Wind vulnerability and strengthening of Bhutanese vernacular roofs

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\textbf{ABSTRACT}

Windstorms can cause significant damage to non-engineered structure and infrastructure due to the lack of consideration of wind force in design and construction. Historical windstorm events reflect that the windstorm damage is different than most of the other dynamic forces such as earthquakes, floods, tsunamis, and landslides. Bhutan frequently observes major windstorm events that cause significant damage to structures and infrastructures. Between April 2008 and May 2021, 51 windstorm events were recorded in Bhutan. Owing to widespread damages and losses in structures and infrastructures, it is imperative to depict the windstorm vulnerability of structures and infrastructures that would be instrumental, especially in a country such as Bhutan where windstorms are frequent and enormous losses are attributed to damage to structures and infrastructures. Based on historical windstorm observations and database, we present forensic interpretations of damage mechanisms and windstorm vulnerability analysis. Apart from this, we also present some strengthening techniques considering inherent vulnerabilities, especially for vernacular constructions in rural Bhutan.

\textbf{1. Introduction}

Roofs of the rural vernacular buildings in Bhutan are highly vulnerable to windstorms due to poor anchorage and weak connections. Global analysis of residential buildings against wind force are reported by many researchers worldwide (see e.g. Peiris and Hill 2012; Stevenson et al. 2018; Gautam et al. 2020; Abdelhady et al. 2022). Similarly, studies related to roof damage and vulnerability are reported by many researchers (e.g. Stewart et al. 2016; Li et al. 2017; Wang et al. 2019; 2020). Roofs are...
one of the most vulnerable components of vernacular buildings when exposed to
wind forces (Lee and Rosowsky 2005; Qin and Stewart 2019, 2020) as roofs would
not be adequately tied to the main structural components. On the contrary, studies
regarding wind performance and vulnerability of vernacular roofs are limited. Many
cases of roof collapse were reported by Gautam et al. (2020) after the 2019 windstorm
in Nepal due to lack of anchorage between the roof and the structural system. The
roof components such as roof cladding, roof sheathing, and trusses are among the
most vulnerable components under wind uplift pressure as damage to these compo-
nents causes loss of lives and property (Lee and Rosowsky 2005; Qin and Stewart
2019). This prompts studies pertaining the behavior of roofs during a windstorm
event. Conner et al. (1987) highlighted that a small change in connection strength
can result in significant variation in structural reliability of connections provided in
the roofing structure. Ellingwood et al. (2004) proposed a methodology to create fra-
gility functions for windstorms and earthquakes. Henderson et al. (2013) conducted
experimental study for various missing nail configurations and concluded that fasten-
ers could be highly effective in load distribution. Wang et al. (2020) performed
experimental analysis of roof overhangs and found that the change in turbulence was
significantly countered by the lower and upper surfaces of overhangs.

The roofs of traditional Bhutanese houses are one of the distinctive aspects of the
Bhutanese architecture but most of them, specifically the ones in the rural areas are
highly vulnerable to damage during a windstorm event. Also, Bhutanese rural build-
ings do not possess adequate safety against dynamic loading such as earthquakes and
windstorms (Chettri et al. 2021a, 2021b; Gautam et al. 2022). Apart from the rural
constructions, nonstructural components of reinforced concrete (RC) and brick
masonry buildings are found to be highly vulnerable when exposed to wind gust
(Gautam et al. 2020). The Bhutan Building Code does not have specific design guide-
lines for traditional Bhutanese houses (Chettri et al. 2021); neither do the guidelines
that exist for other building forms incorporate wind force. To this end, the need for a
study that incorporates windstorm vulnerability of structures is a must for Bhutan.
The outputs of the study will also be important for other areas that observe wind-
storm events frequently.

All the traditional Bhutanese houses owner-built constructions, made by local
manpower without any technical support and guidelines. The roofing system of the
traditional houses located in rural regions are not firmly integrated to the main build-
ing thus the roofs observe considerable damage when exposed to moderate to severe
windstorms that occur quite frequently in Bhutan. Historical studies on windstorm in
Bhutan and the devastating damages to buildings do not exist so far to the best of
our knowledge. To fulfill this gap, we aim to assess vulnerability of Bhutanese roofs.
Furthermore, we also assess the performance of various retrofitting techniques for
rural roofing systems.

