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IMPROVING THE RESILIENCE OF EXISTING HOUSING TO SEVERE WIND EVENTS

Annual project report 2017-2018

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James Cook University, GeoScience Australia & Bushfire and Natural Hazards CRC

Roof Structure of a House under construction

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Cover: Roof structure of a house under construction. Photo: David Henderson.

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ABSTRACT

This project will propose practical structural upgrading solutions based on the latest research that will make a significant improvement in the performance of Pre-80s (Legacy) houses that are impacted by severe windstorms.

The project has analysed existing structural retrofitting details available for some forms of legacy housing and has found that uptake is limited, even when these houses require major repairs following severe storm events.

The work carried out in 2017-18 has focussed on developing cost-effective strategies for mitigating damage to housing from severe windstorms. The major activity has been progressing the VAWS software package by Geoscience Australia (GA) using wind loading and structural response data and other test data obtained by the CTS-JCU:

- Residential structures (i.e. Houses) have been categorized into types based on building features that influence windstorm vulnerability using CTS and GA housing survey data. Two house types were selected and incorporated in the VAWS package. The structural response (i.e. damage progression) with increasing wind speed has been modelled and validated. Testing carried out as part of BNHCRC supported thesis projects have provided additional data.
- Retrofit options and cost-benefit modules will be added to the VAWS model by GA and made available for trialling by end users and stakeholders (i.e. homeowners, builders, regulators, insurers). End-users and stakeholders will be asked to evaluate VAWS and suggest amendments and provide feedback on practicality and aesthetics of potential upgrading methods for these house types. Cost effective guides will be developed for vulnerable house types.
- Case studies will be used to evaluate effectiveness of proposed retrofit solutions for risk reduction. Economic assessment using the same case studies will be used to promote (via the stakeholders and end users) uptake of practical retrofit options.

END USER STATEMENT

Leesa Carson *GEOSCIENCE AUSTRALIA, ACT*

Recent post-event damage investigations and analysis of insurance loss data by the project's researchers have demonstrated the disproportionate contribution to housing loss by legacy, or pre-code, houses. Beyond the physical loss, damage to homes promotes other impacts such as poor physical and mental health, requirements for temporary housing and long-term loss of economic activity from communities highlighting the potential benefits from reductions in housing losses.

The project's survey activities have revealed why current uptake of available mitigation options is suboptimal and also identified previously unaddressed problems in older and modern housing that contribute to loss such as strength of door furniture and water ingress through structurally intact building envelopes.

This year has seen a substantial step forward towards the project's goals with several PhD and undergraduate projects at the CTS-JCU, targeted at specific problems pertinent to the project, reaching completion. The project outcomes will serve to provide an evidence base to inform the development of practical guides to improve the resilience of existing housing. The development of the VAWS software package has also progressed significantly during 2017/18. The practicality of the project outcomes will be ensured via the variety and number of engaged stakeholders that have shown tremendous interest in the research.

Through project publicity such as journal papers, conference papers and presentations to a wide variety of agencies, the project is likely to result in a better appreciation of the benefits of mitigation across a wide cross-section of government, industry and the general population.

INTRODUCTION

Recent damage investigations of housing, conducted by the Cyclone Testing Station (CTS) have shown that the majority of houses designed and constructed to current building regulations have performed well (structurally) by resisting wind loads. Pre-80s houses are more vulnerable to wind damage. The poor performance results from design and construction failings, poor connections (i.e. batten/rafter, rafter/top plate), or from degradation of components or elements (i.e., corroded screws, nails and straps, and decayed or insect-attacked timber). Hence, practical structural retrofit solutions are important for improving the performance of housing. These studies also show that wind driven water-ingress related damage at wind speeds below design are common across all (including Post-80s contemporary) house types.

The issues of unsatisfactory construction practices when renovating, degradation of materials (lack of advice on maintenance), etc. are not constrained to northern Australia. Damage investigations in Brisbane, NSW and WA 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. Outcomes from this survey indicated a lack of awareness of this information and a lack of explaining the benefits (i.e. reduction in insurance premiums) as being major reasons for a low uptake of these upgrading provisions. The practicality (ease) of carrying out the retrofitting of existing houses were also identified as an impediment.

This project will attempt to address these shortcomings.

BACKGROUND

WIND LOADS ON HOUSING AND STRUCTURAL PERFORMANCE

Damage surveys carried out by the following Cyclone Larry, Cyclone Yasi and many others by the CTS have shown that homes correctly designed and constructed to the Australian building standards introduced in the 1980s generally performed well. Around 20% of the pre-1980s housing in some areas experienced significant roof loss. The relatively low incidence of roofing damage to post-1980s buildings indicates that modern building codes and practices produce houses with better structural performance in severe windstorms. However contemporary houses can experience water ingress damage from wind-driven rain.

- 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 in many houses with or without apparent exterior 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). 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 to surrounding buildings, thus failing to meet specific objectives and performance requirements of the NCC.

WIND LOADING CODES AND HOUSING VULNERABILITY

The fluctuating winds subject the building envelope and structure to spatially and temporally varying loads. The structural design of houses use AS4055 and AS/NZ1170.2, and other related standards such as AS1684 to derive the wind loads and design the structural components and connections. HB132 provides details on retrofitting of existing houses.

Maintaining a sealed building envelope is also important 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 can be dramatically increased. These internal pressures act in concert with external pressures, increasing the load on cladding elements and the structure. The increase in internal pressure caused by this opening can double the load in certain areas, increasing the risk of roof failure, especially if the building has not been designed for a dominant opening.

Houses in cyclonic regions designed in accordance with contemporary design standard AS4055 Wind Loads for Housing incorporate load cases for internal pressure increase from a breached envelope. Houses in non-cyclonic regions designed to AS4055 are not required to account for this load case, thus making them more vulnerable to damage, if such an opening were to occur.

New houses are a small fraction of the overall housing stock, and most Australians will spend the majority of their lives in houses that are already built. In addition, 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.

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 each of these house types. The models focus on the chain of connections from roof cladding fixings down to wall tie-downs and account for situations such as a breached building envelope.

Figure 1 is an example of the CTS method that shows the percentage of houses (of a specific type) that are damaged versus the gust wind speed, in a cyclonic region C, suburban site. These wind speeds can be related to the design wind speed and the return period using AS/NZS 1170.2. These vulnerability curves show the significant decrease in damage to housing that could be achieved if pre-1980s houses were upgraded with opening protection and improved connections.

Data available from GA's National Exposure Information System (NEXIS), desktop surveys and the CTS database is used to establish common housing classifications for various regions around Australia. This project will then define a suite of House Types for all parts of Australia and use the analysis method used by the CTS to produce vulnerability models for these types of houses. This technique is being codified in the software package VAWS being developed by GA. This process has progressed significantly in 2017/18 with the VAWS package being validated for assessing structural damage for two types of houses.

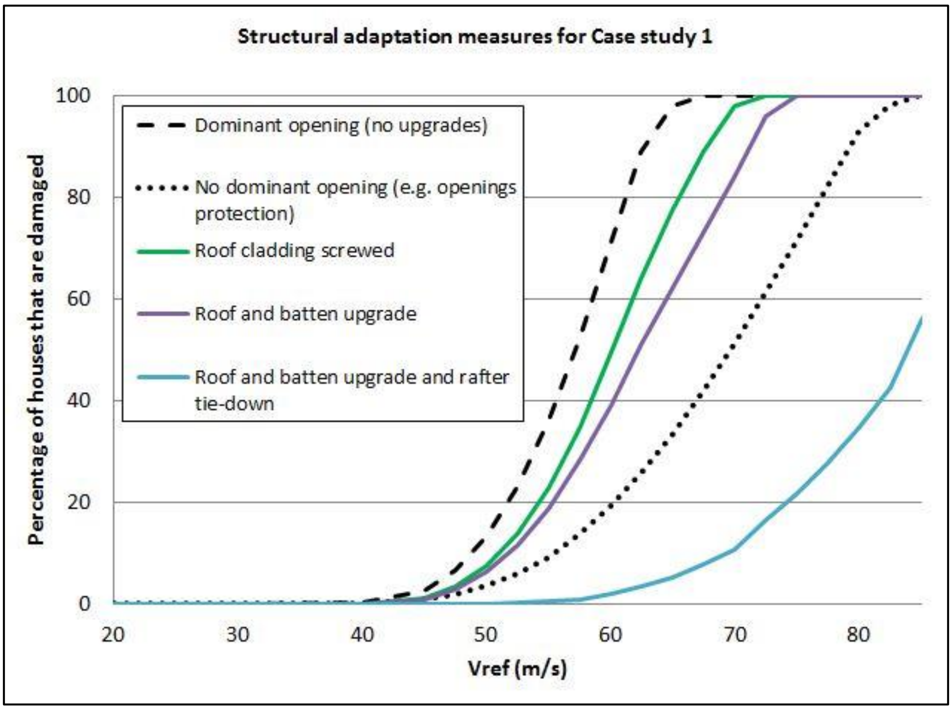


FIGURE 1. ESTIMATED DAMAGE FROM WIND LOADS TO HOUSES WITH DIFFERENT STRUCTURAL ADAPTATION MEASURES FOR HOUSE MODEL

PROJECT ACTIVITIES

STUDENT PROJECTS

Korah Parackal, PhD Student

- CRC Showcase 3MT talk - July 2017
- AFAC17 Poster - September 2017
- CRC Association Early Career Finalist Talk + Youtube Video - May 2018

Mitchel Humphreys, PhD Student

- AFAC17 Poster - September 2017

JCU Engineering Undergraduate Thesis projects

The CTS staff supervised seven JCU Civil Engineering undergraduate students; Drew Conway, Nicholas Paine, Ha Le Tuan, Lalin Chhoeuk, Nicoline Thomson, Gavin Crouch and Kyron Day, who completed thesis projects in 2017 on "Internal pressure in industrial buildings", "Design of building envelopes to resist cyclonic winds" and "Wind loads on roof and wall connections". Nicoline Thomson's Thesis was awarded the AWES Undergraduate Thesis Award for 2017.

Testing on doors:
The work by Nicoline Thomson, was extended to study design of a standard external door for cyclonic conditions. Additional tests were conducted by replacing the timber doorframe with a steel doorframe and assessing various types of doors and lock mechanisms under loads. The results showed that the readily available doors and lock mechanisms are mostly not appropriate for use in cyclonic regions. Only the more expensive products returned results suggesting that they could potentially be used in cyclonic regions, but these are less likely to be used under the current circumstances in the absence of a standard. It is recommended that the design of door systems as well as selection of these systems should be framed by appropriate standards. Figure 2 shows a typical failure at the door lock.

Testing on soffits:
Soffit damage has been observed following cyclonic events both on contemporary and older houses. Lalin Chhoeuk conducted a study, as part of her thesis "Design of soffits and eaves to resist wind loads in cyclonic regions" where the failure mode of soffits and soffit-to-batten connections were studied.

Two configurations of soffit to batten connections (hand driven and gun driven nails) were tested. Tests that used gun nails, gave failure pressures of soffit to batten connection of about 2 kPa whilst tests that used hand driven nails, produced failure pressure of 4.3 kPa (more than double the strength of the gun nails tests). Figure 3 shows a typical pull through failure of at the batten to soffit connection.

Outcomes from of these projects will be used to develop evidence based input data for VAWS.

