Resilient Buildings: Informing Maintenance for Long-term Sustainability

Final Industry Report, Project 1.53

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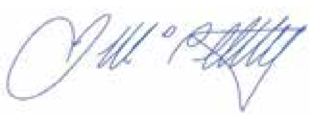
This Final Industry Report summarises research carried out in SBEnrc Project 1.53 — Resilient Buildings: Informing Maintenance for Long-term Sustainability. The Project Research Report Parts 1-4 (available at https://sbenrc.com.au/research-programs/1-53/) describes the research process and outcomes in a more comprehensive manner.

Preface

The Sustainable Built Environment National Research Centre (SBEnrc), the successor to Australia's Cooperative Research Centre (CRC) for Construction Innovation, is committed to making a leading contribution to innovation across the Australian built environment industry. We are dedicated to working collaboratively with industry and government to develop and apply practical research outcomes that improve industry practice and enhance our nation's competitiveness.

We encourage you to draw on the results of this applied research to deliver tangible outcomes for your operations. By working together, we can transform our industry and community through enhanced and sustainable business processes, environmental performance and productivity improvements.



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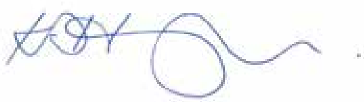

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Core Members of SBEnrc include Aurecon, BGC Australia, Queensland Government, Government of Western Australia, New South Wales Roads and Maritime Services, New South Wales Land and Housing Corporation, Curtin University, Griffith University and Swinburne University of Technology.

We are grateful for the contributions of the workshop and interview participants and persons consulted from various stakeholder organisations such as Australian Windows Association, Australian Building Codes Board (ABCB), Australasian Fire and Emergency Services Authorities Council (AFAC), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Department of Fire and Emergency Services (DFES) – Western Australia, and Facilities Management Association of Australia (FMA).

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Executive Summary

Resilience of buildings is a national objective in disaster mitigation. Often, maintenance is a missing link to improving the resilience of buildings in extreme events. The performance of the buildings decreases over time and without effective maintenance, their vulnerabilities to extreme events will increase. This SBEnrc Project 1.53 Resilient Buildings: Informing Maintenance for Long-term Sustainability aimed to examine the role of maintenance in making buildings more resilient to the extreme weather impacts of bushfires, floods and water ingress from cyclones and high winds. This project focused mainly on low-rise public buildings and the use of technical knowledge to inform policy and practice. The methodology included literature reviews, workshops, interviews and industry consultations looking for gaps in current policy and practice. The Project Research Report (Parts 1-4) provides further details on each aspect of the research and supporting references.

The key recommendations from this SBEnrc Project P1.53 are:

1. A maintenance schedule for building assets should be provided as part of the design for durability.
2. A maintenance manual for each building should be made available for the people responsible for its maintenance.
3. Accurate as-built documentation should be made available for maintenance purposes.
4. Routine maintenance inspections should be used to detect prevailing and new emerging risks to building resilience.
5. An appropriate procurement framework for responsive maintenance should be developed.
6. ‘Build back better’ for sustainable resilience against natural hazards.
7. Establish maintenance responsibilities for whole-of-life value and sustainability.
8. Develop smart infrastructure with advanced digital integration for efficient maintenance and effective resilience.

The project outcomes of key recommendations and implementation strategies will be useful to building owners, governments and industry stakeholders. The creation of a ‘Framework for specifying building maintenance’ is recommended, from which individual building maintenance manuals can be compiled.

Contents

Introduction

Natural disaster hazards are significant risks in Australia. The cumulative value of total losses from natural disasters for the period 1967-2013 was AUD $171.5 billion *(2013 price equivalent)*, in which the cost of death and injuries was $15.3 billion[1]. Specifically, the proportions of natural disaster losses in Australia during this 46-year period were: (i) 32% from storms, (ii) 28% from floods, (iii) 19% from cyclones, (iv) 17% from bushfires, and (v) 4% from other extreme events (such as earthquakes).

Losses across Australian States and Territories and different event types are shown in *Figure 1*.

This SBEnrc project, 1.53 Resilient Buildings: Informing Maintenance for Long-term Sustainability, aimed to examine the role of maintenance in making low-rise buildings more resilient to the extreme weather events of cyclones/high winds, bushfires and natural floods, using technical knowledge to identify gaps and inform policy and practice. The research methodology included focused literature reviews, brainstorming discussions with the research teams and the project steering group, interviews and workshops with industry practitioners and correspondence/consultations with project affiliates and other stakeholders. The Project Research Report (Parts 1-4) provides further details and references for each aspect of the research[2].

[1] The information on losses for the 46-year period (1967 to 2013) is extracted from: Handmer, J., Ladds, M. and Magee, L. (2016) Disasater Losses from Natural Hazards in Australia, 1967-2013.

[2] SBEnrc Project 1.53 webpage: https://sbenrc.com.au/research-programs/1-53/

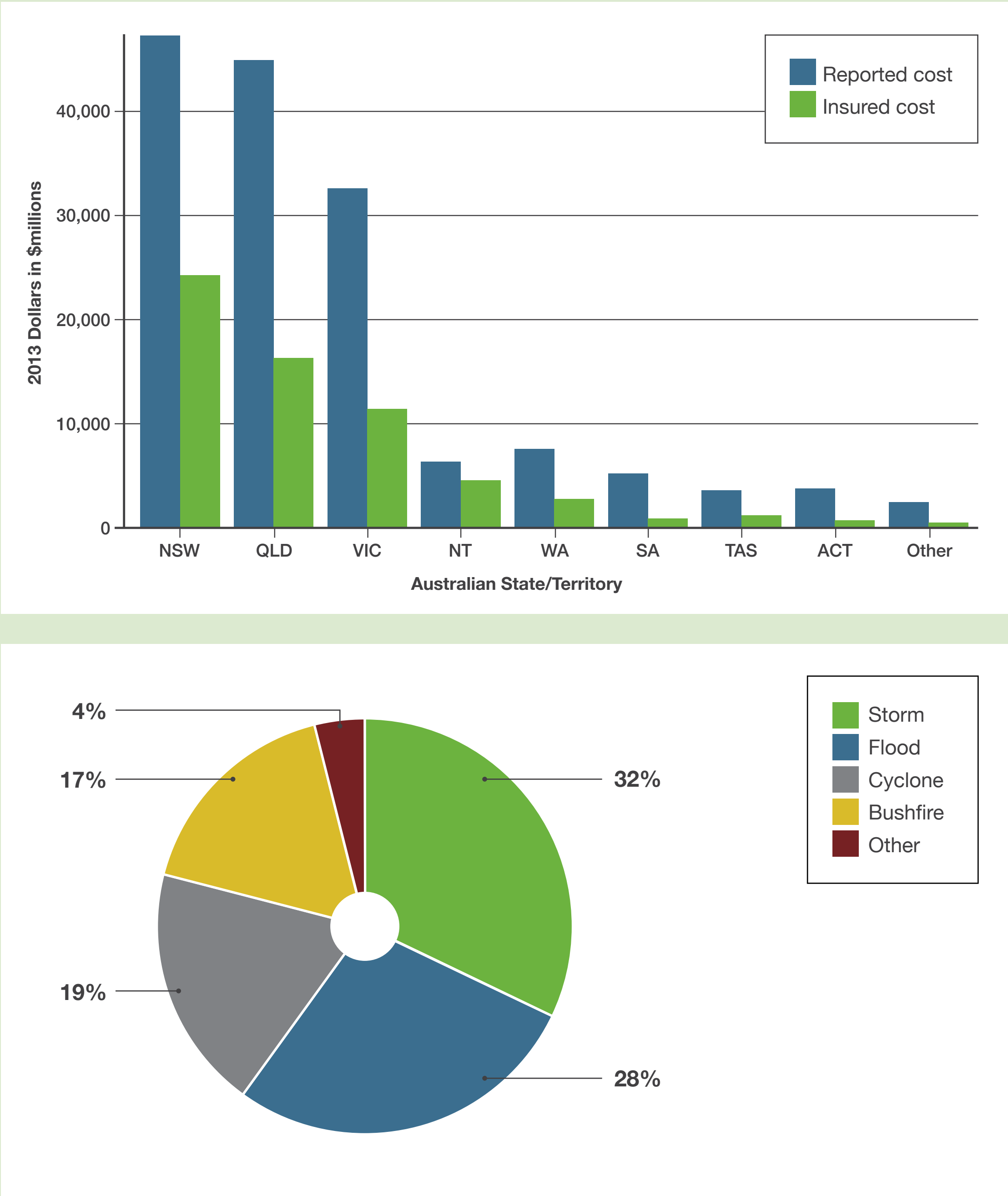


Figure 1. **The attribution of total disaster losses to extreme events in Australia – 1967 to 2013**

Maintenance of buildings – a key post-construction agenda

Maintenance activities are undertaken while the buildings are in use to keep the building performance at a level safe and acceptable to the users. Maintenance activities include periodic and post-event inspections, repairs, replacements, refurbishments and retrofits. Resilience of a building is its ability to survive and be restored after extreme events. Maintenance should be considered as part of the building's durability performance-based design. According to ISO 15928-3:2015, a maintenance schedule is a key component in the description of structural durability performance. Different strategies for maintenance may be adopted, depending on how the building is designed for durability. Maintenance of performance-based design is problematical; for example, the replacement of non-standard and novel products.