2. Bhutanese vernacular roofs

Bhutanese buildings can be classified into 13 types as per the population and housing
survey conducted in 2017 by the Royal Government of Bhutan (Figure 1) but can be
broadly categorized as reinforced concrete (RC), masonry, and others. Among the three types of buildings, 33.37% are RC and 42.81% are masonry buildings. The rest of the buildings classified as others are wooden (7.76%), wattle and daub (7.11%), plywood (3.26%), cane/palm/trunk/bamboo (2.88%), various other types (2.48%), and cardboard (0.33%). Most of the RC buildings are located in the urban areas of the country whereas masonry and other types of buildings are concentrated in rural areas.

Stone and mud are used to construct the walls and other structural components of the building and varieties of locally available timber are used for making different parts of doors and windows, components of the roofing, and other parts of the buildings such as wooden flooring and cornices above doors and windows. For the roof covering, wooden roof cover (Shinglep) would be used in the past but corrugated galvanized iron (CGI) sheets have replaced most of them lately. The design of the roof of a traditional Bhutanese house is very distinguishable because the roof is raised high above the main building in layers which makes the space under the roofs, attic floor, usable for various purposes such as drying fodder and vegetables and storing other necessities. The roofs of the traditional houses not only serve its basic purposes but also shows the social status as well as accentuate aesthetic of the building. According to the Bhutanese Architectural Guidelines (Ministry of Works and Human Settlement 2014), there are four types of traditional Bhutanese roofs (Fig. 2), viz., Jabzhi roof, Jamthok (attic) roof, Drangim roof, and Chenkhep roof. Jabzhi roofs are either single layered or multi layered roofs, which are square hipped having four
distinctive corners as depicted in Figure 2a and e. This type of roof is mostly provided in buildings having greater importance such as the monasteries. The roofing material for the Jabzhi roof is usually gold-plated metals. The eaves of the roof are then ringed with a metal curtain embellished with decorative and sacred iconographic carvings known as Chuzha Chulo. When gold is not available, the Jabzhi roof is painted in yellow color. The four sides of the Jabzhi roof are capped off usually by the heads of auspicious animals such as the Garuda or dragon or by a sculpture known as Chuju Patra. These caps are made up of brass or copper and usually gold plated. The gable roofs have smaller gable portion on top of the main roof. The roofs are in two different levels where the upper layer (smaller gable) is raised up at the center such that it forms a large area in the middle of the attic below. The upper layer of the Jamthok (attic) roof does not have windows under it and is left open to allow air to flow through. However, in some cases, where the attic area is converted to a habitable space, the space under the upper layer of the Jamthok roof is framed into a horizontal line of clerestory windows on two sides and often decorated with Horzhu and Pem Choetse. These roofs are also a type of gable roofs, where a smaller gable is at the top of the main gable roof. The smaller gable roof at the top is of the same length as that of the main gable at lower level. A typical Bhutanese house with Drangim roof is presented in Figure 2c and g. The upper layer of the Drangim roof does not have windows under it and is left open to allow for air to flow through. Chenkhep means the additional roof that is provided at the top of the Rabsel (Bhutanese ornamental windows), which is a cantilever projection out of the main building structure. These additional roofs are lean-to roof that are placed above the Rabsel but at the lower level than the main roof which is shown in Figure 2d and h. Although the Bhutanese Architecture Guidelines has specified four different types of roofs in the traditional Bhutanese architecture, many rural houses can be found with a conventional gable roofing.
The main components of the Bhutanese vernacular roofs are made of timber, but they are assembled with minimum to no use of nails and screws. The vertical struts or the king post at the center are called Shari and the ones at the sides are called Shathung and these struts are simply saddled over a rafter plate made up of timber, which is known as Dingri. The struts are placed at the top of Dingri in such a way that the weight of the parts above it keeps it stable. The central king post (Shari) supports the central ridge of the roof called Gungchen and the struts at the side (Shathung) support timber purlins called Gungchung. Dingri is supported by vertical timber props called Lhiuchung, which rests at the top of flat wooden member known as Gha placed on the slab of the attic of the house. The rafters of the roof, Tsim, are supported by Gangchung and Gangchen. The rafter is usually made from small tree trunks that are round shaped, usually. The wooden shingles known as Shinglep are used for the roof covering and are placed on top of the timber battens known as Dangchung which are placed over the rafters (Tsim). The wooden shingles are held in their place by applying load on top of them. The rafters are spaced in such a way that there is enough space in between the two rafters for the workers to fit during its construction. Figure 3 illustrates the details of a typical Bhutanese gable roof.

