Shelter 5: Structural Assessment - Pakistan

1.1 Introduction and Purpose

Arup was commissioned to carry out a structural review to assess and validate selected shelter designs for the IFRC. This document summarises the information gathered for and the key outcomes of the verification of the structural performance of Shelter 5, built by the Pakistan Red Crescent Society.

Summary Information

Location: Pakistan – Khyber Pakhtunkhwa (NWFP) and Gilgit-Baltistan (Northern Areas)

Disaster: Flood, July 2010

Materials: Timber frame (poplar or acacia), corrugated steel sheet roofing and plastic sheeting (bricks for wall and roof insulation locally sourced by homeowners)

Material source: Timber sourced locally and roof sheeting sourced both internationally and locally

Time to build: 1 day

Anticipated lifespan: 24 months

Construction team: 4 people

Number built: 10,000

Approximate material cost per shelter: 500CHF

Approximate programme cost per shelter: 500CHF

Shelter Description

The shelter consists of 7 triangular frames, connected by a ridge pole that is supported by two 2.74m high vertical columns at each end. The shelter is 4.3m x 5.7m on plan and has a low (0.9m) brick wall constructed inside the frame to provide protection against flood damage and retain warmth. The pitched roof of 44 degrees is corrugated steel sheeting nailed to purlins spanning between the frames. The roof sheeting is laid on top of a locally available insulating material and plastic sheeting. The foundation of the shelter is provided by burying the rafters and columns approximately 0.3m in to the ground on top of stone footings. Guy ropes over the roof sheeting have been used to help prevent uplift under wind loads.

It is expected that the materials in the shelter kit will eventually be used for rebuilding permanent housing, and it is therefore easily dismountable and the materials all reusable. The timber is not treated so will rot where buried in moist ground, but acacia timber does have natural resistance to termite attack. However, this may not be a concern given the short intended lifespan of the structure, although treatment would be recommended where timbers will be re-used in permanent homes.

This assessment is based on the input documents listed in Appendix A. We have used some information provided for a previous bamboo version of the shelter and adapted this to suit the details of the timber shelters provided.

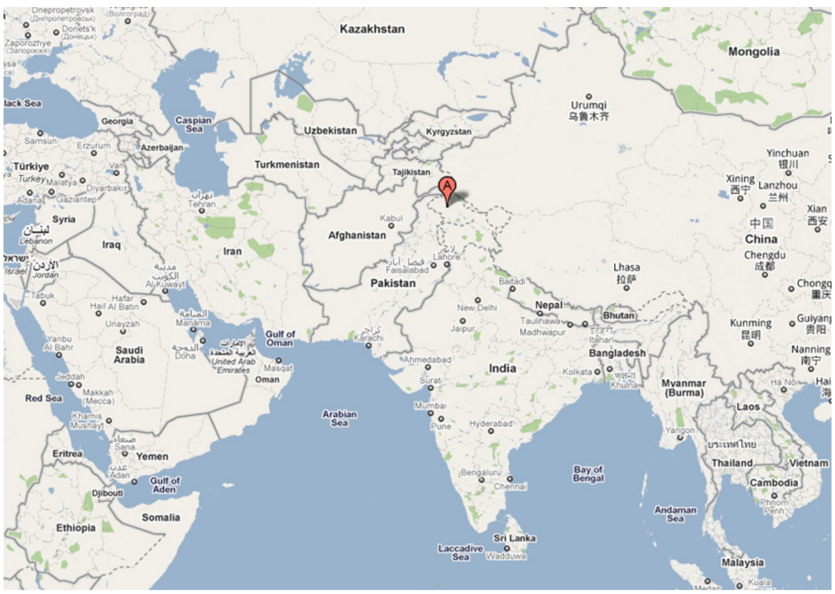
1.2 Location and Geo-hazards

1.2.1 Location of Shelter

Pakistan – Khyber Pakhtonkhwa, North West Frontier Province (NWFP)

Gilgit – Baltistan, Northern Areas

It has been assumed that these shelters have been used in the northern mountainous region of Pakistan, and therefore have been designed using data for the Gilgit area. The approximate location is shown on the map below.



