RAAC playbook

Version Draft
Date 2024

CATAPULT High Value Manufacturing

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Who are the Manufacturing Technology Centre?

Established in 2011, MTC is a leading independent research and technology organisation at the forefront of manufacturing innovation. We combine the power of pioneering mindsets with inspired engineering excellence to drive progress across industries and positively impact society.

Home to some of the world's brightest minds and, through our world-class technologists and engineers, we partner with businesses who require breakthrough innovative solutions to major societal and industrial challenges that they or others cannot or will not solve.

What is the High Value Manufacturing Catapult?

We are part of the High Value Manufacturing Capapult (HVMC) network - a group of seven research, development and innovation centres, supported by Innovate UK, that works with manufacturing businesses of all sizes and from all sectors and is focused on accelerating new concepts in manufacturing and bringing original research to market.

Figure 1: *The HVM Catapult Network - HQ and locations.*

RAAC Playbook

Foreword

This document is a draft output from the UKRI RAAC Impact Programme, led by the Manufacturing Technology Centre (MTC). It has been written by multiple authors, documenting the Research and Development conducted from a selection of the programme's key work packages.

This draft is not authoritative industry guidance but aims to collate publicly available guides for RAAC in section 1 and document the research from the programme's work packages, including the research methodologies, conclusions and next steps in section 2.

This draft document is not statutory or industry best practice, it is based on the work of the MTC and does not represent the full extent of knowledge on RAAC within the UK. The MTC is a Research and Technology Organisation (RTO) and not a structural or civil engineering organisation. The information contained within this draft document is an independent view of the ongoing situation and history of RAAC, aiming to provide a new perspective and review potential technology and technical solutions that could be adopted from other industries. Any solutions or technology documented within this draft should be considered in conjunction with existing industry guidance and by competent engineering professionals. This playbook is not an industry standard, nor does it supersede existing British or European Standards. It is recommended that further versions are published with subsequent updates, with the aim to define an industry wide standardised approach to dealing with RAAC.

The information contained in this document is a summary of the research outputs from the UKRI RAAC Impact Programme and is not intended to amount to advice on which you should place reliance upon as the MTC is not a structural or civil engineering organisation. You must obtain professional or specialist advice before taking, or refraining from, any action on the basis of the content in this document, including applying due diligence with the adoption of any of the technologies / methods captured in this document. The MTC does not make any express or implied warranties, representation or undertaking whatsoever in relation to any of the content in this document (including the accuracy, quality or fitness for any purpose of the content). You understand and agree that your use of the information in this document is entirely at your own risk and that this document is provided on an "as is" and "as available" basis.

Introduction to the Playbook

What is a Playbook?

In general terms, a Playbook is a practical guide to help navigate key stakeholders through a complex situation, while a Rulebook provides guidelines and rules that must be followed as a reference guide. Given the complex nature of the landscape surrounding RAAC, there is a need for a Playbook in the first instance.

What is the RAAC Playbook?

The purpose of the RAAC Playbook is to curate the best publicly available, relevant, information for RAAC into a single source, and to provide a relevant information around “living with RAAC and “dealing with RAAC” for multiple stakeholders, across public and private estates.

MTC are facilitating the creation of this first draft edition of the Playbook, as a consolidated and curated repository of the best-available knowledge and information at the time of publication and are not the originator of the collated research within section 1 of the Playbook.

For simplicity, an overview of publicly available documents has been provided, which is not exhaustive and aims to provide a high-level background, outlining gaps in knowledge and understanding. It is recognised that additional information and data may currently exist and is intended to be captured in subsequent updates, alongside new outputs and learning from ongoing and planned research and investigations.

As a result of the above statements, this document has been prepared and released as a first draft.

What is the purpose of the RAAC Playbook?

The RAAC Playbook will be an informative document for construction professionals, estate managers, and other stakeholders dealing with RAAC in various building types. The goal is to empower them with a standardised approach needed to confidently assess the presence and condition of RAAC, in an objective, consistent and robust way. Its development aims to:

- Strengthen understanding by aggregating existing knowledge into a centralised resource that encompasses various perspectives, experiences, insights and enabling technologies related to RAAC.
- Maintain documentation of research and technical progress.
- Define standard methodologies for each of the UKRI RAAC Impact Programme’s work streams and map these across standardised categories.
- Define the next steps and what needs to be done to ensure a joined-up approach across government, industry, and academia.

UKRI RAAC Impact Programme

Securing £3m from Innovate UK enabled further vital research into RAAC. By gaining a better understanding of its integrity, buildings which are in the most urgent need of repair can be identified, ensuring the safety of occupants. The funding was used to facilitate industry collaboration into using Non-Destructive Testing (NDT) to identify RAAC in buildings and assess its condition. The programme also included development of an automated way to collect and analyse data about RAAC so that cases can be assessed rapidly and more cost-effectively. The programme investigated solutions to be developed for replacing or monitoring RAAC, potential for a future training programme to be created, and a 'Playbook' to be produced for dealing with the material. This project built on our capabilities in NDT and metrology, data analytics and informatics, as well as our previous work completed as part of Innovate UK's Construction Innovation Hub, a programme which we led in partnership with BRE.

The RAAC Playbook seeks to capture the knowledge and key insights from this funded programme and layout the decision-making process for how to approach the RAAC problem. Edition one is the draft for review, not the finished version. This is a comprehensive aggregation of publicly available information, laying the foundation for subsequent updates. This draft first edition aims to begin a move towards a standardised approach across industry and government in tackling RAAC.

COMMON TERMS & DEFINITIONS

To help guide you through this document, we have outlined a **few key terms** and **descriptions** that reoccur throughout.

AAC – Autoclaved Aerated Concrete

RAAC – Reinforced Autoclaved Aerated Concrete

Rebar – Reinforcing Bar

HVM Catapult – High Value Manufacturing Catapult

IStructE – The Institution of Structural Engineers

BRE - Building Research Establishment

Readers can navigate the document using the buttons in the footer of each page.

Section 1: Introduction to RAAC

What is RAAC and where can it be found?

RAAC is the reinforced version of Autoclaved Aerated Concrete (**AAC**). The lightweight cementitious material is typically reinforced by steel bars or mesh to enhance its structural strength.

RAAC was widely used in construction across the UK from around the 1950s until the mid-1990s. RAAC planks up to approximately 6.5m length were installed in roofs, floors and walls of buildings such as schools, hospitals, housing developments, and other public and private buildings from the mid-fifties. RAAC planks were adopted by industry because of the benefits, such as: being a lightweight solution, enabling rapid installation, having inherent insulation properties and were also a cost-effective option. RAAC manufacturing is reported to have ended in 1982 in the UK, although RAAC planks remain globally available and have been found in UK buildings built in the mid-1990s.

Figure 2 shows an example of a RAAC roof plank stored at the MTC.

Why has RAAC become a concern?

Over the years concerns have been raised regarding the performance of RAAC, including work by the BRE in 1996 and a Standing Committee on Structural Safety (SCOSS) report in 2019, [1, 2].

Following collapses in 2017 and 2018 [3], the IStructE released further guidance to advance the understanding of the material performance [4, 5]. The BRE revealed the existence of concerning '*cracking*' and '*corrosion*' in RAAC roofing panels in 1996. Subsequently, in 2019, SCOSS warned that RAAC planks were *'past their expected service life'* and that *'roofs with RAAC planks could collapse [2].*

Figure 3 shows shear failure of a RAAC plank.

What action has been taken so far?

Following the SCOSS [2] warning, different bodies have offered published reports and guidance to raise concern or facilitate the identification and assessment of RAAC planks, which can be seen in Figure 4 overleaf.

Provisional data in a study commissioned by the Building Safety Regulator estimates RAAC usage in current UK building stock. It is estimated there is a 90% likelihood that there are between 1.3 million and 4.4 million RAAC panels in England.

In the UK, RAAC can be found in schools, hospitals, dwellings and other public and private buildings. The lack of knowledge regarding the exact number and location of buildings with RAAC, along with uncertainty about the actual state of planks, increases the risk of experiencing unforeseen collapses.

RAAC: *Reinforced Autoclaved Aerated Concrete.*

AAC: Autoclaved Aerated Concrete.

Soffit: The underside of any architectural structure.

Figure 2: An upside-down roof plank sample, with soffit uppermost

Figure 3: Shear failure of a RAAC plank during flexural test by Loughborough University and Lucideon Ltd as a part of the NHS-funded RAAC research programme undertaken in 2021-2023

100 years of RAAC

HISTORICAL BACKGROUND + EVENTS

GUIDANCE, ALERTS, REPORTS

UK DESIGN GUIDANCE

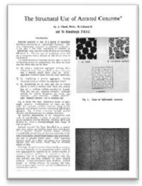
OTHER PUBLICATIONS

1924
AAC invented in Sweden
by Johan Axel Eriksson

1930s
RAAC used as a
structural component

1950
RAAC imported to UK
UK manufacture of RAAC starts

RAAC used in the UK from 1950 to mid 1990s



1982
UK manufacture of RAAC ends

1985
BS 8110 Part 2 -
Structural Use of Concrete

1988
NIST: A review of autoclaved
aerated concrete products

1991
BRE tests on pla
housing developm

BSI Dr

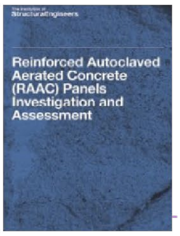
1997
BS 8110 Part 2 section 6 -
Rules for designing with RAAC
removed after BRE works

1999
Twelfth Report of SCOSS
recommends inspection
of roofs built before 1980

2001
Learning from Constr
Applied Forensic Eng
13 'Reinforced aircret

SCOSS Alert – Failure of Reinforced
Autoclaved Aerated Concrete Planks
Aim: to warn of the RAAC problem.
Outcomes: It provides background, guidance on identification, inspection and managing of planks.

IStructE Reinforced autoclaved
aerated concrete (RAAC)
Investigation and assessment
Aim: to provide further guidance on RAAC. Outcomes: List of defects by group. High concerns around the shear failure



2022
Loughborough University Programme
Office of Government Property send RAAC
safety Briefing Notice to property leaders
IStructE RAAC Investigation and Assessment

IStructE Reinforced autoclaved aerated concrete
(RAAC) Investigation and assessment -
Further Guidance
Aim: to provide further guidance
Outcomes: further information of risk factors and concerns. Provide a risk classification

2023
CLC RAAC Industry Response Group
IStructE RAAC Investigation and Assessment Further Guidance
Department for Education Identification Guidance

Figure 4: RAAC - 100 Year Timeline

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1961
IStructE - The Structural Use of Aerated Concrete

1969
CP 116-2 - The structural use of precast concrete

1972
CP 110 - Code of Practice for the Structural Use of Concrete

IStructE The structural use of aerated concrete
Aim: to provide an overview of RAAC properties in the lack of any UK standard.
Outcomes: Raised concern on lack of bonding between rebars and concrete and the effects of moisture content

1978
Autoclaved Aerated Concrete – CEB Manual of Design and Technology Comité Euro-International du Betone

1980
RILEM Reports start

nks from
ment

1993
RILEM Reports end

1993
Excessive deflections in RAAC planks reported at schools

1996
BRE IP 10/96 published
raft prEN 12602 published

1994
DfE ask BRE to inspect schools in Essex

BRE IP 10/60 Reinforced autoclaved aerated concrete planks designed before 1980.
Aim: RAAC roof planks before 1980s
Outcomes: It provides guidance on identification and initial assessment. Raises concerns over excessive deflection, short bearing lengths and cracks near the bearings. RAAC planks were not found to pose a safety hazard to building users.

2002
BRE Report 445 (aka IP 7/02) published

Reinforced autoclaved aerated concrete panels: review of behaviour, & developments in assessment & design.
Aim: To examine RAAC planks before the new EN12062 is published. Testing RAAC planks designed before 80s, after prEN 12062 and in between.
Outcomes: Panels found to be safe although concerns around excessive deflection due to greater flexibility of in-service panels. Span-effective depth found to not comply CP110. RAAC roof planks designed to prEN 12062 showed initial satisfactory in-service performance. Smaller span-depth ratio.

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gineering Chapter
te slabs'

2019
SCOSS Safety Alert - Failure of Reinforced Autoclaved Aerated Concrete (RAAC) Planks

2018
Roof collapse at Essex school

DfE & LGA advice to identify schools containing RAAC

2023
Collapse of three buildings with "non-critical" RAAC reported.
DfE advised to close spaces with RAAC

2024
House of Commons RAAC in the UK: Concerns and government response

2024
The RAAC Playbook published by MTC


Reinforced Autoclaved Aerated Concrete (RAAC): Identification guidance
August 2023

DfE Reinforced autoclaved aerated concrete (RAAC): identification guidance
Aim: to provide identification guidance
Outcomes: Guidance on Identification of RAAC, the appointment of surveyor or structural engineer and how to inform DfE

RAAC in UK: concerns and government response
Aim: to discuss the use of RAAC, including in schools and hospitals, and the government's response
Outcomes: Report.

What are the identifiable challenges with RAAC?

The manufacture of RAAC planks stopped in 1982 in the UK (9, 10) but RAAC produced during this time was used after this year. RAAC planks installed before the 1990s present significant challenges related to structural integrity and material degradation, along with identification and assessment of risk factors and management. Living and dealing with RAAC can be a complex process due to the implicated risks and the number of planks that may exist within a building. We have outlined the various challenges below.

Documentation

Many RAAC buildings constructed before the 1990s lack comprehensive documentation regarding design, construction, and maintenance history. The absence of accurate records hinders effective assessment and management of structural risks associated with RAAC, hence posing challenges for building owners, engineers, and regulatory authorities. To date, the MTC's investigation into RAAC roof planks, using publicly available information, has identified a significant challenge in the availability of historical data. Specifically, we do not have:

- Data that correlates the manufacturers, quality or locations.
- Comprehensive catalogues or technical information from manufacturers in the public domain.
- Traceability of RAAC. Where it is, how much was used, and what state it is in.
- Understanding on the impact of the different parameters on the final risk of failure, e.g. excessive moisture content (further details are included in Section 2, technical introduction).
- Repairs maintenance records.

Structural integrity

The aging of RAAC panels, including panels, walls, and slabs, raises uncertainties about their ability to withstand loads and environmental stresses over time. The presence of RAAC planks entails a risk to users with potential loss of life, other building components and room contents, such as expensive equipment. The impact of failure can cause severe disruption in the use of the buildings, such as partial or full closure. This is especially important for full-time operational buildings where any remediation action can be hindered and highly expensive.

The lack of data and traceability results in the inability to correlate the defects or manufacturing type with the collapses reported so far. The scarce data, the wide range of risk factors and the potential increasing vulnerability of RAAC planks after prolonged loading and environmental exposure, cause uncertainties around the RAAC's failure modes and the contributing risk factors.

Identification

Currently whether RAAC is present in a building or not depends on the operator identifying it. This may be made more complex by the presence of suspended ceilings or asbestos containing material, buildings are also often extended or updated, introducing different construction materials. It is essential that the construction materials and structural form used in a building are established.

Detection

The key structural risks are associated with the size of the contact area between the plank and the supporting structure (the bearing), and the presence of transverse steel over the bearings. Currently, both destructive and NDT methods can be used to detect key features of RAAC. To enable large scale adoption of NDT techniques, further research is required to improve accuracy further, reduce costs and ease data processing. Considering the variability of quality and features between planks (even from the same batch) the greater number of planks investigated, the better. The detection of defects is hindered by the drawbacks of destructive testing methods, which are impractical due to the substantial number of planks requiring inspection. This poses a critical issue when seeking effective means of assessing RAAC structures and implementing remedial measures to mitigate potential risks and ensure compliance with safety standards.

Assessment

There are gaps in understanding the contribution of defects and risk factors to the ultimate failure or failure modes of RAAC planks. This, along with the variability and the uncertainties around the condition of planks, may compromise the accurate assessment of the actual condition of planks. As a consequence, accurate risk assessment is difficult to achieve. The above-mentioned variability on features and condition of RAAC planks, even among those from the same batch, limit the extrapolation of results and findings. Therefore, better guidance and assessment tools are needed to support competent professionals in the assessment of RAAC planks' condition.

Remediation

Remediation of RAAC structures presents significant technical and financial challenges. Implementing effective remedial measures to address structural deficiencies, reinforcement corrosion, and material degradation requires careful evaluation, specialised techniques, and substantial investment. When repairing, reinforcing or replacing RAAC, certain buildings may pose challenging circumstances such as those that are in full time operation, have services that cannot be nullified or contain asbestos, among others. Currently, there is no specific guidance that informs on the readiness or feasibility of existing remediation practices in the case of RAAC and/or provides a standardised methodology to ensure that better remedial practices are followed. Documenting a standardised approach for the remediation of RAAC, including the decision-making process, would be beneficial to industry.

Management

Living and dealing with RAAC becomes a managing activity for those accountable for the asset. Currently certain buildings have implemented RAAC management practices. NHS hospitals are one example of this, however there is a lack of guidance to inform other building owners and managers on how to implement these practices. Unified methodologies are needed.

In terms of methods that support the constant surveying of the condition of RAAC planks, better automated monitoring systems are needed. These would facilitate and support the surveying practices, minimising the number of surveyor and visits on-site, setting alarms, or monitoring areas with restricted access.

Regulatory compliance

There is a lack of clear guidance relating to regulatory compliance for RAAC in existing buildings. Addressing the challenges of RAAC requires a multidisciplinary approach involving structural engineers, material scientists, building owners, and regulatory authorities. Comprehensive assessment, monitoring, and maintenance strategies are essential to ensure the continued safety, durability, and performance of RAAC structures in the UK.

A standardised approach to dealing with RAAC

Through working with the Construction Leadership Council (CLC) RAAC IRG Technology Subgroup the UKRI RAAC Impact Programme has adopted the suggested terminology to define categories as part of a standardised approach.

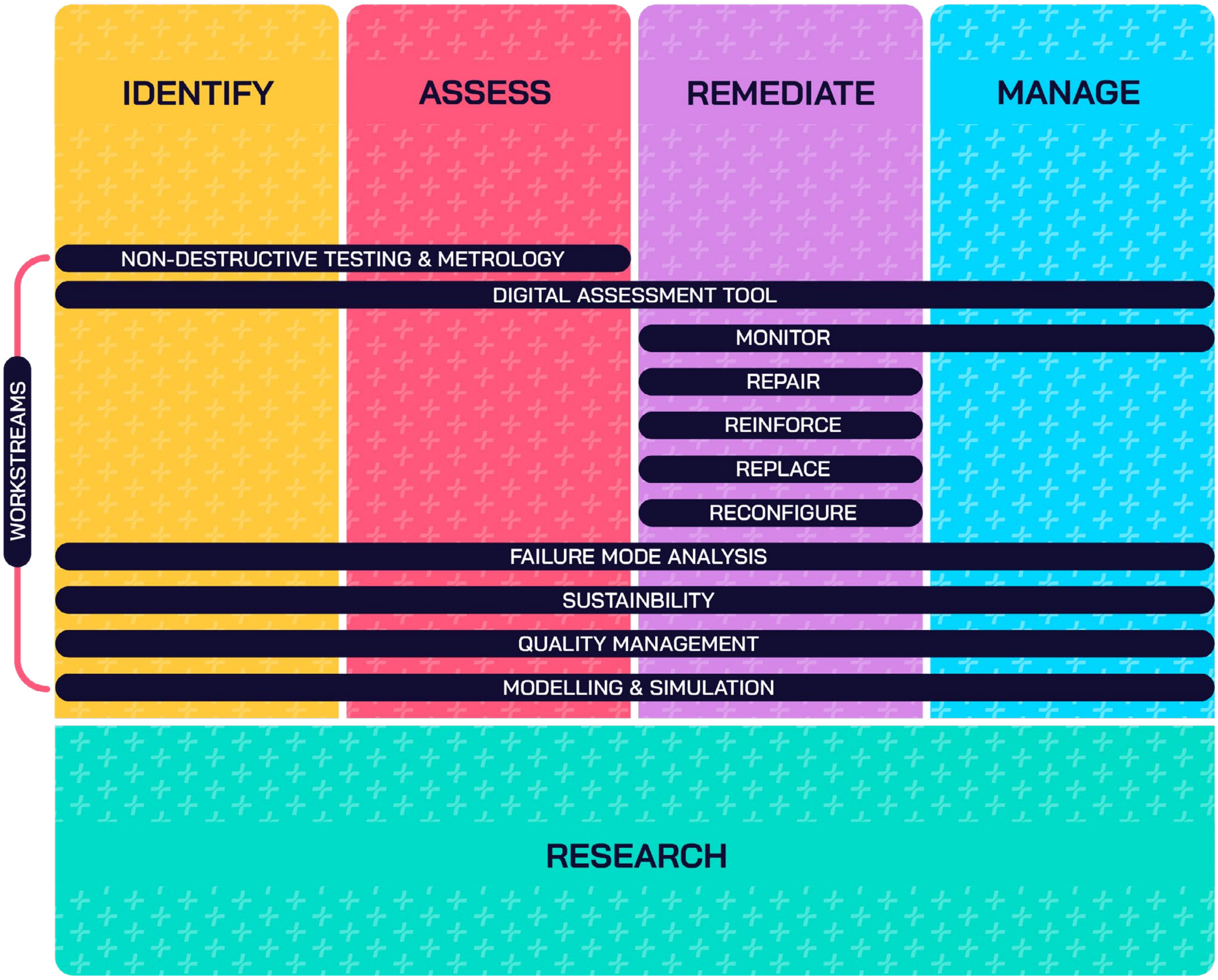

Figure 5: A standardised approach to dealing with RAAC

Bibliography

[1] **Building Research Establishment**, "IP10/96 Reinforced autoclaved aerated concrete planks designed before 1980," BRE Electronic Publications, 1996.

[2] **SCOSS Alert**, "Failure of Reinforced Autoclaved Aerated Concrete (RAAC) Planks.," Standing Committee on Structural Safety, 2019.

[3] **House of Commons Library**, "RAAC in the UK: Concerns and Government Response," 10 January 2024. [Online]. *Available here*.

[4] **The Institution of Structural Engineers RAAC Study Group**, "Reinforced Autoclaved Aerated Concrete (RAAC) panels: Investigation and assessment," 7 March 2022. [Online]. *Available here*. [Accessed 15 July 2024].

[5] **The Institution of Structural Engineers RAAC Study Group**, "Reinforced Autoclaved Aerated Concrete (RAAC) Investigation and Assessment – Further Guidance," 17 April 2023. [Online]. *Available here*. [Accessed 15 July 2024].

[6] **Eurocodes,** "Eurocode - Basis of structural design - EN 1990:2002 + EN 1990:2002/A1:2005," 2024. [Online]. *Available here*. [Accessed 15 July 2024].

[7] **SCOSS**, "Twelfth Report of SCOSS. Structural Safety 1997-99: Review and recommendations," SCOSS, London, 1999.

[8] **RICS**, "How to locate RAAC – and what to do about it," 18 September 2023. [Online]. *Available here*.

[9] **Construction Leadership Council**, "Information and FAQs on reinforced autoclaved aerated concrete (RAAC) from the Construction Leadership Council," November 2023. [Online]. *Available here*.

[10] **The Institution of Structural Engineers,** "IStructE statement & FAQs: Reinforced Autoclaved Aerated Concrete (RAAC)," 25 October 2023. [Online]. *Available here*.

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- How was RAAC manufactured?
- Material properties
- Where can RAAC products be found?
- Roof planks - common features
- What are the risk factors and failure modes?
- Failure modes and defects explained

RAAC construction products

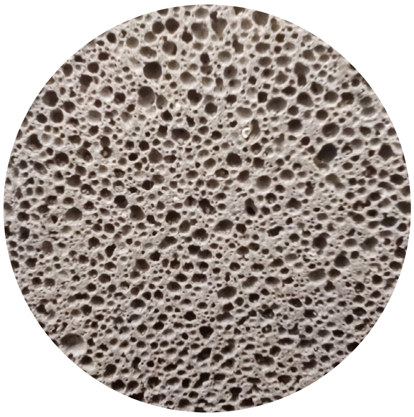
Reinforced aerated autoclaved concrete (RAAC) is the reinforced version of autoclaved aerated concrete (AAC), a lightweight cellular material typically reinforced by steel bars or mesh to enhance its structural strength.

Unlike concrete, AAC does not contain coarse aggregates thus the term ‘concrete’ may lead to confusion. Additionally, the physical and mechanical properties of RAAC greatly differ from those of concrete.

Figure 6 shows the visual differences between ACC and concrete.

It is important to note that throughout its existence RAAC has been known by various other names. Originally, names like “reinforced aircrete slab”, “aerated silicate” or “cellular silicate” were proposed by Short & Kinniburg in 1961 [1] and Satish Desai in 2001 [2] aiming to avoid confusion about the material’s concrete properties among users and designers. Additionally, RAAC was marketed under various commercial brand names [3].

In this Playbook we use the term ‘RAAC’ because it is currently the most widely recognised term among audience groups.



(a) AAC

(b) Concrete

Figure 6: *Cut section of (a) AAC (Source Loughborough University) and (b) Concrete (in this case containing recycled aggregates) (source MTC)*

How was RAAC manufactured?

The bubble structure of RAAC is created through a gasification method, which involves a chemical reaction that typically uses aluminium powder, or through air entraining methods commonly used in in-situ aerated concrete.

The manufacturing process involves mixing a slurry of binder (such as cement or lime), ground siliceous materials, a foaming agent, and other admixtures [4, 1, 5]. This mixture is then poured into steel moulds that contain a preformed, coated, welded reinforcing cage, all within a warm environment. The moulds are only partially filled; as the chemical reaction occurs and forms gaseous bubbles, it causes the material to rise and fill the mould. Once the setting occurs, the material solidifies into a self-standing but inherently weak structure. The material is then cured, demoulded, trimmed, and autoclaved. Autoclaving improves the properties of cement-based compositions (already strengthened through hydration) and is particularly important for mixes that contain lime as a binder.

Key steps of the manufacturing process can be seen in Figure 7.

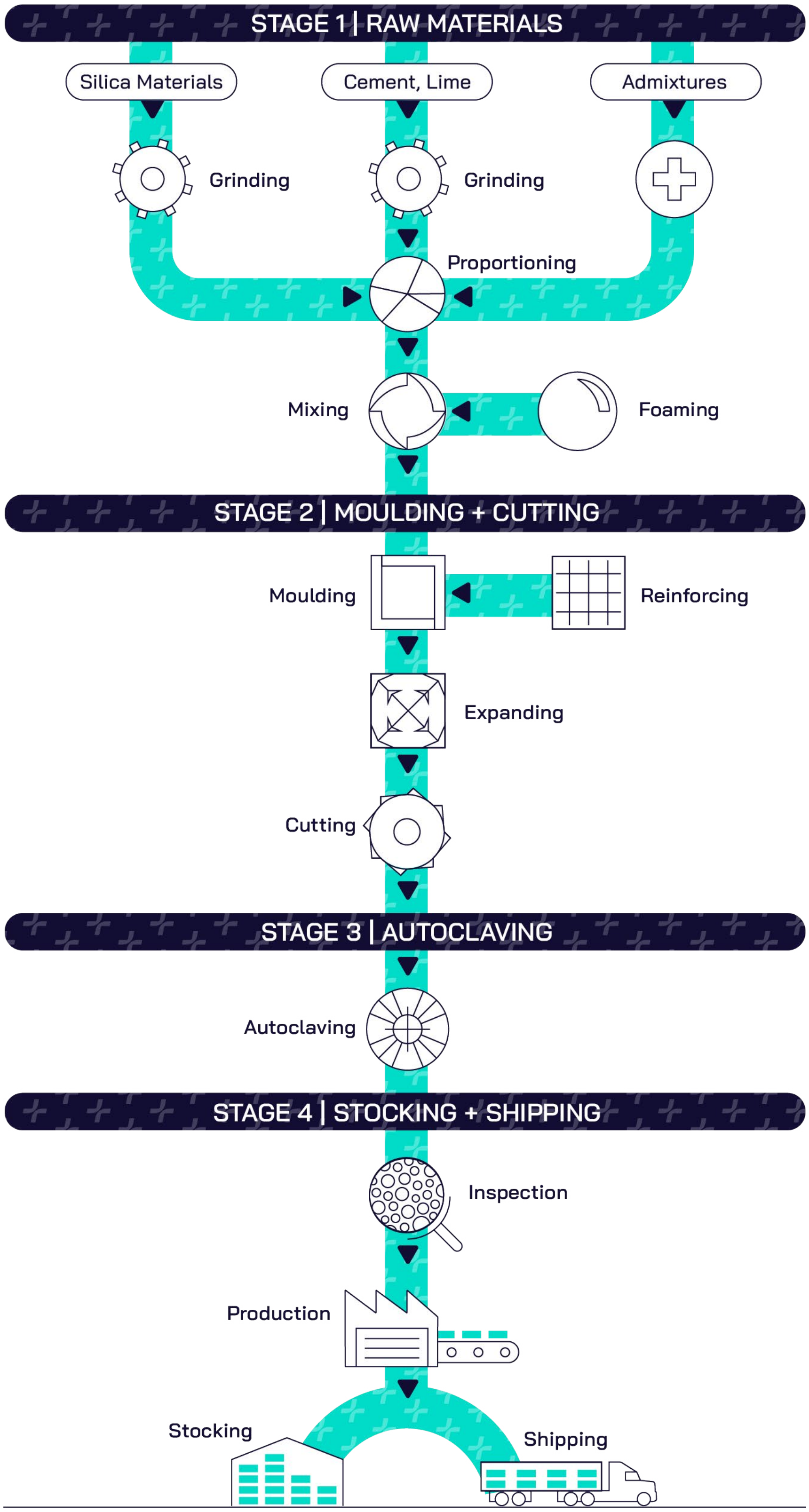


Figure 7: *Steps in manufacturing process of AAC/RAAC (adapted from Mathey and Rossiter [5] and Fudge, 2019 [4])*

Material properties

The material is a result of the combination of calcareous binders which can be made of lime or different types of Portland cement, siliceous materials like silica flour, pulverised fuel ash, Ground Granulated Blast-Furnace Slag or ground burnt shale, a foaming agent and other admixtures.

Detailed information on the material properties can be found in various literature authored by Short and Kinniburgh [1], Mathey and Rossiter [5], and Desai Satish [2]. Although it is out of the scope of this Playbook, these properties are detailed in Table 1.

The key feature of RAAC is its low density due to the high porosity. A wide range of values are reported in literature, referring to the oven-dry densities or density at equilibrium.

Lower grades were used for insulation properties while greater values were employed in structural components.

According to Short and Kinniburgh, densities as low as 480kg/m³ were used for structural components resulting in larger sections to provide the requested rigidity. In any case, typical AAC average density has a range of 600 to 800kg/m³ [6].

Table 1: RAAC and Reinforced Concrete (RC) Properties [1, 5, 3, 7, 2]

Property	RAAC	Reinforced Concrete
Density	400-1000 kg/m³	2400 kg/m³
Aspect	Aerated (pumice-like). No coarse aggregates. Internal cut face.	Non-aerated structure. Coarse aggregates. Cast face.
Compressive Strength	2-7N/mm²	>15N/mm² (old and lightweight concretes) >25N/mm² (actual concretes)
Direct Tensile strength	15-35% of compressive strength	6-12% of compressive strength
Elastic modulus (Young's Modulus) and creep	1000-3000 N/mm² (increases with density and compressive strength increase) Falls with moisture increase. Long-term elastic modulus is half of short-terms elastic modulus - Greater **deflection**s expected.	30000-40000 N/mm²
Planks Reinforcement	Unribbed commonly coated **rebar**.	Commonly ribbed and uncoated rebar. In old structures might not be ribbed.
	Welded transverse rebar to anchor longitudinal rebar due to poor bond.	Absence or lower amount of transverse rebar (normally, not welded).
Permeability & corrosion protection	Carbonation rate is much higher than concrete. AAC does not provide a significant protective barrier	Coated bars not common. AAC does not provide a significant protective barrier.
	Cracks/**spalling** may not be visible on the soffit due to the porous matrix accommodating rebar volumetric expansion	When rebar is corroded, there are visible cracks on the surface near the rebar.
	Coated bars are common (bituminous or cement-rubber latex coatings).	Forms cracks and spalling from corrosion affecting the length of the rebar.

Compressive strength: *The maximum compressive load a body can bear prior to failure, divided by its cross-sectional area. [8].*

Tensile strength: *The maximum tensile load a body can withstand before failure divided by its cross-sectional area [8].*

Young's Modulus: *property of the material that tells us how easily it can stretch and deform and is defined as the ratio of tensile stress to tensile strain. (University of Birmingham)*

Creep: *deformation of structure under sustained load (Ref: International Journal of Engineering Development and Research (IJEDR)*

Deflection: *the degree to which a part of a longitudinal structural element is deformed laterally (in the direction transverse to its longitudinal axis) under a load.*

Rebar: *is short for "reinforcing bar" and specifically refers to steel bars used to reinforce concrete structures.*

Spalling: *used to describe areas of concrete which have cracked and delaminated (detached) from the substrate due to different causes such as freeze and thaw, corrosion or accidental actions.*

Where can RAAC products be found?

RAAC panels can be found in the form of slabs, known as 'planks', in flat and pitched roofs, floors, façades, load-bearing walls and partition walls or lintels.

Roof planks were widely used, but floor planks seem not to be so commonplace. Additionally, the floor planks were installed with a screed cover on top.

The scope of the UKRI RAAC Impact Programme focused on roof planks. Figure 8 shows this in the context of construction elements, and Figure 9 shows examples of RAAC in use.

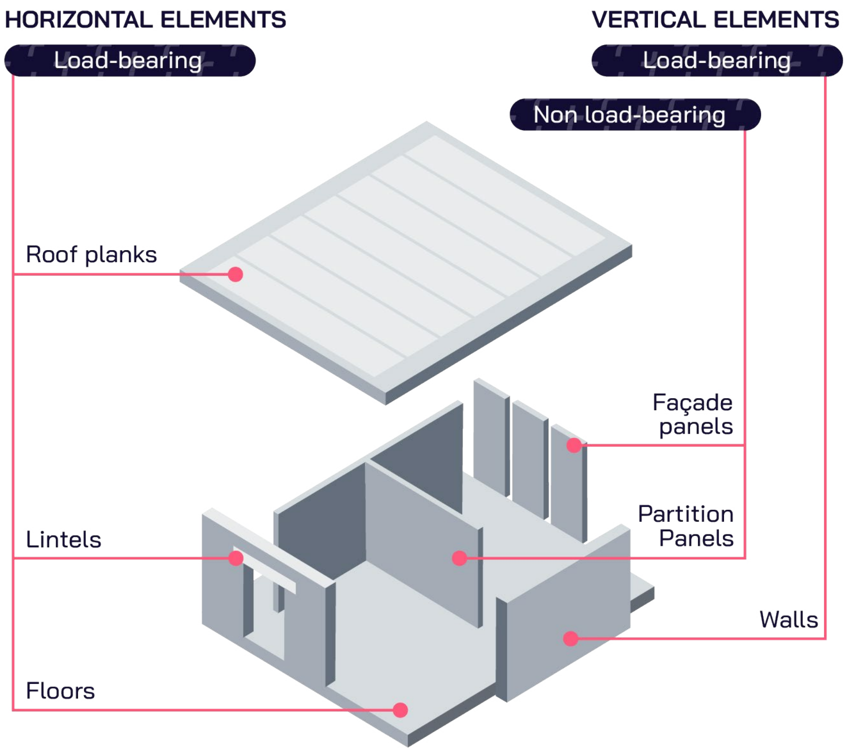


Figure 8: *RAAC construction components according to their structural function.*

Figure 9: *(a) A roof with RAAC planks on reinforced concrete structures (source: MTC. With permission of Airedale Hospital), (b) RAAC planks in the façade ([Reinforced Autoclaved Aerated Concrete (RAAC): Identification guidance (publishing.service.gov.uk)](#)) (c) a RAAC load-bearing wall (source: MTC. With permission of Leighton Hospital).*

Roof planks - common features

RAAC planks were manufactured in a range of sizes. RAAC planks up to approximately 6m (longer planks can also be found) were reported, with thicknesses ranging from 75mm to 250mm. The most common width is 600mm although other widths can be found, sometimes within the same building. High span-to-depth (s/d) ratios have been reported in literature up to s/d ≤ 30 for roof loading.

Planks commonly have chamfered edges as shown in Figure 10 (b). To enable load share between adjacent planks, a groove along the length of the planks is filled with mortar and a continuity rebar is commonly placed, as shown in Figure 10 (a). However, the effective planks' interaction improvement by the filled grooves has been put into question [3]. Different groove shapes can be found in literature [1].

A reinforcing cage is embedded within the plank as shown in Figure 10 (b). Longitudinal rebars at the bottom of the plank provide the load-bearing capacity. The welded transverse rebars at the end and intermediate position anchor the longitudinal rebars and increase the shear strength capacity at the bearing (Loughborough University research NHS-funded RAAC research programme undertaken in 2021-2023). The planks span between bearing beams that can be in-situ or precast concrete, steel or masonry bearing-walls. The planks span between supports that are typically in-situ or precast concrete beams, steel beams or trusses, or masonry walls, see Figure 11.

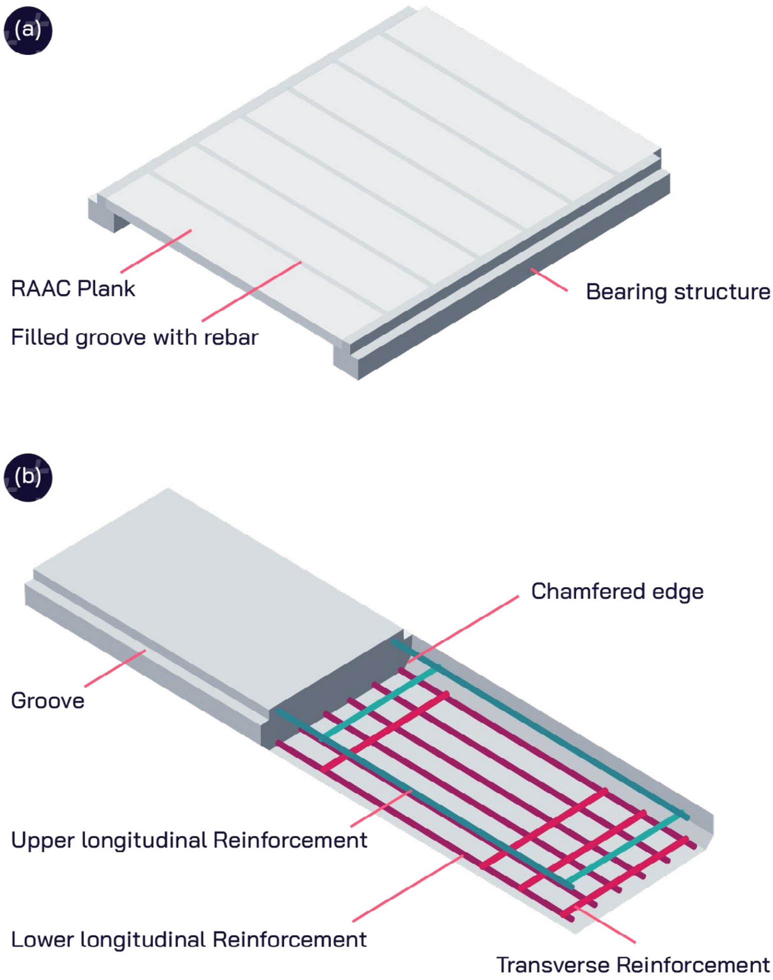


Figure 10: *RAAC roof planks spanning between beams (a) and a RAAC plank and components (b) (based on BRE IP10/96 report [7])*

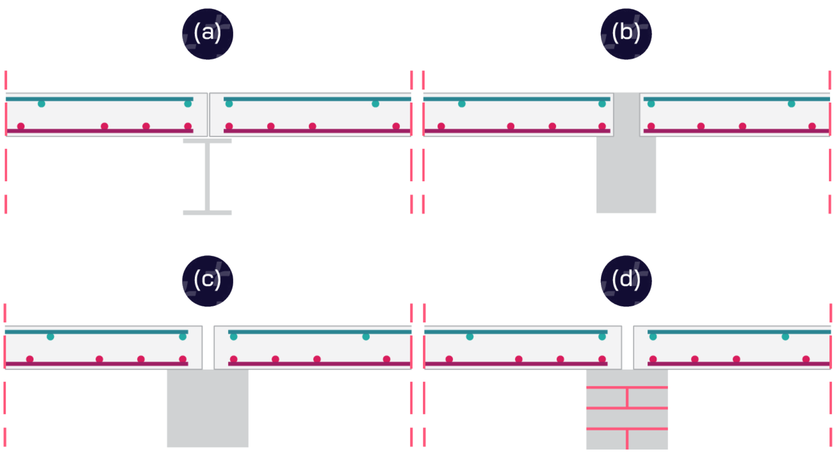


Figure 11: *Planks on (a) steel beam, (b) precast concrete beam, (c) in-situ concrete beam and (d) masonry load-bearing wall.*

What are the risk factors and failure modes?

According to the Institution of Structural Engineers [6, 9] several defects and damage types have been identified and reported due to the performance, manufacturing processes, construction installation processes of the planks and subsequent builders work and modifications during the life of the building.

These defects include excessive deflection, cracks, material degradation, misplaced or a lack of transverse rebar over bearings, and corrosion. The risk and seriousness of these defects depends on the type and severity that the defect or damage presents, and their simultaneity leading to the failure of the planks. Specifically, the presence of the transverse reinforcement is key to ensure the bonding between the longitudinal rebars and the matrix, and its placement over the bearings is critical to avoid brittle shear failure at the bearings.
A summary of the defects and risk factors are included here.

