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# Cyclone resistant housing in Fiji: The forgotten features of traditional housing

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ABSTRACT

Fiji housing stock suffers extensive damage during the annual cyclone season, leading to high costs in repairing and reconstructing the damaged properties. Historically Fijian houses were resilient, and the communities could self-recover from natural hazards. The country's more recent disasters have been beyond the country's ability to self-recover. Reasons for this include reliance on international aid, new housing types and materials, population changes and the loss of traditional building methods. Tropical Cyclone Winston in 2016 led to over 30,000 damaged houses, and many villages were totally destroyed. Navala was one of the damaged villages in the inner west, where most of its houses were constructed mainly as traditional houses. In this village, fifty percent of houses survived the cyclone. This study investigates Navala traditional houses, their constructability, and the apparent ability of its houses to resist cyclone hazards. The study's main findings show that traditional knowledge of building traditional houses still exists. Also, traditional houses, especially those with central posts, performed well during the cyclone and complied with the internationally recommended cyclone-resistant structural features. The study analysed the construction of traditional houses and highlighted the unique cyclone-resistant features that could be recommended for regional implementation in future constructed houses.

## 1. Introduction

In a post-disaster situation, organisations involved in housing reconstruction aim to provide better housing to the surviving communities compared to their pre-disaster situations. However, post-disaster reconstruction projects encounter challenges that limit options for achieving the intended objectives. Some of these are material shortages [1], financial problems [2], and lack of skilled labour [3]. Other challenges are in the construction approaches where community involvement is limited, and the cultural traditions are neglected in favour of modern, often imported, construction methods and materials. More importantly, most modern post-disaster constructed houses often fail to survive in the face of another natural hazard. For instance, in the case of central Vietnam, which is prone to cyclones, before 1985, most of the population lived in traditional houses built from locally available materials. The locals were able to rebuild their houses within a matter of days in case they were being destroyed [4]. However, after 1986 and as a result of the government Economic Renovation Program, the “Doi Moi” [5], the locals started shifting to building houses using modern materials. The new houses were regularly damaged, and the locals had to rebuild them, impacting their lives and savings and increasing their vulnerability [4].

Similarly and in the study of the reconstructed houses post the 2004 Indian Ocean tsunami in Thailand and specifically in the Rangong Province [6]. described the region as famous for its long flood season, and the locals used to construct their houses on a perme-

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able sand foundation that protected houses from floods. However, houses reconstructed in the region by relief agencies failed to use such features and houses were constructed on an impermeable clay foundation which led to more flood damage to the reconstructed new houses.

Langenbach [7] describes traditional architecture as architecture that has evolved from human observations and experiences over centuries. Traditional architecture usually incorporates locally available materials in constructing houses, making it an economical solution for housing [8]. Traditional architecture also reflects the community's needs in the housing interior and exterior and, more significantly, the ability to withstand the prevalent natural hazards in its geographic location [9]. The housing assessments post the Kashmir earthquake in 2005, the earthquakes in Nepal in 2015, and in Turkey in 2011 confirmed that the traditional houses tended to have an outstanding performance during regional natural hazards events [10–13]. and hence, traditionally built houses survived the regional natural hazard with either minor or no damage.

The South Pacific Islands are prone to various natural hazards due to their geographic location [14]. Many traditional houses are constructed using natural materials and techniques in the region. Those traditional techniques were proven to resist various regional natural hazards, which was the case in Vanuatu following Cyclone Pam in 2015. Using traditional “thatched” houses in saved many lives during the cyclone [15,16]. However, there has been a gradual decline in traditional houses' use and features. Given the way to timber frames, contemporary houses are the most prevalent housing type in the region. This was the case in Samoa as reported by Franco et al. [17] and later in the Samoa Post Cyclone Evans Disaster needs analysis [68]. Cowling [18] also mentioned that there are very few traditional-style houses in Tonga as there has been a significant move towards more contemporary housing.

Fiji, for instance, as one of the most populated nations in the South Pacific, is subjected to a reoccurring season of tropical cyclones. In February 2016, Tropical Cyclone Winston, a category five cyclone, made landfall on Fiji and destroyed almost 30,000 homes affecting 62% of the total population [19]. The destroyed houses were mostly contemporary, timber-framed structures with pitched roofs covered with corrugated steel sheets.

One of the villages in Fiji that were partially damaged during the cyclone was Navala village. Navala is located in the interior of Viti Levu island of Fiji and is considered one of the few remaining traditionally constructed villages in Fiji. The village community claimed that the traditional houses performed better during the cyclone and that most damages occurred due to flying debris from contemporary-built houses. This paper investigates whether traditional housing in Fiji, using the village of Navala as a case study, is a sustainable, cyclone-resilient housing solution. Structural features of the traditional houses and their resistance to damage from the prevalent regional hazard will be analysed.

To implement better reconstruction policies, there is a need to analyse the traditional houses and evaluate their features based on the theoretically and practically proven house construction with cyclones resistant features.

## 2. Issues with post-disaster shelters

Post-disaster, and especially when a disaster causes damage to the housing stock, agencies during the recovery focus on repairing, retrofitting or constructing new temporary or permanent houses for the affected communities [20]. Reconstruction, especially in large-scale permanent shelter projects, often faces complications related to financial capacity and the shortage of building materials and skilled labour [1,21]. For example, during reconstruction post the 2004 earthquake in Indonesia, the government built over 100,000 houses but found significant obstacles relating to importing building materials, logistics, security and local regulations; in addition, the constructed houses were of low quality [2]. What was observed by Kennedy et al. [22] during the recovery projects in Aceh, Indonesia, was the expectations of the affected local communities and agencies in charge of reconstruction were to construct modern masonry dwellings. Even though masonry dwellings have poor seismic performance and the locally, self-constructed timber dwellings tended to be safer.

