# Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of risk of collapse

Prepared by WSP UK Ltd.

**RR1213 (2025)**

**Research Report**

Prepared 2024

First published 2025



**Reinforced autoclaved aerated concrete (RAAC) is a form of construction used in England between the 1950s and 1990s. RAAC panels were used for walls, floor and roofs. RAAC was used across a range of different residential, commercial and government buildings. Recent years have seen a small number of RAAC panel failures. In HSE report RR1212, estimates are provided for the number of RAAC panels present in England.**

**This report uses estimates of the number of RAAC panels in England in combination with different collapse rates to estimate the probability of any collapses occurring whilst a person is below panels. As the precise number of RAAC panel collapses which happen each year is not known, it is known to be small, a range of different RAAC panel collapse rates are analysed.**

**As discussed in this report, there are a range of different risk factors which increase the likelihood of RAAC panel collapse, and a range of different monitoring and mitigation measures which can be used to reduce the likelihood that a RAAC panel collapses. As a baseline, the identification of RAAC is the most effective method of reducing the likelihood of RAAC panel collapse occurring with people under the panels. If RAAC remains unknown there is an increased risk that deterioration may be occurring, that adverse loading may be applied to the RAAC, or that deterioration to the RAAC indicating imminent collapse may go unidentified.**

**DOI: https://doi.org/10.69730/hse.25rr1213**

This report and the work it describes were funded by the Health and Safety Executive. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

# Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of risk of collapse

**Zachariah Wynne, WSP**
**Philip Carey, WSP**
**Matthew Palmer, WSP**

**WSP UK Ltd.**
62-64 Hills Road, Cambridge, CB2 1LA, UK.

WSP is an engineering professional services consultancy with experience in the identification and assessment of reinforced autoclaved aerated concrete (RAAC). WSP have been appointed by the Health and Safety Executive to provide an estimation of the number of RAAC panels in England and assess the potential risks which RAAC may pose.

# Key Messages

Reinforced autoclaved aerated concrete (RAAC) is a form of construction material used in England between the 1950s and 1990s. RAAC panels were used for walls, floor and roofs. RAAC was used across a range of different residential, commercial and government buildings. Recent years have seen a small number of RAAC panel failures.

Previous work by WSP estimated that there are between 1.3 million and 4.4 million RAAC panels in England. It is likely that the majority of these RAAC panels are located in non-residential buildings. This report uses the estimates of the number of RAAC panels in England to estimate the probability of RAAC panel collapse in England occurring. Using the estimated probability of RAAC panel collapse, the probability of any collapses occurring whilst a person is below the RAAC panel is then estimated.

As the precise number of RAAC panel collapses which happen each year is not known, a range of different RAAC panel collapse rates are analysed. All available evidence would suggest that the number of RAAC panel collapses occurring in England each year is low.

For example, an average of one RAAC panel collapse has been publicly reported per year in recent years. When combined with the median estimate of there being 2.5 million RAAC panels in England, this results in an annual RAAC panel collapse rate of 1 in 2.5 million. Based on broad assumptions of where RAAC panels are located, and the occupancy profiles of those buildings, it is estimated that in this scenario the annual probability of one or more people being below RAAC panels at the time of collapse is between 6.1% and 14.0%. It should be noted that, the probability of one or more people being below RAAC panels at the time of collapse increases significantly if the RAAC panel collapse rate increases or is higher than has been publicly reported.

Considering the country wide building stock, for all collapse rates, the building sectors where we are most likely to see individuals under RAAC panel at the time of collapse are retail and healthcare. This does not account for the effect of any mitigation measures which may have been installed which may change these likelihoods. The higher likelihood in these building sectors, relative to the wider building stock, is due to the extended hours of operation, higher occupant densities and the estimated number of panels.

As discussed in this report, there are a range of different risk factors which increase the likelihood of RAAC panel collapse, and a range of different monitoring and mitigation measures which can be used to reduce the likelihood that a RAAC panel collapses.

The identification of RAAC is the most effective method of reducing the likelihood of RAAC panel collapse and the likelihood that people are below the RAAC panels at the time of collapses. If RAAC remains unknown there is an increased risk that deterioration may be occurring, that adverse loading may be applied to the RAAC, or that deterioration to the RAAC indicating imminent collapse may go unidentified.

# Executive Summary

## Background

This report presents an initial estimate of the number of Reinforced Autoclaved Aerated Concrete (RAAC) panels that may collapse in England and the likelihood of those collapses occurring whilst people are below the RAAC panels. These numbers are presented alongside commentary on RAAC failure mechanisms, risk factors that increase the likelihood of RAAC panel collapse, and measures for inspecting, monitoring and mitigating RAAC panels. RAAC was used throughout construction projects in England between the 1950s and 1990s due to being a lightweight and relatively low-cost material.

**Note: The results presented in this report are estimates only. There is a large range provided for these estimates, reflecting the limited data available at the time of writing.**

The estimated probabilities of RAAC panel collapse (and the likelihoods of people being below the panels at the time of collapse) derived in this report is to be used to inform a wider discussion on how the safety risks posed by RAAC may be managed.

## Methods

To determine an as accurate as possible estimate of the likelihoods and risks posed by RAAC panels, WSP compiled and reviewed available data on previous RAAC panel collapses, occupant densities and occupancy rates of managed buildings in England. This is presented alongside the latest knowledge on managing, monitoring and mitigating RAAC panels and risk factors that impact the likelihood of RAAC panel collapse occurring.

In the first part of this research, it was estimated that there are between 1.3 million and 4.4 million RAAC panels in England with a median estimate of approximately 2.5 million RAAC panels. These panels may be spread between 9,000 and 33,000 buildings across a variety of sectors. In recent years, an average of one RAAC panel is publicly reported as collapsing each year. We do not know how many additional collapses are occurring which are not publicly reported. All available evidence would suggest that the number of RAAC panel collapses occurring in England each year is low. It is uncertain how the rate of RAAC panel collapses will change over time. Continued structural degradation of the RAAC is likely to increase the collapse rate over time. However, the removal and mitigation of RAAC panels will act to decrease the collapse rate over time.

This report only considers the likelihoods that people are below a RAAC panel at the time of collapse, and not the consequences which might arise from such an event. As the current RAAC panel collapse rate is unknown, a range of potential collapse rates are analysed and presented throughout this report.

## Findings

A collapse rate of 1 in 2.5 million panels annually could be derived from the median estimated number of English RAAC panels and the annual average number of publicly reported RAAC panel collapses. Using this collapse rate and assuming the median estimate for the number of English RAAC panels, our modelling shows a 37.7% probability of observing zero collapses in a given year, a 35.6% probability of observing one collapse, and a 25.7% probability of observing two or more collapses in a year. For this collapse rate, alongside conservative estimates of the amount of time for which people are directly below RAAC panels and the modelling techniques employed, it is estimated that the probability of one or more people being below RAAC panels at the time of collapses and therefore put at risk of serious harm is approximately 7.5%.

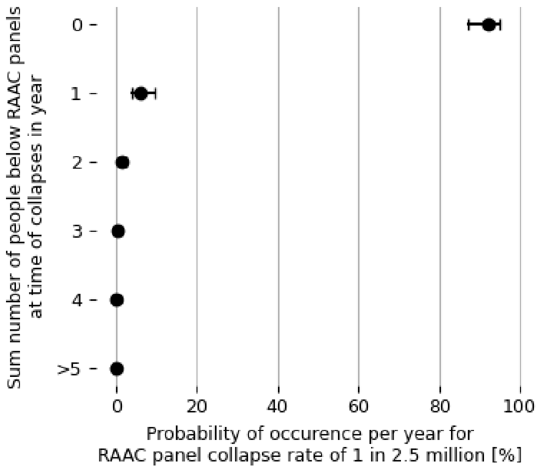


**Figure 1. Median probability of N total people being below RAAC panels at the time panel collapses per year. Error bars show range in which 90% of analysis simulations fall.**

Using a collapse rate of 1 in 500,000 RAAC panels annually (the upper limit considered in our modelling) and the estimated likely upper limit total number of English RAAC panels per year of 4.4 million, our modelling shows a 0.8% probability of observing zero collapses in a given year, a 3.7% probability of observing one collapse, and a 95.5% probability of observing two or more collapses in a year. Under this scenario, alongside conservative estimates of the amount of time for which people are directly below RAAC panels and the modelling techniques employed, it is estimated that the probability of one or more people being below RAAC panels at the time of collapses and therefore put at risk of serious harm is approximately 49.1%.

Considering the country wide building stock, for all collapse rates, the building sectors where we are most likely to see individuals under RAAC panel at the time of collapse are retail and healthcare. This does not account for the effect of any mitigations measures which may have been installed which may change these likelihoods. The higher likelihood in these building sectors, relative to the wider building stock is due to the extended hours of operation, higher occupant densities in these sectors and estimated number of panels in these sectors.

# Conclusions

This report presents an overview of strategies for managing, monitoring and mitigating the risks posed by RAAC panels. As a baseline, the identification of RAAC is the most effective method of reducing the likelihood of RAAC panel collapse and the likelihood that people are below the RAAC panels at the time of collapse. If RAAC remains unknown there is an increased risk that deterioration may be occurring, that adverse loading may be applied to the RAAC, or that deterioration to the RAAC indicating imminent collapse may go unidentified.

# Contents

# 1 Introduction

## 1.1 Background

Reinforced Autoclaved Aerated Concrete (RAAC) panel construction is a form of construction used in England from the 1950s to the 1990s. RAAC panels were used for walls, floors and roofs across a range of residential, commercial and government buildings. Recent years have seen a small number of RAAC panel failures , resulting in an increased awareness of this form of construction and the potential risks posed by these panels.

This report builds on previous work by WSP (RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels), which estimated the current number of RAAC panels in England, to assess the risks posed by RAAC panels.

### 1.1.1 What is RAAC?

For the purposes of this report, RAAC is defined as having four key characteristics:

1. It has a chemically aerated concrete mixture,
2. The aerated concrete mixture was hardened through an autoclave process,
3. It contains reinforcement bars,
4. It does not contain aggregate.

RAAC panels in England were produced and marketed under a wide range of different names including Siporex, Durox, Ytong, Durisol, Argex and Leca. RAAC panels are known to have been manufactured domestically and are also likely to have been imported from Europe and the wider world.

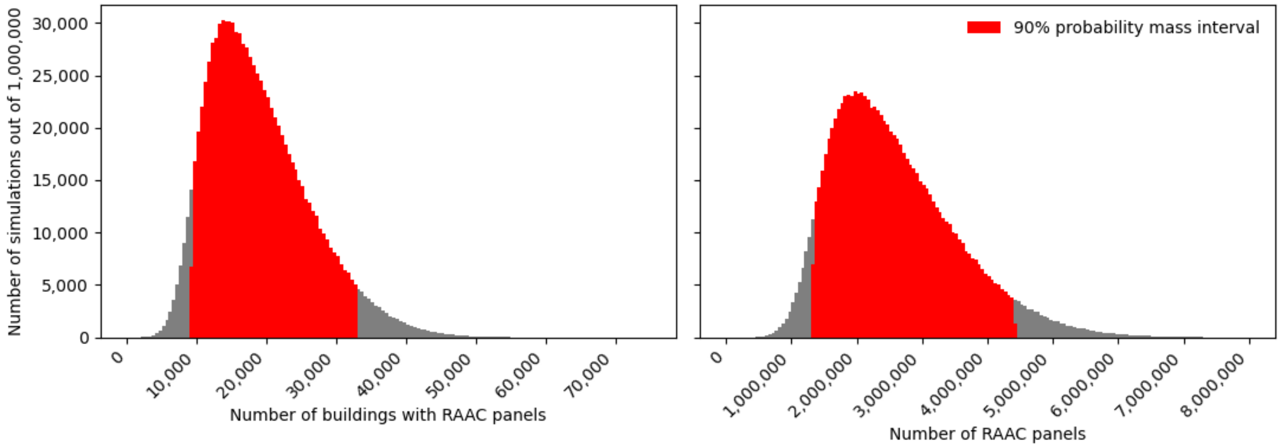


**Figure 2. Estimated number of buildings with RAAC and number of RAAC panels in England. Left subplot histogram bin width of 1,000. Right subplot histogram bin width of 50,000 (RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels).**

## 1.2 Research aim

This report presents an informed assessment of the potential risks posed by RAAC and strategies for mitigating those risks.

It does this by providing an initial estimate of the potential number of RAAC panel collapses in England, the likelihood of people being below the RAAC panel at the time of collapse, the mechanisms and risk factors impacting RAAC panel collapse and the strategies that have been used to mitigate those risks.

The findings of this report are intended to guide and inform the wider discussions on coordinating the future management of RAAC in England.

## 1.3 Scope of report

This report provides initial estimates of the number of RAAC panels collapses that may occur in buildings in England and the probability that people are below the RAAC panels at the time of the collapses.

These estimates are based on publicly available datasets, or data collected independently by WSP (and anonymised) as part of other previous or ongoing RAAC panel surveys. While every effort has been made to ensure the data used is accurate and up to date, the accuracy of the estimates are limited by the accuracy of these datasets. Every effort has been made to reflect the uncertainty in the data within the estimates presented.

This report, which concludes a wider project to assess the risks posed by RAAC panels, does **not** include:

- Assessment of the likelihood that the person or persons below RAAC panels at the time of collapse are seriously harmed.
- Estimates of the number of RAAC panels in Wales, Scotland or Northern Ireland.
- Any analysis or assessment of the likelihood of failure of individual RAAC panels or similar products.
- A comprehensive list of all known buildings containing RAAC in England.

The findings of this report are based on a review of information available as of March 2024, with the estimated numbers of RAAC panels based on information available in October 2023.

## 1.4 Report structure

This report is divided into four sections:

- **Section A** assesses the probability of RAAC panel collapse.
- **Section B** assesses the probability that people are below a RAAC panel at the time of collapse.
- **Section C** describes the types of RAAC failure mechanisms and factors which increase the probability of RAAC panel collapse.
- **Section D** describes measures which can reduce the risk of RAAC panel collapse, and measures which mitigate the consequences of RAAC panel collapse if it were to occur.

## 1.5 Building sectors

Results throughout the report are presented by building sector, as described in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels. The building sector categorisations used in this study are:

- Residential:
  - Social houses
  - Private houses
  - Social flats
  - Private flats
- Non-residential:
  - Arts, community and leisure
  - Education
  - Emergency services
  - Factories
  - Health
  - Hospitality
  - Offices

- Shops
- Warehouses
- Other

## 1.6 Number of RAAC panels

A summary of the estimated number of RAAC panels by sector and period of construction is provided in Figure 2. Full details of the methodology used to arrive at these estimates are provided in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels.

# 2 Section A – Probability of RAAC panel collapse

To estimate the risk posed by RAAC panels in England, the probability of an individual RAAC panel failing in a variety of settings needs to be considered and the potential consequences of that failure must be assessed.