Excessive in-service deflection

Description

Excessive in-service deflections (above Span/250) with transverse cracks spreading from the centre of the planks to the ends. Differences in deflection between adjacent planks are common.

Potential causes/origin

- Insufficient span-to-depth ratio.
- Insufficient bond reinforcement-AAC.
- Excessive loading.
- Creep, excessive moisture content and lowering in the elastic modulus over time.

Risks

- Increase of ponding water, therefore, increase of loading.
- Failure of water-proofing systems.
- Concentrated stress at the supports.
- Cracking of rebars' coatings.

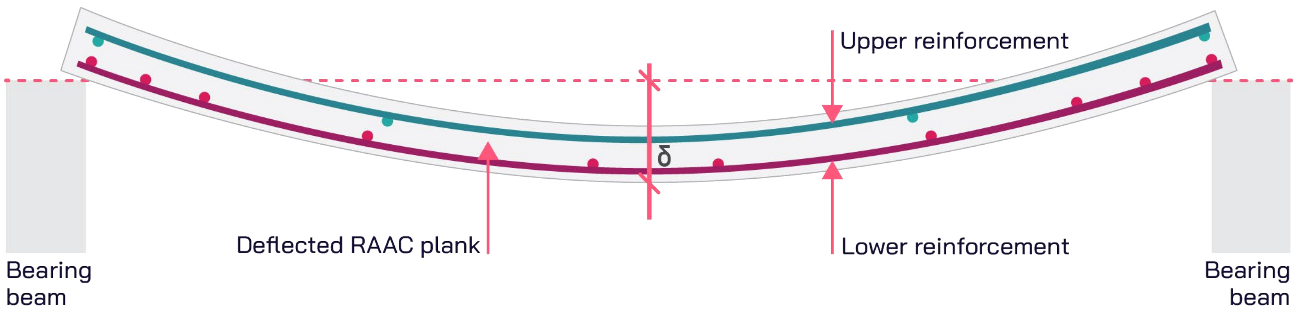


Figure 12: *Excessive deflection of planks*

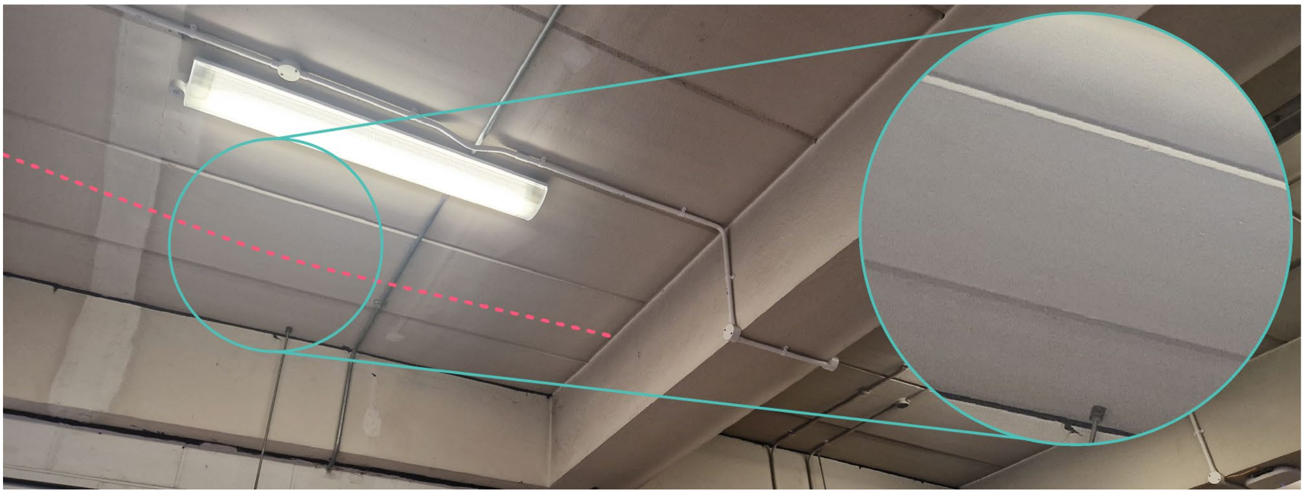


Figure 13: *Excessive differential deflection in a row of planks (Source: MTC. With permission of Airedale general Hospital)*

Cracking and spalling in the soffit of panels

Description

Cracking and spalling in the soffit of panels. Cracks are commonly transverse or longitudinal.

Potential causes/origin

- Excessive deflection.
- Restraint.
- Shear failure.
- Corrosion.

Accidental damage risks

Cracks can be the manifestation of the failure of the structure for different reasons (e.g.: excessive deflection, corrosion of the reinforcement, accidental damage, etc). Besides the risks associated with these causes, unsealed cracks expose the rebar reinforcement to external aggressive agents such as CO_2 and moisture. Although, due to the porous nature of ACC a full carbonated matrix is expected, minimising the exposure of rebars with cracked coatings to CO_2 and moisture is desirable.

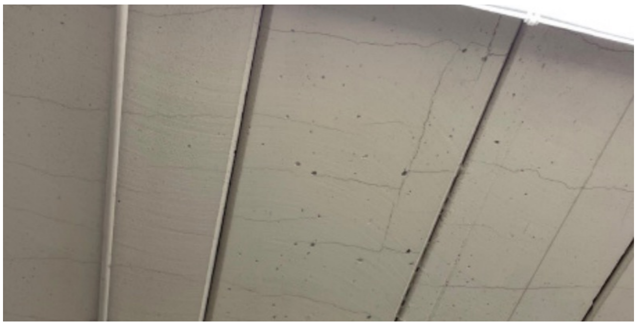


Figure 14: *Transverse and longitudinal cracks in RAAC roof planks [10]*

Figure 15: *One of the sectioning cracks located 30cm along a RAAC plank. Source: MTC, 2023.*

Corrosion of reinforcement

Description

Corrosion of the rebars exposed to the environmental actions. Unlike reinforced concrete (which has higher density), corrosion in RAAC might not form visible cracks on the surface due to the high volume of air bubbles. However, it can form longitudinal cracks or spalling.

Potential causes/origin

- High permeability and the exposure to external aggressive agents (CO_2) in combination with moisture.
- Water ingress (leaks) can be observed through efflorescence or stains within the soffit.
- Rebar coating breakdown.

Risks

- Reduction of bond and anchoring between the reinforcement and concrete.
- Loss of strength capacity.
- Spalling/falling debris.
- Corrosion of the welded transverse rebars at the ends.

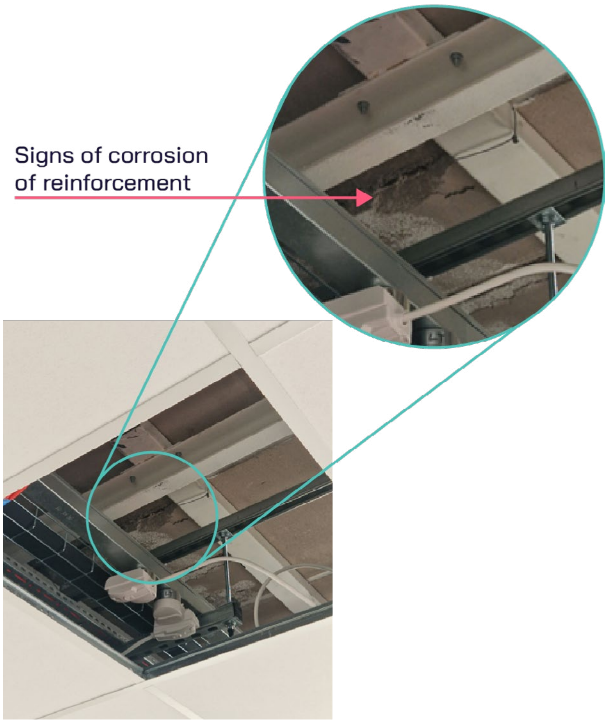


Figure 16: *Signs of corrosion of reinforcement (Source: MTC. With permission of Leighton Hospital)*

Hygrothermal: *Of or relating to a combination of humidity and temperature.*

Efflorescence: *Crystalline deposit of salts that can form when water is present and that remains after water evaporation.*

What are the risk factors & failure modes?

Excessive moisture content

Description

Planks exposed to excessive moisture content that may or may not be visible. In some cases, due to the excessive moisture, the pattern of the reinforcement can be observed on the surface.

Potential causes/origin

High moisture content in the environment, leaks, condensation, and others. Although it was believed [1] that RAAC had an optimum performance under a wide range of climate conditions, RAAC is very sensitive to moisture content [2] which ideally would be at 5%.

Risks

- Loss of strength capacity and bond strength capacity.
- Corrosion.

Figure 17: *Signs of excessive moisture content. (Source: MTC. With permission of Airedale general Hospital)*

Misplaced transverse reinforcement/ Insufficient anchorage of longitudinal rebar

Description

Missing longitudinal and transverse rebars have been observed in different panels over the end bearing.

Potential causes/origin

- Lack of quality control.

Risks

- Low shear capacity and/or a brittle failure mechanism leading to sudden failure with little warning.

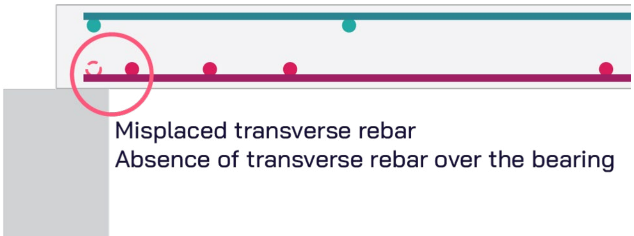


Figure 18: *Missing transverse rebar. The absence of transverse rebar over the bearing.*

Short bearing lengths

Description

Short bearing lengths[1] permitted by standards, reduced the range of acceptable tolerances during manufacturing and installation. This has increased the risk of misplacing the transverse rebars and reducing the bearing surface area.

Potential causes/origin

- Poor design, manufacturing and installation.

Risks

- Loss of structural integrity.
- Increased risk of shear failure.

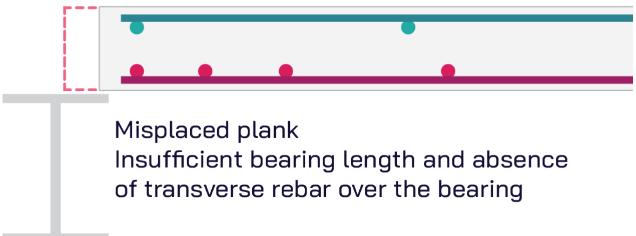


Figure 19: *Misplaced plank. Insufficient bearing length and absence of transverse rebar over the bearing.*

1 IStructE guidance for minimal acceptable bearing length is 75mm for all cases.

Cutting of panels post manufacture

Description

Panels completely or partially cut to adjust to the required length or to enable the installation of skylights or services. Those done during the construction of the building were supported by hangers connected to the adjacent planks, while other surface solutions such as L brackets were observed when the penetrations were installed afterwards.

Potential causes/origin

- Poor concepting during the design and/or workmanship during installation. Lack of quality control/design management.

Risks

- Missing transverse rebars on top of the bearing resulting in shear failure.
- Strength reduction of planks.
- Point (concentrated) and torsional loads on adjacent planks.

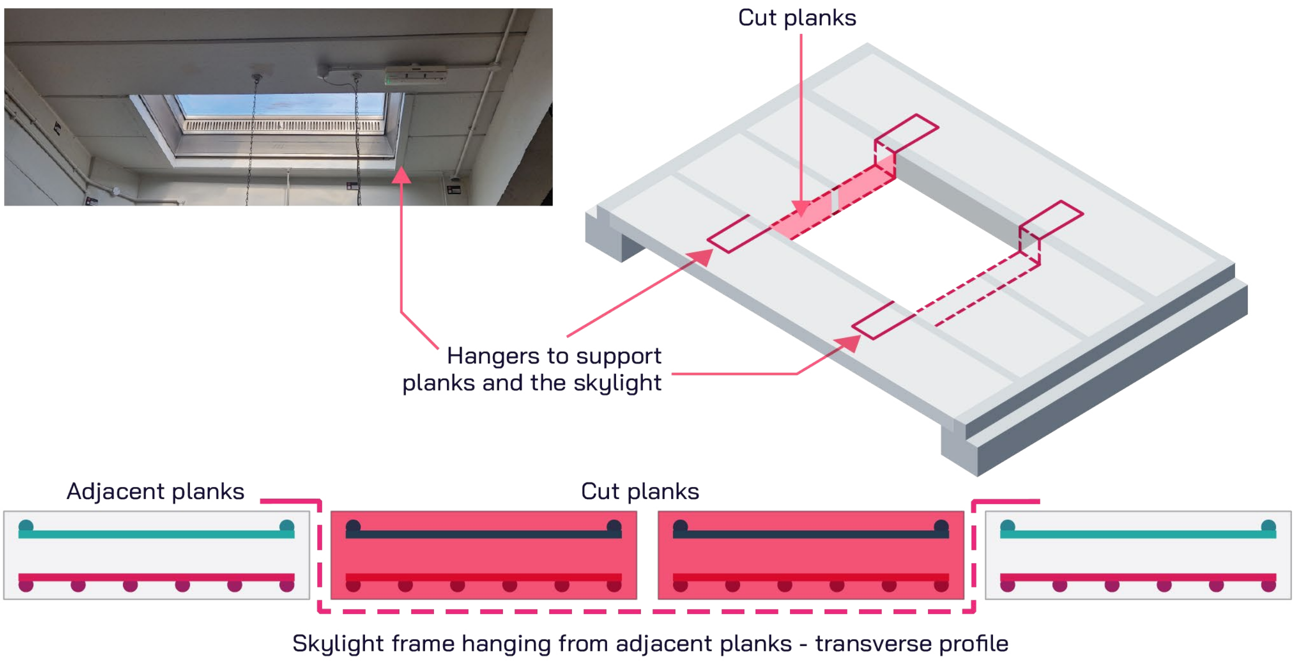


Figure 20: *Cut panels around installation of skylight (Source: MTC. With permission of Airedale general Hospital)*

What are the risk factors & failure modes?

Structural damage due to builder's work

Description

Other damaging actions affecting the integrity of planks such as fracture of planks.

Potential causes/origin

- Poor workmanship.
- Lack of understanding of RAAC planks structural design, performance and weaknesses.

Risks

- Cutting transverse reinforcement resulting in shear failure.
- Structural failure.

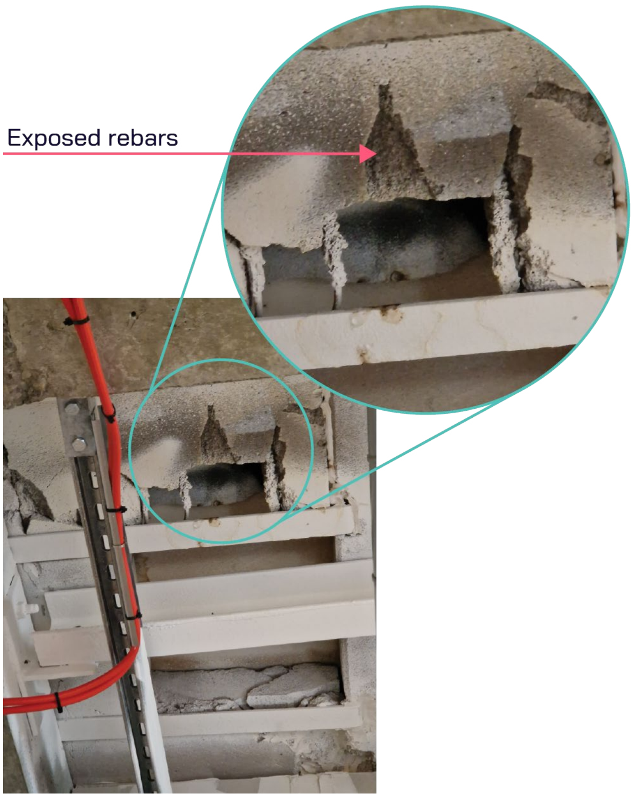


Figure 21: *Exposed rebars due to poor workmanship (Source: MTC. With permission of Leighton Hospital)*

Insufficient bond and/or anchorage between reinforcement and concrete

Description

Not a visible defect. The lack of bond between concrete and reinforcement or the inexistence or corrosion of transverse rebars.

Potential causes/origin

- Cavities or voids around the reinforcement 'shadow effect'.
- Ineffective bonding between the coating and the AAC.

Risks

- Lack of anchoring and load transfer of reinforcing rebars with AAC resulting in excessive deflection.

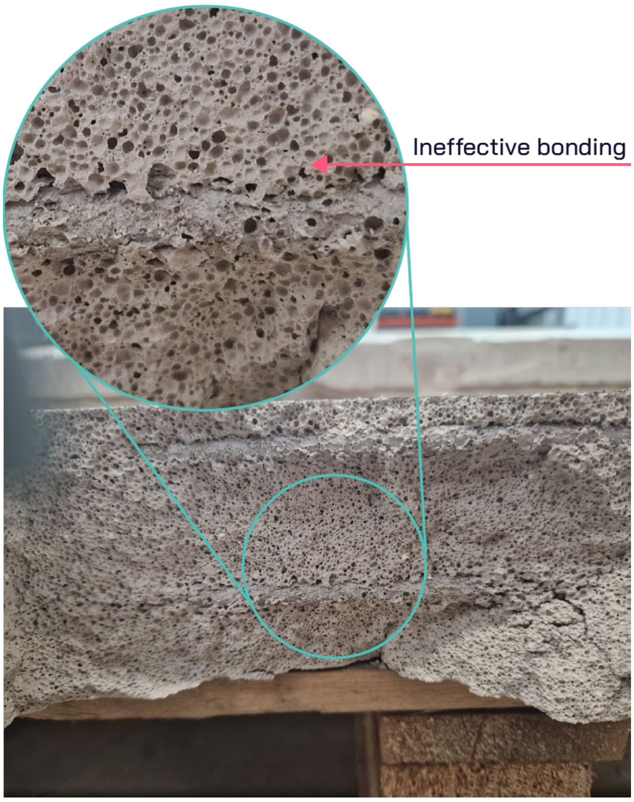


Figure 22: *Ineffective bonding between rebar and AAC*

Other defects or risk factors

Other defects and risk factors that might be found (not exhaustive):

- Panel distress caused by overloading (i.e. ponding water, services hanging from, or on top of, planks).
- Ineffective or inappropriate previous repairs.

Failure modes & defects explained

The simultaneity and severity of the defects increase the probability of occurrence of failure.

The ultimate failures of RAAC can be grouped into four types: Excessive deflection (Flexural failure, serviceability limit state (SLS) failure, and ultimate limit state (ULS) failure), shear failure, local instability, and material degradation, as shown in Figure 23.

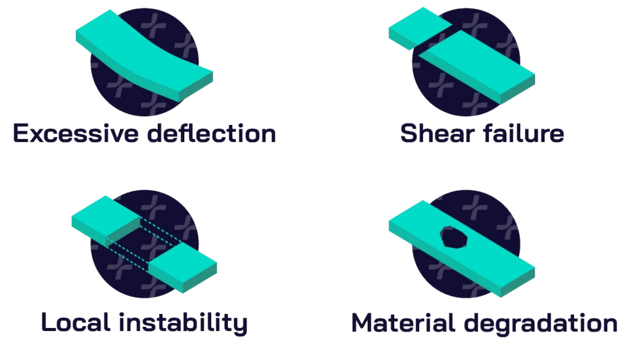


Figure 23: *Different RAAC failure types*

Excessive deflection (Flexural failure, SLS failure and ULS failure)

The Building Research Establishment (BRE) states that excessive in-service deflections are associated with RAAC roof planks [7] indicating a lack of stiffness and planks working close to their ultimate state. Before reaching the ULS, the SLS is passed. Excessive deflections result in the formation of cracks along the planks, increased ponding of water and the potential failure of water-proofing systems.

Excessive deflection can be the result of insufficient span-to-depth ratio, slippage between the reinforcement and AAC due to insufficient bonding or missing transverse rebars, excessive loading, excessive moisture content during or after installation, defective autoclaving, a lower elastic modulus than expected, and the development of creep strain over time, or the simultaneity of any of these [3, 2].

While the serviceability failure does not imply the ULS failure of the material, deflections greater than 1/50 can lead to the collapse of the plank [3]. Nonetheless, mid-span deflections greater than 1/100 require remedial works in all cases [9]. In addition, the induced rotation of planks can effectively reduce the surface contact between plank and bearing support thereby increasing the stress and increasing the risk of shear failure, see Figure 24.

The design of aerated concrete planks was influenced by their low strength and elastic modulus. In the 1960s there was no universally accepted design method for RAAC among countries and it was not regulated. As a result of this, no design codes of practice existed in the UK. European manufacturers based their designs on the elastic theory, limiting deflections to 1/400th of the span under working loads, or on tests to destruction methods. The latter could be a cause of the high span-to-depth ratios of up to 30, utilised in RAAC roof planks. It must be considered that, in the case of following the testing procedure, strength reduction and deflection increase due to the long-term effect of prolonged exposure to moisture or loading, might be overlooked [1].

Similarly, this approach would not consider the development of creep strain with time. Additionally, it has been reported [3] that the gravimetric moisture content of AAC could be of some 20-30% reaching the advised -by manufacturers- moisture equilibrium (5%) after several years in a dry indoor environment. Although, the real contribution of AAC to the final performance is under discussion, this could also be behind the poor performance of planks if they were installed before drying out to an acceptable level or the moisture was entrapped due to the application of other coatings or roofing membranes before reaching such level [2]. Figure 24 demonstrates how excessive deflection might be responsible for shear failure.

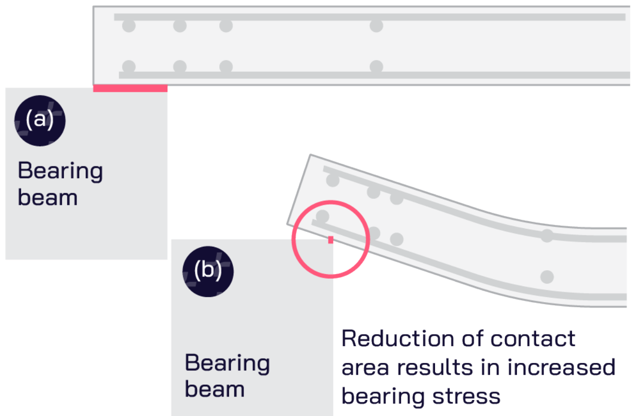


Figure 24: *(a) Full sufficient contact area of end bearing in RAAC panel with supporting element, (b) Excessive deflection may lead to shear failure due to the increase of shear stress after the reduction of area of contact.*

Static loading: *(Static action) action that does not cause significant acceleration of the structure or structural members (11)*

Failure modes & defects explained

Shear failure

Failure of structures due to excessive shear stress may lead to collapse with little or no previous warning. There are concerns regarding the sufficiency of the bearings of planks, arising from the short bearing length. The condition and position of the transverse rebars are also matters of concern.

Shear failure was not considered to be a concern during the initial period of RAAC usage. In an IStructE paper published in 1961 [1], Short and Kinniburgh reported that shear failure was found to be a secondary failure for RAAC planks, whilst the primary failure was associated with the excessive anchorage stresses between the reinforcement and the concrete due to a deficient bond. Planks containing cement-rubber coated rebars showed better bonding in comparison to those coated with bitumen. The former failed due to excessive shear. It was highlighted that the shear failure occurred particularly after planks were subjected to prolonged loading under exposed conditions.

After recent investigations undertaken by Loughborough University as a part of the NHS-funded RAAC research programme (2021-2023), a close dependency between the shear capacity and the position of the transverse rebars with regards to the bearing length was identified as a critical factor. The IStructE guidelines in parallel indicated that planks with bearing lengths below 75mm must be considered as critical despite the length or the loading of the plank [9].

The recent findings on the susceptibility of RAAC planks after decades of service align with observations made in the past on planks subjected to prolonged loading Figure 25 (a), (b) and (c) look at the influence of transverse rebar placement.

Further research is needed to fully understand this type of failure.

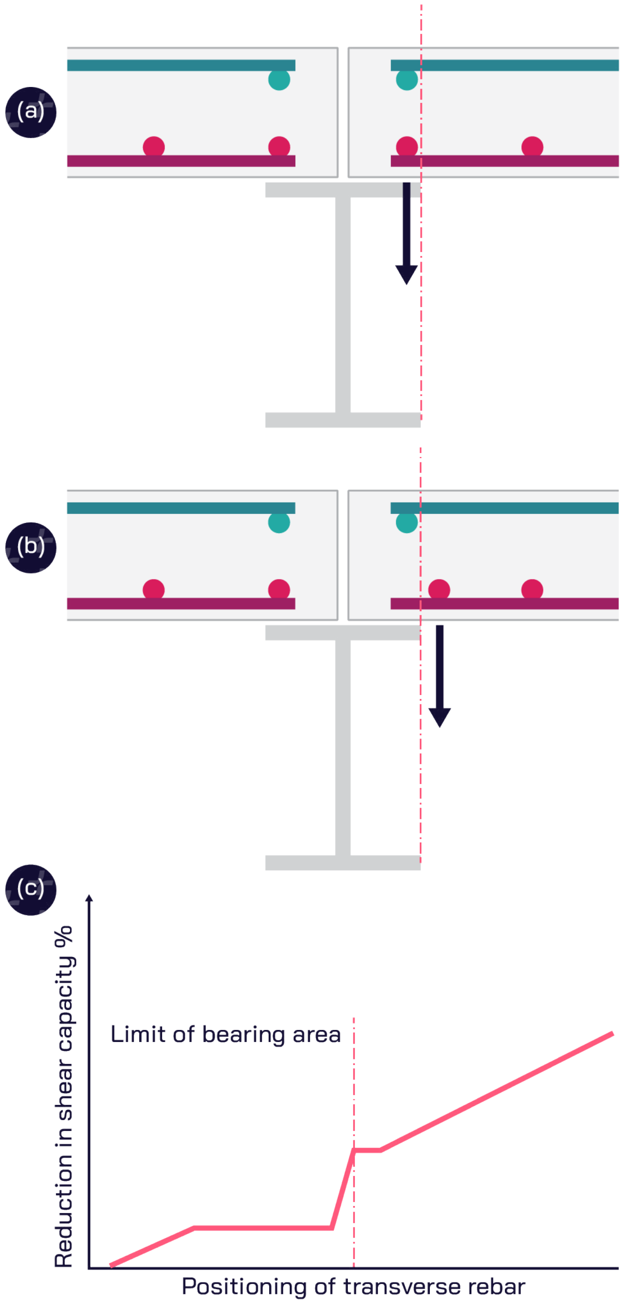


Figure 25: *Influence of transverse rebar placement, based on Loughborough University research (a) transverse rebar within the support length (b) Transverse rebar outside of bearing (c) Reduction in shear capacity against the location of the transverse rebar to the bearing.*

Local instability of planks

Cut planks are not a failure mode, but a defect. Complete or partially cut planks which are trimmed or untrimmed, with an understanding that 'trim' is the steel hanger, are common in buildings containing RAAC planks (trimming is a general civil engineering term for providing additional support around holes and penetrations). Trims hung from the top of adjacent planks, were commonly used Figure 26 (a). This practice puts the adjacent planks under undesired point loading and creates torsional moments compromising the structural integrity of the plank, as shown in Figure 26 (a, b). Other scenarios with local instability of planks include inadequate remediation, as shown in Figure 26 (c).

Material degradation

The existence of other types of defects can lead to the degradation of the matrix of the reinforcement, diminishing the strength capacity and durability of the planks.

For instance, open cracks can expedite the corrosion of the rebars. The coating on the rebars may also fracture due to external factors such as excessive deflection and thermal actions etc. Water ingress decreases the compressive strength of the material even after the leak is remediated and, similarly, the moisture content can reduce the strength capacity. The bond can be reduced over time depending on the type of coating and the exposure to moisture. Additionally, hygrothermal changes may also degrade the material and the plank.

The material shows vulnerability over time. The combination of risk factors will be impacting of the material properties and the strength capacity of planks.

Point (concentrated) load:
A load acting on a very small area of a structure. This is distinct from a distributed load, which is a load that acts evenly over a structural member or over a surface that supports the load.

Hygrothermal:
Of or pertaining to the effects of both humidity and temperature on a material or system.

(a)
(b)
(c)

Figure 26: *(a) Vertical displacement in short planks supported by a hanger -supported by adjacent planks- that also supports the skylight installed, (b) detail of the hanger, (c) "L" bracket installed on the soffit of planks to support a sectioned plank (With permission from Airedale General Hospital).*

Chapter 2:
A standardised approach to RAAC

- A standardised approach to RAAC
- RAAC problem statement & assessment matrix

A standardised approach to RAAC

Working with the Construction Leadership Council, RAAC Industry Response Group, Technology Subgroup, the UKRI RAAC Impact Programme has adopted the following terminology to define categories as part of establishing a standardised approach. Doing so enables a common language and clearer definitions to be established.

Table 2: RAAC Categories Applied (non-sequential)

1	Identify	To correctly determine and report the presence of RAAC.
2	Assess	The issues to be considered allowing the condition of RAAC components to be identified and assessed.
	Remediate - Repair	A measure to rectify a defect in the structure (BS EN 1504-9:2008). Defect: unacceptable condition that may be in-built or the result of deterioration or damage.
3	Remediate - Reinforce	Use of reinforcement to retain and/or strengthen the RAAC for a determined duration.
	Remediate - Replace	The act of removing RAAC panels and substituting these with alternative systems.
4	Manage	Issues to be considered in identifying approaches to the management and monitoring of RAAC before and after any remediation works.
5	Research	To discover the latest information, understanding and knowledge that informs future RAAC strategies.

Table 3: Context Definitions Applied

Technology Solution(s)		Any product, system, process, software, material, kit of parts etc., that could be applied to improve the identification, assessment, remediation, and management of RAAC.
	Existing	Any of those above that are available in the marketplace for purchase and use/purchase 'off the shelf' – "Technology Readiness Level (TRL) 9" [12]
Availability Status	Emerging	Any of those above that are in the process of being developed and/or tested for release to the marketplace in next 1-3 years (TRLs 4-8).
	Required	A problem area where no current or emerging technology exists but a solution has been identified as required.

RAAC problem statement & assessment matrix

PROBLEM	DESCRIPTION
IDENTIFY	
Accuracy	Right first time assessments (to extend the capacity to identify RAAC)
Non-invasive	During inspection, reduce exposure to hazards and contamination to improve safety
Constraints	Detect RAAC within hidden or hard to reach areas (to minimise possible exposure to asbestos-cont
Speed	Faster detection rates to reduce potential risk to life
Cost-effective	Enable greater capacity to complete detection (due to the extent of RAAC in buildings)
ASSESS	
Variability	Identify why some of the same batch of panels perform differently
Reinforcement - corrosion	Identify non-destructive testing (NDT) methods to assess the risk from levels of reinforcement corr
Reinforcement - end bearing(s)	Position of rebar over the bearings (including validation of NDT to determine position)
End bearing(s)	Dimensions, position, and seating arrangement (includes materials used and building movement)
Reinforcement - position in panel	Number, size, and position of reinforcement within the span of a panel
Autoclaved aerated concrete (AAC) quality	Identify methods to assess the condition e.g. effectiveness of curing process, impact of the concre
Moisture content	Identify methods to assess the moisture content of AAC using NDT methods
Environmental condition(s)	Quantification of risk factors e.g. water, humidity, aggressive conditions etc.
Panel modifications	Identify when panels have been cut or modified
Deflection	Develop methods to quickly measure deflection of panels
Reinforcement - coating type	Identify whether reinforcement coatings affect durability
Compressive strength	Identify NDT methods to assess AAC compressive strength
Cracking	Location, size, depth, size, type, progression etc.
REMEDIATE - REPAIR	
Repair end bearings	Guidance on effective end bearing strengthening
Repair cut panels	To restore inappropriate handling, cutting, preparation, installation or maintenance, repairs
Durability	Identify methods to prevent deterioration of RAAC in roof, floor, and wall panel(s)
Repair panels	Guidance on the repair of roof (and floor panels?)
Cracking	Preventative measures to infill and inhibit further cracking and/or weakening
Ingress	To prevent ingress from water, CO_2, chloride, etc.
Corrosion	To preserve, restore, increase resistivity, and cathodic control (protection and anodic areas)
Damage	From water, impact, combined water/frost, cyclical weathering, etc.
Spalling	To reinstate structural strength and durability
Repair material specification	To rectify manufacturer defects (voidage around reinforcement and incorrect cover to tension steel
Intrusive investigation	To repair damage caused by investigation through destructive testing
Visual	To improve aesthetics
REMEDIATE - REINFORCE	
Defects in RAAC - structural strengthening	To maintain current integrity/service life
Structural supports	Methodology to actively support the panel(s)
Strengthen end bearings	Guidance on methods to effectively strengthen end bearings
Failsafe	Guidance on approaches to stop falling items
REMEDIATE – REPLACE	
Strategic decision	Guidance on replacement options and decision-making processes
Building stability	Guidance on where removal could affect overall building stability
Temporary works required for removal	Advice on temporary works during removal
MANAGE (MONITOR AND REASSURE)	
Monitoring	Advice on approaches for the effective monitoring of RAAC components
Deflection	Advice on quantity and progression of deflection in panel(s)
Condition	Advice on condition of panel(s)
RESEARCH (LONG-TERM REQUIREMENT)	
Water ingress (short-term)	Impact of exposure to water ingress on short-term strength of panels
Water ingress (long-term)	Impact of exposure to water ingress on long-term strength of panels
Water ingress (durability)	Impact of water ingress on long-term durability of panels
Assessment tool(s)	Combined data and findings for predictive modelling and responses
Assessment calculation(s)	For various items above to help improve understanding of the situation
Variability	Difference in performance of seemingly similar panels from the same batch

PREPARED BY: Steven Yeomans (MTC), Martin Liddell (Sweco & IStructE Study Group), Veronica Torres de Sande (MTC), Andy Macfarlane (Curtins), Abbie Romano (Mott MacDonald), Chris Goodier (Loughborough University), Matthew Palmer (WSP), Tony Jones (Concrete Centre) plus others.

	IMPORTANCE - PRIORITY			IMPORTANCT - IMPACT			AVAILABILITY OF TECHNOLOGY SOLUTION(S)		
	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	EXISTING	EMERGING	REQUIRED
			●			●		+	+
			●			●		+	
taining materials)			●			●			+
		●				●			+
		●			●				+
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Chapter 3:
Non-destructive testing & metrology

- Non-destructive testing & metrology
- Description of technology trials
- Ground penetrating radar (GPR) on-site trials
- Ultrasonic testing (UT) onsite trials
- X-Ray backscatter (XBS) onsite trials
- NDT trial conclusions
- Metrology trial conclusions
- Barriers, challenges, key insights and next steps

Non-destructive testing & metrology

The purpose of this section is to:

- Introduce the concepts of Non-Destructive Testing and Metrology.
- Provide an overview of the considered inspection technologies for RAAC examinations.
- Determine the most appropriate systems from those identified based upon the outcomes of the validation studies.

What is Non-destructive Testing (NDT)?

Non-destructive testing (NDT): *a method of testing something that does not damage it. NDT is also known as non-destructive examination (NDE), non-destructive inspection (NDI) and non-destructive evaluation.*

NDT is a testing and analysis technique used by industry to evaluate the properties of a material, component, structure or system for characteristic differences, defects and discontinuities, without causing damage to the original part. Due to a focus on ageing infrastructure, there is a demand within the built environment to improve the speed, cost, accuracy and reliability of traditional examination methods.

The development of a robust, reliable and scalable RAAC testing system is required to inspect, evaluate and monitor potential RAAC issues, especially in higher risk or difficult to access locations. The assessment and development of NDT methods are urgently needed to support fast, reliable and digitally managed structural surveys. Rapid investigations have become essential to address the overwhelmingly large RAAC inspection challenge facing the UK.

An initial investigation into the suitability of NDT techniques, specifically to support RAAC examinations, found that there was very limited literature on assessment of NDT methods. However, it was found that RAAC is currently examined using two widely adopted methods as shown in 7. Other organisations have conducted trials using some NDT methods, such as Ground Penetrating Radar (GPR), but there is a lack of publicly available literature on the effectiveness of this technology.

VISUAL INSPECTION METHOD

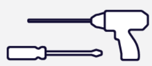
EFFECTIVE APPLICATION

- RAAC identification
- Water ingress detection (also potentially assessible with moisture meters)
- Surface damange detection

CHALLENGES

- Subjective and can be unreliable in certain conditions
- Lack of quantitative traceability

INTRUSIVE INSPECTION METHOD



EFFECTIVE APPLICATION

- 'Screwdriver' test/remove samples for identification
- Drilling to measure reinforcement positions over end bearings

CHALLENGES

- Damages RAAC panels, could reduce integrity
- Creates noise and dust
- H&S risks when disturbing RAAC if asbestos is present
- Slow and costly

Figure 27: *The two main groupings of RAAC assessment methods for the key metrics of RAAC identification, surface damage, water ingress detection and end bearing reinforcement detection and positioning*

Non-destructive testing & metrology

What is metrology?

Metrology *is the science of measurement using three fundamental quantities of length, mass, and time, which all other mechanical quantities, such as area, volume, acceleration, and power, can be derived. Metrology can be used as applied, technical or industrial metrology as an application of measurement to manufacturing and other industrial sectors.*

Within the built environment, there is a requirement to identify inspection systems that are capable of tracking NDT systems whilst they are being used to examine RAAC panels. It is important to understand the limitations of the current inspection methods to assess suitable technologies. To effectively tackle the RAAC crisis, it is critical to develop reliable and scalable RAAC monitoring systems to enable reduced frequency of inspections for higher risk areas and difficult to access locations. It is essential to effectively inform decisions on required remediation work. There are available inspection technologies that could provide reliable and repeatable monitoring solutions to inform decision-making. Therefore, there is an opportunity to adapt existing technologies used in other industries and to develop new technology using information from real situations, which can potentially effectively identify and apply corrective remedies.

Application

Existing RAAC surveys consider factors such as the position of transverse reinforcement, support bearing lengths, panel thickness, water ingress, panel deflections and cracking as key to assessing structural integrity. These surveys however are slow, manual and present health and safety risks (e.g. presence of asbestos, working at height).

To evaluate the condition and risk of RAAC panels effectively, there are known limitations to their identification and examination, such as access, large quantity of planks and their structural variability. Although the use of non-intrusive NDT methods is discouraged (due to its alleged lack of accuracy), high cost and complex data processing and intrusive investigations may cause undesired disruptions, produce dust, are time consuming and disturb asbestos, if present.

This presents an opportunity for MTC to investigate the feasibility of using NDT and metrology technologies for examining RAAC initially concentrating on the following:

- Understanding the position of transverse reinforcement (across panel width).
- Particularly important to understand the position of transverse anchorage reinforcement over bearings.
- Identify evidence of water ingress.
- Identify evidence of deformation of RAAC panels (deflections).
- Identify cracking of panels (indicative of deformation).

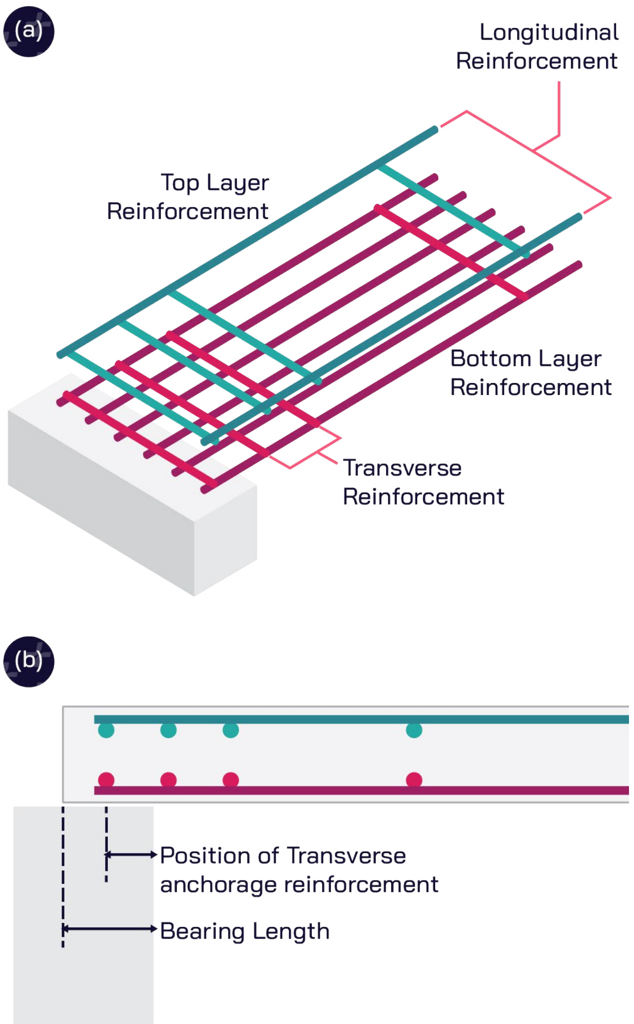


Figure 28: *Illustration of the typical reinforcement arrangement found with RAAC, highlighting the definition of bearing length and position of transverse anchorage reinforcement. (a) Isometric view, (b) side view.*

What are the benefits?

