The Institution of Structural Engineers

Reinforced Autoclaved Aerated Concrete (RAAC) Panels Investigation and Assessment

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1 Introduction

In 2019 SCOSS[1] published the safety alert "Failure of Reinforced Autoclaved Aerated Concrete (RAAC) Planks" following the sudden collapse of a school flat roof in 2018. The collapse occurred at the weekend and fortunately there were no casualties.

Following the collapse, the IStructE formed a specialist Study Group of Members with experience of RAAC panels, either through advising clients on identification, management and remediation or through academic research on the material. Participation in the expert group was by invitation.

This report has been prepared by members of the IStructE RAAC Study Group to improve awareness of RAAC amongst the wider structural engineering community and share recent findings to assist those who are asked by clients to advise on the management and mitigation of RAAC panels. It is recommended that the reader also familiarises themself with the 2019 SCOSS alert and the other key references at the end of this document.

This report should be considered as an interim update and more detailed guidance will be issued in the future. It is not intended to be definitive guidance and focuses principally on the performance of RAAC roof panels, although some of the findings may be relevant to floor and wall panels. Skill and expertise will be required to assess the structural integrity and condition of RAAC panels and to advise clients on management and remediation measures.

2 Background

Reinforced Autoclaved Aerated Concrete (RAAC) is a lightweight cementitious material. It is aerated and has no coarse aggregate, meaning the material properties and structural behaviour differ significantly from ‘traditional’ reinforced concrete. RAAC has been used in building structures in the UK and Europe since the late1950’s, most commonly as precast roof panels in flat roof construction but occasionally in pitched roofs, floors and wall panels in both loadbearing and non-loadbearing arrangements.

In the 1990s structural deficiencies became apparent; and these are discussed in papers by the Building Research Establishment (BRE) (reference IP10_96 and IP7_02). The panels in question were supplied, designed and installed pre-1990. Since that time, new European Standards have been developed and published to prevent under-design and to ensure long term durability. BS EN 12602 was first published in 2008 and would cover panels supplied in the UK since that time.

In May 2019 the Standing Committee on Structural Safety[1] (SCOSS) issued an alert after being notified of the failure of roof panels in a school.

Members of the IStructE Study Group have recently specified and implemented survey and monitoring programmes to assess the condition of RAAC panels and have designed management, remediation, or replacement solutions where RAAC panels were considered to pose an unacceptable structural safety risk to occupants. There is also representation from members of Loughborough University who are leading on a major research programme into RAAC. The research is in early stages and periodic updates will be published as the research progresses.

3 Characteristics of RAAC

RAAC panels are distinguishable from traditional reinforced concrete members in a number of ways. The Autoclaved Aerated Concrete (AAC) material is aerated, hence having the benefit of being considerably lighter than traditional concrete. Typically, AAC has a density of 600-800kg/m³ compared to 2400kg/m³ for traditional concrete. This aerated nature and reduced density, influences other key material properties including:

- **Compressive strength**

Typically, in the range of 2-5N/mm² and therefore much lower than traditional concrete. Flexural, shear, and tensile strengths are also similarly reduced compared with traditional concrete.

- **Reinforcement anchorage**

Because of the aerated nature of the material the AAC will not form adequate bond strength with the reinforcement. The reinforcement is also smooth and not ribbed. Tensile forces are therefore predominantly transferred to the reinforcement via transverse reinforcement bars being welded to the longitudinal reinforcement with bars over the bearings of the panels for end anchorage. The position and effectiveness of the transverse reinforcement over the bearing is critical to the shear capacity of the panels at their bearings.

- **Permeability**

The aerated material is highly permeable. As a result, cover to the reinforcement does not protect against environmental conditions as with traditional concrete and the cover zone can be expected to be highly carbonated. Prior to manufacture the reinforcement was covered with a coating to protect it against corrosion.

- **Elasticity and Creep**

The aerated nature and lack of coarse aggregate means that the elasticity and creep characteristics of AAC are substantially inferior to traditional concrete which has an impact on long term deflections of the RAAC panels.

Photo of RAAC samples showing variability of the material

Photo showing bubble formation on reinforcement

4 Summary of Recent Investigations and Research

In recent years contributors to this paper have been commissioned by several clients, mostly from the public sector, to investigate the performance of RAAC panels in buildings that are currently in use. The investigations have included:

- Visual inspections – crack and defect recording.
- Surveys – vertical deflection measurement and condition assessment.
- Non-destructive testing – cover meter and radar techniques to determine reinforcement location on reinforcement positioning.
- Intrusive surveys – verification of reinforcement position at panel bearings, exposure of reinforcement to identify corrosion, electrochemical testing for reinforcement corrosion.