Build Back Better (BBB) was introduced by the united nations (UN) special envoy for the tsunami recovery in 2006 after the Indian Ocean tsunami to address the shortcomings and lessons learned from the tsunami recovery. The BBB framework recovery framework recommended ten propositions for providing better quality in all aspects of relief and recovery activities [23]. According to Mannakkara and Wilkinson [24]; structural resilience is one of the main guiding principles of BBB that comes under disaster risk reduction. It is then described as the improvement of structural designs of the reconstructed houses to provide better protection to the house owners and reduce their vulnerability. Since its inception, the BBB became the guiding principle for many post-disaster reconstructions worldwide and became the slogan for many recovery programs [25].

### 2.1. Post-disaster recovery in Fiji

Fiji has a long history of recurring extreme weather conditions, usually cyclones. Historically, self-recovery after each natural disaster was a traditional norm practised by native Fijians, including food redistribution, reconstruction of damaged houses, or even whole village relocation [26]. The traditional *bure* was a prominent housing type that supported Fiji's self-recovery until the 1940s [27,28]. The Colonial Government, by the end of the nineteenth century, started the Hurricane Reserve Fund after the 1895 cyclone to cover expenses of restoring the damaged public works as a result of the reparative threats of damages due to cyclones. After the severe cyclone of 1904, the government provided food provisions to the devastated province of Lau while the people of Lau were rebuilding their houses [29].

The Fijian government was not involved in house rebuilding activities until late March 1910, when an intense cyclone damaged all the houses on Bau Island; the government initiated a programme to build 80 homes in the devastated region. The help provided under that project was in the form of traditional building materials and grants for the victims.

In February 2016, Tropical Cyclone Winston (TC-Winston) struck Fiji and affected more than half of its population and housing stock [30]. Caimi [69] claimed that the traditional houses in Fiji were in gradual decline and formed only 3% of the housing stock in Fiji at the time of the cyclone. Based on the post-disaster needs assessment report (PDNA) [30], after TC-Winston, the Fijian government developed the disaster recovery framework (DRF) [31]. The DRF sets out the vision and the guiding principles for recovery in the short and medium term. Accordingly, the government pledged not just to restore Fiji to the situation before TC-Winston but to consider this an opportunity for BBB in Fiji. Similarly, in the same report, BBB was defined as building houses to a higher construction standard, thus reducing vulnerability and improving living conditions.

Soon after TC-Winston, the government launched a program to help the affected communities rebuild their homes. The program was an owner-driven assisted scheme which provided the affected, low-income families with grants to purchase hardware to rebuild the houses. The grant ranged from 1500 Fijian dollars (FJD) for partially damaged houses and up to 7000 FJD for destroyed houses [32]. While the government described the program as a -initiative, several stakeholders from local and national governments were concerned about the degree to which the program embraced the BBB principles [25]. The help for homes program (HFH) did not provide the homeowners with the required technical support for constructing more substantial cyclone-resistant houses. However, providing technical support should be a cornerstone for any BBB recovery project, which was the case in BBB recovery after the 2009 Sumatera earthquake in Indonesia and the post-Sikkim 2011 earthquake in India [33,34]. In both cases, the technical support helped homeowners integrate their reconstructed homes with earthquake-resistant features.

Some technical guidance was provided by non-governmental organisations (NGOs) through workshop training within the affected communities using the build-back safer handbook [35]. The handbook provided best practices on basic modern carpentry and some recommendations for constructing stronger homes. However, it was not oriented towards training locals on cyclone-resistant features when reconstructing houses.

### 2.2. Building back better using internationally accepted cyclone-resistant features

When considering cyclone hazards, there are several recommendations for cyclone-proof housing. Some building standards provided recommendations for both engineered and non-engineered housing like the Building Indian Standards [36] and guidelines for construction practices like the guidelines for improving wind/cyclone resistance of housing issued by the building material and technology promotion council [37]. In addition to various publications that discussed housing best practices and elements to be considered in housing design specific to cyclone-prone areas [38–44]. From these building standards, guidelines, and publications, five features are emphasised and highly recommended to be considered for a cyclone-resistant house: a hipped roof shape, hurricane-strapped joints, narrow overhangs, stone foundations, and a low centre of gravity with minimum protected wall openings.

#### 2.2.1. Roofs: hipped roofs

The four-sided hipped roof offers an excellent distribution of wind loads on the roof structure. Taher [43] noted that decades of research had proved that a hipped roof is better than a gabled roof in case of hurricanes. In a model study, Taher also showed that a hipped roof with four slopes with 30° experienced the lowest wind pressure and performed better than a gabled roof. [45,46]. tested the effect of wind on roofs with different pitches ranging from 10° to 30° and confirmed that the 30° pitched roof resulted in the least negative wind pressure coefficient. The maximum action of wind on hip roofs was less severe compared to gabled roofs. The local peak negative pressure on the hip roof was roughly less by 50% than on the gabled roofs [46].