Figure 2. Typical Lock Mechanism Failure

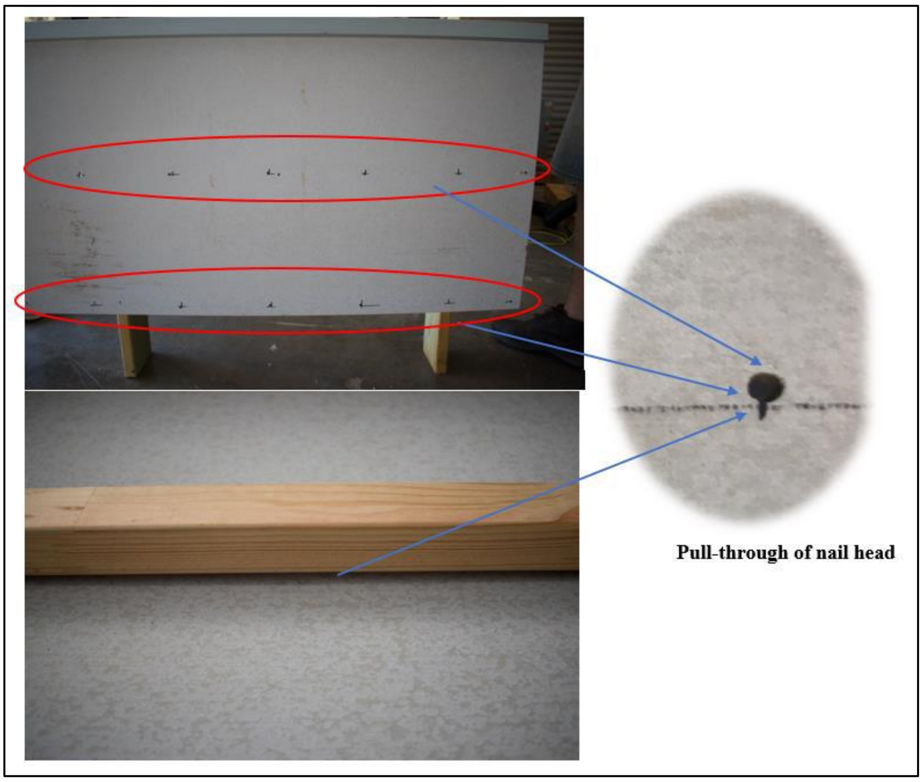


Figure 3. Typical Failure mode of soffit-to-batten connection (Plain shank nails)

CONFERENCE PAPERS AND PRESENTATIONS

Asia Pacific Conference on Wind Engineering (APCWE, December 2017)

Three papers were presented in at the 9th APCWE in Auckland, NZ. Figure 4 shows JCU-CTS students that presented papers at the Conference.

Humphreys M., Ginger J., and Henderson D., *Internal Pressure Fluctuations in Large Open Plan Buildings*, 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December, 2017.

Parackal, K., Ginger J., Smith D. and Henderson D, *Load sharing between batten to rafter connections under wind loading.* 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December 2017.

Bodhinayake G., Ginger J., and Henderson D., *External and Internal Pressure Fluctuations on Industrial-Type Buildings*, 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December 2017.

Australasian Wind Engineering Society Workshop (AWES, April 2018)

Five papers were presented in at the 19th AWES workshop in Torquay, Victoria.

Humphreys M., Ginger J., and Henderson D., *Effect of Opening Geometry on Full-Scale Internal Pressure Measurements,* 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, 4-6 April, 2018.

Bodhinayake G., Ginger J., and Henderson D., *Correlation of internal and external pressures on building cladding elements*, 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

Wehner, M., H. Ryu, J. Ginger, M. Edwards, D. Henderson, K. Parackal, D.J. Smith, *Modelling residential mitigation effectiveness for severe wind*. 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

Smith, D.J., D.B. Roueche, R.J. Krupar, F.T. Lombardo, D.J. Henderson, *Parallels in tropical cyclone design strategies and building performance for Australia and U.S.,* 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

Nicoline Thomson, David Henderson, John Ginger, *Design of Potential Dominant Openings to Resist Cyclonic Winds*, 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

International Workshop on Wind-Related Disasters and Mitigation, Sendai, Japan (2018)

Henderson, D., D.J. Smith, G. Boughton, J. Ginger, (2018) Damage and loss to Australian engineered buildings during recent cyclones. *International Workshop on Wind-Related Disasters and Mitigation,* Sendai, Japan.

FIGURE 4. (L-R) JCU-CTS PHD STUDENTS KORAH PARACKAL, MITCHELL HUMPHREYS AND GEETH BODHINAYAKE AT THE ASIA PACIFIC CONFERENCE ON WIND ENGINEERING IN AUCKLAND, NZ, DECEMBER 2017

STAKEHOLDER ENGAGEMENT

Queensland Tropical Cyclone Consultative Committee (QTCCC)

The committee is jointly 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 pre-cyclone season (2017) meeting was held in Mackay and was part of the pre-season briefings for regional areas. David Henderson gave a presentation on CTS activities.

The post-season QTCCC meeting was held in May 2018 in Brisbane where David reported on updates to housing resilience project and guidelines for renovating/building in cyclone regions.

LDMG and DDMG meetings - Post TC Debbie

David Henderson 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 the upcoming revisions in AS/NZS1170.2. A number of Working Groups have been formed for revising AS/NZS1170.2. John is chairing the Working Groups on Section 5 and Appendix D.

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 shows the CTS Stand and display at the event.

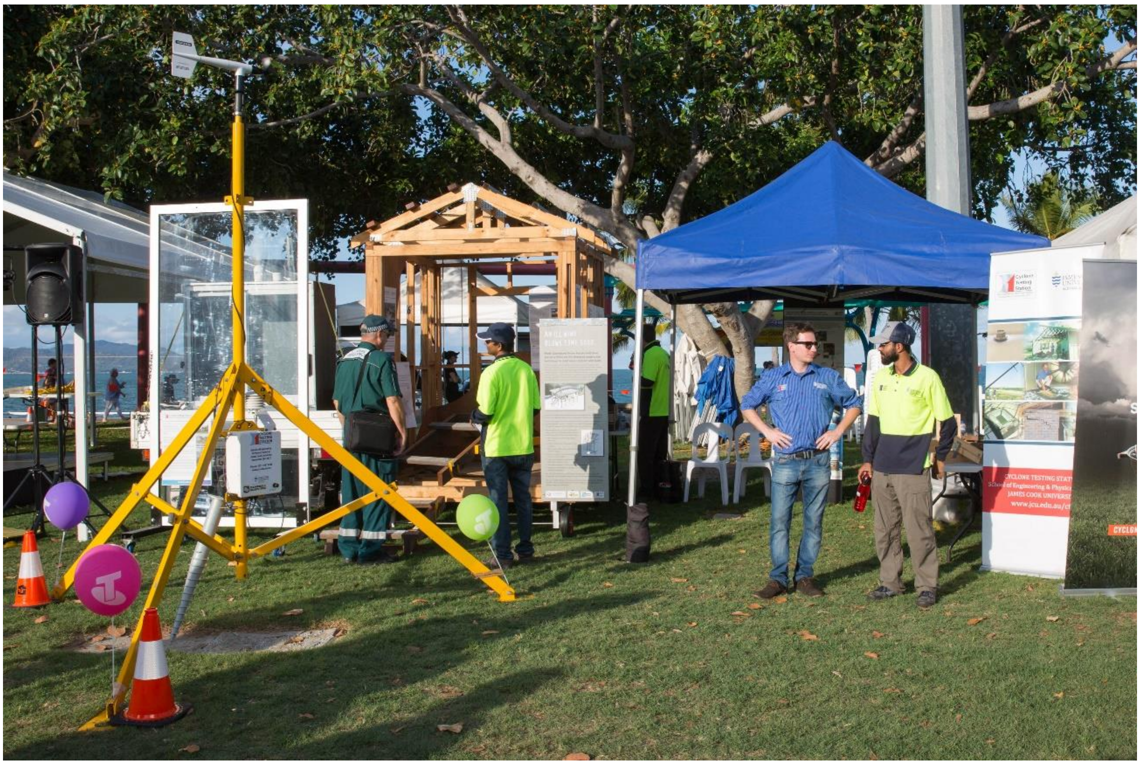


FIGURE 5. CTS STAFF AT CYCLONE SUNDAY CTS STAND IN TOWNSVILLE OCTOBER 2017

RESEARCH ACTIVITIES

VAWS Development

To-date the software tool (VAWS v2.1) has been developed to model the structural damage, damage from windborne debris and damage from water ingress. Major updates include:

1. Change of debris impact criterion: impact boundary instead of stretched footprint

2. Change of logic in modelling debris damage: a Poisson distribution to Monte Carlo simulation to account for damage by individual debris item,
3. Use of flag_cpe in computing wind load such that connection load can be calculated using local or structural pressure coefficients as appropriate,
4. Display of influence and patch data through GUI, and
5. Setting up log facility to keep track of major computation processes.

Input data checking

The input data for VAWS includes nineteen user-prepared csv files specific to each house type, some of which can be large depending on the complexity of the house modelled. The programme was enhanced to conduct a series of checks on the input data to detect gross input errors. The checks incorporated are detailed in Table 1. In addition, several views have been added to the GUI to enable the user to visually check geometry and influence coefficients.

TABLE 1. INPUT DATA CHECKS ENABLED INTO THE VAWS SOFTWARE.

Input file	Checks
conn_groups.csv	1. Check that each *damage_scenario* entry is also listed in damage_costing_data.csv 2. Check that each *flag_pressure* entry is a valid entry. 3. Check that each *dist_dir* entry is one of col, row, patch or none.
conn_types.csv	4. Check that each *strength_mean, strength_std, dead_load_mean*, *dead_load_std* and *costing_area* entry is >=0 5. Check that each *group_name* entry is also listed in conn_groups.csv
connections.csv	6. Check that each *conn_type* entry is also listed in conn_types.csv. 7. Check that each connection has 3 or 4 sets of coordinates.
coverage_types.csv	8. Check that each *failure_strength_out_mean* entry is <=0. 9. Check that the remaining numerical entries are >=0.
coverages.csv	10. Check that each wall_name entry is a valid wall number. 11. Check that each *area* entry is >=0. 12. Check that each *coverage_type* entry is also listed in coverage_types.csv.
coverages_cpe.csv	13. Check that each numerical entry is between -5 and +5.
damage_costing_data.csv	14. Check that each *envelope_factor_formula_type* entry is either 1 or 2. 15. Check that each *internal_factor_formula_type* entry is 1 or 2.
damage_factorings.csv	None
footprint.csv	16. Check that each row has two numeric values.
front_facing_walls.csv	None
house_data.csv	17. Check that *cpe_cov* and *cpe_str_cov* are between 0 and 1. 18. Check that *Cpe_k* and *Cpe_str_k* are >0.
influence_patches.csv	19. Check that each *Damaged Connection* is a valid connection name. 20. Check that each *Connection* is a valid connection name. 21. Check that each *influence coefficient* is between -10 and 10.
influences.csv	22. Check that each *conn_name* is also listed in connections.csv. 23. Check that each *Zone* name is also listed in zones.csv. 24. Check that each *influence coefficient* is between -10 and 10.
water_ingress_costing_data.csv	25. Check that each *name* is also listed in damage_costing_data.csv, other than “WI only”. 26. Check that each *formula_type* entry is either 1 or 2.
zones.csv	27. Check that each area is >=0 28. Check that each cpi_alpha is between 0 and 1. 29. Check that each zone has either 3 or 4 pairs of coordinates.

