figure 57.

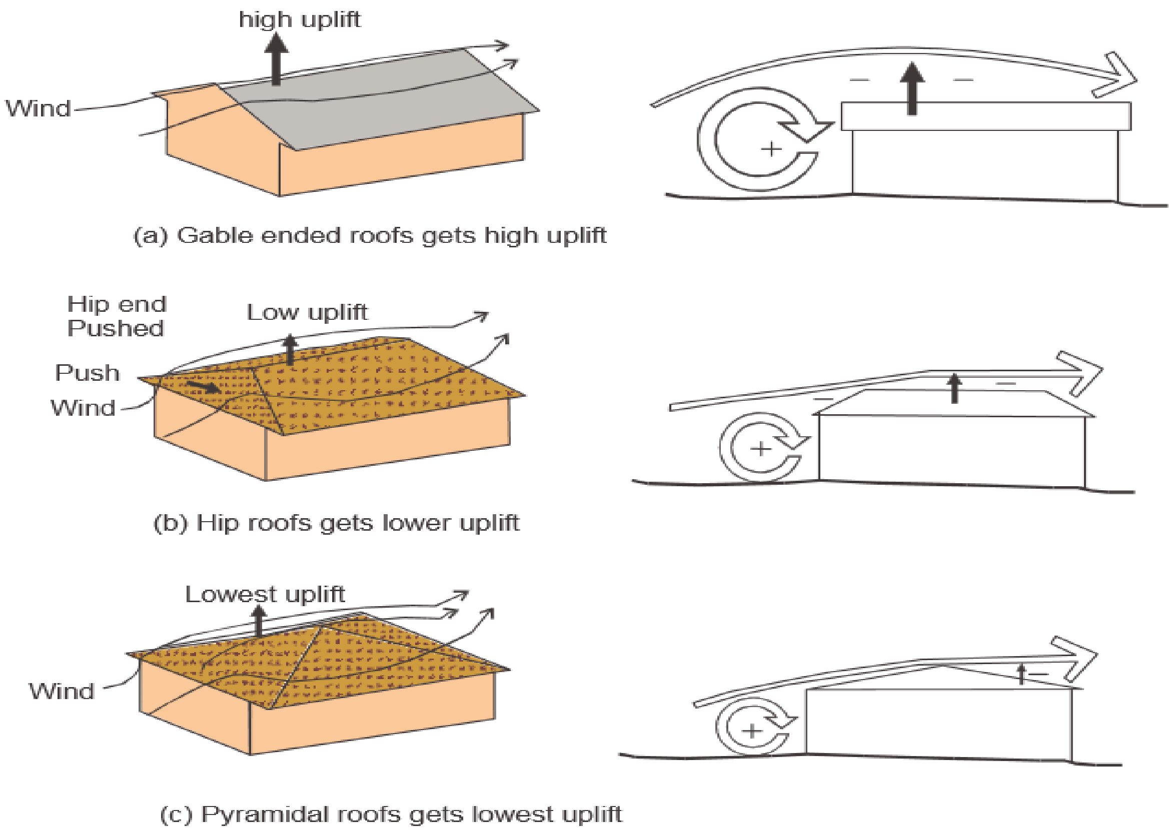


Figure 57: Roof type effect on uplift pressure (Bhandari et al., 2005)

4.4.2 Roof Configurations and Connections

Bhutanese roof members act as independently and do not act as a rigid during the windstorm. Therefore, it is important to make the roof rigid by making the tie beam, rafter, purlin and roofing materials firmly connected using the wooden bracing or nail connections. Taking the example of Japanese roof, the rafters and purlins can be connected using the wires, straps or ropes as shown Figure 58.

Figure 58: Japanese thatched roof connection using ropes

Figure 59: Use of support string (L) and metal straps (R) during the reconstruction in Paro

The use of support string helps to hold down the roof structure to prevent from the uplift during the windstorm. The support string should be anchored to the ground to withstand the wind pressure. As shown the in figure 59, the use of metal straps to connect the purlin to rafter and then to struts to reduce the uplift of roof during windstorm.