In addition Ozmen et al. [47], confirmed that the critical suction on roofs decreased as the roof pitch increased. The maximum critical suction was observed on 15° pitch roofs and a minimum at 30° and 45° pitch. In a wind tunnel experiment on different roof pitches at 16.7°, 26.6° & 36.9°. Tominaga et al. [48], confirmed that the pressure on the roof windward becomes positive as the pitch increases. In addition to this, Gavanski et al.[49]confirmed that the roof slope between 37° and 45° experienced less uplift pressure on the roof sheeting on the windward side.

Regarding the roof supporting structures Meecham D et al. [46] reported that the pressure on the entire span of the gabled roof structure was twice that on the entire span of the hip roof structure at similar wind speeds. Thus, it was concluded that the performance of hipped roofs over gabled roofs was superior under heavy winds.

#### 2.2.2. Structural connections: hurricane straps

Metal straps are standard in contemporary hurricane-proof houses, especially for structural connections. The experimental testing achieved by Riley and Sadek [50] focused on two types of roof connections with the wall joints. One of the roofs used a regular toe-nailed connection, and the other used a hurricane-strapped connection. The results showed that the hurricane-strapped connection had a significantly higher uplift capacity compared to the standard toe-nailed connection. However Graettinger et al. [51], mentioned in a study assessing house damage post-Hurricane Katrina that using only hurricane straps was not enough to secure the connection. An essential aspect is to choose the critical joints to be strapped and fixing the strap to the proper orientation is critical to ensure the continuity of the load path from the roof to the foundation. In the same context Stevenson et al. [52], highlighted that the selection of the joints to be strapped has a significant impact on house performance. Stevenson et al. recommended doubling up or reinforcing other framing members, as when hurricane straps are used in the roof-to-wall connections, the failure will be shifted to framing members and joints (which Stevenson suggested doubling or reinforcing).

#### 2.2.3. Roof extensions: eaves and overhangs

In hurricane-proof houses, minimising roof overhangs reduce the uplift of the entire roof. This uplift usually initiates the failure of the whole roof, resulting in severe building damage. That was the reason behind recommending overhang width not exceeding

300 mm in hurricane-proof housing [43,53]. Similarly, it is not recommended to have houses with verandas. It was noticed in a vulnerability assessment of housing after Hurricane Katarina that the house models with verandas suffered whole roof structure collapse during the hurricane [54]. In his fieldwork on houses damaged due to strong winds Minor [55] indicated that the failure of the building envelope would trigger the collapse of the whole structure and suggested that a well-designed building envelope would protect the entire house from damage.

#### 2.2.4. House foundations

The INTERTECT relief and reconstruction corporation report (1982) [41] stated that elevated continuous stone foundations prevent wind from passing under the house floor in cyclone-prone areas. Wind under the house floor was proven to cause uplift and overturn some houses [56]. Elevated stone foundations protect the house base from erosion and the whole house from being washed out due to high tides or flash floods [37]. Also, where timber posts are used as the central supporting structure, they should be treated with wood preservatives and embedded deep enough in the ground to provide adequate attachment to the foundation [36]. When using a concrete foundation, the concrete should be poured in an excavated bore with the timber post embedded into the concrete to provide adequate anchorage. For concrete blockhouses, a concrete strip foundation would be the best alternative [37].

#### 2.2.5. House walls: low centre of gravity with short walls

A low centre of gravity means having the heavier part of the house at the base and using lighter material as the height increases [41]. As wind exerts positive pressure on the windward-side wall of the house and a negative suction pressure from the leeward side, the shorter walls decrease the area directly exposed to wind pressure [57]. The wind forces exerted on the walls of a house are also governed by the shape of the building and its location with respect to hills and valleys [42]. The house's layout should preferably be square or rectangular, although closer to a square is generally for better distribution of wind loads [56].

For the wall openings, it is recommended that cyclone-resistant houses have minimum wall openings in the form of windows, which should have wooden shutters or planks. It was observed by Amini and Memari [58] in their review of various cyclone-damaged houses that non-shuttered wide wooden windows were damaged as a result of heavy winds and flying debris which caused a pressure build-up inside the house, which led to the roof being blown out and hence caused extensive damage to the building [56].

## 3. Research approach

### 3.1. Overview of the 2016 Tropical Cyclone Winston and the recovery process in Fiji

Tropical Cyclone Winston made landfall on the Fiji Islands in February 2016. As per the United Nations Office for the Coordination of Humanitarian Affairs in Fiji, the Western Region and the Koro Islands were the most affected by the cyclone affecting 540,000 people, or 67% of the country's total population [30]. According to the Fijian Ministry of Economy, the estimated cost of recovery for the destruction caused by TC Winston to the housing sector was 730.86 million FJD [31].

The havoc caused by Tropical Cyclone Winston was massive, leaving inhabitants in the affected areas without food or shelter. The livelihood of the affected communities was disturbed due to the loss of crops and damage to houses and public services. Tropical Cyclone Winston also destroyed roads and infrastructure, which affected access to and from the villages [59].

Fig. 1 illustrates the size of the pass of TC-Winston, with the pink and orange sections showing how the cyclone affected almost all the Fijian islands. The overspread of the destruction was the heaviest in nearly 40 years, where previously Fiji was struck by Tropical Cyclone Bebe in 1972. The Fijian government estimated the total recovery and reconstruction costs post the cyclone to be over 1.69 billion FJD; the combined damages and losses due to TC-Winston were more than 20% of the country's gross domestic product (GDP) in 2016 [59,60].