Input file	Checks
zones_cpe_eave_mean.csv	30. Check that each *name* is also listed in zones.csv. 31. Check that each zone has values for 8 directions. 32. Check that each Cpe is between -5 and 5.
zones_cpe_mean.csv	33. Check that each *name* is also listed in zones.csv. 34. Check that each zone has values for 8 directions. 35. Check that each Cpe is between -5 and 5.
zones_cpe_str_mean.csv	36. Check that each *name* is also listed in zones.csv. 37. Check that each zone has values for 8 directions. 38. Check that each Cpe is between -5 and 5.
zones_edge.csv	39. Check that each *name* is also listed in zones.csv. 40. Check that each zone has values for 8 directions. 41. Check that each value is 1 or 0.

User manual

During 2017-2018 a comprehensive User Manual for VAWS has been prepared. The manual describes the logic implemented in VAWS in detail, the input and output data and also instructions on how to use the program.

Input Data Preparation

The preparation of input data progressed from preparing input data for test scenarios, where data was created for artificial test houses to test specific functionality of VAWS, to preparing input data for actual houses for the project. Input data for two houses has been prepared as described below. Preliminary analysis of the input data using VAWS has been undertaken. The output from VAWS for these two house types will enable calibration of the software's output to loss data from other sources such as post-cyclone damage surveys, full-scale experimental work and detailed finite-element analyses.

Input data for the following two house types has been prepared for VAWS:

- A contemporary rectangular gable-roofed house with metal sheet roof and reinforced masonry walls as described by Figure 6.
- A high-set rectangular gable roof-roofed house typical of 1960's construction in north Queensland with metal sheet roof and fibre-cement wall cladding as described by Figure 7.

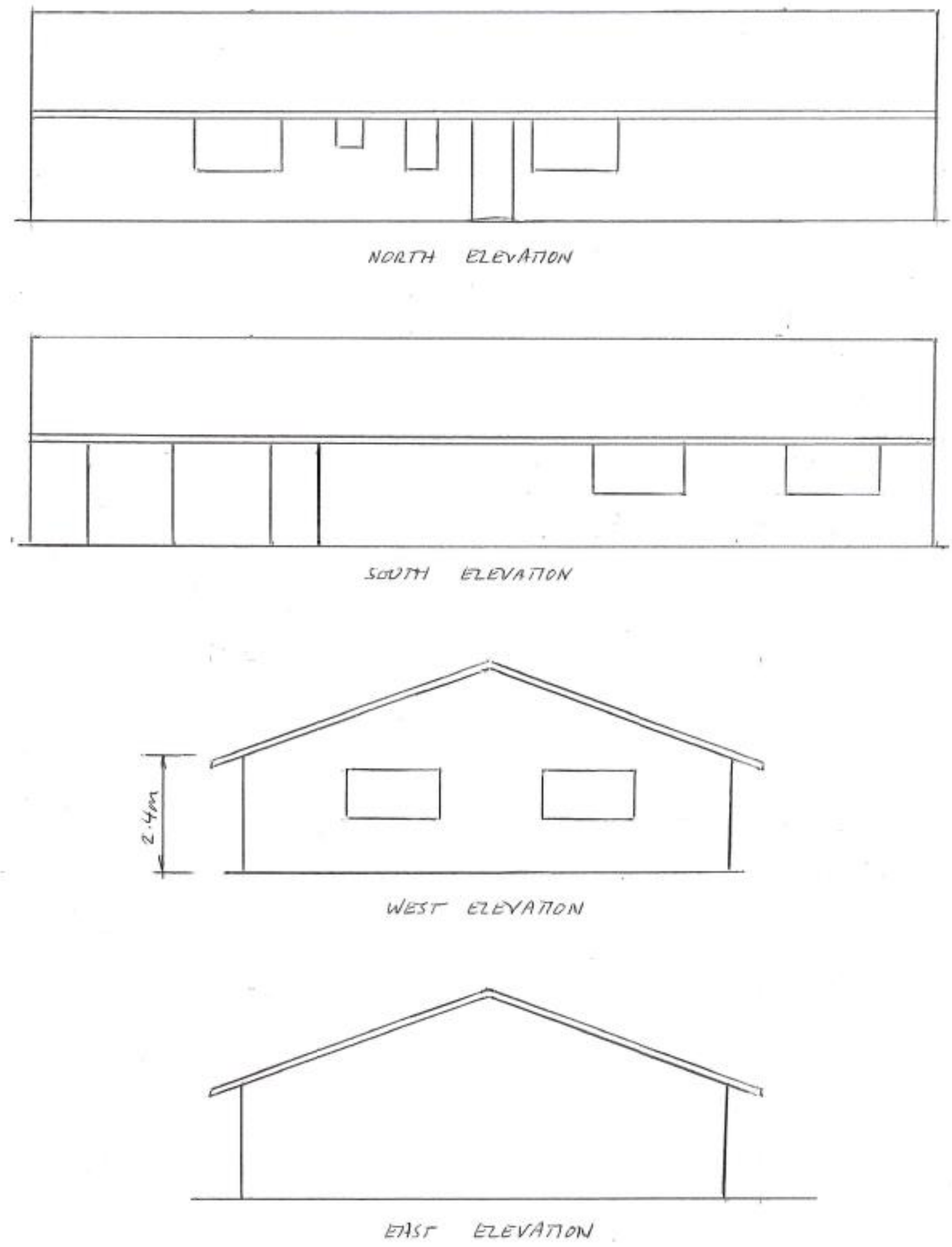


FIGURE 6. HOUSE TYPE 1; A CONTEMPORAY RECTANGULAR GABLE-ROOFED HOUSE WITH METAL SHEET ROOF AND REINFORCED MASONRY WALLS.

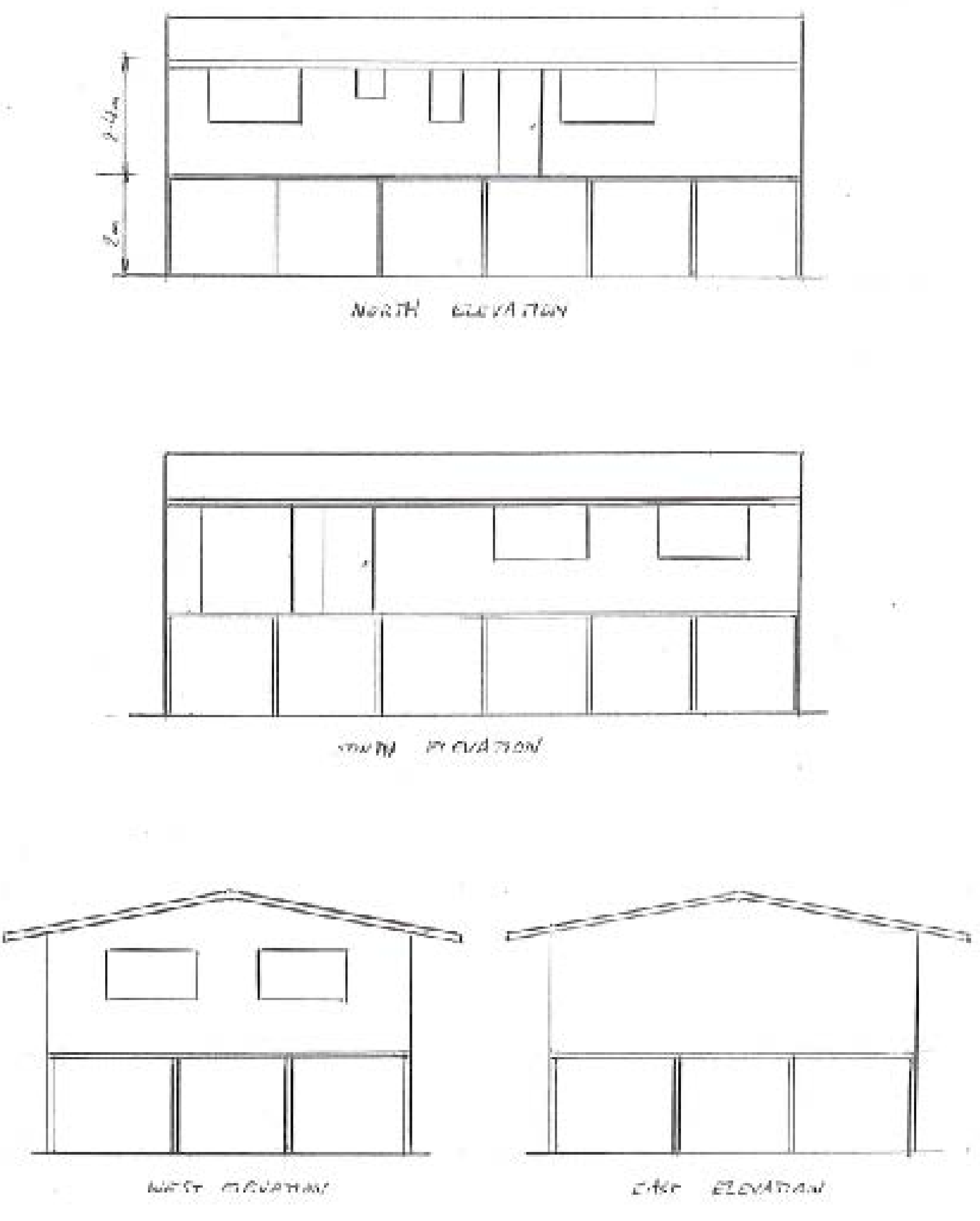


FIGURE 7. HOUSE TYPE 2; A HIGH-SET RECTANGULAR GABLE ROOF-ROOFED HOUSE TYPICAL OF 1960'S CONSTRUCTION IN NORTH QUEENSLAND WITH METAL SHEET ROOF AND FIBRE-CEMENT WALL CLADDING.

The modelling below includes damage to roof sheeting, battens, roof structure, consequential damage to interior finishes due to envelope loss, damage to wall cladding and windows, and water ingress damage.

- **Contemporary reinforced masonry house**

This house consists of reinforced masonry walls with a trussed roof system supporting battens and metal sheet roofing. The modelled house includes a set of wall openings (windows and doors) which, for the purposes of this model were assumed to be identical to those of the 1960's high-set house described below. Note that the failure momentum and resistance to wind pressure values of the reinforced masonry walls mean that the walls (other than windows and doors) remain intact at all wind speeds. The connection capacities and wall coverage capacities are derived from data analysed by the CTS and GA. External pressure coefficients were sourced from Jayasinghe, (2012).

- **1960's high-set fibre-cement clad house**

The framing system for this house consists of hardwood stud walls and a hardwood framed roof system supporting timber battens and metal roof sheeting. The roof framing consists of rafter pairs at approximately 900mm centres with a collar tie to every second rafter pair. The connection capacities and wall coverage capacities are derived from data analysed by the CTS and GA. For this model, total loss was assumed when the roof structure damage reached 50%. External pressure coefficients were sourced from JDH, 2007.