The Australian National Construction Code (NCC) currently contains no maintenance provisions as these are principally deemed as post-construction activities. This is a policy decision from the States and Territories (S&T). Maintenance is considered as a S&T responsibility in Australia. All S&Ts have developed their guidelines for the maintenance of essential safety measures. Maintenance for habitability aspects (e.g. aesthetic and comfort) are generally carried out by the building owners or facility/property managers or occupants. Systems and arrangements for preventative maintenance targeting long-term resilience and mitigation are at an infancy stage in many client organisations. Also, in most cases there is generally no maintenance manual for the buildings. While there is considerable information on building maintenance, there is no single source of reference to inform the users, particularly on condition assessment or preventive maintenance for natural disasters such as high winds/cyclones, floods and bushfires.

In 2018, Shergold and Weir reported to the Australian Building Ministers Forum on the effectiveness of compliance and enforcement of the Australian building regulatory system[3]. As per their recommendations, a building manual in digital format is required to be provided which should have: (i) as-built construction documentation; (ii) maintenance requirements; (iii) assumptions made in performance solution; (iv) building product information; and (v) conditions of use. According to the British Research Establishment (BRE) report[4], only 32% of the total building repair cost is spent on making the repairs and the remaining 68% is usually spent on: (i) producing tender documents; (ii) comparing prices (where not covered by a schedule of rates); (iii) placing orders; (iv) checking work in progress; (v) checking work on completion; (v) measuring completed work quantities; (vi) raising invoices; (vii) validating invoices; and (viii) negotiating discrepancies. Efficient and more resilient building stock in the public sector could be achieved through effective procurement arrangements of responsive maintenance with relevant partnering and alliance frameworks.

[3] Shergold, P. and Weir, B. (2018). Building Confidence – Improving the effectiveness of compliance and enforcement systems for building construction industry across Australia – February 2018; https://www.industry.gov.au/sites/g/files/net3906/f/July%202018/document/pdf/building_ministers_forum_expert_assessment_-_building_confidence.pdf

[4] Prior, J.J. and Nowak, F. (2005). Repair it with effective partnering – Guide to contractual relationships for cost effective responsive maintenance, British Research Establishment (BRE) report.

Maintenance and resilience of buildings for bushfire risks

Bushfires are unplanned fires in vegetation areas such as forest, woodland, shrub land, and grassland. In Australia, bushfire risks are critical in dry summer seasons as there is a greater potential for spread of fire from hazards such as burning embers, radiant heat and direct/indirect flame contact. Bushfire occurrence is a recurrent concern in several regions and often results in property damage/ destruction and sometimes in injuries/fatalities.

Bushfire attack mechanisms and building losses

In the event of a bushfire, a building could be ignited by a range of mechanisms:

- Direct exposure to flames from a bushfire – where there is an insufficient set-back distance between buildings and the dominant bushfire vegetation (DBV) such avs forest, scrub, crops or a combination.
- Direct ember attack – which is the most common cause of ignition and loss of buildings due to bushfires. Ember density is directly proportional to the distance between building stock and DBV. Under extreme circumstances, embers can travel a long distance (1 to 10 km). Short distance embers (within 1 km of a fire front) are often found in prolific numbers and tend to have greater impact. Typically this mechanism is responsible for over 90% of ignitions leading to building loss in an urban environment.
- Radiation due to a fire associated with DBV – in which (i) the building vulnerabilities are dependent on radiation exposure and duration of exposure; (ii) the radiation experienced by an object is a function of the temperature of radiant heat source, its geometry and orientation and distance between the object and the radiator; and (iii) the intensity of received radiation is a function of set-back distance, type of vegetation and the flame height.
- Secondary radiation – such as from fire associated with an adjacent building, object or vegetation. If a neighbouring building or object catches fire, then the duration of burning may be between 15 -20 minutes which is significantly longer than the duration of a passing flame front. The resulting radiation may be significant depending on the separation distance between this building/object and the subject building.

Assisted by wind, burning embers, radiant heat and flames may (i) enter the building and directly ignite its contents, (ii) enter the building envelope and ignite combustible elements within the cavities of the building envelope and later ignite the building contents, (iii) cause the building façade or façade elements to break, distort or yield, leading to one of the above processes, and/or (iv) ignite the façade of the building leading to one of the above processes. The combined effects of wind and fire may lead to structural failure well below the ultimate design wind speed, but this has not been investigated in detail anywhere.

Bushfire risk assessment

A building's vulnerability for bushfire risk is dependent on its location and resistance capacity. Several parameters contribute to the location hazard levels and the Bushfire Attack Level assessment procedure of AS3959 is a fair description of the site hazard characteristics for bushfire risks. Property bushfire resistance characteristics depend on the building itself and the surrounding elements such as gardens, fences and combustible materials.

Occupant vulnerability is a key factor in bushfire emergencies. While maintenance can contribute to lowering the risk of ignition for all buildings within the designated bushfire prone areas, 'high risk' buildings, such as hospitals, may need additional consideration such as access, fire-fighting facilities, and evacuation route. Seeking advice from bushfire experts is recommended for complex cases and high risk categories. An example of a Bushfire Risk Assessment is given in *Figure 2*.

Location Hazard vs. Property Bushfire Resistance = Building Vulnerability

Location Hazard	Property Bushfire Resistance		
	High (H)	Medium (M)	Low (L)
High (H)	M	H	H
Medium (M)	L	M	H
Low (L)	L	L	M

Building Vulnerability vs. Occupant Vulnerability = Bushfire Risk

Building Vulnerability	Occupant Vulnerability		
	Low (L)	Medium (M)	High (H)
High (H)	M	H	H
Medium (M)	L	M	H
Low (L)	L	L	M

Figure 2. **Example of a Bushfire Risk Assessment**

Building regulations and standards in Australia

The performance requirements for construction in designated bushfire prone areas (defined in States and Territories Regulations) are in Volumes 1 and 2 of the National Construction Code (NCC). The specific clause from the NCC is: 'A building that is constructed in a designated bushfire prone area must, to the degree necessary, be designed and constructed to reduce the risk of ignition from a bushfire, appropriate to: (a) potential for ignition caused by burning embers, radiant heat or flame generated by a bushfire; and (b) intensity of the bushfire attack on the building.'

The draft NCC 2019 introduces a systematic verification method based on an ignition probability threshold of 10% under the influence of appropriate bushfire design action. By considering the asset perspective and occupancy type, it clusters with importance level (IL) 1 to 4 for determining the bushfire design action assigns an annual probability of exceedance to each IL – e.g. IL = 2 for a small motel or boarding house; IL = 3 for a large hotel; IL = 4 for an aged care building.

Australian Standard AS3959 has outlined a method of determining the Bushfire Attack Level for a site, with a step-by-step procedure including factors such as climate, slope of ground and vegetation variations. In addition, a set of deemed-to-satisfy provisions are available in AS3959 (e.g. for Class 1, 2 and 3 buildings) and in The National Association of Steel-framed Housing (NASH) Standard (e.g. for Class 1 and 10a).

