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STRUCTURAL PERFORMANCE EVALUATION OF CYCLONE RESILIENT HOUSES DAMAGED DUE TO TSUNAMI AFTER THE JANUARY 2022 HUNGA-TONGA-HUNGA-HA'APAI VOLCANIC ERUPTION

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ABSTRACT

Natural Hazards have been occurring more frequently in Tonga compared to past years due to effect of Climate Change. Before the January 2022 event, strong storm sea surges from a Tropical Cyclone destroyed coastal areas at 'Eua Island that acted like a tsunami disaster. After the event of January 2022, there have been more frequent earthquakes occurred near Tonga and more coastal protection were damaged as well as bulk of the housing stock at the coastline. The Cyclone Resilient Houses (CRH) that had been popularized in the past 40 years for housing reconstruction programs are now questionable after the January 2022 event. For this purpose, the study is to perform structural performance evaluation of the CRH timber shear walls using the AS 1684.2 – 2010 Capacity of Wall Bracings on timber framed structures. This is assessed against the demand lateral forces from tsunami in addition to wind and earthquakes based on the Australia standard AS 1170.2 and AS 1170.5 - 2002 and tsunami force using the Japanese guideline. The analysis result shows that the capacity of the shear walls is safe in the case of tropical cyclones because of the adequate nailed connections. The CRH is also safe from earthquakes because the CRH has added capacity from steel strap bracing and stud ties. As for tsunami load, it is too big to compare against the capacity of the CRH and therefore CRH can never withstand tsunami with inundation depth over 1m. Therefore, the priority focuses on reinforcing strength of CRH in terms of tsunami by raising floor heights above ground to no more than 3m with concrete or wooden poles that would not increase tsunami wave pressures when it reaches the building. Moreover, this can be ignored if relocation can be made to build CRH on higher grounds and/or build coastal protection and planting mangroves over the coastal area of the inundated areas. Nevertheless, this draws attention into enforcing structural performance evaluation of buildings to suggest future disaster mitigation planning of housing.

Keywords: Cyclone Resilient Houses, Performance evaluation, Tsunami, Earthquakes, Horizontal force

1. INTRODUCTION

In the 2017 World Risk Index Report, Tonga is ranked as the second most as-risk country in the world in terms of exposure to natural hazards. Tonga is a small group of islands located in the Pacific, of which approximately 170 islands with a population of 100,700 inhabiting 36 of the islands according to the Tonga Census Report of 2016. The main island with the capital city is home to 74% of the population. Tonga was highly affected after a most recent disaster on January 15, 2022, by a violent eruption of Hunga-Tonga-Hunga Ha'apai (HTHH) undersea Volcano at 5:10pm local time. The eruption then generated a powerful Tsunami that hits various coastal areas of the Kingdom of Tonga rendering heavy damage to infrastructures across the Kingdom. A lot of the damage is associated with the tsunami-

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affected locations for the building infrastructure and the common damages identified were buildings with only the foundations remaining. After the Initial Damage Assessment carried out by the Government Ministries in Tonga, the observed maximum inundation depth recorded was up to 10m high. Moreover, the target of this study focuses on the Cyclone Resilient Houses (CRH) that have been used in Tonga in the past 40 years for Housing Reconstruction Programs. It was also developed through a time where no building regulations were in place, and building construction and type were all traditional. The CRH also known as the Hurricane house was becoming common in Tonga in the past however, some suffered severe damages from the tsunami after the 2022 HT-HH volcanic eruption. Therefore, there is a need to re-evaluate the structural performance of the CRH against tsunamis in addition to cyclones and earthquakes to suggest future disaster mitigation planning of housing.

2. DATA

The focus of this study is based on the inundated areas after the January 2022 event, and where the Cyclone Houses were observed with damages. They are (1) Kanokupolu village under the capital island of Tongatapu, (2) ʻAtata Island and (3) ʻEua Island. The damages to the CRH in relation to the inundation depths were identified in the ʻEua Island and the ʻAtata Island. Figure 1 shows the location of the CRH at ʻOhonua, ʻEua within 50m from the shoreline without any coastal protection in the area.