This section presents estimates of the probability of RAAC panel collapse, based on previous estimates of the number of RAAC panels in England and prior observations of the numbers of RAAC panel collapses as publicly reported.

## 2.1 Output structure of Section A

To ensure that the full risk profile of RAAC panel collapse is effectively conveyed, the results in this section are presented as both the average number of RAAC panel collapses which are expected to occur per year under a variety of scenarios and the probability of $N$ RAAC panel collapses occurring per year.

This method of presenting the results is selected as a simple average number of RAAC panel collapses which may occur per year may not accurately convey the probability that, in a given year, there are non-negligible probabilities that no RAAC panel collapses occur. Similarly, a higher number of RAAC panel collapses may occur. Calculating the probability that a large number of RAAC panel collapses occur in a given year provides a metric for quantifying the impact that this would have on society's acceptance and perception of the risk posed by RAAC panels.

## 2.2 Methodology for Section A

The average number of RAAC panel collapses which would be expected to occur in a given year ($\lambda_{RAAC}$) is given by the estimated number of RAAC panels in England ($N_{RAAC}$) multiplied by the likelihood of a single RAAC panel failing in a given year ($P_{collapse}$):

$$\lambda_{RAAC} = N_{RAAC} \times P_{collapse}$$

As discussed above, the average number of RAAC panel collapses per year is believed to be a poor metric for conveying the risks posed by RAAC panel collapse.

A more interpretable metric for assessing the risks posed by RAAC panel collapse is the probability that $k$ RAAC panel collapses occur within a given year. The probability of these different numbers of RAAC panel collapses occurring within a given year can be modelled using a Poisson distribution. A Poisson distribution expresses the probability of $k$

independent events occurring in a time period, given that it is expected that $\lambda$ events occur within that time period:

$$P(Event\ occurs\ in\ period) = \frac{\lambda^k e^{-\lambda}}{k!}$$

For $N$ RAAC panels in England, the expected number of RAAC panel collapses ($\lambda$) is the average number of RAAC panel collapses that are expected to occur in a year.

### 2.2.1 Number of RAAC panels

Estimates of the number of RAAC panels in England were produced in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels. One million separate simulations were run with different input parameters to generate estimates of how many RAAC panels are in England and which building sectors these panels are likely to be located in. This large sample set of simulations was used as a proxy for the uncertainty in the data arising from unknown numbers of buildings in England, unknown floor areas and unknown likelihoods of buildings containing RAAC.

Based on the information available and the modelling techniques employed in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels, these simulations showed a 90% likelihood that there are between 1.3 million and 4.4 million RAAC panels in England, as shown in Figure 3.

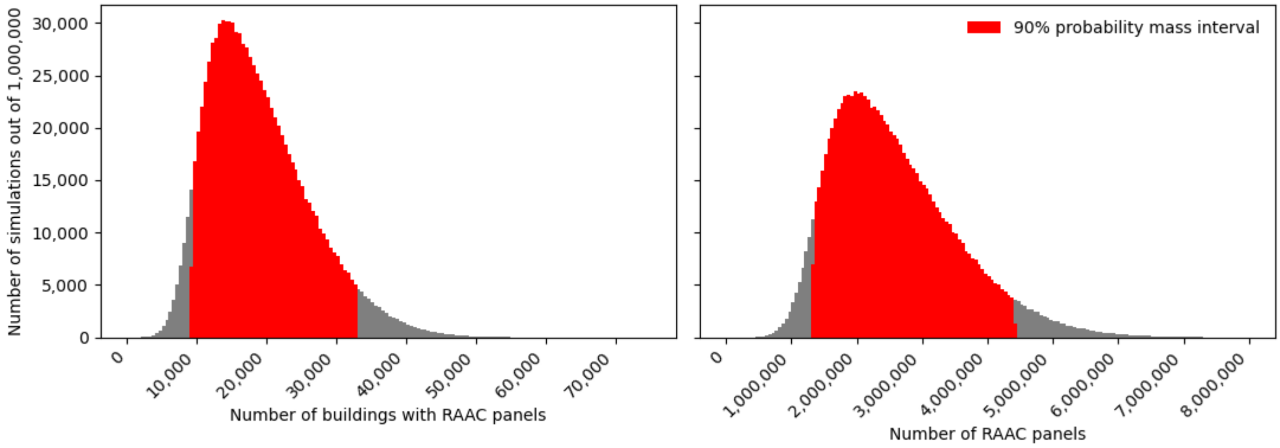


**Figure 3. Estimated number of buildings with RAAC and number of RAAC panels in England. Left subplot histogram bin width of 1,000. Right subplot histogram bin width of 50,000.**

Assuming that the prevalence of RAAC is broadly consistent across different building sectors, it is likely that the majority of RAAC panels are in commercial buildings, as shown in Figure 4. The information available would suggest that the vast majority of RAAC panels in England are roof panels.

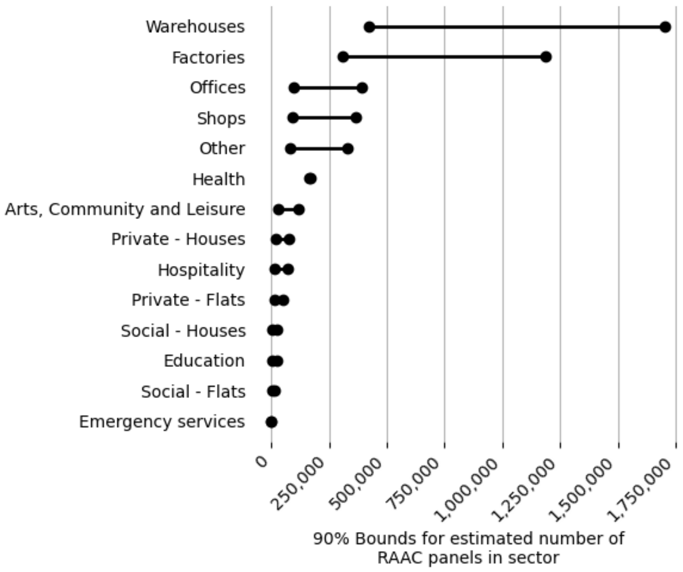


**Figure 4. Estimated number of RAAC panels in England according to building sector.**

The results presented in Figure 3 and Figure 4 are estimated through compiling the results of the one million simulations generated in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels. This same set of simulation results is used as inputs for this study.

As discussed at length in RR1212, due to the limited data available, the estimate number of RAAC panels in England are based on broad assumptions on the prevalence of RAAC. The number of RAAC panels in each sector has primarily been estimated using the number of buildings constructed in the periods where RAAC was in use, and the RAAC prevalence as inferred from the Department for Education RAAC surveys. This RAAC prevalence has been applied to all non-residential building sectors.

There is a large degree of uncertainty in the results for a specific sector. For example, if the RAAC prevalence in warehouses was substantially lower than education settings, the total number of RAAC panels in England would be at the lower end of the range of results estimated in RR1212.

### 2.2.2 Known RAAC panel collapse incidents

A summary of RAAC panel collapses and reported failures in England as reported by the Collaborative Reporting for Safer Structures UK (CROSS-UK) is provided in Table 1.

**Table 1. Known instances of RAAC panel collapse.**

| Reference | Date | Sector | Notes | Source |
|---|---|---|---|---|
| **A** | 2017 | Education | Shear failure of single panel due to ponding water. | https://www.cross-safety.org/uk/safety-information/cross-safety-report/failure-raac-planks-schools-908 |
| **B** | 2019 | Education | Partial failure due to roof leaks. | https://www.cross-safety.org/uk/safety-information/cross-safety-report/failure-raac-planks-schools-908 |
| **C** | 2019 | Retail | Spalling of RAAC panels without collapse. | https://www.cross-safety.org/sites/default/files/2019-05/failure-reinforced-autoclaved-aerated-concrete-planks.pdf |
| **D** | 2018 | Inferred to be Education. | Collapse of multiple RAAC panels. Roof had been recently resurfaced and there was hot weather at the time of failure. | https://www.cross-safety.org/sites/default/files/2019-05/failure-reinforced-autoclaved-aerated-concrete-planks.pdf |

The failures presented in the table above are limited to those which have been publicly reported.

It is expected that a larger number of collapses than those listed in the table above will have occurred and not been publicly reported.

Three out of the four publicly reported RAAC panel collapses occurred in education settings. This is likely due to a confluence of different factors. For publicly funded schools, there may be an increased sense of duty to report on RAAC panel collapses compared to commercial sectors. Education settings may also be more exposed to the risk factors, discussed in Section C, which increase the likelihood of RAAC panel failure occurring. In contrast, WSP are not aware of any publicly reported RAAC panel collapses which have occurred in healthcare settings, despite healthcare settings having 160,000 known RAAC panels.

Based on the above, estimating the RAAC panel collapse rate based on the estimated number of RAAC panels in the education sector alone is believed to be a poor indicator of the true RAAC panel collapse rate in England. This conclusion is supported by additional evidence including the absence of RAAC panel collapses which have been reported to CROSS-UK since 2019. Alongside this, given the scrutiny of RAAC which has occurred in the past 12 months, if high numbers of RAAC panel collapses were regularly occurring it is expected that this would have generated some level of public or industry awareness. Similarly, if large numbers of collapses were regularly occurring, it is likely that one of these collapses would have occurred whilst someone was below the panel, something which has not been found in WSP's extensive literature review.

All current evidence available to WSP would suggest that the number of RAAC panel collapses occurring in England each year is low and likely to number in the single digits.

No direct evidence of RAAC panel collapses which occurred prior to 2017 were found during WSP's literature review. This may be due to a lack of public interest, and/or a lack of mechanisms for reporting such collapses. Alternatively, such collapses may have been reported using more general terminology to refer to the RAAC such as "concrete planks" or "concrete panels".

### 2.2.3 Estimated RAAC panel collapse rate

The rate at which RAAC panel collapses are currently occurring is currently unknown. At present, it has been estimated by WSP, based on publicly available information, that there is approximately one RAAC panel collapse reported per year. For the purposes of this report, RAAC panel collapse has been defined as the panel falling from its support.

The rate of RAAC panel collapse cannot be estimated from the one reported RAAC panel collapse per year as the precise number of RAAC panels in England is not known and it is likely that the number of RAAC panel collapses that occur each year is higher than that which is reported.

Therefore, in this study, the consequences of a range of potential RAAC panel collapse rates are assessed. This range is taken as varying from 1 in 0.5 million RAAC panels collapse per year and 1 in 10 million RAAC panels collapse per year.

For the purposes of benchmarking the results presented elsewhere in this section, a range of different collapse rates, derived using the results from RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels, are presented below:

- If there are 1.3 million RAAC panels in England (lower bound estimate from RR1212) and there is an average of 1 collapse per year the collapse rate is **1 in 1.3 million**.
- If there are 2.5 million RAAC panels in England (median estimate from RR1212) and there is an average of 1 collapse per year the collapse rate is **1 in 2.5 million**.
- If there are 4.4 million RAAC panels in England (upper bound estimate from RR1212) and there is an average of 1 collapse per year the collapse rate is **1 in 4.4 million.**

As discussed previously, it is expected that not all RAAC panel collapses which occur in England are publicly reported on in a given year. This is accounted for in the range of collapse rates used throughout this section. For example, the collapse rate of **1 in 500,000** used in this section approximately translates to the following:

- If there are 1.3 million RAAC panels in England (lower bound estimate from RR1212) and the collapse rate is 1 in 500,000, there would be an average of 2.6 RAAC panel collapses per year (of which an average of 1 is publicly reported).
- If there are 2.5 million RAAC panels in England (lower bound estimate from RR1212) and the collapse rate is 1 in 500,000, there would be an average of 5.0 RAAC panel collapses per year (of which an average of 1 is publicly reported).
- If there are 4.4 million RAAC panels in England (upper bound estimate from RR1212) and the collapse rate is 1 in 500,000, there would be an average of 8.8 RAAC panel collapses per year (of which an average of 1 is publicly reported).

#### 2.2.4 Modelling assumptions in Section A analysis

In the Section A analysis, there are broad uncertainties in the data which impact the predicted number of RAAC panel collapses:

- The exact number of RAAC panels in England is unknown. In report RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels, archive information was combined with available survey data to estimate a distribution of possible numbers of RAAC panels in England.
- The likelihood of a single RAAC panel collapsing is unknown. RAAC collapse is rare and infrequent. For the purposes of the analysis presented in this report, the limited number of past collapses that are known to WSP have been studied and likely collapse patterns and occurrence rates have been derived.
- The distribution of RAAC panels between different building sectors is unknown. It appears likely that the rate of RAAC panel collapse will vary between building sectors, due to different maintenance regimes, quality of construction and construction typologies. As part of the analysis presented in report RR1212, available information on historic usage of RAAC was combined with building stock data to estimate likely distributions of RAAC panels across building sectors.

For the purposes of the analysis presented within this section, and in light of the limited data available, it is assumed that the rate of RAAC panel collapse is constant across building sectors. This assumption and accompanying explanation is discussed further in Section C.

There are multiple failure mechanisms which can result in RAAC panel collapse, as discussed further in Section C. For the purposes of the analysis presented in this section, a single RAAC panel collapse rate has been taken that is a sum rate of RAAC panel collapse by any failure mechanism. As discussed further in Section C, if further data was available, this assumption could be refined to reflect differing rates of RAAC panel collapse arising from different failure mechanisms.

For the purpose of the initial modelling of RAAC panel collapse, it is assumed that RAAC panel collapses are independent events. That is, the collapse of one RAAC panel has no impact on the likelihood of other RAAC panels collapsing. The known occurrence of multiple panels failing simultaneously and the implications of this on the results presented are discussed further in Section B, subsection 3.7.

As the number of RAAC panel collapses is expected to be low and the uncertainties within the data are broad, the reduction in the number of RAAC panels due to a single RAAC panel collapse is not explicitly accounted for within the model. Initial estimates suggest that the impact of this is negligible and is dwarfed by other sources of uncertainty.

## 2.3 Average number of RAAC panel collapses per year

The average or expected number of RAAC panel collapses per year for a range of different RAAC panel collapse rates is plotted in Figure 5. In this figure, the 90% probability mass interval gives an indication of the uncertainty in the results which arises due to the unknown number of RAAC panels in England.