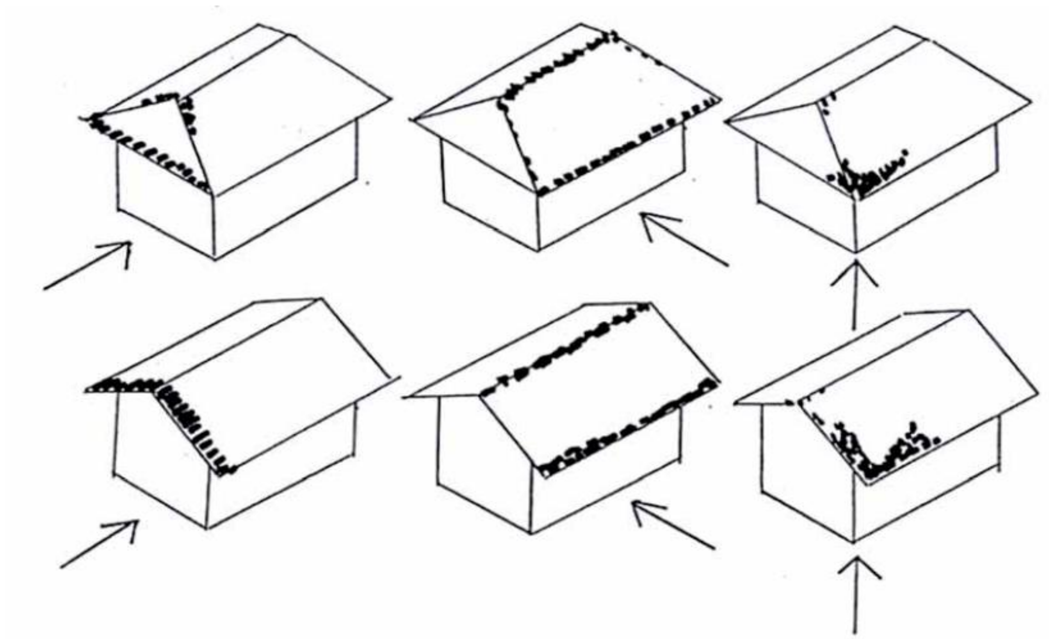


Figure 60: Most likely locations of roof damages (Source: Points to Note for Wind Resistant Design in Philippines, Tamura)

As you can see from the Figure 60, most likely locations of roof damages during the strong wind are at the gable end, corners and roof ridge. Therefore, it is important to fix these locations to reduce the damages during the strong wind. Following the few mitigation measures:

1. Use of gable end, corner and roof ridge stiffener as shown in Figure 62
2. Bracing the roof members as shown in Figure 62
3. Bracing the large roof overhangs > 450mm or avoid large roof overhang

4. Use of 10-20kg sand bags as shown in 

5. Figure 61

6. Use of support string or guy-wire or ropes (Figure 59 & figure 61)

7. Use of G.I hook, G.I coach screw square head and G.I crank bolt (figure 63)

8. Use of metal straps Figure 59

9. Use of sufficient side laps and end laps as shown in Figure 63

10. Use of rubber washer instead of bitumen washer

Figure 61: Support string or guy-wire or rope and sand bags (L) and wooden shingle over CGI sheet metal with stone (R)

Figure 62: Gable end stiffener, roof ridge stiffener, corner stiffener and overhang ties (L) and additional purlins & bracing (R)