1.2.2 Hazards

A summary of the natural hazards faced in this region of northern Pakistan is given below[1]:

- HIGH Earthquake Risk. This region of Pakistan is close to known fault lines and in the past has experienced severe earthquakes. The Building Code of Pakistan has been used to determine the Peak Ground Acceleration (PGA).[2] The area has been classified as Zone 3 (see Table 2.2 for Gilgit) and the PGA for a 475 year return period is therefore between 0.24-0.32g (see Table 2.1).
- MEDIUM Wind Pressures. The Building Code of Pakistan will be used to determine wind pressures from a minimum basic wind speed of 120km/hr. See Section 1.8.3 for further wind loading details.
- HIGH Flood Risk. High rainfall in the monsoon season between June and October leads to high runoff and widespread flooding. Mudflows may also be a risk.
- HIGH Landslide Risk due to earthquakes or flooding since shelters are likely to be located near steep and therefore potentially unstable slopes.
- Cold climate reaching extremes of -30 degrees centigrade with large amounts of snow in winter.

1.3 Geometry

The geometry was determined using the photos and construction manual for a similar bamboo shelter and the timber shelter bill of quantities provided.[3]

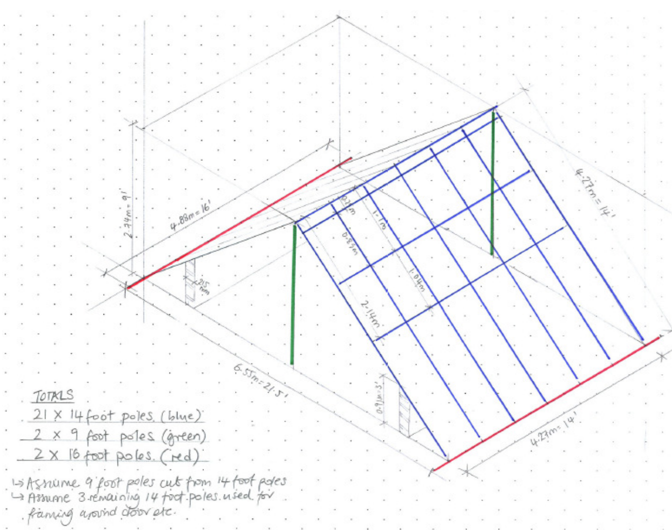


Figure 1.1 – Sketches of Geometry[4]

[1] See Appendix A, Reference 2 – general information used only since shelter location not Balochistan.
[2] See Appendix A, Reference 1.
[3] See Appendix A, References 4, 5 and 6.
[4] Refer to drawing 005 for accurate dimensions, sketch is indicative only.

Figure 1.2 – Photograph of Similar Bamboo Shelter

The timber framed shelter consists of seven triangulated frames of sloping rafters forming a pitched roof of 43.8 degrees. These frames are connected using a ridge pole supported by two 2.74m high vertical columns at each end. The shelter is 4.27m x 5.72m on plan and has a 0.9m high, 215mm thick brick wall constructed inside the frame to prevent flood damage, provide warmth and to enable excavation below ground level.

The roof is clad with steel corrugated sheeting nailed to purlins spanning between the triangulated frames. The roof sheeting is laid on top of a locally available insulating material and plastic sheeting. The foundation of the shelter is provided by burying the rafters and columns directly in to the ground and in some cases adding rocks as ballast. The foundation poles bear onto buried stone footings. Guy ropes over the roof sheeting have been used to prevent uplift under wind loads.

Geometrical Assumptions:

- All connections are nailed and assumed to act as pinned connections.
- The column foundations are formed by burying the columns 1' (0.305m) into the soil onto a stone which provides a larger bearing surface. The stone is assumed to have minimum dimensions 200 x 200mm x 100mm thick. Resistance to uplift of the roof is provided using rope guys fixed to inclined stakes buried into the ground.
- The brick wall is not connected to the timber frame and is assumed to be unrestrained at the top, except when forces cause it to bear laterally outwards onto the rafters.
- The roof sheeting extends only down to the top of the wall as shown in photographs, rather than all the way down to the ground.
- The space between the frame, roof and wall on the front and back walls is assumed to be covered with sufficiently fixed plastic sheeting, wooden planking or similar.

1.4 Structural System

- Vertical loads are transferred from the longitudinally spanning roof purlins back to the inclined rafters and then back directly to the ground at one end and to the ridge beam which spans between vertical columns. The column bases transfer these forces by bearing onto stones and back to the soil.
- In the transverse direction the stability comes from the frame action of the triangulated rafters.

- In the longitudinal direction stability is provided by the roof sheeting acting as a diaphragm which relies on the use of the recommended nail spacing. This however is not a code compliant lateral resistance system and is inadequate.
- Limited uplift and sliding resistance is provided by burying the columns into the ground. Additional resistance is provided by three transverse and two longitudinal guy ropes acting in tension only. These are anchored into the ground using wooden stakes which resist these forces using the shear resistance and mobilising the weight of the soil. Some resistance is also provided by the weight of the structure.