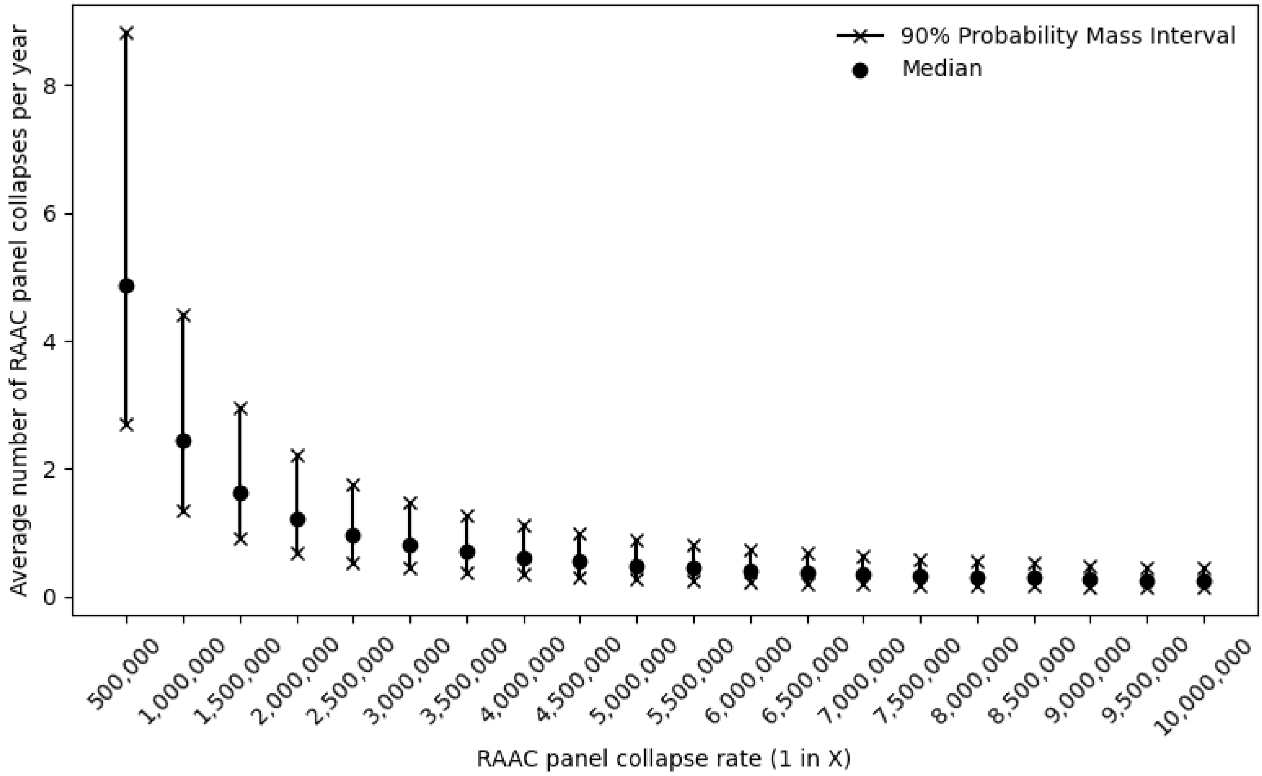


**Figure 5. Estimated average number of RAAC panel collapses in England for varying RAAC panel collapse rates. Results plotted to show bounds of 90% probability mass interval (the range between the 5th and 95th percentiles of the 1 million independent simulations) alongside the median result (50th percentile).**

The 90% probability mass interval, as defined by the 5$^{th}$ and 95$^{th}$ percentiles of the 1 million simulations of number of RAAC panels in England, shows that if the failure rate of RAAC panels was 1 in 0.5 million, there would be an average of between 2.7 and 8.8 RAAC panel failures in England per year.

The failure rate of 1 in 2.5 million gives the result closest to what has previously been anecdotally reported, with a median average failure rate of 0.97 panels per year and a 90% probability mass interval of between 0.54 and 1.77 RAAC panels failing per year, on average.

## 2.4 Probability of RAAC panel collapses

The median estimated probability of RAAC panel collapses for each of the different RAAC panel collapse rates is presented in Figure 6.

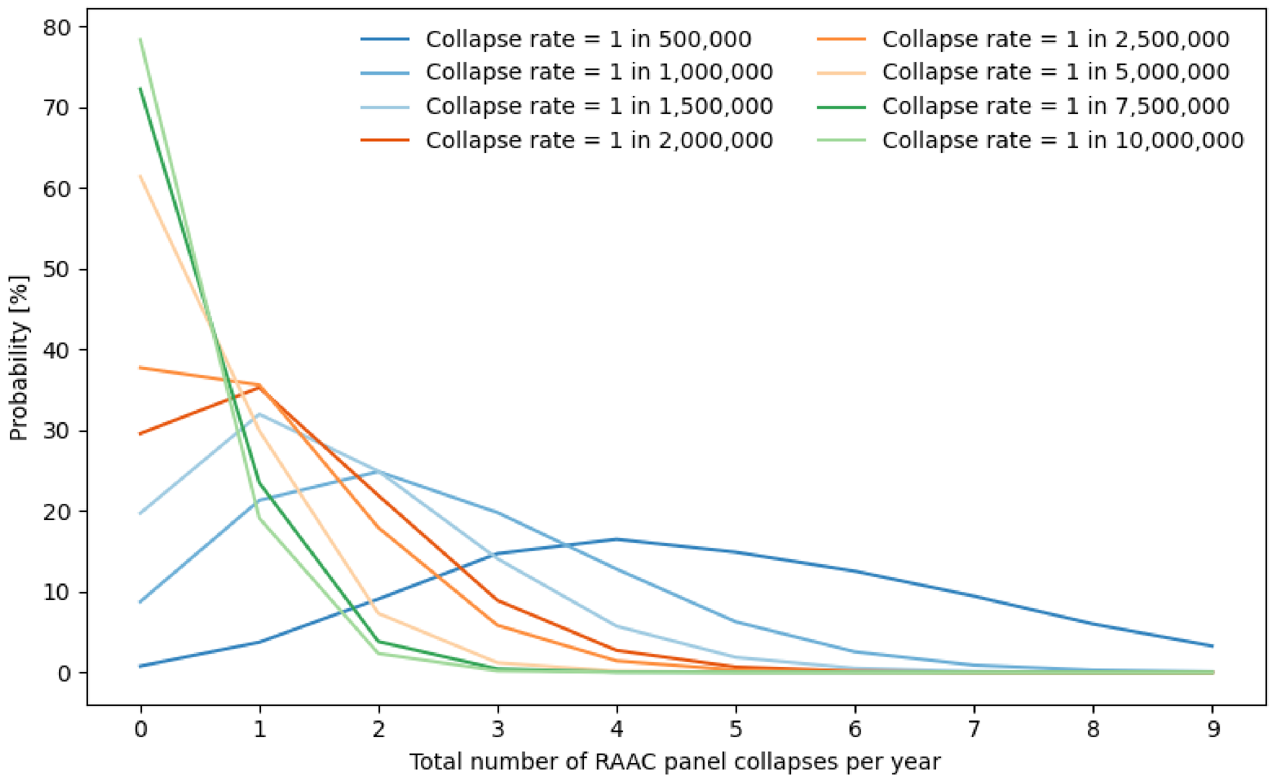


**Figure 6. Median probability of N RAAC panel collapses occurring in a given year for varying RAAC panel collapse rates.**

In Figure 6, the median probability of RAAC panel collapses is calculated as the 50th percentile of the results for the 1 million simulations of number of RAAC panel in England calculated in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels.

The results presented in Figure 6 show that if the rate of RAAC panel collapse was 1 in 0.5 million, the probability of observing zero RAAC panel collapses in a year is less than 5%. In contrast, if the rate of RAAC panel collapse was 1 in 10 million, there is 78.4% probability of observing zero RAAC panel collapses in a year.

A selection of 90% probability mass interval (the range of probabilities of RAAC panel collapses between the 5th percentile and the 95th percentile of the results for the 1 million simulations of number of RAAC panel in England calculated in RR1212) are presented in Figure 7.

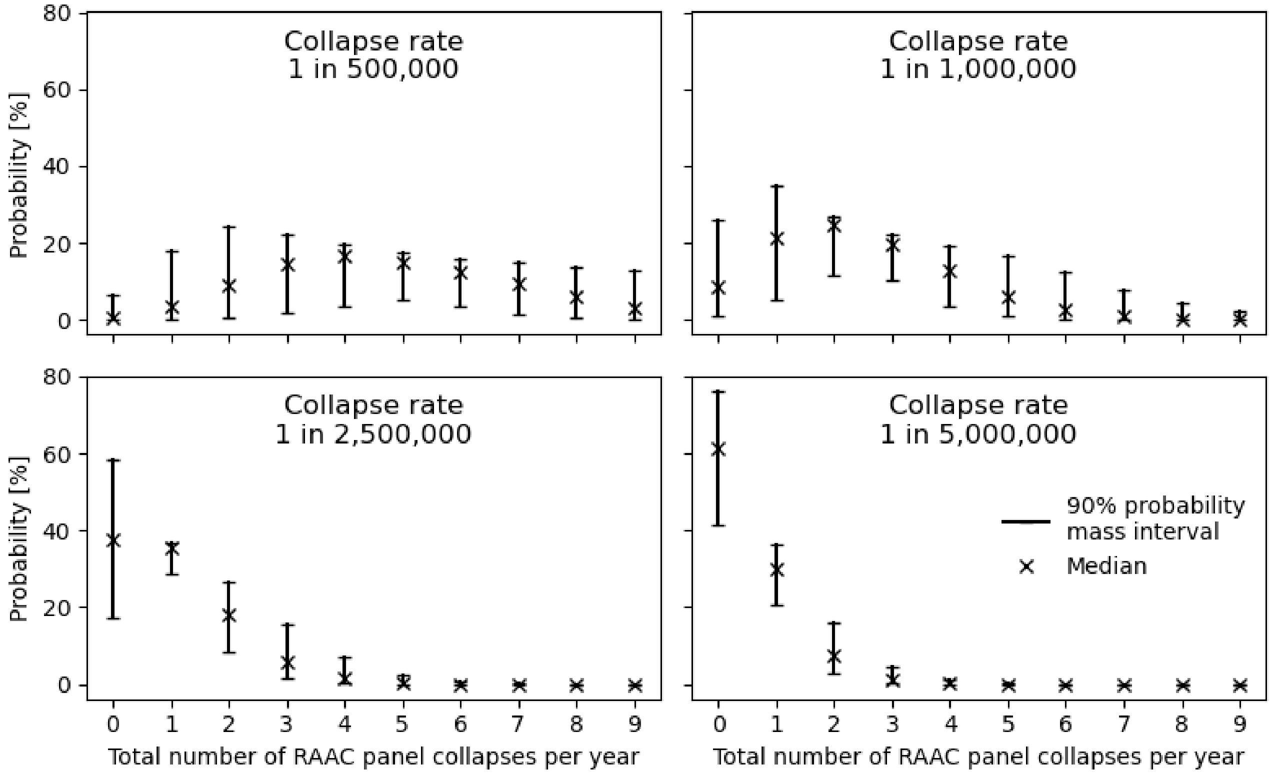


**Figure 7. 90% probability mass interval of the probability of N RAAC panel collapses occurring in a given year for selected RAAC panel collapse rates.**

The analysis shows that as the collapse rate increases, we would be likely to observe a much higher variation in the number of RAAC panel collapses year-on-year. If the collapse rate is low (below a rate of 1 in 5 million RAAC panels collapse in a year), the probability of observing zero RAAC panel collapses in a year significantly outweighs the likelihood of observing more than one RAAC panel collapse in a year.

Based on the previous reports of RAAC panel collapse, the lower bound estimate of collapse rate is taken as 1 in 2.5 million (bottom left subplot of Figure 7). Based on this observation, and assuming the rate of RAAC panel collapse has not been significantly decreased by recent publicity surrounding RAAC panels, there is a significant probability that two or more RAAC panel collapses may be observed in a given year. Based on the data available and the assumptions discussed in previous sections, it is deemed exceptionally unlikely that more than ten individual and independent RAAC panel collapses would occur within a given year.

Tabulated outputs for selected results are provided in Table 2 to Table 7.

**Table 2. Probability of observing specific numbers of RAAC panel collapses per year for a RAAC panel collapse rate of 1 in 500,000**

| No. RAAC panel collapses per year | Probability of Occurrence [%] – Lower bound | Probability of Occurrence [%] - Median | Probability of Occurrence [%] – Upper bound |
|---|---|---|---|
| **0** | 0.01 | 0.76 | 6.69 |
| **1** | 0.13 | 3.73 | 18.10 |
| **2** | 0.57 | 9.08 | 24.44 |
| **3** | 1.68 | 14.70 | 22.31 |
| **4** | 3.69 | 16.49 | 19.51 |
| **5** | 5.21 | 14.89 | 17.52 |
| **6** | 3.40 | 12.53 | 16.03 |
| **7** | 1.40 | 9.44 | 14.84 |
| **8** | 0.47 | 5.99 | 13.81 |
| **9** | 0.14 | 3.27 | 12.78 |

**Table 3. Probability of observing specific numbers of RAAC panel collapses per year for a RAAC panel collapse rate of 1 in 1 million**

| No. RAAC panel collapses per year | Probability of Occurrence [%] – Lower bound | Probability of Occurrence [%] - Median | Probability of Occurrence [%] – Upper bound |
|---|---|---|---|
| **0** | 1.21 | 8.74 | 25.87 |
| **1** | 5.35 | 21.31 | 34.96 |
| **2** | 11.77 | 24.87 | 27.05 |
| **3** | 10.31 | 19.79 | 22.38 |
| **4** | 3.60 | 12.80 | 19.43 |
| **5** | 0.97 | 6.26 | 16.73 |

| No. RAAC panel collapses per year | Probability of Occurrence [%] – Lower bound | Probability of Occurrence [%] - Median | Probability of Occurrence [%] – Upper bound |
|---|---|---|---|
| **6** | 0.22 | 2.54 | 12.43 |
| **7** | 0.04 | 0.89 | 7.84 |
| **8** | 0.01 | 0.27 | 4.32 |
| **9** | 0.00 | 0.07 | 2.12 |

**Table 4. Probability of observing specific numbers of RAAC panel collapses per year for a RAAC panel collapse rate of 1 in 2.5 million**

| No. RAAC panel collapses per year | Probability of Occurrence [%] – Lower bound | Probability of Occurrence [%] - Median | Probability of Occurrence [%] – Upper bound |
|---|---|---|---|
| **0** | 17.11 | 37.73 | 58.23 |
| **1** | 28.86 | 35.60 | 36.78 |
| **2** | 8.52 | 17.92 | 26.56 |
| **3** | 1.54 | 5.82 | 15.69 |
| **4** | 0.21 | 1.42 | 6.92 |
| **5** | 0.02 | 0.28 | 2.44 |
| **6** | 0.00 | 0.04 | 0.72 |
| **7** | 0.00 | 0.01 | 0.18 |
| **8** | 0.00 | 0.00 | 0.04 |
| **9** | 0.00 | 0.00 | 0.01 |