Output

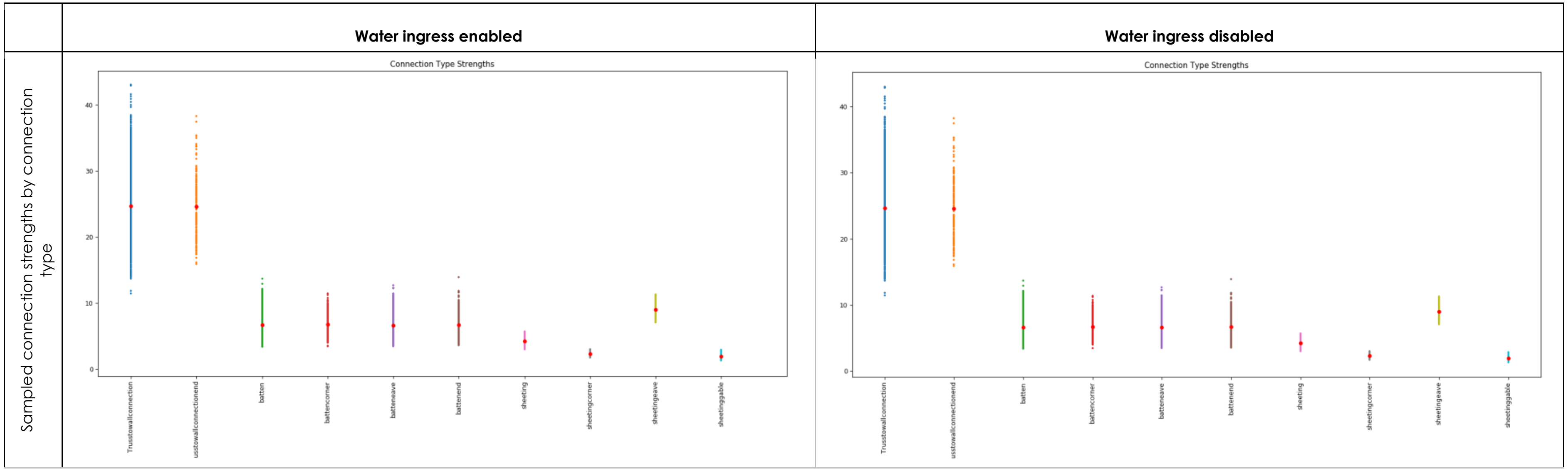
A selection of outputs from VAWS for the two house types is presented below. In each case the hazard parameter is the 0.2s gust wind speed at 10m height at the house.

For the modern reinforced masonry house two sets of results are given; one with water ingress included and one without water ingress. The latter will enable comparison of the output with laboratory testing of the trussed roof system. Note that for this house the modelled damage index will not reach 1.0 as the reinforced masonry walls will always remain intact.

Modern metal roof / block wall house with water ingress

Figure 8 shows output from the VAWS model run with and without water ingress.

FIGURE 8. VAWS OUTPUT FOR THE MODERN METAL ROOF / BLOCK WALL HOUSE MODELLED WITH AND WITHOUT WATER INGRESS



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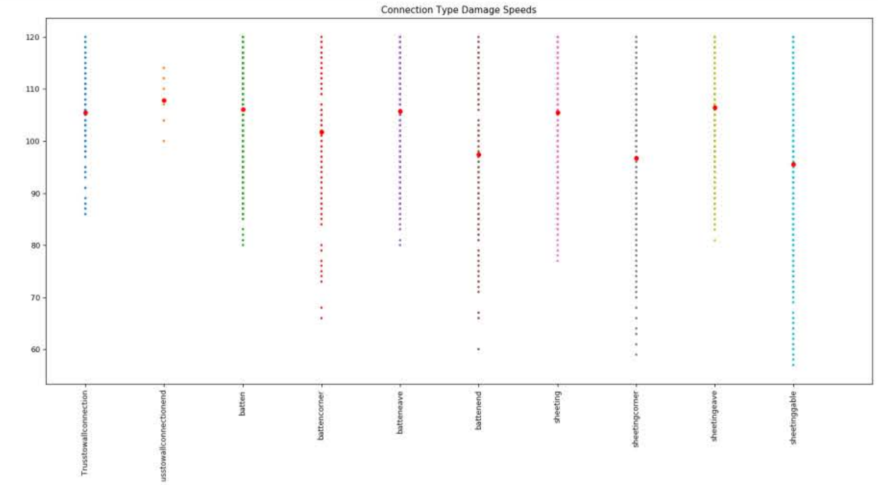
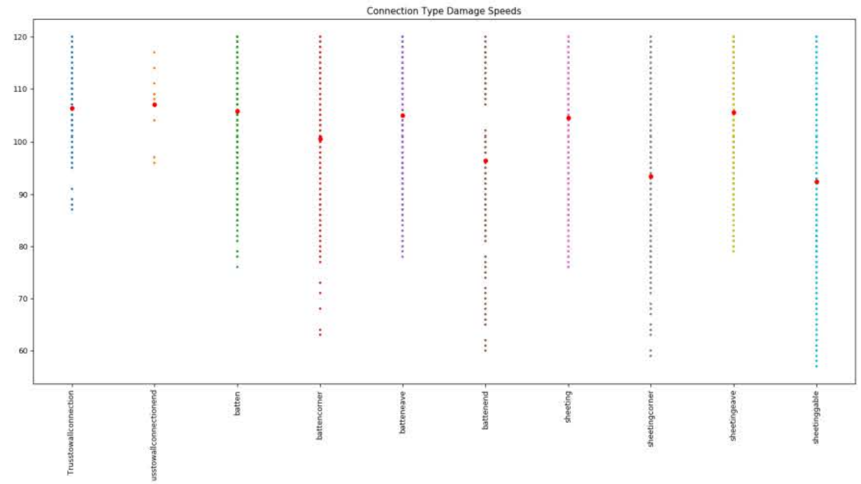
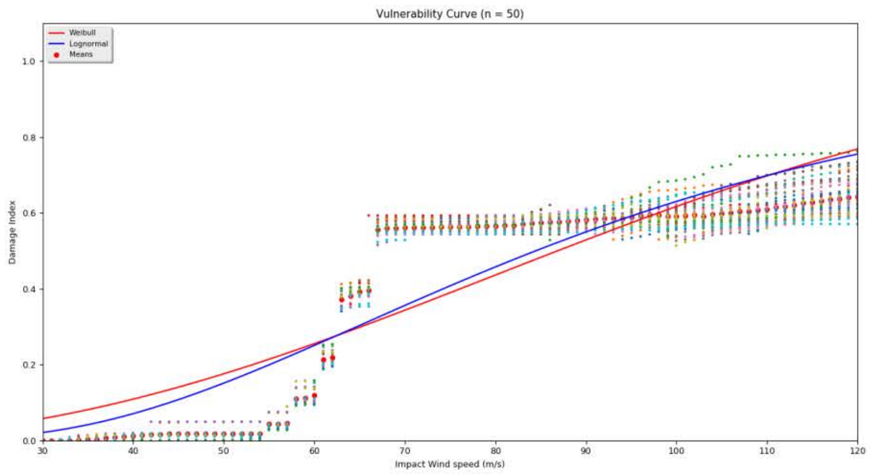
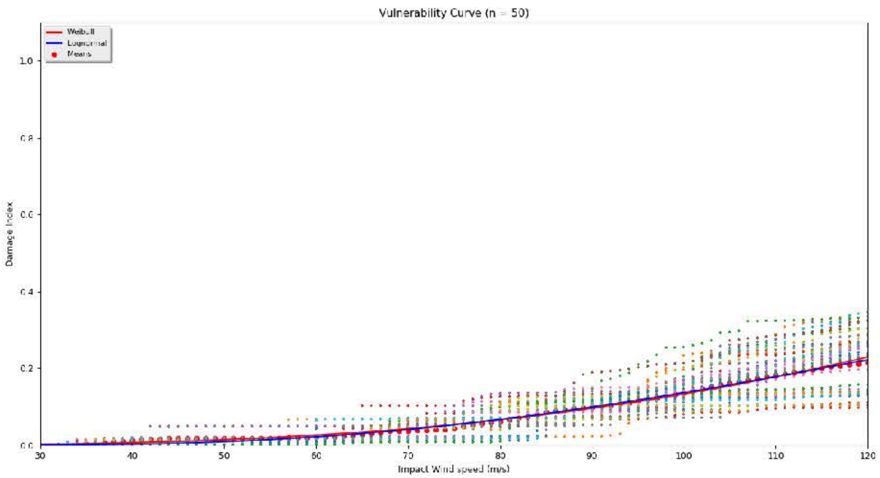
Gust wind speed at connection failure by connection type		
Vulnerability curve		

