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IMPROVING THE RESILIENCE OF EXISTING HOUSING TO SEVERE WIND EVENTS

Annual project report 2016-17

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Cover: Complete roofing failure from TC Debbie (2017) in Prosperine. Cyclone Testing Station

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ABSTRACT

Damage investigations carried out by the Cyclone Testing Station (CTS) following severe wind storms have typically shown that Australian houses built prior to the mid-1980s do not offer the same level of performance and protection during windstorms as houses constructed to contemporary building standards. Given that these older houses will represent the bulk of the housing stock for many decades, practical structural upgrading solutions based on the latest research will make a significant improvement to housing performance and to the economic and social well-being of the community.

Structural retrofitting details exist for some forms of legacy housing but the uptake of these details is limited. There is also evidence that retrofitting details are not being included into houses requiring major repairs following severe storm events, thus missing the ideal opportunity to improve resilience of the house and community. Hence, the issues of retrofitting legacy housing, including feasibility and hindrances on take-up, etc., must be analysed.

The primary objective of this research is to develop cost-effective strategies for mitigating damage to housing from severe windstorms across Australia. These evidence-based strategies will be (a) tailored to aid policy formulation and decision making in government and industry, and (b) provide guidelines detailing various options and benefits to homeowners and the building community for retrofitting typical at-risk houses in Australian communities. Specific task items include:

- Categorize residential structures into types based on building features that influence windstorm vulnerability using CTS and Geoscience Australia housing survey data. From these, a suite will be selected to represent those contributing most to windstorm risk
- Involve end-users and stakeholders (i.e. homeowners, builders, regulators, insurers) to assess amendments and provide feedback on practicality and aesthetics of potential upgrading methods for a range of buildings. Cost effective strategies will be developed for key house types
- Vulnerability models will be developed for each retrofit strategy using survey data, the authors' existing vulnerability models, and the NEXIS database of Australian housing characteristics. Case studies will be used to evaluate effectiveness of proposed retrofit solutions in risk reduction. Economic assessment using the same case studies will be used to promote uptake of practical retrofit options

END USER STATEMENT

Martine Woolf, *GEOSCIENCE AUSTRALIA, ACT*

Legacy housing can form a significant portion of damages during cyclones, as events in the past years have demonstrated. This project will identify options to improving resilience of legacy buildings to severe wind. This is an important part of building the resilience of communities where such housing is prevalent. The project has published a range of papers in both international and domestic journals, as well as presenting at leading conferences. It includes a number of PhD projects.

The project builds up a comprehensive picture of building resilience and mitigation, going beyond 'traditional' engineering approaches by employing social media and website to investigate mitigation behaviours. The project's involvement in response and follow-up on events such as TC Debbie, as well as the tremendous interest from industry underscores the relevance of the work to stakeholders. It is particularly exciting to note that this project has already contributed to a very tangible outcome; insurers in Queensland now offer direct incentives for mitigation by reducing premiums to customers who retrofit their homes. With its high profile, this project is likely to result in a better appreciation of the potential of mitigation for improving the resilience of legacy buildings in general.

INTRODUCTION

Damage investigations carried out by the Cyclone Testing Station (CTS) following severe wind storms have typically shown that Australian houses built prior to the mid-1980s do not offer the same level of performance and protection during windstorms as houses constructed to contemporary building standards. Structural retrofitting details exist for some forms of legacy (pre-1980s) housing but the uptake of these details is limited. There is also evidence that retrofitting details are not being included into houses when undertaking major renovations or requiring repairs following severe storm events, thus missing the ideal opportunity to improve resilience of the house and community. Hence, the issues of retrofitting legacy housing, including feasibility and hindrances on take-up, etc., must be analysed. The primary objective of this project is to develop cost-effective strategies for mitigating damage to housing from severe windstorms across Australia. Strategies will be (a) tailored to aid policy formulation and decision making in government and industry, and (b) provide guidelines detailing various options and benefits to homeowners and the building community for retrofitting typical at-risk houses in Australian communities.

Tropical Cyclone Tracy caused significant damage to housing in December 1974, especially in the Northern suburbs of Darwin [1]. Changes to design and building standards of houses were implemented during the reconstruction. The Queensland Home Building Code (HBC) was introduced as legislation in 1982 (with realization of the need to provide adequate strength to housing). By 1984 it is reasonable to presume that houses in the cyclonic region of Queensland were being fully designed and built to its requirements.

Damage investigations of housing, conducted by the Cyclone Testing Station (CTS) over the past fifteen years have suggested that the majority of houses designed and constructed to current building regulations have performed well structurally by resisting wind loads and remaining intact. However, these reports also detail failures of contemporary construction at wind speeds below design requirements, in particular for water-ingress related issues. The poor performance of these structures resulted from design and construction failings, poor connections (i.e. batten/rafter, rafter/top plate) (Figure 1), or from degradation of construction elements (i.e., corroded screws, nails and straps, and decayed or insect-attacked timber). Hence, the development of retrofit solutions for structural vulnerabilities are critical to the performance longevity of both legacy and contemporary housing.

Damage surveys invariably reveal some failures due to loss of integrity of building components from aging or durability issues (i.e., corrosion, dry rot, insect attack, etc.). The CTS conducted a detailed inspection of houses built in the 1970s and 1980s in Darwin [13]. Although the majority of surveyed houses appeared in an overall sound condition, they had potential issues like decay of timber members, corrosion at connections, missing/removed structural elements, etc. The damage survey after Cyclone Yasi showed substantial corrosion of roof elements in houses less than 10 year old [6]. This study confirmed that ongoing maintenance is also an important part of improving community resilience in severe weather.

FIGURE 1. WIND-INDUCED FAILURES OF ROOF BATTENS TO RAFTERS ON PRE-80S CONSTRUUCTION DURING TC DEBBIE. THERE WERE EXAMPLES OF NEW ROOF CLADDING SCREWED TO BATTENS BUT NO RETROFITING OF UPGRADED BATTEN TO RAFTER CONNECTIONS (E.G. STRAPS OR SCREWS) WERE OBSERVED.

The issues of poor construction practices in renovation, degradation of materials (lack of advice for maintenance), etc. are not constrained to northern Australia. Damage investigations in Brisbane, Dubbo and Perth revealed similar issues.

Considering the prevalence of roofing failures due to inadequate upgrading techniques, current building industry literature for upgrading the wind (and water-ingress) resistance of existing Australian housing were reviewed. In parallel, a brief internet-based questionnaire was distributed to a wide range of Australian building industry constituents in order to identify specific limitations of current upgrading guidelines.

BACKGROUND

WIND LOADS ON HOUSING AND STRUCTURAL PERFORMANCE

The wind field within a cyclone is known to be highly turbulent. Dynamic fluctuating winds subject the building envelope and structure to a multitude of spatially and temporally varying loads. Generally, the structural design of housing uses peak gust wind speeds for determining the positive and negative pressure loads the structure must resist. The storm duration and temporally varying forces are important for assessing elements of the envelope and frame (i.e., roofing, battens, connections, etc.) that may be subject to low cycle fatigue.

Maintaining a sealed building envelop is critical to the wind resistance of buildings. If there is a breach on the windward face, (i.e., from broken window or failed door), the internal pressure of the house can be dramatically increased. The internal loads act in concert with external pressures, increasing the load on cladding elements and the structure. Depending on the geometry of the building, the increase in internal pressure caused by this opening can double the load in certain areas, increasing the risk of failure, especially if the building has not been designed for a dominant opening.