It is noted that that some testing methods used on traditional concrete to check for reinforcement condition (carbonation testing and chloride ion concentration) are not appropriate to RAAC construction. Resistivity and half-cell testing require careful interpretation and the use of different assessment criteria. Further research is underway on testing methods.

Research work being led by Loughborough University is at an early stage. The following research has been conducted to date:

- Literature review.
- Preliminary finite element modelling of the structural performance of roof panels.
- Investigation into the corrosion performance of wall panels.
- Preliminary lab-based material characterisation.
- Preliminary site based structural testing.

This paper is mainly focused on the use of RAAC in roof panels which has been the focus of most of the investigations undertaken recently. Future works will also include wall panels. Floor panels will also be considered as well as providing further definitive guidance on the issues affecting roof panels. This guidance is expected to become available during 2022.

5 Summary of Latest Experience

The collapse reported in the SCOSS Alert in 2019 showed some visual evidence of a shear failure close to the support. This failure mode was different to those discussed by the earlier BRE papers and the failure suggests that there may be a risk of sudden structural failure of RAAC panels.

The findings from the BRE papers and the latest experience of the Study Group suggest that the key defects in RAAC panels include:

Performance Defects	Manufacturing Defects	Construction Defects
• High in-service deflections • Cracking and spalling in the soffit of panels • Corrosion of reinforcement • Deterioration in condition • Panel distress caused by overloading • Panels acting independently with limited load sharing	• Misplaced transverse reinforcement • Insufficient anchorage of longitudinal steel • Voidage around reinforcement • Incorrect cover to tension steel	• Cutting of panels post manufacture • Short bearing lengths • Missing reinforcement e.g. linking dowel anchorage • Structurally damaging builders work

In general, it has been observed that there is a high degree of variability between panels even where they were part of the same contract and installed immediately adjacent to one another. When determining the condition of RAAC panels within a building, caution should be taken with assessing the results from discrete sampling and allowance made for the potential variability of the properties being considered.

While many of the above defects have previously been discussed in published guidance, recent work by the specialist Study Group has identified some additional considerations for some of the above:

- **Misplaced reinforcement / Insufficient anchorage of longitudinal steel**

The reliance of the tension reinforcement on welded transverse bars means that the workmanship by the manufacturer of the reinforcement cages and their placing in the moulds is critical to the structural performance of the installed panel. The placing of the cages has been found to be variable across a batch of panels. There is also some evidence of the longitudinal reinforcement terminating short of the bearing which gives rise to concern regarding the shear capacity of panels. The numbers of transverse bars has also been found to vary from panel to panel within the same building.

- **Cutting of components post manufacture**

The cutting of components could give rise to locations where transverse anchorage bars are not in place over the bearing length of the panel. Cut components can occur when panels were made to a length and subsequently cut prior to installation to suit the position of the panel. Penetrations through the panels at the time of installation were often provided with straps off adjacent panels or independent structural trimmers but the panels were often cut to the reduced length.

- **Short bearing lengths**

The design guides and Codes of Practice permitted bearing lengths as short as 45 mm on steel supports. Short bearing lengths increase the vulnerability to misplaced reinforcement at the time of manufacture or incorrect positioning of the components during installation.

- **Structurally damaging builder's work**

Many instances have been found where building refurbishment has resulted in builders-work holes within panels. No instances of structural failure have been seen by the contributors, but the strength had been reduced by alarming amounts and raised concerns regarding the integrity of damaged panels.

- **Corrosion of reinforcement**

Due to the aerated nature of RAAC and low tensile and compressive strengths, corrosion of reinforcement does not always lead to spalling of the concrete cover so corrosion can often be concealed. Corrosion at the end anchorage is of particular concern. Corrosion could reduce secondary bond stresses, damage the welds to the transverse reinforcement and reduce load capacity of components. The moisture needed for corrosion to occur could either be due to leakage from failed waterproofing, services failure or interstitial condensation.

Because of the aerated nature of the AAC material there are instances where intrusive surveys have shown corrosion of reinforcement has been advanced without any indication on the soffit of the panels. This differs significantly from the performance of traditional concrete where expansion of the products of corrosion typically leads to surface cracking or spalling. Blown RAAC cover through reinforcement corrosion has also been observed in many occasions.

- **Cracking in the soffit of panels**

Due to the high deflection of panels, transverse cracking is common and longitudinal cracking has also been seen in many panels. Where transverse cracks are close to the bearing, say within the end 300mm, this could indicate high shear stresses or bond failure and should be taken as a potential warning sign of a failing panel.

- **Overloading**

Due to the high deflections, there can be occurrences of ponding water or the build-up of vegetation resulting in loading higher than design allowances. The addition of roof level services can also add loading for which the building was not originally designed.