**Table 5. Probability of observing specific numbers of RAAC panel collapses per year for a RAAC panel collapse rate of 1 in 5 million**

| No. RAAC panel collapses per year | Probability of Occurrence [%] – Lower bound | Probability of Occurrence [%] - Median | Probability of Occurrence [%] – Upper bound |
|---|---|---|---|
| **0** | 41.37 | 61.43 | 76.31 |
| **1** | 20.63 | 29.94 | 36.44 |
| **2** | 2.79 | 7.29 | 16.11 |
| **3** | 0.25 | 1.19 | 4.74 |
| **4** | 0.02 | 0.14 | 1.05 |
| **5** | 0.00 | 0.01 | 0.18 |
| **6** | 0.00 | 0.00 | 0.03 |
| **7** | 0.00 | 0.00 | 0.00 |
| **8** | 0.00 | 0.00 | 0.00 |
| **9** | 0.00 | 0.00 | 0.00 |

**Table 6. Probability of observing specific numbers of RAAC panel collapses per year for a RAAC panel collapse rate of 1 in 7.5 million**

| No. RAAC panel collapses per year | Probability of Occurrence [%] – Lower bound | Probability of Occurrence [%] - Median | Probability of Occurrence [%] – Upper bound |
|---|---|---|---|
| **0** | 55.52 | 72.26 | 83.50 |
| **1** | 15.05 | 23.48 | 32.67 |
| **2** | 1.36 | 3.81 | 9.61 |
| **3** | 0.08 | 0.41 | 1.89 |
| **4** | 0.00 | 0.03 | 0.28 |
| **5** | 0.00 | 0.00 | 0.03 |

| No. RAAC panel collapses per year | Probability of Occurrence [%] – Lower bound | Probability of Occurrence [%] - Median | Probability of Occurrence [%] – Upper bound |
|---|---|---|---|
| **6** | 0.00 | 0.00 | 0.00 |
| **7** | 0.00 | 0.00 | 0.00 |
| **8** | 0.00 | 0.00 | 0.00 |
| **9** | 0.00 | 0.00 | 0.00 |

**Table 7. Probability of observing specific numbers of RAAC panel collapses per year for a RAAC panel collapse rate of 1 in 10 million**

| No. RAAC panel collapses per year | Probability of Occurrence [%] – Lower bound | Probability of Occurrence [%] - Median | Probability of Occurrence [%] – Upper bound |
|---|---|---|---|
| **0** | 64.32 | 78.37 | 87.35 |
| **1** | 11.81 | 19.10 | 28.38 |
| **2** | 0.80 | 2.33 | 6.26 |
| **3** | 0.04 | 0.19 | 0.92 |
| **4** | 0.00 | 0.01 | 0.10 |
| **5** | 0.00 | 0.00 | 0.01 |
| **6** | 0.00 | 0.00 | 0.00 |
| **7** | 0.00 | 0.00 | 0.00 |
| **8** | 0.00 | 0.00 | 0.00 |
| **9** | 0.00 | 0.00 | 0.00 |

## 2.5 Probability of RAAC panel collapses by sector

As the rate of RAAC panel collapse has been taken as constant across building sectors, the probability of observing a RAAC panel collapse in any given building sector is equal to the probability of observing a given number of collapses multiplied by the fraction of the number of panels that are localised in a sector.

The median probabilities of observing RAAC panel collapses, subdivided by building sector, is presented for a collapse rate of 1 in 1 in 2.5 million in Figure 8.

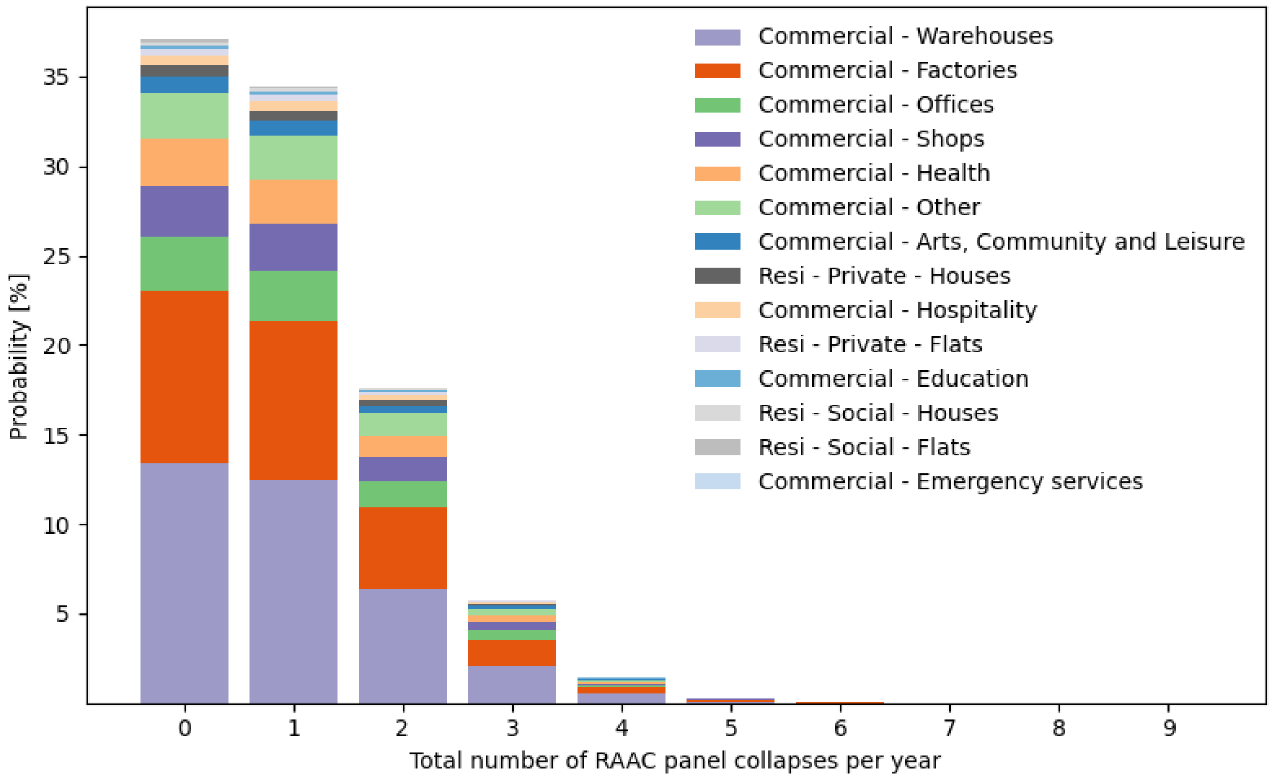


**Figure 8. Median probability of observing N RAAC panel collapses per year, stratified by building sector, for a RAAC panel collapse rate of 1 in 2.5 million.**

As shown in Figure 8, the most likely places to observe RAAC panel collapses are warehouses and factories, with the probability of collapses occurring in these sectors outweighing all other building sectors combined.

## 2.6 Section A summary

Based on the data available and the modelling assumptions detailed within this report, a range of probabilities of observing RAAC panel collapses in England has been calculated.

If the collapse rate of RAAC panels is 1 in ten million (the lowest RAAC failure rate considered plausible given historic patterns of RAAC panel collapses), there is between an 11.8% and 28.4% probability of observing a RAAC panel collapse in a given year. The probability of observing two or more RAAC panel collapses in a single year for the same RAAC panel collapse rate is between 0.8% and 6.3%.

If the collapse rate of RAAC panels is 1 in 2.5 million there are approximately equal probabilities that zero RAAC panels collapse in a given year (median result 37.7%) or one RAAC panel collapse occurs in a given year (median result 35.6%). The median probability of observing two RAAC panel collapses in a year is 17.9%, the median probability of observing three RAAC panel collapses is 5.8% and the median probability of observing four or more RAAC panel collapses is approximately 1.8%.

If the collapse rate of RAAC panels is 1 in 0.5 million there are equal probabilities of observing fewer than four RAAC panel failures in a year and observing four or more RAAC panel failures in a year. There is a meaningful probability that nine or more RAAC panel collapses may occur in a year.

A RAAC panel collapse rate of 1 in 2.5 million results in a median prediction that there is an average of 0.97 RAAC panel collapse per year, approximately equal to the currently publicly reported rate of an average of one RAAC panel collapsing per year.

Greater clarity on the number of RAAC panel collapses occurring each year is required to further refine the range of uncertainty. Based on publicly reported cases to date, alongside the assumptions made in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels, it appears likely that the RAAC panel collapse rate is greater than 1 in 2.5 million due to underreporting of RAAC panel collapses. As can be seen in Figure 6, this results in a significant probability that two or more RAAC panel collapses will occur per year.

On the assumption that the RAAC panel collapse rate is broadly equal across all building sectors, it is likely that the majority of RAAC panel collapses will occur in commercial settings, specifically warehouses and factories.

# 3 Section B - Probability of people being below a RAAC panel at time of collapse

The probability that in England in a given year one or more people are below a RAAC panel at the time of collapse is equal to the probability of an individual RAAC panel collapse occurring, multiplied by the probability that one or more people are below the RAAC panel at the time of collapse.

The probability of RAAC panel collapse for a range of collapse rates is presented in Section A of this report.

The likelihood of a person being below the RAAC panel at the time of collapse can be estimated by incorporating data from:

- The percentage of the year that building is occupied.
- The average occupant density of the building.

These two factors will vary by building sector: offices and shops will have a much higher occupant density than factories and warehouses. In contrast, offices are typically occupied for shorter time periods than warehouses, which may operate 24 hours a day.

## 3.1 Methodology for Section B

For the purpose of estimating the number of people who may be below a RAAC panel at the time of collapse in England, it is assumed that anyone who is within 0.6m of the centreline of RAAC panel at the time of a collapse is “below” the RAAC panel. This is a broad, conservative assumption when analysing singular RAAC panel collapses.

The consequences of a RAAC panel collapse on the person or people below the panel at the time of collapse is unknown. As a typical RAAC panel weighs between 35kg and 120kg, it is likely to cause injury to any people below the panel at the time of collapse.

Collapse of a RAAC panel may also result in the collapse of roof mounted services and service grids beyond the width of the panel itself. The additional width considered in the analysis (0.6m either side of centreline, versus 0.6m typical total width of RAAC panel) accounts for the likelihood that people adjacent to the panel at the time of collapse may be impacted by debris from the collapse, or the collapse of roof mounted services/ceiling grids.

The implications of simultaneous failure of more than one RAAC panel are discussed in subsection 3.7.

The average or expected number of people below a RAAC panel at the time of collapse ($\lambda_{below\ panel\ during\ collapse}$) is given by the number of RAAC panel collapses per year ($N_{collapse}$) multiplied by the average number of people below the RAAC panel at the time of collapse ($N_{people}$):

$$\lambda_{below\ panel\ during\ collapse} = N_{collapse} \times N_{people}$$

As discussed in the previous section, the average number of people below a RAAC panel at the time of collapse per year is believed to be a poor metric for conveying and assessing the risks posed by RAAC panel collapse.

There are two different variables for which probabilities can be independently calculated:

- The probability of $N$ RAAC panel collapses occurring within a given year.
- The probability of $N$ people being below the RAAC panel at the time of collapse.

The distributions of both these probabilities can be approximated using the Poisson distribution, introduced for RAAC panel collapse probabilities in the previous section. This distribution approximates the expected distributions of people below any given RAAC panel at the time of the day, including the possibilities that groups of people may be gathered in a single location for periods of time.

The probability $P(k\ collapses)$ of different numbers ($k$) of RAAC panel collapses occurring within a given year for an expected number of RAAC panel collapses $\lambda_{collapse}$ has been modelled using a Poisson distribution.

$$P(k\ collapses) = \frac{\lambda_{collapse}^{k} e^{-\lambda_{collapse}}}{k!}$$

Similarly, the probability $P(k_{people})$ of different numbers ($k_{people}$) of people being below the RAAC panel at the time of collapse, given an average or expected number of people below the RAAC panel $\lambda_{people}$, is modelled using a Poisson distribution.

$$P(k\ people) = \frac{\lambda_{people}^{k_{people}} e^{-\lambda_{people}}}{k_{people}!}$$

The distribution of probabilities for different numbers of people being below the RAAC panel at the time of collapse is calculated for occupied building hours. This full probability distribution is then scaled down by the percentage of the year for which the building is unoccupied. The probability of zero people being below the RAAC panel is then adjusted, such that it is a combination of the probability that zero people are below the panel during occupied hours and a 100% probability that zero people are below the panel during unoccupied hours.

The probabilities of $j$ people being below a panel at the time of the collapse may be calculated as:

$$P(j\ people\ below\ collapses) = P(One\ collapse) \sum_{sectors} P(sector)P(k\ people\ in\ sector)$$

Where $P(sector)$ is given by the proportion of the total number of RAAC panels in England which exist in a given sector.

### 3.1.1 Collapse scenarios

The probability of differing numbers of people being below RAAC panels when they collapse in a year for all possible numbers of RAAC panel collapses is calculated by considering the different collapse scenarios under which they occur. A collapse scenario is defined here as the sum number of people who are below RAAC panels at the time of collapses in a given year.

The equations used in calculating the probability of different numbers of people being below RAAC panels at the time of collapses in a given year are provided in Appendix A.

Within the analysis presented within this section, the probabilities for the collapse scenarios were calculated for between zero and twenty RAAC panel collapses per year, and accounting for up to five people being below the RAAC panel at the time of collapse. These bounds were empirically selected based on where the probability of an event occurring dropped below five significant figures (less than 0.01%).

## 3.2 Likelihood of people being below RAAC panel at the time of collapse

The likelihood of a person being below RAAC panels at the time of collapse is a product of the percentage of the year for which a building is occupied and the average number of people beneath the RAAC panel at the time of collapse.

### 3.2.1 Percentage of year for which building is occupied

The assumed values for the percentage of the year for which a building is occupied, alongside the basis for the calculation are presented in Table 8 to Table 11.