Residential structures in cyclonic regions designed in accordance with contemporary design standard AS4055 Wind Loads for Housing [3] are required to incorporate load cases for internal pressure increases created by envelop breaches. Houses in non-cyclonic regions designed to AS4055 are not required to account for this load case, resulting in a higher probability of failure if such an opening were to occur.

The National Construction Code [18] is continually reviewed to ensure that it supports acceptable performance of new housing. However, only a small fraction of our housing stock is replaced over the course of a year, therefore most Australians will spend the majority of their lives in houses that are already built. Further, from an emergency management, community recovery, and insurance perspective, the majority of the risk is in housing stock that already exists.

The complexity of housing structures does not lend them to simple design and analysis due to various load paths from multiple elements and connections with many building elements providing load sharing and in some cases redundancy. Different types of housing construction will have varying degrees of resistance to wind loads. From a review of building regulations, interviews, housing inspections, and load testing, the CTS classified housing stock in the North Queensland region into six basic classifications [14].

For each of these classifications, the CTS developed preliminary housing wind resistance models to give an estimate of the likely failure mode and failure load for a representative proportion of houses. The models focus on the chain of connections from roof cladding fixings down to wall tie-downs and incorporate parameters like building envelop breach.

The Geoscience Australia NEXIS data base is used to establish common housing classifications for various regions around Australia [17]. Vulnerability models for these types of building systems will be derived.

AS/NZS 1170.2 [2] provides information for selecting the design wind speed related to the return period. Using vulnerability curves developed by CTS, Figure 2 **Error! Reference source not found.** shows the percentage of housing damaged versus the return period for homes in a typical cyclonic region C, suburban site. These curves show the significant decrease in damage to housing that could be achieved if pre-1980s houses were upgraded with protecting openings and improved connections.

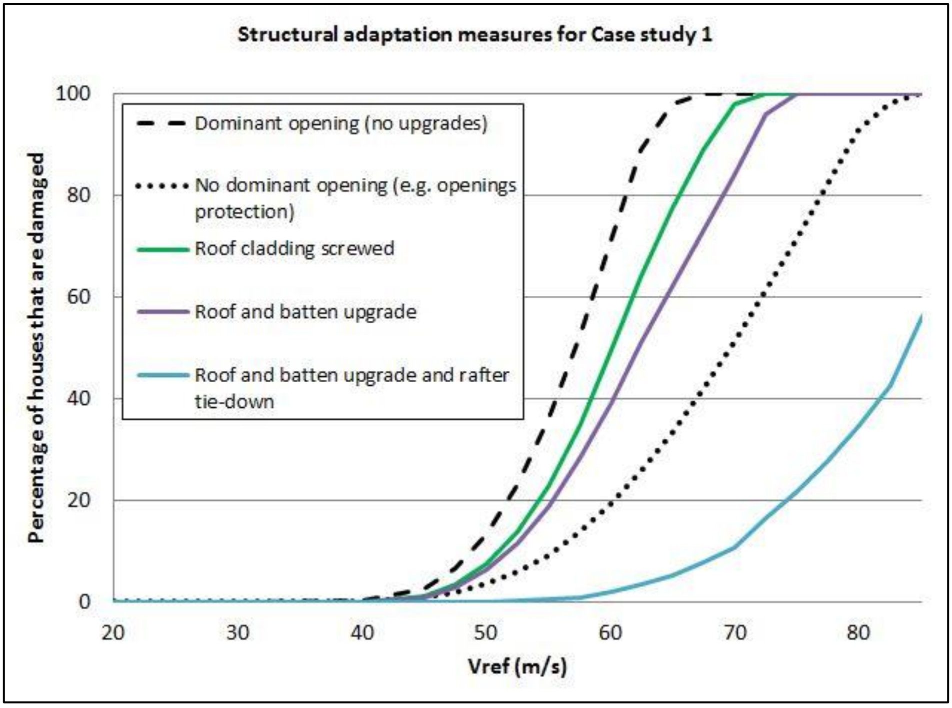


FIGURE 2 ESTIMATED DAMAGE FROM WIND LOADS TO HOUSES WITH DIFFERENT STRUCTURAL ADAPTATION MEASURES FOR HOUSE MODEL AS SHOWN IN **ERROR! REFERENCE SOURCE NOT FOUND.**[19]

POST-EVENT DAMAGE OBSERVATIONS

Following Cyclone Yasi in 2011, Boughton et al [6] showed that homes correctly designed and constructed to the Australian building standards introduced in the 1980s generally performed well under wind load actions. Damage survey results indicated that in the worst affected areas, about 3% of post-1980s homes experienced significant roof damage, in contrast to approximately15% for pre-1980s homes. More than 20% of the pre-1980s housing experienced significant roof loss in some areas. The relatively low incidence of roofing damage to post-1980s buildings indicates that modern building practices deliver better performance for the roofing structure in severe wind event conditions.

A damage survey following Cyclone Larry [7] showed that although wind-induced structural damage was minimal for 95% of contemporary housing, these houses experienced water ingress damage from wind-driven rain. A survey conducted by Melita [10], details building envelope failures during Cyclone Larry. Approximately 75% of post-1985 homes experienced water ingress through breaches in the building envelope (i.e. broken windows, punctured cladding, failed fascia or guttering, etc.). In many cases replacement of internal linings, cabinetry and contents were required.

These observations are similar to those of other post-event damage assessments in Australia (e.g. Cyclone Winifred [11], Cyclone Vance [12], Cyclone Ingrid [8], and Cyclone George [5]). Consistent findings include:

- In general, contemporary construction performance for single family residential housing was adequate under wind loading
- Significant structural damage to legacy (pre-1980s) housing was typically associated with loss of roof cladding and/or roof structure. There were many examples of legacy housing with relatively new roof cladding installed to contemporary standards (i.e. screwed fixing as opposed to nailed) but lacking upgrades to batten/rafter or rafter/top-plate connections, resulting in loss of roof cladding with battens attached
- Corrosion or degradation of connections and framing elements initiated failures
- Where wind-induced structural failures were observed for contemporary housing, they were often associated with either poor construction practice or design faults
- Breaches in the building envelope (i.e. failed doors and windows, debris impact, etc.) exacerbated failure potential from increased internal pressures
- Extensive water ingress damage was observed for structures with or without apparent exterior building damage

These observations suggest the majority of contemporary houses remained structurally sound, protecting occupants and therefore meeting the life safety objective of Australia’s National Construction Code (NCC) [18]. However, contemporary homes did experience water ingress (resulting in loss of amenity) and component failures (i.e. doors, soffits, guttering, etc.) with the potential for damage progression to other buildings, thus failing to meet specific objectives and performance requirements of the NCC.

PROJECT ACTIVITIES

PROJECT RECRUITMENT

Mitchell Scovell, PhD Student

CTS collaborator Mitchell Scovell has been extended CRC Associate Student status. His PhD work comes from the Department of Psychology and James Cook University. His research project, "An investigation of the psychosocial factors that influence cyclone mitigation behaviours in homeowners" compliments this engineering-based CRC project well and will inform the retrofit guidelines and other outputs of the project.