It is worthy to note that the rural constructions limit the number of roofing parts to struts, rafters, and ridges. The connection of ridges to struts and the rafters to ridges are very weak and susceptible to damage by dynamic loads such as wind and hailstorms. The wooden props (Lhiuchung) supporting Dingri are not found in some of the rural houses, instead Dingri is found to be supported directly by the walls. Figure 4 shows some of the common roofs found in Bhutanese vernacular buildings.

3. Roof damage by windstorm in Bhutan

Insured infrastructure damaged by windstorm in Bhutan are compensated by the Royal Insurance Corporation of Bhutan Limited. Per the insurance statistics, Figure 5 shows the economic loss in the country due to wind induced damage in the past 27 years (1994–2021). Similarly, the total number of affected buildings in the past 27 years is presented in Figure 6. As shown in Figure 6, stone masonry buildings are the most affected building types by windstorm. Subsequently, the common roofing provided in stone masonry buildings is the most affected roofing type.
Figure 4. Common practice of roof construction; (a) Without Lhiuchung and Gha, (b) Dingri resting on wall, (c) extensive usage of circular section as main truss members, (d) congested and non-engineered joints, (e) several shorts purlin and not joined properly, (f) several openings to raise risk of uplift pressure, (f) the Jamthok opening as main concern of uplift pressure.

Figure 5. Economic loss due to windstorm.
Information regarding the damages caused by windstorms in Bhutan are collected from various organizations such as the Ministry of Work and Humans Settlement (MoWHS) and the Department of Disaster Management (DDM). Some of the common housing types in Bhutan such as stone masonry and rammed earth structures were found to be mostly affected during historical windstorm events. Some notable damages occurred during historical windstorm events are presented in the following section.

3.1. Displacement failure

Displacement of truss member was mostly observed in trusses with large spans that were susceptible to the movement of the weak joints and truss members (Figure 7).

3.2. Anchorage failure

It was observed that there is lack of structural integrity between walls and truss system, therefore it enhances vulnerability against the wind gust uplift. It is observed that struts and the ties are simply rested on the walls which leads to poor diaphragm action during windstorm and earthquake. Figure 8 demonstrate the failure of roof due to lack of integrity.

Failure due to weak connections

Traditional Bhutanese trusses lack proper connection between the members. It is to be noted that joints are not designed considering joint reactions, rather judged and provided by local carpenters. There is no proper connection between the two jointed members as shown in Figure 9. The use of circular members, especially the rafter, could also result in weaker connection.
Figure 7. Failure of truss due to displacement of members.

Figure 8. Anchorage failure of roof between walls.

Figure 9. Damage to roofs due to weak member connection in rural houses.
4. Empirical vulnerability analysis of Bhutanese vernacular roofs

Vernacular buildings are one of the least studied building types in Bhutan and adjoining regions. Historically collected roof damage data was clustered into four groups of roofs in various types of buildings as rural house, school/NFE, lakhangs and dratshang, and public infrastructures. As shown in Table 1, roofs of the rural houses are the most affected roofing types followed by school and nonformal education building roofs. It is interesting to note that even temple and public infrastructure roofs are heavily damaged due to windstorm although it is expected that public infrastructures are superior constructions than the residential ones (Gautam et al. 2016).