The programme focussed on the demonstration of NDT and metrology capabilities with quantitative evidence and prioritise identifying gaps in process and risk factors. If NDT and metrology can be proven to give the accuracy and practical use in the field, then there are several obvious benefits:

- Greater coverage potential of RAAC panels through rapid and non-invasive NDT and metrology, building greater confidence in the risk within assets.
- Reducing the number of intrusive investigations required (e.g. avoid disturbing asbestos, reducing dust and noise).
- Accelerated complete inspection cycle time as no remedial work required after NDT and metrology, unlike intrusive examinations.
- Improved traceability (digital outputs) of plank conditions (e.g. recorded and validated data).
- Enhancing the decision-making process of responsible parties on course of action (i.e. better understanding of risk with larger quantitative inspection datasets available following NDT and metrology, support business case for resolution).

Non-Destructive Testing and Metrology

Metrology - generic methodology

MTC's inspection system down-selection process as shown in Figure 29, is a series of rigorous steps to determine the most appropriate inspection systems for a specific inspection task. The down-selection process can be adapted to determine the most various types of inspection system depending on the specific application.

1 PROBLEM DEFINITION

DESCRIPTION: Observation of current process and/or collection of information about components to be inspected with the new inspection system.

PURPOSE: Set the operating principles in which the inspection systems must perform to achieve the required performance. Understand the environment in which it must be used, how the system must work and the outputs required.

2 TECHNICAL SPECIFICATION

DESCRIPTION: Highlight the important criteria by which the inspection systems will be assessed and ranked. Weighting should be decided with an appropriate expert. This will result in the creation of a numerical matrix of criteria

PURPOSE: Generate a list of key criteria identified as most critical to the inspection requirements to form the basis of the technical specification. Develop a numerical comparison between potential systems to make an informed decision on appropriate options.

3 FIRST STAGE DOWN-SELECTION

DESCRIPTION: A preliminary down-selection stage based upon the critical criteria of the inspection process to remove inappropriate systems. This will be supported by the numerical matrix to filter appropriate systems.

PURPOSE: Identify specific systems within the chosen operating principles that may be appropriate for the target application set in the problem definition. The down-selection will determine if the system is appropriate to progress to the next stage for further assessment.

4 SECOND STAGE DOWN-SELECTION

DESCRIPTION: Perform trials on the selected inspection systems in order to populate the remaining fields of the numerical matrix to determine the most appropriate inspection system. Representative artefacts are required for performance analysis of the selected inspection systems.

PURPOSE: Task-specific performance assessment of the progressed systems validated through a series of trials. These trials could take place in a controlled or real environments depending on maturity of technology.

5 SYSTEM VALIDATION

DESCRIPTION: A Measurement Systems Analysis (MSA) study, usually using Gauge Repeatability and Reproducibility (GR&R), to determine the repeatability and the reproducibility of the most appropriate inspection system to ensure it can perform within the process requirements.

PURPOSE: MSA Study Details

GR&R process

6 SYSTEM PROCUREMENT

DESCRIPTION: Purchase the most appropriate system for the application and ensure the system can perform within the required specification.

PURPOSE: For larger projects consider scalability, future supply, compatibility, robustness, and ease of use.

Figure 29: *MTC's standard down-selection process used to determine the most appropriate technology systems*

Key inspection criteria filtration activity

Key criteria from the technical specification focus on operating principles that fulfil the required function of the inspection system, such as portable by a single operator, measurement accuracy better than 5cm or set up time of less than 30 minutes. The operating principles are the fundamental physics behind how a system works, independent of the system manufacturer or model. From the identified operating principles, the systems will be scored against all the criteria in the technical specification, giving each system an effective total score with applied weightings.

As part of the UKRI RAAC Impact Programme, The MTC focused on the NDT and metrology technologies shown in Figure 30 and 31 to assess the main challenges with RAAC examinations.

NDT SYSTEM

GROUND PENETRATING RADAR (GPR)	**DESCRIPTION:** Measure the phase, amplitude and time of flight of radio signals to construct volumetric images in 3D to give positional information of subsurface structures and defects.	**TYPICAL USE:** Subsurface reinforcement and utility mapping, thickness measurements, void detection, and moisture mapping.
ULTRASONIC TESTING (UT)	**DESCRIPTION:** High frequency mechanical waves (e.g. sound waves) used to probe for differences in material acoustic properties to map the subsurface of assets.	**TYPICAL USE:** Subsurface reinforcement mapping, thickness measurements, void, and delamination detection.
X-RAY BACKSCATTER (XBS)	**DESCRIPTION:** XBS imagers emit beams in a fan pattern, then detect X-rays that are scattered back towards the imager's detector to detect radiation reflected from the surface of the examined object, generating a 2D image.	**TYPICAL USE:** Contraband inspection, hidden element inspection.
X-RAY COMPUTED TOMOGRAPHY (XCT)	**DESCRIPTION:** The sample is irradiated with X-rays to create two-dimensional (2D) radiographs, and then mathematical algorithms create the virtual 3D cross-sectional representation highlighting both internal and external features.	**TYPICAL USE:** Internal structure measurement, defects and porosity quantification, dimensional measurements, and roughness analysis.

Figure 30: *NDT technologies considered for RAAC inspection*

Non-Destructive Testing and Metrology

METROLOGY SYSTEM

MACHINE VISION SYSTEMS (MVS)	**DESCRIPTION:** Machine Vision systems uses different cameras, lighting sources and targets to detect or track an object moving through space.	**TYPICAL USE:** Detecting defects in mass produced components, and automated detection of presence of items in a space that should be clear.
INDOOR GLOBAL POSITIONING SYSTEM (IGPS)	**DESCRIPTION:** iGPS is a technology that uses a network of devices that connect to one another to calculate the internal position of an object in which it is tracking. There are several subcategories within iGPS, but specifically for this project we focused on Ultra-wideband (UWB). UWB can accurately measure the distance between Radio Frequency (RF) transceivers by calculating the time taken for the radio signals to move from point to point allowing devices to calculate accurate locations in real time.	**TYPICAL USE:** Tracking components in manufacturing facilities, tracking assets in storage yards, and tracking safety equipment around human operators.
LASER TRACKER & TACTILE PROBING (LTTP)	**DESCRIPTION:** Laser trackers project a laser beam onto an optical target in contact with an object being measured. The device then determines the three-dimensional position of the target. The inclusion of tactile probing allows for 6 Degrees of Freedom (6DoF) measurement. The probe contacts the object being measured and the probe device that houses the probes is then measured by the reflector, eliminating the need for the laser tracker to have a direct line of sight with the object.	**TYPICAL USE:** Aerospace and automotive inspection applications. High accuracy and large volume inspection applications, typically high value manufacturing.

Figure 31: *Metrology systems trialled to observe the condition of RAAC*

The UKRI RAAC Impact Programme - Metrology & NDT

The general approach was to adopt the MTC's standard down-selection process, as shown in Figure 32, to determine the most appropriate inspection technologies for the UKRI RAAC Impact Programme, specifically for RAAC roof panels. This includes an approach to validation and deployment of the down-selected inspection systems. Additional effort was made to be more open and flexible in trying a wider range of solutions, aimed to increase the chances of a positive outcome. The initial work completed followed the first four stages of the down-selection process:

The NDT and metrology systems were subject to separate down-selection processes:

- The selection of the NDT solution to non-destructively assess and record if RAAC is present in each panel and inspect the internal structure of the panel.
- The selection of the metrology solution to measure the absolute deflection of panels and their comparative deflection with neighbouring panels.

The initial activities are shown in Figure 33.

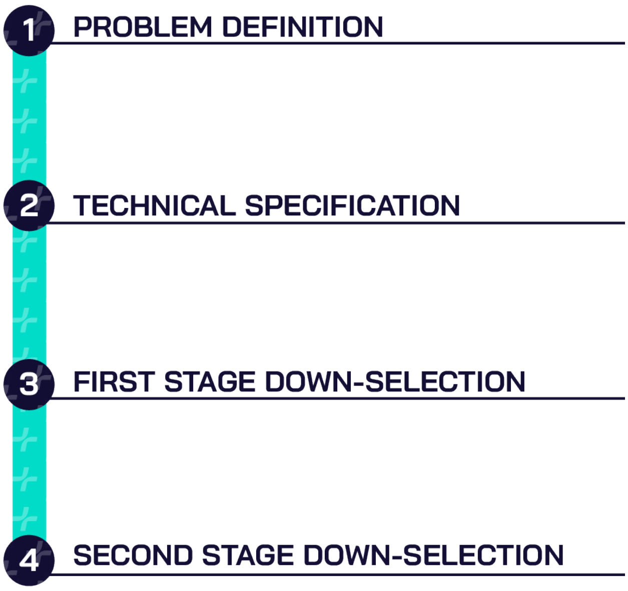


Figure 32: *Diagram of the generic methodology applied to the UKRI RAAC Impact Programme*

Non-Destructive Testing and Metrology

NDT

1 PROBLEM DEFINITION

The problem definition set out the key objectives of the inspection system required. These were:

- Non-destructively assess and record if RAAC is present in each panel
- Detect and inspect each RAAC panel to determine the level of deterioration of the internal structure
- Instantly feedback information to the operator.

2 TECHNICAL SPECIFICATION

An initial assessment of available NDT methods applied in industry to establish the most critical criteria for system comparison, shown below:

- Distinguish internal structure and positioning
- Detection and identification of water ingress
- Measure unexposed bearing locations.

3 FIRST STAGE DOWN-SELECTION

The first stage down-selection involves the full scoring of each system against the criteria to determine systems to progress. The NDT systems were selected from the following types.

- GPR
- UT
- XBS
- XCT.

4 SECOND STAGE DOWN-SELECTION

The task-specific performance of the inspection systems was determined through a series of validation studies, at the Airedale General Hospital (AGH) site. These trials supported the selection of appropriate non-destructive methods to detect the presence of RAAC, assessed its safe working conditions and identified any additional functional life.

METROLOGY

1 PROBLEM DEFINITION

The problem definition set out the key objectives of the inspection system required. These were:

- Measure absolute deflection of RAAC panels
- Measure comparable between neighbouring RAAC panels
- Monitor the condition and changes in the RAAC panels over time by measuring deflection.

2 TECHNICAL SPECIFICATION

An initial assessment of current metrology methods i.e. used at AGH, and their associated limitations, to establish the most critical criteria for system comparison, shown below:

- Machine Vision
- Indoor Global Positioning System (iGPS)
- Laser Tracker & Tactile Probing (LTTP).

3 FIRST STAGE DOWN-SELECTION

Involves the full scoring of each system against the criteria to progress appropriate measurement systems for detecting deflection of RAAC panels. All UWB iGPS progressed as they are the most practical method for tracking the NDT systems, along with the highest scoring MVS and LTTP systems. These systems progressed to the validation trials.

4 SECOND STAGE DOWN-SELECTION

This stage of the down-selection is where the task-specific performance of the identified systems was validated through a series of measurement trials. Specifically, each metrology system was used to track an NDT system in space whilst inspecting RAAC samples of known integrity. The identified systems were validated in both live and controlled environments in the laboratory.

Figure 33: *MTC's standard down-selection process to determine the most appropriate inspection systems for RAAC*

Criterion

As part of the MTC down selection process, criteria as shown in Table 5 are used to assess each technology.

Table 4: Criterion to Assess Appropriate Inspection Systems

1.1	Temperature range
1.2	Temperature change rate
1.3	Temperature compensation
1.4	Humidity (non-condensing)
1.5	Vibration
1.6	Lighting
2.1	Size of the measurement system
2.2	Footprint of the measurement system
2.3	Weight of the measurement system
2.4	Power supply
2.5	Battery life
3.1	Capital cost
3.2	Running costs
3.3	Estimated modification cost
3.4	Estimated cost for software license
4.1	Calibration frequency
4.2	Calibration duration
4.3	Verification frequency
4.4	Verification time
4.5	Validation frequency
4.6	Validation duration
4.7	Preventative maintenance frequency
4.8	Setup time
4.9	System conditioning time
5.1	Maximum survey size (single measurement)
5.2	Survey stitching
5.3	Tracking ability
5.4	Capable of measurement in regions without line of sight
5.5	Inspection speed
5.6	Non-contact inspection
5.7	Automated inspection
5.8	Targetless acquisition
6.1	Computational requirements
6.2	Data representation
6.3	Data filtering
6.4	Data registration
6.5	Post-processing analysis time
6.6	Automation of data analysis
6.7	Offline processing
6.8	Data file size
6.9	Exporting of data
6.10	Hardware requirements
6.11	Data comparison with previous datasets
7.1	Training time required for operating the measurement system
7.2	Training time required for the software for data acquisition
7.3	Training time required for software for analysing data
8.1	Ease of data capture
8.2	Ease of data processing
9.1	Hazardous emissions
9.2	Personal protective equipment (PPE) required
10.1	Ruggedness
10.2	Consumable replacement
11.1	Technical support
11.2	Software support

Description of technology trials

Due to the varied environments in which RAAC panels are located, practical, flexible and versatile inspection solutions are required. Initially, the selected systems are assessed by their physical attributes within a controlled environment, including portability, ease of set up, ease of use in situ and ease of removal.

The second phase of the validation process involved the deployment of the inspection equipment to site locations to collect inspection data from various real-world environments. The data was used to assess the equipment's performance under expected conditions. Additionally, the data quality collected can be analysed and help identify other challenges encountered during data collection, such as line-of-sight issues due to mechanical, electrical and plumbing (MEP) obstructions.

Ground penetrating radar (GPR) on-site trials

These are the main aims of site trials for GPR technology on RAAC panels:

- To detect and map the reinforcement positions within exposed panel sections.
- To detect and map water ingress.
- To detect transverse reinforcements at bearing locations.
- To detect and measure end bearing length of supported panels.

What is reinforcement mapping?

This is a method which uses ultra-high frequency radars, which are thought to be an ideal system for locating and inspecting reinforcement without damaging the existing structure. It is a quick test method which examines spacing, initiation of spalling and cover for the desired structural member whilst gathering information for the multi-layered reinforcements [13].

How reinforcement mapping can be used

To validate the GPR inspection capabilities, scans were done using the Proceq GP8800 inside several different rooms within a hospital estate featuring RAAC ceiling panels.

Figure 34: *Hospital rooms where GPR trials were conducted. (a) Room #1, (b) room #2, (Source: MTC. With permission of Airedale General Hospital)*

Figure 34 shows two rooms, both with exposed painted RAAC ceiling panels. The second features skylights with suspected cut panels fitted around the skylight with steel brackets.

A single longitudinal scan and a single transverse scan was conducted to detect and map the transverse reinforcement and longitudinal reinforcement within selected Room #1 panels.

Figure 35 shows the GPR inspection results from Panel 1 in Room #1, clearly showing the two transverse reinforcement bars and five longitudinal reinforcement bars. The panel thickness was also estimated to be 125 mm, which is in line with the known thickness of panels within the estate.

Figure 35 also shows the GPR inspection results from Panel 3 in Room #3, with similar detection of reinforcement bars, except with a strong response being received from the steel back support from the skylight. There is a steel bracket obscuring the bearing region below it, prompting an alternative approach to examine this type of area.

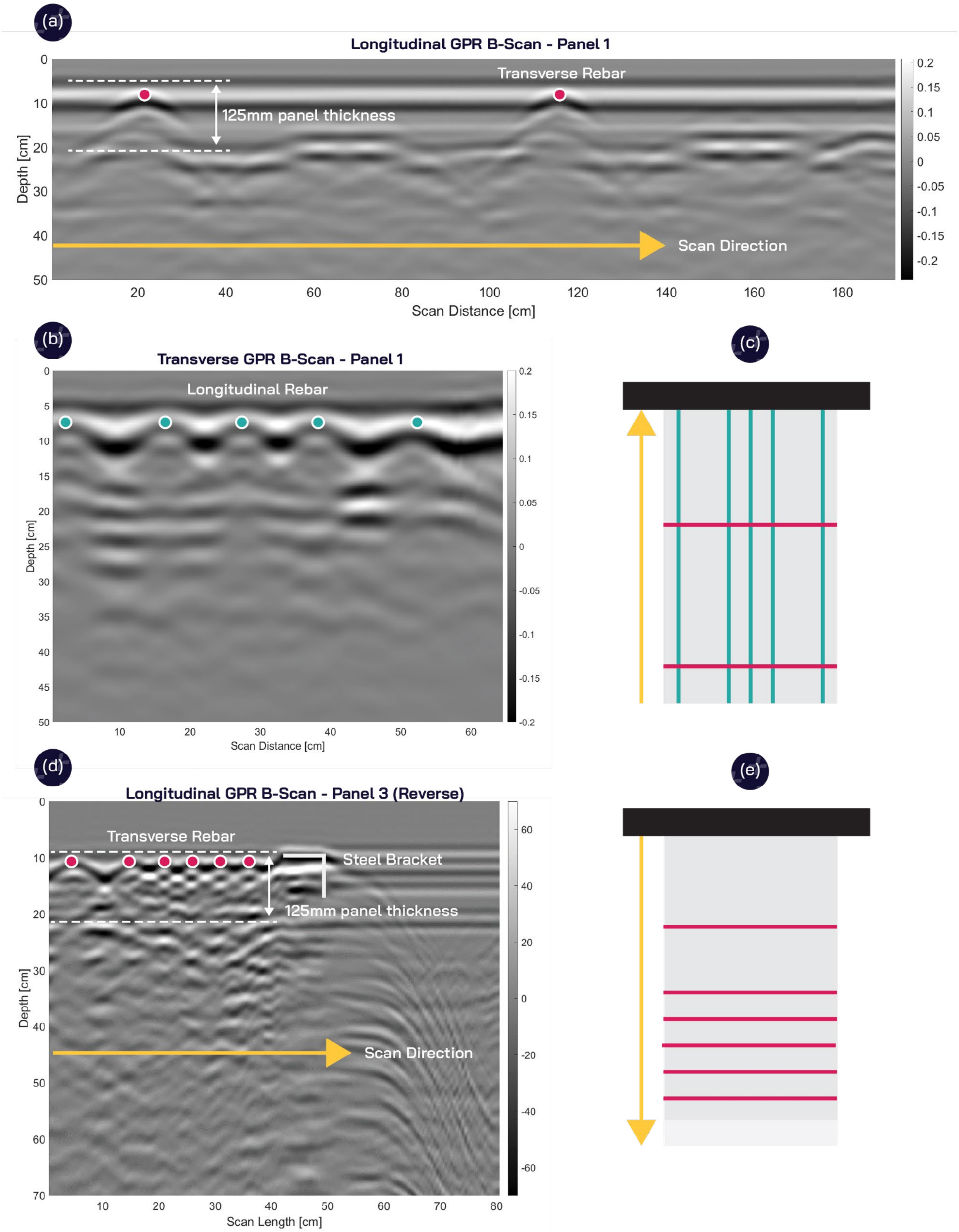


Figure 35: *a) Longitudinal GPR B-scan images of Panel 1 within the hospital estate, b) transverse GPR B-scan image of Panel 1, c) Schematic of the inferred reinforcement structure of Panel 1 from a) and b). d) Longitudinal GPR B-scan images of Panel 3 within the hospital estate featuring a steel support bracket near a skylight, e) Schematic of the inferred transverse reinforcement structure of Panel 3 from d).*

Observations using water ingress mapping

Within Room #1, severe water ingress was observed with rainwater dripping from a RAAC panel (Panel 4), as shown in Figure 36. This panel had subsequently been permanently propped up with a supporting wooden board to ensure its structural integrity. This panel however provided an opportunity to determine the effect of known severe water ingress on GPR inspections.

Another area examined within the hospital estate was Room #2, shown in Figure 37, which featured exposed unpainted RAAC ceiling panels which were visibly damp, however featured no water leakage.

Figure 38 shows the longitudinal B-scan images of two panels. On the left, Panel 4 exhibited severe water ingress in the centre of the panel. Water within the porous RAAC material observed an increase in backwall depth as well as exhibiting a lower amplitude compared to dry regions at both ends of the panel. This resulted in significantly overestimating the position of features within the data e.g. backwall.

On the right, Panel 5 reveals a series of transverse reinforcement bars and an apparent panel thickness of 151 mm, which is larger than the nominal thickness of 125 mm.

This suggests that moisture ingress is present and the wave speed within the panel is slower than in dry RAAC, increasing the backwall depth and the dielectric constant of the damp region of the panel.

This result shows that GPR can be used to qualitatively determine different levels of moisture ingress assuming knowledge of panel thickness is available.

Further research is required to determine if quantitative differences can be determined in the future. In the same way, further research is required to determine the quantitative impact of moisture/ water content on GPR end bearing measurements.

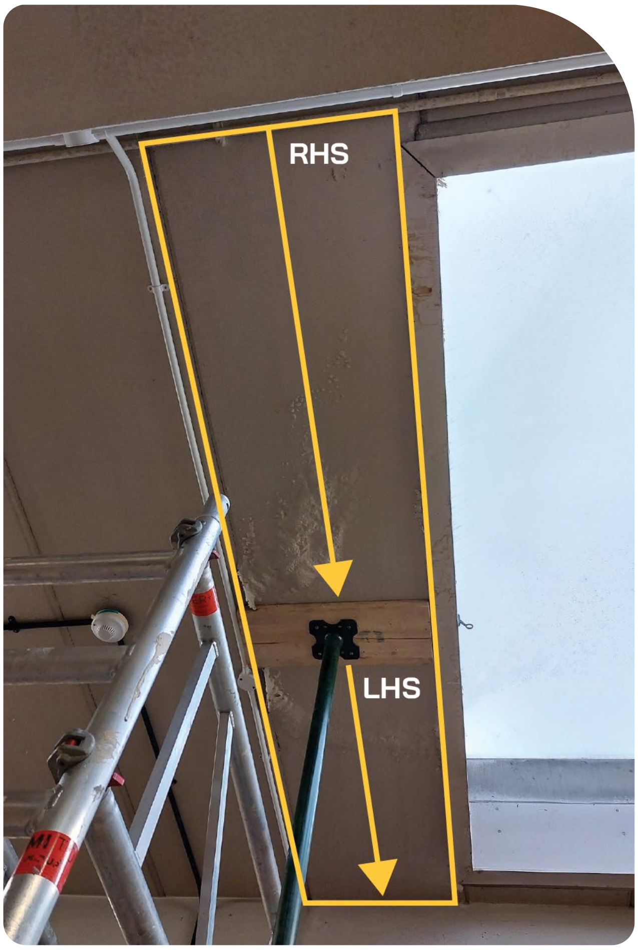


Figure 36: *Photograph of Panel 4 in Room #1 within the hospital estate featuring active water ingress*

Figure 37: *Photograph of Room #2 within the hospital estate where exposed RAAC ceiling panels were present that were noted to be damp (Source: MTC. With permission of Airedale General Hospital).*

Description of technology trials

End bearing inspection method

An angled beam GPR inspection methodology was developed to provide an in-room examination technique for RAAC panel end bearing surveys. The objectives were to:

- Detect and position any transverse reinforcement located within the end bearing region of RAAC panels.
- Estimate the end bearing length of RAAC panels.

The MTC developed 'concrete wedges' to support a specific off-the-shelf (OTS) GPR system (Proceq GP8800). The concrete wedges have fixed angles of 30°, 40°, 50° and 60°, relative to the horizontal surface to be scanned.

An image of the 40° concrete wedge used to conduct angled beam GPR inspection for all onsite trials, is shown in Figure 39 (left).

Figure 39 (b) shows how the concrete wedge is used to inspect on an angled path to the end bearing. It was determined that signal leakage from the front of the wedge, within the 50° and 60° wedges, made them undesirable for end bearing examinations, hence only the 30° and 40° concrete wedge were trialled.

To trial and validate the inspection capabilities of the angled-beam concrete GPR wedge that was developed, the system was trialled within the hospital estate across multiple different areas. Destructive intrusive drilling surveys were conducted on the surveyed panels to physically verify the GPR measurements collected.

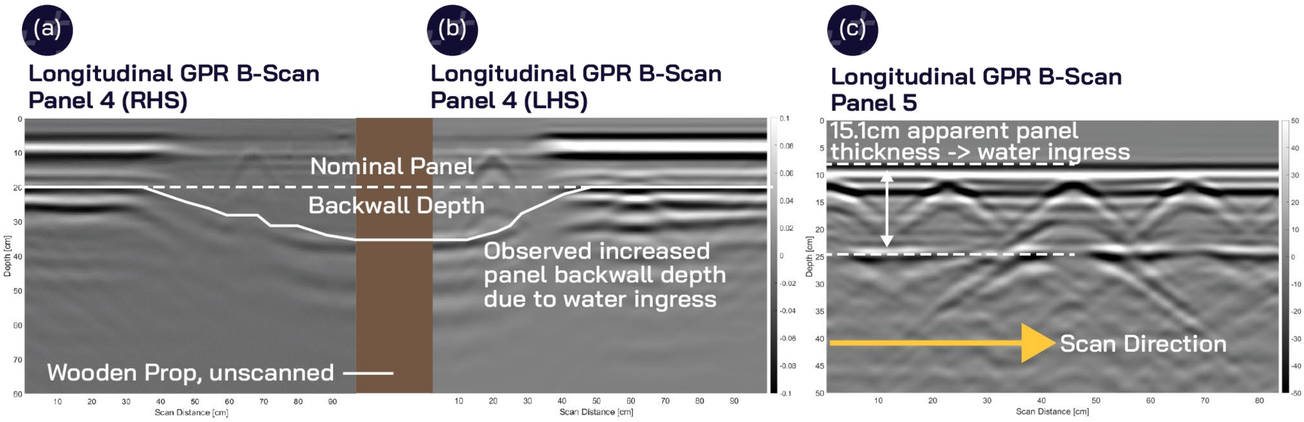


Figure 38: *(a) Stitched longitudinal B-scan of Panel 4 located in Room #1, (b) showing a defined region of water ingress. (c) Longitudinal GPR B-scan image of Panel 5 located in Room #2 in the hospital estate, showing a series of transverse reinforcement bars.*

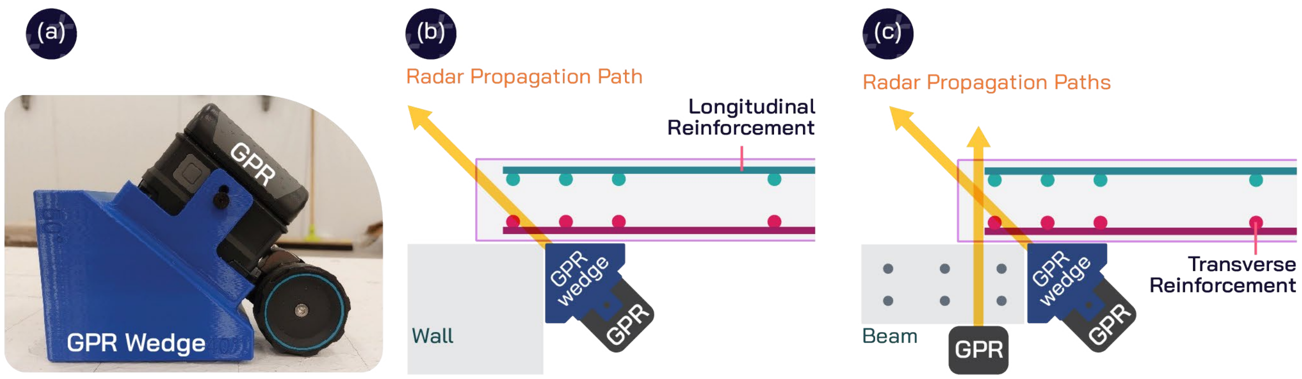


Figure 39: *(a) Model of GPR scanning device, (b) diagram to show purpose of wedge between wall and panel, (c) diagram to show purpose of wedge between beam and panel.*

Examples of breakouts created during the intrusive validation surveys are displayed in Figure 40, showing how the method exposed transverse reinforcement bars within the end bearing region, as well as locating the back of the RAAC panel to measure the bearing length.

Figure 40 also shows Room #4, where additional angled beam GPR was investigated, as an example of an area with a reduced accessibility RAAC panel arrangement.

Figure 41 suggests that there are at least two transverse reinforcement bars in the end bearing region at estimated bearing positions of 30 mm and 92 mm, using the 30° concrete wedge. The scan also estimates a worst-case end bearing length of the panel to be 219 mm.

The B-scans from Panel 9 in Room #4 using the 40° concrete wedge shown in Figure 41 (right) suggests that there are at least two transverse rebar in the end bearing regions at estimated bearing positions of 4 mm and 57 mm, with an estimated end bearing length of the panel to be 80 mm.

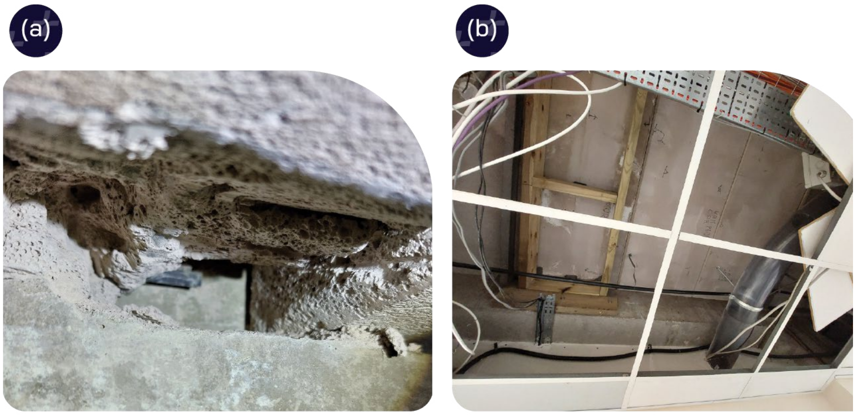


Figure 40: *(a) Photograph of an intrusive break-out region to physically locate transverse reinforcement over end bearing and measure the bearing length, (b) Photograph of Room #4 where RAAC ceiling panels hidden behind a suspended ceiling with electrical and plumbing utilities congesting the ceiling space (Source: MTC. With permission of Airedale General Hospital)*

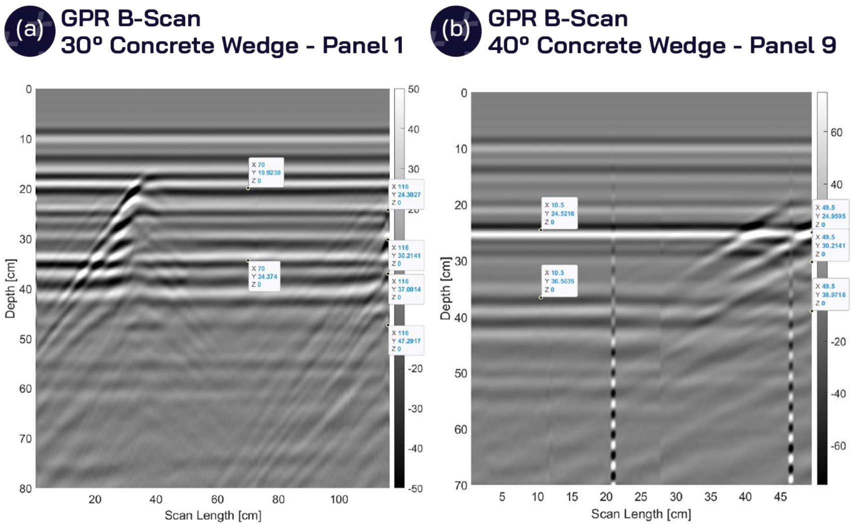


Figure 41: *(a) Angled beam GPR B-scan of Panel 1 in Room #1 using the 30° concrete wedge, (b) Angled beam GPR B-scan of Panel 9 in Room #4 using the 40° concrete wedge*

Ultrasonic testing (UT) onsite trials

The onsite trials investigated whether an ultrasound-based NDT approach can detect the presence of RAAC panels within a building roof. The trial activities were carried out at hospital and school locations:

- Multiple spot UT measurements on ceiling RAAC panels.
- Spot measurements, in some cases, on the entire length of the RAAC panel.

UT measurements were carried out on the RAAC panels classified at highest risk by the hospital estates team, with four separate rooms used for trials. Figure 42 shows UT scanning of RAAC panels in Room#1 and Room#4. A total of 19 RAAC panels were scanned with 184 spot scans across the four rooms.

UT measurements were also carried out on numerous RAAC panels within the sports hall at school #3. UT measurements were taken on a total of 38 panels, with one spot scan on each panel.

Owing to access limitations within the individual hospital rooms, and to support movement of the scaffolding tower, measurements were limited to certain regions of the RAAC panels.

Figure 43 shows the scanning technique and a schematic of UT device locations with reference to the RAAC panel.

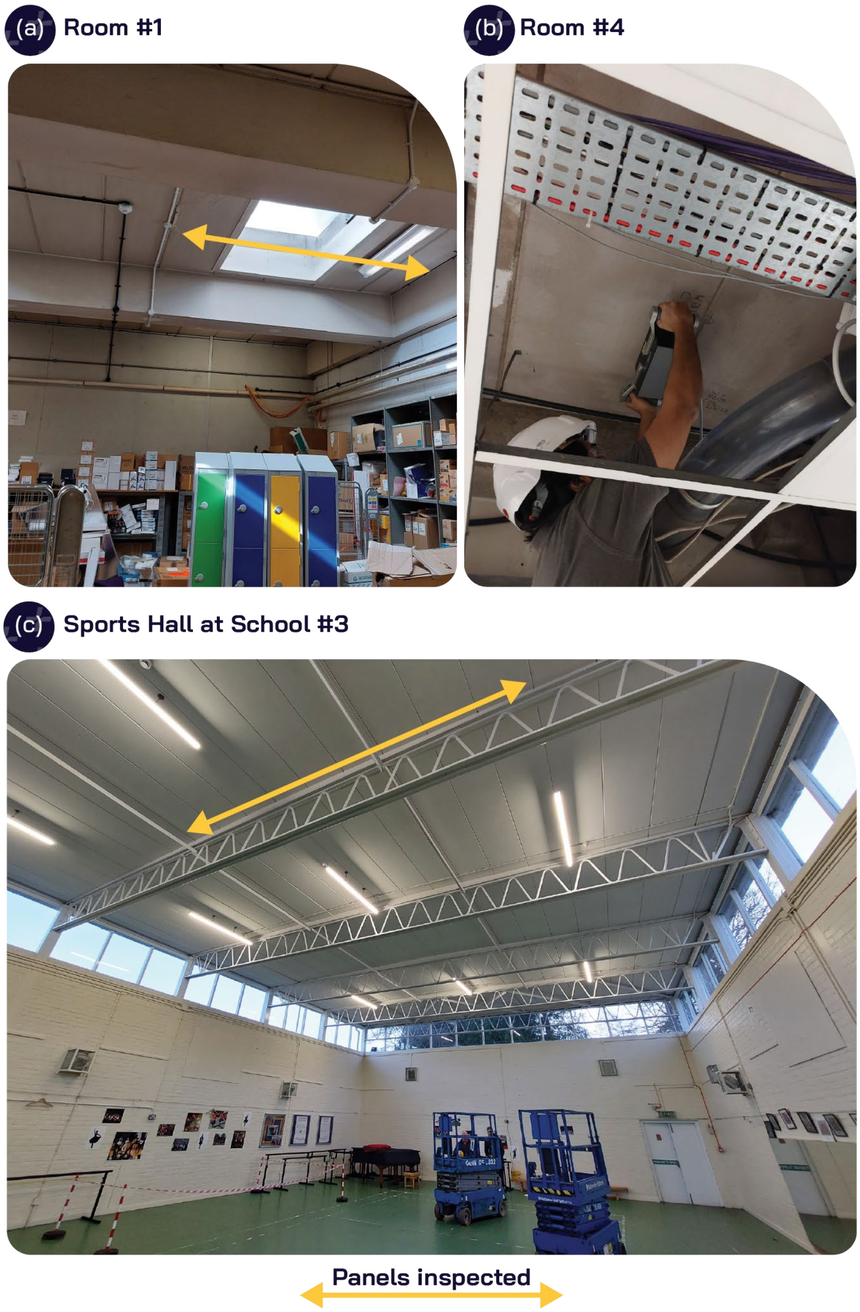
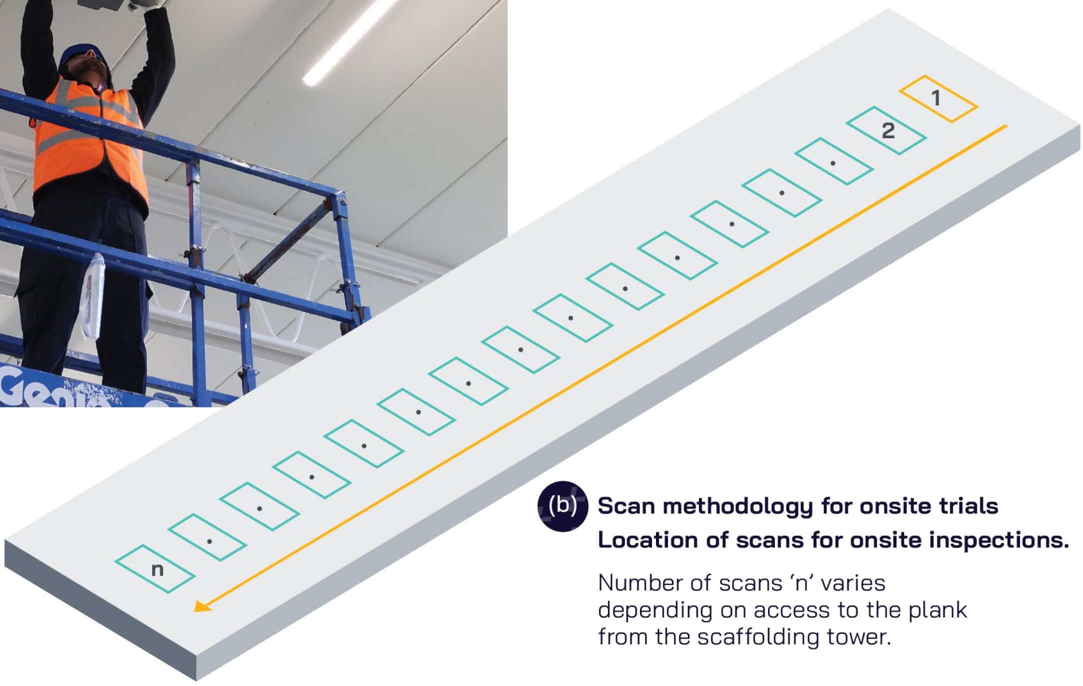


Figure 42: *Panel locations in Room#1, UT device scanning in Room#4 within the hospital estate (Source: MTC. With permission of Airedale General Hospital). Panel locations in the sports hall at school #3*

(a) **UT scanning technique**



(b) **Scan methodology for onsite trials**
Location of scans for onsite inspections.

Number of scans ‘n’ varies depending on access to the plank from the scaffolding tower.

Figure 43: *(a) The UT scanning technique from scaffolding tower.*
(b) A schematic of UT device locations with reference to the RAAC panel.

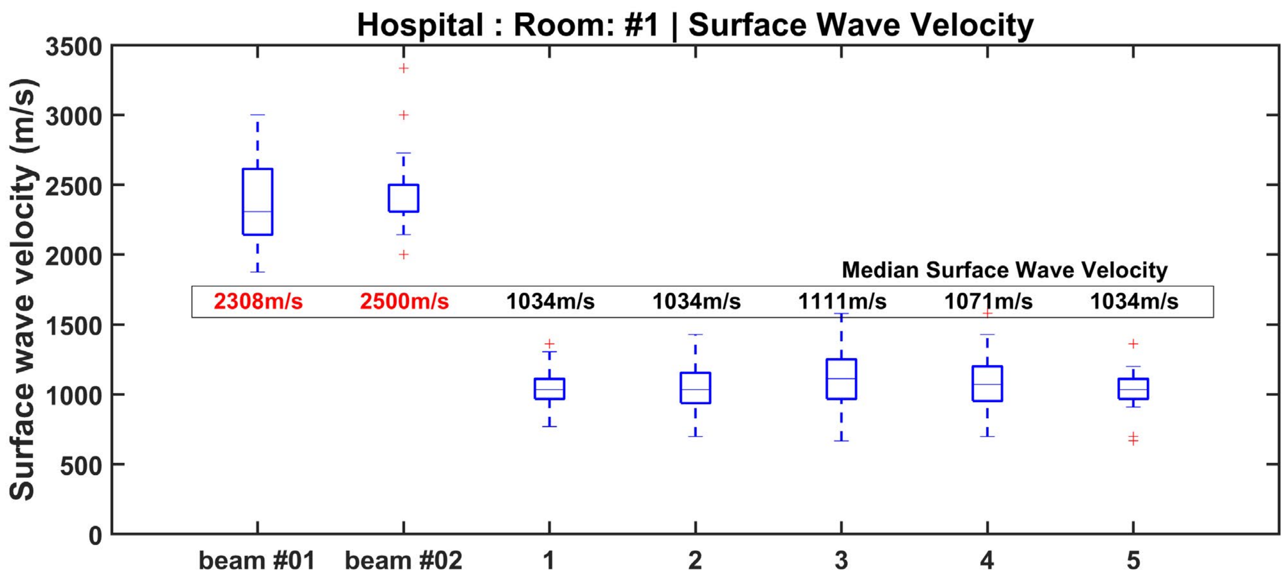


Figure 44: *Room 1 surface wave velocity mapping*

The results from the onsite trials have been able to further validate estimated results found using contact ultrasonic array NDT equipment in laboratory trials. The surface wave velocity variation across the RAAC panels is well below the wave speed in concrete (~2000m/s) highlighting a distinct difference in surface wave velocity observed between reinforced concrete beams and RAAC panels. This indicates that very limited measurement is sufficient for the identification of RAAC. However, attention must be given where coatings, plasterboards or asbestos are present to avoid confusing covered RAAC with concrete. Currently the MTC is working on the development of a protocol to do this.