FIGURE 3. MITCHELL SCOVELL WITH DANIEL SMITH AND END-USER COLLABORATORS FROM SUNCORP AT THE ANNUAL 2016 CYCLONE SUNDAY EVENT IN TOWNSVILLE

SEVERE TROPICAL CYCLONE DEBBIE ANALYSIS

Severe Tropical Cyclone Debbie, classified by the Bureau of Meteorology as a Category 4 storm crossed the Queensland coast in the Airlie Beach region around midday on Tuesday 28 March 2017. CTS teams investigated the performance of houses; larger residential structures such as apartments, strata properties and resort accommodation; commercial and public buildings; and sheds. The study area included the communities of Bowen, Proserpine, Airlie Beach, Hamilton Island, Dingo Beach, Wilson's Beach and Conway Beach. The CTS damage surveys commenced on Thursday 29 March through to 10 April.

In terms of the BNHCRC project, aims of the investigation were to:

- Estimate the peak gusts by using the SWIRLnet and BoM data at a number of different locations in the affected area and compare them with the damage to buildings within the impacted area.
- Assess the capacity of buildings to withstand wind loading and debris impact loading.
- Assess the extent of damage to houses and larger buildings from wind-driven rain, focusing on the performance of windows, doors, gutters and flashings.
- Examine older houses and other buildings to determine the need for retrofitting, and assess the effectiveness of any structural upgrades. Aspects of lack of maintenance were also examined.
- Determine the extent of structural damage from storm surge in the study area.

Prior to the release of the formal report, the CTS released a technical bulletin detailing possible hidden damage within roof areas of "older" homes, so that home owners, builders and insurers would be alerted to this possibility and carry out inspections accordingly.

https://www.jcu.edu.au/__data/assets/pdf_file/0012/430014/CTS_Tech_Bulletin_TC_Debbie_2017.pdf

The technical bulletin was also disseminated through the QBCC and Timber Queensland.

Full report on TC Debbie is available here:
https://www.jcu.edu.au/__data/assets/pdf_file/0009/461178/TC-Debbie-report.pdf

The buildings within the study area were estimated to have experienced wind speeds lower than their relevant design wind speed. However, there were many observations of damage to contemporary construction. For example, damage ranged from a few instances of major structural failures of roof structure, through to damage of many cases of internal linings from wind driven rain water ingress via damaged flashings or water via windows and doors.

Batten to rafter or truss connections were the most commonly observed failure in the roofs of older buildings.

Timber battens and timber rafters were both typically spaced at 900 mm centres. In buildings where batten to rafter connections failed, battens were a range of sizes with widths typically 70 to 90 mm and thicknesses typically 35 to 45 mm. The battens were commonly nailed to the rafters with two 75 mm long x 3.15 mm diameter plain shank bullet head nails. This fixing method predates contemporary house construction details (screws or straps). These failures at the batten to rafter on the older houses often led to large panels of the cladding with battens attached separating from the rest of the roof structure. The resultant wind driven debris often caused additional damage to the house or neighboring houses.

In some cases, the failures in older buildings was due to deterioration of connections from corrosion or timber members from rot or termite activity. To help prevent damage in future wind events, regular inspection and maintenance of all older houses is recommended. Mitigation strategies to improve the resilience of communities need to include promotion of maintenance along with retrofitting strategies.

The report also provides recommendations to improve the performance of building structure and cladding systems including: adequate detailing for roof to wall connections; improved fixing of flashings, retrofitting options for older buildings; improvements in windows and door furniture that are subjected to repeated wind loads; and revision of storm surge guidelines.

CONFERENCE PAPERS AND PRESENTATIONS

Australasian Wind Engineering Society Workshop (AWES, 2016)

Papers were presented in July by Daniel, Korah, and Mitch at the 18th AWES workshop in Adelaide. Daniel's paper reviewed vulnerability modelling to date for Australian housing and recent findings from analysis of Cyclone Yasi claims data. Mitch's paper discussed internal pressure fluctuations in industrial buildings. Korah's paper discussed correlation of peak wind loads at batten-truss connections. John Ginger also presented during the wind loading day of the conference on aerodynamic shape factors for buildings, freestanding structures and attachments, etc.

Australasian Fire & Emergency Services Authorities Council (AFAC, 2016)

Daniel and David presented at the AFAC conference in Brisbane where a project poster was presented. CRC PhD student Korah Parackal also presented on preliminary findings from an analysis of the November 2014 Brisbane thunderstorms. Meetings were held aside from the conference with project partners from Geoscience Australia. In particular, potential upgrades to the vulnerability modelling program VAWS were discussed.

24th Australasian Conference on Mechanics of Structures and Materials (ASMSM, 2016)

David and John presented at the December 2016 biennial Australasian Conference on the Mechanics of Structures and Materials (ACMSM) in Perth. This conference has become an important event among academics, practitioners and researchers not only in the Australasian region, but internationally.

Americas Conference on Wind Engineering (ACWE, 2017)

Daniel and Korah travelled to Gainesville, Florida and presented papers at the 13th ACWE conference. The US and Canada are major centres of wind engineering internationally and the majority of literature on testing of light framed structures (i.e. houses) originates from North America. The conference was a unique opportunity to validate and improve the methods and testing used thus far in Korah's Ph.D. research. Korah and Daniel presented research including that supported by the BNHCRC. Korah's presentation on progressive failures to wind loads was well received and sparked much interest among the audience. These progressive failures occur when few roof connections fail and load is redistributed to neighbouring connections, overloading them and resulting failure of a large number of connections in rapid succession. Such failures under wind loading are complex processes and current methods to account for such failures in catastrophe models can be improved.

FIGURE 4. DANIEL AND KORAH AT THE AMERICAS CONFERENCE ON WIND ENGINEERING IN GAINESVILLE, FL

Engineering for Climate Extremes Partnership Workshop (ECEP, 2017)

David travelled to Sydney and presented at the first Southern Hemisphere workshop of the Engineering for Climate Extremes Partnership, under the theme of Building resilience in an evolving risk landscape.

STAKEHOLDER ENGAGEMENT

BNHCRC RAF and CTS Advisory Board Meeting (2016 October)

Two end user/stakeholder workshops were held in October, 2016:

- Workshop 1 - 5 October, James Cook University, Townsville
- Workshop 2 - 18 October, Australian National University, Canberra

Workshop 1 was held in conjunction with the Cyclone Testing Station's (CTS) Advisory Board meeting, and Workshop 2 was held during the BNHCRC Research Advisory Forum (RAF). There were 14 and 20 attendees for Workshops 1 and 2 respectively. There was representation from; insurance, construction, building product manufacturers, Institutes for Architecture and Engineering, Master Builders, Housing Industry Association, and State and Federal government.

To elicit feedback questions were posed to the group. Some of the questions and summarised responses to each are:

1. Should retrofitting only be considered if it passes a minimum of current "building code" requirement (i.e. 1:500)?

CTS: Retrofitting of Pre-80 houses should be done by identifying vulnerable components and determining the best "bang for the buck". Define types of vulnerable houses (in various regions (cyclonic/non cyclonic) of Australia). Provide retrofitting to bring the house to a minimum acceptable standard. What is this level? HB132.2 (or AS1684). Or will the work from this project produce solutions that will specify what needs to be done to get the house to a Bronze, Silver or Gold level.

CTS: Roof cladding and fixings are replaced at a regular intervals 20-30 years unlike the major structure. Hence are we able to design the envelope for a lower design wind speed 200 year return period and attain a similar risk to the rest of the structure. This can also be assessed as part of the cost-benefit analysis.