Figure 1: Damaged CRH at ʻOhonua, ʻEua with different inundation depth

In the ʻAtata Island, the damages observed to the CRH were different in comparison to the damages seen at the ʻEua Island. Figure 18 shows the location of the damaged CRH according to different inundation depths. The damages observed were different at high points and low points of the island. At high points, no structural damage was observed as shown in Figure 2. However, at low points of the Island where inundation depth reached 6 m, the damaged CRH showed some structural damage to the shear wall panels as shown in the Figure 2.

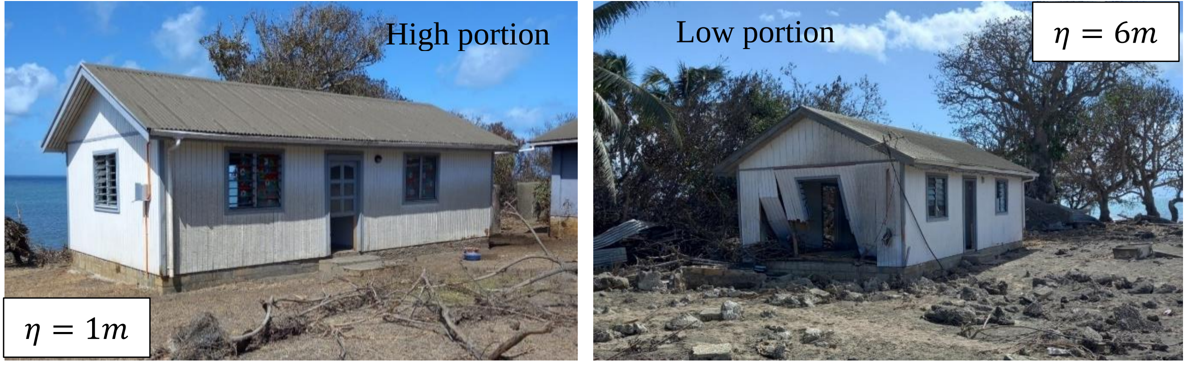


Figure 2: Damaged CRH with different inundation depths at low and high points of ʻAtata Island

3. ANALYSIS MODEL

The Cyclone Resilient House is a 2-room timber-framed structure on RC slab and foundation. It is designed to 70m/s design wind speed and in Wind Region C high cyclonic areas. The shear wall panels of the structure are the focus of the analysis in this research based on the damages occurred after the January 2022 event whereby the sub-structure was still firm while the super-structure was badly damaged due to the lateral force induced by the tsunami. The floor plan of the CRH is outlined in Figure 3.