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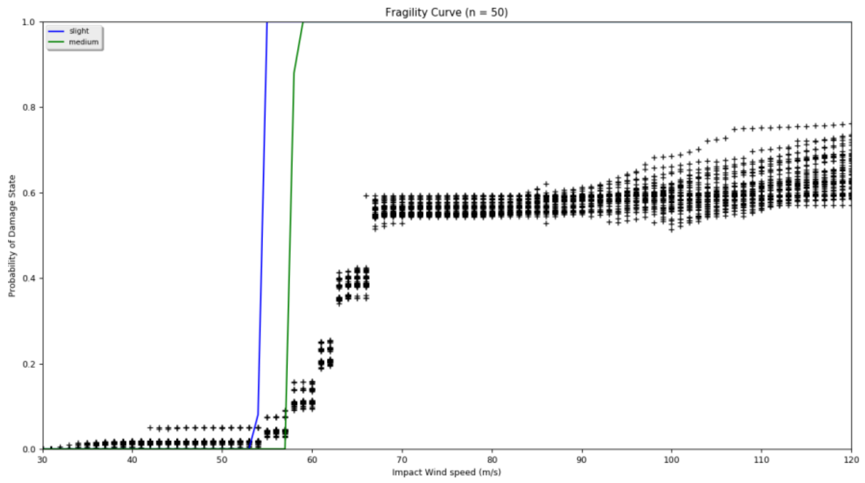
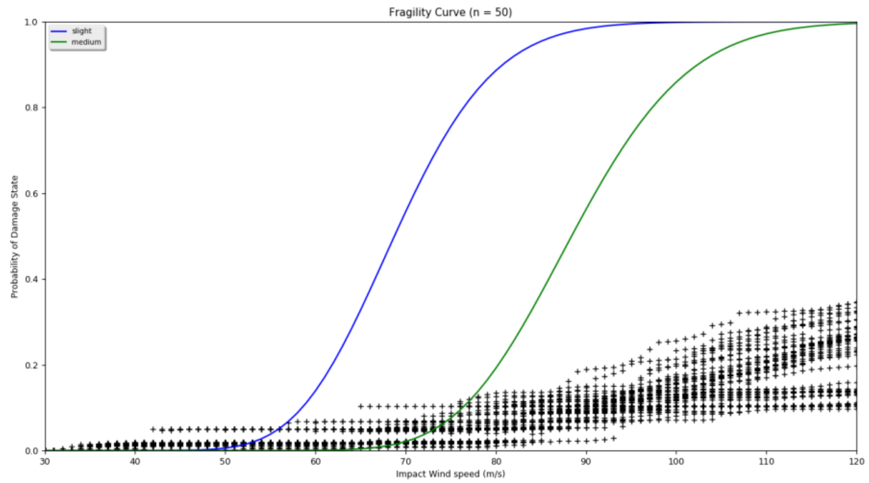
<tr><td>Fragility curves</td><td>
</td><td>
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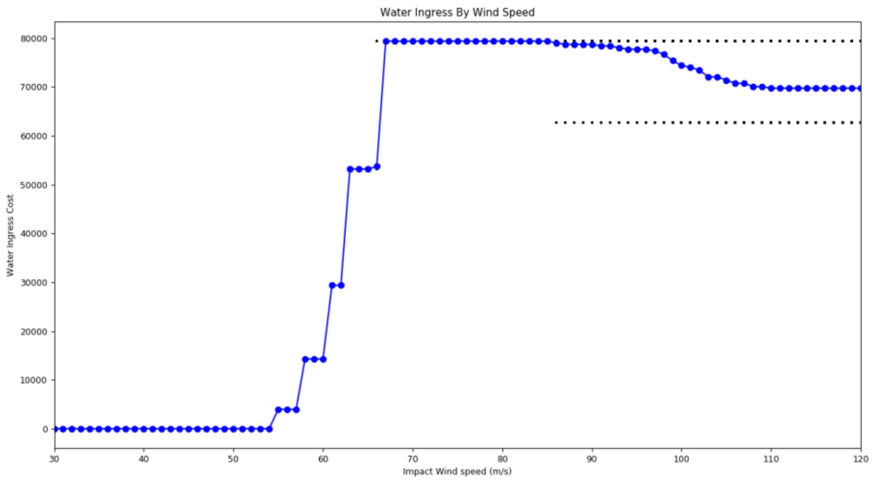
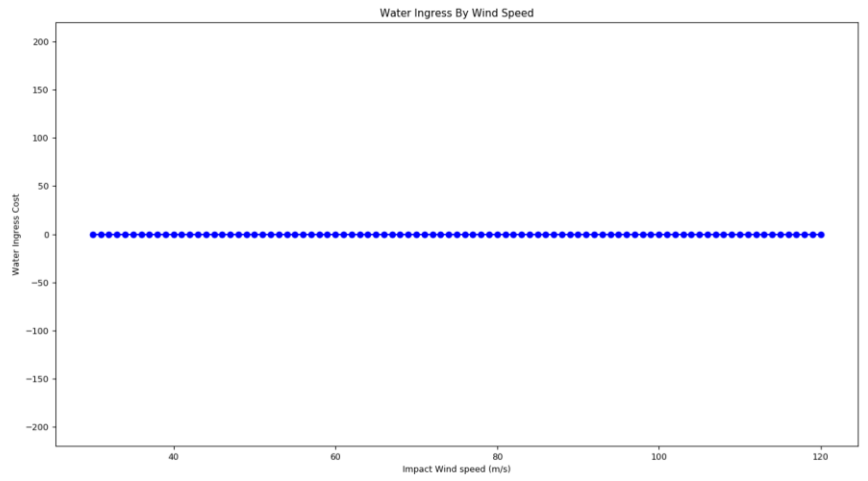
<tr><td>Loss due to internal damage from water ingress</td><td>
</td><td>
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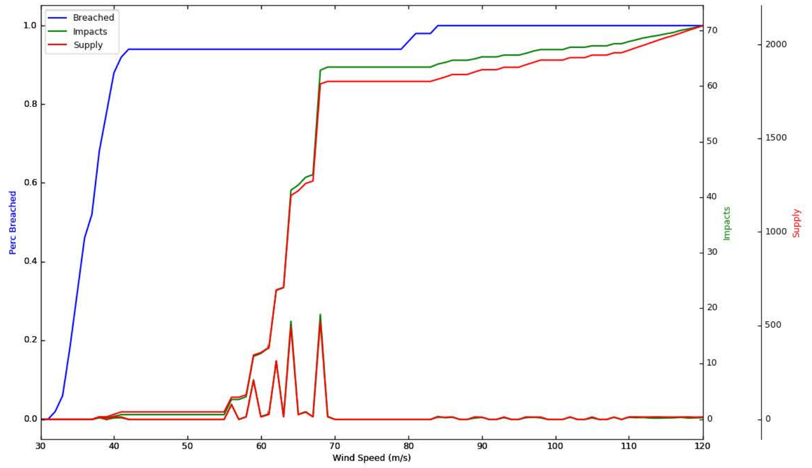
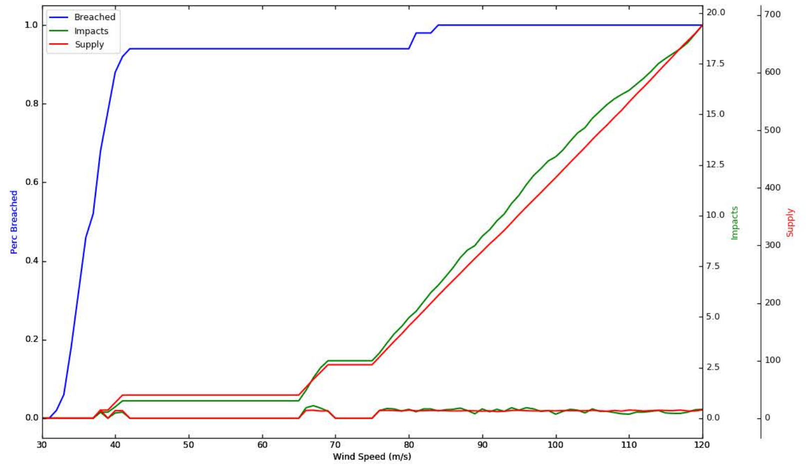
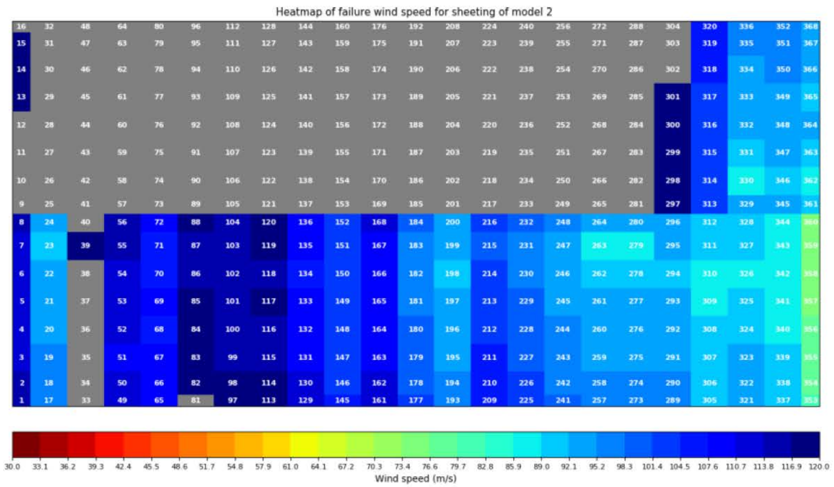
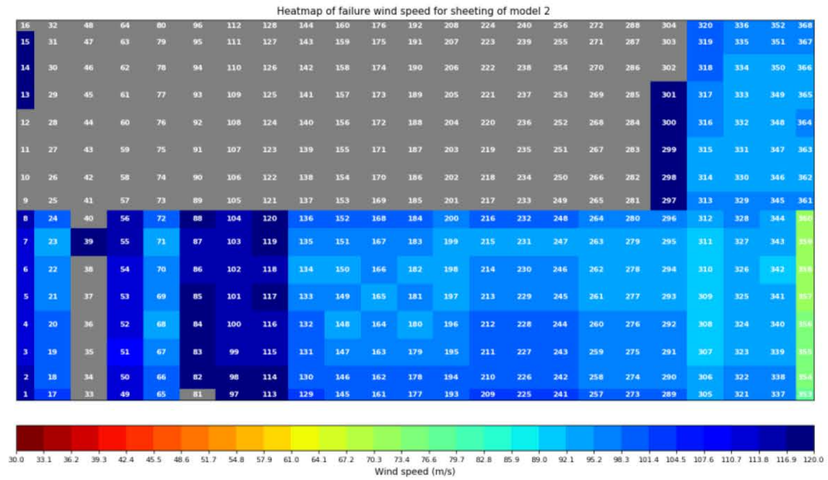
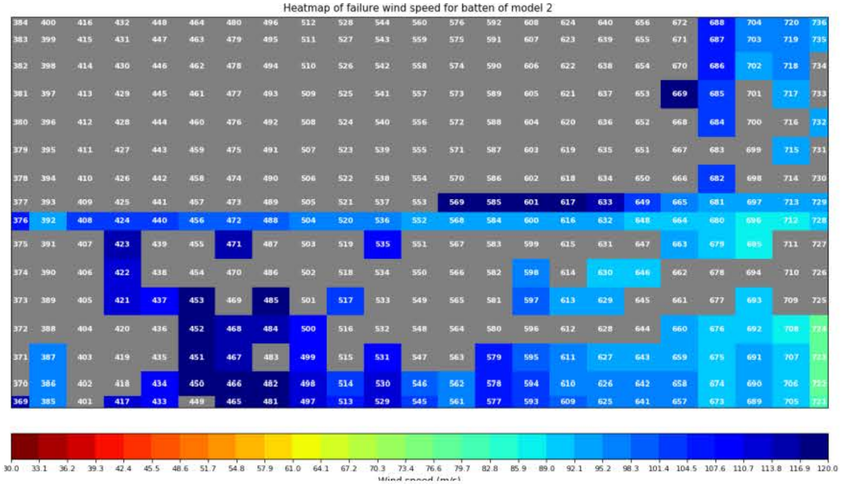
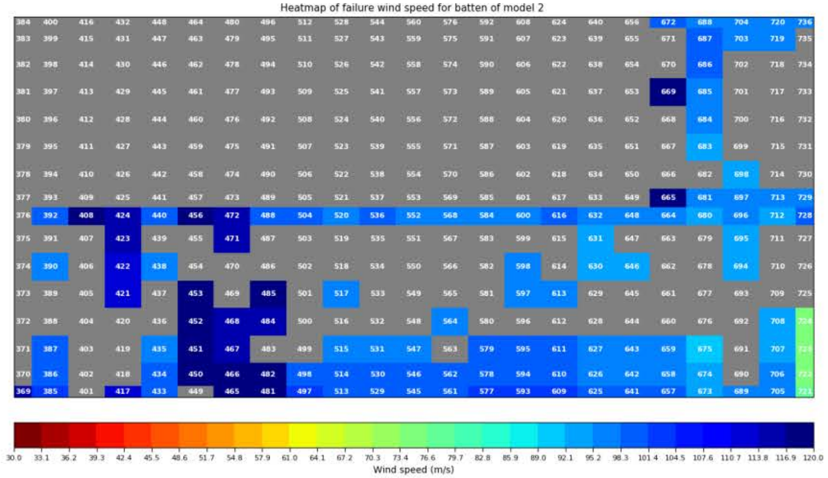
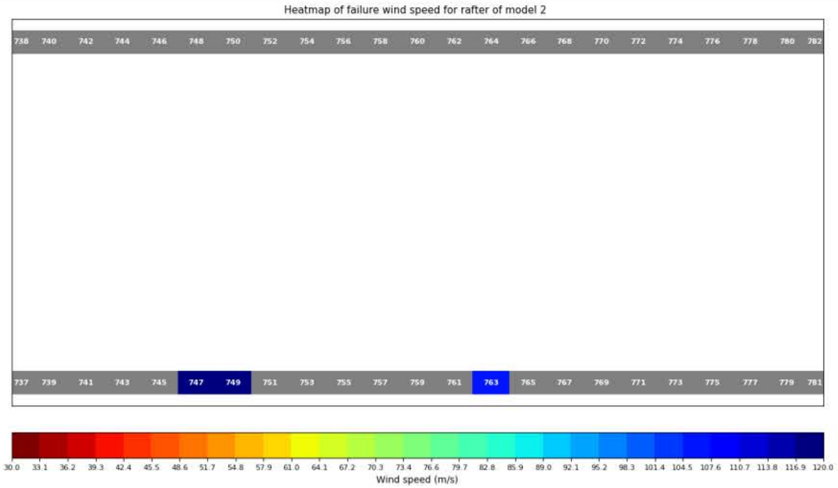
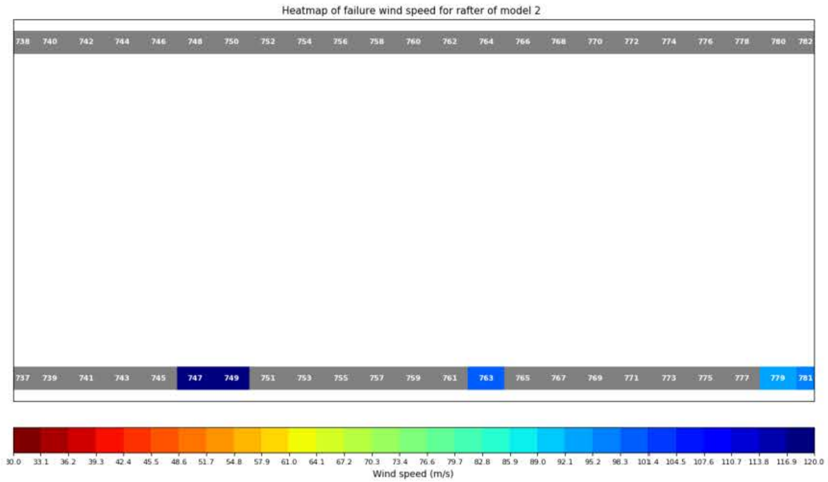
	Water ingress enabled	Water ingress disabled
Debris impact and internal pressurisation with gust wind speed		
Example heat map of gust wind speed at roof sheeting connection failure		