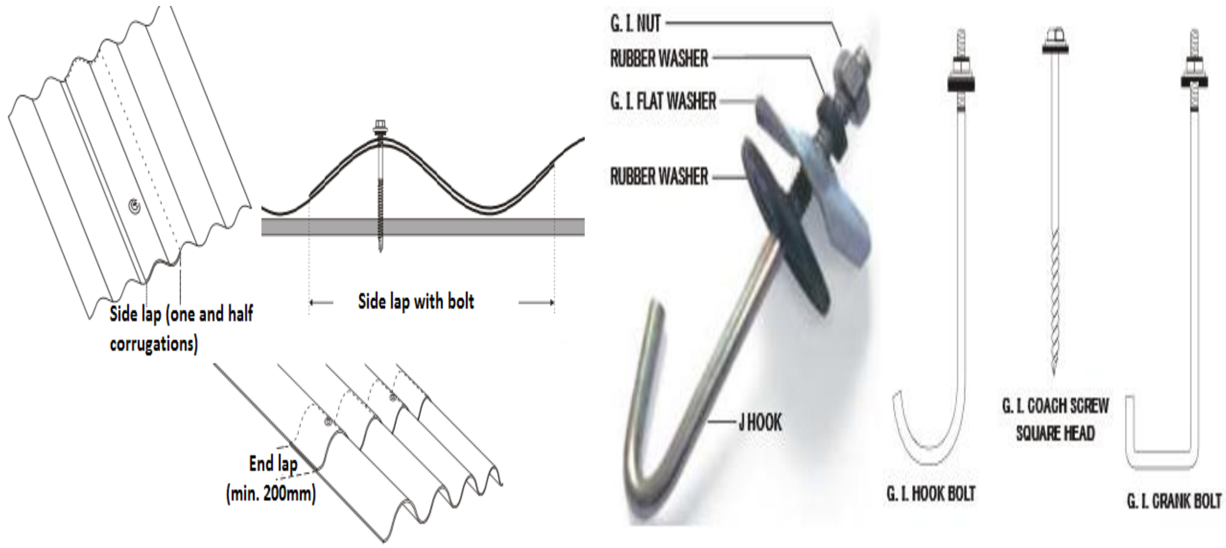


Figure 63: Laps in CGI sheet metal and types of hooks & bolt (source: Tata steel limited)

CHAPTER 5: DISCUSSIONS

5.1 Comparison of Bhutan and Japan Roofs

The comparison of the rural home roof of Bhutan and Japanese traditional roofs were carried out based on the literature review and site visit as shown in

Table 8. In the case of the roof types, there is lot of similarity in the roofs and common roof types are gable, gable + hip roofs. It was observed that gable + hip roof type in Japan fully closed as compared to the Bhutanese roof, where there keep the triangular shape in the roof as an open for wind passage. Most of the Japanese roofs used tiles for the residential houses, which is heavy as well as wind resistant as compared to Bhutan roof with CGI sheet metal which is very light and vulnerable during the strong wind. One of the most different between Bhutan and Japan roof is the roof overhang. It was observed that Bhutanese roof has large overhang as compared to Japanese roofs. The Japanese roofs are anchored or connected rigidly to the main structures as compared to the Bhutanese roof, which is simply supported on the roof floor and vulnerable during the strong wind. Therefore, it was observed that the Japanese roof is more wind resistant as compared to Bhutanese roofs.

Table 8: Comparison of Japanese and Bhutanese roofs

Sl No.	Descriptions	Bhutan	Japan
1	Type of roof	gable, gable + hip roof (combined), lean roof, Jamthok (monitor) roof & etc.	gable(kirizum), hip(yosemune), gable + hip (irimoya), hogyo roof and etc.
2	Type of roof material	corrugated galvanized iron (CGI) sheet metal, shingles, thatch, banana leaves, bamboo, slates & etc.	tiles, thatch, plank, shingles, bark & etc..
3	Roof configuration	roof members act independently and no rigid connections	members are connected rigidly using the screws or bolt or

		between members.	nails
4	Roof overhang	large roof overhang (500mm-2500mm)	less roof overhang (around 0 – 1500mm) usually around 600mm
5	Roof angle	roof slope between 12 °- 15°	roof slope various based on the location, e.g. in the snowy areas, roof slope is steep
6	Trusses specification	square or rectangular shape tie beam, timber batten purlin, circular rafters	most members are circular timber
7	Roof-to-wall connection	simply supported	rigid connections using bolt or nails