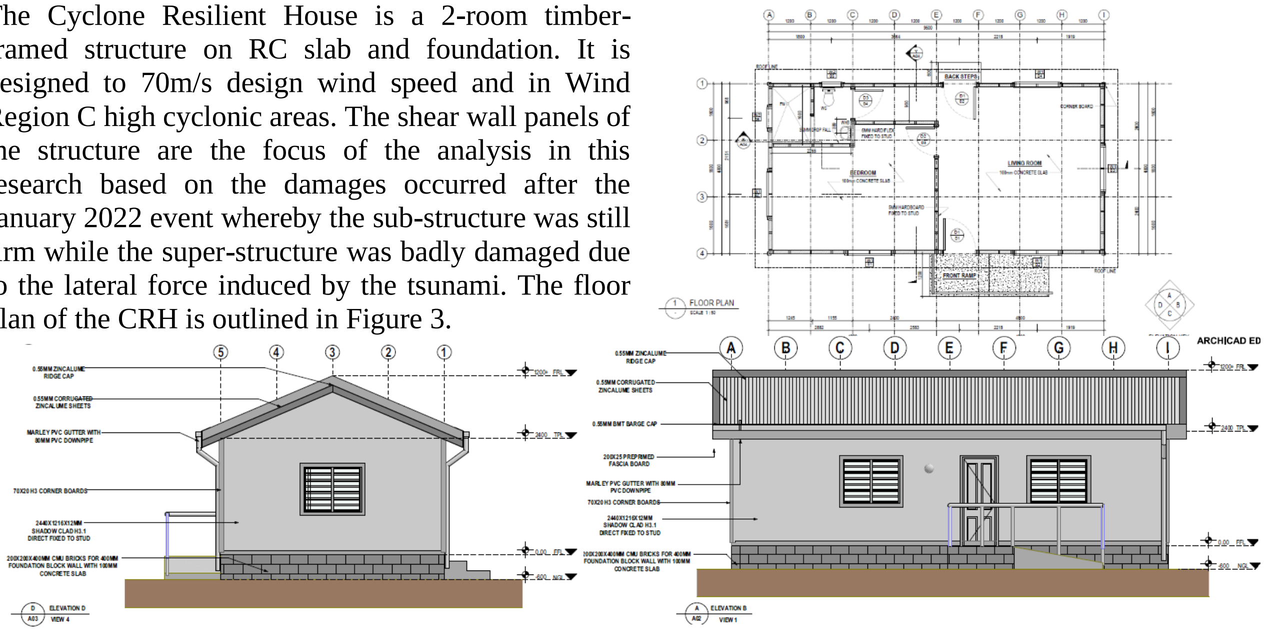


Figure 3: Floor plan and elevation of the CRH

The structure of the timber shear wall comprises of three things: timber frame, plywood cladding and the nail for connections of the two. The timber-framed structure is based on the Australia Standard AS1720 – 1997. This 100mm x 50mm sized timber is framed according to Figure 4 for each wall sections in both x and y directions.

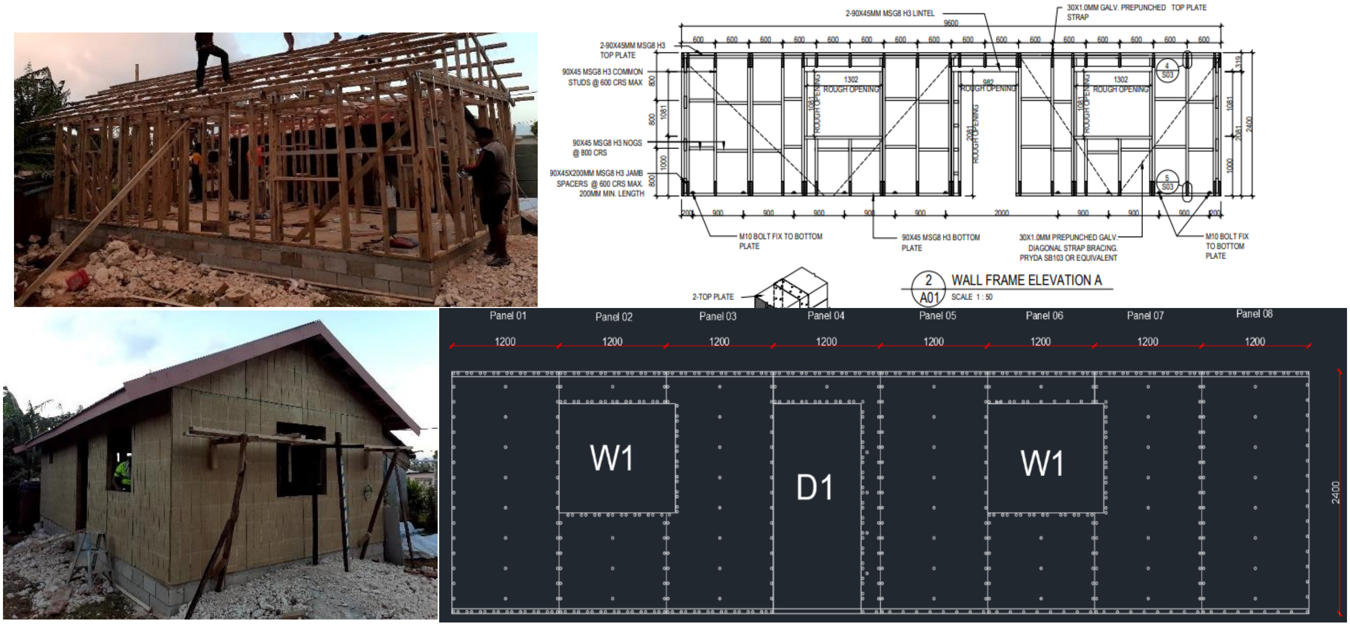


Figure 4: Shear walls from timber framed to bracing and nailed connections to timber panels

3.3. Horizontal Design Forces

Step 1: WIND

The design wind load that Tonga follows as per the National Building Code (NBC) of Tonga - 2007 is the Australia Standard AS/NZS1170.2 – 2002 for Structural Wind Actions. The NBC has a standard design wind speed, V_R = 70m/s that is used for all wind design load. The following procedure outlined in that standard is what was used in this study.