2. What are implications (pros and cons) if there are different "levels" of retrofit criteria? What is the role of cost/benefit analysis for the various levels?

Insurance Industry: We have strong interest in an industry wide rating system for housing vulnerability. Each tier of the rating system could have a corresponding set of retrofit criteria needed to bring the home up to the "Gold" (i.e. most resilient home) level.

Construction Industry: Need to use added value to house as incentive. Also use insurance premium reductions to incentivise. Roofing retrofits are not a DIY project. This project needs to be part of the word to get out to homeowners and then licensed contractors should perform the works properly.

ABCB: suggests that some forms of partial retrofit are not acceptable as an upgrade. ABCB feels that if the roof is replaced, a complete load path should be established from roof to foundation.

Note: It was suggested we examine the cost-benefit of mitigation upgrades before vs after a severe wind event. It is important to communicate the difficulties of retrofitting post-event to homeowners.

3. How do we get homeowners to upgrade?

Construction Industry: Owners of homes needing new roofs need to know they are adding value not just spending money. I think they will need the insurance companies to tell them they will get added bonus of lower premiums if this work is carried out. You will find though that most will not upgrade unless they require a complete new roof. No one will buy a house with an ugly roof even if it is safer.

4. Do new purchases or retrofit works for roofing require code compliance certification?

QBCC says no but their rule (the code or standard adopted by others may be different) is that if 50% needs to be replaced then you should bring everything up to code. This is based on their interpretation of AS 1684 (design standard for timber structures). QBCC suggest we need to make it so that if 50% needs to be replaced then it all needs to be brought up to code on a consistent Australia wide basis, this is not the case yet.

Insurers (Suncorp and RACQ) are currently unsure whether they require AS 1684 full load path upgrade when replacing roofs. This could be a big opportunity for driving this policy and getting QBCC on board.

Insurance: If they a homeowner is required to replace 50% of the roof, does insurance cover the whole roof? Yes most insurers will cover to do the whole job, not just the damaged part in that case.

Queensland Tropical Cyclone Consultative Committee (QTCCC)

The committee is joint chaired by the Head of the Qld BoM and QFES. Its role is to provide information and respond to issues from across the local, state and federal levels in relation to cyclone awareness, preparation, planning, response and recovery. The CTS is an invited member of the QTCCC.

The QTCCC held its pre-cyclone season (2016) meeting at CTS at JCU Townsville campus. David gave a presentation on CTS activities. The Committee members and representatives from many local councils attended the tour and demonstrations at the CTS laboratories.

The post-season QTCCC meeting was held in June 2017 in Brisbane. A companion BOM and QFES Forum was held the following day where several agencies and researchers presented results from post-impact survey work conducted in the aftermath of Severe Tropical Cyclone Debbie. The CTS presented information from its SWIRLnet deployment, damage survey of wind and wind driven rain impact, and findings from survey of damage from storm surge.

LDMG and DDMG meetings - Post TC Debbie

David presented findings from the CTS SWIRLnet deployment and damage survey to the Local Disaster Management Group and the District Disaster Management Group. The CTS is a specialist member of the Townsville LDMG.

AS/NZS 1170.2 Committee Meetings

John Ginger is in the BD 6/2 committee responsible for recent revisions related in the wind loading standard AS/NZS1170.2. The latest revisions in to AS/NZS1170.2 have been ratified by the ABCB and its counterpart in New Zealand.

Cyclone Awareness and Preparation Events in Townsville

The CTS participated in the community awareness events in Townsville (including "Cyclone Sunday") to promote homeowner preparations (general home maintenance and inspections prior to season, and immediate preparations prior to cyclone).

FIGURE 5. PROJECT TEAM AT CYCLONE SUNDAY IN TOWNSVILLE WITH MAYOR JENNY HILL

RESEARCH ACTIVITIES

VAWS Development

To date the software tool (VAWS) has been developed to model the damage to roof sheeting, roof battens, roof structure, wall cladding, lower storey structure, damage from windborne debris and damage from water ingress.

Data has been enabled into VAWS for a single house type: a high-set, fibro clad Queenslander type house dominant in residential building structures in the 1960's and early 1970's from south-east Queensland to Darwin.

Completed VAWS development

Algorithm

To date the work on the algorithm code has focused on the following parts of the code:

- Alteration to change influence coefficients to connection – connection rather than connection –zone (except for cladding connections)
- Review and subsequent alteration of the code relating to redistribution of loads in roof cladding and batten components.
- Alteration of debris module:
  - Change the vulnerability curve for source houses used to define the number of generated debris items to match that of the target house rather than a predefined curve.
  - Changing the method of counting debris item impacts from those landing in the target house polygon to the number of debris item trajectories crossing the target house polygon. This facilitates the incorporation of non-rectangular house shapes by virtue of not having to artificially stretch the footprint to calibrate the number of impacts. The number of impacts has been scaled to the output of the previous code so that the output of the debris module is identical with the previous version. Figure 6 shows a simulation of the proposal with the target house represented by the red rectangle and the source houses represented by the black dots. Debris item flight paths are represented by the blue lines. When a blue line crosses the target house footprint it is counted as an impact.

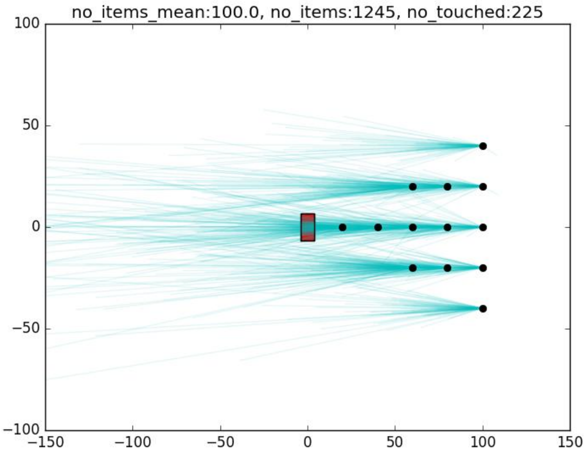


FIGURE 6. PLOT OF SIMULATED DEBRIS ITEM FLIGHT PATHS

- Removal of the use of a database for storing data
- Removal of the C library for random sampling from statistical distributions
- Correction of the bugs in the costing module
- Changing the directory structure for input and output

GUI

Work on recoding the GUI for VAWS has commenced and will be progressed as the algorithm code is completed.

To date:

- The GUI code has been reviewed and branches consolidated.
- Dependency on windows packaging has been removed and references to windows specific libraries also removed to make the software more platform agnostic with the aim to open source the application in the future.
- The use of a database has been removed and replaced with csv files for simplicity and to remove complexity and dependencies on specific database libraries.

Base VAWS use-case

The flowchart describes the base use-case for VAWS, or how the user would interact with the program.