**Table 8. Occupancy rates for residential buildings**

| Sector | Number of occupied hours per day | Source | Number of days occupied per year | Source | Occupancy Rate [%] |
|---|---|---|---|---|---|
| **Social houses** | 14 | Assumed 6pm to 8am | 365 | Assumed occupied 365 days per year | 58.3% |
| **Private houses** | 14 | Assumed 6pm to 8am | 365 | Assumed occupied 365 days per year | 58.3% |

| Sector | Number of occupied hours per day | Source | Number of days occupied per year | Source | Occupancy Rate [%] |
|---|---|---|---|---|---|
| **Social flats** | 14 | Assumed 6pm to 8am | 365 | Assumed occupied 365 days per year | 58.3% |
| **Private flats** | 14 | Assumed 6pm to 8am | 365 | Assumed occupied 365 days per year | 58.3% |

**Table 9. Number of occupied hours per day for non-residential building sectors.**

| Sector | No. occupied hours per day | Source |
|---|---|---|
| **Arts, Community and Leisure** | 12 | Inferred from Proportion of all workers by SIC section and time of day “usually” worked, 2022, UK (Office for National Statistics, 2022) |
| **Education** | 6.5 | Based on a Review of time in School and 16 to 19 settings (Department for Education, 2021) |
| **Emergency services** | 24 | No widescale survey data found - Assumed occupied 24 hours per day. |
| **Factories** | 12.1 | No widescale survey data found - Assumed 15% of factories are operational 24 hours, and 85% are operational 10 hours a day (conservative). |
| **Health** | 24 | No widescale survey data found - Majority of healthcare RAAC panels located in large best-buy hospitals which are in part operation 24 hours per day. |
| **Hospitality** | 10 | No widescale survey data found - Assumed to be midday to 10pm. |
| **Offices** | 10 | No widescale survey data found - Assumed 8am to 6pm. |
| **Shops** | 12 | No data found - Assumed 12 hours as a balance between high street shops (typically 9am to 5pm) and supermarkets and out of town retail (longer opening hours). |
| **Warehouses** | 12.1 | No widescale survey data found - Assumed 15% of factories are operational 24 hours, and 85% are operational 10 hours a day (conservative). |
| **Other** | 12 | Broad category - Assumed 50% of hours are occupied. |

**Table 10. Number of occupied days per year for non-residential buildings.**

| Sector | No. days occupied per year | Source |
|---|---|---|
| **Arts, Community and Leisure** | 300 | No widescale survey data found - Assumed to be greater than offices, but less than shops. |
| **Education** | 190 | Based on local authority maintained schools' requirement as described in House of Commons library report "The School Day and Year" (House of Commons Library, 2023) |
| **Emergency services** | 365 | No widescale survey data found - Assumed occupied 365 days per year. |
| **Factories** | 300 | No widescale survey data found - Assumed to be greater than offices, but less than shops . |
| **Health** | 365 | No widescale survey data found - Majority of healthcare RAAC panels located in large best-buy hospitals which are in part operation 365 days per year. |
| **Hospitality** | 365 | No widescale survey data found - Assumed to be 365 days per year. |
| **Offices** | 252 | No widescale survey data found - Assumed Monday to Friday plus 8 days bank holidays. |
| **Shops** | 356 | No data found outside of requirements to close on Christmas Day and Easter Sunday (House of Commons Library, 2022). Assumed Monday to Sunday plus 8 bank holidays. |
| **Warehouses** | 300 | No widescale survey data found - Assumed to be greater than offices, but less than shops. |
| **Other** | 365 | Broad category – Conservatively assumed 100% of days occupied. |

**Table 11. Calculated occupancy rates for non-residential buildings.**

| Sector | Occupancy Rate [%] |
|---|---|
| **Arts, Community and Leisure** | 41.1% |
| **Education** | 14.1% |
| **Emergency services** | 100.0% |

| Sector | Occupancy Rate [%] |
|---|---|
| **Factories** | 41.4% |
| **Health** | 100.0% |
| **Hospitality** | 41.7% |
| **Offices** | 28.8% |
| **Shops** | 48.8% |
| **Warehouses** | 41.4% |
| **Other** | 50.0% |

### 3.2.2 Average number of people below a RAAC panel

A person is defined as being below a RAAC panel if they are within 0.6m of the centre line of a RAAC panel. Assuming a typical RAAC panel has dimensions of 3.0m by 0.6m, this results in a zone with dimensions of 1.2m x 3.0m in which people are considered to be 'below' a RAAC panel. This additional area beyond the standard width of a RAAC panel accounts for the possibility that a RAAC panel collapse may result in ceiling grids and services being brought down in areas adjacent to the span of the RAAC panel.

The area below a RAAC panel is $1.2\text{m} \times 3.0\text{m} = 3.6\text{m}^2$.

Average occupant densities are drawn from a range of sources. Where possible, sector specific and UK specific values have been preferred over values that come from broader sectors or from other countries.

The average occupancy densities by building sector, alongside notes on data sources and the equivalent number of people below a RAAC panel, are presented in Table 12. These values are converted into the number of people 'below' the RAAC panel using the equations below:

$$GIFA\ per\ person = x\ \therefore\ People\ per\ m^2 = 1/x$$

For a nominal area of 3.6 $m^2$:

$$No.People\ under\ RAAC = People\ per\ m^2\ \times 3.6\ m^2 = \frac{3.6}{x} = \frac{3.6}{GIFA\ per\ person}\ people$$

**Table 12. Average number of people below RAAC panel by building sector**

| Sector | Average GIFA per occupant ($m^2$) | Source | Average No. of people below RAAC panel during occupied hours |
|---|---|---|---|
| **Social houses** | 37 | English Housing Survey Floor Space in English Homes – Main report (Ministry of Housing, Communities & Local Government, 2018)<br><br>Note: Data sourced from BRE Housing in the UK: National comparisons in typology, condition and cost of poor housing (Building Research Establishment, 2013) | 0.10 |
| **Private houses** | 37 | English Housing Survey Floor Space in English Homes – Main report (Ministry of Housing, Communities & Local Government, 2018)<br><br>Note: Data sourced from BRE Housing in the UK: National comparisons in typology, condition and cost of poor housing (Building Research Establishment, 2013) | 0.10 |
| **Social flats** | 37 | English Housing Survey Floor Space in English Homes – Main report (Ministry of Housing, Communities & Local Government, 2018)<br><br>Note: Data sourced from BRE Housing in the UK: National comparisons in typology, condition and cost of poor housing (Building Research Establishment, 2013) | 0.10 |
| **Private flats** | 37 | English Housing Survey Floor Space in English Homes – Main report (Ministry of Housing, Communities & Local Government, | 0.10 |

| Sector | Average GIFA per occupant ($m^2$) | Source | Average No. of people below RAAC panel during occupied hours |
|---|---|---|---|
| | | 2018)<br><br>Note: Data sourced from BRE Housing in the UK: National comparisons in typology, condition and cost of poor housing (Building Research Establishment, 2013) | |
| **Arts, Community and Leisure** | 4 | Numbers based on Table 6.2 of Chartered Institution of Building Services Engineers (CIBSE) Guide A Environmental design - Leisure - Hotel reception (Lush, Butcher and Appleby, 2013). | 0.90 |
| **Education** | 1.5 | Numbers based on Table 6.2 of CIBSE Guide A Environmental design - Education - Teaching Spaces (Lush, Butcher and Appleby, 2013). | 2.40 |
| **Emergency services** | 10 | Numbers based on Table 6.2 of CIBSE Guide A Environmental design - Hospitals - Treatment Rooms (Lush, Butcher and Appleby, 2013). | 0.36 |
| **Factories** | 69.1 | Numbers rationalised from number of manufacturing workers in the UK (Office for National Statistics, 2023). | 0.05 |
| **Health** | 10 | Numbers based on Table 6.2 of CIBSE Guide A Environmental design - Hospitals - Treatment Rooms (Lush, Butcher and Appleby, 2013). | 0.36 |
| **Hospitality** | 4 | Numbers based on Table 6.2 of CIBSE Guide A Environmental design - Leisure - Hotel reception (Lush, Butcher and Appleby, 2013). | 0.90 |
| **Offices** | 9.6 | Numbers based on British Council for Offices report - Office Occupancy: Density and Utilisation. (BCO, 2023). | 0.38 |
| **Shops** | 5 | Numbers based on Table 6.2 of CIBSE Guide A Environmental design - Retail - | 0.72 |

| Sector | Average GIFA per occupant ($m^2$) | Source | Average No. of people below RAAC panel during occupied hours |
|---|---|---|---|
| | | Retail Stores or Supermarkets (Lush, Butcher and Appleby, 2013). | |
| **Warehouses** | 50 | Numbers based on Table 6.2.2.1 of ASHRAE Ventilation for Acceptable Indoor Air Quality - Miscellaneous Spaces - Shipping/receiving areas (ASHRAE, 2021). | 0.07 |
| **Other** | 12 | Broad category - Assumed to be lower than shops and offices, but higher than warehouses and factories. | 0.30 |

## 3.3 Average sum number of people below RAAC panel at time of collapse per year

The average sum number of people below RAAC panels at the time of collapses per year is presented in Figure 9. These values are based on the average number of people below the RAAC panel at the time of collapse multiplied by the average number of RAAC panel collapses per sector for a range of RAAC panel collapse rates.

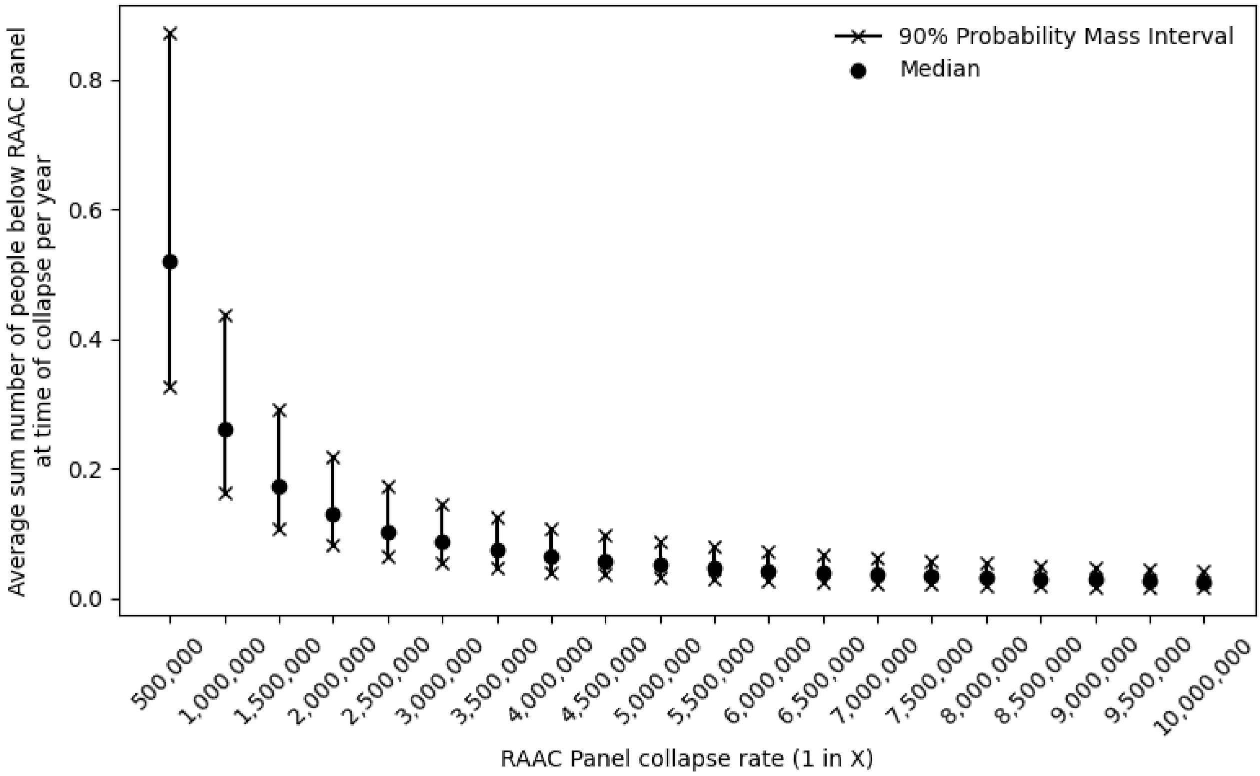


**Figure 9. Average sum number of people below RAAC panels at the time of collapses in a year for varying RAAC panel collapse rates.**

The breakdown of the median values from Figure 9 by building sector is presented in Figure 10.

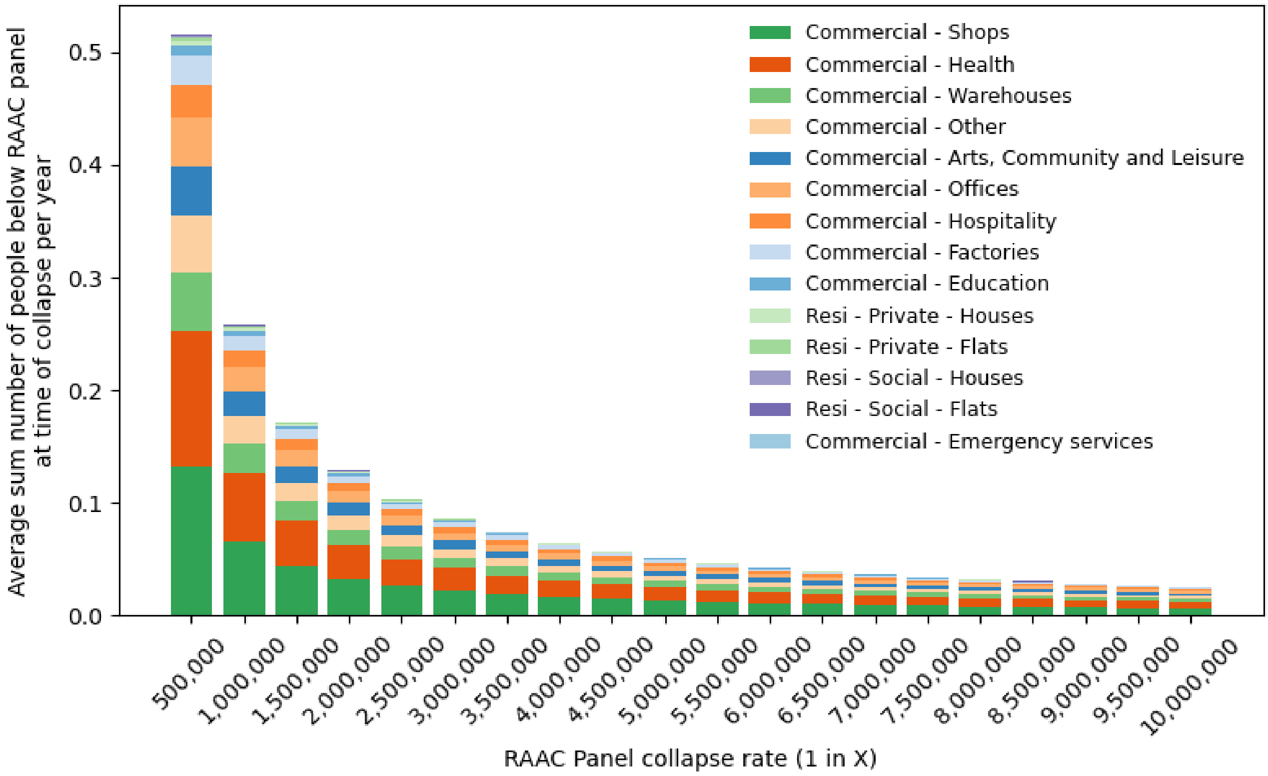


**Figure 10. Average sum number of people below RAAC panel at time of collapse for varying RAAC panel collapse rates, segmented by sector in which people are below the RAAC panel at the time of collapse.**

Based on the assumption of equal RAAC prevalence across non-residential building sectors, discussed at length in the RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels, the majority of RAAC collapses were expected to occur in factories and warehouses. However, Figure 10 shows that if a person was below a RAAC panel at the time of collapse in any scenario, it is most likely to occur in shops or healthcare settings. This outcome is a function of the higher occupant densities (shops) or higher percentage of the time for which the building is assumed to be occupied (healthcare settings).