Since there were no wind speed recording stations in the affected areas, we used the field accounts to correlate damage with the wind speed. The reports by the Royal Government of Bhutan, especially the Department of Disaster Management (DDM), Ministry of Work and Human Settlement (MoWHS), and the Department of Geology and Mines (DGM) presented the impacts of the windstorms in terms of economic losses, injuries, and fatalities. The damage description suggested in Fujita scale (Fujita 1971) are compared with the damage descriptions in the available reports and the wind speeds for the damage locations are assigned. Using the estimated average wind speed and damage statistics as reported in Table 1, fragility functions for the roofs of rural houses, schools/NFEs, and lakhangs/dratsangs are developed. Fragility curves for windstorm hazards depict the relationship between wind speed and exceedance probability of a certain damage state (Gautam et al. 2020). The exceedance probability of any damage state (DS-i) can be effectively presented in terms of lognormal distribution for empirical damage data sets as confirmed by several researchers (Shinozuka et al. 2002; Porter et al. 2007; Gautam 2018; Gautam et al. 2018; 2020; 2021). The two-parameter lognormal fragility function can be depicted as:

\[ P_{DS-i}(V) = \Phi \left[ \frac{\ln(V)}{\beta} \right] \] ...

where, \( P_{DS-i}(V) \) depicts the conditional probability of exceeding or reaching particular damage state (DS-i) as a function of intensity measure (V), \( \Phi \) is the Gaussian cumulative distribution function, \( \alpha \) is the median, and \( \beta \) is the logarithmic standard deviation for the particular damage state (DS-i). Wind speed (V) in m/s is used as

| Damage state | Damage state definition | Type of roof | # |
|--------------|------------------------|--------------|---|
| DS-3 | Collapse/beyond repair; reconstruction needed | Rural house | 1285 |
| School/NFE | 73 |
| Lakhang and dratshang | 67 |
| Public infrastructure | 32 |
| DS-2 | Major to severe damage to roof; major retrofit/repair required | Rural house | 2025 |
| School/NFE | 57 |
| Lakhang and dratshang | 48 |
| Public infrastructure | 33 |
| DS-1 | Slight to minor damage to roof; minor repair required | Rural house | 3922 |
| School/NFE | 68 |
| Lakhang and dratshang | 85 |
| Public infrastructure | 34 |
Table 2. Lognormal distribution parameters for Bhutanese roofs.

| Type of roofs | Damage states | Lognormal distribution parameters |
|---------------|---------------|-----------------------------------|
| Rural houses  | DS-1          | \( 41.53 \) \( \beta \) 0.60     |
|               | DS-2          | \( 62.43 \) \( \beta \) 0.68     |
|               | DS-3          | \( 86.49 \) \( \beta \) 0.70     |
| Schools       | DS-1          | \( 25.36 \) \( \beta \) 0.67     |
|               | DS-2          | \( 38.94 \) \( \beta \) 0.84     |
|               | DS-3          | \( 64.72 \) \( \beta \) 1.02     |
| Lakhangs      | DS-1          | \( 38.99 \) \( \beta \) 0.77     |
|               | DS-2          | \( 63.00 \) \( \beta \) 0.92     |
|               | DS-3          | \( 101.24 \) \( \beta \) 1.05    |

Figure 10. Fragility functions for rural house roofs.

Figure 11. Fragility functions for school building roofs.
the intensity measure to derive empirical fragility functions for common Bhutanese
goals. A summary of the lognormal distribution parameters is presented in Table 2.

The fragility functions for the roofs of rural house, schools including nonformal
educational buildings, and temples (lakhangs and dratsangs) are presented in Figures
10–12, respectively. As shown in Figure 10, no significant damage is expected for the
wind speed up to 10 m/s. After 10 m/s, DS-1 initiates; however, DS-3 is initiated only
beyond 15 m/s. Wind speed below 20 m/s can be considered weak as exceedance
probabilities for DS-1, DS-2, and DS-3 are respectively 10%, 5%, and 2.5%. When
wind speed reaches 100 m/s, more than 90% of the roofs of rural buildings are
expected to observe DS-1 damage state, 75% of the roofs of rural buildings are
expected to observe DS-2 damage state, and almost 60% roofs of the rural buildings
are expected to observe DS-3 damage state.

As shown in Figure 11, the roofs of schools are more vulnerable than the roofs of
rural houses. Damage initiation for all three damage states is observed at a wind
speed less than 10 m/s. At 20 m/s wind speed, exceedance probabilities of DS-1, DS-2,
and DS-3 are respectively 35%, 20%, and 12%, which indicate the severity of the roofs
of school buildings when compared with the roofs of rural houses. At 100 m/s wind
speed, almost all roofs of schools are expected to observe DS-1, 85% of the roofs are
expected to observe DS-2 damage state, and 65% of the roofs are expected to observe
DS-3 damage state.