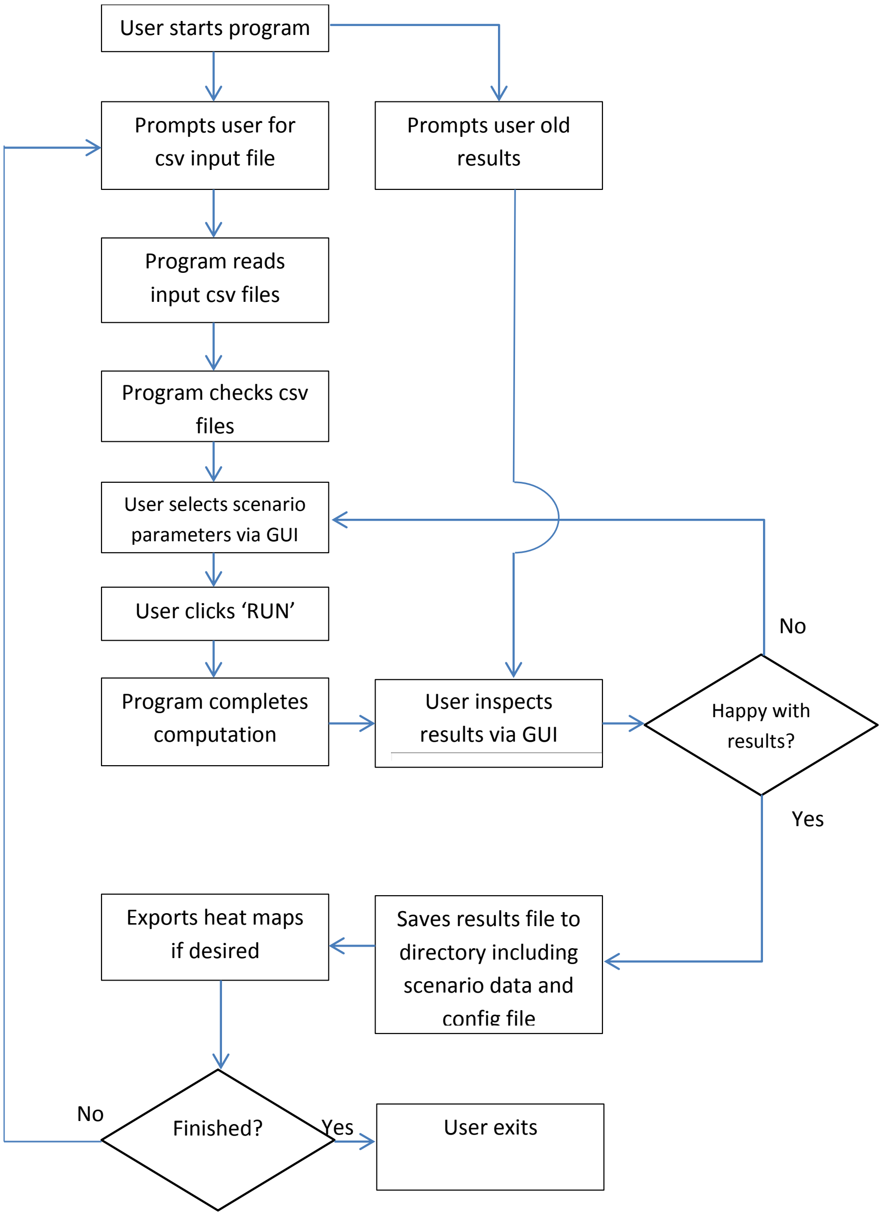


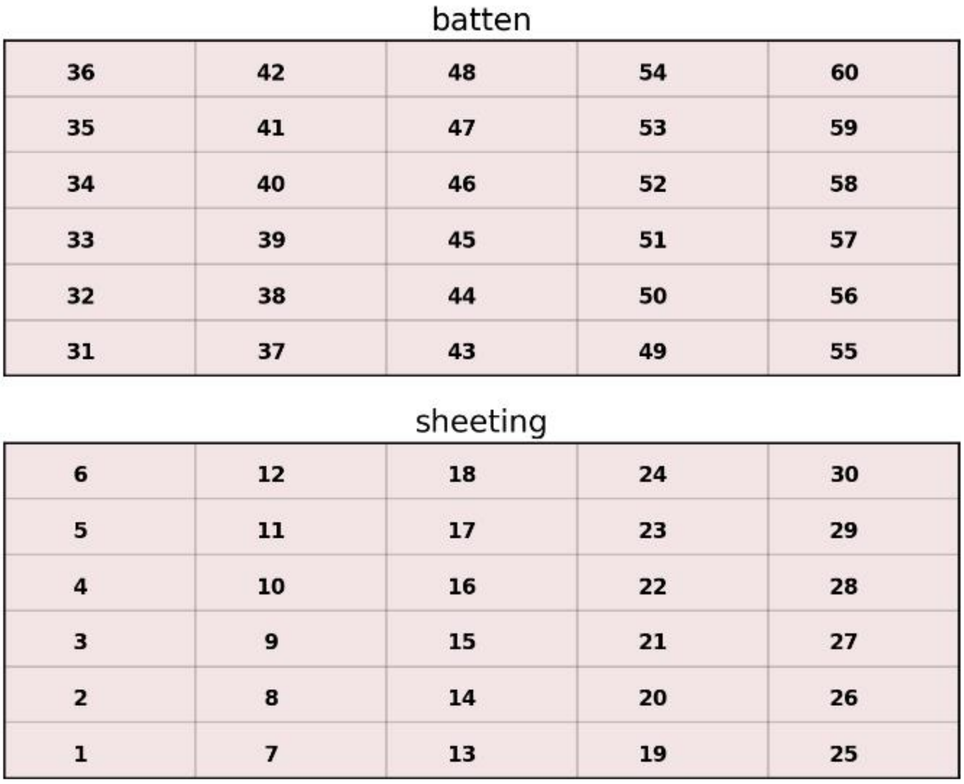
FIGURE 7. BASE USE-CASE FLOWCHART FOR VAWS

Test scenarios

Testing of the software has progressed with each test scenario intended to test a particular aspect of the code. Eighteen test scenarios have been run to date, three of these are outlined below together with their results. Typically the software computed values are compared to values calculated by hand to check that the software is functioning as intended.

Test scenario 1

Designed to test whether the code correctly calculates connection forces. Tests the computation of sheeting connections forces by influence coefficients from zones. Tests computation of batten connection forces by influence coefficients from sheeting connections. Dead load is set to be zero.



batten

36	42	48	54	60
35	41	47	53	59
34	40	46	52	58
33	39	45	51	57
32	38	44	50	56
31	37	43	49	55

sheeting

6	12	18	24	30
5	11	17	23	29
4	10	16	22	28
3	9	15	21	27
2	8	14	20	26
1	7	13	19	25

FIGURE 8. PLAN VIEW OF ROOF PART MODELLED IN TEST SCENARIO 1. NUMBERS DENOTE CONNECTION ID

The tables below present a selection of connection loads calculated both by the software and by hand at a wind speed of 20m/s. the two calculation methods yield similar results.

Connection id	**31**	**35**	**39**	**45**	**51**	**60**
Group name	batten	batten	batten	batten	batten	Batten
VAWS Computed load (kN)	-0.005	-0.098	-0.151	-0.063	-0.019	-0.010
Hand calculation (kN)	-0.005	-0.098	-0.151	-0.063	-0.019	-0.010

Connection id	1	11	15	21	25
Group name	sheeting	sheeting	sheeting	sheeting	Sheeting
VAWS Computed load (kN)	-0.005	-0.194	-0.019	-0.019	-0.010
Hand calculation (kN)	-0.005	-0.194	-0.019	-0.019	-0.010

Test scenario 2

Designed to test whether the code correctly calculates which sheeting connections have broken at various wind speeds and redistributes loads as expected to adjacent sheeting connections. Dead load set to be zero. Fixed connection strengths modelled by zero standard deviation of connection strengths. Tests distribution upon connection failure from an interior cladding connection, an eave connection and a ridge connection.