1.5 Member Sizes

The table below shows the key timber frame member sizes that have been assumed for the structural assessment. These sizes have been based on information given in the photographs and Bill of Quantities referenced in Appendix A. The table does not include secondary timber framing to form doors or other non-structural elements. The full list of elements is given in the updated Bill of Quantities in Appendix B.

Member Description	**Length (m)**	**Member Size (mm)**
Vertical Columns	2.74	75mm diameter pole
Ridge Beam	4.27	75mm diameter pole
Inclined Rafters	4.27	75mm diameter pole
Roof Purlins	4.27	75mm diameter pole

1.6 Materials

The timber for the frame was procured locally, and the materials for the walls and roof insulation provided by the homeowners. The roof sheeting was sourced either locally or internationally as available. It has been assumed that the timber frame is made from untreated poplar or acacia timber poles connected using 10d or 20d nails.

1.6.1 Material Assumptions

Type	IFRC Specification	Arup Assumption	Comments
Masonry	Locally available bricks and mortar – in some cases mud mortar	Standard size 215 x 102 x 65 mm clay bricks	No checks carried out therefore no brick or mortar strengths assumed
Roof Insulation	Rice straws, grasses and barks	Assumed to be palm matting or similar with maximum weight of $1kg/m^2$	
Timber	Poplar (or acacia) timber poles, 3' diameter – visually graded	Grade 2 structural Aspen, density $420kg/m^3$, Young's Modulus $6895N/mm^2$, bending strength $4.14N/mm^2$	
Galvanised Steel Roof Sheets	10' x 3.5' corrugated galvanised iron roof sheets with standard corrugation and 26 gauge	Galvanised steel corrugated sheets, 75mm spacing x 18mm trough height. Sheet sizes 1.83m long by 8/10 corrugations wide (0.6-0.75m)	0.45mm sheet thickness assumed, weight $0.056kN/m^2$
Plastic Sheeting	4 x 6m sheets	Polyethylene sheet with braided core (HDPE/LDPE) – $200g/m^2$	Nailed to timber using 10d nails spaced at 150mm centres
Rope	Polyethylene 12mm diameter		
Thin rope	3/8" diameter for tying poles		
Nails	Galvanised round head nails 3" or 4" long with galvanised steel round heads and cured washers 1.5" diameter and 1.5" diameter round rubber washers	10d/20d nails	Assume 2 nails for all timber connections and washers are used to nail roof sheet in accordance with guidelines in C.3.

1.6.2 Poplar Poles

The frame has been made using 75mm diameter round poplar poles. The timber used is White poplar (*Populus Euphratica*) or acacia (*Acacia Nilotica*) both native to Pakistan. The timbers are untreated; however Acacia wood is naturally resistant to termite and insect attack. The members have been visually graded for degradation, cracking, taper and sweep.

Aspen is a close relation to white poplar and is therefore thought to have the most representative properties. For the purposes of design the tabulated design properties of No. 2 grade structural Aspen have been used. These are given in the NDS for Wood Construction 2005 which has been used to check the members. This is conservative for acacia wood which is stronger and stiffer.

1.7 Codes, Standards and References

General

The IBC (International Building Code) 2009 has been used as a basis for the design checks on the shelters since it is widely accepted worldwide, particularly for extreme loading cases such as earthquakes or strong winds. Other codes have been referenced where appropriate or where the IBC was thought to be less applicable. This includes where appropriate.

Other references used for this shelter:

- Standards referred to by IBC 2009 including: ASCE 7-10 (2010), NDS for Wood Construction, ACI 318 for Concrete, and AISC for Steel.
- UBC 1997 Volume 2 for preliminary wind calculations and parts of seismic calculations.
- Building Code of Pakistan (Seismic Provisions – 2007), Government of Islamic Republic of Pakistan Ministry of Housing and Works, Islamabad, 2007. This is based on the UBC 1997 referenced above.

1.8 Loads

1.8.1 Dead Loads

- Self-weight of structural materials applied in accordance with the densities specified in Section 1.6.1.

1.8.2 Live Loads

- The ground floor of the shelter is formed from the ground in that area so no loading checks are required.
- For IBC compliancy a live load of 0.96kN/m^2 on the roof should be applied[1]. In this case however, snow loads will govern and have been calculated for up to the full depth of the shelter to account for drifting on one side only. The loads have been calculated using Reference 7, Appendix A, resulting in a variable vertical line load of up to 3.25kN/m for a 6' drift depth being applied directly to the rafters.