Maintenance for improved bushfire resilience of buildings

Maintenance has a key role in reducing the risk of ignition due to ember actions. Gaps around the edges of the roof or along the roof's ridge, eaves and roof line provide pathways for the entry of embers into a roof space. The same is true with respect to ventilation openings into spaces below suspended floors, if there are combustible surfaces against which embers can accumulate. Open vents can also allow the entry of embers into the interior space, and evaporative coolers, due to their combustible filters, are susceptible to ember attack, especially if they are not operating at the time of the fire and the filters are dry. The accumulation of embers against exterior combustible surfaces can also result in ignition. Gaps greater than 3 mm are sufficient to allow the entry of some types of ember. Hence the standard requirement to have vents and weep holes screened with metal mesh with a maximum aperture of 2 mm unless they have an aperture less than 3 mm. The external facade shall be prevented from having gaps greater than 3 mm. Doors and windows in bushfire risk zones are required to have a protective metal mesh with maximum aperture of 2 mm. A set of useful inspection points consolidated from the literature follows:

- External ignition points such as timber decks, eave fascia boards and/or gutters, timber window frames, timber stairs, timber door frames, red cedar cladding, gapped board around stumps, exposed timber beams, timber wall frames, doormats, fabric veranda roofs, timber shingle roofs, plastic roof panels, veranda/pergola, timber framing behind air conditioning units, bitumen roof membranes, canvas awnings and weather boards.
- Ember entry points such as door jams, windows that are not tight-fit, flues and chimneys, gaps in roofing or flooring systems and gaps in building facades
- Ember accumulation points such as re-entrant corners, roof valleys, gutters, unprotected sub-floor areas, wall/roof cavities, under decks and between decking boards above bearers, door thresholds and window frames.

Recommendations to enhance maintenance and resilience of buildings for bushfires

1. All buildings in designated bushfire prone areas should be maintained to reduce the risk of ignition due to ember attack.
2. An integrated database of critical maintenance items for buildings and their surrounding areas should be established. In addition, a list of key maintenance items for bushfire risks should be compiled for each individual building.
3. For high risk buildings, relevant bushfire experts should be consulted for more accurate assessments and suitable measures to lower the risks for the building and its occupants.

Maintenance and resilience of buildings for flood vulnerabilities

Floods are common and recurrent extreme events in all States and Territories in Australia. The Bushfire and Natural Hazard Cooperative Research Centre has reported that floods are the most financially costly and the second deadliest natural hazard in Australia. The complexities and uncertainties of flood risks are diverse in Australia, including the effects of variable rainfall, climate change and cyclones, across more than eight climatic zones[5].

Flood types impacting buildings include:

- Fluvial (river) flooding – when a watercourse swells due to heavy and/or prolonged rainfall.
- Pluvial flooding – when substantial water pools on the ground or is unable to drain away.
- Closed-basin flooding – when a closed body of water receives excessive runoff.
- Flash flooding – when a rapid overland flow of water occurs due to high intensity rainfall.
- Sewer (drainage) flooding – when pipes and sewers are not adequate to cope with rainfall.
- Coastal flooding – when inundation of land occurs in coastal regions due to storms or high tides.
- Groundwater flooding – when ground water levels rise above the surface.

Flood impacts and building damage

Natural floods and water ingress vulnerabilities from high winds such as severe storms and cyclones cause significant damage to low-rise buildings in Australia. The tangible impacts are mainly acute/short-term damage and chronic/long-term deterioration. Intangible impacts include the stress of dealing with builders/repairers/insurers, emotional losses and fear of resilience for future floods.

Floods can damage structures and non-structural components of buildings due to a range and combination of flood forces/actions including:

- Hydrostatic forces and resultant actions
  - Lateral pressure; e.g. when water rises on one side of a structure, such as a wall
  - Capillary rise; e.g. when capillary action causes upward movement of dampness/wetness
- Hydrodynamic forces and resultant actions
  - Lateral pressure caused by water flowing around a building
  - Suction by localised changes in velocity/pressure; e.g. around corners and through gaps
  - Turbulence due to irregular fluctuations in velocity
  - Breaking and non-breaking waves
- Buoyancy and resultant actions; the whole building or its components float or cause other damage
- Impact forces of floating debris and resultant actions
  - Static actions; e.g. sediment accumulation inside or outside the building
  - Dynamic actions; including concentrated and distributed forces
  - Erosion actions; e.g. associated with dragged soils/gravels/other debris
- Non-physical actions; such as chemical (e.g. rust and corrosion of reinforcement) and biological elements (e.g. mould by singular/ multicellular fungi and timber decay)

[5] The Australian Building Codes Board (ABCB) mapped the states and territories of Australia into eight climate zones for the National Construction Code - i.e. (1) High humidity summer, warm winter; (2) warm humid summer, mild winter; (3): hot dry summer, warm winter; (4) hot dry summer, cool winter; (5) warm temperate; (6) mild temperate; (7) cool temperate; and (8) alpine.

The extent and duration of flood exposure as well as the condition of a building can sway the risk of damage. Typical types of building damage from flood impacts include:

- Damage to foundations from geotechnical/soil failures.
- Damage to walls and building components; e.g. cracks, dampness, warping, flaking and lifting.
- Damage to floors; e.g. lifting of flooring, decay of joists, springy boards, sub-floor moisture.
- Damage to utilities and non-structural components; e.g. HVAC (heating, ventilation and air conditioning), plumbing, electrical and mechanical systems.

Multi-hazard occurrences can enhance the risk levels; for example, flood after cyclone/windstorm, flood after flood, flood after fire, flood after mudflow and flood after a hailstorm. Climate change effects may further increase flood occurrences and associated risks. Increased demand for new housing and non-residential buildings may increase pressures to build in areas at risk to floods.

Figure 3 illustrates considerations in enhancing building resilience to flood risks.