	Water ingress enabled	Water ingress disabled
Example heat map of gust wind speed at batten connection failure		
Example heat map of gust wind speed at roof structure connection failure		

1960's high-set fibre-cement clad house with water ingress

Figures 9 to 17 show example output from VAWS for the 1960's high-set fibre cement clad house. Note the inability of the fitted curves in Figures to match the onset of damage at about 33m/s gust wind speed.

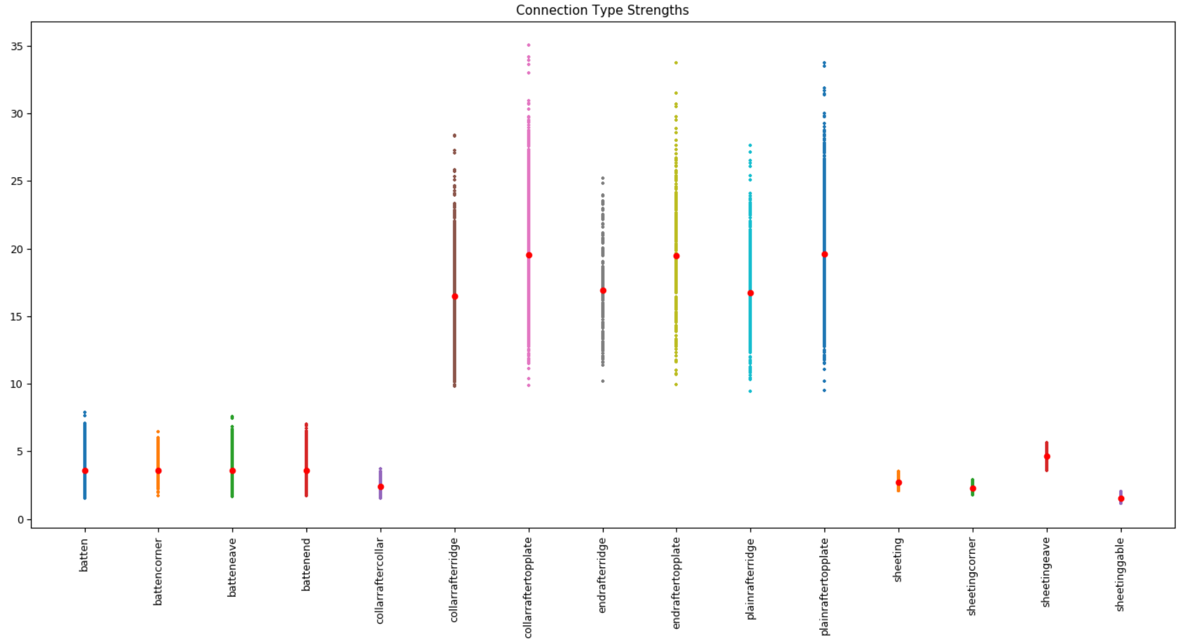


FIGURE 9. SAMPLED CONNECTION STRENGTHS BY CONNECTION TYPE SHOWING THE RANGE OF INDIVIDUAL CONNECTION STRENGTHS SAMPLED BY VAWS AROUND A SPECIFIED MEAN

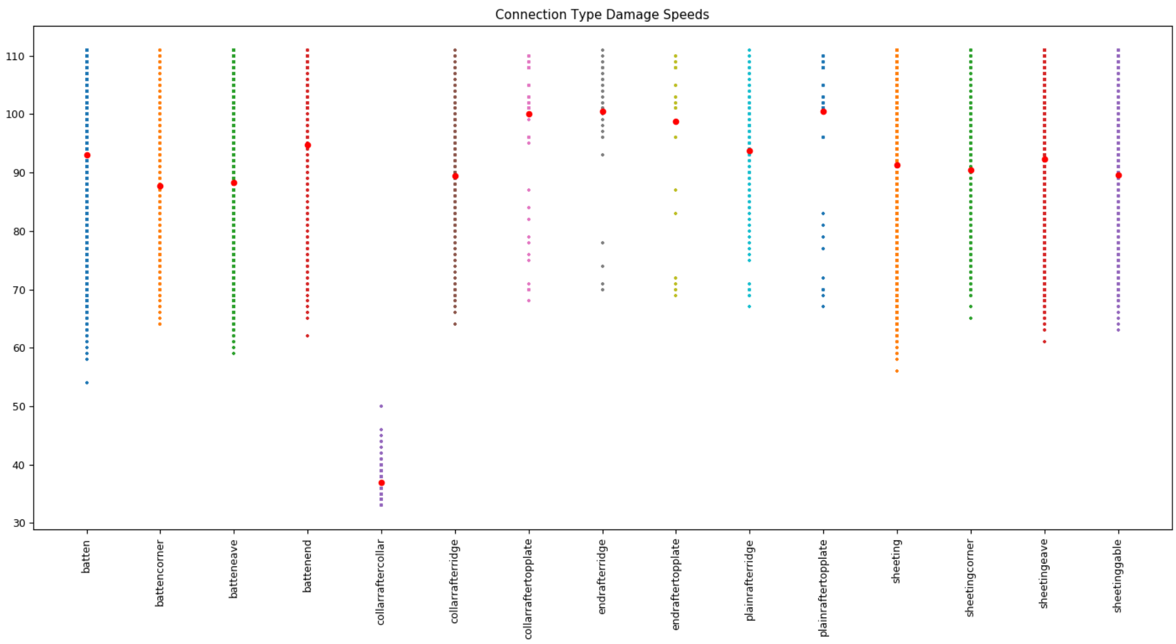


FIGURE 10. GUST WIND SPEEDS AT CONNECTION FAILURE BY CONNECTION TYPE MODELLED BY VAWS.