Warehouses are deemed to have a higher average sum number of people at risk of being below a RAAC panel at the time of collapse than factories due to the assumed slightly increased hours of operation and a slightly higher occupant density.

## 3.4 Probability of people being below RAAC panel at time of collapses

The probability of varying numbers of people being below RAAC panels at the time of collapses in England for a given year is plotted in Figure 11.

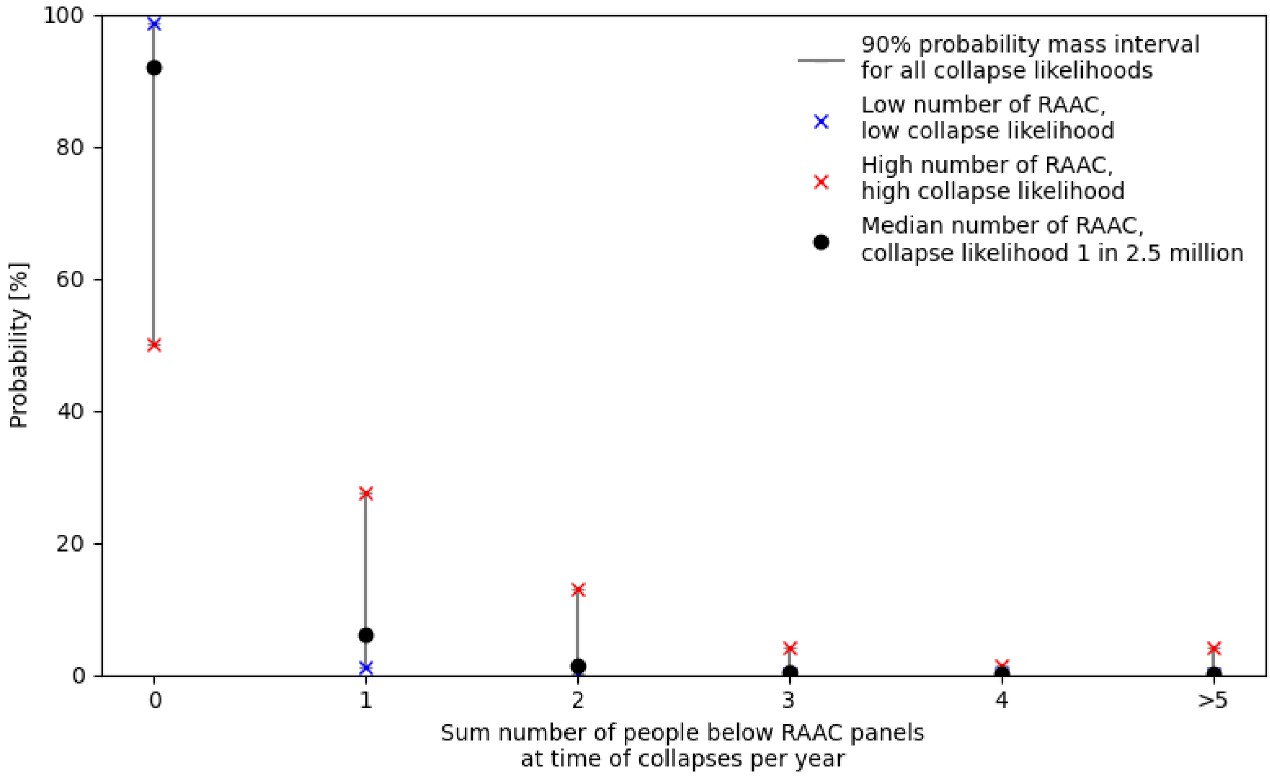


**Figure 11. Probability of varying numbers of people below RAAC panels at the time of collapses in a given year.**

The lowest probabilities that people are below RAAC panels at the time of collapses is when there is a low number of RAAC panels (the number of RAAC panels is fewer than 1 million) and the RAAC panel collapse rate is low (1 in 10 million panels collapse in a given year, an average of one RAAC panel collapse occurring every 3 to 10 years). In this scenario, there is a 98.7% probability that there are no people below the RAAC panels at the time of collapses in a given year.

At the opposite end of the scale, if there is a high number of RAAC panels in England (more than 4.4 million RAAC panels) and the RAAC panel collapse rate approaches 1 in 0.5 million panels collapse in a given year, there is a 50.1% probability of observing zero people below the RAAC panel at the time of any collapses in a given year. There is a 27.4% of probability of observing one person below a panel at the time of collapse in a given year and a 22.4% probability of observing two or more people below RAAC panels at the time of collapses in a given year. To contextualise these results, these probabilities are associated with between 4 and 8 RAAC panel collapses occurring in a typical year.

If the number of RAAC panels is close to the median value estimated in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels (approximately 2.5 million RAAC panels) and the collapse rate is 1 in 2.5 million RAAC panels collapse in a given year (corresponding to an average of one RAAC panel collapse observed per year), it is estimated that there is 92.0% probability of zero people being below RAAC panels at the time of any collapses in a year, a 6.1% probability of observing a single person below a panel at the time of collapse, and a 1.4% probability of observing two people below RAAC panels at the time of collapse in a given year.

The interplay between number of RAAC panel collapses, the distribution of RAAC between sectors, and the total number of RAAC panels in England is complex. If the RAAC panel collapse rate is high but the total number of RAAC panels in England is low, such that there is a high likelihood that a significant proportion of RAAC panels are located in the NHS Best Buy hospitals, the model would predict an increase in the probability of five or more people being below RAAC panels at the time of collapses in a year. This is a result of the higher occupant density and occupied hours assumed for healthcare settings and the assumed failure rate being equal across all sectors. This result is an outlier within the data and fails to reflect the fact that the RAAC panels in the NHS Best Buy hospitals are regularly inspected, well maintained and, in many instances, have fail-safe measures installed, significantly reducing the likelihood of collapses occurring in these settings.

To aid with interpreting the results, the probability of one to three people being below RAAC panels at the time of collapses is plotted for each RAAC panel collapse rate in Figure 12. The results for zero people being below RAAC panels at the time of collapses is plotted separately in Figure 13. In these figures, the error bars are used to indicate the range in which 90% of all simulation results fall.

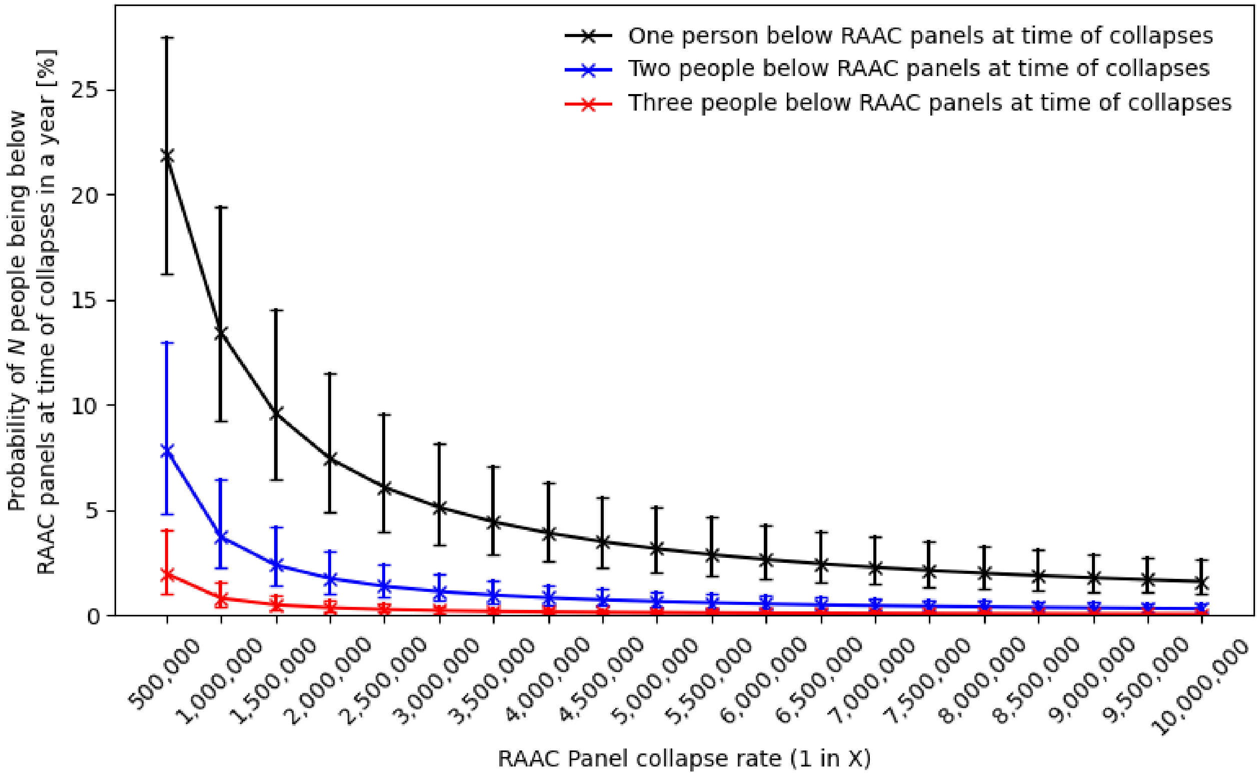


**Figure 12. Probability of varying numbers of people being below RAAC panels at the time of collapses in a given year.**

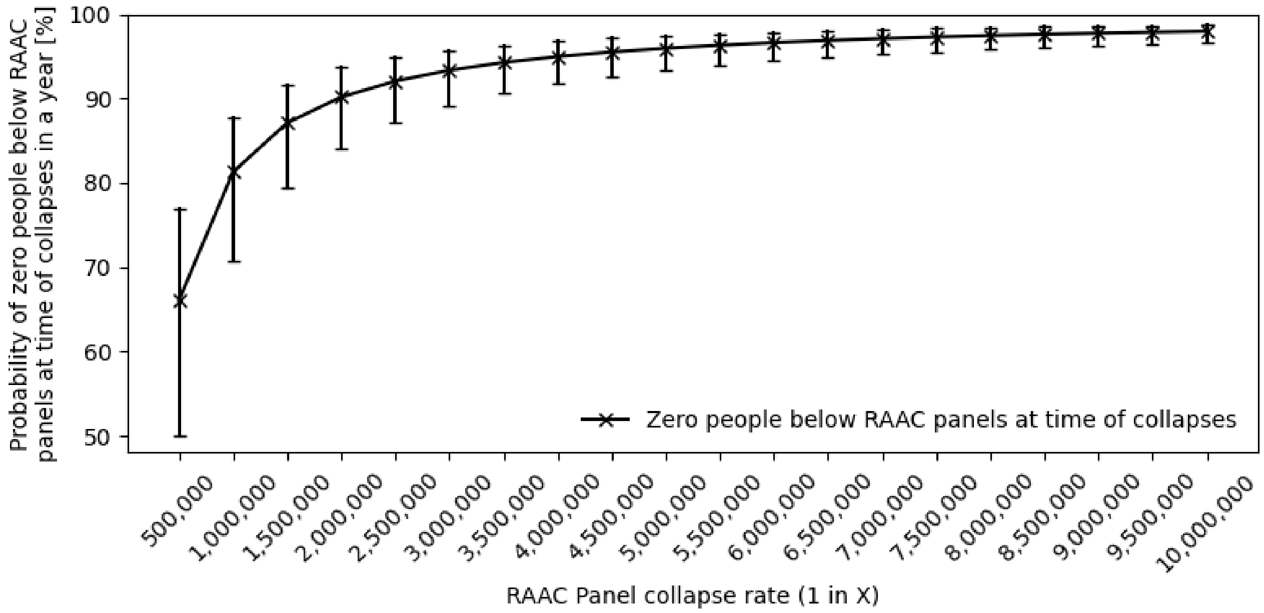


**Figure 13. Probability of zero people being below RAAC panels at the time of collapses in a given year.**

Note, the relationship between the probability of people being below RAAC panels at the time collapse occurs and the number of RAAC panel collapses expected to occur in a year is broadly linear. The results appear to be non-linear in Figure 12 and Figure 13, as the rate of RAAC panel collapse is expressed as a ratio (1 in *N* panels collapse in a given year). For comparison, the data presented in Figure 12 is reproduced in Figure 14 with the RAAC failure rate expressed as a percentage of RAAC panels that fail in a given year.

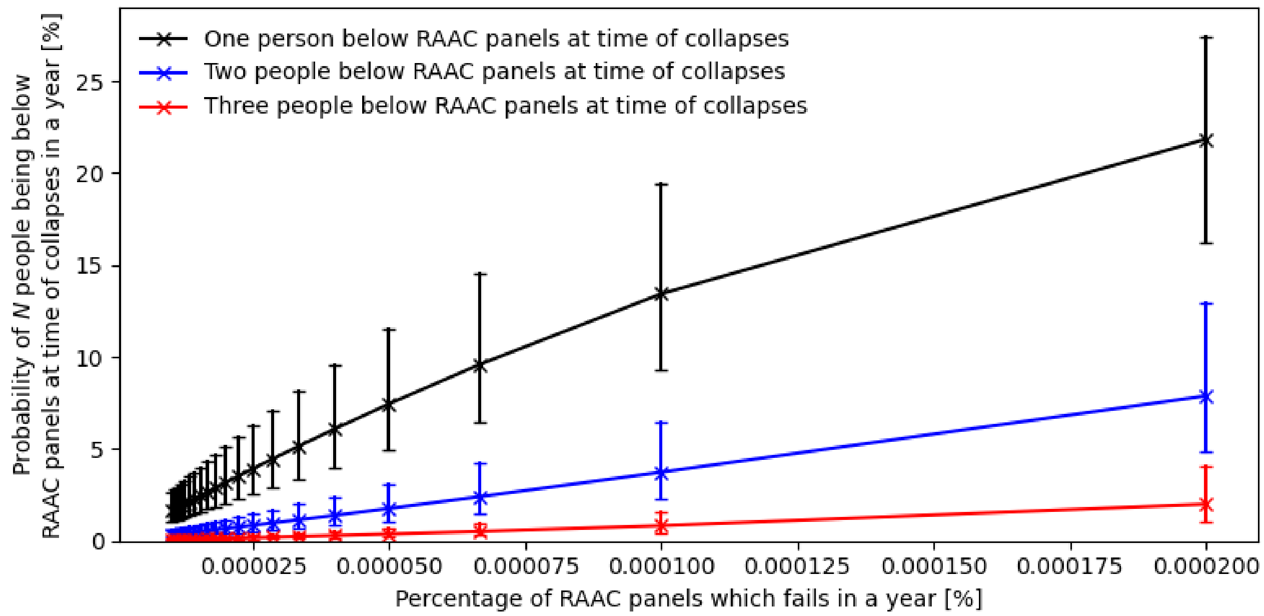


**Figure 14. Probability of varying numbers of people being below RAAC panels at the time of collapses in a given year plotted against percentage of RAAC panel stock failing in a year.**

The small amount of non-linearity that is observed within the results is a function of the interplay between the probability of RAAC panel collapse and the possibilities for people to be below those panels at the time of collapse. As the number of RAAC panel collapses which occur in a given year increase, there is an increased number of scenarios in which one or more people are below the RAAC panel at the time of a number of those collapses.