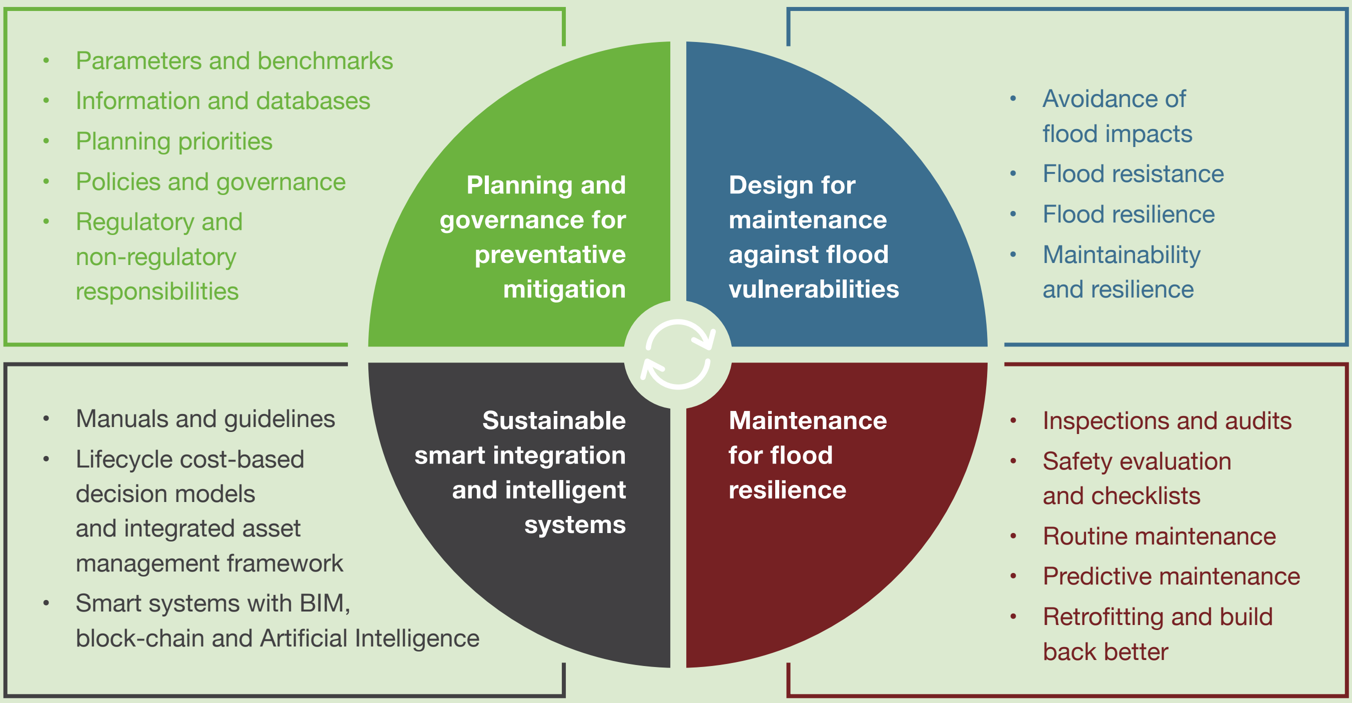


Figure 3. **Enhancing building resilience to flood risks**

Planning and governance for preventive mitigation

Useful parameters and benchmarks for planning buildings resilient to flood hazards include: Annual Exceedance Probability, Australian Height Datum, Probable Maximum Flood, Defined Flood Event and Flood Planning Level. References for planning and estimating riverine/coastal flood vulnerabilities include the HAZUS flood technical manual[6]. Additional benchmarking references for resilience planning include the European Union Floods Directive, UK Environment Agency report on National Flood and Coastal Erosion Risk Management Strategy, UK House of Commons reports on Future Flood Prevention[7] and Flood and Water Management Act 2010[8], and the USA Federal Emergency Management Agency Policy Standards for Floor Risk Analysis and Mapping.

Design for maintenance against flood vulnerabilities

Design strategies for avoiding flood impacts on buildings include: (i) siting, site layout and elevating land; (ii) preventive landscaping and surrounding improvements; (iii) drainage and soak-away systems; (iv) impermeable boundary walls; (v) raising the lowest floor level of a building with a threshold height above the likely design flood level.

Designing for maintainability will enhance the resistance and resilience of buildings against flood risks. Some noteworthy points consolidated from the recent literature include:

- Building design in flood hazard areas should conform to requirements and guidelines such as ABCB[9] and ASCE/SCI 24-14[10].
- It will be valuable to consider performance-based flood design in accordance with standards and guidelines such as ASCE/ SEI 24-05, FEMA 543, FEMA P798 and FEMA P 424.
- Roof drainage design should consider the effects of duration, intensity and frequency of rainfall, and design rain loads and secondary roof drain data.
- Primary drainage systems shall be designed for a rainfall intensity equal to or greater than the 60-min duration/100-year return period (frequency) storm (ASCE7-16).
- The 2015 International Plumbing Code requires the use of 100-year return period/60-minute duration for the design of both the primary drainage system and the secondary drainage system. From a structural engineering standpoint, the critical duration for most roof geometries (the duration which maximises the hydraulic head) is closer to 15 minutes than 60[11].

[6] FEMA (2011). Multi-hazard loss estimation methodology flood model Hazus®-MH 2.1 Technical Manual. Federal Emergency Management Agency, Washington, DC, USA.

[7] HC (2017a). Future flood prevention: Government's response to the Committee's Second Report of Session 2016-17. House of Commons (HC) – Environment, Food and Rural Affairs Committee, UK.

[8] HC (2017b). Post-legislative scrutiny: Flood and Water Management Act 2010. House of Commons (HC) – Environment, Food and Rural Affairs Committee, UK.

[9] ABCB (2012a). Construction of buildings in flood hazard areas, Version 2012-2, Australian Building Codes Board (ABCB), Australia; ABCB (2012b). Standard for construction of buildings in flood hazard areas 2012 – Australian Building Codes Board (ABCB), Australia.

[10] ASCE (2014). Flood resistant design and construction, ASCE Standard ASCE/SCI 24-14. American Society of Civil Engineers (ASCE), USA.

[11] Chock, G., Ghosh, S.K., O'Rourke, M., and Stafford, T.E. 2018. Significant changes to the minimum design load provisions of ASCE 7-16, ASCE Press.

- Each portion of a roof shall be designed to sustain the load of all rainwater that will accumulate on it, if the primary drainage system is blocked, plus the uniform load caused by water that rises above the inlet of the secondary drainage system at its design flow (ASCE7-16).
- If the secondary drainage systems contain drain lines, such lines and their point of discharge shall be separate from the primary lines. The total head corresponding to the design flow rate for the specified drains shall be based on hydraulic test data[12].
- Where a roof drain is installed in a sump pan located below the adjoining roof surface, reductions in hydraulic head and rain load on the adjoining roof should only be credited when based on hydraulic analysis from a qualified plumbing engineer. (ASCE 7-16)
- As water accumulates, roof deflection allows additional water flows. If the structure does not possess enough stiffness to resist this, failure by localised overloading may result (ASCE 7-16).
- For existing buildings in a high-risk category, suitable retrofitting and design improvements should be adopted, including elevation, relocation, flood proofing and barriers[13]

Maintenance for flood resilience

Factors influencing building maintenance for flood resilience include: type of material and construction; age of the building; design and height; attached equipment, annexures and non-structural/utility fixtures; influence of regulatory policies and regimes; condition of the building; current and intended purpose; documentation (e.g. format, detail, quality); location and extreme event exposure; social factors; economic factors (e.g. lifecycle costs); safety and health aspects; environmental and energy/resource aspects; materials, including spares; workforce (e.g. availability, cost, knowledge and skills, workmanship, integrity/trust). Repairing and maintaining flood-damaged buildings is generally a reactive maintenance strategy. Safety evaluation is a critical requirement before repairing flood damage. Establishing inspection contexts and checklist items would be relevant for proactive maintenance of buildings for flood resilience[14].

[12] Chock, G., Ghosh, S.K., O'Rourke, M., and Stafford, T.E. 2018. Significant changes to the minimum design load provisions of ASCE 7-16, ASCE Press.

[13] FEMA (2014). Homeowner's guide to retrofitting - six ways to protect your home from flooding, FEMA P-312: 3rd Edition, Federal Emergency Management Agency, Washington, DC, USA.

[14] Useful reports include:

ATC (2004). Field manual: safety evaluation of buildings after windstorms and floods, ATC-45, Applied Technology Council, California, USA.

Bravery, A.F., Berry, R.W., Carey, J.K., Cooper, D.E. (2003). Recognising wood rot and insect damage in buildings, BR 453, British Research Establishment, UK.

BRE (1997a). Repairing flood damage: immediate action, Good Repair Guide 11 – Part 1, British Research Establishment, UK.

BRE (1997b). Repairing flood damage: ground floors and basements, Good Repair Guide 11 – Part 2, British Research Establishment, UK.

BRE (1997c). Repairing flood damage: foundations and walls, Good Repair Guide 11 – Part 3, British Research Establishment, UK.

BRE (1997d). Repairing flood damage: services, secondary elements, finishes, fittings, Good Repair Guide 11 – Part 4, British Research Establishment, UK.

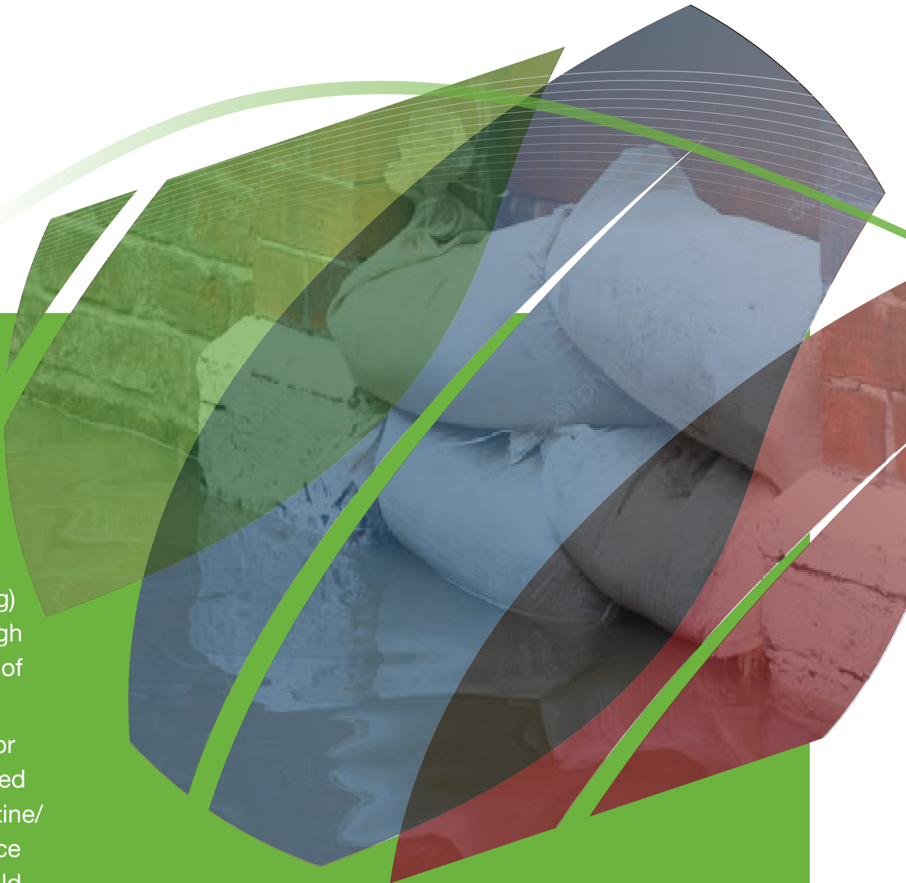
BRE (2006). Repairing flooded buildings – an insurance industry guide to investigation and repair. Flood Repairs Forum, BRE Press, British Research Establishment, UK.