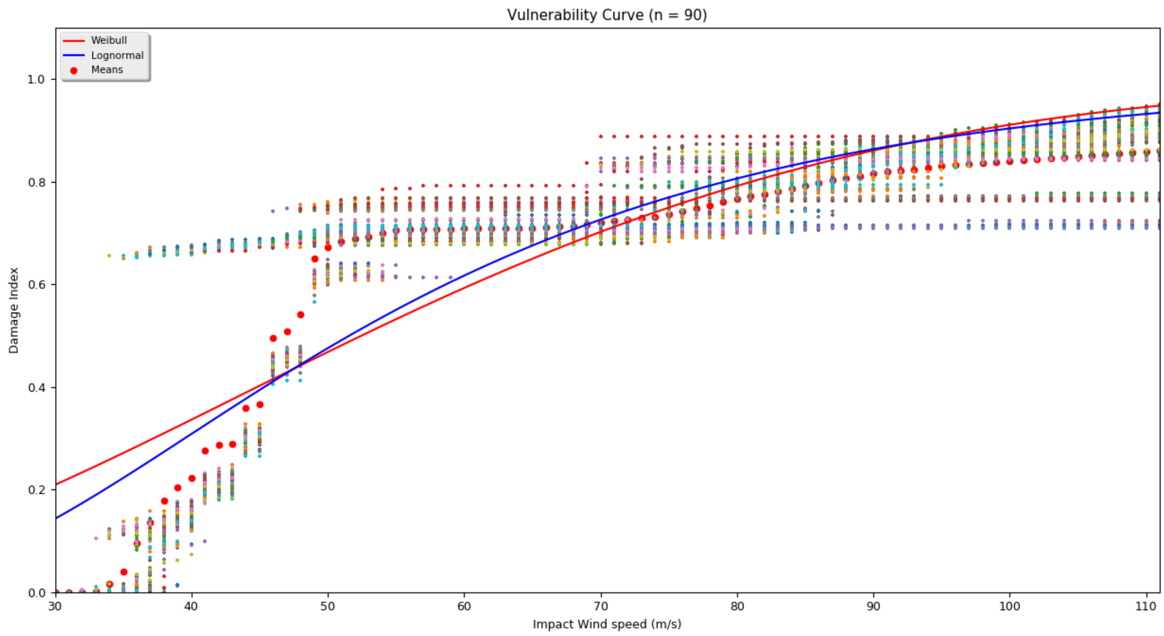


FIGURE 11. MODELLED VULNERABILITY CURVE

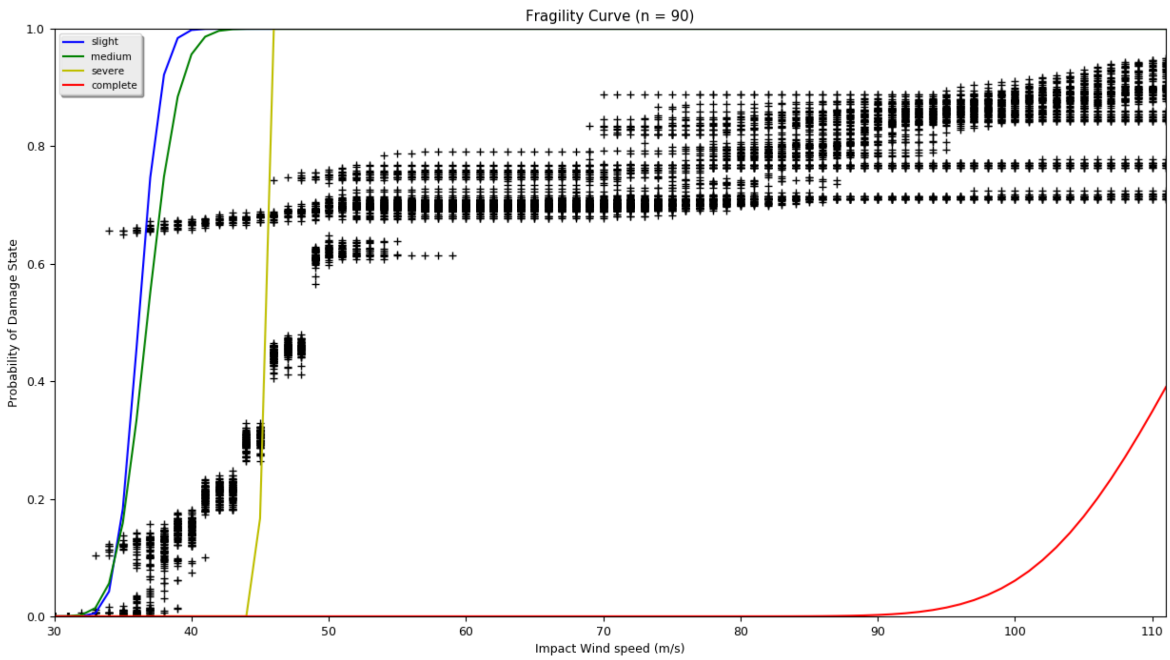


FIGURE12. MODELLED FRAGILITY CURVES

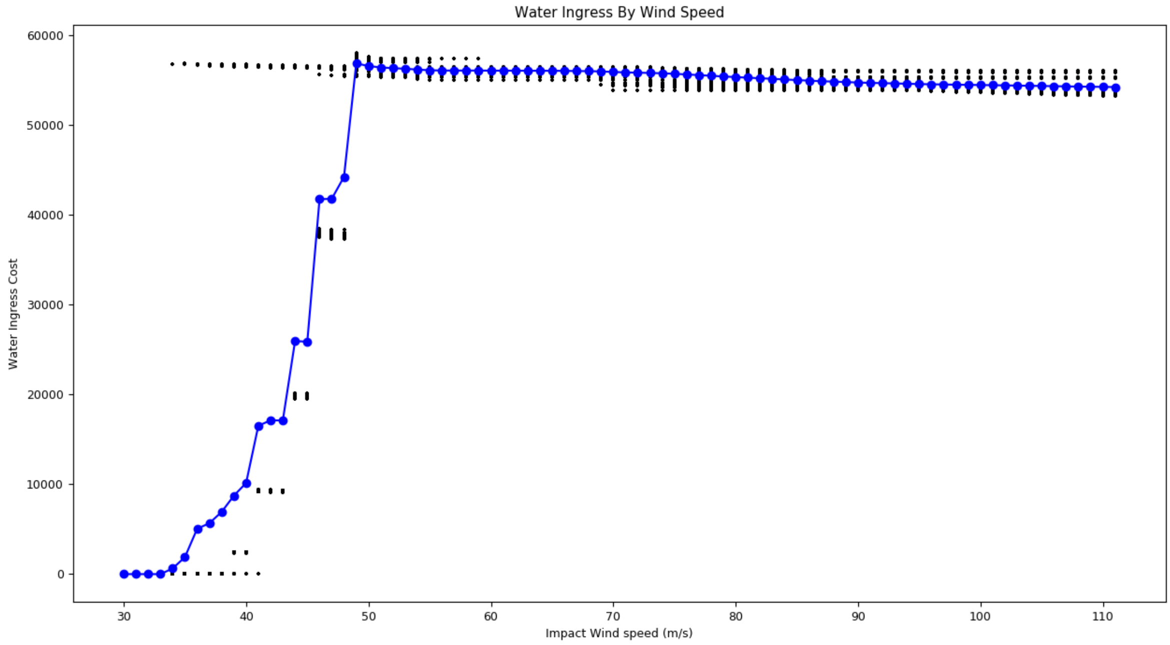


FIGURE13. MODELLED DOLLAR LOSS DUE TO DAMAGE FROM WATER INGRESS WITH GUST WIND SPEED. NOTE THE SIGNIFICANR LOSS DUE TO WATER INGRESS AT LOW GUSTW IND SPEEDS PRIOR TO ONSET OF STRUCTURAL DAMAGE.

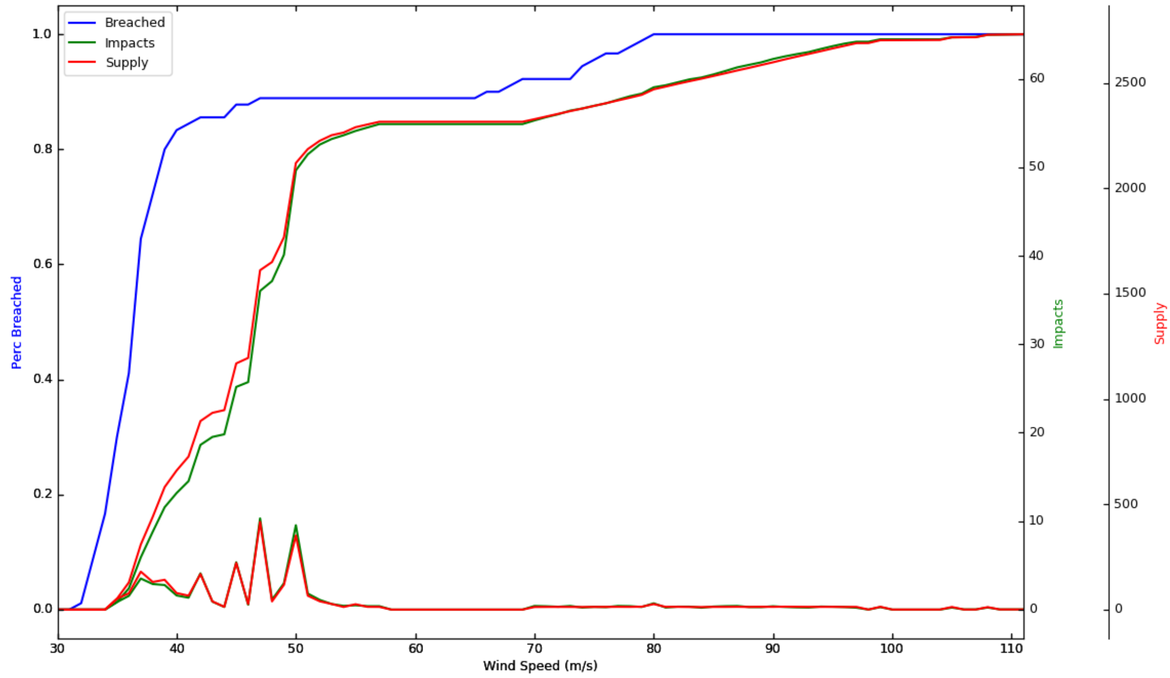


FIGURE 14. RESULTS OF DEBRIS DAMAGE AND PRESSURE INDUCED FAILURES OF WINDOWS AND DOORS. NOTE THE OCCURRENCE OF BREACHED BUILDING ENVELOPE PRIOR TO ONSET OF DEBRIS IMPACT AT ABOUT 32M/S GUST WIND SPEED INDICATING THE FAILURE OF A WINDOW OR DOOR DUE TO EXTERNAL PRESSURE.

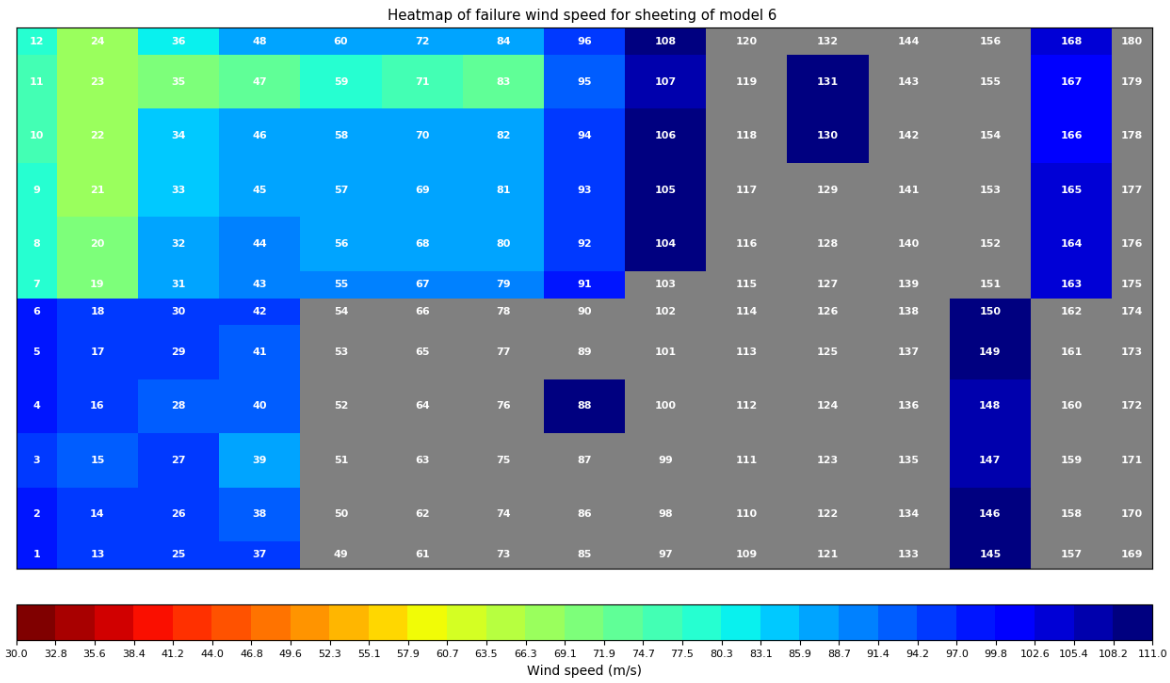


FIGURE 15. EXAMPLE HEAT MAP OF ROOF SHEETING CONNECTION FAILURE GUST WIND SPEED FOR A SINGLE INSTANCE OF THE HEOUSE TYPE (MODEL 6 OF 90). THE WHITE NUMBERS REFER TO CONNECTION NUMBERS.

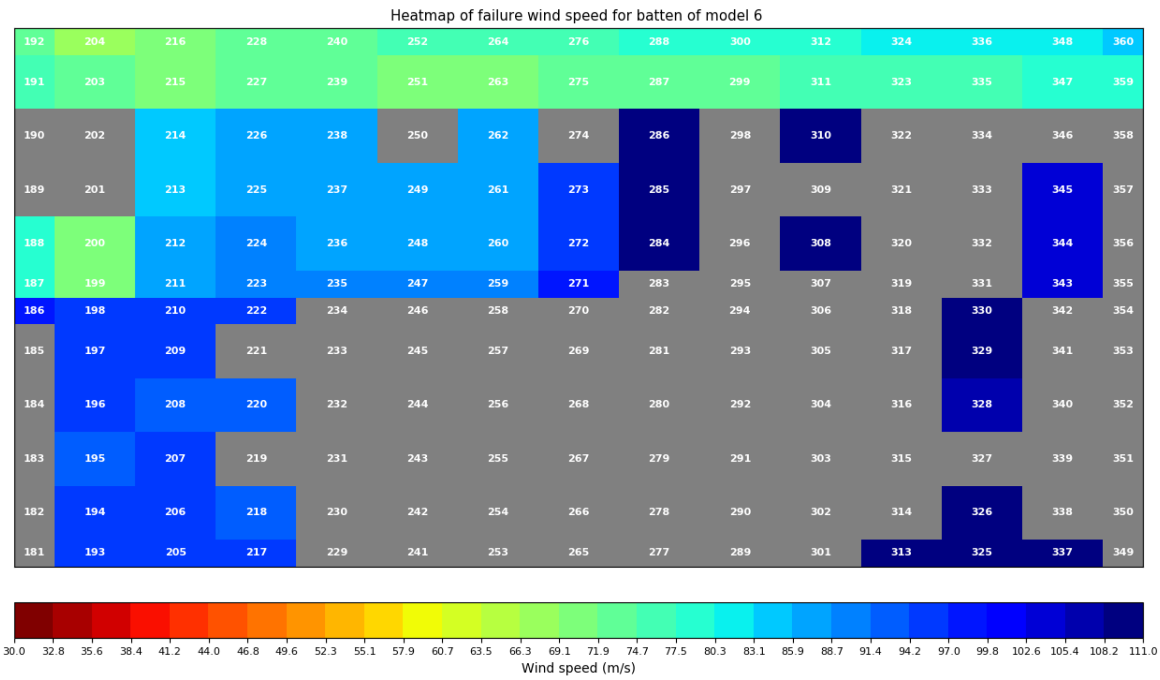


FIGURE 16. EXAMPLE HEAT MAP OF BATTEN CONNECTION FAILURE GUST WIND SPEED FOR A SINGLE INSTANCE OF THE HEOUSE TYPE (MODEL 6 OF 90). THE WHITE NUMBERS REFER TO CONNECTION NUMBERS.