The onsite trial confirmed the measurement of the surface wave velocity on RAAC, and traditional concrete could be used to distinguish between the two materials, as RAAC is half that of traditional concretes. The MTC have found that UT can be used as an objective identification tool for RAAC by measuring surface wave velocity. Further development of a smaller compact UT device that can be deployed using an extender pole, could significantly save time and reduce health & safety concerns.

X-Ray backscatter (XBS) onsite trials

The XBS inspection conducted during onsite trials revealed significant findings related to the presence of rebar and the identification of cracks. Multiple longitudinal and transverse scans were conducted on multiple RAAC panels, ranging from scans focused solely on the RAAC panels to scans encompassing additional features such as skylights. These scans were aimed at assessing the penetration capabilities of the XBS system and evaluating the structural integrity of the RAAC panels in those areas.

Notably, the inspection system identified multiple transverse and longitudinal internal reinforcement, distinguished the gaps between each RAAC panel, and detected cracks. However, further analysis is required to determine the depth of cracks from the XBS images.

Figure 45 shows six-line stitched transverse scans of RAAC panels within Room #3, showing five longitudinal rebars and two transverse rebars. The slight misalignment of scanned images can be attributed to the manual scanning process of the RAAC panels, particularly in maintaining a consistent scanning speed.

Inconsistencies in scanning speed resulted in variations in image lengths, making alignment and stitching difficult. Additionally, discrepancies in scanned distance leads to inconsistencies in the starting and ending points of each scan line, prompting potential automated scanning solutions to improve accuracy and efficiency in future inspections.

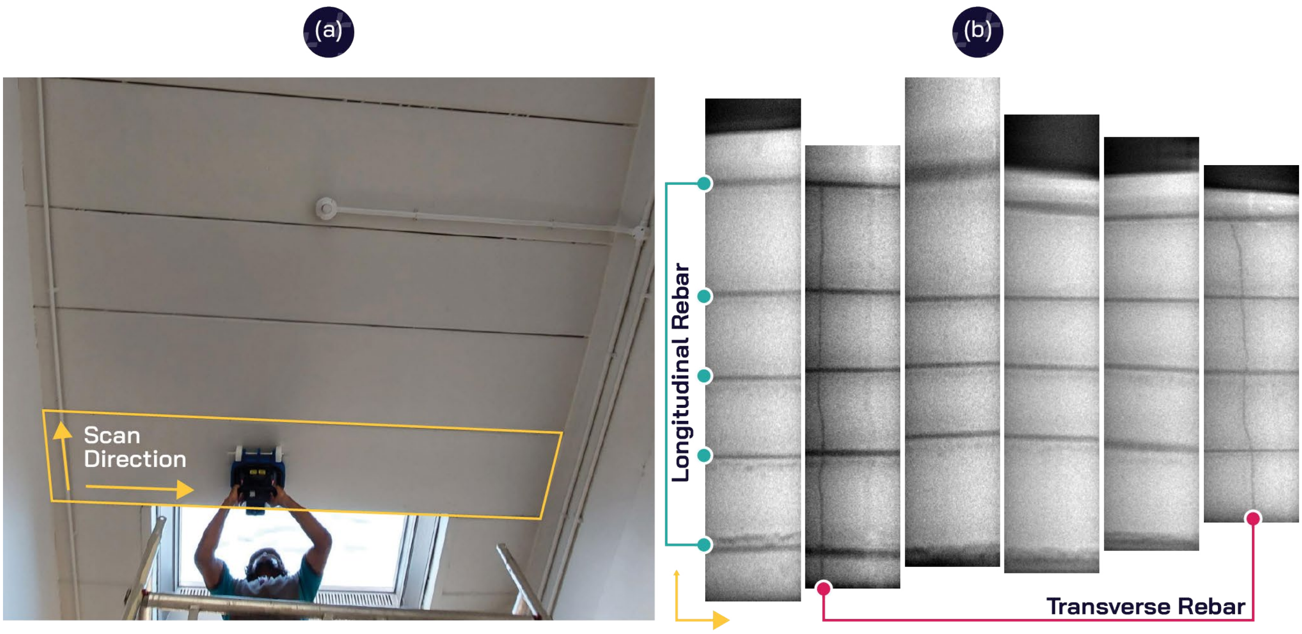


Figure 45: *(a) A photo of the RAAC panel scanned and (b) the processed and stitched transverse line scans of RAAC panels in Room #3, with the longitudinal and transverse rebar highlighted.*

NDT trial conclusions

Ground penetrating radar (GPR)

GPR has been shown to be able to readily detect and map transverse and longitudinal reinforcement within exposed sections of RAAC panels. From only one longitudinal scan and one transverse scan, the reinforcement arrangement of the exposed sections of a RAAC panel can be assessed.

In future work, correlation of the measured dielectric constant value of RAAC to a quantitative moisture ingress estimate could be possible. As well as mapping the spatial extent of water ingress, GPR also has the added benefit of being able to potentially detect ingress before it becomes visually evident. Current visual surveys rely upon seeing water stains and calcite build-up to detect, meaning moisture had penetrated through the entire thickness of the panel at that point.

To tackle the challenge of examining the hidden end bearing region of RAAC panels, a room-based, angled beam GPR inspection methodology has been developed. The angled beam GPR inspection technique has been shown to be able to detect transverse reinforcement within end bearing regions. The results show 100% success rate within the validated results, as well as the bottom corner trap reflection response used to estimate the end bearing length of a panel.

Good agreement in terms of positioning the transverse reinforcement over the bearing as validated by intrusive surveys:

- For the panels considered during validation with end bearings less than 100 mm, the average positional error of bearing transverse reinforcement was 5 mm for a sample size of six, and the average positional error of the end bearing length was 4 mm for a sample size of four.
- For the panels considered during validation with end bearings greater than 200 mm, the average positional error of bearing transverse reinforcement was 12 mm on a sample size of 16 and the average positional error of the end bearing length was 21 mm for a sample size of eight.
- For all panels considered during validation, the average positional error of bearing transverse reinforcement was 10 mm on a sample size of 24, and the average positional error of the end bearing length was 15 mm with a sample size of 12.

It is therefore suggested that the methodology and the specific GPR system utilised was able to achieve a positional measurement error for reinforcement within trials. This should be in line with the expected tolerances of the system, for example a 5 mm encoder step size tolerance and 4.5 mm time step size tolerance.

The positional measurement error for end bearings was larger than for reinforcement, which is possibly due to the corner trap response being weaker in amplitude compared to rebar. There is ambiguity in a number of the panels in terms of identifying the correct response, which related to the corner trap and often leads to a conservative low estimation of the end bearing that is being calculated.

Ultrasonic testing (UT)

UT was found to be effective in the detection of RAAC panels but there a few practical considerations to overcome. However, there are ways to use the UT technique more efficiently, if it is to be adopted.

Pundit PD 8050 weighs about 3.5kgs and requires erecting and moving scaffolding to access the ceiling panels, so it may be time consuming to cover larger rooms with a lot of RAAC panels.

A smaller 3-channel ground-operated UT device with extender and/or telescopic poles would be a preferred method to ease H&S restriction and improve inspection timings.

Such smaller devices are not commercially available. Therefore, additional outreach work is required to engage with equipment manufacturers to explore further possibilities.

Synthetic aperture focusing technique (SAFT) imaging can only provide a qualitative understanding of the internal features. This is a time-consuming approach in comparison to GPR for mapping internal features. It works on both exposed and painted RAAC panels and causes no damage at all. Currently it is deployed by taking single spot measurements on a panel <5s. It is not recommended for widespread use. Attention needs to be paid where coatings, plasterboards or asbestos are present to avoid confusing covered RAAC with concrete. Currently the MTC is working on the development of a protocol to do this.

X-Ray backscatter (XBS)

The XBS onsite trials, have provided valuable insights into the feasibility and effectiveness of utilising XBS technology for identification of RAAC panels. Through comprehensive experimentation and analysis, several key findings have emerged:

- Successful identification of internal features: The XBS inspection revealed significant findings related to the presence of rebar and the identification of surface cracks in the RAAC panels.
- Multiple transverse and longitudinal rebars were successfully identified, providing crucial information about the internal reinforcement of the RAAC structures.
- Challenges and considerations:
  - Despite the success in identifying internal features, challenges were encountered during the manual scanning process. Inconsistencies in scanning speed and alignment issues posed difficulties in achieving accurate and consistent results.
  - XBS wheel encoders were developed.
  - In addition, testing during the onsite trials and image artifacts and alignment were corrected. However, further work is required for full implementation of the encoders within the XBS system.
  - Additionally, concerns regarding H&S risks associated with XBS technology necessitate further investigation and the development of comprehensive safety protocols.

Metrology trials

The first stage down-selection identified the following measurement systems suitable and available for site trials:

- Leica BLK360
- Leica BLK2GO
- Leica Disto S910
- Leica ATS600

During this phase, site trials took place at two locations - a hospital and a school. At these sites, several locations were constructed entirely of RAAC panels and were made available for trials, with each exhibiting a unique situation and set of risks.

During the site-based trials, the data quality from each piece of equipment was analysed to determine accurate measurements of RAAC panel deflection, data collection, and accessibility for system setup and use.

The main inspection focus point within each trial area was to select the most appropriate locations for trialling the measurement systems. The MEP services in the roof space and the room layout would sometimes cause difficulties in conducting planned trials in a timely manner and would therefore, as seen in this case, focus on higher-risk elements of the RAAC, as can be seen in Figure 46.

The point clouds shown in Figure 47, were generated from the measurements of the room produced by each measurement system to make them easier to view. A colour map representing distance from a plane fitted to the floor, has been applied.

NDT trial conclusions

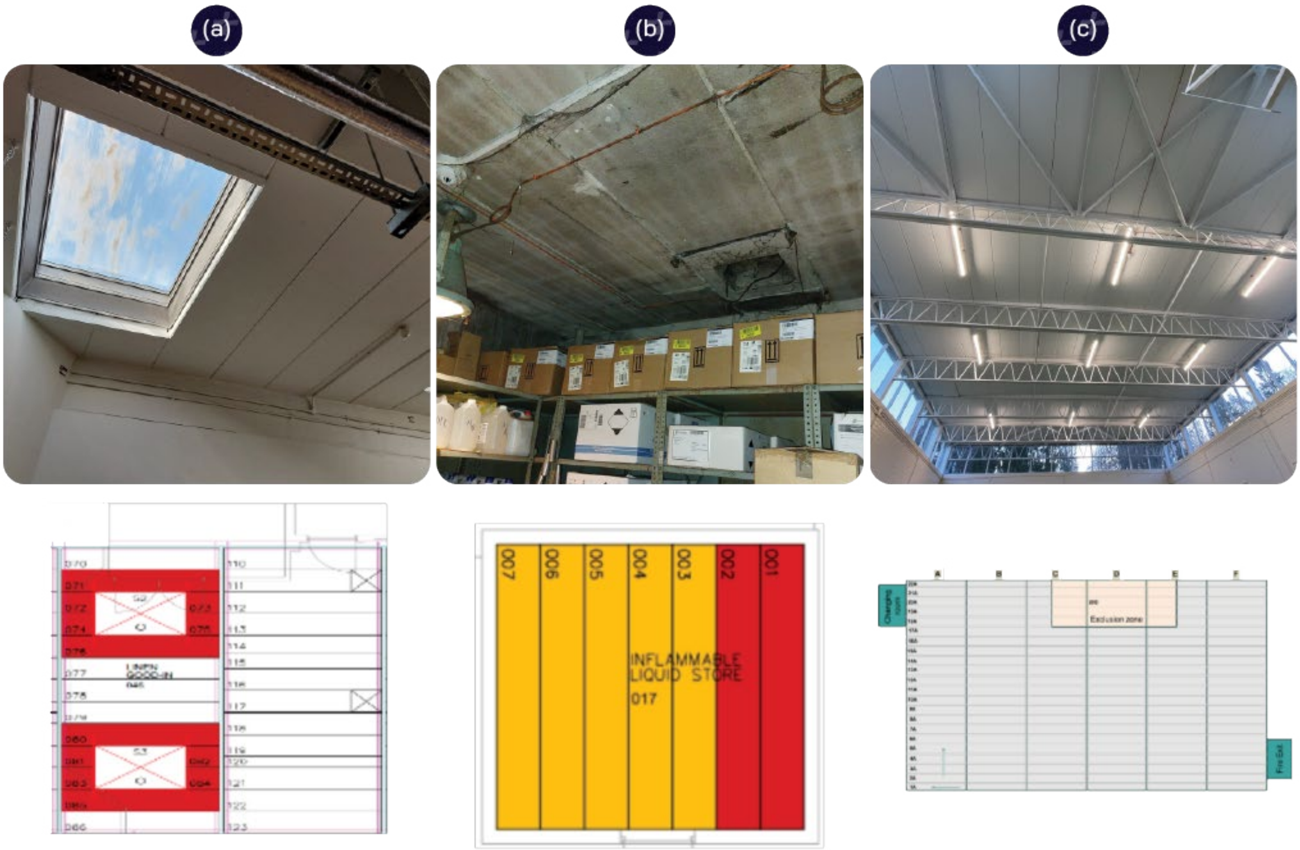


Figure 46: *Building location and ceiling layout for (a) hospital linen room, (b) liquid store and (c) school sports hall*

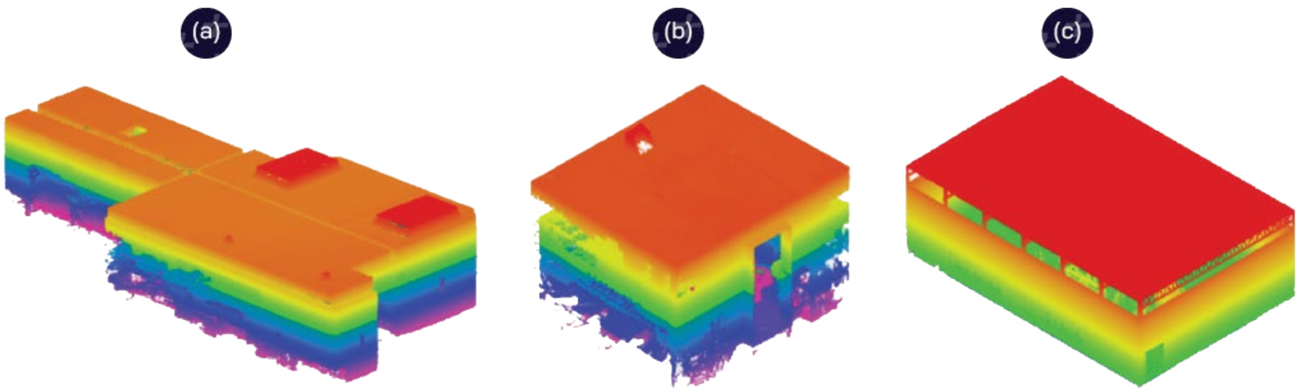


Figure 47: *Captured 3D point cloud of (a) hospital linen room, (b) liquid store and (c) school sports hall*

Point cloud: *discrete set of data points in space. The points may represent a 3D shape or object.*

Once a dataset is aligned with a common coordinate frame, the ceiling panel can be extracted using filtering along the z-axis. Removal of walls, supports, and MEP elements can be performed using the point selector tool in PolyWorks if required. The ceiling planks from each measurement technique are shown in Figure 48, where visualisation was achieved using the PolyWorks software. Here, a plane was fitted to the ceiling panels for each dataset and then a 'Measure Deviations from Feature Primitives' action performed to obtain a colourmap which represents distance from a flat plane.

To observe the ability of each measurement technology to detect RAAC plank deflection, an analysis of individual panels from the ceiling layout is shown in Figure 49. The dataset captured using the iPad Pro and Polycam software was discounted due to the visible high distortions of the ceiling data, which did not even show the panel sections.

Figure 50 is a plot of all the points on a panel using for the BLK2GO, ATS600, and Disto S910 datasets viewed from the side of the panel. The BLK2GO data has a much larger measurement spread than the ATS600 or Disto S910, covering approximately ± 10 mm. By voxelsing the dataset into discrete volumes and computing the mean of each voxel along the span of the panel, a better estimate of panel deflection can be achieved.

The Disto S910 shows close correlation with the ATS600 data. However, due to the manual nature of data capture, there is the potential of user error to be considered. Additionally, capturing an adequate number of points to describe a panel is too time consuming as it may take approximately 15 minutes to be practically applied for large inspection areas.

It can be seen from Figure 50, that the ATS600 contains some outlier datapoints, which can be removed using a k-nearest neighbour filtration approach. The scikit-learn Python library has an implementation of Density-Based Spatial Clustering of Applications with Noise (DBSCAN), which can handle such tasks.

By plotting different zones of a plank, as shown below in Figure 52 the panel is twisted as well as deflected. To determine deflection, an identified plank is first extracted from the dataset, the plank is then split into distinct regions across the width as demonstrated in Figure 52 (a), where three of these regions are highlighted. Each of these sections are then individually levelled to remove the impact of twist and the maximum deflection extracted, to reduce the potential impact of noise or missing data. A second order polynomial can also be fitted to the data and the vertex found.

Voxelising: *Process of converting a 3D object into a discrete grid of small cubes (voxels)*

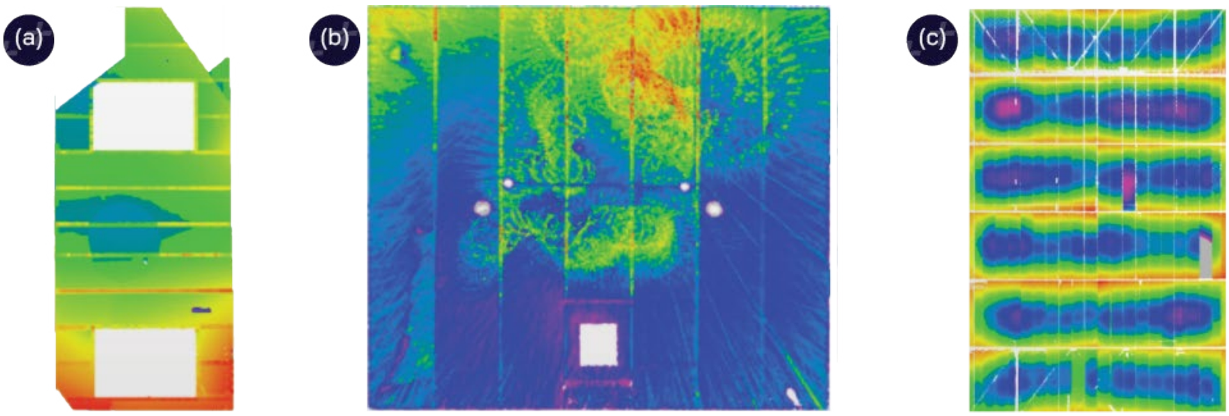


Figure 48: *Colour deflection maps of the ceiling for (a) hospital linen room, (b) liquid store and (c) school sports hall*

NDT trial conclusions

Figure 49: *(a) Panel measured by BLK2GO, (b) panel measured by ATS 600, (c) deflection map of ceiling.*

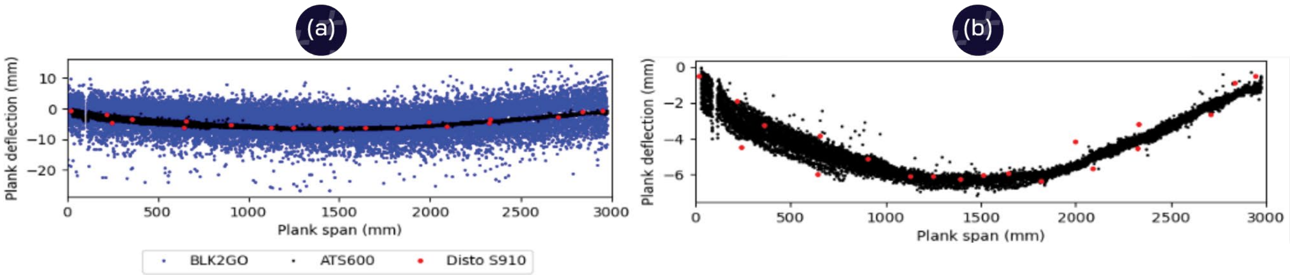


Figure 50: *RAAC panel cross section measured by the (a) ATS600, BLK2GO, and Disto S910 and (b) only ATS600 and Disto S910 data*

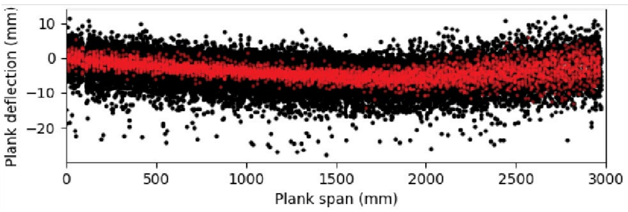


Figure 51: *RAAC panel measurements showing data from two different systems dataset1 (black), dataset2 (red).*

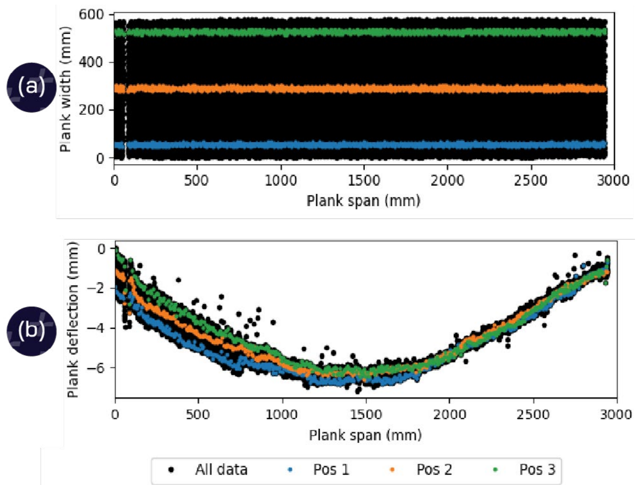


Figure 52: *(a) RAAC panel top view with three measurement areas and (b) RAAC panel side view showing the deflection at each measured region*

Metrology trial conclusions

Metrology trial conclusions

Contrary to visual inspection processes that do not have the ability to determine or track the dimensional change in deflection of panels, the trials have shown the ability to allow panel-based risk assessments to obtain accurate measurements of ceilings made from RAAC.

The site-based trials at the hospital and school highlighted the requirement for speed in surveying the ceiling due to, and dependent on, large numbers of panels, rooms, and sites. The measurement technique should also be flexible. It is essential that datasets are easily assembled so that the system can be moved around the room and, in doing so, reducing the effects of line-of-sight occlusions from ceiling hanging MEP.

The main highlights from the metrology trials are as follows:

- The Leica ATS600 was found to be the most suitable measurement system for monitoring deflection in RAAC planks from the floor. This system can be programmed to create a user-specified density point cloud of the measured target with accuracy, exceeding the technical requirements.
- The ATS600 demonstrated an ability to accurately capture RAAC panel deflection. Yet it perhaps would benefit from the integration of supplementary methodologies to enhance the speed of ceiling data acquisition.
- Trials found that, due to the long setup and measurement times of the ATS600, an intermediary assessment using a BLK2GO with software analysis is the best approach. This is to determine the minimum number of positions needed to capture the required RAAC panels and the placement of tracking nests would speed up the measurement process.
- The results show that the only other system that could meet the accuracy-based requirements was the Leica Disto 3D. However, it is highly prone to operator errors and demands significant time investment for the capture of large areas, rendering it impractical.
- The Leica BLK2GO was identified as not suitable for use in monitoring of RAAC panels, however, it was able to very quickly capture the entire room with a dense point cloud and can discern neighbouring RAAC panels.
- The BLK2GO, while lacking in adequate accuracy for deflection monitoring, was able to rapidly capture full coverage of a room with the ability to identify individual RAAC planks. This feature positions it as a viable candidate for the automation of RAAC ceiling plan generation. Moreover, with targeted advancements, it holds the potential to refine the ATS600 system's placement and the arrangement of nests via a simulation, thereby reducing the impact of occlusions and minimising measurement time.
- Based on the trial results, the ATS600 is recommended for application with the potential use of the BLK2GO, to create a RAAC ceiling plan. It includes highlighted areas of interest and in the creation of a simulation, it minimises the required number of ATS600 positions to get full coverage and nest positioning.
- It is recommended that these be further investigated, with the deployment approach of the ATS600 through a combination of automation, and position optimisation. A strategy to semi or fully-automate the extraction of a RAAC ceiling plan using the BLK2GO dataset is required. There is a need to explore potential alternatives to measuring RAAC where there is inaccessibility due to MEP or false ceilings.

Metrology & NDT - barriers, challenges, key insights & next steps

Barriers

Despite the known issues with RAAC and the need to understand the real complexities and consequences of not eliminating risks associated with RAAC, barriers still exist to the practical development of RAAC solutions. To support the next steps in identifying and dealing with the RAAC problem, more work is necessary to eliminate these barriers and tackle RAAC.

Apart from some of the barriers mentioned above, there are a few other considerations that must be addressed:

- There are very limited trials proving that existing NDT technology can work for RAAC and therefore there is a requirement for evidence to support investigation and remediation activities.
- Currently, it is difficult to distribute NDT solutions and activities on a large scale due to technology availability, which is unlike readily available and cost-effective metrology equipment.
- Like most specialised expertise, there are limited resources with the right skillsets to operate the inspection technology and interpret readings.
- The opportunity to train inspection experts for future RAAC activities will be limited due to it being a complex topic, the time restraints and potentially high costs.

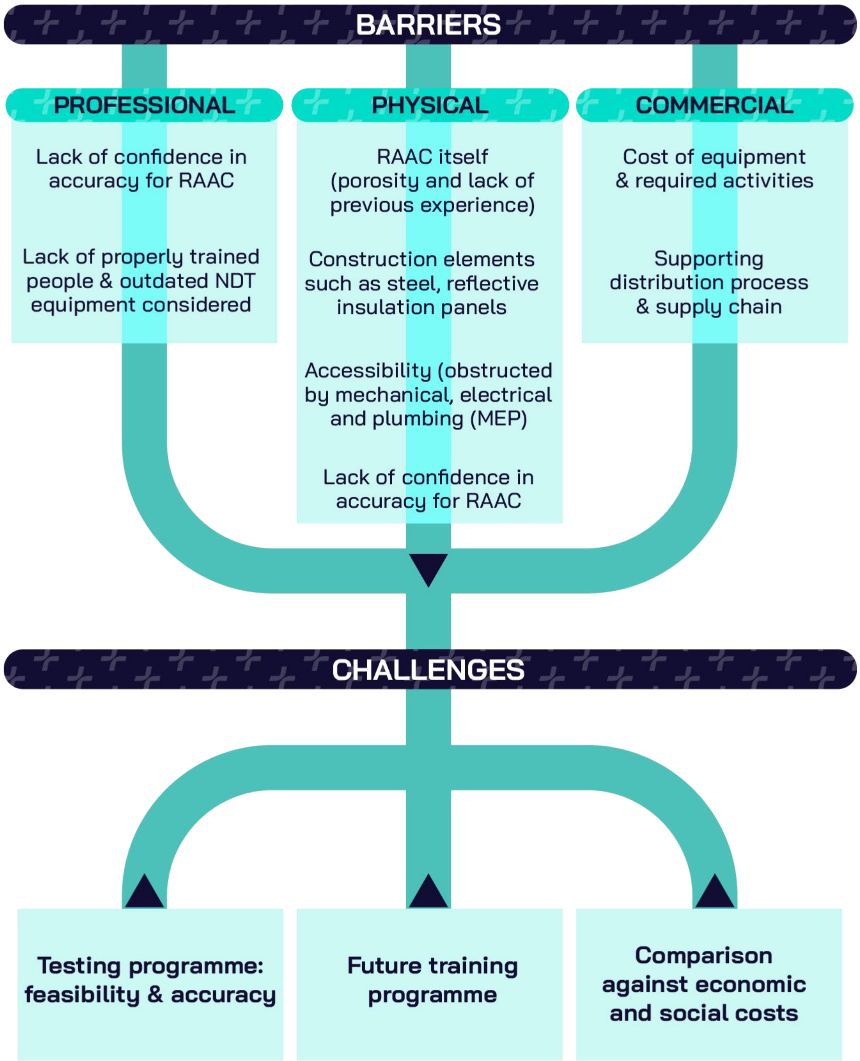


Figure 53: *Barriers, challenges and next steps*

Challenges

There are many challenges facing the development, support and distribution of the appropriate inspection processes to deal with the RAAC problem. Therefore, much work is required to understand these challenges and provide sufficient time, cost and collaboration to tackle them effectively.

Apart from some of the challenges mentioned above, there are other considerations that must be addressed:

- The physical environment in which this type of technology is being applied in terms of the manual handling and movement of mobile devices in hard-to-reach areas and tight spaces, like ceiling cavities.
- The perception of some inspection methods needs to be addressed and all stakeholders need to be educated about the limited levels of risk and the safe requirements for use in the field. For example, an XBS is not dangerous, but does require a large exclusion zone when in use.

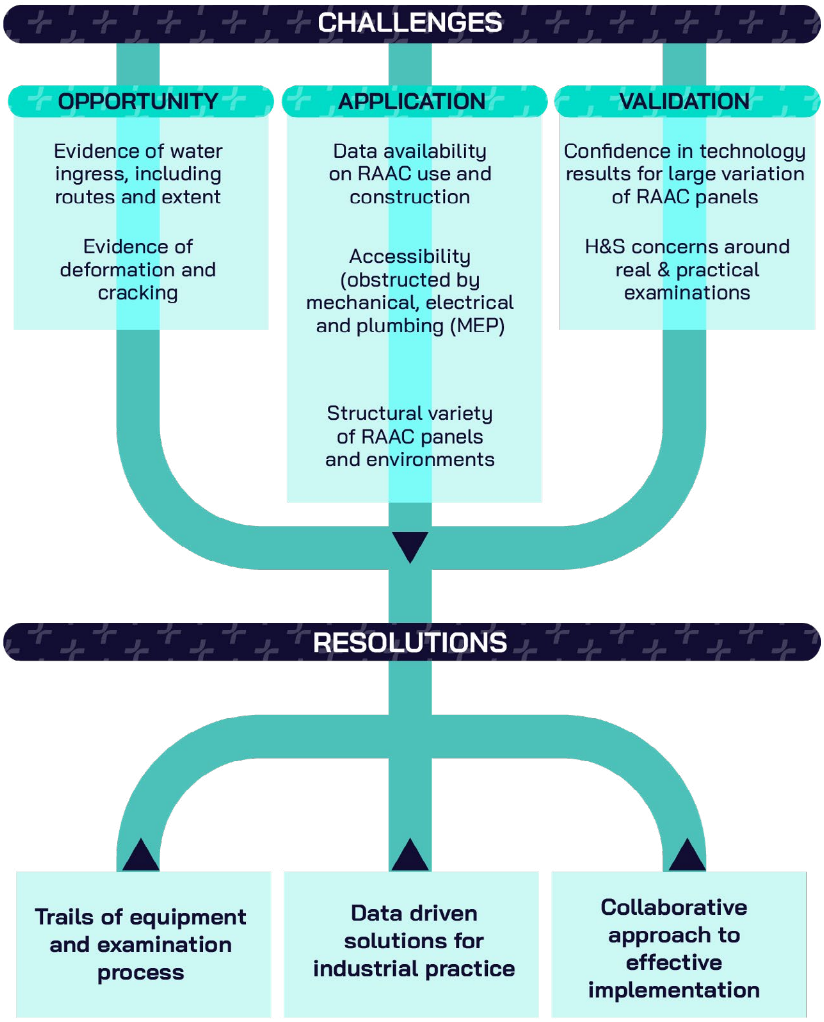


Figure 54: *Challenges and resolutions*

Metrology & NDT - barriers, challenges, key insights & next steps

Key Insights

Although there are proven technologies to investigate 'normal' concrete, these are not proven for RAAC. As a result, the trials have produced some initial evidence that some of these technologies can be utilised for RAAC inspection. Other key insights and successes include:

- Physical trials engaged with real projects, these have proven that GPR is readily able to detect transverse and longitudinal rebar within the RAAC panels, including the measurement of RAAC panel thickness and rebar depth.
- Inspection of RAAC panels in a roof construction, attempted from the internal ceiling rather than the external roof surface, has presented the opportunity to develop real inspection solutions for RAAC.
- A new approach has been developed to inspect the end bearing region of RAAC panels, consisting of a 3D printed wedge designed to allow angled GPR inspection at 30°, 40°, 50° and 60°.
- There is real potential to develop new and adaptable technology systems for RAAC to tackle similar future issues that require a similar approach.
- New methodology has been developed to calculate mid-point panel deflection, to limit the amount of access required to the end bearings.
- There has been adapted use of strain gauge for deflection measurement and monitoring of RAAC panels over a set period of time.
- Physical demonstrator of the test system at the MTC and Airedale General Hospital (AGH) to better communicate the practical application of these technologies.
- There has been development of solutions biased towards those responsible for any resolution. For example, to help building owners and estate managers understand the problem and support decision-making.
- Depending on results of the initial testing regime, the collection of inspection techniques could be realistically utilised by surveyors to challenge the RAAC detection problem.

Next Steps

Some supporting activities to address the wider adoption of NDT and metrology technologies for RAAC in the future will focus on the following elements:

- Cost reduction exercises of detection equipment, technology infrastructure and supporting resource.
- Simplified set up methods to develop efficient, effective and minimal disrupted solution.
- Testing for data confidence to validate the wider use of the technology for a variety of RAAC.
- Validation of inspection methods and results.
- To implement and test the solution in real RAAC site and iterate software on their in-situ system.
- Investigating potential automated/autonomous inspection solutions, in terms of the inspection equipment and data post-processing.
- Engagement with decision-makers:
- Utilise current engagement with AGH and potentially other hospitals and schools.
- Collaborate with responsible stakeholders to support informed decisions on remediation work.
- To provide these solutions as a viable service. Further automated investigations are required to make the inspection process and data processing more user-friendly for less skilled users.
- Collect further data from more RAAC environments and potential training material for the different inspection pieces. Understanding and implementing how others could use it if they wanted to.

Chapter 4:
DAT: Digital Assessment Tool

- DAT: Introduction
- What are the challenges?
- DAT Methodology
- DAT Functional Scope
- Description of users
- DAT: key insights, barriers and next steps?

DAT: Introduction

The Digital Assessment Tool (DAT) stands as a pivotal online platform designed specifically to streamline the collection, visualisation and sharing of reinforced autoclaved aerated concrete (RAAC) information across the UK. Its comprehensive functionality extends support throughout every stage of the RAAC management process, from initial identification to rigorous assessment, remediation, and continuous monitoring.

Central to its efficacy is the establishment of a UK-wide RAAC database, offering unparalleled visibility into the current state and evolution of RAAC nationwide. This database serves as a cornerstone for ensuring strategic alignment and resource allocation, as well as enabling the development of RAAC guidance and analytic models.

Leveraging advanced analytics methods applied to non-destructive examination (NDE), survey, and condition monitoring data, the DAT enables organisations to identify and assess RAAC safely, quickly, and accurately.

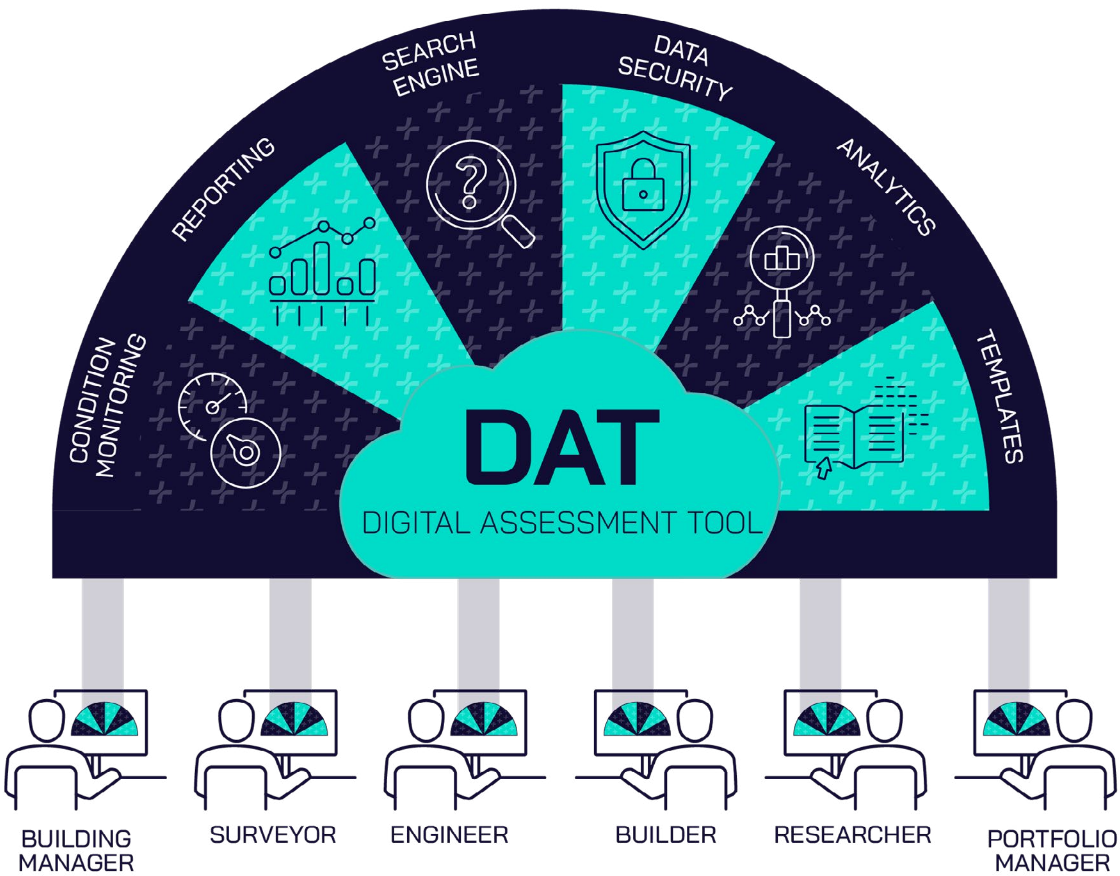


Figure 55: Digital Assessment Tool Schematic

What are the challenges?

Building analytic models, capable of accurately identifying instances of RAAC and detecting defects based on inputs such as human observations and measurements, non-destructive tests (NDTs), and condition monitoring, would enable structural engineers to perform better informed risk assessments. Moreover, the availability of robust risk assessment frameworks is key to evaluating the severity and potential impact of identified RAAC issues, facilitating informed decision-making in risk management strategies.

Integration between disparate components of the RAAC ecosystem, including data collection, analysis, visualisation, and sharing is essential for effective management of RAAC data. Robust data management practices must be established to handle diverse RAAC data types while ensuring integrity, confidentiality, and availability. Additionally, developing standardised interfaces and application programming interfaces (APIs) is important to facilitate systems integration efforts and ensuring compatibility across platforms.

Developing the DAT to accommodate increasing user loads and panel monitoring requirements, without compromising performance, is imperative. Implementing scalable solutions such as distributed computing and load balancing can support the growing demand for RAAC assessments. Furthermore, optimising resource utilisation and throughput is essential to ensure the DAT's ability to handle concurrent assessments and real-time data processing efficiently, enabling seamless scalability as the user base and monitored panels expand.

Agreeing on a standardised RAAC data model across different stakeholders poses a significant challenge. It requires consensus on a universal model, catering to diverse needs across sectors for widespread adoption. Additionally, establishing a model for sharing stakeholders' data presents another hurdle, necessitating careful negotiation to address concerns regarding privacy, security, and ownership. Managing errors in analytic models and addressing the consequences of inaccurate outputs is complex, especially in determining liability with multiple stakeholders involved.

Finding an owner for the DAT to cover operation and maintenance costs is critical, particularly for users in schools and similar settings lacking budgetary resources. Establishing sustainable funding mechanisms or sponsorship is necessary for continued availability and accessibility.

Furthermore, establishing a framework for third-party providers to access RAAC data for developing analytic models requires careful consideration to balance innovation with data privacy, security, and regulatory compliance.

DAT Methodology

The DAT is intended to support each of the phases of the RAAC management process, as shown in Figure 56.