High loading associated with regular maintenance of roof top plant and repeated loading under roof walkway routes can accelerate deterioration and the development of cracking.

- **High in-service deflections**

While the impact of high deflections on flexural cracking was discussed at length in the BRE papers, a further consideration is the impact of rotation of the panel on bearing stresses. The high deflections may give rise to a possibility of concentrated loads occurring at the support of panels which may increase the risks of bearing and shear failure – this effect will be subject to detailed consideration in the research programme.

- **Voidage around reinforcement**

The method of manufacture meant that bubbles could have coalesced and formed larger voids around reinforcement. Some evidence has been found but the frequency of such effects is uncertain.

- **Water Ingress**

Water ingress raises the risk of reinforcement corrosion which could affect structural integrity even after the cause of the water leak has been corrected. There is also some concern regarding the deterioration of AAC material strength where moisture content is raised and again the affect may persist when moisture contents return to normal.

- **Continuity reinforcement**

Instances have been seen where continuity bars have been placed possibly to provide a degree of continuity between butt ended panels. However, this reinforcement is missing in some buildings or locations and the effects on panel strengths is uncertain.

Damage caused by drilled holes for services penetrations.

Damage caused by roof vent installation

6 Guidance on assessment methodology

In carrying out their work, the Study Group has learnt a number of lessons regarding how RAAC can be effectively assessed and remediated.

6.1 Survey & Testing Techniques

In order to objectively assess the condition of RAAC panels a detailed survey is required to be undertaken. It is likely that repeat surveys will be required to monitor ongoing deterioration and so a repeatable approach is necessary for both the survey and the data recording system used to enable interrogation of the data and year by year comparison. Photographic records of examples of cracking types will enable a repeatable survey by multiple operatives. The surveys should inspect each panel and include:

- Measurements of deflections
- Records of crack patterns and or delamination
- Recording of any evidence of water leaks
- Hammer tap testing for any signs of debonding concrete, particularly near the supports.
- Record of any signs of panels cut after manufacture.
- Record of any alterations or penetrations through the panels after construction.

The work has shown that re-surveying is necessary to determine if deterioration is progressive and re-surveying on an annual basis may be sensible.

Due to the age of the buildings the presence of asbestos in any surface coatings should be considered prior to commencing investigations.

6.2 End Bearing Assessment

The condition of the end bearing needs to be carefully assessed. The design codes at the time permitted end bearing lengths as short as 45 mm and the design of RAAC panels relies on the position of transverse reinforcement welded to the longitudinal reinforcement being over the bearing to provide end anchorage to the reinforcement. The low strength of the AAC material, hence very low bond stresses, means that assumptions for end anchorage and pull-out resistance for traditional concrete cannot be assumed for RAAC components.

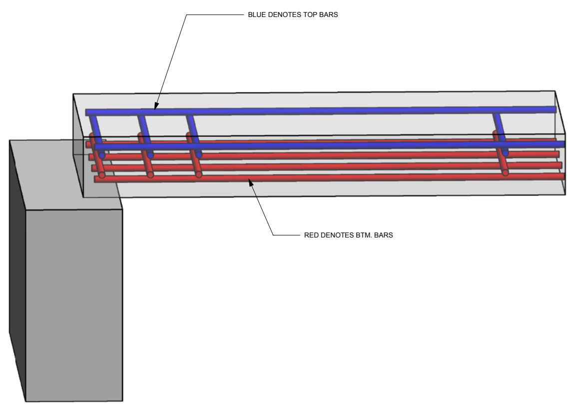
Experience gained by the contributors has identified that manufacturing and construction tolerances can mean that the end transverse reinforcement can be misplaced and cases of the bar being in front of the bearing face have been found. In these cases, the resistance to sudden shear failure is uncertain and there is the possibility that this mechanism led to the failure reported in the SCOSS[1] Alert.

Surveys to assess the end bearings are critical to assess the structural integrity of panels.

6.3 Condition Assessment

It should be noted that some common testing methods used on traditional concrete are either not deemed suitable for RAAC panels or should be considered in detail before being recommended. These include:

- Carbonation testing – the aerated nature and low permeability of the AAC material means carbonation can be expected in the cover zones. Corrosion protection for the reinforcement is provided by coating the bars rather than cover.
- Core sampling – the softness of RAAC means that it can generally be identified by surface testing without the need of removal of a core. The fragility of RAAC panels has meant that in some instances the drilling process has caused damage to a panel.
- Covermeters & Penetrating Radar. Neither technique is effective when trying to detect through foil backed insulation. Covermeter surveys can identify the main reinforcement configuration but is not effective at locating the transverse reinforcement at the end bearings. Radar techniques have been used in some surveys, where foil backed insulation is not present although the data needs extensive off site processing. Experience has shown that radar can generally position this critical transverse reinforcement to a tolerance of about 15mm. Due to the tolerance, in many instances with small end bearing, radar scanning does not prove that reinforcement bars are over the supports. The results also need some intrusive surveys to calibrate the findings and roof coverings may need to be removed to facilitate the survey. Experience is that although useful in some circumstances the costs associated with the use of radar needs to be assessed against installing enhanced bearing strengthening or failsafe measures in the absence of sufficient confidence in the location of the transverse reinforcement.