[1] 'International Building Code', ICC, 2009 – Table 1607.1.

1.8.3 Wind Loads

The wind loads have been calculated in accordance with the method specified in the Building Code for Pakistan (Reference 1, Appendix A). This uses a wind speed of 120km/hr with a methodology similar to that used in the UBC97. The pressures have been determined using the values given in the table below. The pressure coefficients have been determined assuming an enclosed structure.

Convert basic wind speed to pressure Table 16-F	$q_s = 0.68$ kN/m^2
Assume exposure class C and height of 0-4.6m – Table 16-G	$C_e = 1.06$
Importance Factor – Table 16-K	$I_w = 1.0$
Pressure coefficients assuming an enclosed structure – Table 16-H	C_q – varies for each element

The resulting pressure before modification by pressure coefficients was found to be 0.72kPa and the resulting pressure on the windward wall 0.58kPa. The maximum uplift pressure on the whole roof is 0.5kPa and the resulting maximum lateral force on the shelter in the longitudinal direction is 6.4kN.

1.8.4 Seismic Loads

The seismic loads were determined using the PGA region defined in Section 1.2.2 from the Pakistan Building Code (See Reference 1, Appendix A). The method employed by this code is identical to that set out in the UBC97. The short period design acceleration has been determined based on the UBC methodology and the equivalent lateral force procedure has been used to calculate horizontal loads for design. The resulting shear force assumed to act at ridge level is 4.4kN, so the wind loads govern.

Design basis PGA (PGA_d) from UBC97 Table 16-Q for Soil Profile D	$PGA_d = 0.36g$
Assume structure response in 0.5-1.5s period (UBC 16-3) to get S_{DS}	$S_{DS} = 2.5*PGA_d$
Assume Risk Category I (Table 1.5-1 low risk to human life in event of failure) in Table 11.6-1	Seismic Design Category D
Importance factor assuming risk category I – Table 1.5-2	$I_e = 1.0$
Assume no codified seismic lateral system – Table 12.2-1[1]	R = 1.0

1.9 Calculation Plan

1.9.1 Design Methodology

The performance of each shelter has been assessed by checking that the structure as assumed from the information provided is safe for habitation. Relevant codes and standards have been used as the baseline for identifying appropriate performance/design criteria, but the structure has been checked against code requirements: if variations from this are made, assumptions and reasoning for lower factors of safety and alternative standards have been justified. Logical reasoning was therefore used where necessary and upgrades suggested in order for the shelter to meet these criteria.

The shelter has been assumed to be enclosed since it has only one door at the front and this is not large enough to cause higher internal pressures and therefore mean the shelter should be treated as partially enclosed. It has therefore been assumed that the plastic sheeting on front and back walls has sufficient strength and is sufficiently fixed so that it will transfer wind loads back to the timber frame without damage.

1.9.2 Structural Checks

For a summary of the checks performed to assess the building, refer to Appendix C.

[1] Connections are not considered sufficient to provide diaphragm action of the roof in the longitudinal direction and no bracing has been provided in the plane of the roof.

2 Results of Structural Assessment

2.1 General Key Findings

I. All primary structural members perform adequately under dead and seismic loads. It is however advisable to provide in plane bracing in the roof to give a more robust stability system rather than relying solely on the steel roof sheeting. These braces would be 5mm diameter steel cross bracing ties.

II. The column foundations perform adequately in bearing under vertical, seismic and dead loads. In both the seismic and wind loading cases the overall uplift and shear on the column foundations cannot be resisted by the weight of the shelter. Some additional uplift resistance will be provided by the guy ropes, but it is recommended that an alternative foundation with a greater uplift and shear capacity is provided (for example Type 2, 4 or 5, Section C.1).

III. Under snow and wind loads the vertical columns, rafters and purlins are overstressed. Under wind loads the addition of A-frame bracing and an additional purlin at the eaves will overcome this. The additional purlin will provide support to the edge of the roof sheet and ensure it is adequately fixed to reduce uplift. In addition to these measures, under snow loading the number of triangulated frames and purlins must be increased to support roof sheeting and reduce the bending stresses in the rafters.