Step 2: EARTHQUAKE

The NBC of Tonga adopt the Australia and New Zealand Standard NZS 1170.5 – 2002 for Earthquake Design Actions as there is currently no seismic design code for the country. There was an update to the NBC for Tonga in 2019 which utilities specific hazard maps that was developed only on the capital island of Tongatapu under the Multi Hazard Data Risk Assessment (MHDRA) for Tongatapu Project funded by the Asia Development Bank (ADB). In this update, ground motion is defined as a single value of 0.7g across the country with a 10% probability of exceedance in 50years, equivalent to a 500-year period.

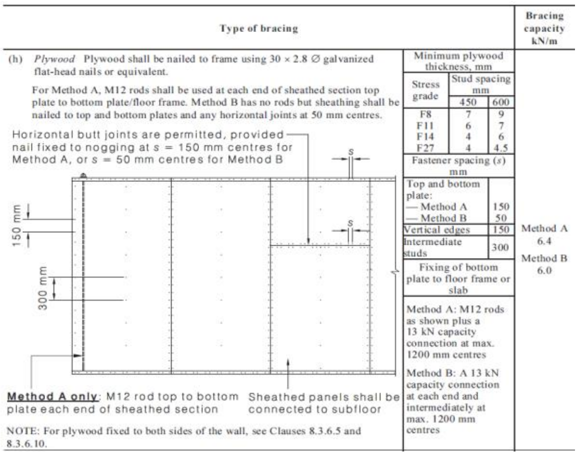
Step 3: TSUNAMI

In Tonga, currently there is no guidelines regulated for Tsunami Loads or have it mentioned in the NBC. We know that it has been just recently that Tonga started to have frequent tsunami and earthquakes, and the Government of Tonga is now considering the effects of the tsunami on the private housing. Therefore, for the purpose of this study the Japanese guideline for the tsunami forces on buildings was adopted and used.

4. RESULTS AND DISCUSSION

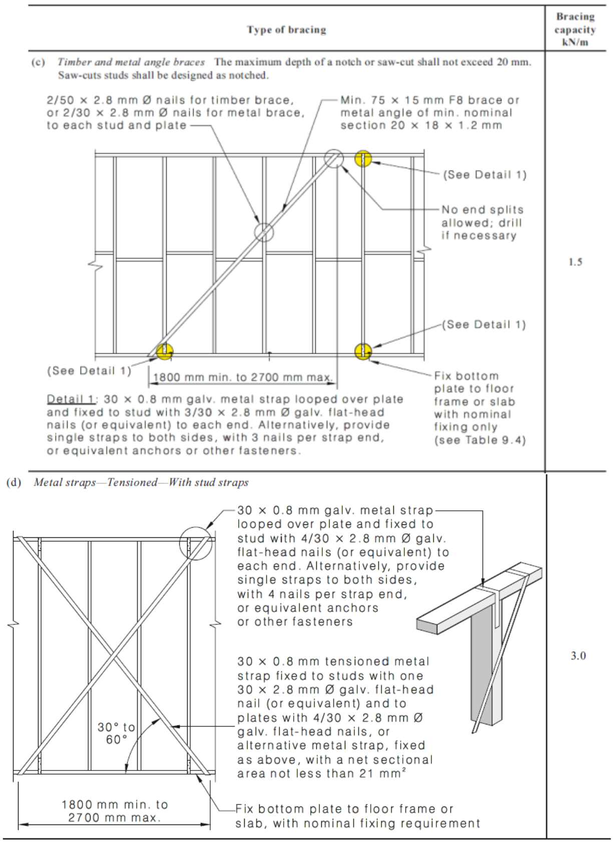
4.1. Horizontal Load Carrying Capacity of the CRH