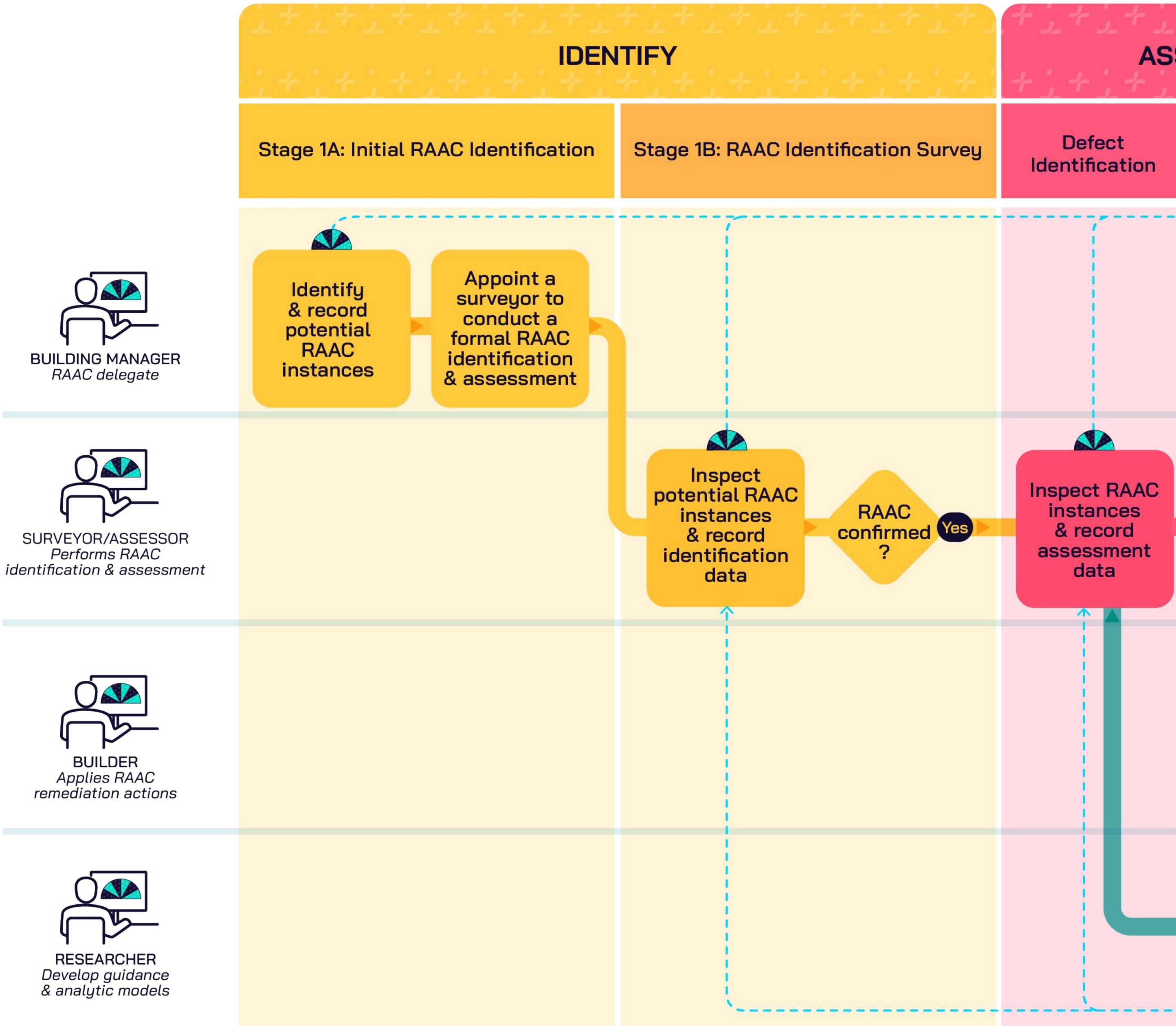


Figure 56: RAAC management process workflow

IDENTIFY:
IDENTIFICATION PROCESS

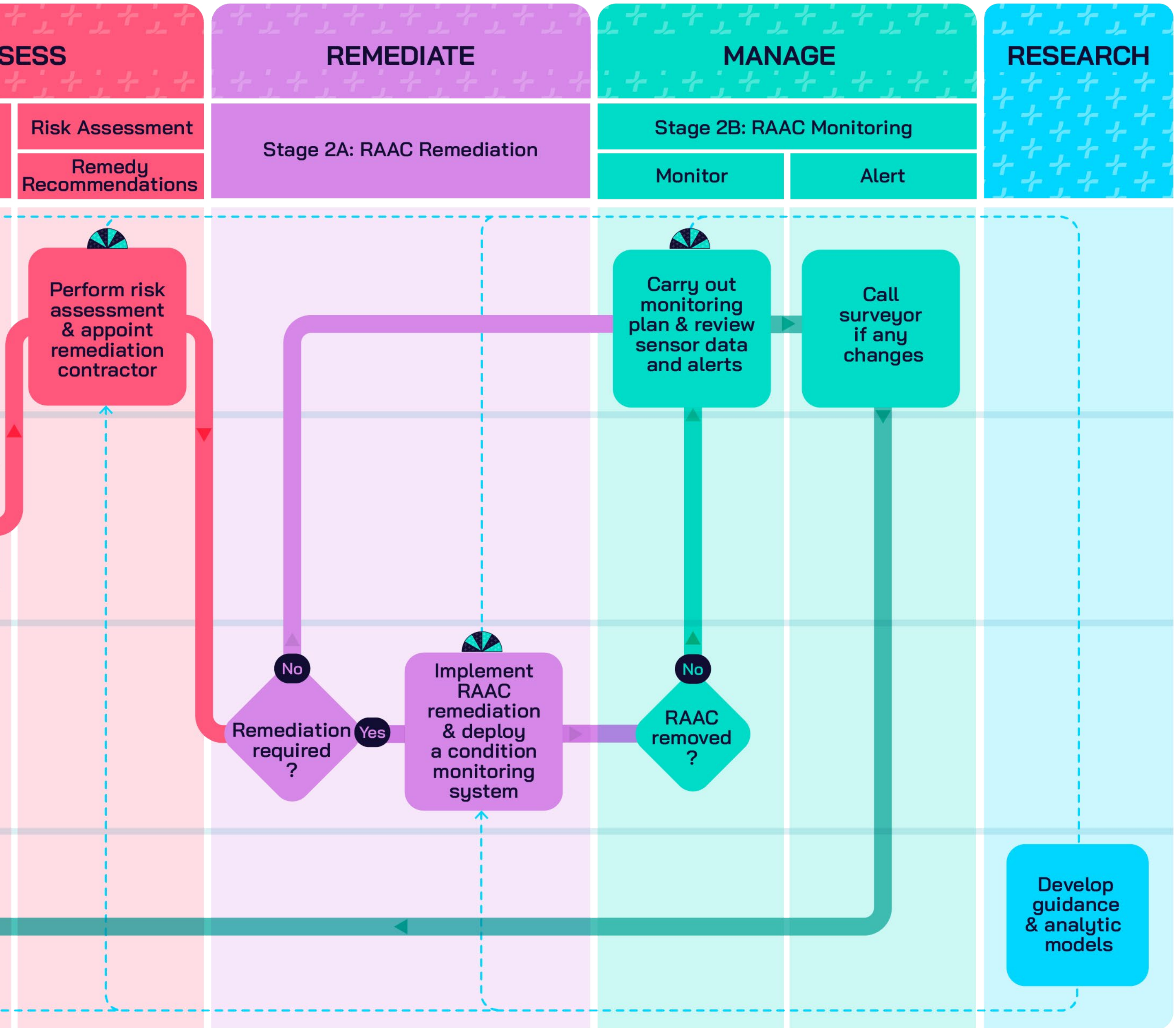
During this phase, the building manager makes an inventory of potential RAAC panels and appoints a surveyor or structural engineer to confirm their composition. The surveyor performs an identification survey, potentially generating an ultrasound dataset, which is uploaded to the DAT for historical record and automated analysis. While the surveyor is responsible for RAAC identification, the DAT provides an indication of whether a panel is made of RAAC based on the analysis of the uploaded ultrasound dataset.

ASSESS:
ASSESSMENT PROCESS

During the assessment phase, a structural engineer assesses the risk associated with identified RAAC panels by conducting a defect identification survey and submitting a risk assessment job to the DAT. The DAT facilitates the logging of all survey data, including NDT datasets. Automated risk assessment processes survey data and previous NDT dataset analyses, providing a risk category for each RAAC panel based on a selected risk assessment framework, such as that published by the IStructE [9]. Ultimately, the structural engineer assigns a risk category to each RAAC panel.

REMEDIATE:
REMEDIATION PROC

During the remediation p
actions recommended b
are considered. The buil
remediation actions and
company for implementa
actions are captured in t
reference.



CESS

phase, any remediation
y the structural engineer
ding manager decides on
appoints a construction
ation. All remediation
the DAT for future

MANAGE:

MANAGEMENT PROCESS

During the management phase, a plan for scheduled inspections is implemented. If relevant changes in the condition of the RAAC panels are observed, a structural engineer is called to repeat the assessment. The DAT also supports the long-term storage of condition monitoring data from RAAC panels, if a local monitoring system is installed. Additionally, the DAT offers a dashboard for remote monitoring of RAAC panels and can display aggregated data from multiple RAAC panels and buildings.

RESEARCH:

RESEARCH PROCESS

During the research phase, researchers can access RAAC data generated by system users to enhance their understanding of RAAC and produce better guidance material and analytics models.

DAT Functional Scope

The DAT allows for users to search and download RAAC data to produce updated guidance material and accurate models for RAAC identification and assessment. The DAT functional scope is illustrated in Figure 57 - DAT functional scope. Each function of the DAT addresses the requirements of specific user types.

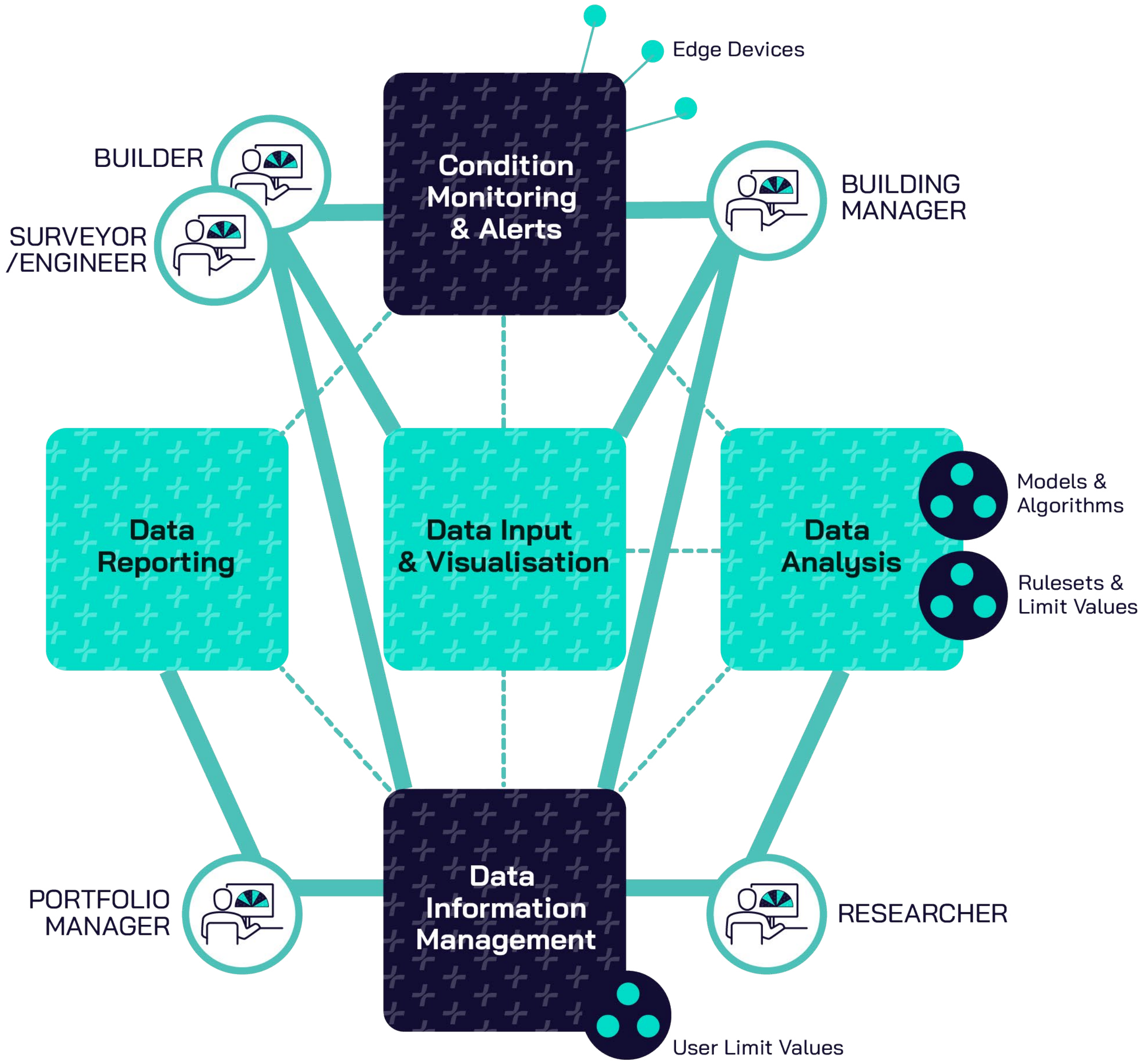


Figure 57: DAT functional scope

Description of users

The diversity of users that may use the DAT will increase over time. This could include business analysts, insurance companies, government officials, and more. For simplicity, only basic users of the system have been formally considered. These can be found below in Table 5: DAT Users.

Table 5: DAT Users

User	Description	System usage
Building manager	This is the person responsible for managing RAAC at a particular site.	They will manage the site's master data and may input data from internal surveys into the system, this will be performed by site personnel. They will upload datasets and media files, and request analyses. They may appoint contractors to input data into the system. They will monitor any changes to the data due to new surveys, updated sensor data or alerts. They may report RAAC failures.
Portfolio manager	This person will manage, or at least have visibility of, more than one site.	They will review reports for individual sites. They will review reports of multiple sites showing aggregated data and statistics. They may review specific files belonging to one of their sites.
Surveyor	This is a contractor appointed to conduct a RAAC identification and/or assessment survey on a building manager's site.	They may review historical data from RAAC panels, input new survey data, upload datasets and media files, and request analyses. They may review sensor data to include it in their report or for safety reasons. They may review or update specific files belonging to one of their sites which they have been given access to. They may publish guidance material, case studies, and any other kind of information to their own site within the document management system (DMS).
Engineer	This is a contractor appointed to conduct a RAAC identification and/or assessment survey on a building manager's site.	Like the surveyor, but structural engineers can additionally perform risk assessments.
Builder	This is a contractor appointed to conduct any kind of building work on a building manager's site, whether that's related to RAAC or not.	They may review historical data from RAAC panels adjacent to their work area, input new remediation data and media files. They may review sensor data to include it in their report or for safety reasons. They may review or update specific files belonging to one of their sites which they have been given access to. They may publish guidance material, case studies, and any other kind of information to their own site within the DMS.
Researcher	This role could be embodied by several professionals. It could be a subject-matter expert that develops and publishes RAAC guidance; a data scientist that works for a research organisation that develops analytic models; a structural engineer an organisation that has produced a RAAC assessment framework, etc. The 'researcher' usually works for organisations such as universities, Research and Technology Organisations (RTOs), and professional institutions, but they could also work for an independent analytics or construction company, or any other private or public entity.	They will be able to publish RAAC guidance material to the DMS. They may access anonymised monitoring and survey data from the monitoring and analytics platforms to develop, validate and improve methods to identify RAAC, assess its integrity, or detect, measure, etc. any features that support the former. They may upload models to the analytics platform that will become available to other users to perform analyses on their data. In the future, there may be a way to monetise this, so more parties become interested in developing better analytics methods to identify RAAC and assess its integrity.

DAT: key insights, barriers and next steps?

Several insights and lessons have emerged throughout the delivery of the UKRI RAAC Impact Programme at the MTC. Firstly, establishing a UK-wide repository for RAAC data could greatly enhance collaboration and knowledge-sharing among stakeholders. Additionally, there is a clear need for a standardised data collection framework to ensure consistency and interoperability across RAAC initiatives. Most importantly, we have learned that monitoring and analytics capabilities are essential for data owners, as is incentivising them to share data for their own benefit, so they can then enjoy access to better guidance and analytic models.

Barriers?

Barriers to adoption include upfront license costs, particularly problematic for end users with limited budgets such as school head teachers. Concerns over data privacy and liability also hinder adoption, along with the lack of a long-term owner for the solution. Overcoming these barriers requires addressing financial, legal, and organisational considerations to build trust and facilitate widespread adoption. For future adoption, finding an organisation willing to own and fund the solution's operating and maintenance costs is crucial.

Next Steps?

Immediate next steps include piloting and validating the DAT alpha version with owners of RAAC assets and showcasing the DAT's capabilities at conferences and events for increasing awareness and adoption.

Exploitation opportunities include hosting third-party analytic models on the DAT for RAAC identification, defect detection, and risk assessment, incentivising research companies to develop such models by allowing them to generate revenue. This, in turn, will derive in higher-quality models made available to RAAC asset owners.

RAAC asset owners are encouraged to contact the MTC to discuss potential collaboration opportunities. While full adoption of a tool such as the DAT may not be feasible in all cases, some may benefit from access to analytics or condition monitoring capability.

Chapter 5:
Monitor

- Monitor: Introduction
- Monitor: Methodology
- Monitor: barriers, challenges, successes

Monitor: Introduction

Disclaimer: *this section covers the MTC's independent review of the Monitoring of RAAC through the UKRI RAAC Impact Programme. Existing industry guidance includes that provided by the IStructE on investigation and assessment [6] [9].*

What are the key problems?

Determining if RAAC planks are degraded is expensive and, if based on judgement rather than evidence, increases the risk of error. There is also a lack of experienced and competent engineers and surveyors to determine the condition of RAAC appropriately.

Once it has been identified that there are RAAC panels, and they have been prioritised by their low, medium, high or critical risk, frequent inspection will be preferred or required depending on the situation, severity and developing strategy. RAAC planks may exist in areas with restricted access making them difficult to inspect.

What are the challenges?

- Accuracy of inspection.
- Keeping an estate operational.
- Keeping disruption to a minimum.
- Resources – limited in-house surveyors continuously undertaking visual monitoring of the RAAC panels.

What are the opportunities?

- Monitoring changes in the conditions of RAAC planks would enable required intervention to be based on risk level.
- other factors / defects to consider as well as deflection.

Monitor: Methodology

A flowchart showing MTC's down-selection process to design a condition monitoring system in shown at Figure 58 - RAAC management process workflow.

The following criteria were used to down-select the monitoring system:

- Cost – low to high.
- System Reliability – scale of system failure modes.
- Ease of Installation – skilled operators and installation.
- Frequency of Maintenance – inspection period.
- Universality – level of adaptation required for different scenarios.
- Supply Chain Readiness – established supply chain, low lead times.
- Manufacturability – bespoke vs off-the-shelf.
- User Input Required – frequency of manual input.

1 PROBLEM DEFINITION

Observation of current process and/or collection of information about conditions that would need to be monitored.

2 REQUIREMENT CAPTURE & SYSTEM ARCHITECTURE

Highlights the important criteria by which the sensing systems will be assessed and ranked. Weighting should be decided with an appropriate panel. This will result in a numerical matrix of criteria.

3 CONCEPT DESIGN & DOWN-SELECTION

A preliminary down-selection stage based upon the critical criteria of the monitoring process to remove inappropriate systems. This will use the numerical matrix to filter inappropriate systems.

4 DETAILED DESIGN

Perform trials on the selected inspection systems to populate the remaining fields of the numerical matrix to determine the most appropriate inspection system. Representative artefacts are required for performance analysis of the selected inspection systems.

5 SYSTEM VALIDATION

A measurement system analysis (MSA), using gage repeatability and reproducibility (GR&R) to determine appropriate inspection system to ensure it can perform within the process requirements.

6 SYSTEM BUILD AND INSTALLATION

Purchasing the most appropriate system for the application and ensuring the system can perform within the required specifications.

Figure 58: MTC's down-selection process

Monitor: Methodology

Monitor Methodology Applied to UKRI RAAC Impact Programme

The selection and validation of reliable and appropriate condition monitoring systems for RAAC will provide responsible parties with options to support their key decisions on how to manage an ongoing presence of RAAC.

Once RAAC has been identified and assessed for condition, key decisions regarding setup, implementation, deployment and maintenance of the chosen monitoring system can be made. Additional considerations on top of the methodology for the monitoring systems include:

- Establishing areas of high risk or areas difficult to access that should be monitored.
- Choosing the most appropriate monitoring system and setup.
- Operational risk areas, prioritising high operation areas over low operation areas.
- Determining frequency of monitoring based on the RAAC condition.
- Ensuring the monitoring solution is practical and affordable.
- Gathering relevant data to inform subsequent remediation decisions.

Important environmental and performance requirements considered in choosing the correct monitoring system include:

- Expected lifespan of the monitoring system use .
- Installation environment to be encountered.
- Required maintenance and upkeep of the monitoring system.
- Data gathering frequency and output format.
- Redundancies within the system depending on potential applications.
- Cost of the system.
- Accuracy of the system.

The required monitoring system specified as part of the national UKRI RAAC Impact Programme can be broadly split into two categories:

- **Sensing system** – The type of measurement detection used to monitor.
- **Instrumentation** – The setup of devices or equipment used to monitor.

Sensing system

With regards to the RAAC panels, the sensing system was split into two elements:

- **Moisture ingress sensor** – to detect moisture ingress
- **Deflection sensor** – to detect midpoint deflection

Instrumentation, networking and power

For the RAAC panels the instrumentation system was split into two elements:

- **Local instrumentation** – This is the unit to convert raw signals into usable readings.
- **Edge device** – This might be an independent unit that connects the Operational Technology (OT) layer to the Information Technology (IT) layer, or might be part of the local instrumentation. Whatever its form, this device is expected to allow interaction with the IT layer, collation of data for the IT layer, and deal with required security inherent within an IT layer device. OT systems are autonomous, isolated, self-contained, and run-on proprietary software. In contrast, IT systems are connected, lack autonomy, and typically run on popular operating systems like iOS and Windows.

Due to the size of the end deployment, a distributed system should be used under most circumstances.

- As part of the down-selection process of the monitoring system, the options were compared using the down-selection identified in the methodology.

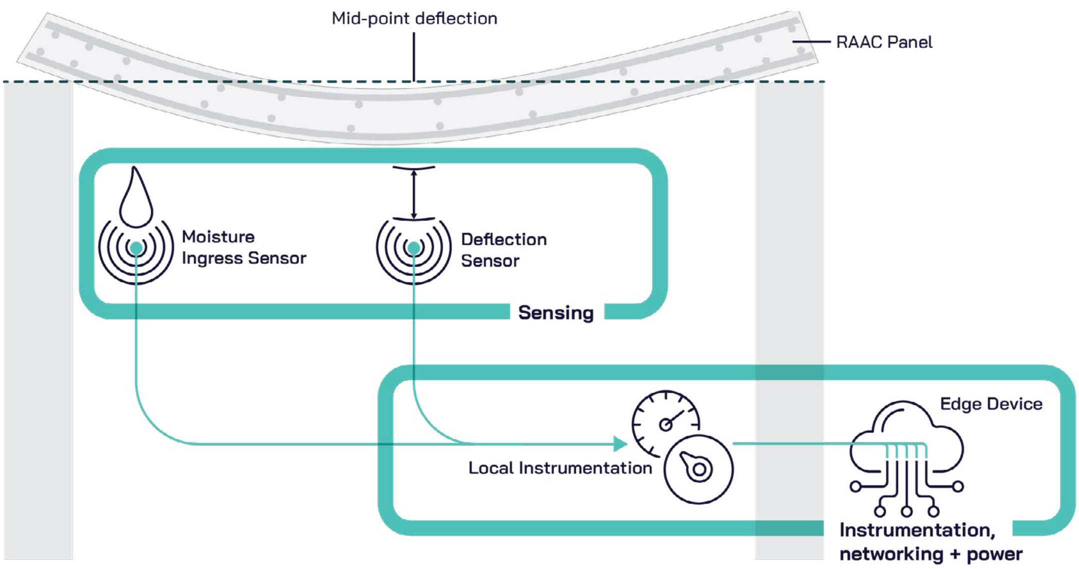


Figure 59: Monitoring System Overview

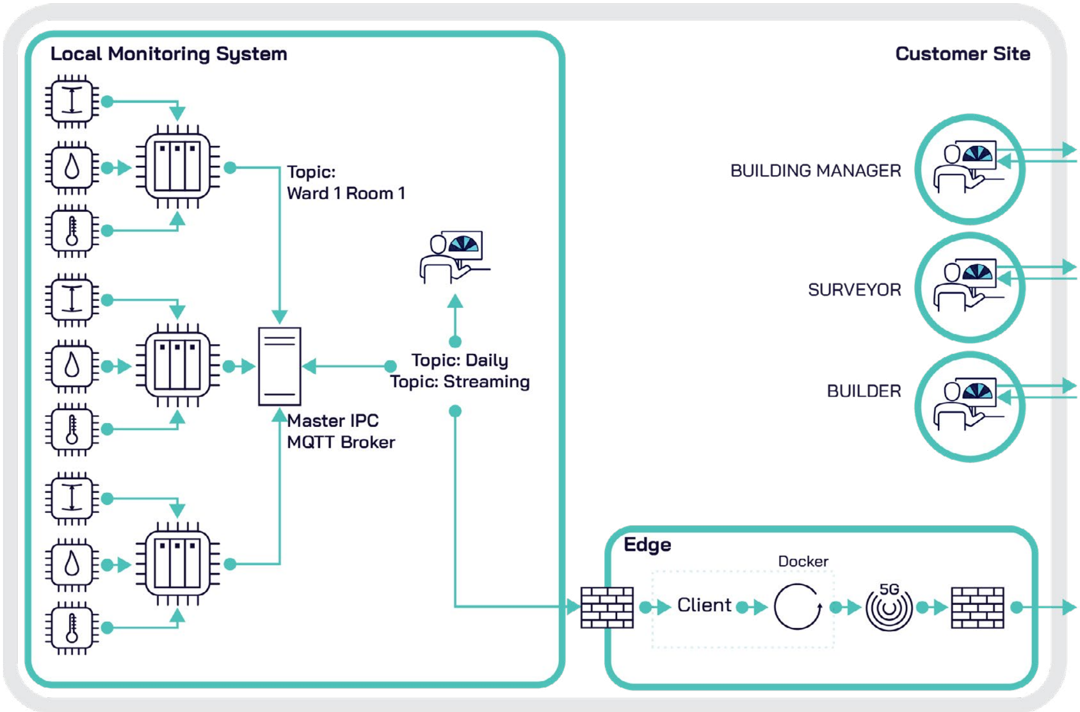


Figure 60: Monitoring System Architecture

HMI: *Human Machine Interface*

IPC: *Industrial PC*

Monitor: Methodology

Evaluation of sensing system

To evaluate the potential solutions for sensing systems, the steps below were followed:

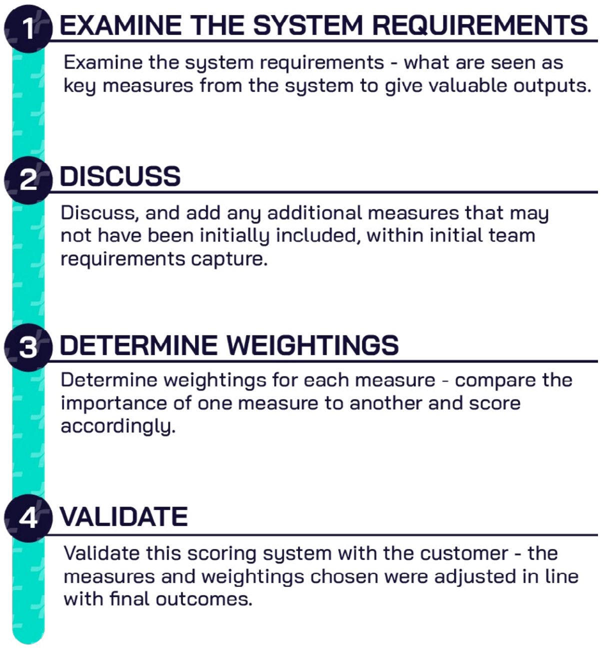


Figure 61: Steps followed to evaluate potential sensing systems' solutions

Ingress sensing

From initial research, six methods of detecting water ingress were chosen for the down-selection process:

1. Capacitive liquid sensing.
2. Moisture level sensors with pins.
3. Pinless moisture level sensor.
4. Enclosed humidity sensor.
5. Microwave system.
6. Water ingress sensor.

From these methods, 'Water ingress sensor' was found to be the only viable option for further testing following down-selection.

Deflection sensing

From initial research, 14 potential concepts for deflection sensing were identified, from which four were found appropriate for further testing:

1. Ultrasonic distance sensors
2. Photoelectric distance sensors
3. Static inclination sensors
4. Strain gauges with multiple mounting points

For each of the potential devices chosen for testing, the MTC was able to create a proof-of-concept setup for both lab-based and site testing to evaluate the proposed solutions.

Monitor: barriers, challenges, successes

Barriers

There may be some barriers to adoption of proposed monitoring solutions in the future, such as:

- Ensuring a business case for operation – for example consideration of monitor vs remediation strategy and budgetary constraints, as well as other actions.
- Simplified setup methods.
- Validation testing for data confidence.

What are the challenges?

- Data availability and validation.

What are the successes?

- Potential to develop new and adaptable technology systems to help deal with the current RAAC problem and similar future issues that require a similar approach.

What are the next steps?

Validation of methods and results

To implement and test the proposed solution on a real RAAC site and iterate software on their in situ system, utilising current engagement with Airedale.

- Operate the monitoring system long-term with connection to the digital assessment tool.
- Additional monitoring system trials, such as expandability of the system and further verification of the monitoring system through accelerated failure testing.
- UK Conformity Assessed (UKCA) marking.
- Work with industry to commercialise.
- A full socioeconomic assessment and feasibility of rolling out this technology at scale, for priority applications.
- Identify if the business case supports installing a monitoring system which will keep a 24/7 watch on panel deflection and water ingress.
- Development of a costing tool, to provide analysis in building a business case to install the condition monitoring system, where required.

Figure 62: MTC RAAC Event Monitor Demonstration

Chapter 6: Remediate

- Remediate: Introduction
- Repair: Background
- Repair: Methodology
- Repair: Barriers, conclusions, next steps
- Reinforce: Background
- Reinforce: Methodology
- Reinforce: Barriers, conclusions, next steps
- Replace: Background
- Replace: Methodology
- Replace: Barriers and next steps

Remediate: Introduction

Disclaimer: *the following chapters on Remediation: Repair, Reinforce and Replace include a new perspective and independent view gathered from MTC during the UKRI RAAC Impact Programme. This research does not supersede existing industry guidance or national standards relating to remediation.*

Various remedial options can be considered for managing underperforming or damaged RAAC planks, or those with uncertain grades that compromise structural integrity and occupant safety. These measures can also be chosen as a preventive approach.

When remediating RAAC, potential actions can be grouped into three different strategies: **repair, reinforce, and replace**. The definitions are detailed below:

Repair (and prevent): *the process aiming to enhance the durability by addressing localised damage or defects in the planks. For example, cracks and material degradation.*

Reinforce (and retain): *this strategy aims to provide functional substitution by incorporating additional support to enhance the load bearing and deflection capacity or restore the structural safety of the roof system by using retaining systems. Strengthening methods based on the intimate collaboration between the material and the reinforcing elements would be part of this classification, however, as explained afterwards, these methods were discarded.*

Replace: *this describes the act of removing the RAAC planks and substituting these by alternative systems, commonly with enhanced properties.*

Currently, there is no specific standardised methodology to adopt when remediating RAAC planks. As reference documents the standard BS EN 1504-9:2008 and the Concrete Society report no.TR 54 -both focusing on the remediation of reinforced concrete (RC) structures only, and not RAAC, were examined [14, 15]. The methodology and terms used in these documents were observed, and the applicability to the RAAC problem adopted, as shown in Figure 63.

Options: *these range from doing nothing for a period of time, through to various remediation methods, and to demolition of all or part of the structure.*

Principles: *these are the concepts underlying the remediation method. For example, the protection against ingress of moisture and aggressive substances, strengthening the structure, etc.*

Methods: *these are the means of achieving the objectives of the principle. For example, applying mortar by hand, spraying grout, etc.*

Remediate: Introduction

The aforementioned documents recognise a range of options for the accountable person(s) for a building to take when managing a structure, that is applicable to buildings containing RAAC, as shown Table 5: DAT Users (14, 15). Similarly, Figure 63- Steps in the design of appropriate solutions and definitions, adapted from (14) and (15), shows remedial factor considerations according to the Concrete Society. From 'Do nothing for a specific period but monitor' (see Monitoring section) to 'Demolish all or part of the structure'. This section covers the last four steps.

- Defects assessment & identification of causes
- Options selection
- Principles adoption
- Methods selection
- Materials selection & remediation specification
- Future inspection & maintenance requirements

Figure 63: Steps in the design of appropriate solutions and definitions, adapted from (14) and (15)

- Do nothing
- Do nothing for a specific period but monitor
- Re-analyse, possibly downgrade the use of the structure
- Prevent or reduce further deterioration (without improvement)
- Repair, protect or strengthen (reinforce) all or part of the structure
- Reconstruct or replace all or part of the structure
- Demolish all or part of the structure

Figure 64: Range of options for the accountable person(s) for a building containing RAAC. Based on (14) and (15)

Table 6: Remedial Factor Considerations (15)

General	Check that chosen option is suitable for use and accords with the diagnosis of the problem. Intended use, design life and service life. Required performance characteristics. Long-term performance of repairs. Whether there will be further opportunities for protection, repair and monitoring. Cost of further repairs. Cost of alternative options including future access and maintenance. Properties and method of preparation of substrate. Appearance.
Health & Safety	Risk and consequence of structural failure both local and global. Risk of spalled material causing injury. Impact of repair or protection on occupiers, users and the general public.
Structural	Effect of no repairs – in other words 'Do nothing'. Changes in dynamic or direct actions (loads) during and after repair. Means of carrying loads during and after repair. Inspection and maintenance requirements.
Environmental	The exposure of the structure and whether it can be changed locally. Noise and nuisance during repairs. Protection of all or part of the structure from its environment including protection of substrates during repair.

Engineering design process for remedial solutions

The RAAC remediation strategies' scope aimed to review the existing principles and methods, assessing their feasibility when remediating RAAC roof planks and provide technical solutions to mitigate the risk, ensure the structural integrity, extend the service life of buildings containing RAAC roof planks and/or incorporate or improve certain features and properties.

The MTC approach merges the design process of remedial actions defined by the Concrete Society and British Standards Institution with the MTC engineering process. The aim is to gain a wider understanding of the problem and technical requirements, while assessing the feasibility of different methods, Figure 64 - Range of options for the accountable person(s) for a building containing RAAC. Based on [14] and [15]. The approach is divided in the three strategies aforementioned: repair, reinforce and replace.

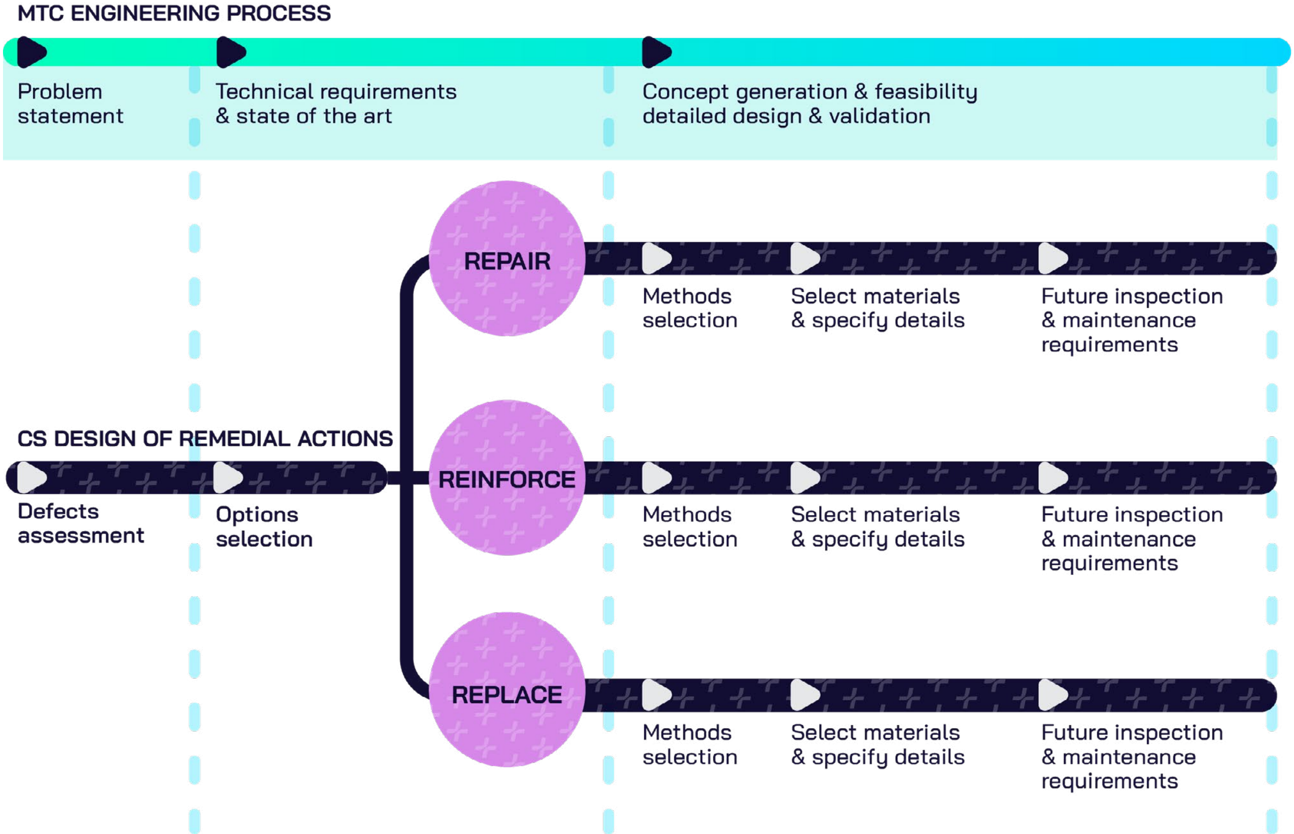


Figure 65: MTC engineering design process merged with definition of remedial actions from [15] and [14]

Repair: Background

Disclaimer: *the following review of concrete repair techniques was conducted during the UKRI RAAC Impact Programme Solutions have not been fully trialled, validated or approved by chartered structural engineer. There is a need for further research in this field.*

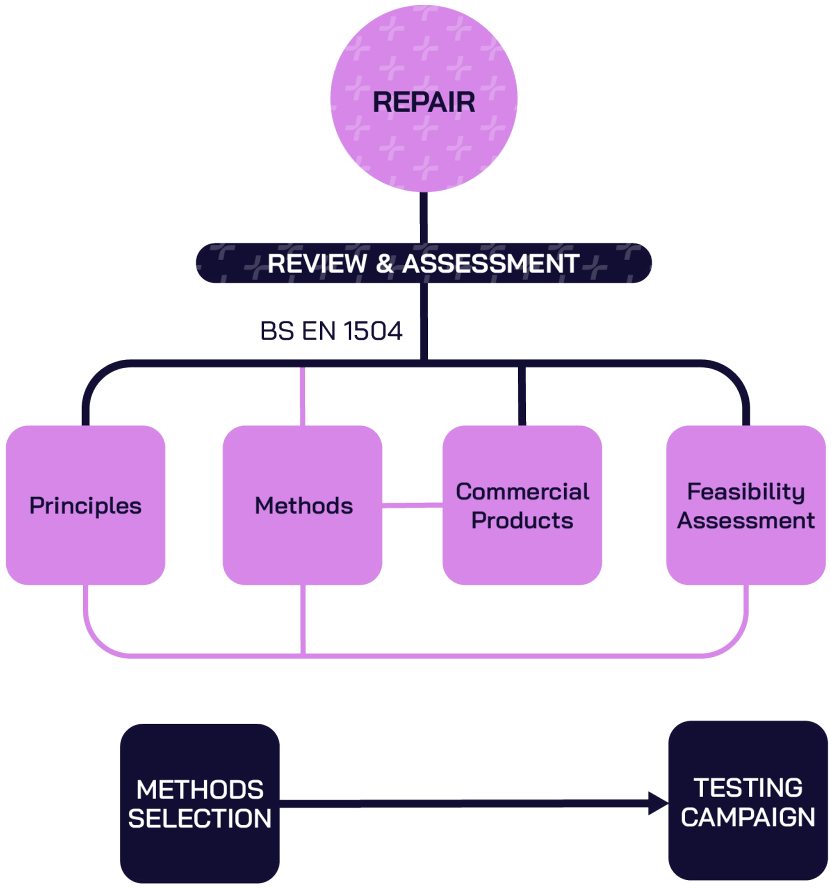


Figure 66: Proposed methodology for repair process

RAAC planks may have defects such as cracks, water damage, corrosion, defects due to intrusive investigation and other defects that may lead to further degradation of the matrix or the reinforcement and the ultimate reduction of the service life, and will need repairs. For instance, water ingress decreases the compressive strength of the material and corrosion reduces the effective section area of the reinforcement and breaks the connection of the transverse rebars to the longitudinal ones. An example of a plank affected by a water leak is shown in Figure 67.

There is a lack of research and industry knowledge in this field when it comes to RAAC. To the knowledge of the contributing authors, there are no specific repairing products for RAAC in the UK marketplace and, to date, none were found in foreign markets. Additionally, there is a lack of understanding on the compatibility of available commercial repairing products for other materials with RAAC, such as conventional reinforced concrete. Different physical properties, such as elastic modulus, porosity and strength capacity between RAAC and other construction materials, mean most of the available repairing products might not be suitable and may cause further damage. In addition, the certain invasive application methods may cause further damages to the planks.

Figure 67: (a) Planks affected by an inactive leak and efflorescence around the bearings. The position of the rebars is drawn onto the surface consequently (Source: MTC. With permission of Airedale General Hospital). (b) Plank affected by an inactive leak, efflorescence, and corrosion with the spalling of the cover (Source: MTC. With permission of Leighton Hospital).

It is important to highlight the potential risks associated with repairing RAAC. For instance, RAAC is very sensitive to moisture changes [3], therefore, there might be potential products that may protect the planks against environmental changes that can lead to further damage. However, a counterproductive effect could be achieved if there is no previous experience with RAAC, for example, use of non-breathable coatings applied onto planks with high moisture content.