The literature review, brainstorming discussions and consultations with industry partners and stakeholders associated with this research revealed the following key points:

- Routine inspection and maintenance for flood resilience of buildings could be a shared responsibility at appropriate levels relevant to all related parties.
- Developing maintenance manuals for flood resilience of buildings and a library/knowledge portal of maintenance checklists would be useful.
- Routine maintenance could target value procurements with performance specifications.
- Standardisation and certification of flood resilience materials and flood protection products, would enhance the reliability of maintenance and the effectiveness of inspections.
- Education and training across the maintenance supply chain (e.g. repairers) is needed.

Sustainable smart integration and intelligent systems

Predictive maintenance can yield the best value and sustainable resilience of buildings against natural hazards such as floods. However, developing predictive maintenance systems for practical use requires significant quality datasets of independent and dependent parameters and variables of building stock maintenance. It would be useful to link predictive models with integrated databases of building assets with 'as built' information, condition assessment (periodical and post-flood) and cost data (maintenance, repair/retrofit, lifecycle). The maintenance decisions for flood hazards need to be rationalised through integration of building information modelling (BIM), discrete and real-time monitoring frameworks, advanced data analytics and artificial intelligence (AI) including machine learning and deep learning systems.



Recommendations to enhance maintenance and resilience of buildings for flood risks

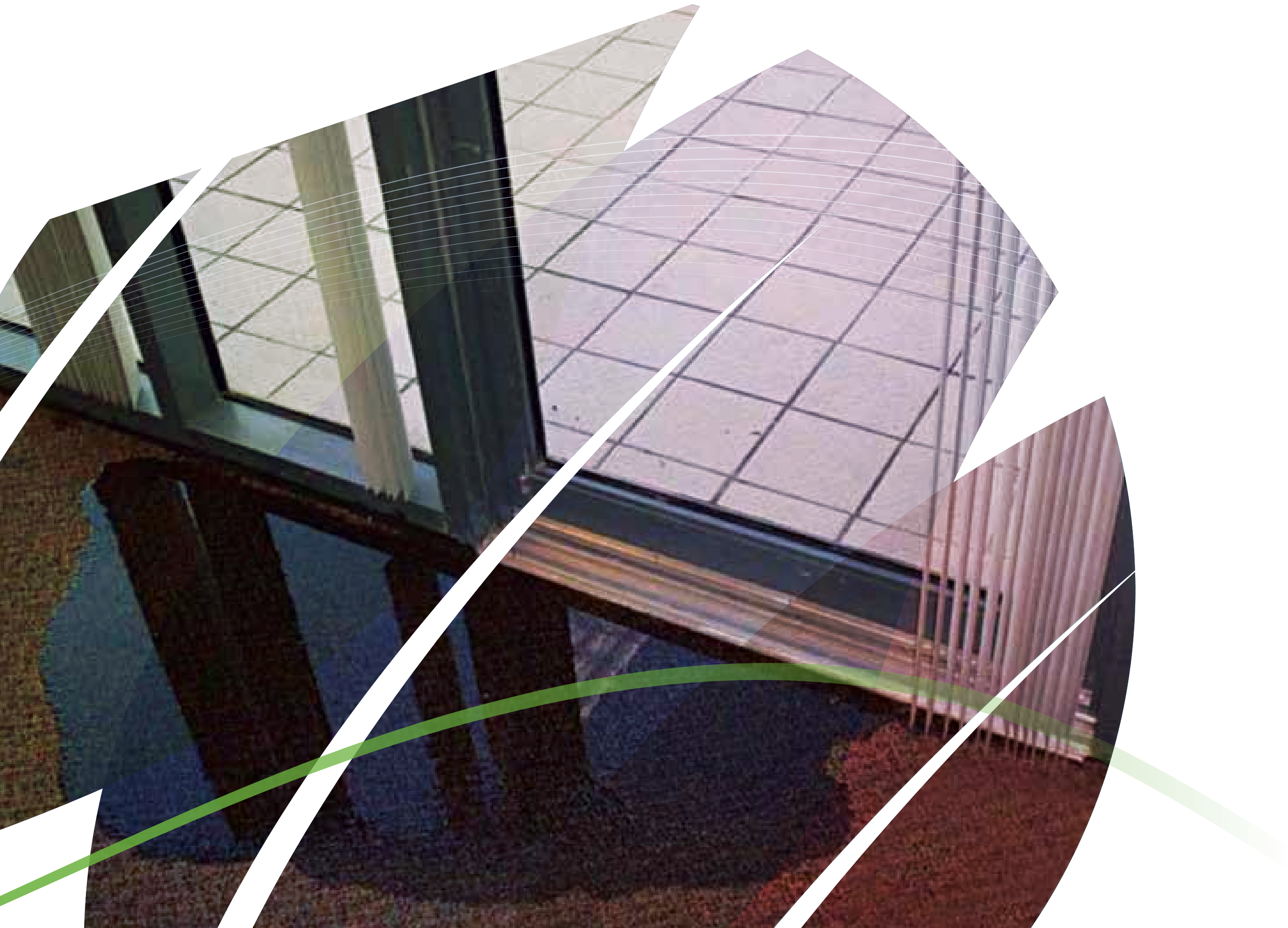
1. All properties (including buildings and landscaping) in flood prone areas should be maintained through continuous monitoring and routine maintenance of critical components.
2. Maintenance checklists of critical components for the properties should be developed and integrated with appropriate databases and systems for routine/continuous condition monitoring and maintenance decisions for flood resilience. The checklist should cover all building structural elements, finishes, utilities and non-structural fixtures and landscaping within the property.
3. Strict regulatory controls for building permits and ‘mature’ governance of maintenance for flood resilience need to be developed.
4. All new designs should include responsible design for maintainability embracing flood resistance and/or flood resilience aspects. Responsive construction/maintenance should be considered, embracing relevant flood resilient technologies and materials in new constructions and retrofitting of existing constructions for resilience.
5. Flood resilience planning agendas should be developed for new development and maintaining existing building assets.
6. A ‘smart’ systems approach with development of maintenance manuals, smart systems and integrated databases linked with building information and lifecycle cost-based predictive/decision-support models is required for futureproofing resilience for flood vulnerabilities.
7. As a non-mandatory arrangement for foolproof flood resilience, certifications for the maintenance supply chain and flood resilience products/materials could be considered.

Maintenance prevention strategy to mitigate wind-driven rainwater ingress through windows and external glazed doors in social housing

The building envelope consists of various elements that have to work together in order to protect the structure against rain, wind, sleet and snow. In coastal cities and towns in northern Australia, windows and external glazed doors in buildings are particularly vulnerable to recurrent serviceability failure caused by wind-driven rain during cyclone events. Maintenance prevention strategies are particularly important for government infrastructure and building assets, since government is responsible for the lifecycle maintenance of these. Maintenance prevention strategies at the design, construction and inspection stage of building procurement are the missing links to improving resilience.