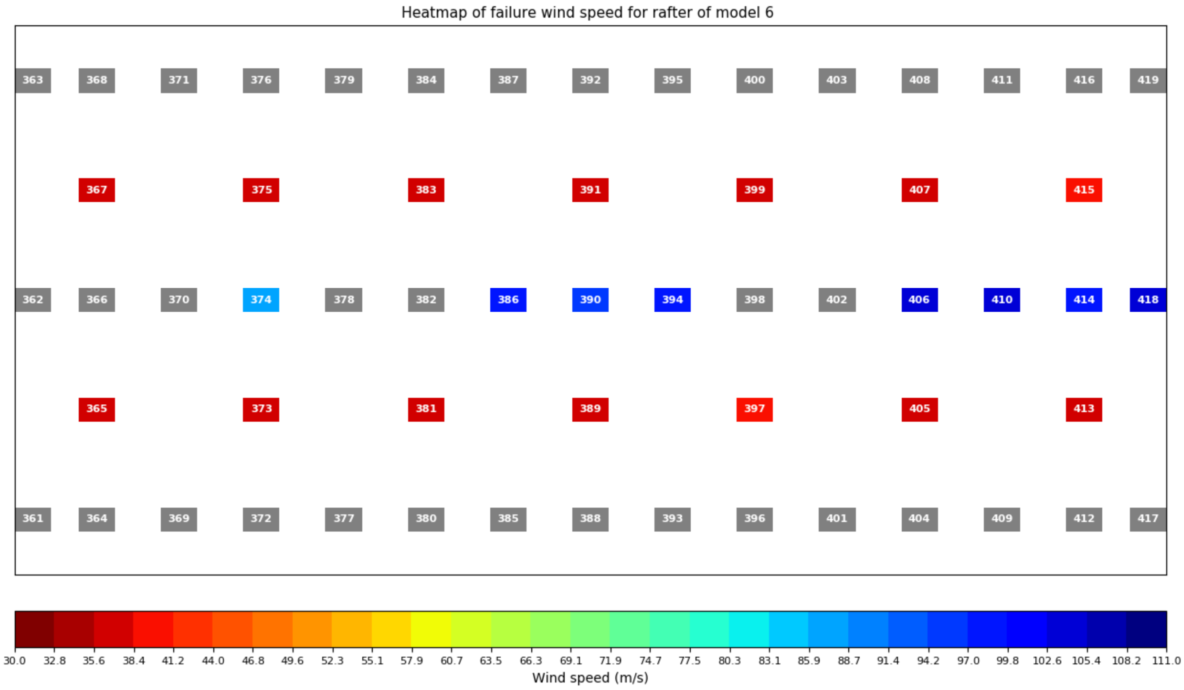


FIGURE 17, EXAMPLE HEAT MAP OF ROOF STRUCTURE CONNECTION FAILURE GUST WIND SPEED FOR A SINGLE INSTANCE OF THE HEOUSE TYPE (MODEL 6 OF 90). THE WHITE NUMBERS REFER TO CONNECTION NUMBERS.

Discussion of VAWS output

The example results shown above for two house types demonstrate several features of the modelled vulnerability that the project will address during the next year:

- The degree of damage at lower gust wind speeds is strongly influenced by water ingress and debris damage. Input data for parameters that are used to model water ingress and debris damage will need to be sourced from experimental work and critically assessed.
- The type of vulnerability curve fitted to the model outputs will need to be examined so that the best fit possible is achieved.
- The degree of damage at which a house is considered destroyed will need to be examined and possibly included in the software.

Influence coefficients roof structure load effects

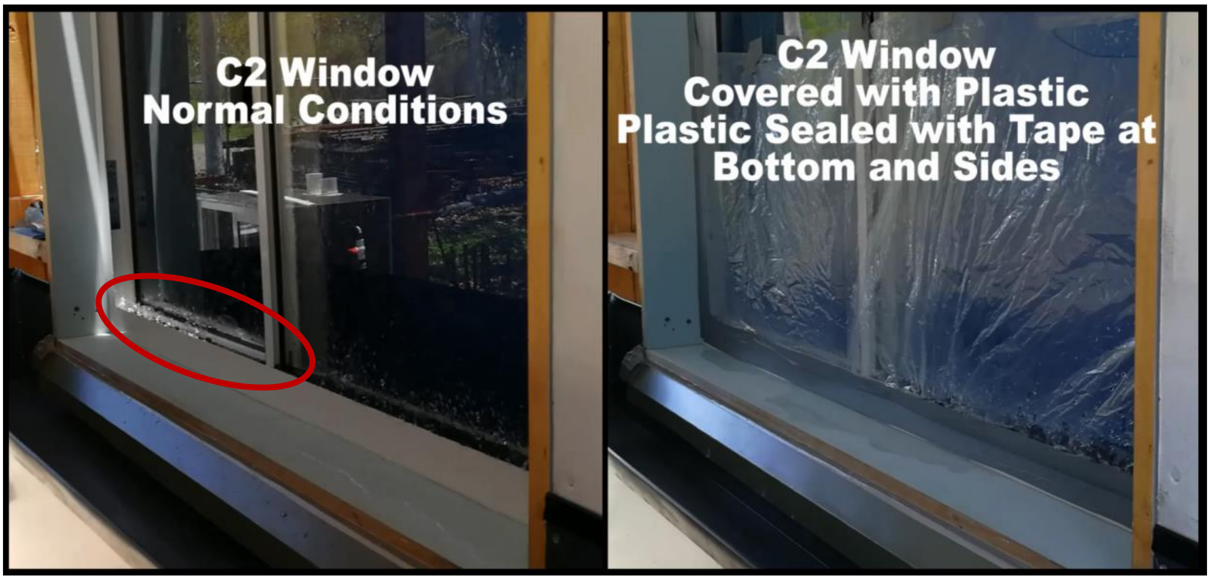
An underlying foundation of the VAWS tool is the modelling of structural behaviour of the house structure to the wind load. A traditional house structure is a multitude of members (battens, rafter, top plates, linings, etc.) and connections (nails, skew-nails, straps, etc.). The members and connections 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 developed to provide the needed input data for VAWS.

Wind driven rain water ingress

Damage surveys conducted by the CTS following severe events such as Tropical Cyclones Yasi, Marcia and Debbie highlight the large amounts of wind driven rain water ingress entering our homes and resulting in significant damage. The water damaged plasterboard ceiling and wall linings, carpets, timber floors, wiring and contents. Many people reported they had tried to deal with the volumes of water entering their house during the cyclone and had put themselves at risk of serious injury while working in front of windward windows or doors.

Analysis of insurance claims data has shown that water ingress is a major contributor to losses in residential construction in recent events. Approximately 80% of claims analyzed from TC Yasi mentioned water ingress with approximately 70% of those claims having no breach of the building envelope. That is, the wind driven rain was entering via “undamaged” windows, doors, flashings, etc. This is not surprising given that the test pressure for the Australian water resistance test requirements for windows and doors is roughly a tenth of the wind load strength design pressure.

In a project also supported by IAG and Suncorp, the CTS has developed a test chamber where we have been trialing several retrofit methods for reducing wind driven rain entry through typical windows and doors (Figure 18).



(a) (b)

Figure 18. Wind driven rain test chamber at CTS; (a) water bubbling over sills during dynamic pressure trace; (b) simple retrofit retaining water from entering house.

PUBLICATIONS

Book Chapters

Henderson D., Smith D.J., Carter R., and Smith D., *Damage from Impact* Chapter 5 in *Wind-Borne Debris Hazards*, Editor: Kaye N., ASCE, 2018, DOI-10.1061/9780784414965.ch05

Krupar, R.J. and D.J. Smith, *Hurricanes and Climate Change: from Hazards to Impact, Chapter (TBD) - Poleward migration of tropical cyclone activity in the Southern Hemisphere: perspectives and challenges for the built environment in Australia* (in press) 2018.

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Jayasinghe N.C., Ginger J.D., Henderson D.J., and Walker G.R, *Distribution of wind loads in metal-clad roofing structures*, J. Structural Engineering, DOI: 10.1061/(ASCE)ST.1943-541X.0001992(2018).

Parackal, Korah I., Ginger, John D. and Henderson, David J., *Wind Load Fluctuations on Roof Batten to Rafter/Truss Connections*, Journal of Wind Engineering & Industrial Aerodynamics, 175, pp. 193-201 2018.

Smith, DJ., Krupar, RJ., Henderson, DJ., Mason MS., *Analysis of rapid damage assessment data following severe windstorm events*, Australian Journal of Emergency Management 32 (4) (2017).

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Humphreys M., Ginger J., and Henderson D., *Internal Pressure Fluctuations in Large Open Plan Buildings*, 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December, 2017.

Parackal, K., Ginger J., Smith D. and Henderson D, *Load sharing between batten to rafter connections under wind loading.* 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December 2017.

Bodhinayake G., Ginger J., and Henderson D., *External and Internal Pressure Fluctuations on Industrial-Type Buildings*, 9th Asia-Pacific Conference on Wind Engineering, Auckland, New Zealand, 3-7 December 2017

Humphreys M., Ginger J., and Henderson D., *Effect of Opening Geometry on Full-Scale Internal Pressure Measurements,* 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, 4-6 April, 2018.

Bodhinayake G., Ginger J., and Henderson D., *Correlation of internal and external pressures on building cladding elements*, 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

Wehner, M., H. Ryu, J. Ginger, M. Edwards, D. Henderson, K. Parackal, D.J. Smith, *Modelling residential mitigation effectiveness for severe wind*. 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

Smith, D.J., D.B. Roueche, R.J. Krupar, F.T. Lombardo, D.J. Henderson, *Parallels in tropical cyclone design strategies and building performance for Australia and U.S.,* 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

Nicoline Thomson, David Henderson, John Ginger, *Design of Potential Dominant Openings to Resist Cyclonic Winds*, 19th Australasian Wind Engineering Society Workshop, Torquay, Victoria, April 4-6, 2018.

Smith, D.J., R.J. Krupar, D.J. Henderson, *Analysis of convective windstorm events using QFES Rapid Damage Assessment (RDA) data and dual-doppler radar.* AFAC 2017 Fire and Emergency Services Conference, Sydney, Australia 2017.

Roueche, D.B., F.T. Lombardo, D.J. Smith, R.J. Krupar, *Fragility assessment of wind-induced residential building damage caused by Hurricane Harvey (2017).* American Society of Civil Engineers (ASCE) Forensic Engineering 8th Congress, Austin, TX, U.S.A2018.

Henderson, D., D.J. Smith, G. Boughton, J. Ginger, *Damage and loss to Australian engineered buildings during recent cyclones.* International Workshop on Wind-Related Disasters and Mitigation, Sendai, Japan 2018.

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