5.2 Recent Windstorm Damages

Based on the 2011 and 2013 windstorm damages, assessment was carried out using the reports and damaged pictures. As per the recent natural disaster in Bhutan, windstorm was one of the most frequent hit disasters compared to other natural disasters. Gable roof is one of the common rural home roofs in Bhutan, which is weak during the strong wind as compared to hip roof. From the 2011 and 2013 windstorms, it was learned that rural home roofs are very vulnerable during the strong wind. During 2011 windstorm, 93.30% damaged were rural home roofs as compared to other public structure 6.7%. During 2013 windstorm, 93.05% damaged were rural home roofs as compared to other public structures 6.95%.

Therefore, Bhutan rural home roofs are highly vulnerable to strong wind due to its weak connections or joinery, large overhang, inadequate timber sections, non-engineered roof member configurations over the new roofing materials and no roof-to-wall connections. In the both windstorms, failure mode is similar since most of the structures failed due to the gable roof end or edge failure, roof ridge failure, pull through failure and over turning of roof failure causing the full-blown off.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this study, Bhutan rural home roof was assessed based on two windstorms in Bhutan using the damage reports and damage pictures. Also, post damage survey was carried out in four districts to assess the past damages and reconstructions. A comparative study was carried out between Japan and Bhutan roof based on the roof type, roof materials, connections, roof overhang and roof configurations. Based on the literature review and calculations of the damages, following conclusions were drawn:

1. Most of the Bhutan rural home roofs were gable roof type with large roof overhang between 500mm and 2500mm. It was found that gable roof is weak during the windstorm especially with the large roof overhang.
2. The light weight corrugated galvanized iron (CGI) sheet metal was used as roof materials in most part of Bhutan. During the change of roofing material from shingle to CGI, roof configuration was not much changed and causing the problem of full blown-off of roof during the windstorm.
3. In the comparative study, it was concluded that Japanese traditional roof is well designed and wind resistant as compared to Bhutanese roof. Japanese roof have rigid connections between the members and roof is well connected to the foundation. In case of Bhutanese roofs, all member acts independently and not connected to each other. Also, roof is simply supported on the roof floor.
4. One of the most failure during the two past windstorms in Bhutan, many roof failed due to the pull-through failure. Since rural home roof nail connection spacing is between 500-

600mm, which is greater than the recommended spacing of 480mm in the previous research.

5. It was found that the western region roof has large overhang as compared to the roof of central and southern region. Also, western region roof used support string to hold down the roof as compared to the central and southern region roof, where roofs are anchored to the walls.

6.2 Recommendations

In this study, Bhutan rural home roof was assessed based on the literature review and damage reports of 2011 and 2013 windstorms. But it is not sufficient to conclude that Bhutan rural home roofs are still unsafe during the windstorm. Therefore, in the future study, more experimental test is required to conclude the behavior of Bhutan rural home roofs.

In this study, two windstorms were examined based on the reports but could not recommend the best connections and joinery for rural home roofs. Therefore, it is important in the future study to come up with the best connection details.

In this study, due to the time limit the large overhang was assessed based on the literature review only and could not examined the real effect of the large overhang of Bhutan roof. Therefore, it is important to examine the large roof overhang effect during the windstorm.

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ANNEXURE-1

The purpose of this survey is to document the existing housing design and constructions practices with particular attention to roofing and housing structures and their vulnerability to wind and rain storms. This information will be used to train the local artisans and government engineers based on the research recommendations to improve the construction design and practices for wind resistance.

The survey shall be carried out on each house in the selected gewog. The gewog are selected based on the past windstorm damage in the Dzongkhag. The survey form should be filled as per the question below.

SURVEY FORM

Name of Owner ....**Thram No**......................**House No**.........................

Village ....**Gewog**...Dzongkhag.................................

Insured ☐ **Not Insured** ☐ other..

Type of construction (please tick): Rammed Earth ☐ RCC ☐ Bakal ☐ Mud Block ☐ Ekra ☐

Hut (CGI sheet/Bamboo) ☐ Stone/brick ☐ other ....