The analysis procedure adopted for this research is based on the Australian standard, "Residential timber-framed construction (AS 1684.2 – 2010)." The AS 1684.2 – 2010 sets out the requirements for the construction of conventional stud-framed walls considering wall frame members. The total capacity of bracing walls shall be the sum of the bracing capacities of individual walls. The two types of structural wall bracing in the CRH are of the (1) steel bracing and (2) timber sheet bracing in Figure 5. It also provides the unit bracing capacity (kN/m) for the typical wall bracing systems. The CRH uses Type B bracing unit using Pryda Strap Brace (SB103) or Pryda Speedbrace with design capacity of 3kN/m for wall heights up to 2.7m as shown in Table 4. The location and distribution of bracing shall be provided in both directions as shown in Figure 6.



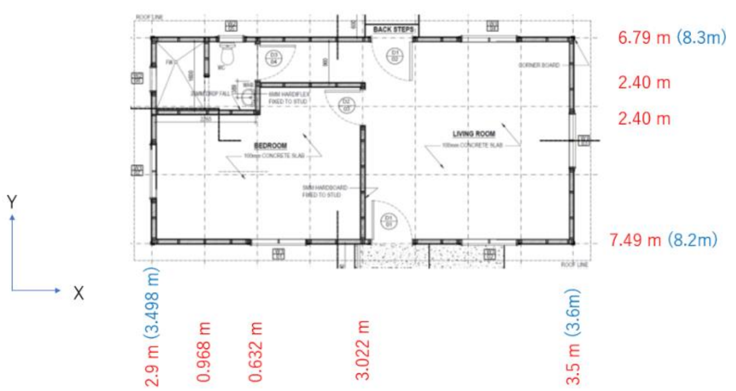
Type of bracing				Bracing capacity kN/m
(h) *Plywood* Plywood shall be nailed to frame using 30 × 2.8 Ø galvanized flat-head nails or equivalent. For Method A, M12 rods shall be used at each end of sheathed section top plate to bottom plate/floor frame. Method B has no rods but sheathing shall be nailed to top and bottom plates and any horizontal joints at 50 mm centres.	Minimum plywood thickness, mm			Method A 6.4 Method B 6.0
	Stress grade	Stud spacing mm		
		450	600	
	F8	7	9	
	F11	6	7	
	F14	4	6	
	F27	4	4.5	
	Fastener spacing (*s*) mm			
	Top and bottom plate: — Method A — Method B	150 50		
	Vertical edges	150		
	Intermediate studs	300		
	Fixing of bottom plate to floor frame or slab			
	Method A: M12 rods as shown plus a 13 kN capacity connection at max. 1200 mm centres			
	Method B: A 13 kN capacity connection at each end and intermediately at max. 1200 mm centres			
NOTE: For plywood fixed to both sides of the wall, see Clauses 8.3.6.5 and 8.3.6.10.				

Figure 6: Length of Wall bracing – timber panel



Type of bracing	Bracing capacity kN/m
(c) *Timber and metal angle braces* The maximum depth of a notch or saw-cut shall not exceed 20 mm. Saw-cuts studs shall be designed as notched. Detail 1: 30 × 0.8 mm galv. metal strap looped over plate and fixed to stud with 3/30 × 2.8 mm Ø galv. flat-head nails (or equivalent) to each end. Alternatively, provide single straps to both sides, with 3 nails per strap end, or equivalent anchors or other fasteners.	1.5
(d) *Metal straps—Tensioned—With stud straps*	3.0

Table 4: Types of steel bracing used in the CRH



Total Length
X-direction: 19.08 m (7.098 m)
Y-direction: 11.022 m (16.5 m)
Red: Timber panel
Blue: Steel strap

Figure 5: Type of timber sheet bracing used in the CRH

The structural performance evaluation of the CRH in comparison of Demand and Capacity is shown in Table 6.