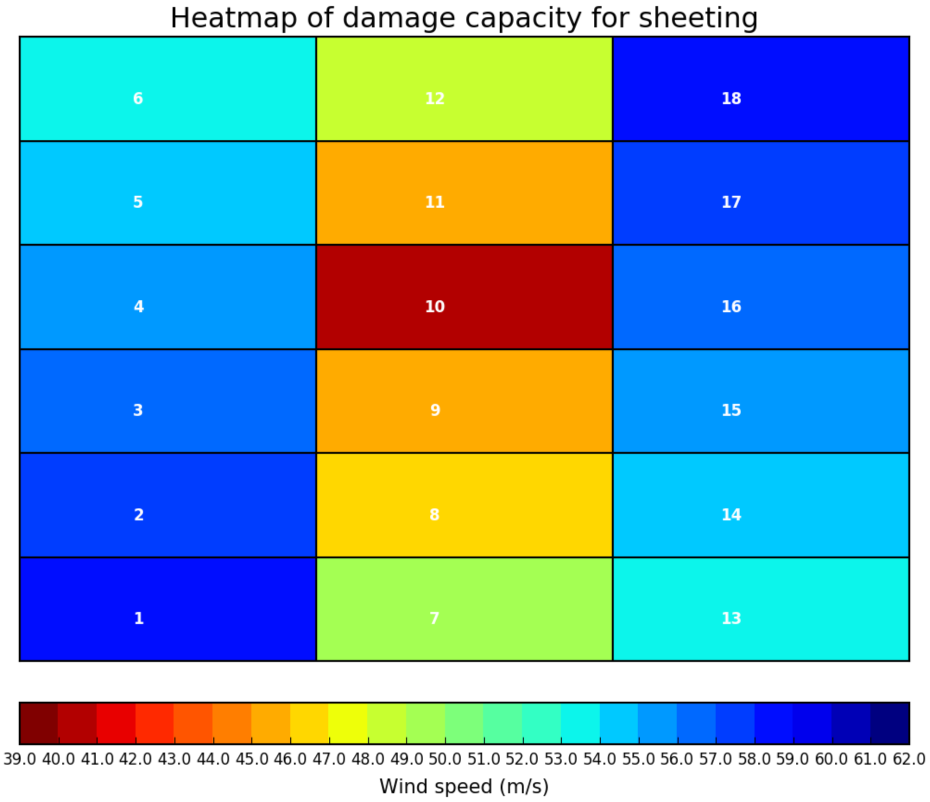


FIGURE 9. PLAN VIEW OF HEATMAP OF FAILURE WIND SPEEDS FOR ROOF SHEETING CONNECTIONS MODELLED IN TEST SCENARIO 2. CONNECTIONS 6, 10, 13 WERE MODELLED WITH ARTIFICIALLY HIGH CPE VALUES COMPARED TO THE OTHER CONNECTIONS. FAILURE CAN BE SEEN TO INITIATE AT THE HIGHLY LOADED CONNECTIONS AND PROPAGATE AWAY FROM THE FAILED CONNECTIONS AT SUBSEQUENT WIND SPEEDS. ROOF SHEETING IS CONTINUOUS UP AND DOWN THE PAGE

The table shows expected failure wind speeds and sequences as calculated by hand. The values compare well with the heatmap.

Connection id	Expected failure wind speed (m/s)	Connection id	Expected failure wind speed (m/s)	Connection id	Expected failure wind speed (m/s)
1	Next wind speed step after connection 2 fails	7	Next wind speed step after connection 8 fails	13	52.1
2	Next wind speed step after connection 3 fails	8	Next wind speed step after connection 9 fails	14	Next wind speed step after connection 13 fails
3	Next wind speed step after	9	44.9	15	Next wind speed step after

	connection 4 fails				connection 14 fails
4	Next wind speed step after connection 5 fails	10	39.8	16	Next wind speed step after connection 15 fails
5	Next wind speed step after connection 6 fails	11	44.9	17	Next wind speed step after connection 16 fails
6	52.1	12	Next wind speed step after connection 11 fails	18	Next wind speed step after connection 17 fails

Test scenario 3

Designed to test whether the code correctly calculates which batten connections have failed and redistributes loads as expected. Sheeting connections modelled with artificially high strengths to ensure failures occur in batten connections. Fixed batten strengths modelled by zero standard deviation of connection strengths. Tests distribution from interior and gable batten connections.

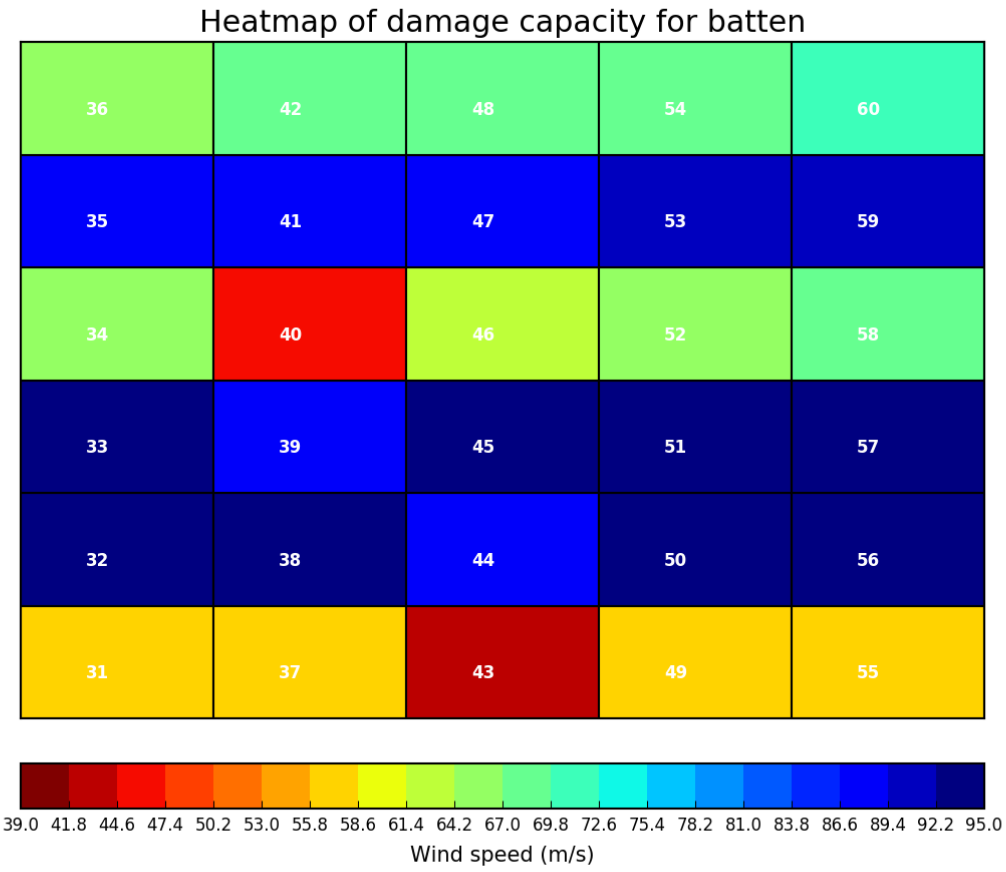


FIGURE 10. PLAN VIEW HEATMAP OF FAILURE WIND SPEEDS FOR BATTEN CONNECTIONS MODELLED FOR TEST SCENARIO 3. THE CPE VALUES FOR THE ZONES ABOVE CONNECTIONS 36, 40 AND 43 WERE MODELLED ARTIFICIALLY HIGH (APPROXIMATELY 70 TIMES AS HIGH AS THE SURROUNDING CONNECTIONS). FAILURES IN BATTEN CONNECTIONS CAN BE SEEN TO INITIATE AT THE HIGHLY LOADED CONNECTIONS AND PROPAGATE AWAY AT SUBSEQUENT WIND SPEEDS

The table below shows expected failure wind speeds and sequences as calculated by hand for batten connections. The values and failure sequence compare well with the heatmap.