Another example of inappropriate repair includes geometry restoration with cement-based mortars or concretes, which would lead to the detachment of the patch due to different elastic modulus and porosity of both materials. This was further expanded by the Institution of Structural Engineers stating that: *"Repairs need careful consideration. Repair mortars commercially available are both stronger and denser than RAAC. Large areas of concrete reinstatement may not be able to generate sufficient bond to remain in place"* [6].

What are the research gaps?

The following points summarise the research gaps:

- There is no robust knowledge and experience on the feasibility of repairing products and the suitability of the application methods on RAAC in the public domain.
- There is a limited business case as well as a short amount of time to develop specifically designed products.
- There is no data available in the public domain that investigates the necessity and viability of preventing further damage, with a cost-benefit analysis weighing up the positive impact of a repair measure against the cost and effort.

Repair: Background

What are the challenges?

The following technical and non-technical challenges can define the solution.

Technical challenges

- RAAC physical properties affecting the compatibility of repair products with RAAC.
- RAAC vulnerability to moisture fluctuations and high levels of moisture.
- Commercially available repair products in UK are designed for other types of construction materials such as concrete.
- Repairs need careful consideration. Commercially available repair mortars are both stronger and denser than RAAC, with a different elastic modulus, making them incompatible with RAAC.
- Certain repair methods may damage the material matrix of the AAC.

Non-technical challenges

- Requirement for a long-term repair product testing campaign to fully understand the efficacy of repair methods for RAAC.

What are the opportunities?

Repairing options for RAAC entail research opportunities such as:

- Assessing the feasibility of current commercial products and application methods for repairing and protecting different defects, of RAAC/ AAC products and maintaining the current state or extending their service life, as displayed in Figure 68.
- Developing and/or adjusting the current commercial products and application methods for repairing and protecting RAAC/ AAC products to extend their service life.
- Designing novel inspection and testing procedures to assess the effectiveness of the repairing solution.

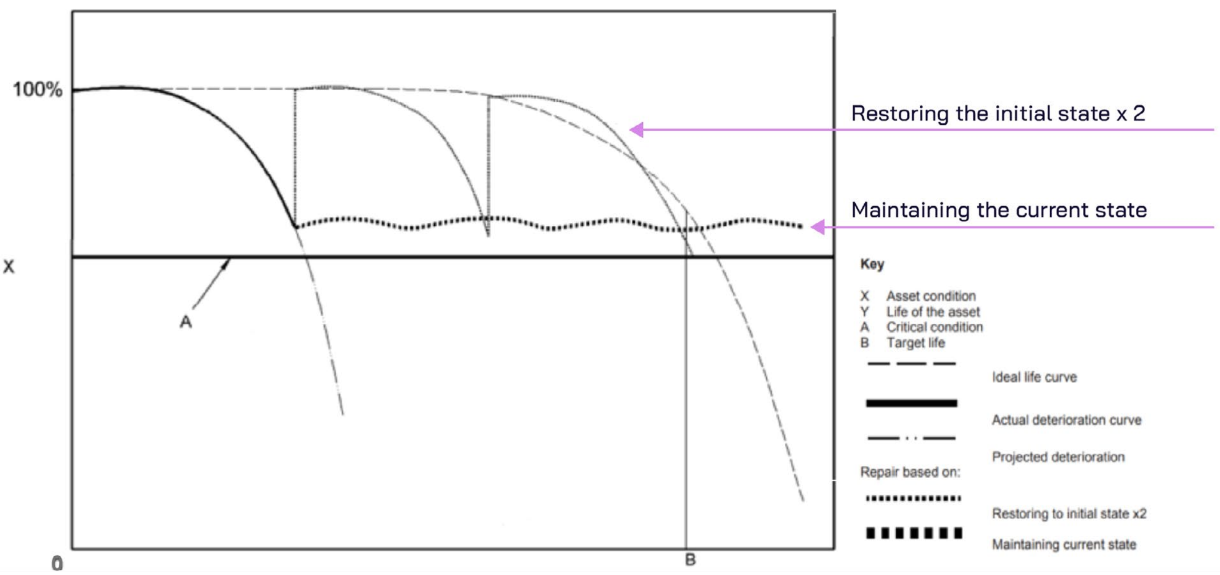


Figure 68: Typical repair cycles over the life of a deteriorating asset (source: [14])

Repair: Methodology

Currently, there is no standardised approach to be applied when designing or selecting appropriate repairing methods for RAAC. Since no guidance exists in the public domain, the methodology contained in BS EN 1504 [14] was reviewed. This guidance has a clear structure that can be extrapolated to other materials with certain limitations, and it is widely known by industry. The principles and methods more relatable for RAAC degradation and protection were selected.

When assessing the feasibility of existing repairing products for RAAC, the phases listed in Table 5: DAT Users should be followed. The laboratories need to be ISO9000 accredited and ideally have experience of testing RAAC.

Methodology applied to the UKRI RAAC Impact Programme

Following the IStructE and repairing materials suppliers' advice, and awareness of the lack of understanding on the compatibility of lighter and more porous mortars with RAAC, methods based on the use of mortars or cements were discarded at this stage. Additionally, the structural strengthening methods were reviewed as part of the reinforce chapter and were, therefore, discarded for this strategy.

The MTC linked with industry to identify and investigate the feasibility of a range of different products and methods for RAAC repair, including the different principles defined in BS 1504. The methodology proposed in Table 7 was followed. Most promising materials were supplied by repairing materials' suppliers to investigate their feasibility for repairing RAAC. Based on industry feedback, the MTC investigated the following BS 1504 methods as options to reduce material degradation of RAAC: hydrophobic impregnations, impregnations, and coatings.

The MTC has designed an experimental campaign to test the effectiveness of coatings and impregnations. The most promising products were down-selected and provided by industrial partners to be tested according to the designed experimental campaign. As stated above, currently this piece of work is on hold due to the need for additional funding to cover longer testing periods.

Table 7: Repair Methodology Feasibility Investigation

Select principles	1.1	Define the scope and the defects to be repaired
	1.2	Review existing principles
	1.3	Select principles of interest
Select method(s)	2.1	Review existing methods
	2.2	Define criteria for down-selection
	2.3	Down-select methods and products to be investigated
Test campaign design	3.1	Review and select properties to be investigated
	3.2	Design experimental campaign (test methods' definition, number of tests, duration etc.)
Test laboratory scale	4.1	Run experimental campaign
	4.2	Assess results
	4.3	Assess repeatability (same laboratory)
	4.4	Assess ability to reproduce (other laboratories)
Assess application method	5.1	Assess viability of application methods
	5.2	Design application method
Test in real environment	6.1	Define experimental campaign
	6.2	Test in real environments (materials and application methods)
	6.3	Monitor and assess
	6.4	Extrapolation to other scenarios
Acceptance of method	7.1	Acceptance of testing
	7.2	Dissemination and commercialisation (if any)
	7.3	Maintenance strategy

Repair: Barriers, conclusions, next steps

Barriers

- There is a lack of a coordinated approach across the UK.
- There is a need for industry, suppliers and testing laboratories to run coordinated testing at a national level.
- There is a risk that many of the currently available repairing material may not be suitable for RAAC.
- Business case for the development of new products – as RAAC is no longer used in new buildings.

Conclusions

- The challenges and research gaps for repairing opportunities have been identified.
- Limited RAAC repair options were found in the UK market. Current repairing options might not be suitable for RAAC, due to the potential incompatibility and the intrinsic vulnerability of the material.
- The potential risks associated with using repairing materials, for which performances have not been tested for RAAC, was highlighted.
- Collaborative research is needed to run a long-term experimental campaign to gain a better understanding of the feasibility of using repairing materials for RAAC.

Next Steps

- Create a collaborative research project with partners from academia, industry and testing facilities to increase knowledge and provide further guidance.

Industrial Case Study: Repair

Sika Ltd

Client: NHS England
Contractor: Gunite Eastern Ltd.

Repair and protection methods are enabling a long-term strategic approach to be taken to replace or rebuild high-risk structures. These buildings are one of a handful of facilities that the government has committed to replacing by 2030, with activities therefore focused on maintaining the existing estate and reducing risk to patients and staff in the interim period.

The buildings are constructed with 200mm thick load-bearing RAAC panels, with a barrier coating to protect the structure from environmental exposure. Over its 50-year service life, the approximate 6,000m² surface of the structure has degraded, leaving localised cracking and deterioration.

In this case, a suite of Sika products was used both to perform remedial actions and to provide long-term protection against future exposure. These activities included:

- Surface preparation of concrete and exposed reinforcement
- Protection of exposed reinforcement
- Priming of locations requiring repair
- Concrete repairs
- Crack-bridging levelling coat
- Crack-bridging anti-carbonation coating

The state of the existing coating was assessed over the 6,000m² treatment area to understand if the new coating system could be applied on top of the old, or if all existing coatings needed to be removed to ensure performance. Any coatings showing clear delamination and degradation were automatically removed. For remaining existing coatings to be deemed acceptable for overcoating, they had to pass adhesion testing carried out in accordance with BS EN 1542, with acceptance limits set by Sika.

Key products used to carry out the concrete repairs included a primer and bonding bridge for both the reinforcement and RAAC concrete and an R2 concrete repair mortar to match the strength of the substrate. After a suitable curing period, Sikagard® 545 W Elastofill was applied to the panels to provide a consistent stippled finish and mask the junctions of repaired and unrepaired areas. Sikagard® 550 W Elastic was then applied to provide anti-carbonation and weather protection.

This approach will extend the life of this structure, with the aim of keeping this critical national infrastructure functioning until a replacement is completed by 2030. The same specification is currently being used to repair another NHS hospital with external RAAC load-bearing panels and will be the third hospital where Sika systems have been used to repair and protect RAAC panels which need to be retained.

Sika have conducted an extensive review of their products to support RAAC repair and have concluded there are no perfect solutions available, this is in line with the key next step identified as part of the UKRI RAAC Impact Programme - create a collaborative research project with partners from academia, industry and testing facilities to increase knowledge and provide further guidance.

Figure 69: *Evidence of localised cracking and deterioration*

Figure 70: *Remedial work on RAAC Panels, (a) close-up of effected RAAC panels, (b) impacted structure*

Reinforce: Background

Disclaimer: *the following solutions are concepts only, generated during the UKRI RAAC Impact Programme 2024 and have not been fully trialled, validated or approved by a chartered structural engineer.*

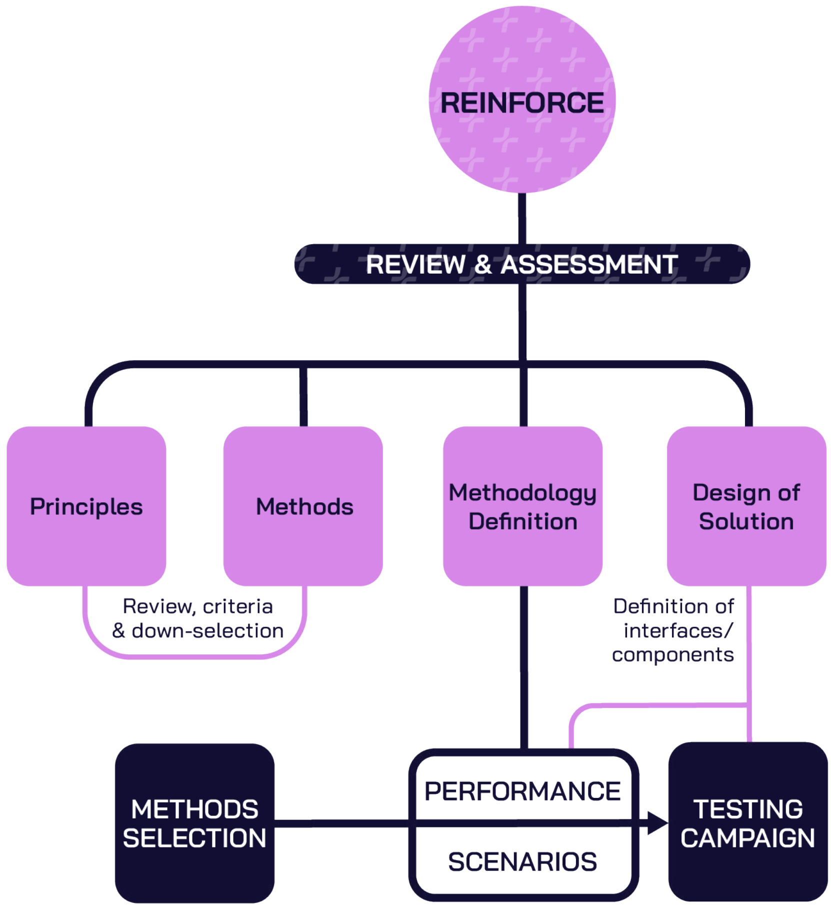


Figure 71: Proposed review and assessment for reinforce process

The reinforcing or retaining solutions are deemed to restore a satisfactory level of structural safety of those RAAC roof areas where it cannot be guaranteed, due to the presence or simultaneity of defects, to prevent catastrophic failure. The action of reinforcing or retaining can range from one single plank to the entirety of the roof.

These solutions can also be deployed if aiming to increase the loading capacity. For example, installing external units of services on the roof or, simply, as a preventive measure, with special interest in cases in which a replacement strategy is expected in the future (see the Reinforce to Replace strategy, figure 78).

Different approaches can be taken when designing a technical solution in terms of structural performance. The strategy may aim to follow one of the following approaches, as shown in Figure 72.

- **Structural strengthening:** in this document, this concept was used for those principles aiming to restore or improve the structural capacity by using methods with high dependency on the existing material, such as externally bonded reinforcement or section enlargement.
- **Functional substitution/alteration:** this is the approach by which the new structural elements or systems are designed to substitute the structural function of the existing structural element or to provide additional support such as shortening the span of the planks or extending the bearing length. The solution is designed to avoid the failure of planks.
- **Bearing length extension:** this focuses only on the provision of additional support at the bearings where they might be insufficient according with the current guidance.
- **Failsafe (collapse mitigation system):** this solution aims to retain a plank or group of planks in case of failure, preventing them from falling to keep occupants and equipment safe.

It may be tempting to consider using solutions designed for other types of structures, such as those for reinforced concrete structures. As a part of the UKRI RAAC Impact Programme, existing methods for strengthening, reinforcing, or retaining other types of structures have been reviewed, Figure 58; MTC's down-selection Process, and the readiness or potential feasibility for RAAC assessed. It was found that there is no or limited experience on the use of certain structural retrofitting techniques when it comes to RAAC. This is the case of strengthening methods where performance relies on the close collaboration between the element to be reinforced and the reinforcing solution, such as epoxy-bonded solutions. Besides material incompatibility, some solutions may be counterproductive or unfeasible due to the increased weight or the disruption they may cause.

To the knowledge of the authors, only failsafe and functional substitution concepts have been installed in buildings containing RAAC. Examples of these approaches are captured in the industrial case studies, showcasing the actions undertaken at Leighton Hospital and the next generation for RAAC Lift® – RCS Services.

The industry partners consulted, agreed on the current non-feasibility for strengthening methods until further knowledge is acquired through research. However, besides the agreement in the approach, industry is working in silos on what it has been described as a 'learning by experience' journey, due to the lack of a standardised approach.

Reinforce: Background

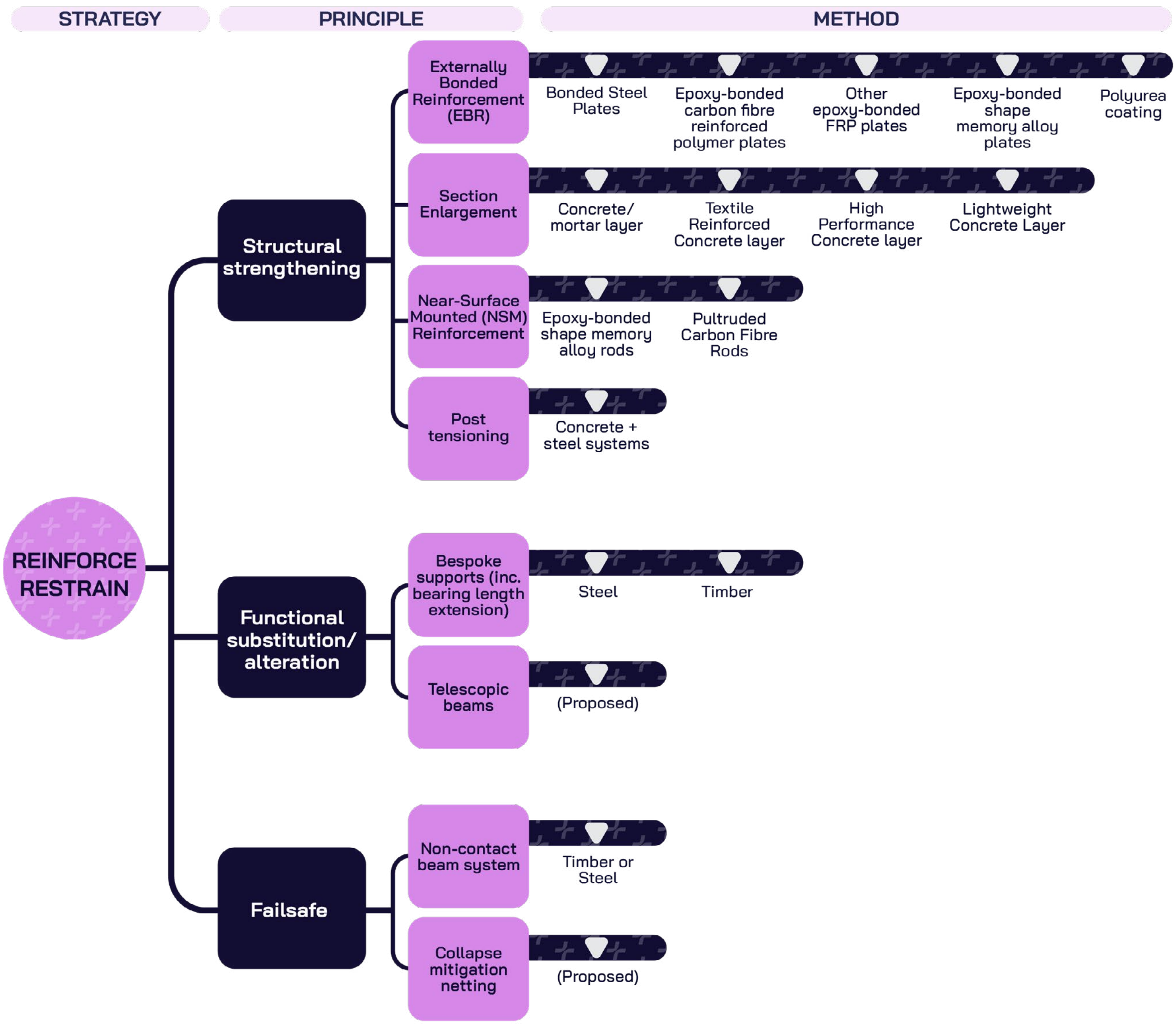


Figure 72: Reinforcing and retaining methods reviewed, organised by principles.

What are the research gaps?

The identified gaps are summarised below:

- There is little to no experience for structural retrofitting methods for RAAC planks other than using substructures for functional substitution or failsafe systems.
- There is little to no experience in the compatibility of AAC and other materials, such as resins/adhesives or mortars/concretes, for strengthening solutions.
- There is no clear guidance on the designed strength capacity of planks to be considered when designing the solutions.
- There is a lack of a standardised approach or clear guidance when investigating reinforcing and retaining RAAC structures. Therefore, different assumptions might be considered, even for the same type of approach, for example, the number of failing planks to be considered in the case of designing failsafe solutions.
- There are no manufacturing-led solutions that guarantee the structural integrity while minimising the disruption and adapting to the different range of scenarios.

What are the challenges?

When designing or selecting a technical solution, aiming to ensure the structural integrity of a roof formed by RAAC planks or keeping the occupants and the building contents safe, different technical and non-technical aspects and challenges need to be considered. Figure 63 - Steps in the design of appropriate solutions and definitions, adapted from [14] and [15] provides a list of potential constraints but are not limited to those which will ultimately define the approach and the solutions.

What are the opportunities?

There is a clear understanding of what principles would enable the quickest response for implementation with greater feasibility. Nonetheless, industry and building owners could benefit from the adoption of more industrialised approaches. These benefits could include accelerating the response at all stages of the work, such as design, installation and dismantling, and in doing so, minimising the disruption and costs. Therefore, it was found that there are opportunities for innovation in:

- Creating standardised methodologies and guidance to be followed by engineers, designers and contractors when aiming to reinforce/retain RAAC planks.
- Designing manufacturing-led solutions to accelerate the response and minimise disruption.
- Creating decision-making tools to facilitate informed solutions.
- Extrapolating this approach to other existing assets and structures beyond RAAC.

Table 8: Technical and non-technical challenges for reinforcing solutions

Constraints			
	Existing structure	**Building construction**	**Operational**
Technical Challenges	• Existing frame • Frame variations (material, sections and other features) • Variability in spans • RAAC planks • Low strength capacity • Fragility and creep • Excessive deflection • Unknown compatibility with other materials • A risk to work on top of planks	• Limited space for installation and/or storing. • Unmoveable furniture • Mechanical, electrical and plumbing (MEP) congested areas • Accessibility • High rooms • MEP congested areas • Asbestos-containing materials (ACM)	• Full-time operational areas / buildings • Restricted areas • Air quality and noise restriction requirements • Circulation • Occupancy
	Scale	**Approach**	**Governability**
Non-Technical Challenges	• Unknown scale of the problem • Labour shortage	• Lack of standardised approach • Lack of data and tools to support effective decision-making	• No guidance • Industry working in silos. • Little or non-discussion around how to accelerate

Reinforce: Methodology

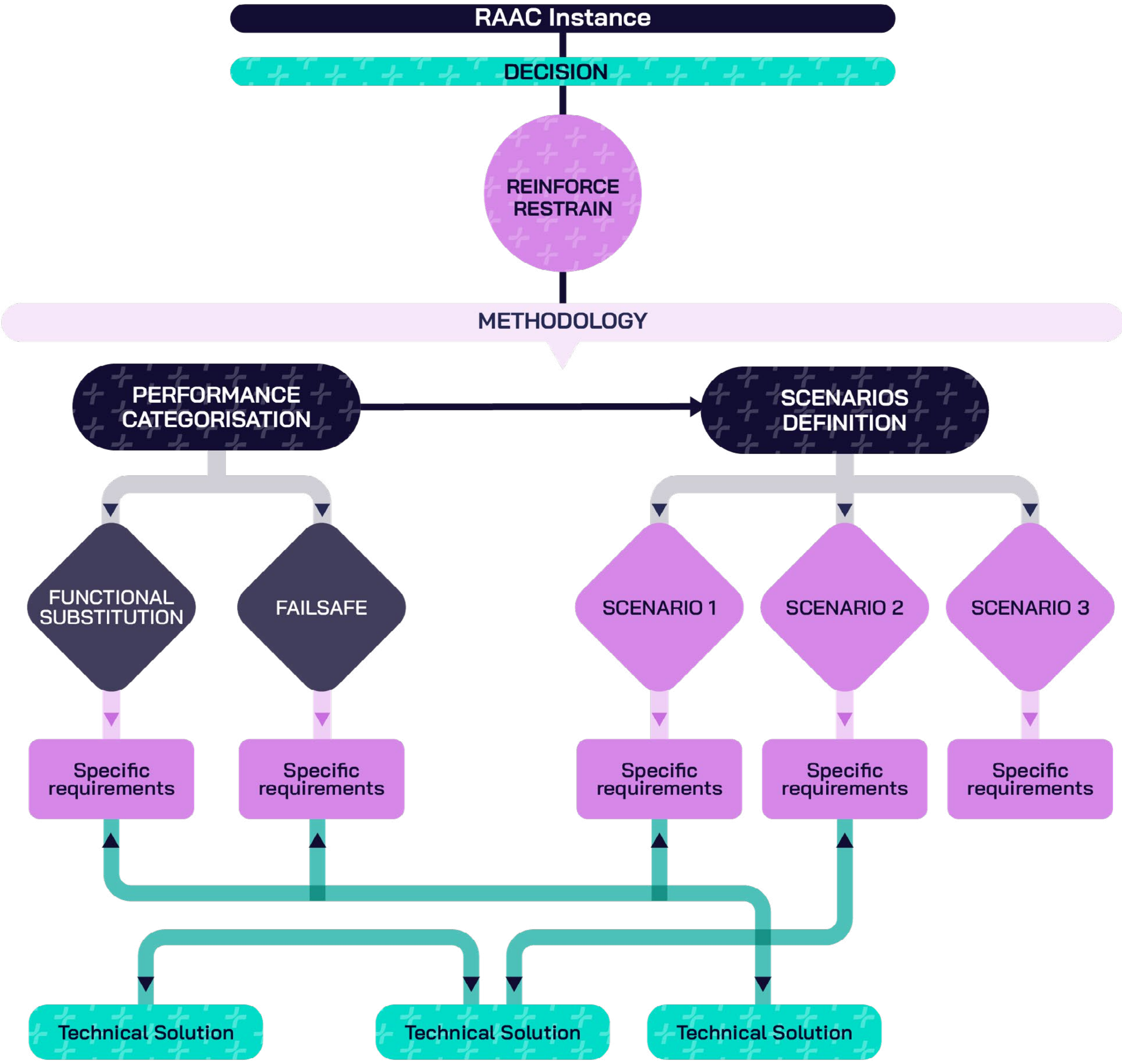


Figure 73: Proposed methodology for reinforce process

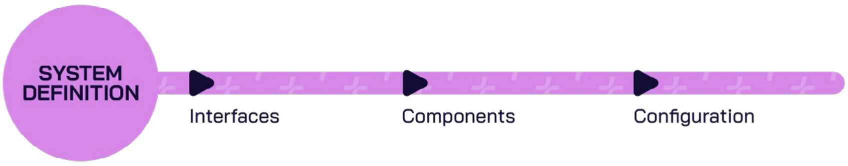


Figure 74: System definition for reinforce

Performance categorisation

Effort has been made to categorise solutions based on their performance (what type of approach defines the solution, functional substitution/alteration or failsafe?), and to provide a clear map of these concepts and the existing possibilities. This aims to lay the foundations for a methodology that allows engineers, designers and other stakeholders to make guided decisions when designing, selecting or applying technical solutions, as shown in Figure 64 - Range of options for the accountable person(s) for a building containing RAAC. Based on [14] and [15]. The technical solutions can be designed and selected by considering one performance category or a combination of both, to satisfy the requirements for specific scenarios. Currently, there is no common agreement on the parameters to be considered for each structural approach, especially for the failsafe approach. There is an attempt to provide a clearer definition below. This definition was based on experience, structural standards, such as Eurocode, and input from industry partners.

Functional substitution/alterations: These solutions are designed to minimise the planks' structural requirement by providing additional support and taking all the loading away from the planks with consideration of a permanent (**persistent**) or **transient** situation. Ideally, to ensure this, the planks should be jacked up and then released to ensure the transmission of the loading to the new elements. However, due to the technical difficulties that this entails and risks due to the fragility of RAAC, it is common to just install the substructure and assume that the planks would, at some point, rest on them completely. In any case, the transmission of the loading between planks and the solution needs to be guaranteed, for instance, by filling the gaps with adequate transmission material. The maximum deflection allowance for the new substructure should take into consideration the existing deflection of planks. The RAAC Lift® system shown in the case studies has an integrated system to jack up the planks and allow the deformation recovery.

*In normal use, the structure is in a **persistent** situation; under temporary conditions, such as when it is being built or repaired, the structure is in a **transient** situation; under exceptional conditions, such as during a fire or explosion, the structure is in an accidental situation or (if caused by an earthquake) a seismic situation.*

***Ultimate Limit States** (ULS) are concerned with the safety of people or the structure (Eurocode 7)*

Failsafe: The failsafe would consider an accidental situation. The design values of actions for **ultimate limit states** (ULS) could be those considering an accidental design situation, instead of a persistent or transient situation, reducing the loading requirements. If it is assumed that the plank may fail, then short bearings do not need to be extended and the contact between planks and the system is not required. However, this decision will rely on the condition assessment and analysis of risk. In addition, the 'functional substitution' needs to consider the entire load area affecting the structural element, while, when using the 'failsafe' concept, this can be reduced to a few planks believed to be affected by the failure of one plank. A failsafe subtype may exist if the scope of the design is the retention of falling debris. This is a complementary system that cannot be used alone to guarantee the structural integrity. The need for the bearing extension can be discussed when any of these approaches are followed. In the functional substitution approach the shear at the plank ending would be highly reduced, while in the failsafe approach, if the planks are 'allowed to fail', the extension of the bearing length may be counterproductive. However, there is still a lack of understanding on the shear capacity of planks and each plank may have different features. Therefore, the final decision will be down to the structural engineer's technical decision.

Scenarios definition

Multiple scenarios may exist when designing the reinforcing solutions of RAAC roofs in a building, depending on the existing frame, materials and spans, room for installation (MEP, fixed furniture) and other operational constraints. These need to be identified and further requirements captured when assessing the suitability of the technical solutions.

Technical solution - System definition

Once the most viable solution is identified, according to the specific requirements and criteria, the solution needs to be defined and designed, with special attention given to the interfaces and components and potential configurability. This is especially important when defining industrialised solutions such as off-the-shelf (OTS) kits-of-parts that enable a response at pace and scale. The main challenge is the specific conditions of the existing building, the reason why remediation solutions tend to be bespoke. However, the industrialisation of these solutions is an area to explore that could bring many benefits. To make it feasible, there is a need to work on interfaces and solutions that enable the adaptability to cover, for instance, variable length.

Reinforce: Methodology

Methodology applied to the UKRI RAAC Impact Programme

Method identification

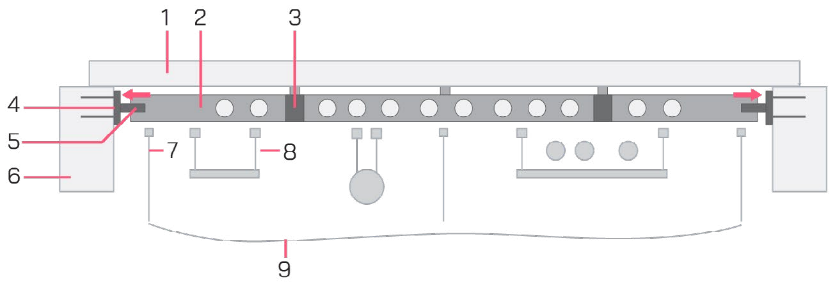
Applying the methodology proposed, the MTC identified a kit-of-parts as the most feasible solution when aiming, as a requirement, to cover a wide range of scenarios to accelerate the response Figure 84. This is of special importance for those building owners or contractors facing large surface areas to be reinforced.

Kit-of-parts: *A collection of repeatable, standardised building components that are pre-engineered and designed to create a variety of assemblies which define part or all of a finished building (Source: Construction Innovation Hub Product Platform Rulebook)*

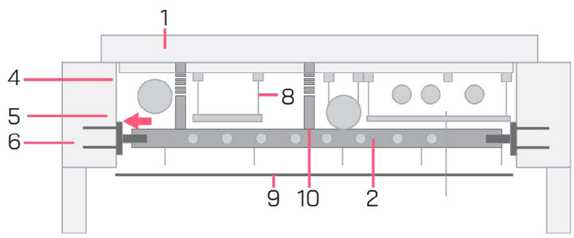
System definition – interfaces and components

To accelerate the response and the implementation of the solutions, the MTC approach aimed to streamline the integration and combination of OTS components and interfacing components that facilitate the adaptability of the manufacturing-led solutions to the variability of requirements.

SYSTEMS EXAMPLE
Components for scenario 1



SYSTEMS EXAMPLE
Components for scenario 3



1. Existing bearing structure – RAAC plank
2. Reinforcing system – Beam
3. Reinforcing system – Joist
4. Reinforcing system – Plate/bracket or connection and anchoring to existing bearing structure
5. Reinforcing system – Adaptability
6. Existing bearing structure – Beam
7. Reinforcing system – Hanger for ceiling/falling debris system
8. Reinforcing system – Hanger/rack for services
9. Reinforcing system – Ceiling/falling debris system

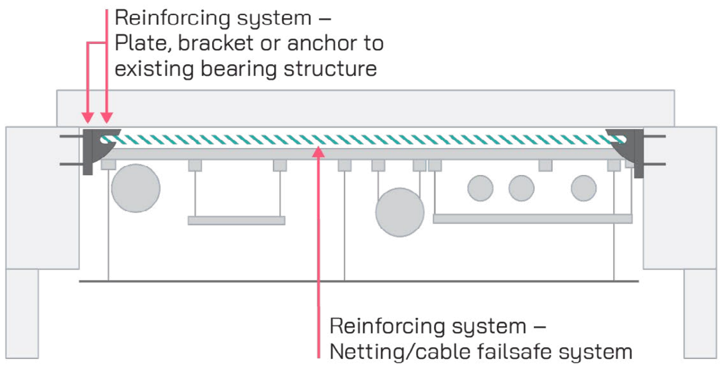


Figure 75: Conceptual sketches for the identification of components for different scenarios

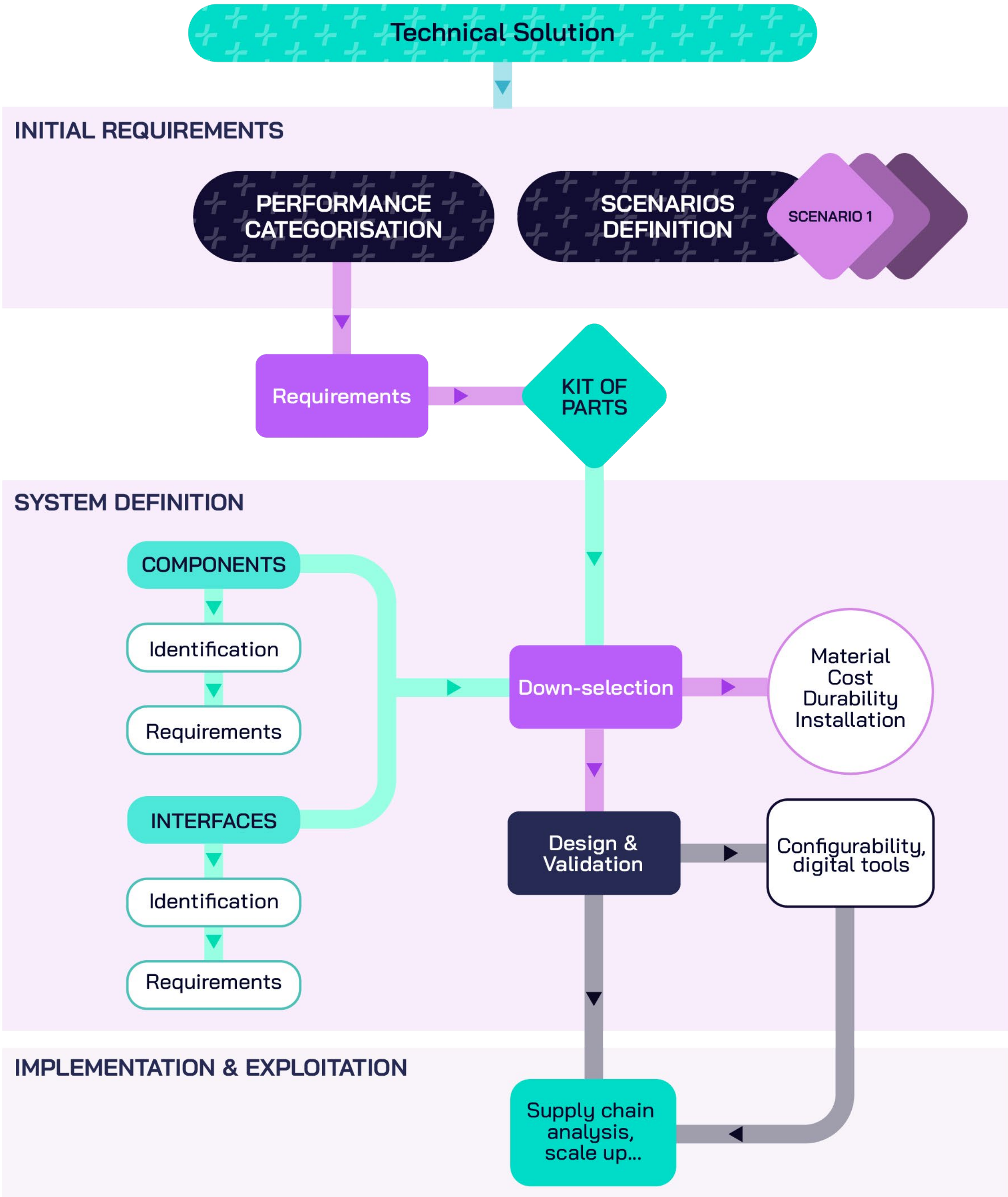


Figure 76: Methodology followed to design the kit of parts.

Reinforce: Methodology

Applying a kit-of-parts

The MTC design team investigated the application and further development of the kit-of-parts for reinforcing solutions. As a first approach, the most common scenarios in hospitals (those buildings, besides full-time operational industrial buildings, that may represent major challenges) were defined.

The scenarios definition (Figure 77) helped to understand the needs and potential strategies. An initial system definition has been proposed based on discussions among experts from different backgrounds, and the application of the MTC design engineering methodology and tools such as FMEA (see How FMEA can be applied to the UKRI RAAC Impact Programme?). The outputs of this phase can be summarised as:

- Interfaces identification and assessment.
- Compatibility requirements definition.
- OTS components identification and selection.
- Non-OTS components design.
- Initial structural assessment and parametric design.
- Rules for configuration.
- Initial bill of materials (BOM), standard operating procedures (SOP) and sustainability metrics.
- Further work is needed to move into the phase detailed system definition and final validation.

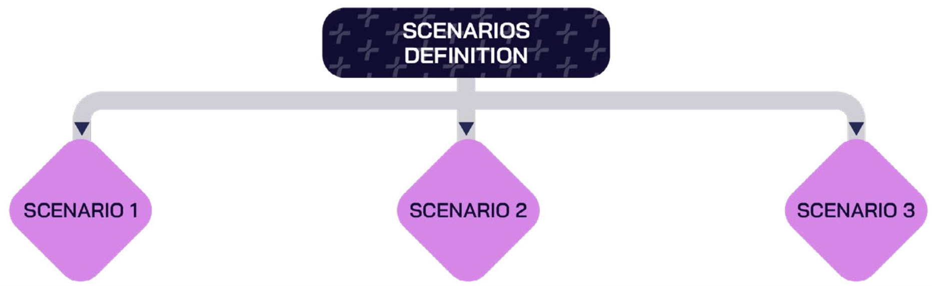
Configuration

A Standardised kit-of-parts based approach allows for rapid design iteration and variability, freeing up the design team to focus on other value-added activities. Configuration tools using a Knowledge-Based Engineering (KBE) approach, saves time when designing the solution and enable the integration of different compatible components.

Reinforce to Replace (R2R) strategy

There may be cases in which the replace strategy might not be an immediate option due to budget, time or logistic constraints, but there will still be a need to put in place reinforcing solutions to guarantee the safety of users and content. Under these circumstances, temporary emergency solutions, such as the installation of props or the closure of certain areas can be used until the replacement takes place. However, these solutions cause severe disruptions.

The Reinforce to Replace (R2R) strategy arises as a smart approach worthy of consideration for those cases pointed out above. In essence, it is a solution designed to satisfy three situations: the reinforcing stage, the dismantling or removal of RAAC planks, and the replace stage. Acting as reinforcement, substructure for a work platform, and substructure for bearing the new improved roof, respectively. The approach promotes a wider thinking to consider all the actions occurring at the different stages. Using the reinforcement as the substructure for the future replacement will minimise the cost and workload of having differentiated solutions.