To develop a maintenance prevention strategy, first a literature review identified the failure modes of residential buildings from cyclones and high winds. Subsequent data collection included workshops and phone interviews with design and construction professionals from manufacturing and building firms, inspection firms and window installers, as well as government. Thematic analysis of the workshops and interviews identified a number of contributing factors to the susceptibility for wind-driven rainwater ingress through windows and external glazed doors in social housing.

The research team also explored the standard of design and as-constructed documentation, installation quality, inspections regimes, Australian standards, and the knowledge and training of window installers. The findings indicated that the current glazing process is sometimes of insufficient quality, resulting in recurrent repairs and the overall lower quality of the construction. There is little opportunity for government representatives to inspect and assure work quality with the current standard of documentation and during the preparation and installation currently provided.



Core recommendations for prevention strategies to mitigate wind-driven water ingress

Seven core recommendations were developed:
(1) construction documentation (including drawings and specifications) (CD);
(2) contract documentation;
(3) preparation and installation procedure;
(4) auditing checklist (AC);
(5) installation quality form (IQF);
(6) openings certificate (OC);
(7) auditing checklist grade (AC grade).

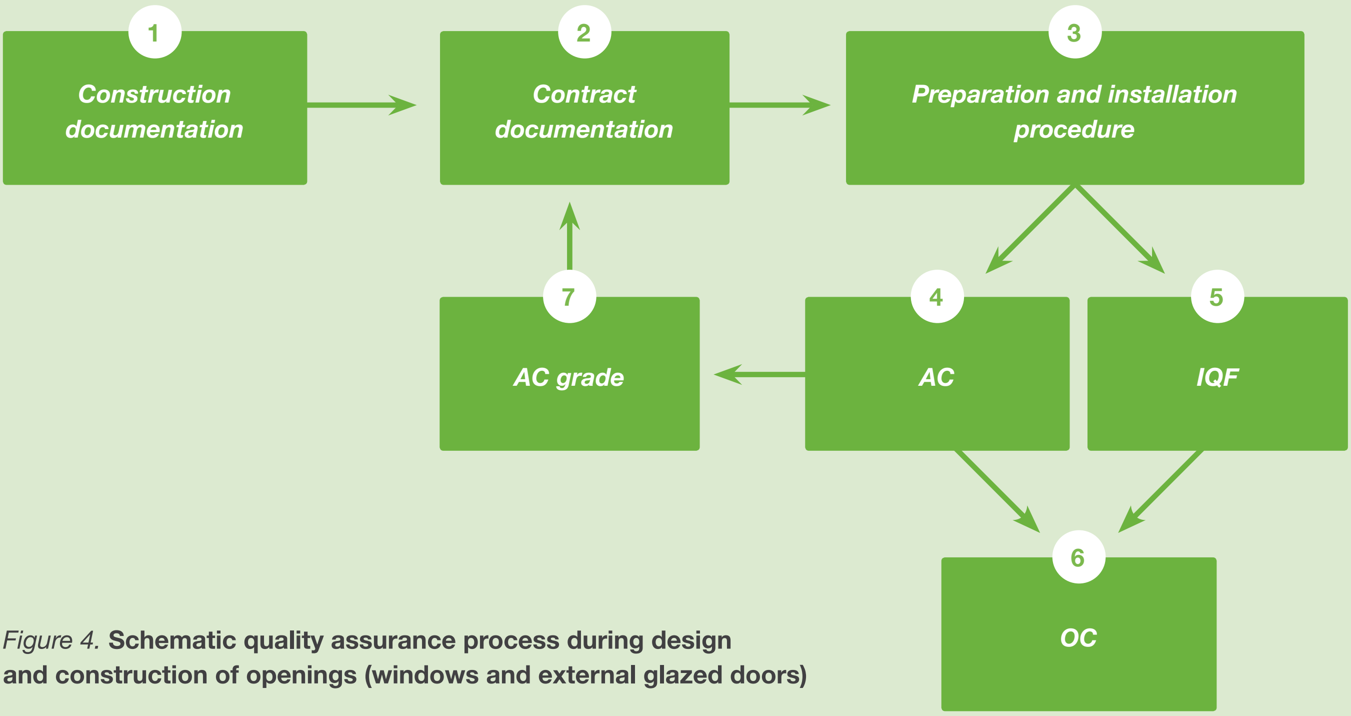


Figure 4. **Schematic quality assurance process during design and construction of openings (windows and external glazed doors)**

Quality assurance process using a social housing example

1. ***Construction documentation:***

   Social housing projects are often procured through *'Construction only'* or *'Design and Construction'* processes. The recommended quality assurance process (Figure 4), has to adapt the order of items 1 and 2 according to these processes. For 'Design and Construction', Contract documentation is before Construction documentation, but for 'Construction only', the process is reversed. Research indicated that the move towards 'Design and Construction' procurement has resulted in poorer quality design and as-constructed information being produced by contractors. The industry workshops revealed the need for: (a) improved documentation and (b) providing more specific information on detailed requirements from the contractor within the tender documents.

   For *'Design and Construction'* arrangements, it is recommended that either: (a) that process be limited to projects where detailed documentation is not required; or (b) the building contractor be required to provide fully detailed construction documentation and specifications for the documentation stage and for as-constructed records on handover of the project.

   For *'Construction Only'* projects: (i) the client should ensure that fully detailed construction documentation and specifications are provided in the documentation stage; and (ii) the builder is required to provide as-constructed records on handover of the project including detailed design documentation and specifications to describe the installation of windows and external glazed doors. Specifically, thorough construction documents for windows and glazed door openings are required for the buildings in wind regions C (ultimate design wind speed 232.2 kilometers/hour) and D (ultimate design wind speed 318.8 kilometers/ hour) as per the Australian Standards AS/NZS 1170:2:2002. The design specifications for construction and maintenance should cover: (a) durability and compatible sealants; (b) preparing the substrate; (c) preparing the opening with appropriate membrane system; (d) curing; (e) head, side angle flashing, sub-sill and dam ends; (f) flashings, drip moulds, storm moulds and trims; (g) fasteners; and (h) storm shutters.

2. ***Contract documentation:***

   The tendering process should include the recommended quality assurance process within the contract for all forms of procurement. The contract requires agreement between both the client and contractor. The contract should describe a quality assurance process relating to the preparation and installation of windows and external glazed doors in an effort to increase quality and direct liability in the construction phase. The contract should include preparation and installation procedures for windows and external glazed doors as well as IQF, AC, OC and AC grade. This recommendation should apply to all contract types; i.e. both Construction contracts, and Design & Construct contracts.

3. ***Preparation and installation procedure:***

The preparation and installation procedure of windows and external glazed doors to masonry openings is detailed in two stages as shown below, with further detail in the Project Research Report Part 4.

Stage 1 – Openings preparation

(i) Ensure all primer, waterproofing membrane and sealants are compatible before installation.

(ii) Prepare the substrate in accordance with AS 4654.2 and Australian Window Association to provide appropriate fall as per design (minimum 15 degrees as per AWA).

(iii) Ensure opening is clean, dry and free from debris.

(iv) Provide a continuous water-stop throughout the perimeter of the opening.

(v) Prepare opening with appropriate primer and waterproofing membrane system in accordance with AS 4654.2. Multiple layers of membrane should be applied to ensure membrane is free from any holes or gaps that will allow water to penetrate the substrate. Ensure membrane has no gaps and extends at least 200 mm past the opening.

(vi) Components of membrane systems shall be cured as per manufacturer specifications. Curing times between applied membrane coatings should be taken into account.

(vii) Install appropriate specified sub-sill, angled metal dam ends, head drip moulds and side angles, noting that the head-sill, side angle and flashings must be directed to flow into the sub-sill without any obstructions and the back and end dams provide additional water-stop.

(viii) Ensure approved primer and sealant is used for a water-tight seal and appropriate corrosion resistant fasteners are used as per specified wind load or engineer's specifications. Fasteners must be over and under-sealed to prevent moisture penetrating the opening. Allow appropriate clearances for thermal expansion and free flowing drainage.