Connection id	Expected failure wind speed (m/s)	Connection id	Expected failure wind speed (m/s)	Connection id	Expected failure wind speed (m/s)
31	Next wind speed step after connection 37 fails	41	86.1	51	Next wind speed step after connection 33 fails
32	Next wind speed step after connection 38 fails	42	Next wind speed step after connection 36 fails	52	Next wind speed step after connection 34 fails
33	Next wind speed step after connection 45 fails	43	43.7	53	Next wind speed step after connection 47 fails
34	Next wind speed step after connection 46 fails	44	86.1	54	Next wind speed step after connection 48 fails
35	Next wind speed step after connection 41 fails	45	111.1	55	Next wind speed step after connection 49 fails
36	65.1	46	63.3	56	Next wind speed step after connection 50 fails
37	56.0	47	Next wind speed step after connection 35 fails	57	Next wind speed step after connection 51 fails
38	111.1	48	Next wind speed step after connection 42 fails	58	Next wind speed step after connection 52 fails
39	86.1	49	56.0	59	Next wind speed step after connection 53 fails

Connection id	Expected failure wind speed (m/s)	Connection id	Expected failure wind speed (m/s)	Connection id	Expected failure wind speed (m/s)
40	46.0	50	111.1	60	Next wind speed step after connection 54 fails

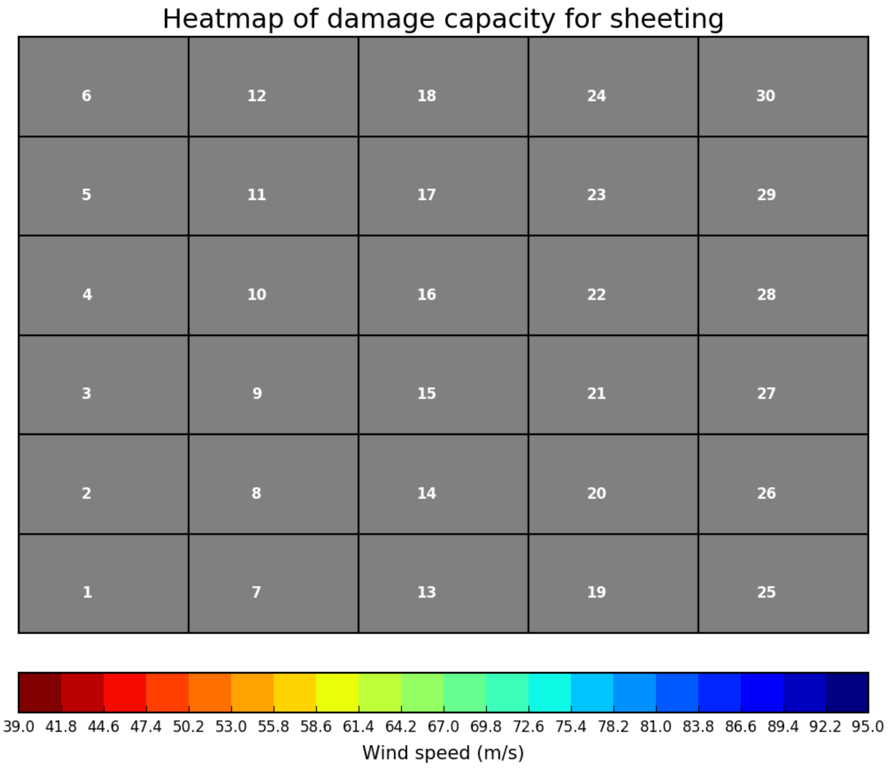


FIGURE 11. PLAN VIEW OF HEATMAP OF FAILURE WIND SPEEDS FOR ROOF SHEETING CONNECTIONS MODELLED FOR TEST SCENARIO 3. THE STRENGTH OF THE SHEETING CONNECTIONS WAS MODELLED ARTIFICIALLY HIGH (APPROXIMATELY 10 TIMES NORMAL) TO ENSURE THAT FAILURES OCCURRED IN THE BATTEN CONNECTIONS HENCE ALL CONNECTIONS SHOW AS GREY.

Influence coefficients for the hold-down force of roof to wall connection (RWC)

An underlying foundation of the VAWS tool is the modelling of structural behaviour of the house structure to the wind load. A traditional house structure is a multitude of members (battens, rafter, top plates, linings, etc.) and connections (nails, skew-nails, straps, etc.). The members and connections have various spacings and strengths. There is load sharing across the members depending on the capacity and stiffness. Since we cannot test every house, models need to be developed so that we can estimate the capacity of existing construction as well as to assess changes, such as from retrofitting. Therefore, the numerical models are being developed to provide the needed input data for VAWS.

Finite element model (FEM) details for hip ended pitch frame construction house

- Type 1: Ideal connection model (applied load was 2 kN on roof cladding), See Figure 12 and 13
- The FEM model was developed for the general and hip-end region roof structure of pitched roof house. The model consists of eleven types of components: corrugated steel roof cladding, timber battens, rafters, ridge beam, collar tie, top plates, hip-rafters, ceiling joist, ceiling battens and ceiling.
- The roof pitch was 22.5° with overhang of 650 mm
- 4000 x 760 mm, 0.42 BMT corrugated metal sheets were used for the roof cladding. The metal roof cladding was attached to the timber batten (75 x 38 mm) with three screws per corrugated metal sheet based on the field survey.
- Two plain-shank nails were used for the batten to rafter connection
- Skew nails were used to connect the roof to wall, ridge beam to rafter and rafter to hip-rafter.
- Collar ties were installed every second rafters in the general rafter region (i.e. Rafters B, D and F)
- The inter-component connection properties used were obtained from previous studies, individual connection tests and FEM.
- The modelling methodology was similar to the FEM of Satheeskumar et al. 2017.
- Pin supports were enforced on the bottom surface of top-plate at wall stud locations, end surface of top-plates, ridge beam and ceiling battens at gable end of roof.