### 3.2. Study area and demographics

This study analysed the traditional building method used in the village of Navala regarding its cyclone resistance features. Navala is located in Ba province, Qaliyalatini district, in northwest Viti Levu in the interior highlands Fig. 2 on the bank of the Ba river, as shown in Fig. 3, the village consisted of six clans forming five villages consolidated into one big village in the nineteenth century. Most village inhabitants are farmers, planting cassava, sugarcane, and several cash crops. Before TC-Winston, the majority of the 140 houses in the village were traditional *bure* houses. There were only four timber-framed houses with iron roofs, in addition to the village school, the teacher's accommodations, and the church. Fig. 4 shows the bure and timber frame houses in Navala village.

At the time of the study, the village's population was almost 870. By 2018, the total number of houses was 140, of which 80 were built as traditional *bure* houses and 60 as timber-framed houses with iron roofing. A church and a primary school are located inside the village.

Navala is considered a remote village. Its location in the interior highlands of Viti Levu limits accessibility to the village. Only one (dirt) road leads to the village with a crossing over the Ba River. In a flood situation, the only bridge leading to the village is closed, cutting off access to the village, which was the case after TC-Winston. The villagers have a well-practised custom of communal work, or *solesolevaki,* in the iTaukei language, as it is a traditional village. The *solesolevaki* helped speed up village recovery without relying entirely on help from outside the village.