Stage 2 – Openings installation

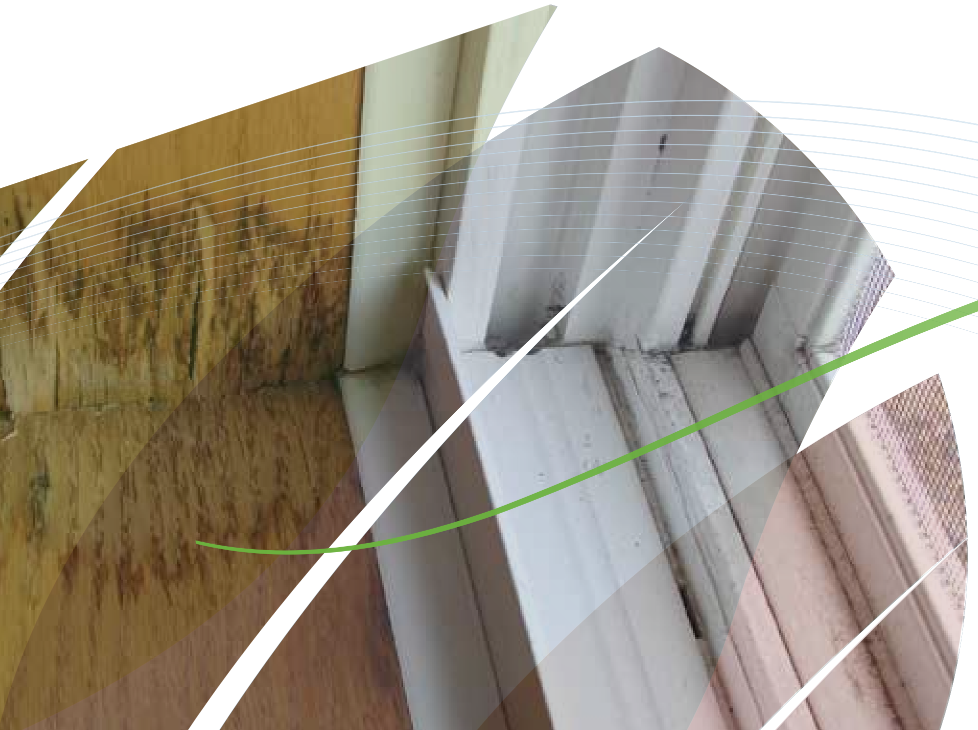
(i) Ensure the correct window and door specifications for terrain category and building height .

(ii) Ensure weep holes are free from debris and are free flowing.

(iii) Install window and door and frame to the opening as per manufactures specifications.

(iv) Ensure appropriate specified flashings, mouldings and trims are installed to ensure the prevention of water ingress.

(v) Storm shutters and awnings are to be installed as per manufactures specifications.



4. ***Auditing Checklist (AC):***

The Auditing Checklist for a building has to be completed during the inspection of windows or external glazed doors by superintendents. The objective is to check they are installed adequately and note a relevant grade (i.e. Satisfactory/Unsatisfactory). Another objective is to place responsibility and liability on contractors and superintendents. The AC is to be completed by the superintendent, accompanied by the supervisor responsible for the activity. The AC is completed at two stages: (i) upon completion of the opening membrane and flashing system; and (ii) on completion of the glazing installation. The superintendent should give reasonable notice (e.g. 2 weeks) to the primary contractor before performing the AC. A building certifier may also inspect building work at any time, whether or not the certifier is given a notice for an AC for the work. The number of windows and external glazed doors to be checked on site will be a minimum of 25%, identified by a unique identification tag or sticker. An Installation Quality Form (IQF) completed by the primary contractor will display a unique sicker to ensure the appropriate number of inspections occur evenly over all levels of the building. The frequency will vary according to the site schedule and each opening will have its own independent check list.

AC - Auditing Checklist

Use this checklist to help identify potential water Ingress risks that may be caused by an insufficient waterproofing membrane and flashing system. This inspection is to be carried out after the opening has been prepared for the installation of the window or door.

To: .... ***Attn:*** .... ***Date:*** ....

Project: .... ***Project No.:*** .... ***Time:*** ....

Issued By: .... ***Received By:*** .... ***Comments:*** ....

Superintendent

	MEMBRANE & FLASHING SYSTEM	YES	NO
1.	Adhesion of waterproofing membrane	☐	☐
2.	Waterproofing membrane termination	☐	☐
3.	Sealants, over sealing & adhesion	☐	☐
4.	Minimum falls in substrate	☐	☐
5.	Continuous water stop	☐	☐
6.	Sub head & sub sill	☐	☐
7.	Dam ends	☐	☐
8.	Appropriate drip moulds & flashing	☐	☐
9.	Fasteners	☐	☐

Further information provided below:

1. Check waterproofing is free from protrusions & voids. Check adhesion with sealants & substrate.
2. Check waterproofing membrane cover (minimum 180mm).
3. Check adhesion with waterproofing membrane and substrate. Ensure the over sealing of fasteners.
4. Check fall are in accordance with AS 4654.2.2012 (minimum 1:100).
5. Check water stop provided (Rebated and/or fixed metal angle).
6. Check sub sill up & down turn flashing heights and sealant are sufficient.
7. Ensure dam ends have sufficient sealing and allow for drainage.
8. Ensure the flow of water down he building is directed away from openings below.
9. Check the amount & fasteners used are appropriate for the region.

Further Comments:

Figure 5. **Auditing Checklist (AC)**

[15] Build Back Better in recovery, rehabilitation and reconstruction (2017): https://www.unisdr.org/files/53213_bbb.pdf

5. ***Installation Quality Form (IQF):***

   The primary contractor is responsible for completing the IQF in conjunction with relevant installation documentation (e.g. in Queensland – Form 16) and providing this to the superintendent. For visual evidence, the IQF should include photographic documentation of each completed stage of the installation. It is recommended that (a) the number of windows and external glazed doors documented is a minimum of 25%; and (b) an indicator tag/ sticker is allocated once the opening has been documented. The objective of the IQF is to (a) check whether the external openings are installed satisfactorily and (b) raise liability and responsibility for contractors/builders in placing sufficient attention to windows and external glazed doors as a building element that is significantly important to the building envelope.

6. ***Openings Certificate (OC):***

   Once the AC and IQF have been completed, the superintendent provides the Openings Certificate (OC) to the contractor. The aim of the OC is similar to that of the AC and the IQF, in that it documents responsibility for the information provided from both the contractor and superintendent. For all building projects located in Wind Regions C and D, the AC and IQF together will have to document 50% of the openings of the project. Also, the approach could be considered for all building projects where vulnerability to wind-driven rain has been identified (e.g. coastal high-rise buildings). For example, in the Queensland Form 16, the addition of the AC and IQF in item ‘4 Description of component/s certified’.

7. ***Auditing Checklist grade:***

   The AC grade highlights the importance of providing a satisfactory installation to mitigate the potential for water ingress. It is recommended to implement the AC and the IQF for different activities during the construction process and use the results as quality indicators of the as built construction and in subsequent tendering. Where tenderers have a poor record of providing quality construction, they will receive poor experience ratings for subsequent government tenders. This grade is provided for each of the primary contractors and should be reviewed on acceptance of the tendering process.

Other recommendations:

The following recommendations are to the wider industry and not within the control domain of the Project’s industry partners:

- *Australian standards:* The ‘openings’ standard for Australia is AS 2047 – 2014. The water penetration resistance test described in AS/NZS 4420.1:2016 occurs under static wind load in which the test specimen is subjected to water sprayed uniformly and continuously over the exterior face. The Cyclone Testing Station (CTS) at James Cook University is conducting tests to replicate high dynamic range (HDR) pressure consistent with cyclonic pressure. Their preliminary findings indicate that static pressure water penetration tests are inadequate for characterising cyclonic events and most windows would have some form of water penetration during cyclone conditions. The CTS may propose new requirements for AS 2047-2014 and AS/NZS 4420.1:2016.
- *Knowledge transfer and education:* Special emphasis and additional efforts should be placed on educating builders and installers on the importance of quality installation of windows and glazed doors in order to reduce the life-cycle maintenance costs of buildings. The Australian Window Association (AWA) provides industry training to improve familiarisation with relevant windows and glazed doors installation. The Australian Institute of Waterproofing (AIW) provides industry training to improve familiarisation with waterproofing systems. While there are courses and online materials available, installers in regional northern Queensland may not be receiving adequate training on the latest best practice installation and waterproofing procedures.