Table 6: Capacity vs Demand of the CRH

CAPACITY			
Direction	**Timber Panel**	**Steel Strap**	**Total**
X (Longtidunal)	114.48	16.05	130.53
Y (Transverse)	66.13	24.75	90.88
DEMAND			
Direction	**Wind**	**Earthquake**	**Tsunami (h=1.0m) [*]**
X (Longitudinal)	29.72	73.08	52.92
Y (Transverse)	61.52	73.08	105.84

Note: [*] represents amplification factor a = 1.5

The result in Table 6 shows that for wind hazard, the capacity of the CRH can overrule and will be safe during a tropical cyclone with heavy wind gusts. As for earthquake hazard, the capacity of the CRH is also higher than the demand therefore the CRH would be considered safe during an earthquake. The tsunami destructive forces can only be compared to the capacity of the CRH when the tsunami inundation depth is 1m. For inundation depths of more than 1m, the tsunami forces are way above the capacity of the CRH. The tsunami load is very large that the destroyed houses were located near the shore in less than 100m from shoreline. For CRH located in higher grounds, the tsunami force is obstructed and will slowly reduce the tsunami forces by the time it reaches that location. For this reason, the CRH can never be recommended for housing reconstruction for tsunami resilient houses as evident from the results in Table 6.

The following can be concluded from the analysis results:

i. Shear walls capacity depends mainly on the nail-joint properties although not specifically enforced in the construction of the CRH. Increasing the number of nail joints leads to increasing the shear wall racking capacity.
ii. CRH can also be used as an Earthquake Resilient House.
iii. CRH is not safe for tsunami when the tsunami inundation depth exceeds 1m. CRH should not be recommended to build at coastlines because of its vulnerability to tsunami disaster.
iv. Alternatives in place to substitute for CRH in the case of tsunami shelter reconstructions.
v. Cost review analysis of different type of structures.

5. CONCLUSIONS

The objective of this study was to fully assess the current capacity of the CRH that had been used over the past 40 years in Tonga for post-disaster housing reconstruction activities. Currently in Tonga, there is no certain guidelines for structural performance evaluation of buildings. The two methods used in this study are very useful to use even for the MOI when they evaluate damages of public infrastructures so that they can provide what retrofitting techniques can be used. Although the retroffiting method was not covered in this study but it is important for a start to develop guideline for performance evaluation of different type of structures. This study covered methods for timber framed structure. The primary analysis of the CRH focused on the shear wall panels which was also noted in the results that the capacity of the nailed connections alone cannot overcome the earthquake demand until the steel strap bracings were used. However, for the tsunami lateral forces it was too big to even compare to the capacity of the CRH or any other engineered building in that location. Therefore, other alternatives can be taken into account such as the use of other material type of structures and increasing floor height above ground of CRH or any building in general to reduce tsunami wave pressure projected on the surface area. The result of the cost analysis of the CRH shows that it is becoming more expensive to construct now compared to when it was introduced and not affordable for the government to bare and be able to build a lot of houses to accommodate all the affected households Therefore, there is a need to investigate other alternatives such as utilizing local materials that will eliminate the cost of delivery of materials from abroad. To do this, we need more detailed approach into research and to conduct tests to evaluate performance of the local construction materials, and we also need more engineered suggestions on how to use them to meet minimum requirements set out in the Tonga National Building Code.

6. ACTION PLAN

The limitations of DRM measures within government in terms of both structural and non-structural countermeasures needs to be addressed.

(1) Non-structural Measures:

- Develop tsunami hazard maps for Tonga through tsunami simulation and numerical analysis and regular refinement of hazard maps but especially for earthquakes to include updates on active faults, surface deformation measurements and so forth.
- Develop country hazard zoning maps for Tonga to be used in the NBC and to inform future amendments to the building code.
- Establish Vulnerability Assessment for the building sector considering combination of the exposure hazard maps and structural characteristics of buildings.
- Establish provisions for tsunami guidelines on Structural Design of Tsunami Evacuation (or important) Buildings.
- Introduce and enforce establishment of guidelines for structural Performance Evaluation of timber framed structures following the Australia standard AS 1684.2 – 2010 followed in this study and other guidelines for Performance Evaluation of RC structures using Stera 3D or other Australia standards.

(2) Structural Measures:

Construction of barriers like seawalls, dikes and revetment with considerations to include natural based solutions like planting mangroves at coastal areas.

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