As shown in Figure 12, damage initiation in temple roofs is expected at just below
10 m/s wind speed. At 20 m/s wind speed, exceedance probabilities for DS-1, DS-2,
and DS-3 are respectively 20%, 10%, and 7.5%. Basically, tendency towards collapse is
more prominent in temple roofs than that in the roofs of rural houses. At 100 m/s wind
speed, almost all roofs are expected to observe DS-1 damage state, almost 70% of the roofs are expected to observe DS-2, and 50% of the roofs of temples are
expected to observe DS-3. It is interesting to note that the temple roofs are in partic-
ular less vulnerable than any other roofs at high wind speeds, such as 100 m/s.
Such discrepancy could be due to limited database of temple roof damage in contrast to the rural buildings.

5. Performance assessment of Bhutanese roofs

Apart from empirical vulnerability analysis, we assessed the performance of Bhutanese roofs using analytical approach. To do this, we created finite element model of the typical Bhutanese roof in ABAQUS (Dassault Systems 2020). Finite element analysis (FEA) is relevant when connections and joints in a truss member are of interest. The FEA provides the platform to model wooden members and accentuates various interactions in the joints to facilitate effective joint design of all members at same the time (Tippner et al. 2014; Massafra et al. 2020). The most commonly used timber for the construction of roof in rural Bhutan comes from mixed conifers. The mechanical properties of the materials used in FE modeling are summarized in Table 3.

Pressure acting on the roof due to design wind speed is calculated as per IS 875 – part 3 considering commonly followed dimensions of Bhutanese house \((11 \times 9 \times 7.5 \text{ m})\). Considering 50 years design life of a house and design wind speed of 47 m/s, multiplication factor derived from the code are considered as \(K_1 = 1\), for terrain category 1, \(K_2 = 1.05\), and for upwind slope greater than \(3^\circ\), \(K_3 = 1\). Design wind speed is estimated as \(V_Z = V \times K_1 \times K_2 \times K_3\), which is estimated as 49.35 m/s. Similarly, design wind pressure \((P_Z = 0.6(V_Z)^2)\) and effective net pressure \((P = (C_{pe} - C_{pi}) \times P_Z)\) thus calculated are 1461.26 N/m² and –1607.38 N/m² respectively. The net pressure acting is suction type for building height ratio, \(h/w = 7.5/9 = 0.94\) \((0.5 < h/w < 1.5)\) and roof angle= 15°. A summary of estimated parameters is presented in Table 4.

The suction pressure is calculated based on site condition, truss configuration, building dimension and topography of the site and applied uniformly to each rafter. Appropriate boundary conditions are selected to match the real construction and the roof model is developed as illustrated in Figure 13, with simply supported Dingri on two sides by the masonry wall.

Displacement parameter is used to depict the performance of the members and joints. Figure 14 highlights that the rafters are subject to higher stresses and are displaced more than any other parts. Consequently, the rafters are required to be strengthened using additional struts or by connecting the joints with plates and bolts as a retrofitting measure. It is found that most of the truss fail due to large displacement under the design wind speed. The accumulation of stress at the joints could also lead to failure of connections.

| Type          | Material properties of mixed conifers. |
|---------------|----------------------------------------|
| General       | Mass density                           |
|               | 0.0000004 kg/mm³                       |
| Elastic       | Young’s modulus                        |
|               | 9500 MPa                               |
| Poisson ratio | 0.3                                    |
| Plastic       | Yield Strength                         |
|               | 350 MPa                                |
6. Retrofitting of rural building roofs

Some strengthening solutions for the Bhutanese vernacular roofs are proposed and their performance are analyzed in this section. Bhutanese traditional roofs lack proper connections within the system as well as with the main structural wall. Finite element models with retrofitting solutions are prepared and static analysis is carried out to estimate the response of the retrofitted roof. Some of the probable retrofitting measures are described in the following sections.

### 6.1. Addition of struts

The load on the truss is applied in the form of pressure on the rafter as illustrated in Figure 15. The rafter that undergoes large deformation can be strengthened by providing additional strut to decrease the span. The strut reduces the chances of buckling failure as the members are strengthened by new tension and compression struts. Displacement and stress profiles of the truss with and without retrofitting elements are shown in Figures 16 and 17, respectively. It is clearly depicted that retrofitting
elements greatly reduce the stress concentration near the joints of the truss and the region of severe displacement is less in the case of truss with struts.