Recommendations from SBEnrc Project 1.53

1. **A maintenance schedule for building assets should be provided as part of the design for durability.**

   This could allow different strategies for maintenance to be considered as part of service life planning (e.g. replacement of parts and the frequency of inspection); and it could facilitate maintenance actions by providing safe and easy access to components that require maintenance.

2. **A maintenance manual for each building should be made available for the people responsible for its maintenance.**

   Public building assets are wide ranging and diverse. Each building is exposed to different kinds and levels of hazards that will require different kinds of maintenance actions. This is particularly relevant to public assets where personnel changes make it difficult to track how decisions are made and systems are maintained over the service life of the building.

3. **Accurate as-built documentation should be made available for maintenance purposes.**

   It is difficult to maintain buildings without reliable as-built documentation. While design documentation is generally available, as-built documentation is difficult to compile because many changes are made during construction that are difficult to keep track of.

4. **Routine maintenance inspections should be used to detect prevailing and new emerging risks to building resilience.**

   For the building assets, routine maintenance inspection reports used to initiate maintenance actions can also be used to detect signs of emerging risks. This should only be used as a preliminary scan to initiate further investigation, as the causes of emerging risks are often complex.

5. **An appropriate procurement framework for responsive maintenance should be developed.**

   Developing appropriate procurement arrangements with suitable partnering/alliances and frameworks for responsive maintenance should be considered to enhance the efficiency of outcomes and add value. Responsive maintenance might be through employing performance specifications-based organisation of direct labour and/or contractors. For example, a framework of performance-based target cost alliances with appropriate ‘pain and gain’ sharing is relevant for long term maintenance of certain assets or earmarked key components of building stock.

6. **‘Build back better’ for sustainable resilience against natural hazards.**

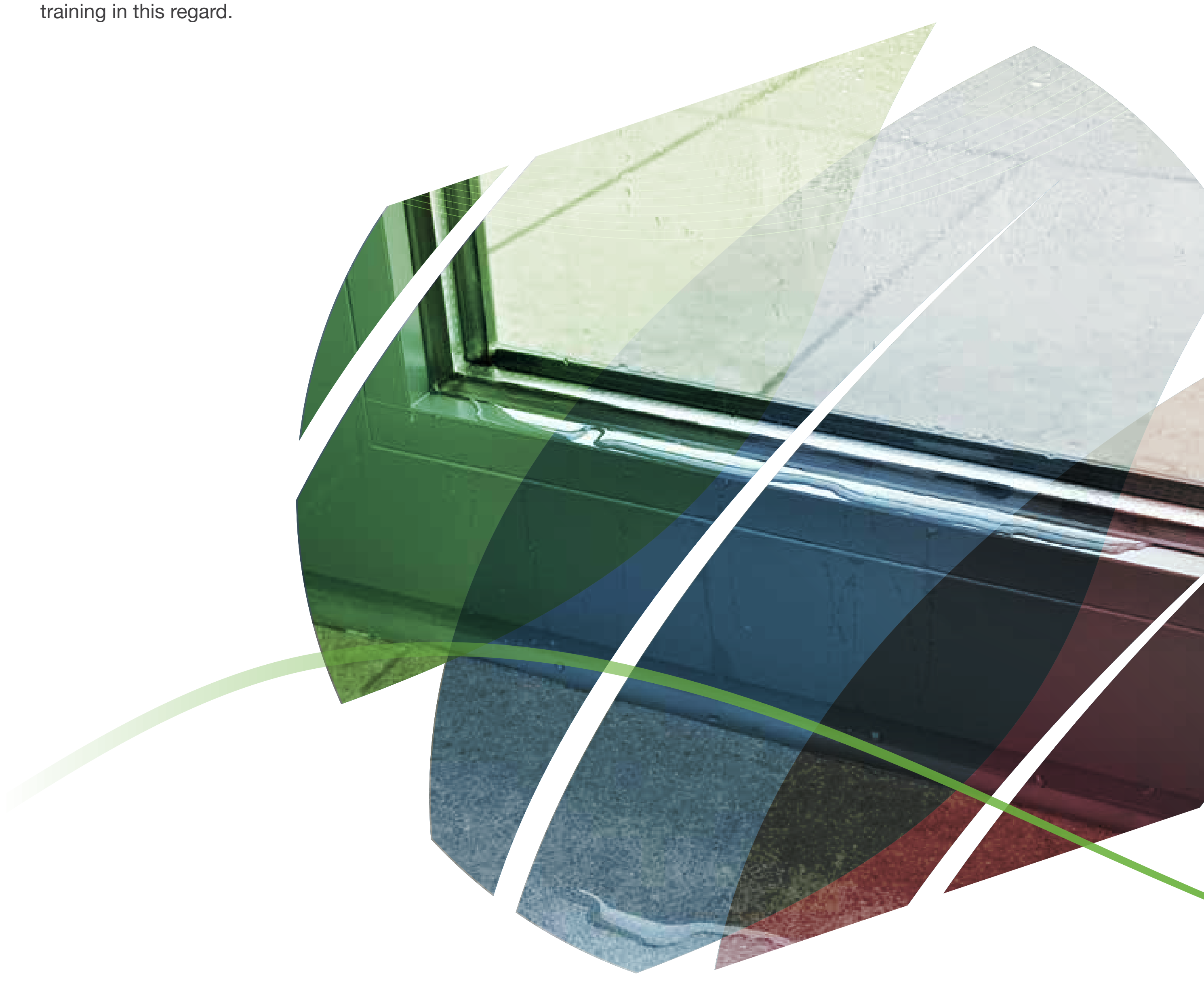
   The ‘build back better’ for sustainable resilience concept of the United Nations Office for Disaster Risk Reduction[15] should be integrated into suitable repair, renovation, retrofit and reconstruction situations. Any occurrence of major repair/ renovation/ retrofit/ reconstruction of buildings or key components provides valuable opportunities such as: (i) potential foolproof prevention of subsequent mitigation requirements for resilience of buildings against disaster risks; and (ii) possibilities for enhancing the sustainability futureproofing.

7. **Establish maintenance responsibilities for whole-of-life value and sustainability.**

   Relevant mandatory and non-mandatory responsibilities aimed at whole-of-life value and sustainability should be established for the property owners, occupants and stakeholders. For this, critical requirements include: (i) improved understanding (e.g. through extensive research) on lifecycle costs of all common building types and key components; (ii) appropriate regulatory and governance frameworks; (iii) checklists and guidelines for non-mandatory responsibilities of different parties; (iv) relevant arrangements for education and training in this regard.

8. **Develop smart infrastructure with advanced digital integration for efficient maintenance and effective resilience.**

   Developing smart infrastructure with advanced digital integration should be considered to enhance the efficiency of maintenance activities and effectiveness of resilience outcomes. The key opportunities identified in this regard is integration of Building Information Modelling (BIM), facility/asset management systems, embedded real-time condition monitoring hardware and software, smart analytics and intelligent systems with block-chain cryptography.



A framework for specifying building maintenance

To implement these recommendations a 'Framework for specifying building maintenance' could be created. Specifying maintenance involves work at all levels from design and construction to specific maintenance actions. It could be designed to cover new buildings and/or existing buildings involving one or all three types of maintenance (essential safety measures, habitability and preventive). An individual building manual for a specific building could be compiled from information provided in the Framework. For example, a non-mandatory framework for existing buildings might contain the following components:

(i) A protocol for compiling a specific building maintenance manual.

(ii) A protocol for regular building inspection and reporting.

(iii) As-built record of elements that may require maintenance or may be affected by maintenance actions.

(iv) A maintenance schedule, including the required maintenance level and frequency.

(v) If a performance-based design was used, assumptions made in deriving the performance solution relevant to the maintenance.

(vi) Lifecycle assessment and deterioration modelling of key components of building assets.

(vii) Building product information relevant to maintenance (and basic procurement/supply chain information).

(viii) Maintenance checklists (if relevant) for: (a) earthquake; (b) bushfire; (c) flood; (d) high winds and cyclones (including water tightness of openings); and (e) hailstorms.

"We receive detailed maintenance advice and schedules for most assets we purchase except our most valuable built assets that are also the most vulnerable to extreme weather events."

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This research would not have been possible without the ongoing support of our core industry, government and research partners:

Find out more:

Project webpage: https://sbenrc.com.au/research-programs/1-53/

Project YouTube video: https://youtu.be/0sZUuEraEBA

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