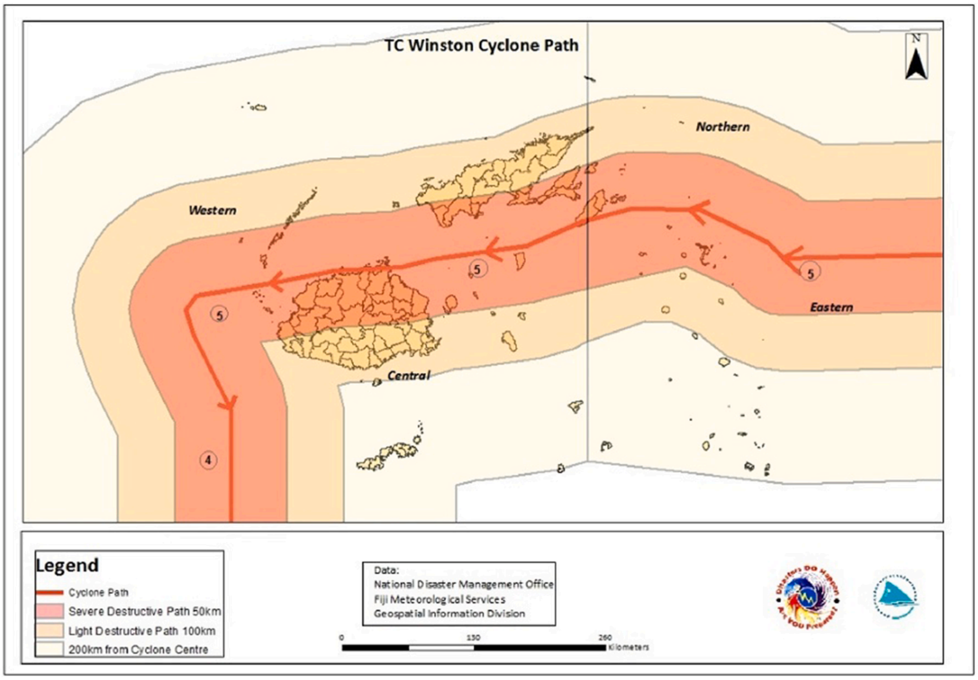

**Fig. 1.** Tropical Cyclone Winston 2016's path (Source: National Disaster Management Office, Fiji).

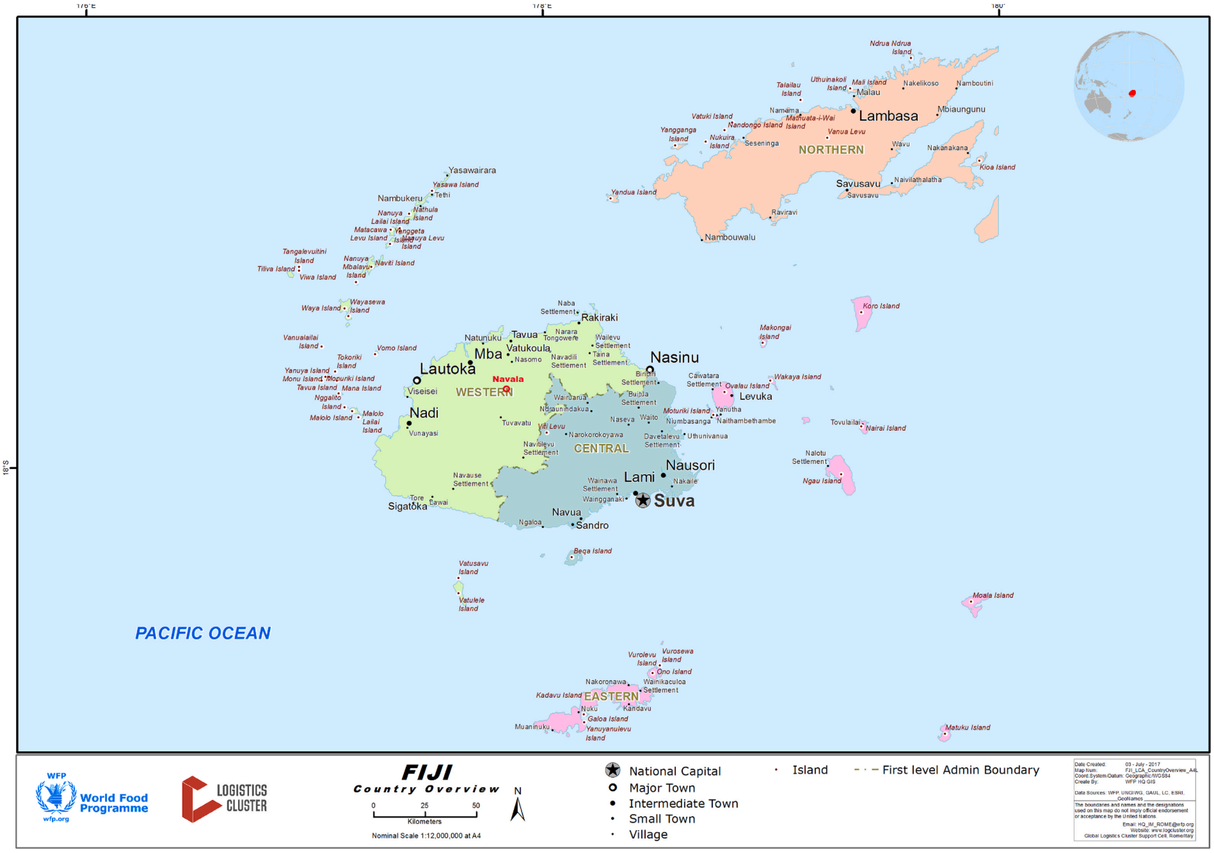

**Fig. 2.** Map of Fiji showing the location of Navala (Source: Logistics Capacity Assessment home page, www.dlca.logcluster.org).

**Fig. 3.** Naval village layout looking north-east (Source: Setoki Tuiteci).

**Fig. 4.** A bure house on the LHS and a timber frame house on the RHS (Source: Setoki Tuiteci).

### *3.3. Research methods*

#### *3.3.1. Interviews and focus group discussion*

Interviews and a focus group were conducted in 2017 with stakeholders involved in the Post TC-Winston recovery. Individual interviews were conducted with a professional architect who documented the damages in Navala village after the cyclone and a local government official for Navala. These two interviews were designed to understand traditional housing in Navala and the community background and activities.

A focus group discussion with the village community was conducted in 2018 to unveil the complexity of the village situation before, during and after TC-Winston. The participants in the focus group were seven members of the village communities, including the village chief. The role played by the community during the reconstruction of the houses was examined. Furthermore, the discussion was formulated to capture the experience of the village communities with the constructed houses. The facilitator asked predefined questions and gave the participants a chance to respond. The facilitator asked some additional questions emerging from the participants' responses. All the responses were audio-recorded to ensure that the village community views were accurately captured. Non-focus group participants were met during the research at Navala, and their observations were recorded via note-taking.

#### *3.3.2. Field observations*

Kumar (2019) detailed that field observation is an essential technique to use when full or accurate information cannot be gathered by questioning. As a sub-classification of the field observation, site observation is an essential technique for gathering actual site information related to the damage situation of houses and the reconstruction status [61].

In this study, site observation was performed in 2018 to capture information about the constructed houses in the studied village. Transect walks were conducted in the village, and different models of traditional houses were visually inspected and measured. The data was recorded via note-taking and digital photographs. The descriptive notes and the digital photos taken for the village houses were classified under categorised activities identified under the cyclone-resistant features.

### 3.3.3. Desktop analysis and verifications

To assess the effect of TC-Winston on the village, the researcher analysed the (PDNA) report together with photos taken soon after the cyclone, which documented the damages to the housing stock in the village. The researcher verified the findings by asking related questions during the focus group discussion to ensure the documents' interpretations reflected the actual situation.

## 4. Study findings

### 4.1. Village damage after Tropical Cyclone Winston

TC Winston made landfall on Navala at almost 9:00 p.m. on the February 16, 2016. For 3 h, the tropical cyclone caused massive damage to the village houses and the livelihoods of the village inhabitants. Most of the villagers evacuated to the village school, while some preferred to remain in their traditional houses as they considered safer. As reported by the Ba provincial office representative, the cyclone claimed a life in the village, a child who died due to an injury caused by a flying iron sheet.

"The houses with king posts, twelve were damaged. Nevertheless, those are very old buildings … only 12 were partly damaged, and none of them was completely damaged. —Navala village focus group.

"The smaller version of the bure was damaged. There were 70 of them out of 140." —Navala village focus group.

As a result of the cyclone, 70 traditional *bure* were totally damaged. Two of the four timber-framed houses were destroyed. In addition to the destroyed houses, 12 traditional *bure* were partly damaged (see Fig. 5 and Fig. 6). The partially damaged houses were the larger version of the *bure* that included direct posts in the middle of the house. Damage to the village's crops and cassava plantations affected the food security of the village community, and the village needed outside help to recover.

### 4.2. Traditional house construction

Building a *bure* requires a collective effort from the village community; everyone in the village knows how to build a traditional *bure* as the traditional knowledge has been passed through generations.