	Scenario 1	Scenario 2	Scenario 3
Span	2m > S < 6m	< 2m	< 2m
Access to structure	Space available for installation	Space available for installation	Space available for installation
MEP	Minimal or no MEP	Minimal or no MEP	MEP congestion
Variations	Existing structure: RC Existing structure: Steel	Existing structure: RC Existing structure: Steel	Existing structure: RC Existing structure: Steel

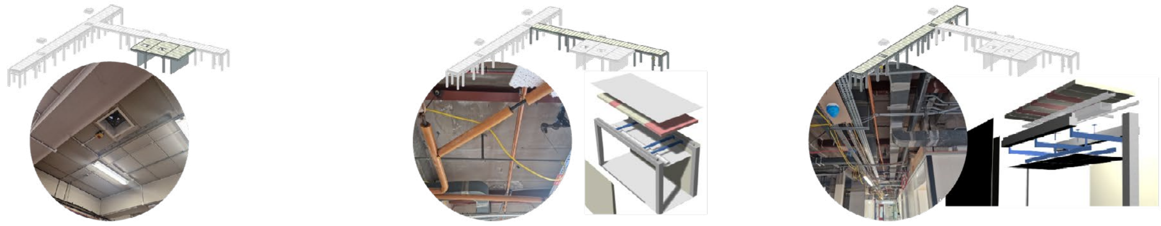


Figure 77: Scenarios Definition

REINFORCE TO REPLACE

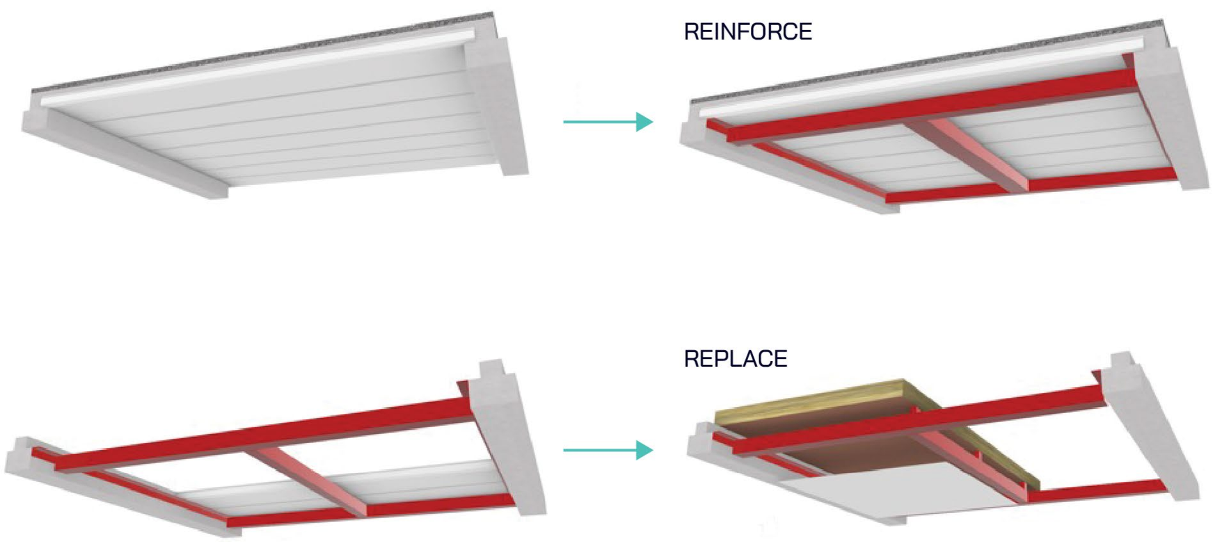


Figure 78: Reinforce to Replace Strategy

Reinforce: Barriers, conclusions, next steps

Barriers

- The lack of tangible data creates a barrier to obtaining the metrics for optimised decision-making.
- A full standardised methodology and the creation of a potential industry standard may take two years to be put in place. However, the MTC is working on liaising with insurance companies to explore the best avenues to promote the implementation of certain approaches.

Conclusions

- The challenges and research gaps for reinforcing solutions were identified.
- Many solutions suitable for reinforcing other existing structures might not be appropriate for RAAC.
- The viability of technical solutions needs to be assessed against the requirements, including the expected structural performance and the potential scenarios besides other specific requirements.
- When aiming to provide a response to a wide range of scenarios, the kit-of-parts is the best system.
- To accelerate the response, the MTC is working on the creation of a kit-of-parts using off the shelf (OTS) components when possible and designing the interfacing components that enable the adaptability.

Next steps

- Continue with the detailed design of the system definition.
- Advanced structural assessment at a component, system and building level.
- Detailed bill of materials (BOM) and instructions for installation.
- Continue with the development of the structural parametric analysis and the configurator.
- Collaborate with industrial partners.
- Validation phase inclusive of prototyping and testing.
- Work with industry partners to obtain the metrics to feed into the decision-making processes and review the solutions.

Industrial Case Studies: Remediation

Decision support framework for RAAC remediation

Partners:
Expedition Engineering
Loughborough University
RAAC Consulting and Solutions (RCS)

Expedition Engineering, Loughborough University and RAAC Consulting and Solutions have developed a resource for building owners who have identified an unsafe RAAC installation and need to develop and efficient and effective remediation plan.

A decision support framework has been established which enables decision-makers to rigorously tailor an options appraisal towards their specific needs and to rank the most appropriate RAAC remediation options for their site.

The development of the framework followed from an observation that approaches to RAAC remediation have varied significantly across the industry, even for ostensibly similar scenarios. There is anecdotal evidence of overly risk-averse decision-making and preference engineering which potentially lead to sub-optimal remediation schemes.

While there is robust literature available explaining how to identify RAAC and assess the risk posed to building occupants, there is a lack of clear guidance on how to remediate the problem. It was felt that a new approach, documenting the options available and providing a method to differentiate between them for a given site, would be of significant value to building owners.

By consulting widely with experienced RAAC practitioners, client representatives, and academia the group has identified and itemised the most common solutions currently implemented in practice. These include:

- monitoring schemes;
- propping schemes;
- bearing brackets;
- various retrofit roof support options; and
- re-roofing.

Each of the generic options has been assessed against a suite of objective criteria which might influence the decision making of the building owner. The framework then introduces a multi-criteria decision analysis following UK Government Green Book guidance to help the user weight the scores based on site-specific factors and generate a short-list of priority options.

The multi-criteria decision-analysis is presented as a simple set of guided questions to be answered by the building owner and their consultant. Behind the scenes the quantitative scores are extracted from each response and an Analytical Hierarchy Process yields a weighted set of criteria for the options sift.

The framework is designed to be used flexibly. Many building owners will gain useful insight from the analysis of generic options presented in this framework; and this material alone can support good decision making. However, building owners who need to further document a rigorous process to unlock capital funds, will find the proposed multi-criteria analysis represents an effective, simple, best-practise approach.

Leighton Hospital end bearing support

Client: Mid Cheshire Hospitals NHS Foundation Trust
Contractor: Robertsons Construction
Consultant: Curtins
Site: Leighton Hospital

Leighton hospital was built in 1972, using significant quantities of RAAC for upper-storey floors and roofs which are structurally loaded, and for walls which are typically non-load bearing due to the steel framing around the planks.

Mid Cheshire Hospitals NHS Foundation Trust have engaged with Robertsons construction and Curtins consultancy to provide support reviewing the RAAC condition and, subsequently, providing remediation services and monitoring recommendations as required.

Leighton presents a number of challenges with respect to RAAC identification, inspection, monitoring and remediation. This is largely due to access to the RAAC itself, a result of its presence across different locations throughout the facility including mechanical, electrical and plumbing (MEP) laden corridors, highly sterile operating wards and high ceiling areas such as stairwells.

One of the key safety factors for consideration when assessing RAAC condition, as identified by the Institution of Structural Engineers (IStructE), is the bearing length and the presence of transverse rebar within that length. Where end bearing conditions are considered a risk, a proactive approach to managing this risk has been taken at Leighton hospital with the installation of angle steel under the bearing location to increase the bearing length and reduce the shear stress applied to the end of the plank. This extension of the bearing length also increases the likelihood that it contains transverse reinforcement.

This reinforcement solution has reduced the risk of plank collapse, however, its use is limited to areas with greater freedom of access to the RAAC planks, such as storage rooms. Installation continues to be disruptive, with hole drilling creating significant noise and further challenges for works around hand-arm vibration (HAVS) and local health and safety (H&S) requirements.

Novel methods for the evaluation of end bearing condition, including bearing length and presence of transverse reinforcement, would be immensely valuable, not only to eliminate physical hole drilling to locate the rebar (and the associated disruption), but to better inform remediation actions such as these.

Figure 79: End bearing strengthening in (a) large width hospital room, (b) hospital corridor. (Source: MTC. With permission of Leighton Hospital)

Leighton Hospital RAAC plank reinforcement

Client: Mid Cheshire Hospitals NHS Foundation Trust
Contractor: Robertsons Construction
Consultant: Curtins
Site: Leighton Hospital

Leighton Hospital was constructed in the 1970s using RAAC. In 2019, the hospital was first made aware of potential risks, associated with its abundant use during construction, and implemented a plan of action to regularly undertake structural surveys to assess RAAC condition and degradation. Subsequently, Curtins consultancy and Robertsons construction have been engaged to support RAAC condition review and provide remediation services.

A hospital setting presents substantial remediation challenges and the requirement for multiple approaches to be considered depending on a variety of factors such as ease of access, risk factor and site location. Visual inspection for key signs of degradation (i.e. water ingress, deflection) were undertaken where possible and used to inform the remediation strategies.

One example of remedial plank reinforcement is used in areas where RAAC planks are easy to access. This approach uses structural steel members, called parallel flange channels (PFCs), to support the RAAC from underneath where there are risks of failure from bending loads. The same solution has been used to support where large sections have been removed to accommodate large utility equipment such as air conditioning (AC) ducting.

Where access to RAAC is significantly compromised (e.g.: in corridors with high density of services), an alternative approach has been adopted to provide reinforcement with limited disruption to hospital operation. Large numbers of Unistrut pieces have been installed underneath the planks at regular intervals, both perpendicular and parallel to planks depending on risk severity, in areas with large quantities of mechanical, electrical and plumbing (MEP) which are critical to hospital function. Although not designed to be structural, the abundant use of Unistrut in this case demonstrates a low cost, temporary risk mitigation strategy as more permanent solutions are developed.

Figure 80: *Parallel flange channels used for large span RAAC panel reinforcement in (a) large span hospital room, (b) around service cut out. (Source: MTC. With permission of Leighton Hospital) (c) Unistrut used to reinforce in space constrained areas (Source: MTC. With permission of Leighton Hospital)*

RAAC Lift® – RCS Services

Client situation

The client organisation is based in a multifloored, Grade 2 listed building which was built in the mid-1970s. Having determined that the building has a significant RAAC presence, a structural assessment was carried out by a multi- disciplinary construction firm. The proposed remediation approach was to remove the RAAC panels and install a new roof at a total cost, including interest on borrowing, of approximately £60m.

In terms of cost, loss of revenue, period of displacement from the building and impact to the listed structure, this outcome was seen as highly sub-optimal by the client organisation. Accordingly, they engaged RAAC Consulting and Solutions ('RCS') and Expedition Engineering to provide a rigorous review of the proposed scheme, using their decision support framework.

Action

The team carried out an Options Selection exercise - comprising structural analysis of the RAAC panels, assessment of specific site conditions and comprehensive data gathering of building owner and occupant priorities, relating to specific criteria. All inputs were then worked through the decision support tool as part of a structured process between the client and RAAC specialist consultants, to optimise the remediation strategy.

Outcome

It was determined that full panel and roof replacement was unnecessary. The best fit solution has emerged as a mixed scheme comprising a range of phased remediation methods. This scheme will provide appropriate levels of structural integrity and support the planned building service- life. It will significantly reduce the total cost of remediation, minimise disruption, and allow for adjacent works to be completed, boosting thermal efficiency of the building.

Figure 81: *RAAC intermediate supports. (Image supplied by RAAC Consulting and Solutions ('RCS'))*

Replace: Background

Disclaimer: *the following solutions are concepts only, generated during the UKRI RAAC Impact Programme 2023 / 2024 and have not been fully trialled, validated or approved by chartered structural engineer.*

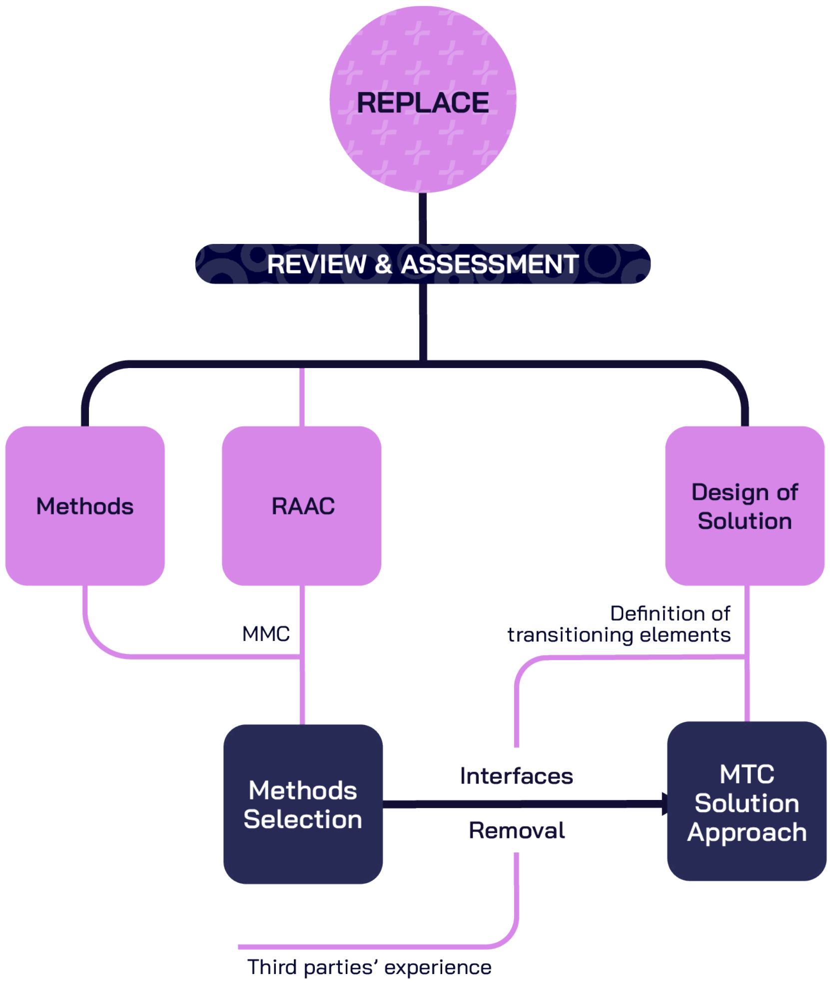


Figure 82: Replace process

Currently there are several building owners, such as the Department for Education and the NHS, aiming to replace all existing RAAC planks in their buildings.

Replacing, especially whilst in use, is a strategy that needs to be carefully planned and managed. While the key goal is having minimal out of service time/disruption to room use, specific considerations must be taken depending on the condition of the planks, the accessibility or roof finishes removal, amongst others. There are associated costs to guarantee the function of the rest of the building. In these types of situations efficient time management is a key factor, as it may result in the reduction of costs and disruptions.

Through discussions with industry partners during the UKRI RAAC Impact Programme, organisations who supply current replacement products or solutions may struggle with the required demand. Alternatively, more industrialised solutions would ensure greater quality, weight control, and improve the envelope's thermal performance, while accelerating the remediation works. However, how are we able to ease the installation of modular construction to existing assets?

Additionally, to enable the replacement of RAAC, removal is needed. Currently there is no clear guidance on the removal of RAAC. Industry partners have been working in silos, removing in the best way they can through consideration of the building's limitations. However, this can be time consuming and presents a risk for workers and building contents if not carried out cautiously.

What are the Research gaps?

The identified gaps can be summarised as:

- Non-existent standardised removal methodology. There is no widely accepted standard practice or guidance for removal best practice.
- Non-existent standardised replacing methodology for installation on existing assets.
- Greater presence of timber based modular systems than steel manufacturers, which may present issues when considering certain building owners' requirements for non-combustible materials.
- Modifications and replacement effect on structural rigidity of existing assets have not been widely reviewed and assessed.
- Interfaces – a lack of consideration from existing systems for interfacing with existing architecture.

What are the challenges?

When designing or selecting a technical solution to replace roofs formed by RAAC planks, different technical and non-technical aspects and challenges need to be considered. The challenges covered in Figure 63 - Steps in the design of appropriate solutions and definitions, adapted from [14] and [15], can be applied when replacing. In addition to this, the removal and disposal of RAAC is another challenge for the success of the replacement strategy.

Solutions must ensure the integrity of the overall structure during and after the replacement, such as the potential need of additional bracing components or the restoration of the resistance to diaphragm forces. This is of special importance for occupied or operational buildings.

Through discussions with industry partners during the UKRI RAAC Impact Programme, other challenges were identified:

- The existing supply chain might be unable to cope with the required speed and quantity of replacement required.
- Modular/modern Methods of Construction (MMC) system level solutions, such as modular offerings, focus on products in isolation and not peripherals in many cases.
- A wide variety of systems are in existence for timber-based construction, but a lack of options for steel structured solutions.

What are the opportunities?

To develop replacement systems that accelerate solution adoption. Industry and building owners could benefit from the adoption of more industrialised approaches. These benefits could mean accelerating a response at all stages of the work, including design, installation and dismantling, and, therefore, minimising the disruption and costs. There are opportunities for:

- Standardised methodology and guidance to be followed by engineers, designers, and contractors when aiming to replace.
- Manufacturing-led solutions to accelerate the response and minimise disruption.
- Creating decision-making tools to facilitate informed solutions.
- Opportunities to investigate temporary mechanical, electrical and plumbing (MEP) rerouting and mobile plant rooms that could be brought to site to facilitate provision of service.

Replace: Methodology

The MTC proposal for replacement is a manufacturing-led solution. This can be divided in three stages: the removal of planks, the design of interfacing components or structure, and the final roofing system.

Removal procedure – *this aims to extract RAAC panels from existing buildings. A configurable kit of parts is proposed to safely remove and lift RAAC.*

Interfacing structure – *this aims to ensure interoperability of replacement products with existing building structures capable of being used in combination with any of the platform-based roofing solutions proposed in previous deliverables, including MTC's lightweight roofing cassette, TATA Trisomet, and Timber Innovations' timber frame cassette.*

Roofing system - *the proposed roof cassette system is a kit-of-parts, including roof cassette, parapets etc, enabling the quick installation of a roof with improved insulation properties without increasing the weight.*

The benefits of using a manufacturing-led approach

The benefits of using the manufacturing-led approach and modular components are beneficial in terms of:

Efficiency

Featuring roof cassettes, parapet walls, detailed roofing edge detail, drainage systems, and auxiliary anchorage for MEP, photovoltaic (PV), and heating, ventilation and air conditioning (HVAC), represents a paradigm shift in commercial construction efficiency. By exploiting offsite manufacturing, each component is precision-engineered to exact specifications in a controlled factory environment. This meticulous crafting process ensures seamless integration and swift installation onsite, significantly reducing construction time and allowing projects to stay on schedule with ease. With the 80/20 method, installation becomes a streamlined process, enabling construction teams to focus their efforts where it matters most, ultimately enhancing overall project efficiency and success.

Sustainability

Manufacturing components offsite reduces material waste and environmental impact, making our system a greener choice for construction projects. Elimination of excess materials cluttering the construction site creates a more sustainable material transportation and handling.

Quality assurance

Every component is crafted to exact specifications in a controlled factory environment, ensuring consistency and reliability across every project. Full traceability provides peace of mind, with a golden thread of information from manufacturing to installation.

Productivity

Reducing dependency on skilled labour and streamlining installation processes, enables the system to enhance productivity by enabling manufacturing and insulation of the system to be carried out by anyone, with minimal training and experience.

The methods designed for each stage followed the MTC design engineering process shown in Figure 65.

The MTC propose a manufacturing-led removal, interfacing and replacing option. This includes options to facilitate the safe, rapid and standardised integration of industrialised solutions with an existing asset.

Final developed solutions have been generated for the following areas to deliver a holistic replacement methodology.

Methodology applied to the UKRI RAAC Impact Programme

Removal

The proposed RAAC removal strategy is focused on minimising impact of removal on existing facilities and built assets while also maximising rate of removal, as can be seen in Figure 65.

The proposed solution consists of a prefabricated mobile stand on which hydraulic jacks are mounted. They are capable of extending to the height of ceiling spaces in hospitals and school buildings. A modular lifting frame, adjustable to the area required to be covered, is assembled on top of the jacks and covered in a retaining net mesh to prevent any fall of debris. This is then lifted to the underside of the RAAC panelling to be removed.

Once the modular lifting frame is accurately positioned below the RAAC panels to be removed, a core drill is then mounted to penetrate panels to fill in lifting flutes that allow lifting eyes to be attached from above. Following the lifting eyes, and ultimately the lifting frame, being slung to a crane, the RAAC can then be separated from existing beams from above.

This allows an area of up to 18m^2 of roof to be removed in one lift to a site external to the building for demolition.

The modular lifting frame has been designed as a kit of parts to allow any size of RAAC paneling to be lifted in a controlled and consistent manner. The modules are sized in multiples of 300mm to accommodate a variety of lift configurations, thus allowing for flexibility of design.

Interfacing structure

Universal interfacing brackets attach to T beam or square beams of sizes between 200mm and 362mm and account for a requirement to create pitch for rainwater runoff. The brackets can then accept the required light gauge steel substructure for the roofing option selected, Figure 89.

Roof cassette

The lightweight roof cassette system has been designed as an offsite manufactured system, which redefines efficiency, sustainability and quality in roof construction.

Figure 84 shows the different stages when replacing RAAC roof planks.

Configuration

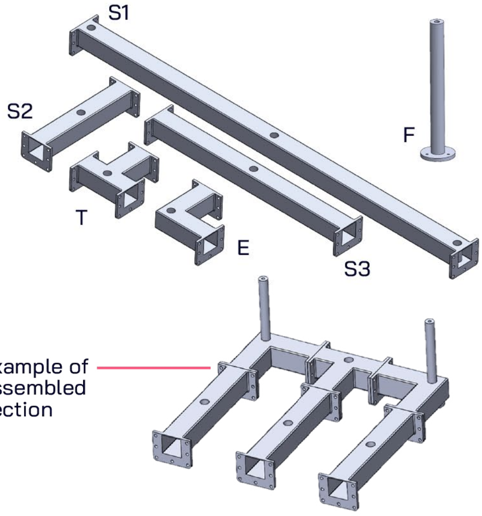
The standardised kit-of-parts based approach allows for rapid design iteration and variability, freeing up the design team to focus on other value-added activities.

Lightweight roof cassette system components are designed for worst case operation scenarios, meaning that a complete roof solution can simply be configured using Knowledge-Based Engineering (KBE) tools, rather than designed from scratch each time.

Replace: Methodology

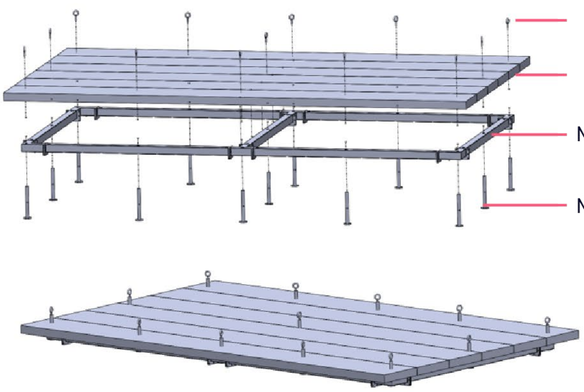
MODULAR LIFTING FRAME KIT OF PARTS

consists of:
S1, S2, S3 – A variable length straight piece.
T – An intermediate T joint piece.
E – Corner piece.
F – Lifting flute designed to be mounted from underneath.

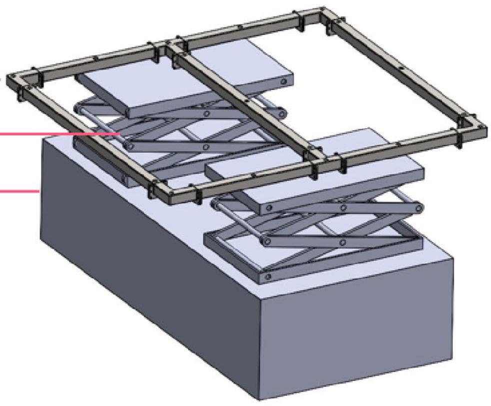


POSSIBLE CONFIGURATION OF THE LIFTING FRAME

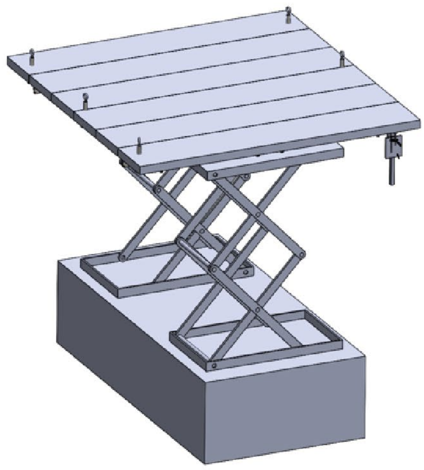
The image shows one of the possible configurations of the lifting frame. The number of lifting flutes to be used is determined by the lifting plan based on the loads to be lifted.



REMOVAL APPARATUS



REMOVAL APPARATUS IN USE



Solution status:

- Concept design
- Detailed design
- Developed design, prototyped and tested

Figure 83: Modular removal system concept (a) Kit of parts for modular lifting frame, (b) modular lifting frame lifting location illustration, (c) proposed removal apparatus (un-extended) and (d) proposed removal apparatus (extended).

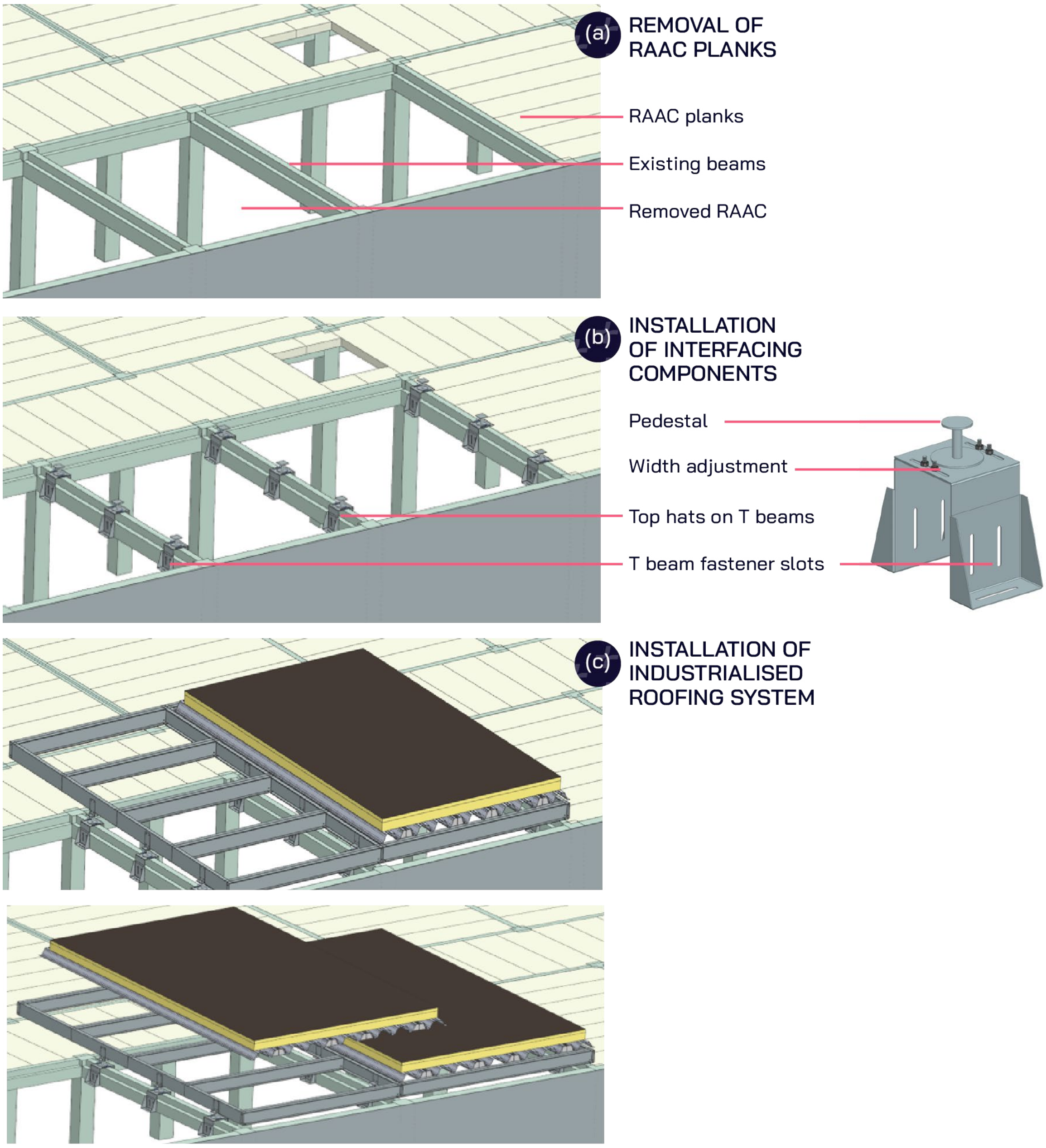


Figure 84: Phases for the replacement of RAAC roof planks (a) Exposed structural T-beams, (b) example interfacing bracket and positioning, (c) example of interfacing frame and lightweight roof cassette deployment.

Replace: Barriers and next steps

Barriers

- The lack of tangible data creates a barrier to get the metrics that enable optimised decision making.
- A full standardised methodology and the creation of a potential standard may take years to be put in place. However, this is not a limiting factor.

Next steps

- Development of a solution deployment manual to create further content on required steps and utilisation of the work completed to date.
- Further development of the modular removal frame concept, detailing end-to-end operations with consideration for disposal and compacting of the lifted panels.
- Further development of the interface system in conjunction with reinforce solutions to harmonise interchangeable kit of parts.
- Opportunity to look into temporary MEP rerouting and mobile plant rooms that could be brought to site to facilitate provision of service.
- Supply chain development involving assessment of supply chain capability to meet expected demand and cost analysis of solution implementation.
- Development of a configurator tool to automate the remediation design plan development and add KBE.
- Site specific considerations for replace solutions.

Chapter 7: Failure Mode & Effects Analysis

- FMEA: Introduction
- FMEA: Barriers, Conclusions, Next Steps

FMEA: Introduction

Disclaimer: *FMEA has not been extensively trialled for RAAC beyond this R&D programme. However, use of this method is common practice in other industries to prioritise risk. FMEA should not replace existing industry guidance for the Risk Assessment of buildings.*

Failure Mode and Effect(s) analysis (FMEA) has its roots in US military standard MIL-STD-1629 (1949). It remains the basis of formal risk identification and migration in many industries worldwide. In manufacturing industries that support the automotive and aerospace industries, the formal practice of Design FMEA (DFMEA) and Process FMEA (PFMEA) is a due-diligence requirement in adherence quality systems like Advanced Product Quality Planning (APQP). As part of the Construction Innovation Hub, APQP was adapted to Construction Product Quality Planning (CPQP) as part of developing a manufacturing approach to construction.

As one of the key aspects of both APQP and CPQP, FMEA is designed to:

- identify potential failure modes
- understand the direct causes and effects of such failures
- assess the risks associated with the failure mode and prioritise them for corrective action, and
- identify and carry out appropriate corrective actions to address the most serious concerns.

There are many variations of FMEA. The most used in manufacturing are:

- DFMEA which focuses on product design, typically at the subsystem or component level. The focus is on design-related deficiencies, with an emphasis on improving the design and ensuring product operation is safe and reliable during the useful life of the equipment.
- PFMEA which focuses on the manufacturing or assembly process, emphasising how the process can be improved to ensure that a product is built to design requirements in a safe manner, with minimal downtime, scrap and rework.

How FMEA can be applied to the UKRI RAAC Impact Programme?

There is recognition that guidance for assessing the risk of RAAC needs to be updated in line with the Health and Safety Executive (HSE). As part of the RAAC Impact programme, the MTC investigated the use of FMEA as a potential tool for assessing risk. Figure 57 - DAT functional scope shows an example of application of DFMEA for RAAC planks.

Assessment								
Potential Failure Mode (what could go wrong)	**Potential Failure Mode Effect** (why is this bad?)	Sev	**Potential Failure Mode Cause** (How could it happen?)	Frequency of occurrence (likelihood of failure)	**Prevention of potential Failure Mode Cause** (What stops this currently)	Det	**RPN**	**Recommended improvement corrective actions**
Shear failure of RAAC Plank	Sudden collapse. Severe injury, loss of life, operational loss, reputational loss, disturbance of dangerous materials (e.g. asbestos), environmental effects/moisture ingress	10	**Transverse reinforcement at anchor missing** due to cutting of panels during installation	10	Intrusive surveys detect missing reinforcement Visual detection of cut planks extend the bearing length	8	800	Objective assessment of RAAC condition using NDT technology to provide more data that will inform remediation action

Figure 85: Example of DFMEA

FMEA: Barriers, Conclusions, Next Steps

Barriers

There are challenges in the application of FMEA to a retrospective scenario, such as degradation of RAAC planks, as opposed to the development of new and future construction products.

Conclusions

FMEA has potential to assist in ranking and prioritising risk of RAAC failure, however further work is required to determine the probability statistics of the occurrence of failures.

Next Steps

Gathering further data could enable a more objective ranking as part of the failure cause occurrence probability. This data can feed into the data assessment tool in conjunction with use of FMEA

Failure Mode and Effects Analysis Rankings GUIDELINES

DFMEA Criteria

Ranking	Failure mode *effect* **Severity**		Failure *cause* **Occurrence** probability			Control method **Detection** effectiveness		Ranking
1	None	No Effect	Extremely unlikely	Failure highly unlikely	1:1.5M	Extremely likely	Can be corrected prior to engineering prototype.	**1**
2	Very slight	Negligible effect on product performance. User not affected	Remote likelihood	Rare number of failures likely	1:150K	Very high likelihood	Can be detected and corrected prior to engineering design release.	**2**
3	Slight	Slight effect on product performance. Non-vital faults will be noticed most of the time.	Very low likelihood	Very few failures likely	1:15K	High likelihood	Has high effectiveness	**3**
4	Minor	Minor effect on product performance. User slightly dissatisfied.	Low likelihood	Occasional failures likely	1:2000	Moderately high likelihood	Has moderately high effectiveness	**4**
5	Moderate	Reduced performance with gradual performance degradation. User dissatisfied.	Moderately low likelihood	Medium number of failures likely	1:100	Medium likelihood	Has medium effectiveness	**5**
6	Severe	Product operable and safe but performance degraded. User dissatisfied.	Medium likelihood	Medium number of failures likely	1:50	Moderately low likelihood	Has moderately low effectiveness	**6**
7	High severity	Product performance severely affected. User very dissatisfied.	Moderately high likelihood	Moderately high number of failures likely	1:20	Low likelihood	Has low effectiveness	**7**
8	Very high severity	Product inoperable but safe. User very dissatisfied.	High likelihood	High number of failures likely	1:8	Very low likelihood	Has lowest effectiveness in each applicable category	**8**
9	Extreme severity	Product failure resulting in hazardous effects highly probable. Compliance with government regulations in jeopardy.	Very high likelihood	Very high number of failures likely	1:5	Remote likelihood	Is unproven, unreliable or unknown	**9**
10	Maximum severity	Product failure resulting in hazardous effects almost certain. Noncompliance with government regulations.	Extremely likely	Failure almost certain	1:2	Extremely unlikely	No design technique available of known, and/or none is planned	**10**

Figure 86: DFMEA Scoring

Chapter 8:
Modelling & Simulation

- Modelling & Simulation: Introduction
- RAAC panel crack model demonstration
- Reinforcement structural modelling
- Building level decision model and analysis
- Strategic assessment of socioeconomic factors for governing bodies
- Summary of key insights

Modelling & Simulation: Introduction

To address multifaceted challenges such as reinforced autoclaved aerated concrete (RAAC), modelling and simulation techniques are used to systematically and analytically approach both basic and complex problems to support better understanding, optioneering of solutions, and identify critical success factors.

Following engagement with government, industry and academic institutes across the UK, to empower RAAC stakeholders in evaluating and resolving RAAC-related issues, a holistic decision-making framework is proposed. The framework is built on the [*16*] and sector agnostic modelling capabilities. The key stages of the framework are:

- Predicting structural criticality of RAAC panels
- Understanding structural reinforcement requirements
- Analysing building level decision factors
- Analysing national socio-economic impact

In this section, examples of modelling and simulation that can be applied to stages of this framework are outlined, as well as future steps, Table 5: DAT Users. The current status of the activities has demonstrated conceptual frameworks. To make progress towards the future vision of this standardised approach, further development activities are required, including further model development, validation and verification of the models, the framework and analyses and supporting knowledge transfer mechanisms for implementation, adoption and exploration. Stakeholder engagement is vital along this journey to ensure validity of the framework against the needs.

Modelling & Simulation: Introduction

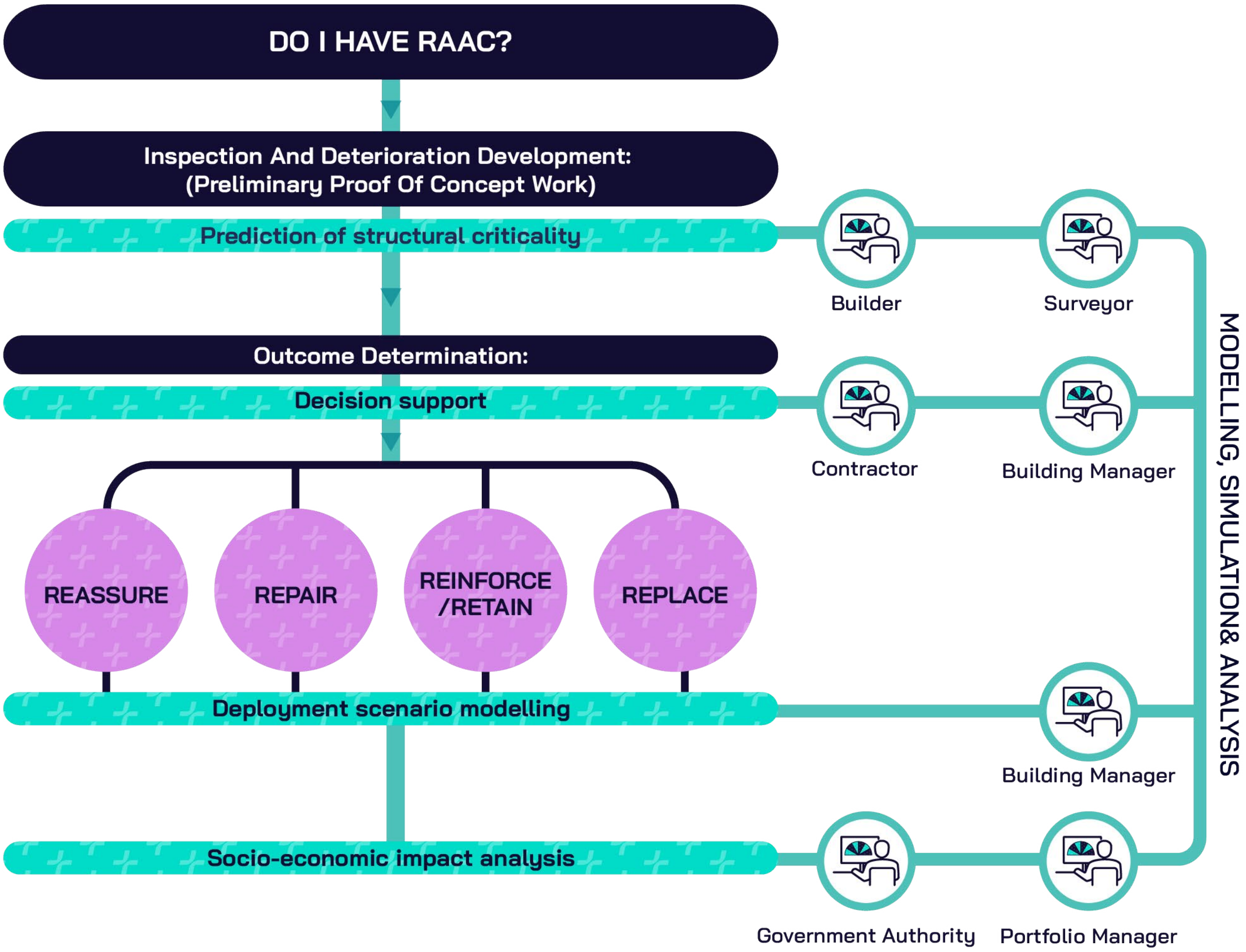


Figure 87: Modelling and simulation for RAAC decision making

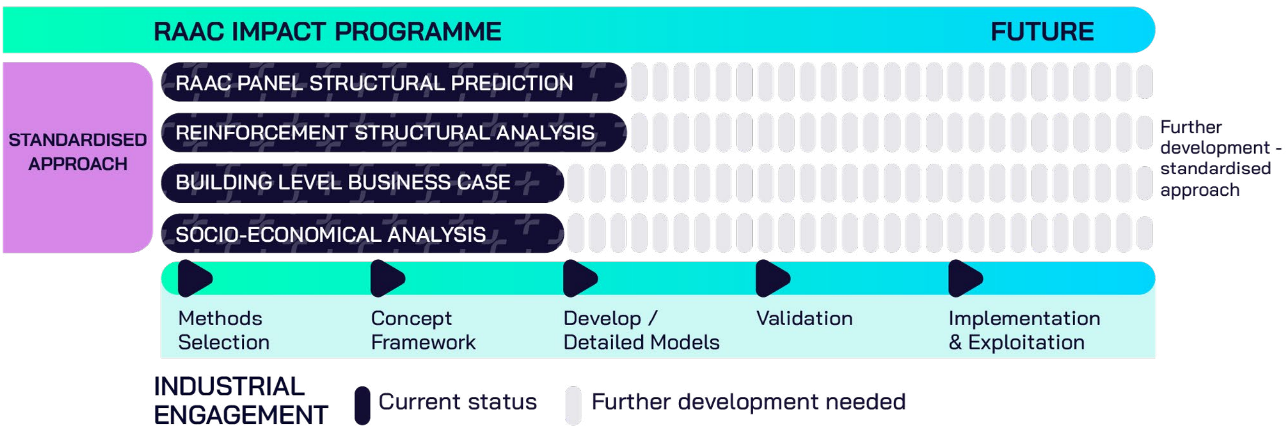


Figure 88: Status of Modelling and Simulation progress.

RAAC panel crack model demonstration

Methodology

Structural modelling through finite element analysis (FEA) is a widely adopted industry standard for structural assessment of components to predict the effect of loads on structures. The method considers material behaviour and the ways in which damage can occur under loading. This type of model can be used to predict a structure's response to real-world loading conditions in a virtual environment.

Methodology applied to the UKRI RAAC Impact Programme

The MTC has applied structural modelling to RAAC to predict damage and failure. This has formed the foundation of a parametric structural model that considers the plank geometry, supporting mechanism and material properties. This work has complemented and expanded on previous studies from the University of Loughborough by enabling study of transverse rebar and support configuration through the width of the panel.