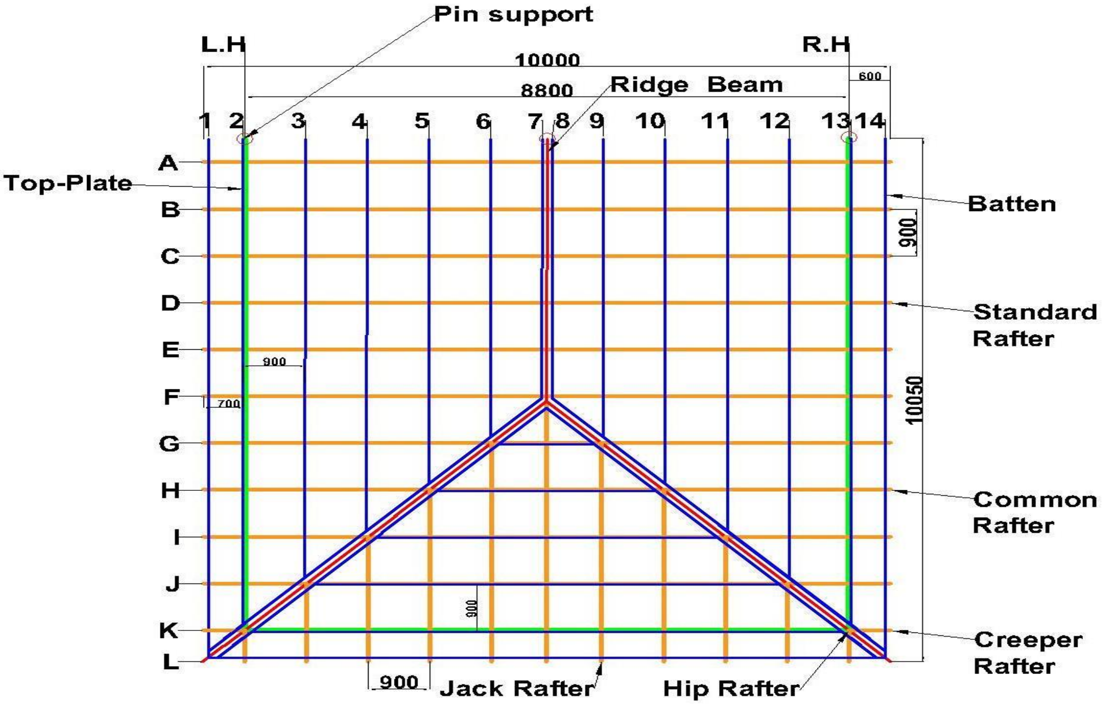


FIGURE 12: PLAN VIEW OF TYPE 1 FEM

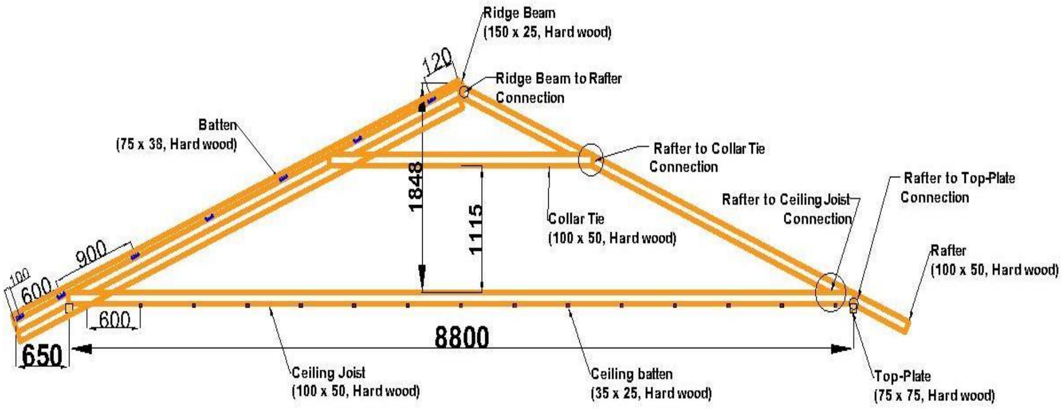


FIGURE 13 ELEVATION OF TYPE 1 FEM

TABLE 1. REACTION FORCE AT RWCS WHEN LOAD WAS APPLIED AT RAFTER A AT BATTEN B2 AND B7

RWCs	**LH**		**RH**	
	Batten B2	**Batten B7**	**Batten B2**	**Batten B7**
	(N)	(N)	(N)	(N)
A	1731.10	47.60	-38.36	129.15
B	120.14	107.54	-12.69	126.67
C	-24.05	80.12	-10.16	111.90
D	8.42	60.29	-10.69	77.70
E	7.68	30.03	-8.61	43.18
F	4.06	-20.27	-4.27	13.12
Total	1847.36	305.31	-84.78	501.73

When the load was applied on Rafter A:

- About 5% of applied load was transferred to the pin supports (i.e. at bottom surface of top-plate at wall stud locations and, end surface of top-plates, ridge beam and ceiling battens) through ceiling joist, ceiling, ceiling battens, top-plate, etc., when load was applied at batten B2.

- About 55% of applied load was transferred to the pin supports (i.e. at bottom surface of top-plate at wall stud locations and, end surface of top-plates, ridge beam and ceiling battens) through ceiling joist, ceiling, ceiling battens, top-plate, etc., when load was applied at batten B7. This higher percentage of load transferred to wall structure is due to the gable end connection to the ridge beam adjacent to batten B7

TABLE 2. REACTION FORCE AT RWCS WHEN LOAD WAS APPLIED AT RAFTER B AT BATTEN B2 AND B7

RWCs	LH		RH	
	Batten B2	Batten B7	Batten B2	Batten B7
	(N)	(N)	(N)	(N)
A	82.65	105.19	-64.77	120.62
B	1570.94	199.99	-78.15	302.97
C	221.83	205.10	-47.56	222.07
D	-48.64	110.47	-14.11	104.44
E	10.26	35.01	-2.69	48.67
F	5.96	14.11	-1.99	24.91
Total	1843.00	669.87	-209.26	823.68

When the load was applied on Rafter B:

- About 10% of applied load was transferred to the pin supports (i.e. at bottom surface of top-plate at wall stud locations and, end surface of top-plates, ridge beam and ceiling battens) through ceiling joist, ceiling, ceiling battens, top-plate, etc., when load was applied at batten B2.
- About 20% of applied load was transferred to the pin supports (i.e. at bottom surface of top-plate at wall stud locations and, end surface of top-plates, ridge beam and ceiling battens) through ceiling joist, ceiling, ceiling battens, top-plate, etc., when load was applied at batten B7.

TABLE 3. REACTION FORCE AT RWCS WHEN LOAD WAS APPLIED AT RAFTER C AT BATTEN B2 AND B7

RWCs	LH		RH	
	Batten B2	Batten B7	Batten B2	Batten B7
	(N)	(N)	(N)	(N)
A	-33.10	20.17	-2.58	42.56
B	185.37	140.20	-3.12	157.35
C	1518.60	176.04	-10.39	261.32
D	226.14	153.93	-1.53	167.61
E	-37.81	85.48	-1.74	83.36
F	8.85	50.04	-6.38	39.19
Total	1868.06	625.86	-25.74	751.39

When the load was applied on Rafter C:

- About 1% of applied load was transferred to the pin supports (i.e. at bottom surface of top-plate at wall stud locations and, end surface of top-plates, ridge beam and ceiling battens) through ceiling joist, ceiling, ceiling battens, top-plate, etc., when load was applied at batten B2.
- About 25% of applied load was transferred to the pin supports (i.e. at bottom surface of top-plate at wall stud locations and, end surface of top-plates, ridge beam and ceiling battens) through ceiling joist, ceiling, ceiling battens, top-plate, etc., when load was applied at batten B7.

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