CORRECTLY POSITIONED REINFORCEMENT

7 Remediation Techniques

Depending on the findings of the condition surveys, the Structural Engineer may need to recommend further monitoring, remediation, strengthening or replacement of RAAC panels. These can include:

- Emergency propping, when panels are deemed to be in a severe condition
- Enhanced end bearing, to mitigate against known deficiencies or unknown/unproven end bearing conditions
- Positive remedial supports, to actively take the loading from the panels
- Passive, fail safe supports, to mitigate catastrophic failure of the panels if a panel was to fail
- Removal of individual panels and replacement with an alternative lightweight solution
- Entire roof replacement to remove the ongoing management liabilities
- Periodic monitoring of the panels for their remaining service life

Repairs need careful consideration. Repair mortars commercially available are both stronger and more dense than RAAC. Large areas of concrete reinstatement may not be able to generate sufficient bond to remain in place.

Galvanic cathodic protection may be appropriate at stopping corrosion of the reinforcement and testing and tests are underway. Repairs should address the possibility of asbestos within any original surface coatings.

End bearing strengthening

Intermediate supports

8 Conclusions

Research is currently ongoing into the structural performance and assessment of aging RAAC panels. The outcome of this research will be comprehensive guidance describing the material properties of RAAC particularly around their potential failure mechanisms. In the interim, experienced gained by the contributors suggests that care is required in the assessment of RAAC and until further guidance is available a cautious approach is recommended.

Issues to be considered include:

- Many RAAC panels designed during the 1960's and 1970's are not performing as expected and structural deficiencies are apparent. Some of these defects can reduce structural integrity.
- The sudden failure of panels has occurred on a small number of occasions.
- Concerns exist regarding the adequacy of the end bearings of roof panels due to the risk of incorrectly manufactured transverse reinforcement or incorrect positioning of panels during construction. This risk may be reduced where higher bearing lengths were used.
- The concerns are greater where panels could have been cut after manufacture (either due to formed opening or services penetrations) or where modifications have been made after construction (often for services penetrations).
- Corrosion of reinforcement is a risk especially if near to the supports and due to the nature of the RAAC construction could have a greater impact upon the structural capacity of the panel than would be expected in traditional concrete.
- Deflection in roof panels exceeding span/100 could indicate that the panels are highly loaded and working close to capacity.
- Visual surveys will help to assess the condition of the panels, but the nature of any warning signs of the sudden failure at the bearings are not fully known.
- Surveys of the end bearings using non-destructive radar can be effective but there is a significant tolerance which needs to be considered and the intrusive works necessary to facilitate the survey may not be cost effective in some situations or at scale.
- Not all defects are visible e.g. corrosion of the reinforcement. Panels which appear to be in a good condition may conceal hidden defects which could present a risk to the integrity of the panels.
- The corrosion of reinforcement could lead to large pieces of AAC falling which presents a risk to occupants.

Assessments of buildings with RAAC panels are recommended to include a balance of risks for the continued use of the building against the benefit of strengthening or replacement of the panels. The assessment should include a robust risk assessment and include consideration to the on-going monitoring and future management of the RAAC panels. The failure of the panels which resulted in the SCOSS[1] Alert was a sudden failure and could be an indication that it was due to a brittle shear failure at or close to the bearing. Based on this a cautious approach to the assessment of RAAC panels is recommended and assessments should only be undertaken by a Chartered Structural Engineer with experience in the investigation and assessment of reinforced concrete structures.

References

- IP10/96 – Reinforced autoclaved aerated concrete panels designed before 1980, BRE1996
- IP7/02 Reinforced autoclaved aerated concrete panels test results, assessment of design, BRE 2002.
- Failure of Reinforced Autoclaved Aerated Concrete
- (Precast Concrete Code of Practice CP 116(1965) British Standard Institute
- BS EN 12602 Prefabricated reinforced components of Autoclaved Aerated Concrete.

[1] *In 2021 SCOSS (Standing Committee on Structural Safety) was integrated into CROSS (Collaborative Reporting for Safer Structures). The role of SCOSS continues under this new name.*

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