Summary of key insights

The structural modelling of RAAC is particularly challenging due to the complex interplay between the ductile steel rebar and the failure modes of concrete. Considering that autoclaved aerated concrete (AAC) is a highly variable material where constituent information suitable for modelling is still scarce. Material characterisation and representation at different scales are required by collecting and testing a variety of RAAC samples to help understand behaviours and the effects of variability.

Once verified, the model and subsequent simulation-driven failure mode analysis should allow performance metrics to be identified with a view to adding them to the Digital Assessment Tool (DAT).

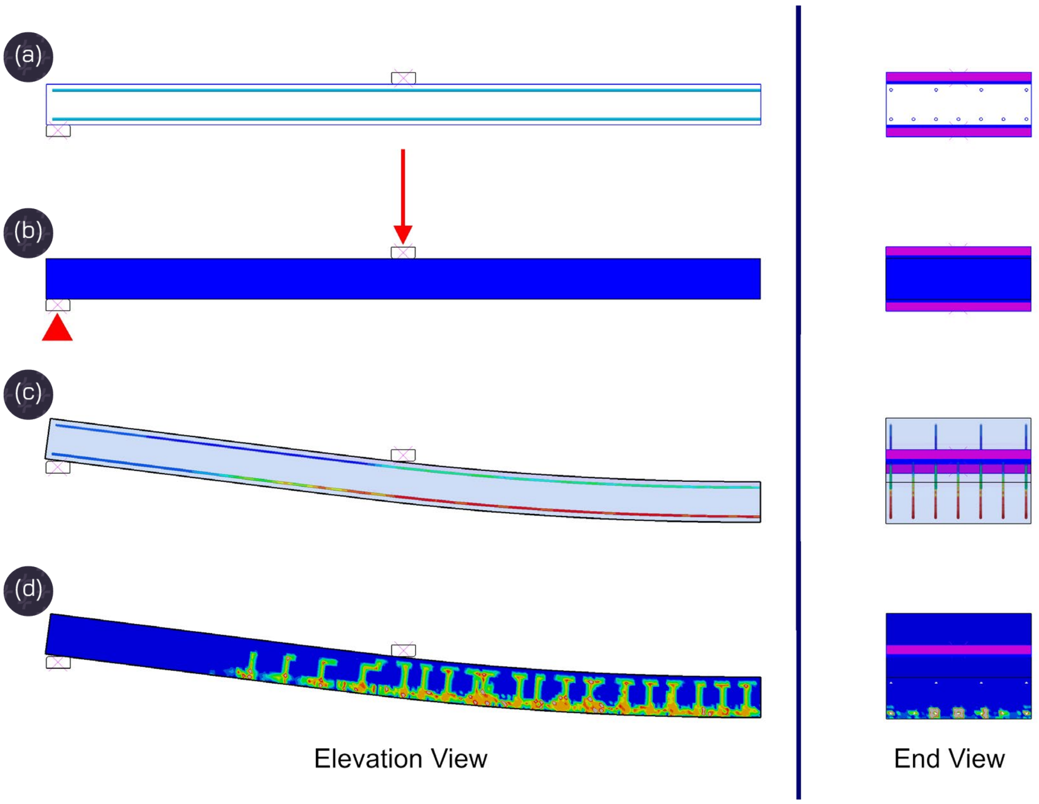


Figure 89: A representative symmetrical model of a flexural test of C50 reinforced concrete showing a) geometry setup with embedded rebar, b) location of vertical load and end support, c) response of rebar and d) crack formation starting at base of panel and moving toward top surface

Reinforcement structural modelling

For any remediation option, it is crucial to determine the resources needed and assess their viability. This is essential for conducting cost-benefit-focused scenario analysis and making informed decisions.

Methodology

In the case of a structural remediation, cost/benefit assessment requires a materials list for a feasible configuration. Structural modelling using the finite element method (FEM) can be employed to analyse multiple scenarios, in this case, a reinforcement remediation option.

Combining a parametric approach within a structural FEA enables the exploration of a range of configurations to determine the most appropriate solution and support selection of the remediation strategy.

Methodology applied to UKRI RAAC Impact Programme

A structural feasibility study of a reinforcement concept for building roof sections that utilised universal beams (I-beam) was conducted (Figure 42).

A parametric model representing a systematic method for quickly assessing and designing an appropriate reinforcement solution has been developed. The approach considered variable bill of materials modelling and addressed the requirements related to maximum allowable deflection.

Summary of key insights

Modelling techniques such as FEM can be used to explore and screen different variabilities and feasibility of different options and to support rapid decision making on the appropriate remediation solution for a given scenario.

Beyond exploration of feasibility, the models can be further utilised to understand the variabilities and safety margins for remediation options and find optimum robust and low-cost remediation solution. These type of modelling and analysis methods which gives indication of bill of materials and provide valuable input to the scenario-based cost analysis.

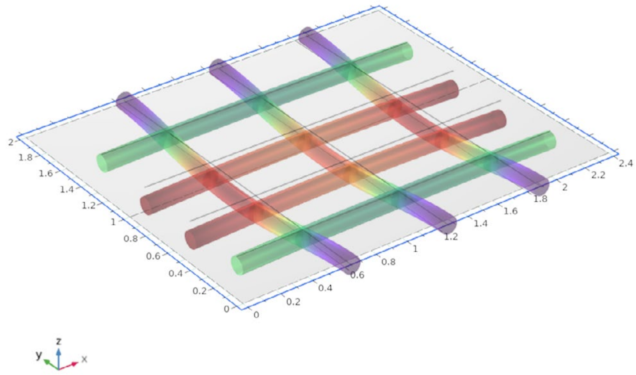
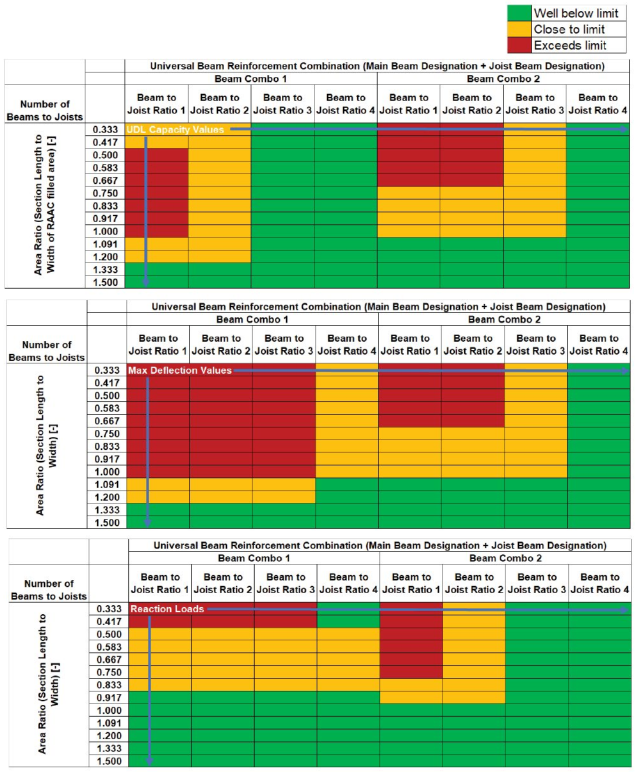


Figure 90: Maximum beam deflection (example case)



Users of these matrices must re-evaluate the limits bases on:

1. RAAC state of deflection
2. Total Loads

Figure 91: RAAC assessment matrix

Building level decision model and analysis

Methodology

Building owners, who have ultimate responsibility for dealing with RAAC, are faced with a complex challenge when investigating and choosing remediation strategies based on impact, risks and value-for-money with appreciated uncertainties. Having dealt with similar challenges within the manufacturing and construction industries [17], the MTC leveraged its modelling and simulation experience to inform and provide support.

Identifying the critical factors - those which have the greatest influence over the final solution – is the first step for constructing a decision-support approach. Tools can then be selected to quantify these factors and, finally, modelling techniques applied to compare different options.

Methodology applied to UKRI RAAC Impact Programme

Following this approach, the MTC performed a literature review and spoke to key stakeholders to identify RAAC specific critical factors. Due to the diversity of RAAC affected buildings, the importance of certain factors will differ. To address this, factors were split into:

- General - those which must be considered by all buildings, and
- Specific - ones which are uniquely important to specific buildings.

Recommended general, and some potential specific factors have been identified, as shown in Figure 93 - Steps in the design of appropriate solutions and definitions, adapted from [14] and [15]. The importance of these factors is unique to each building; therefore, it is important for building owners to perform an assessment to determine the weighting for each factor. To help with this, the MTC identified example modelling tools seen in Figure 94 - Range of options for the accountable person(s) for a building containing RAAC. Based on [14] and [15]], which may be applied to ascertain the importance of each factor and their impact. Dependencies between these factors must also be considered, meaning where each specific factor could impact cost, time and safety metrics.

To maximise the value of the research undertaken in this work, a standardised methodology in the form of a framework was developed, which can be seen in Figure 94 - Range of options for the accountable person(s) for a building containing RAAC. Based on [14] and [15]. This framework can be used as a guide for building owners to understand what information is required to select an appropriate remediation strategy.

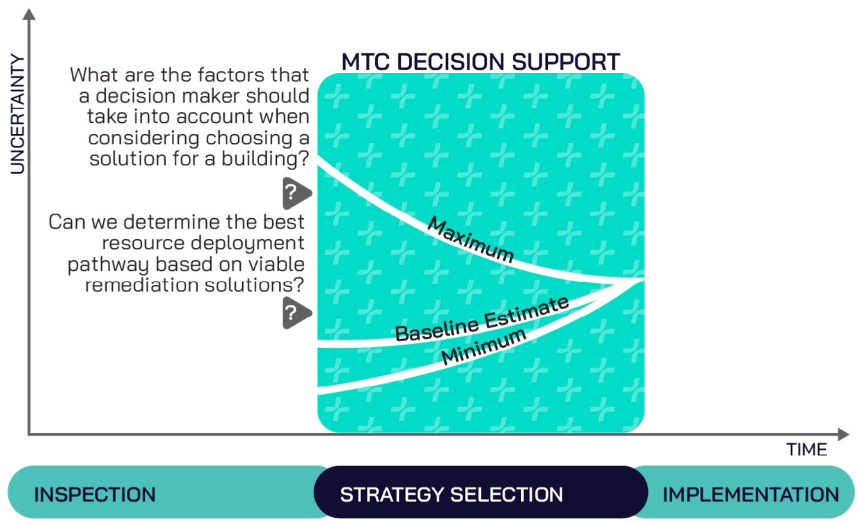


Figure 92: Placement of work within the 'Cone of Uncertainty'

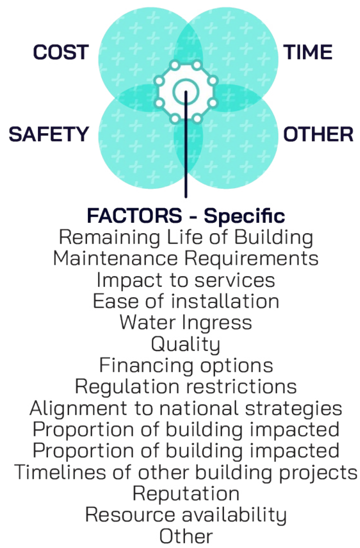


Figure 93: Major factors and key specific factors mapping for building level decision-making

Building level decision model and analysis

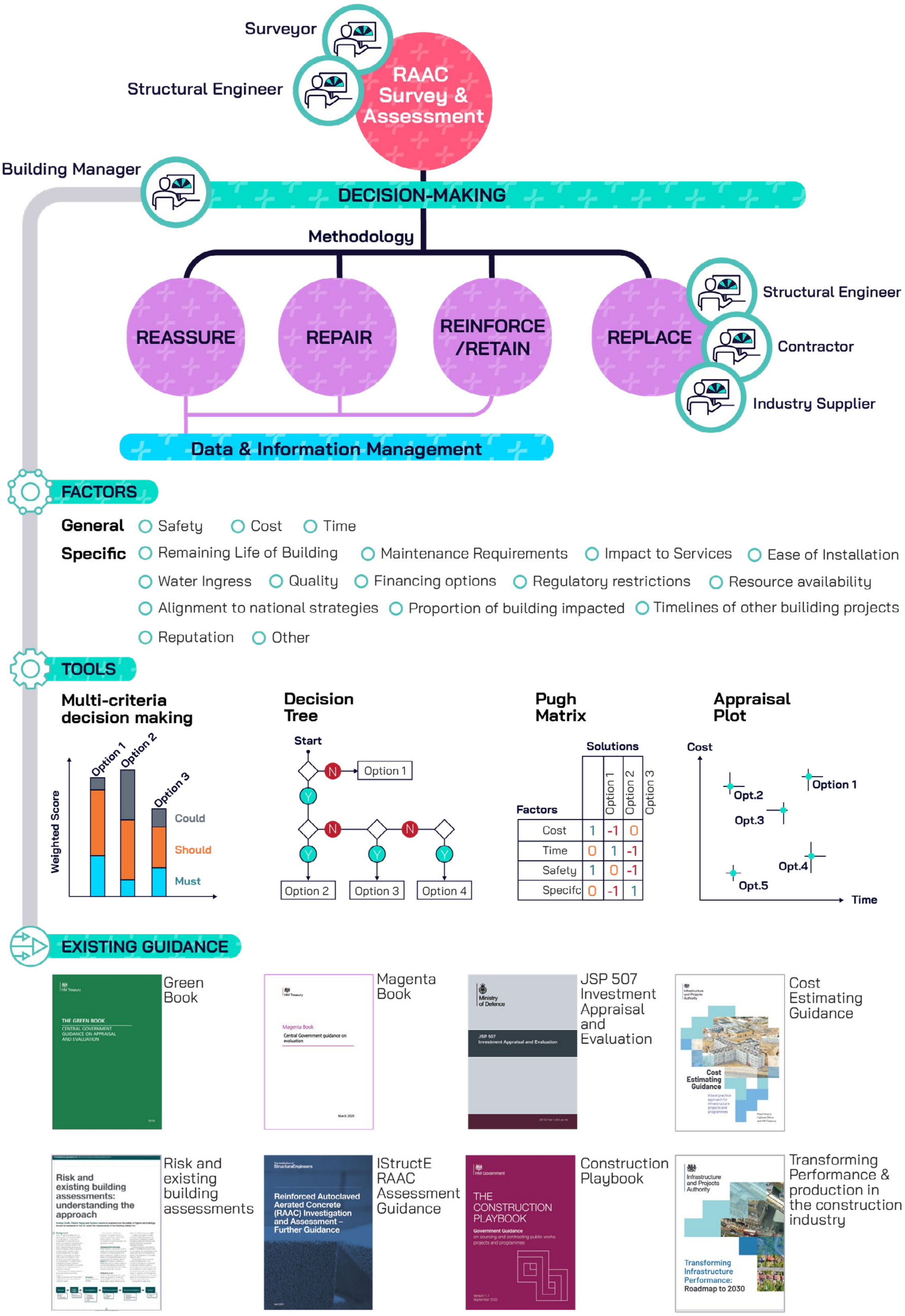


Figure 94: Key decision factor framework, with suggested tools and guidance

Suggested key guidance

- The Green Book [18] – Approved thinking models and methods
- The Magenta Book [19] – Types of evaluation and evaluation approaches
- JSP 507 [20] – Process for reflecting true costs and risks of decisions
- Cost Estimating Guidance [21] – Evidence-based approach to cost estimating
- Risk and Existing Building Assessments [22] – Assessment of high-risk buildings under the Building Safety Act
- RAAC Investigation and Assessment Further Guidance [9] – Guidance for RAAC assessment
- The Construction Playbook [23] – Guidance on sourcing and contracting construction projects
- Transforming Performance and Production in the Construction Industry [17] – Tools and systems to drive performance in construction projects

Summary of key insights

The developed framework is focused on factor identification and remediation strategy selection. The logical next step is to look at applying and testing the framework on real-world examples to validate the approach. Through these case studies, a greater understanding of the factors will be obtained as well as discovery on how they can be better quantified and compared. Suggestions on modelling tools will be refined based on these findings to give a more specific and appropriate guide for building owners to follow. Future scope of the framework could include consideration of solution deployment.

In summary, the current key insights of this work are:

- For systematic and objective decision-making, data from stakeholders, suppliers, for example surveyors and structural engineers. Monitoring systems will be integral to identify the key decision factors and their influence in the decisions.
- The critical General decision factors identified by the MTC are cost, time, and safety. These were collated via a literature review and engagement with key stakeholders. It is suspected that most specific factors can be quantified within these General factors, however further investigation of this will be undertaken in the next phase of work.
- A list of critical specific factors was identified as can be seen in Figure 93 - Steps in the design of appropriate solutions and definitions, adapted from [14] and [15]. This is not exhaustive and may be expanded in the future but it does provide those factors which are identified in the current research.

The accuracy of the decision-making process is determined by the data. With limited initial data and by following the suggested framework, rough order of magnitude estimates for scenario analysis can be obtained. The framework can be further detailed with improved data applied to continuously review and get an improved understanding of the best remediation options.

Strategic assessment of socioeconomic factors for governing bodies

Disclaimer: *After safety critical decisions have been made, including a full risk assessment by a competent structural engineer, long term strategies can be assessed by socioeconomic factors.*

Methodology

Government guidelines around public project appraisal and construction sector best practice can be brought together to provide clear decision-support tools and guidelines to support consistent assessment, in public and private sectors. From these guidelines a common set of definitions and methodologies for analysis are recommended for both project and portfolio managers. Cost and benefits are explored in the Infrastructure & Projects Authority publication [24]; though not all projects within a Government Major Projects Portfolio (GMPP) report their benefits.

Methodology applied to UKRI RAAC Impact Programme

The socioeconomics behind remediating RAAC are multifaceted, influenced by factors such as public safety, efficiency, and broader economic context. Remediation activities may hinder the achievement of governing bodies and local authorities' service objectives, necessitating proactive measures for long-term benefits.

Addressing RAAC issues in public sector buildings necessitates close collaboration among stakeholders, especially local authorities, school leaders, and healthcare management professionals. By working together, decisions can be evidence-based, financially feasible, and prioritised to ensure the safety, functionality, and resilience of educational and healthcare infrastructure.

As RAAC challenges mature, the process around understanding RAAC impact and prioritisation of addressing RAAC, with consideration of long and medium-term impacts and strategies, needs to be transparent and repeatable.

The responsibility of RAAC falls under the purview of building owners and managers. The direct response process for RAAC is well outlined in different governmental departments. Portfolio management understanding of how things like RAAC could affect the strategic objective is not well defined in some sectors. For example, it is reported [25] that there is no transparent way for governing bodies and local authorities to evaluate decision-making around programmes like the New Hospital Programme.

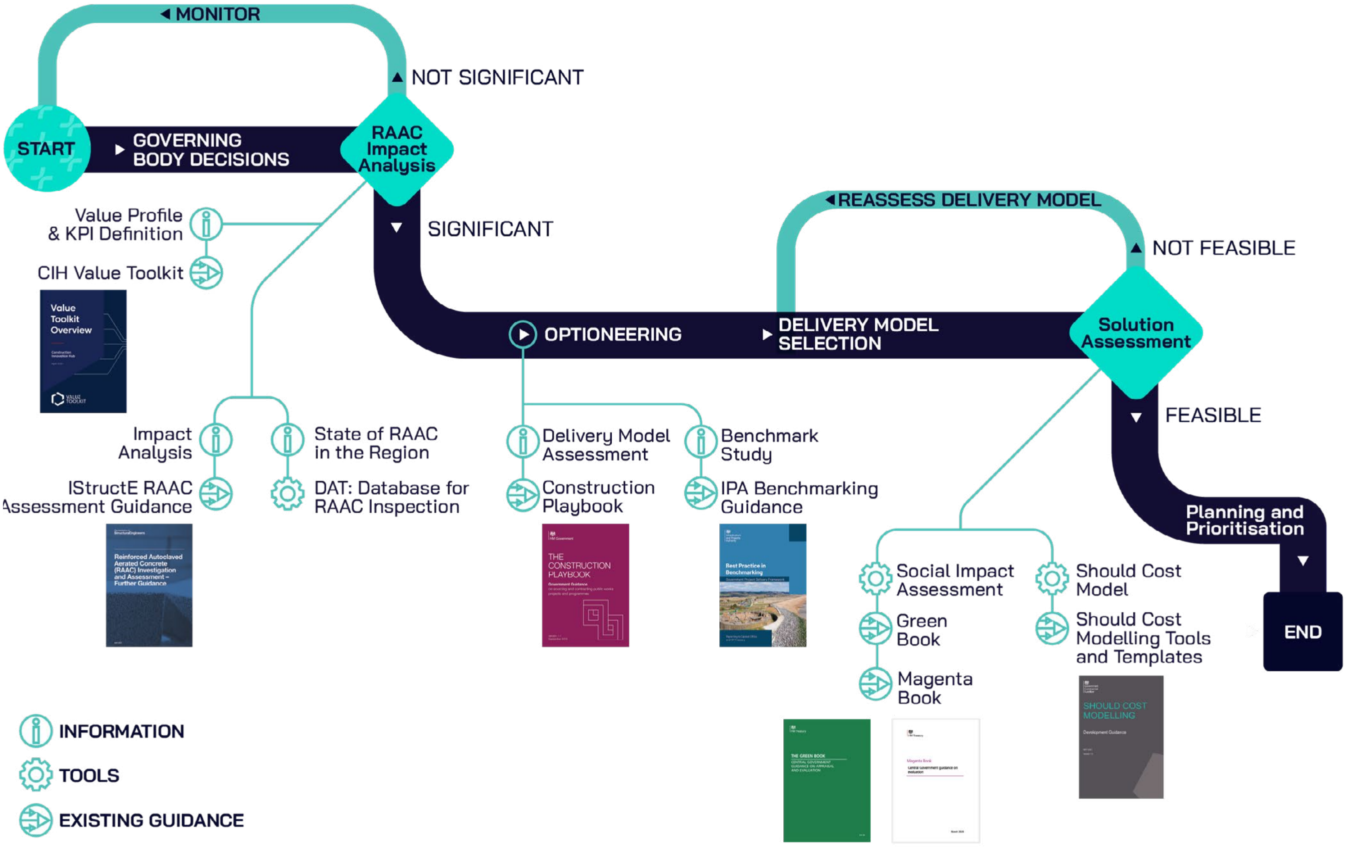


Figure 95: Strategic assessment framework for socioeconomic factors

Summary of key insights

Summary of key insights

A framework is proposed to capture the decision-support process, with the purpose to guide decision-makers to follow best practice in performing portfolio management level assessments. The framework focuses on identification of RAAC impact on local strategic objectives, supporting the delivery model selection and prioritisation of RAAC activities.

The RAAC impact analysis could utilise the Construction Innovation Hub (CIH) value-toolkit [16] to define and create a value profile alongside key performance indicators (KPIs). Information regarding the state of RAAC in the region can be obtained from the DAT. Additionally, the RAAC investigation and assessment guidance [9] can be utilised to understand the risks associated with RAAC and perform an impact analysis.

A Delivery Model Assessment (DMA), as described in the Construction Playbook [23], serves as a strategic compass in the construction realm, defining the interaction between suppliers and the client. It scrutinises potential delivery models throughout the lifecycle, employing tools like Benchmarking [26] and Should Cost Models [27]. This structured approach, rooted in the Green Book [18] appraisal process, ensures informed decision-making and risk management.

As the future work, the following will be considered:

- Validating the framework through user cases and stakeholder engagement.
- Communicating and collaborating with key stakeholders.
- Establishing quality assurance processes during implementation. Refer to the Aqua Book [28].
- Disseminating findings and decisions.

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Section 3: Next Steps

The goal of the RAAC Playbook is to initiate the standardised approach needed to confidently assess the presence and condition of RAAC, in an objective, consistent and robust way. This draft version document the methodologies and research conducted during each of the UKRI RAAC Impact Programme's workstreams.

Collating this information progresses the identification and potential adoption of solutions and technologies to effectively address RAAC in the UK. In this section we explore the decision-making process, emerging roles for addressing RAAC, and the next step in ensuring a standardised approach is adopted at scale.

The MTC engaged with over 60 organisations and 300 people during this programme and would like to thank all for their contributions to the UKRI Impact Programme 2023/2024.

Voice of Industry

Below are some of the views from industry, gathered from estate owners, structural engineers and contractors:

“We need to understand the technical parameters to develop the technical solutions.”

"The only way to measure deflection at present is to remove the whole ceiling grid. We can't do that in a live environment."

"There is a need to be able to measure deflection accurately, ideally remotely."

"There is a need to improve how risk is assessed and analysed."

"We need to enable industry in making informed decisions."

"A standardised methodology is needed."

"The RAAC problem is a symptom of a far bigger and long-running one."

"Current methods are hugely time consuming, expensive and removing the roof covering caused sporeling to the underside."

"Tools supporting the data management are of high interest for us, that is what industry need to manage the amount of data we have”

Decision Making

Figure 96, RAAC Playbook Flow Chart defines a first draft decision-making process developed by the MTC, that could be used to identify the correct course of action, once the presence of RAAC has been confirmed. Once sufficient inspection of RAAC has taken place, a risk assessment should be undertaken in line with IStructE risk guidance: Low, Medium, High and Critical Risk. Once sufficient data has been collected, and the criticality of risk has been assessed, a decision can be made in which action to take from the remediation strategies as well as implementing a monitoring plan to reassure the building or estate owner.

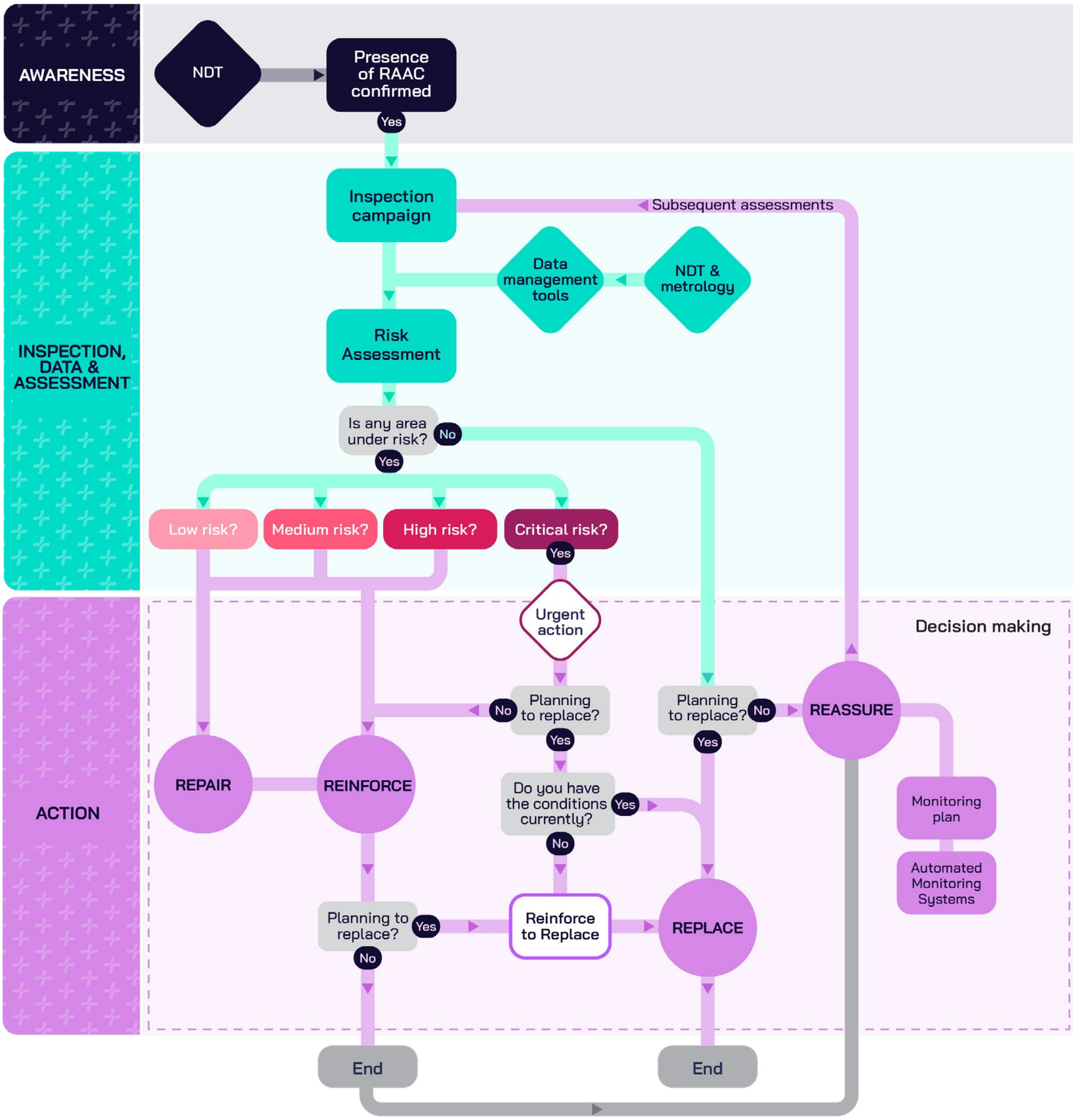

Figure 96: RAAC Playbook Cross-functional flowchart

Stakeholders

To ensure a standardised approach is followed to ensure RAAC is not tackled in silos, government, industry and academia should work together in sharing lessons learned and insights.

- **Government:** Centralise records and co-ordinate a national programme for long term remediation and retrofitting existing assets, appointing appropriate bodies/organisations.
- **Industry:** collaborate with partners and supply chain to increase the scale and pace of adoption of solutions.
- **Academia:** publish research to increase knowledge and understanding of RAAC.
- **Everyone:** disseminate, educate, and collaborate. Adopt a standardised approach.

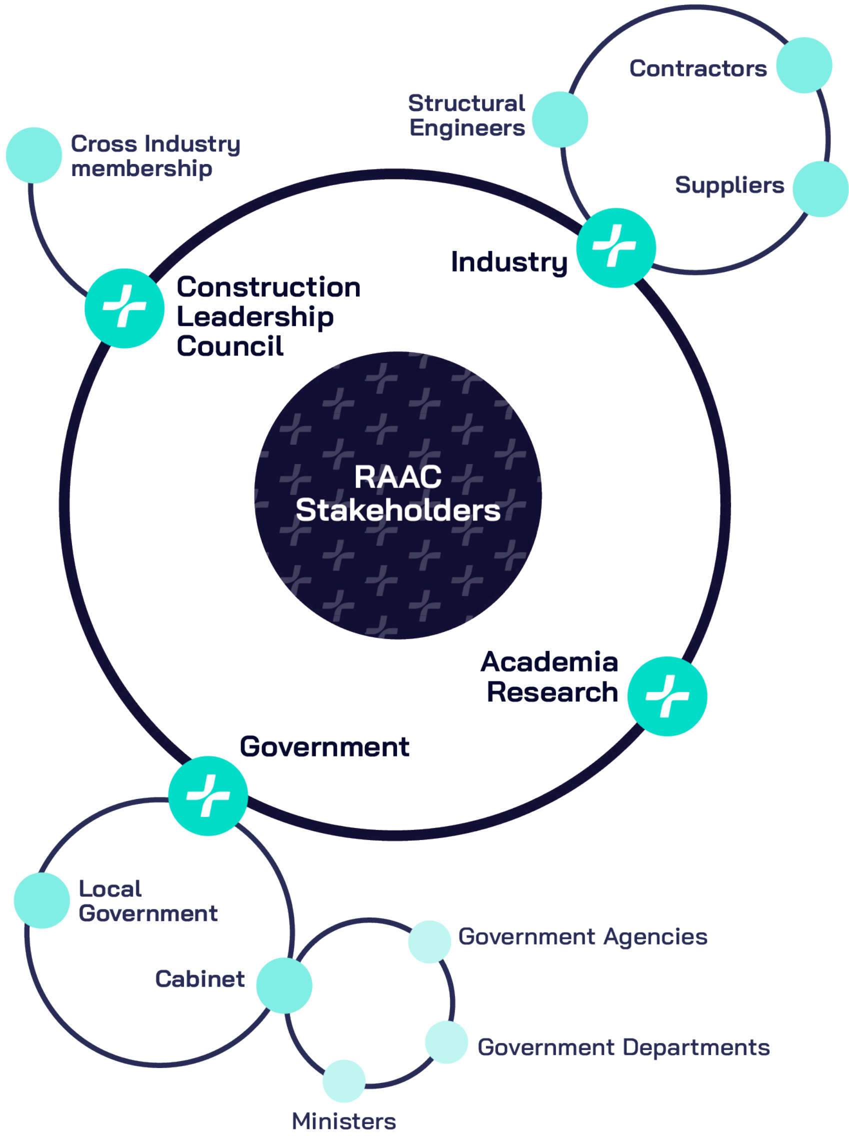

Figure 97: Stakeholders

Building upon a strong foundation

Phase 1 of the UKRI RAAC Impact Programme's has been funded by Innovate UK. MTC, building on the research of Loughborough University and other partners has produced the deliverables set out below. This initial phase sets out a sequential approach to detect, assess and manage RAAC more objectively.

The UKRI RAAC Impact Programme's has completed its initial phase which has focused on key areas of activity:

- The development and verification of NDT techniques, and their application to the detection and objective assessment of the condition of RAAC. These studies demonstrated potential solutions for automated Non-Destructive Testing systems, using portable off the shelf equipment (such as X-ray backscatter, ground penetrating radar etc) in typical real-world environments, such as schools and hospitals.
- Effective RAAC management strategies, considering various failure modes including those arising from past management efforts and manufacturing defects.
- Manufacturing-led concepts for scalable products to replace RAAC roof planks.
- Software algorithm and functional specifications, for a Digital Assessment Tool (DAT) that is intended to automatically assess data collected through NDT scanning, to objectively determine the likelihood of failure
- Engagement with estate owners (client departments, local authorities, government agencies, etc.) and construction sector industry partners, active within the RAAC domain.
- The RAAC Problem Statement & Assessment Matrix developed by the Construction Leadership Council (CLC) RAAC IRG Technology Subgroup. The matrix sets out the existing, emerging and required technology solutions required for managing RAAC.
- The creation of a draft RAAC Playbook, to help inform estate owners and industry partners on the most effective methods of redressing RAAC roof planks.

These activities establish the groundwork for and set the direction of travel for the near-term development and verification RAAC remediation solutions.

Phase 2

Building upon the strong foundation of phase 1 of the UKRI RAAC Impact Programme's, the MTC recommends the following scope as part of phase 2.

Research & development

- Further development of NDT techniques, the Digital Assessment Tool, and condition monitoring into identification and assessment phases.
- Further research to understand prevalence of failures and risk factors.
- Develop greater understanding and modelling of failure mechanisms including end-bearing and deterioration.
- Evaluating the impact of creep/cyclic loading and corrosion of reinforcement.
- Verifying and adapt durability models for RAAC.
- Investigate the impact on future life of RAAC elements. Variable climate conditions might exacerbate the degradation of RAAC structures. To the knowledge of the authors, no public-available study has focused on these effects, which might be essential to predicting the future life of RAAC planks.
- In situ monitoring of environmental data, ideally over a 12-month cycle.
- Accelerated weathering and then structural testing of planks.
- Simulation and assessment of the impact in terms of failure and future life considering potential impact of climate change.
- Automated RAAC detection and assessment in difficult to reach areas.

Long term management & remedial solutions

- Statistical risk analysis of failures and correlate with acceptance data to develop action criteria and empower industry with data driven decision-making tools.
- Digital Assessment Tool, to automate the analysis of the data collected by NDT methods.
- Reviewing surveying and monitoring methods (non-digital and digital) across different asset owners for inspection and data capture (to increase precision, accuracy, reliability, repeatability and consistency)
- Standardised manufacturing led approaches to remedial work (reducing variance in approaches.

Training

- Creating curriculum and training materials for building professionals for NDT scale up in collaboration with academic and industrial partners.
- RAAC Playbook Development: compile a comprehensive reference guide for all aspects of RAAC management.

Deployment & implementation

- Disseminate the programme's solutions and train the required number of appropriate professionals across the country.

Next Steps

How should these approaches be used, adopted, exploited?

- The approaches should be considered the foundation of a clear methodology for addressing RAAC.
- The approaches should assist estate owners in determining best strategies for "living with RAAC".
- The approaches would need to be adopted by industry actors as part of the plan for "dealing with RAAC".
- The design developments and approaches could be carried forward for further development and multiple other built environment applications.

What is needed to make this happen?

- Legislative/policy push and funding support.
- Industrial collaboration, scale and pace of adoption, underpinned by estate owners, academia, and consultants.
- Centralised government programme for RAAC remediation and retrofitting existing assets.

How do we mobilise to resolve this?

- Evidence benefits, conclude the industrialisation and deployment activities.
- Pathfinder programme, blueprint approach.
- Workforce/supply chain/contractor enablement for scale and pace.
- Capacity and competency of solutions (products, process, risk management etc.).

What is needed to make this happen at a large scale?

- Policy, coordination, regulation and standards.
- Economics and financing, a different model for business case.
- Supply chain/network enablement, skills and standardised approach.
- Fiscal incentives, including capital grant support for longevity.

What needs to happen in the immediate future?

- Avoid scaremongering – not all RAAC is bad.
- Learn how best to live with RAAC.
- Adopt practical approach to assessing risk (e.g. asbestos), including new guidance on assessing risk.
- Better co-ordination of addressing RAAC amongst stakeholders.
- Ensure centralised records are available.
- Use data to evidence the scale of RAAC and understand levels of severity.

Coordinated and **collaborative efforts** are needed to make it happen.

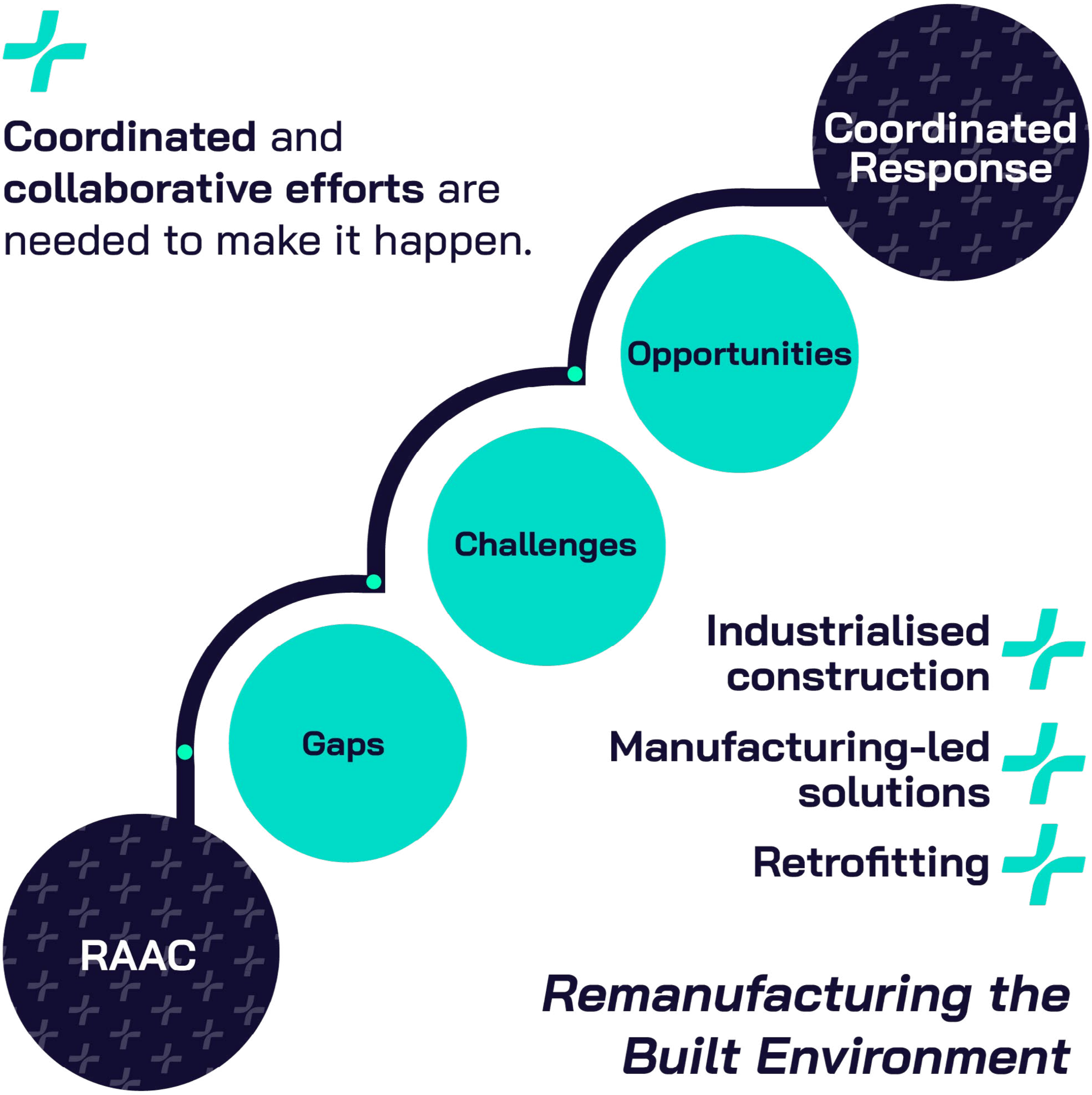

Figure 98: Visualising the potential approach to understanding the next steps

where
progress
happens

mtc where progress happens