Roof Type (please tick): Gable ☐ Hip ☐ Lung-go ☐ Jamthok ☐ Lean-roof ☐

Roof Truss Type (please tick): Timber ☐ Steel ☐ Bamboo ☐ other ....

Type of roofing material: CGI sheet ☐ Shingle (Shinglep) ☐ Slate ☐ Bamboo ☐

Leaves/plastic ☐ Other ....

Number of storey: One ☐ Two ☐ Three ☐ other...

Type of Opening in the attic:

Fully open at four sides ☐ Fully open at three sides ☐
Fully open at two sides ☐ Fully open at one side ☐

Fully closed at four sides ☐ Fully closed at three sides ☐
Fully closed at two sides ☐ Fully closed at one sides ☐

Partly closed at four sides ☐ Partly closed at three sides ☐
Partly closed at two sides ☐ Partly closed at one side ☐

Type of closing material: Shingle (Shinglep) ☐ Bamboo mat ☐ Sheet/CGI ☐ Ply board ☐

Other...

Type of closing: Inclined Closed ☐ Vertical closed ☐ Other...

Roof-to-wall connection: Anchored to Cholo wall ☐ Anchored to roof floor ☐
Simply supported ☐ other...

1

Is there roof support string: Yes ☐ No ☐
If YES, type of support string material: GI wire ☐ Aluminum wire ☐ other ....

Connection materials used between the purlin and rafter and CGI sheet:
GI screw ☐ Toe-nail ☐ J-hook ☐

Whether your house is affected by windstorm in past: Yes ☐ No ☐
If YES, how many times it is affected........................ .Which Year ....Month................
Extent of damage: Fully blown-off ☐ Half blown-off ☐ Partly blown-off ☐

Did you change the roof structure or roofing materials during reconstruction: Yes ☐ No ☐
If YES, specify what you changed?..
..
..

Q1: Year of Construction?

 # The purpose of identifying the year completed is to determine the building code to which the structure was designed and built.

....

....

Q2: Describe the location of house, is it located on hill or valley?

 # The purpose of identifying the location of the house is to determine the wind direction as well as wind obstruction around the house.

....

....

....

Q3: Describe the Orientation of the house? Which direction the front elevation is orientated?

 # The purpose of identifying the orientation of the house is to determine the roof slope, if it is gable roof.

....

....

....

Q4: Is there any wind protection around the house? Any tall trees or neighbor houses?

....

....

....

Q5: Size of opening around the house? I.e. window opening or other opening at first floor/top floor?

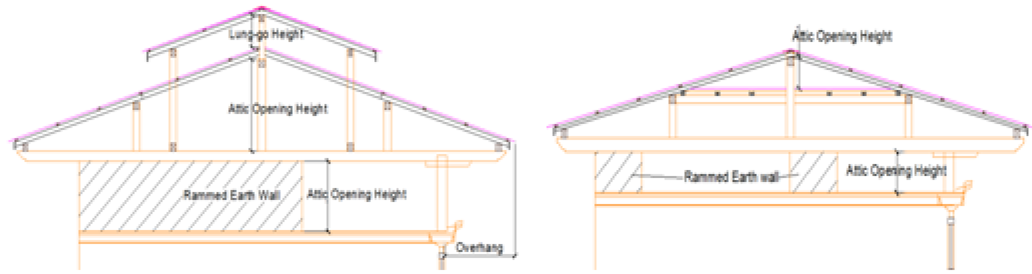
....

....

....

Q6: What is the roof overhang? Measure please.

Q7: Measure the attic opening height? Roof Sample attached



Q8. When did you change your roofing material from Shingle (Shinglep)/leaves/straw to Corrugated Galvanized Iron (CGI) sheet?

Q9. Did you change your roof configuration/roof structure, when you changed the roofing materials?

Q10. Is the anchorage of support string to ground or to wall?

Q11.Other

************************************END***************************************