6.2. Reinforcing with proper nail arrangement

Efficient and well-designed nails in joints have advantage as they transfer the loads through fasteners, thereby reducing stress concentrations (Batchelor et al. 2004). The nails used to connect timber joints should be plain-head and diamond-pointed per IS 723-1972 code. Where rusting of nails is anticipated, galvanized wire nails should be used per the recommendation to avoid rusting. The minimum thickness of the members for the connection with nail should be 30 mm. The diameter of the nails should be in the range 1/11 to 1/6 of the minimum thickness of the members in the connection. The length of nails should be greater than or equal to the total thickness of the member in the connection. For stronger connections, nodal joints should be provided with 2 nails, and lengthening joints should be provided with 4 nails (BIS:1983).
Figure 18 demonstrates the arrangement of nails connecting the timber members. The number of nails required for each connection can be calculated by using the strength of nail, which depends on type of nails used, size of nail, type of timber used for joint, and moisture content of timber, as follows:

\[
\text{Number of nails required for a joint} = \frac{\text{Maximum stress on the member}}{\text{Lateral strength of nail}} \quad ...(2)
\]

6.3. Bolts and plates for connection

In comparison with other fastening techniques, bolts have higher capacity to resist axial load in addition to shear, if they are well designed (Batchelor et al. 2004; Branco et al. 2011). Though bolts have advantages over other connections, there will be stress concentration near the hole provided for bolts, thus bolting is not recommended if member thickness is relatively small (Lokaj and Klajmonova 2014). The notations of joints reflected in Figure 19 are used for analysis and design of plates and bolts.

The stresses in each joint and member are obtained using finite element analysis. The stress pattern shown in Figure 20 depicts the von Mises stress, which is the equivalent stress for each member. As can be observed in Figure 20, connections observe greater stress than other parts of the truss.

Figure 21 illustrates the pictorial representation of bolts (16 mm diameter) and plates (12 mm thick) in various joints considered for analysis. Load in the form of pressure is applied in the FE model as shown in Figure 22. Stress distribution in truss with and without retrofitting elements is presented in Figure 22, which clearly shows that the retrofitted elements greatly reduce stress concentration in the members. In case of load applied for connection with plates, the most common damage would be the failure of the plate itself (Fellow et al. 1999; Branco et al. 2006). In Figure 23, the stress is accumulated on plates which indicates that the metal plates will fail before the failure of truss members.
6.4. Roof anchorage on walls

The low strength masonry structures usually lack bonding between masonry units and thus walls and other building component would not be adequately connected (Gautam et al. 2021; Gautam and Rodrigues 2021). The roofs are simply supported on the surface of the wall to support the gravity load of the trusses and roof.
Figure 22. Application of pressure on FE model: (a) without plate, (b) with plate.

Figure 23. Stress distribution in truss: (a) without steel bolts and plate (N/mm²) (b) with steel bolts and plate (N/mm²).

Figure 24. Truss placement in stone masonry: a) outside view b) inside view.

Figure 25. Embedment arrangement of TMT bar in wall for roof anchorage.
coverings. They perform poorly during lateral shaking caused by earthquakes and uplift of windstorm. Most critical connections in the roof were found to be weak and had no mechanism to support lateral and uplift forces as shown in Figure 24.

The load resisting capacity of a stone masonry or rammed earth can be enhanced by proper construction. Wall with greater load resisting capacity can be used to anchor the roof. A TMT (thermo-mechanically treated) reinforced bar of required size should be inserted on wall under construction to keep the provision to anchor the truss (Figure 25). However, it is not recommended to use in walls that are not built with proper workmanship, or that are less than 300 mm thick.

6.5. Roof cover protection

In the recent windstorms such as the 2021 event, roof failure occurred due to support failure; however, roof cover, purlin, and rafter were found to be intact. This shows that the supports should have higher capacity so that they can resist the suction pressure during windstorms. Though the use of screw with washer is common in urban areas, it is still a new technique in rural areas where unjustified techniques such as hammering the screws is being practiced, which is similar to using nails as most of the threads in screws get damaged during hammering. Screws should be driven with screwdriver for it to fulfill its purpose. Figure 26 illustrates a technique to secure roof with the use of screw to connect roof covering and purlins.