"The village has some carpenters, not traditional carpenters "mataisau"; but we build the same way our forefathers taught us. So everybody knows how to build a house." —Navala villager.

Building traditional houses still exist and are well preserved in Navala village. Carpenters did not have to be descended from a *mataisau* (traditional carpenter) clan or be traditional carpenters to know how to construct a bure.

[62] studied central-pole houses in eight Fijian communities in the early 1980s and outlined the steps for creating a traditional bure. Construction of a traditional *bure* can take from two weeks to two months. The traditional *bure* in Navala is the *rausina* type, in the iTaukei language, which means made of reed or grass. House thatches and walls were mainly constructed out of bamboo reeds,

**Fig. 5.** Partially damaged *bure* houses, with only roof thatches destroyed (Source: The Author).

**Fig. 6.** Completely damaged *bure* houses (Source: Author).

and one of the critical components of the traditional *bure* was the timber posts which differentiate between the various types of *bure* structures.

"It would take up to four days to cut one king post from a tree. We still use the traditional axe and then chip the timber into the shape we need, and that is the core of the house. We then bring it down to the valley, and it may take three to four days to cut and chip it to shape and three days to take it down along the river up to the village." —Navala village focus group.

### *4.2.1. Foundation & floor*

Building a house starts with marking the house layout on the ground. The traditional houses of Navala were built on earth mounds, square or rectangular. The mounds were faced with black rocks acquired from the Ba riverbed and bank (see Fig. 7, left). The foundation can extend up to 1 m above the average ground level. The house foundation is considered a sacred component of the house and is named after the first settler in the village to whom the house owner had a blood relation. The mound is constructed (as in Fig. 6, right). The first several soil layers are placed, and the corner and wall posts are put in position. If the house is to have a centre post, it is placed in position along with the rest of the wall posts. The soil is then compacted around the structure posts, with a top layer of clay forming the internal house floor. The rock perimeter face wall is built afterwards.

### *4.2.2. Structure*

The first thing to be built in the house is the structure posts. In Navala, there are two versions of the traditional *bure*: a version with a centre post (Fig. 8, right) and a smaller version without a centre post (Fig. 8, left). The traditional *bure* house posts are made out of a particular hardwood available in the forests close to Navala, known as *vesi* (*Intsia bijuga*). Both models are timber-framed structures with wall posts holding a wall plate beam. The roof rafters are connected directly from the ridge beam to the wall plate timber beam in both models. The wall posts are cut to the required length. For the corner posts, the top of the post is carved into a crown shape (Fig. 10, left) so that the wall plate beams can rest on the corner posts, the carved top giving enough height for tying the beams from the short and the long side of the house. The intermediate wall posts are carved from the top to form a U shape so that the wall plate beam can rest securely on the post, forming an interlock connection, as in Fig. 10 (right).

The central post is located in the middle of the house and holds a roof ridge beam, which in turn holds the roof rafters from the top (Fig.9, right). Both ends of the ridge beam are supported by two short posts, one on each side (Fig. 9 left). The posts are supported by

**Fig. 7.** Boulders from the river bed used for *bure* mounds (left); a *bure* mound with boulders, dirt backfill, and posts (right) (Source: Author).

**Fig. 8.** (Small version) traditional bure without a centre post (left), (Large version) traditional bure with centre post (right).

**Fig. 9.** Corner and wall posts, bamboo rafters and timber purlins (left); central post with crossbeam struts (right) (Source: Author).

**Fig. 10.** Carved corner post (left); carved intermediate wall posts (right) (Source: Author).

two-beam struts, one on each side, running parallel to the short axis of the house. The centre post (Fig. 9, right) is also supported by two timber crossbeam struts, running parallel to the short axis of the house.

In the case of the small version, the house does not have the main post to hold the ridge beam; two posts are placed at each end of the ridge beam and resting on one beam running along the house's long axis. This beam is supported by two crossbeams running parallel to the short axis of the house. The configuration is shown in Fig. 11.

**Fig. 11.** Structure of a *bure* without a centre post (left); crossbeams and posts holding the ridge beam (right) (Source: Author).

### *4.2.3. Roof*

Both models of the traditional house in Navala have hipped roofs. Model 1, the smaller version, does not have a centre post; hence, the ridge beam is supported by two short posts (Fig. 11, left). In model 2, the larger model has the ridge beam on the top resting on the centre post. Another version of model 1 found in Navala post-Winston, did not have a top ridge beam, and the workers placed the rafters resting on each other from the top, forming a steep pointed top (Fig. 13, right). The rafters are connected midway with horizontal struts (Fig. 11, right). For model 2, after installing the centre pole, the ridge beam is tied to it to form a plan where the roof rafter will be attached to the central pole from the top and going all the way to the bottom wall plate beam. Horizontal struts also hold the rafters from the middle, connecting both long sides of the roof. In addition to the rafter, horizontal purlins are placed under the rafters to keep the spacing from the middle.

The roof slope is almost 30°. The roof rafters are made of bamboo canes or straight tree branches. As shown in (Fig. 14), the netting on top of the rafters with the split bamboo latticework is installed on top of the rafter to form a base for tying the thatches.

**Fig. 12.** *Bure* with the centre post from outside (left); *bure* without a centre post from the inside (right) (Source: Author).

**Fig. 13.** Bamboo reed wall (left); woven bamboo matting wall with a steep pointed roof (right) (Source: Author).

**Fig. 14.** Netting for the roof thatches (left); thatches ready in bundles (right) (Sources: Mark Heard, left; Author, right).