## 3.5 Probability of people being below RAAC panel at the time of collapse by sector

The median probabilities of people being below a single RAAC panel at the time of collapse as estimated from the one million simulations of RAAC panel numbers in England, are separated by sector in Figure 15.

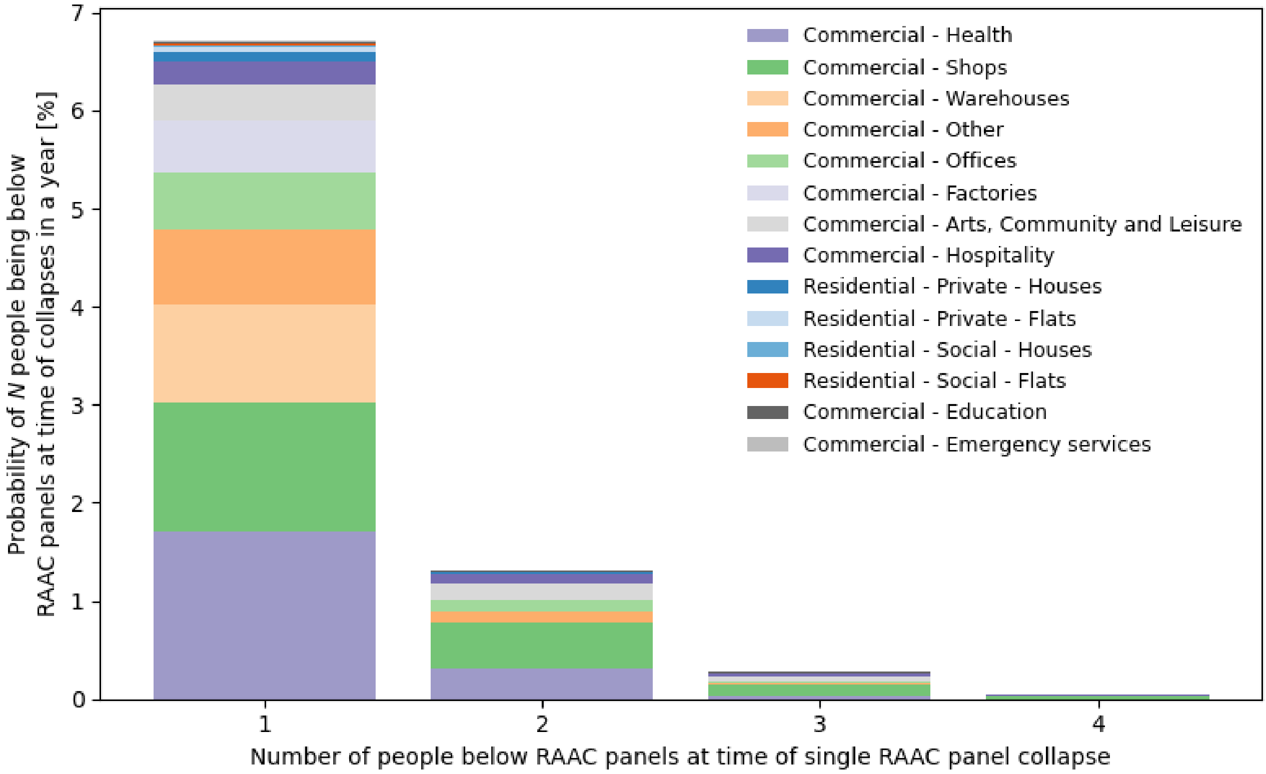


**Figure 15. Median probability of varying numbers of people being below a single RAAC panel at the time of collapse segmented by building sector.**

As would be expected, the breakdown of these probabilities closely mirrors the expected number of collapses by sector presented in Section A.

## 3.6 Changes in risk of people being below a RAAC panel at the time of collapses over time

Consideration of how the risks of people being below RAAC panels at the time of collapses may aggregate over time is complex, as there are a multitude of different factors which are likely to impact the results.

As with all construction materials, it is likely that the rate of RAAC panel collapse occurring will increase over time due to degradation of the materials. This increases the likelihood that a collapse occurs whilst someone is below the RAAC panel. However, the relative magnitude or rate of increase in the rate of collapse is currently unknown.

At the same time, it is likely that the number of RAAC panels present in England will reduce, due to renovation and demolition of RAAC containing buildings. The proposed replacement of the NHS Best Buy hospitals as part of the new hospital programme is likely to lead to a meaningful reduction in the probability of people being below RAAC panels at the time of collapses.

Another factor which must be considered is the impact that people being below a panel at the time of collapse would have on the public’s awareness of RAAC panels. If a RAAC panel collapsed whilst a person was below it, it is expected that there will be a large amount of public and professional scrutiny of the event, including press coverage. Such an event is likely to greatly reduce the public’s appetite for risk, expediting the mitigation, inspection and removal of RAAC panels. This would significantly reduce the probability that people are below RAAC panels at the time of collapses.

Given the factors above, it is believed the most effective way to quantify the risks posed by RAAC panels is to consider the cumulative probability of one or more people being below RAAC panels at the time of collapses over a range of time frames, as plotted in Figure 16. This figure does not account for the factors discussed above, or the mitigation of large numbers of RAAC panels which has already been undertaken to date.

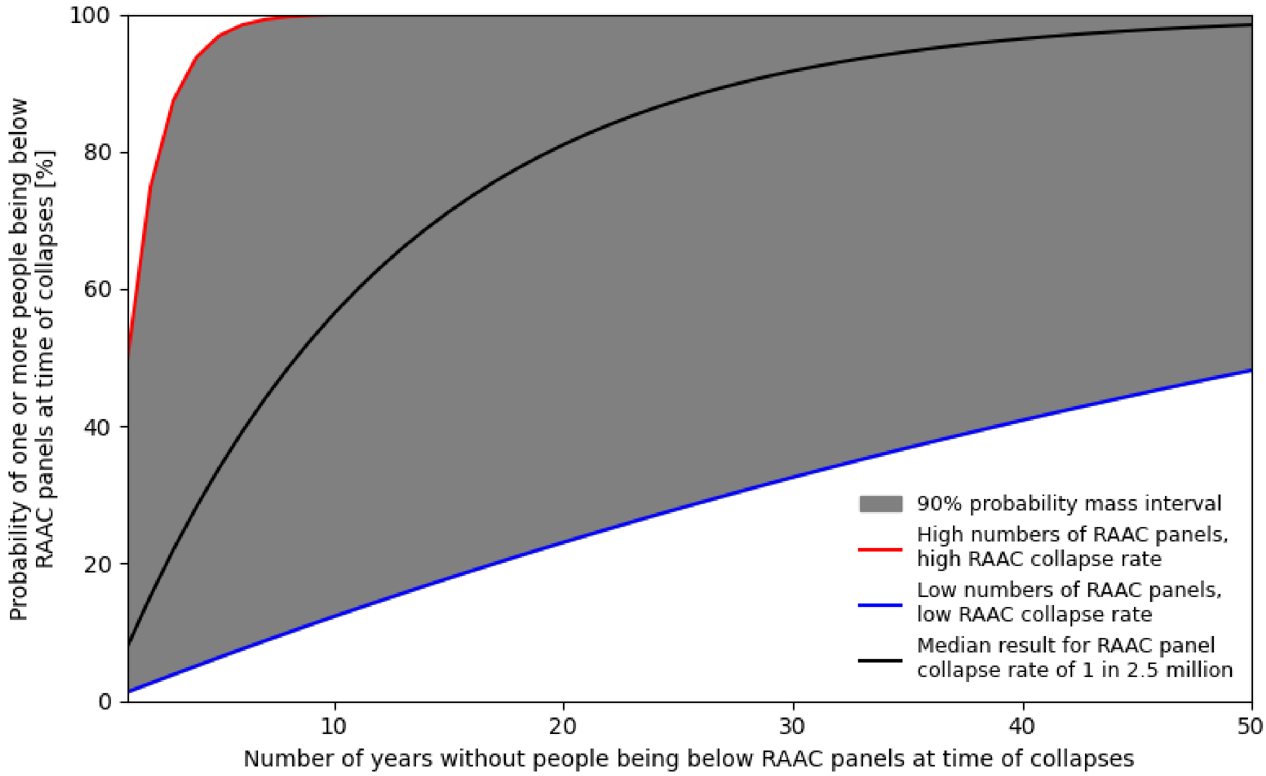


**Figure 16. Cumulative probability of zero people being below a RAAC panel at the time of collapse over time.**

As can be seen in Figure 16, due to the compounding effects of the cumulative probability, alongside the conservative assumptions regarding the probabilities of people being below RAAC panels in various sectors, there are extreme scenarios in which the risk of zero people being below RAAC panels at the time of collapses falls close to zero within ten years. This is an outlier result associated with an average of 8 RAAC panels collapsing per year.

If the collapse rate of RAAC panels is 1 in 2.5 million, equating to an average of one RAAC panel collapse per year, there is an approximately 50% probability of one or more people being below a RAAC panel at the time of collapse when viewed across a 10-year time frame, and an 80% probability of one or more people below RAAC panels at the time of collapses when viewed across a 20-year time frame.

The numbers presented above are highly sensitive to the analysis parameters chosen and are believed to offer a conservative estimate of the risks of people being below RAAC panels at the time of collapses associated with RAAC panel collapse over extended time frames. These numbers do not account for the extensive recent work already undertaken to mitigate the risks posed by RAAC panel collapse.

## 3.7 Implications of simultaneous RAAC panel collapse

Throughout this section, it has been assumed that RAAC panel collapses occur as independent, individual events and that the collapse of one RAAC panel has no impact on the likelihood of neighbouring RAAC panels collapsing.

WSP is aware of one instance of RAAC panel collapse where multiple panels collapsed simultaneously. This incident is documented in the Standing Committee on Structural Safety (SCOSS) Alert from May 2019 (Standing Committee on Structural Safety, 2019). In this incident, a small number of RAAC panels simultaneously collapsed. It is noted in the SCOSS alert that the roof had recently been resurfaced and that the failure occurred in hot weather, suggesting that it may have been induced by thermal effects induced by the membrane action from the new roof coating.

Factors which may induce simultaneous RAAC panel collapse, discussed individually in greater detail in Section C, include:

- Adverse loading across multiple RAAC panels.
- Ponding water.
- Panel collapse impacting adjacent panels.
- Fixings or fittings which act to tie multiple RAAC panels together.
- Movement of end-bearing supports.

If the simultaneous collapse of panels is viewed as a single collapse, the probabilities of RAAC panel collapse as presented in Section A do not change. However, as a larger area is impacted, the probability of one or more people being below the panels at the time of collapse does increase.

To quantify this increase, an analysis was run assuming that the area impacted by a panel collapse is 2.4m x 3.0m, twice that used in previous sections. This area is equivalent to the area directly below four standard width panels (0.6m), or three panels and a 300mm zone either side of the panels. These results are plotted in Figure 17.

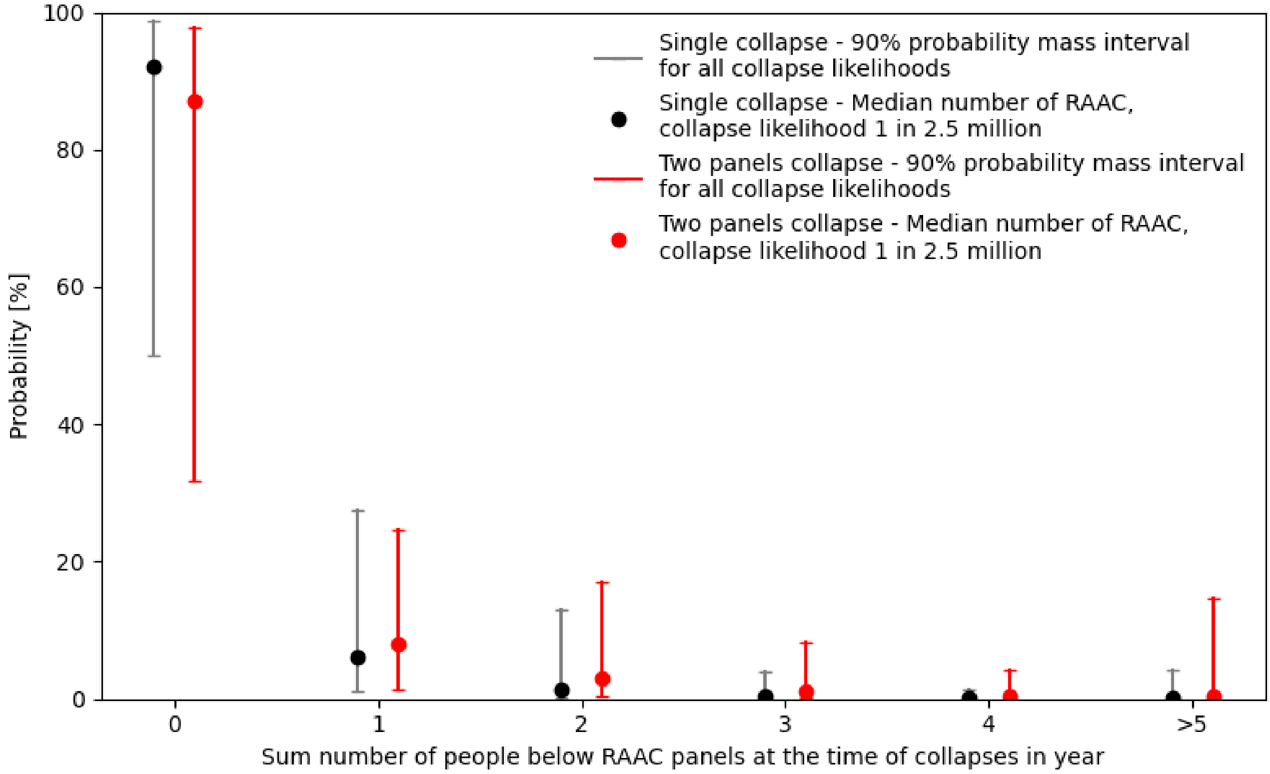


**Figure 17. Probability of varying numbers of people being below RAAC panels at the time of collapses in a given year for independent panel collapse, and simultaneous collapse of four panels.**

As shown in Figure 17, the relationship between the area impacted by RAAC panel collapse and the probability of one or more people being below the RAAC panels at the time of collapses is non-linear. A doubling of the area impacted by the collapse does not result in a doubling of probability that RAAC panel collapse causes one or more injuries. This is the result of a multitude of factors.