3 Conclusions and Recommendations

3.1 Assumptions

- Cladding on front and back of structure will be of plywood or plastic and is assumed to be sufficiently fastened to transfer wind loads back to the frame.
- Plastic sheeting is not pulled taut between purlins and rafters; the corrugated roof sheeting transmits wind and snow forces directly to the timber frame. Fibrous matting has been assumed as insulation – if heavier straw coverings are to be used the structure should be checked accordingly.
- The corrugated sheeting stops just beyond the masonry wall and does not extend outwards to the ground.
- Geometry as given in drawings – columns and rafters are assumed to be embedded by 0.3m into the soil.
- The brick wall is not connected to the frame but where wind pressures act outwards it will impose a horizontal force on the rafters at the top of the wall. The wall has been assumed to be free standing and with the best available mortar quality.
- Fixings have been made using nails only but are of sufficient strength to transmit forces between members. The design and detailing of all connections is critical to the stability of the structure and should be checked for individual cases.
- A stiff soil type has been assumed in analysis of the structure. For sites where liquefaction may be a hazard (near river beds, coastal areas with sandy soils and high water tables), the shelters could be seriously damaged if soil liquefies in an earthquake but such damage is unlikely to pose a life safety risk to occupants.

- Existing foundations are formed by poles bearing down onto a stone footing at least 200 x 200mm x 100mm thick.

3.2 Conclusions

Performance Analysis	
The performance of the frame under gravity and seismic loads is satisfactory. In-plane bracing and A-frame bracing in the roof would improve the stability of the shelter. For extreme snow loads additional purlins and rafter frames are required to support the roof sheeting and reduce the stresses in the members in addition to the inclusion of A-frame bracing.	
Hazard	**Performance**
Earthquake – HIGH	As a whole the shelter does not perform adequately under seismic loads; an alternative foundation solution is required to resist uplift and sliding forces. The masonry wall performs poorly under seismic loads but the height is low. The shelter frame is however lightweight and flexible, therefore posing a low safety risk in the case of damage.
Wind – MEDIUM	The shelter does not perform adequately under wind loads. A-Bracing in the triangular frames and an additional purlin at the eaves must be provided to ensure the rafters and purlins can withstand the wind pressures. In plane bracing in the roof and anchor foundations are also required to resist uplift and sliding.
Flood – HIGH	High rainfall leads to high run-off and mudflows from high ground. Brick walls laid using cement mortar provide flood protection along with the use of sandbags. No specific checks have been carried out to verify the performance of the wall in this case.

Notes on Upgrades:

Alternative wall materials such as nailed plywood sheeting or timber boarding can be used providing the recommendations for wind pressure and snow resistance are taken into account. The roof should not be extended to ground level unless rafter sizes are increased to take the resulting higher snow loads.

The use of the masonry should be kept to low levels only. Upgrading the shelter with masonry or other very heavy materials to a high level or on the roof is not recommended as they will attract high seismic loads causing the structure to perform poorly in an earthquake. Collapse of a heavy roof or unreinforced masonry walls poses a serious risk to the life safety of the occupants.

Watch-its for drawings:

A. CHANGE: Add purlin just below top of wall to support the edge of the roof sheet and transfer wind and snow loads back to the main frame. The roof sheet should be nailed to this purlin at every crest using nails and rubber washers.

B. CHANGE: Use an alternative foundation solution to provide uplift and sliding resistance (Type 2 or 5, C.1) against wind and seismic loads.

C. CHANGE: Treat timber members to prevent rot and insect degradation.

D. CHANGE: Increase number of triangulated frames and purlins (decrease spacing) according to design for expected snow drift loads.

E. CHANGE: Add timber A-bracing member to all triangulated frames to withstand wind and snow loads (7 total).

F. CHANGE: Provide cross bracing ties in roof plane in order to increase longitudinal stability.

G. CHECK: Nail roof sheet at every crest at eaves and ridge and every other crest at intermediate purlins with nails and rubber washers.

H. CHECK: In areas known to have higher local wind pressures adequate foundations and member sizes must be provided to account for this.

I. CHECK: Plastic wall sheeting should be connected back to the timber studs using 8d nails at 150mm centres all round.

J. CHECK: Do not upgrade using masonry above 0.9m due to risk to life safety and increase in seismic force attracted to the structure.

K. CHECK: Use guy ropes to help prevent uplift of shelter. To ensure good performance under wind loads alternative foundation solutions should also be provided.

L. CHECK: Can also be constructed using bamboo members. In this case the appropriate number of members, sizes and fixing details should be designed accordingly.