#### 4.2.4. *Walls*

There were two types of walls in traditional houses in Navala. One was made out of bundles of reeds threaded to a bamboo net from underneath (Fig. 13, left), the same process used for the roof thatches. The other type (Fig. 13, right) was woven bamboo matting. The walls are woven in place or prepared by the women in the village before being installed.

#### 4.2.5. *Thatches*

A vital activity that consumes village time, and is labour-intensive, is roof thatching. In Navala, the thatching is made out of dry bamboo reeds as many naturally growing reeds surround the village. The reeds must be dried first, tied into small bundles (Fig. 14, right), and then threaded with coconut husk into the bamboo nets. The Navala people usually install the thatches from the bottom of the house going upwards towards the ridge.

#### 4.2.6. *Fumigation*

The last activity, fumigation of the bure, is done from inside. The fumigation is usually done by burning wood in a small fireplace inside the house for about one week. The smoke from the burning wood treats the thatches and the roof structure against infestation. Fig. 15 shows the house roof from the inside, where the colour is dark due to the smoke treatment.

### 4.3. *House features regarding cyclone resistance*

Research is available that assists with the understanding of cyclone-resistant housing. Analysis of documentation [29,63–65], and [62] identified different features of the *bure* design and, in particular Campbel [29], describes that traditional *bure* can be seen to have some cyclone-resistant features. However, since 1984, the understanding of cyclone resistance has improved. Hence this paper gives a more current analysis of the features that exist in traditional housing, intending to investigate whether traditional housing in Fiji, using the village of Navala as a case study, is a sustainable, cyclone resilient, housing solution.

It was observed that the village people who construct the traditional *bure* do it in the way that it has been taught by their ancestors, without a thorough understanding of some of the house features. This was observed in some houses where critical joints had been poorly fitted together. As one participant in the focus group explained;

**Fig. 15.** Smoke fumigation of the house interior components.

" If there is another strong wind like Winston when you are in a bure, the bure will give you time to find shelter, and it is very hard for the bure to kill a person. The flying debris from modern houses is dangerous, and it does not give you a warning. It will stay rigid, then all of a sudden, it is blown away. For a bure, it will sway for a bit, and then you will realise that it is time to start moving." —Focus group.

The village community highlighted some critical features they believe are unique to the traditional *bure*. One was related to the time it takes for the bure to collapse; the house does not collapse immediately when subjected to strong winds. Instead, the collapse will gradually occur, giving the house inhabitants enough time to evacuate to a safer place. Another feature was related to the collapse itself. Usually, the damage or failure pattern is to the outside of the house, which would save the inhabitants from being hit by the falling roof structure.

### *4.3.1. Roof: hipped roofs*

Both models of the traditional *bure* houses found in Navala have hipped roofs, as shown in Fig. 16. The hipped roof with four inclined sides was proven to resist strong wind better than gabled roofs [45,46]. As in Fig. 17, the roof slope was measured at 55° from the horizontal plane for the large model and 60° for the smaller model. Even though several studies suggested 30° slope hip roof as optimum for resisting strong wind like [45,47,48]; and few studies even tested 45° slope roof proving less negative wind pressure on the windward [49]. Observation in Navala showed that the large house models with a 55° roof slope showed less damage during the cyclone than the smaller model with a 60° roof slope. The roof rafters are mainly made out of bamboo cane or straight branches, previously seen in Fig. 12 (right). The roof's structural connections are lashed with natural ropes made of flattened bamboo reeds.

### *4.3.2. Structural connections*

Structural connections are essential for cyclone resistance. In Navala, as shown in Fig. 18, it was observed that there are three types of structural connections standard in both bure models; (1) the connection between prominent members, (2) the connection be-

**Fig. 16.** Traditional house with hipped roof highlighted.

**Fig. 17.** Steep-sloped hipped roofs, the large model on the left, the smaller model on the right (Source: The Author).

**Fig. 18.** Interlocking connection (left), lashed connection between rafters and purlins (middle), central post connection (right).

tween primary and secondary members and (3) the connection between secondary members. These connections were all lashed connections using natural ropes. In addition, there was an interlocking connection between the wall posts and the wall's main horizontal beams Fig. 18 (left). Observations of bures with central posts showed those houses that were less damaged during the cyclone, having a central post, as in Fig. 18 (right), taking the loads from the roof structure from various components and delivering them directly to the house foundation.

### *4.3.3. Roof extensions*

Overhangs have been criticised as they are seen as potentially a weak feature in cyclones. The way the traditional bure in Navala is constructed did not allow for overhangs; the eaves did not extend more than the thickness of the roof's thatched layers. This will be all around the house with no roof extensions or overhangs, as typically shown in Fig. 19.

### *4.3.4. House foundation*

Strong foundations have been reported to be essential for cyclone-resistant housing. The people of Navala built the traditional houses on elevated mounds with a rock face on the perimeter Fig. 20 to provide a strong foundation for the timber post and to protect the house from being washed away in heavy rainfall. The foundations in Navala can reach 1 m high. The timber posts are deeply embedded into the foundation, with bore depths ranging from 1.5 m for the corner and wall posts to 3 m deep for the central posts.