6.6. Mortise and tenon joint

Mortise and tenon joints are used to make sturdy joints for frames (Ahmad et al. 2020; Parisse et al. 2021). A rectangular slot is cut at the center of horizontal or inclined member to accept the fitted tenon. The size of the mortise should be exactly one third of the member to be cut to avoid mortise split or tenon breakage. If the tenon size used is optimal for the joints of mortise-and-tenon joints, it results in application of optimal pressure on two contact surfaces of a mortise and tenon. The greatest shear strength can be obtained from the applied optimal pressure eventually leading to the greatest tensile load resistance of a mortise-and-tenon joint (Hu et al. 2018; Song et al. 2018). Figure 27 illustrates the mortise and Tenon joints.

The FE model of mortise and tenon joint is shown in Figure 28. The load is applied in the form of pressure on the vertical strut as depicted in Figure 29. Stress distribution in normal and mortise tenon joints is shown in Figure 30. In mortise
and tenon joint, the stress is distributed in the vertical strut and there is reduction of stress at the contact point. In normal joint, the stress distribution forms a straight profile on vertical strut, which shows that it will undergo shear failure.

6.7. Dovetail joint

The dovetail joints are the strongest of all joints and have large gluing area, proper interlockings, high resistance against pull, attractive, and can hold together without the use of glue (Papanikos et al. 1998; Karel et al. 2016). Figure 31 presents a dovetail
joint in timber connections. The finite element model of the joint is shown in Figure 32. The stress distribution in normal and dovetail joints is shown in Figure 33. In dovetail joints, the stress is distributed in the vertical strut and there is reduction of stress at the contact point. In normal joints, stress distribution forms straight profile on the vertical strut, which indicates that it will undergo shear failure.

6.8. Use of rectangular/flatter members

Most of the traditional Bhutanese houses have circular members used for rafter (Tsim) and purlin (Dangchung). The use of circular members limits the contact
surface between the two members that causes excessive stress accumulation in small area. The circular shape of the members causes difficulty in implementation of some of the retrofitting techniques for the connections. Retrofitting measures such as the use of steel plates are difficult to be provided in such members and the provisions for spacing of bolts or nails are also reduced. On the contrary, the use of rectangular or flatter members in truss helps in providing larger area of contact between two members and also provides the provision for the use of nails or bolts with larger spacing between them. The regularity of the rectangular members also helps in providing retrofitting measures with ease (Rezaei Rad et al. 2020). A comparison of total contact area of circular and rectangular member with other members is shown in Figure 34.

7. Conclusions

Explicit accounts of classification, vulnerability, and strengthening of Bhutanese vernacular roofs considering the most dominant jamthok roof are presented in this paper. Based on the windstorm damage data collected between 1994 and 2021, empirical fragility functions for the roofs of rural masonry houses, schools, and temples are created. It is concluded that the roofs of school buildings are the most vulnerable among the three types of roofs. Based on the forensic damage analysis, joints are found to be the most affected components by windstorms. We performed numerical analysis to assess the performance of various components of roof trusses, and proposed various retrofitting measures based on the performance scenarios. The

Figure 33. Stress distribution in: (a) non-engineered joint (N/mm²) (b) dovetail joint (N/mm²).

Figure 34. Connection of purlin to rafter (a) circular purlin placed on rafter (b) rectangular purlin placed on rafter.
retrofitting techniques are modeled using finite element modeling approach. It is found that the existing roofing system in Bhutan are vulnerable to moderate to strong windstorm and can barely resist severe windstorms that are also expected in the country. Future studies can also incorporate global analysis of buildings and compare windstorm performance. Furthermore, experimental results can ideally improve the understanding regarding fragility functions as well as the strengthening solutions. More meteorological stations can be deployed to capture the actual wind speeds so that the damage statistics could be better correlated with the wind speed to develop more realistic fragility functions.

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**Disclosure statement**

Authors declare no conflict of interest.

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**Data availability statement**

The data that support the findings of this study are available from the corresponding author, [DG], upon reasonable request.

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