M. CHECK: Do not extend roofing beyond the top of the low level wall.

N. CHECK: The walls will not resist seismic loads and may collapse in an Earthquake event.

O. CHECK: Check that the soil type for the shelter location is stiff, otherwise design foundations accordingly.

Appendix A – Source Information

1. Building Code of Pakistan – Seismic Provisions 2007 (BCP SP-2007), Government of Islamic Republic of Pakistan Ministry of Housing and Works, Islamabad, 2007.
2. 'IFRC Hazard Assessment/Pakistan Balochistan', Juliet Mian & Sasha Drozd, December 2010.
3. '20100927 Summary information data collection warm shelter KPK – Transitional shelter Task Group Summary information Transitional Shelter data sheet', CT & JA, September 2010.
4. 'Spec and BoQ Pakistan' and '2011 Final BOQ wintered T shelters', 09/02/2011.
5. Erection Manual in Urdu (translated), Pakistan Red Crescent, 20/12/2010.
6. Relevant bamboo construction photographs including: 'A frame', 'A frame & brick wall', 'A frame & tarp', 'CGI roof sheet over matt, tarp & frame' and 'matting over tarp and A frame', 23/11/2010.
7. 'Interim guidelines for Design and Construction of buildings in Earthquake Affected Areas', ERRA.

Appendix B – Bill of Quantities

The table of quantities below is for the materials required to build the shelter. It does not take into account issues such as available timber lengths and allowances for spoilage in transport and delivery.

Item (Dimensions in mm)	Material Spec.	No.	Total	Unit	Comments
Structure - Foundations					
Stone Bases 200 x 200 x 100thk	-	16	16	Pieces	
Guy rope stakes 75mm dia. (L = 1m)	Timber 3	10	10	m	
Main Structure					
Vertical columns 75 dia (L=3.05m)	Timber 3	2	6.1	m	
Inclined rafters 75 dia. (L=4.27m)	Timber 3	14	60	m	
Ridge beam 75 dia. (L=4.27m)	Timber 3	1	4.3	m	
Floor footing beams 75 dia. (L=4.88m)	Timber 3	2	9.8	m	
Secondary Structure					
Roof Purlins 75 dia. (L=4.27m)	Timber 3	6	26	m	
Covering – Wall, Roof and Floor					
Roof Sheeting 1.85m x 0.75m	Sheet 1	24	33	m^2	
Insulation Material	-	-	27	m^2	
Plastic Sheeting 4m X 6m	Plastic	3	72	m^2	
Masonry 215 x 102 x 65 clay bricks	-	2100	3	m^3	Local material provided at discretion of homeowner
Fixings					
Galvanised Nails – 10d	Nails	1	1	kg	Exact number determined by fixing guidance
Galvanised Nails – 20d	Nails	1	1	kg	
Galvanised steel washers – 1.5" diameter	-	100	100	pieces	
Round rubber washers – 1.5" diameter	-	100	100	pieces	
Polyethylene rope – 12mm diameter	-	-	50	m	For guy ropes
Rope – 9.4mm diameter	-	-	100	m	Exact use unknown
Tools Required					
Hammer	-	1	1	piece	
Hand saw	-	1	1	piece	
Shovel	-	1	1	piece	
Pick axe	-	1	1	piece	
5m tape measure	-	1	1	piece	

Appendix C

Calculation Plan

1) Loading

The timber members have been checked using allowable stress design (ASD) to IBC 2009 which references the National Design Specification for Wood Construction (NDS) 2005. The seismic and wind loading has been calculated using the BCP SP-2007 (See Appendix A, Reference 1) which is based on the UBC97. The loads in Section 1.8 have been combined using the load combinations for allowable stress design found in the BCP SP-2007, Clause 5.12.3.1.

2) Stability

   a. Overturning forces on foundations due to lateral seismic and wind loads

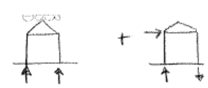
   b. Transverse Stability – key members: columns, primary beams and bracing

   c. Longitudinal Stability – key members: columns, primary beams and bracing

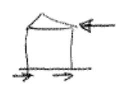
3) Foundations have been checked for the following cases accounting for the effects of overturning:

   a. Bearing pressure

   b. Uplift



   c. Base Shear



4) Primary Members

Check members for a combination of vertical and lateral loads, including: vertical columns, rafters and cross-bracing.

5) Secondary Members

Check members for a combination of vertical and lateral loads, including: roof sheeting, purlins, brick wall and wall cladding on ends. Recommend fixing spacing for roof and wall cladding.

6) Fixings – assumed to be strong enough to transmit all member forces. Connections have been assumed to be pinned for analysis, including at column bases.