### *4.3.5. House walls and layout*

The Indian standards for improving cyclonic resistance of low-rise houses suggest that standard square or rectangular layouts are best for cyclone resistance [36]. The traditional houses in Navala have a rectangular plan. The houses have a considerably short wall with a maximum height of 1.85 m above the foundation level. Most of the traditional houses in Navala have no windows; the only wall openings are three doors, one on each of the long sides and one on one of the short ends of the house. As observed in Navala, the

**Fig. 19.** Roof narrow extensions (eaves).

**Fig. 20.** *Bure* house on a rock-face mound (*yavu*) (Source: Author).

door opening was short and narrow with a sawn timber frame and door (see Fig. 21). In general, the traditional houses of Navala have short walls, no windows, and small wall openings for the doors.

## 5. Discussion

The findings from this research have given an in-depth assessment of the traditional bure in a Fijian village greatly affected by TC-Winston. Significant features for cyclone resistance are in existence in the bure construction. The research identified that the traditional houses' walls are relatively short in height. The maximum wall height in Navala was 1.85 m. Short walls reduce the impact of strong winds on the house due to the small flat vertical area in contact with the wind forces [41]. In addition, the wall openings were minimised, as most houses did not have any windows, only a maximum of three small wooden doors with wooden door frames placed on three sides of the house. The houses were well insulated compared to contemporary houses with corrugated iron roofs, so windows were not necessary for ventilation. In addition, the breathable wall mats or weaves worked against temperature build-up inside the house. Under a strong wind, having no windows protect the roof from exploding and the leeward sidewalls from collapsing as pressure build up inside the house becomes negligible. The findings concerning the house walls and wall openings for cyclone-resistant housing are supported by those reported by Refs. [43,55].

The houses were all built on a raised rock foundation, a recommended practice in flood-prone areas, as the heavy rain associated with cyclones results in a strong flow of surface water that could wash out the house. English et al. [66] recommended a raised foundation for constructing houses in flood-prone areas. Navala villagers have naturally adopted this cyclone and flood-prone feature in traditional housing.

One significant finding n Navala was the two main models of the traditional house. The main difference between the two models, besides the size and the roof slope, was the use of direct posts. The direct post, carved from hardwood timber, was placed in the middle of the house, deeply embedded in the rock foundation down to about 1.5 m. This feature anchored the structure to the foundation and prevented it from being pushed away by strong winds. Post-TC Winston, most of the houses without a direct post were destroyed. The larger bures, which included direct posts, survived the cyclone, a few sustaining only minor damage that could be repaired. The findings highlighted the importance of using direct posts for cyclone-resistant timber-framed houses.

**Fig. 21.** House with thatched walls and roof and three short, narrow doors. (Source: Author).

One of the main features that were found to be strongly recommended by several researchers, like Mechaam D. et al. [46] for cyclone-resistant houses was the hipped roofs and small overhangs. The findings from the traditional village study showed that steep hipped roofs and small overhangs were natural features of the bures in Navala. All the traditional houses investigated in Navala had hipped roofs with a steep slope of 55° degrees for the large models and 60° for the small models. However, several studies [45,47,48] identified a 30° slope as optimum for resisting strong wind conditions; few examined steep slope roofs with a maximum of 45°. From observations in Navala, the large model with a 55° slope was less damaged after TC Winston requiring further research to be done to examine the behaviour of roof slope between 46 and 60 under strong wind conditions.

The eaves were of minimum width and did not extend beyond the thickness of the roof thatches. To make the bures even stronger, roof thatches were tied to a lattice made of bamboo cane. The lattice acts as a damper in substantial wind conditions, allowing the roof to move slightly rather than breaking the roof structure.

All the house connections are rope-tied; the ropes are made of natural sennit (*magimagi*), allowing slight movement of the house's structural connections under substantial wind conditions. Tied connections are highly recommended for cyclone-resistant housing; the contemporary version of this is metal laces, in addition to using nails [40].

The bures of Navala withstood TC-Winston's strength and, because of the limited damage, the villagers could recover their shelters quicker. However, traditional bures are in decline in Fiji, and with this, the village communities could find that they become increasingly vulnerable to housing collapse or severe damage during cyclones.

## 6. Conclusion

The paper has analysed the traditional *bure* features. The bure has unique features which naturally create cyclone resistance. These include their construction on mounds, relatively short walls, limited wall openings, and a hipped roof with steep slopes and small eaves.

Cyclones are a common natural hazard in Fiji. However, it was observed that implementing cyclone-resistant house features was limited in post-disaster housing. The reconstruction of houses without considering cyclone-resistant features provides a short-term solution for an ongoing problem. Navala is a unique case study village in Fiji as the villagers of Navala appear to create sustainable, cyclone-resilient housing solutions using traditional features.

The research showed that the construction of a traditional house involved many technical details; however, the knowledge, labour, material, and tools required to build a traditional house were all available locally. Almost all the house features studied showed high compliance with the recommended cyclone-resistant features.

By paying attention to the structural features of the traditional houses and their resistance to damage from the prevalent regional hazard in Fiji, this paper has demonstrated that traditional knowledge is available to keep communities safe. A focus should now incorporate such cyclone-resistant features in communities regularly affected by cyclones. Traditional methods of construction, close to source resources, and local, historically developed knowledge is in evidence in Navala, but other Fijian villages appear to have lost some of these traditions. It is recommended to implement the learnings from traditional construction features in this research and use those features to assist resilience building in vulnerable communities. By focusing on the learnings from this paper, communities can go some way to build back better after natural hazard events.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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