When the collapse rate is low, the probability of any collapse occurring is already low, hence the change in area affected having no impact. Where collapses do occur, they are primarily expected to occur in sectors where the number of panels is estimated to be higher, such as warehouses and factories. These building sectors are already sparsely populated, so the probability that anyone is below the panel is starting from a low benchmark. Hence, the increases in probability of people being below the RAAC panels at the time of collapses are small.

The exception to this is where the collapse rate is high and there is a large number of RAAC panels in England. As discussed previously, as the number of collapses which occur in a year increases, there is an increased probability that during one of these collapses, higher numbers of people are below the RAAC panel. This results in the increased probability of five or more people being below the RAAC panels at the time of collapses (higher end of 90% probability mass distribution). As previously discussed, this is an outlier result and corresponds to the scenario where 4 to 8 RAAC panel collapses are occurring every year.

## 3.8 Section B summary

Based on the data available and the modelling assumptions detailed within this report, a range of probabilities of people being below RAAC panels at the time of collapses in England have been calculated.

For the purposes of the initial assessment of the risk posed by RAAC and acknowledging the broad uncertainties surrounding the consequences of RAAC panel collapses, conservative assumptions have been made throughout this section, principally that anyone within 0.6m of the centreline of RAAC panels at the time of collapse is considered below the RAAC panel. Alongside this, the numbers used in the assumed percentage of time for which buildings are occupied, and the average occupant densities are believed to be higher than would be measured in targeted surveys of these building sectors.

Based on these broad assumptions, alongside the assumptions and limitations of earlier parts of this work, it is estimated that the probability of a single person being below RAAC panels at the time of collapses in a single year is between a 1.6% and 21.8%. It is estimated that the probability of two people being below RAAC panels at the time of collapses in a single year is approximately a third of this, between 0.3% and 7.9%.

The high level of uncertainty within the probability of people being below RAAC panels at the time of collapses derives from:

- Broad uncertainty in the estimates of the number of RAAC panels in England.
- Broad uncertainty in the likelihood or rate of RAAC panels collapsing.
- Conservative estimates of the probability that one or more people are below a RAAC panel at any given time.

Within these broad estimates, and on the balance of previous evidence on the occurrence rate of reported RAAC panel collapses, the probability of observing one person below a RAAC panel at the of collapse in a year is estimated to be on the lower side of the range given above, with an estimated probability of between 4.0%. and 9.5% (dependent on the number of RAAC panels in England). The probability of observing two or more people below RAAC panels at the time of collapses is estimated at between 1.1% and 3.4%.

No allowance has been made in these estimates for potential changes in the RAAC collapse rate, due to either continued structural degradation of the RAAC panels (due to the factors discussed in Section C), or due to targeted interventions or increased awareness (as discussed further in section D). However, the different RAAC panel collapse rates presented throughout this section provide a broad indication of how these changes may impact the likelihood of people being RAAC panels at the time of collapses.

Assuming the prevalence and collapse rate of RAAC is broadly similar across non-residential building sectors, the building sectors where people are most likely to be below RAAC panels at the time of collapses are shops (due to the higher numbers of shop built in the period of concern in England relative to other building sectors and a higher than average occupant density during occupied hours) and healthcare (due to the assumed 24-hour occupation rate and the relatively high proportion of RAAC panels located within Best Buy hospital if the number of RAAC panels in England is at the lower end of the range estimated in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels).

While it is estimated that the majority of RAAC panels may be located in warehouses and factories, these building sectors have relatively low occupant densities, greatly reducing the likelihood of people being below the RAAC panels at the time of collapses in these sectors.

The potential consequences of simultaneous collapse of RAAC panels has been discussed. As it is expected that the majority of RAAC panel collapses occur in sectors which are sparsely populated and the current probability of RAAC panel collapse has been deemed to be low, it has been shown that under most scenarios simultaneous RAAC panel collapse results in only small increases in the probabilities that one or more people are below RAAC panels at the time of any collapses in a year.

# 4 Section C – Causes and mechanisms of RAAC panel failure

This section provides a short introduction to failure mechanisms of RAAC panels, types of RAAC panel failure and risk factors which increase the likelihood of RAAC panel failure.

## 4.1 RAAC Panel failure mechanisms

Failure of RAAC panels can be divided into serviceability failures, such as superficial cracking or minor deflections, and ultimate limit state failures that result in collapse of the RAAC panel.

This report is primarily concerned with ultimate limit state failures resulting in collapse of the RAAC panel.

Despite this perceived uncertainty in when RAAC panel collapse may occur, the majority of failure mechanisms by which RAAC panel collapse occur exhibit common indications of failure including cracking, spalling and excessive deflection. However, end bearing failure, which is believed to be the primary cause of collapse, often occurs without apparent indications of impending failure.

## 4.2 Risk factors

There are a number of risk factors which impact the likelihood that RAAC panels may fail.

### 4.2.1 End bearing

The primary risk factor which is believed to impact the structural integrity of RAAC panels is the end bearing of the panels.

Between the 1950s and 1980s, the design of RAAC panels was in line with the recommendations of codes CP114: Reinforced Concrete in Buildings and CP116: Structural Use of Precast Concrete. In these codes, it was recommended that an end bearing length of 45mm was provided for roof panels and 60mm was provided for floor panels.

Investigations conducted by WSP have shown that the measured bearing length of RAAC panels may be less than these recommended values, likely due to construction tolerances.

The risk due to poor end bearing lengths arises from the construction of RAAC panels. In a RAAC panel, the longitudinal reinforcement is typically anchored in place by transverse reinforcement located within the end bearing length of the panel. If the bearing length of a RAAC panel is smaller than recommended, or if there was poor tolerance control during manufacture of the RAAC panel, this transverse reinforcement which secures the longitudinal reinforcement may be located outside of the width of the end bearing. During testing undertaken by the Building Research Establishment (BRE) and the University of Loughborough, it was shown that this can substantially reduce the load bearing capacity of the RAAC panels.

To reduce the risk of collapse due to poor end bearing conditions, the current Institution of Structural Engineers (IStructE) guidance (Liddell et al., 2022, Liddell et al., 2023) recommends that all RAAC panels should have a minimum end bearing length of 75mm. Where 75mm end bearing is not provided, it is deemed by the IStructE that there is a significant risk of RAAC panel collapse due to shear failure.

End bearing failure has been identified as the primary cause of the majority of RAAC panel failures that WSP is aware of and is believed to be the primary mechanism by which RAAC panel collapse is likely to occur.

Methods of identifying end bearing of RAAC panels are discussed in the IStructE guidance.

#### 4.2.2 Anchorage reinforcement

An alternative mechanism by which shear failure and subsequent collapse of RAAC panels may occur results from an absence of the transverse reinforcement which anchors the longitudinal reinforcement within the panel.

The mode of failure is currently being investigated by researchers at Loughborough University. The proportion of RAAC panels which are missing transverse end reinforcement is unknown. It is believed to be more likely to occur in RAAC panels manufactured in the 1950s and 1960s, when the standardisation of the panel manufacture process was less widespread and when quality controls may have been lower.

Where transverse anchorage reinforcement is absent, the mode of failure of the panel is similar to that which occurs due to insufficient end bearing and is characterised by shear failure of the end of the RAAC panel.

#### 4.2.3 Cut panels

A cut panel is where a RAAC panel is manufactured at a set length and subsequently cut to a shorter length due to project needs, or where a panel was trimmed to allow for service voids or site constraints as part of the original construction.

Historically, these cut panels were sometimes supported on hangers or narrow steel trimmers, which were affixed to adjacent RAAC panels. Due to the dimensions of these hangers/trimmers, RAAC panels supported in this fashion often have inadequate bearing lengths, substantially increasing the risk of end bearing failure occurring.

Alongside this, it is likely that the locations at which cuts were made along the length of the RAAC panel do not coincide with the locations of transverse reinforcement. Therefore, the longitudinal reinforcement within the RAAC panel is unanchored at the locations of the cut, resulting in an increased risk that shear failure of the RAAC panel occurs.

### 4.2.4 Cracking

Cracking is commonly observed in RAAC panels and may arise from a variety of sources including reinforcement corrosion, damage to the panel due to impact (either during construction or since), water ingress and excessive deflections.

In the IStructE guidance on managing RAAC, cracking of RAAC panels is subcategorised into:

- Major cracking or spalling: This is large and/or deep cracks which may be accompanied by spalling and/or exposed reinforcement.
- Minor cracking or spalling: This is small cracks which are limited to the face of the RAAC panel.

Major cracking or spalling of a RAAC panel may reduce the load bearing capacity of the panel and may act as a mechanism by which additional damage to the RAAC panel, due to water ingress or increased deflection, occurs.

Where cracking occurs within 500mm of the end of a RAAC panel, it may indicate shear cracking and an increased risk that collapse of the RAAC panel will occur.

### 4.2.5 Builder’s works/building modifications

Builder’s work are intentional changes to the RAAC panels which has occurred since the original construction. This may include the cutting of openings to allow service penetrations, or the installation of fixings for services or ceiling grids.

Builder’s work modifications are commonly encountered in RAAC panels due to the ease with which the RAAC panel may be cut. Sometime, trimming beams may be installed around the edge of larger voids. Where fixings have been installed into RAAC panels, it is common to observe multiple failed fixings in the proximity of the current fixing, indicating either the challenges of installing fixings securely into RAAC panels, or a historic pattern of fixture failings.

The major risk associated with builder’s work modifications of RAAC panels is the possibility that longitudinal and/or reinforcement has been cut or damaged. This will reduce the load bearing capacity of the RAAC panel and may provide an interface at which corrosion of the reinforcement may occur.

### 4.2.6 Water ingress

Due to their aerated structure, RAAC panels may become saturated with water, significantly increasing the weight of the RAAC panel itself. Alongside this, there is some evidence that water ingress may reduce the strength of the aerated cement matrix, as well as inducing unseen corrosion of the RAAC panel reinforcement.

Corrosion of RAAC panel reinforcement results in a loss of tensile and bending strength of the RAAC panel, alongside inducing spalling of the RAAC panel as the corroded reinforcement expands. As well as the risks posed by RAAC panel collapse, excessive spalling of the surface of the RAAC panel may result in falling debris.

Due to the aerated concrete mixture, it is possible for significant corrosion of RAAC panel reinforcement to occur before spalling on the surface of the RAAC panel is apparent.

Indicators of water ingress into RAAC panels include staining of the RAAC panel, mineral deposits on the surface of the water panel and mould.

### 4.2.7 Adverse loading of RAAC panels

Ponding water on RAAC panel roofs can significantly increase the load applied to the RAAC panel. This can be further exacerbated by vegetation growth. Similarly, drifting snow may lead to localised increases in the loading applied to RAAC panels.

Non-environmental causes of adverse RAAC panel loading include roofs being accessed or trespassed upon and the installation of new internal or external fixtures, finishes or plant equipment. With regards to the installation of new plant equipment, there is a risk that vibrations from the equipment may increase fatigue cracking of the panels.

A key period in which adverse loading of RAAC panels may occur is during modifications or demolition of a building. Where contractors are aware of the fragility of RAAC panels this can be mitigated through the methodology of the works to be undertaken. However, where the presence of RAAC is not apparent, or where contractors are unfamiliar with the risks surrounding RAAC panels, there is a significant risk that adverse loading or damage to the panels may occur.

### 4.2.8 Deflection

Excessive deflection of RAAC panels can be induced for all the reasons described above. RAAC panels which are exhibiting excessive deflections are at higher risk of failure due to the potential for ponding water to gather at the centre of deflected panels, increasing the loading on the panel, and potential changes in the load distribution and end-bearing restraint of the RAAC panel.

### 4.2.9 Lack of visibility

A cause of concern with RAAC panels is that when a RAAC panel is obscured from view by ceiling grids there can be few indications that RAAC panel collapse is going to occur.

## 4.3 Section C summary

This section has presented an overview of the primary mechanisms by which RAAC panel collapse is likely to occur, alongside risk factors which may increase the likelihood that RAAC panel collapse occurs.

As discussed in previous sections, there is insufficient data to quantify how these risk factors and failure mechanisms impact the likelihood of RAAC panel collapse. However, anecdotal evidence suggests that a lack of sufficient end bearing is a primary mechanism by which RAAC panel collapse occurs and is symptomatic of the majority of the RAAC panel collapses in England studied to date.

If further evidence for how the risk factors impact the likelihood of RAAC panel collapse were to become available, this could be incorporated into the analyses presented in Sections A and B of this report.

# 5 Section D – Mitigating the risks posed by RAAC panels

This section presents an overview of methods to reduce the risks posed by RAAC panels, how those measures impact the likelihood of collapse occurring, and how those measures impact the likelihood of people being below RAAC panels at the time of collapses.

Within this section, the following risk mitigation measures are discussed:

- RAAC awareness and training
- RAAC panel identification
- RAAC panel inspection
- Deflection monitoring
- Non-destructive testing
- Temporary propping
- End-bearing support of RAAC panels
- Grillage support of RAAC panels
- Restricting access to areas including RAAC panels
- RAAC panel removal.

The suitability of each method is highly dependent on the context in which it is applied and is not commented on in this section. The commentary presented in this section is specific to how the mitigation measure impacts the likelihood of RAAC panel collapse, or the likelihood that any RAAC panel collapse occurs whilst people are below the panel.

## 5.1 RAAC Awareness and training

A key step to reduce the risks posed by RAAC panels is increasing awareness of the risks they pose and improving our understanding of how they may be mitigated and reduced.

Recent publicity of the issues associated with RAAC panels has increased the general awareness of RAAC, including how it may be identified and the risks associated with it.

However, based on discussions between WSP and staff who maintain, manage and operate buildings, while there is a growing awareness of RAAC, there still appears to be a feeling of uncertainty among those staff that they could correctly identify RAAC. Alongside this, some media coverage may have had the negative effect of reinforcing false stereotypes about the use of RAAC, such as it only ever being used in flat roof construction. There is also a risk that the media coverage surrounding RAAC may have instilled a false sense of confidence in building operators that they are able to correctly identify whether RAAC is present.

A range of guidance and further training on RAAC identification and management is available including:

- *Reinforced Autoclaved Aerated Concrete (RAAC) panels: Investigation and assessment*, prepared by the Institution of Structural Engineers (IStructE, Liddell, 2022)
- *Reinforced Autoclaved Aerated Concrete (RAAC) Investigation and Assessment – Further Guidance*, prepared by the IStructE (Liddell, 2022)
- *Reinforced autoclaved aerated concrete: identification guidance*, prepared by the Department for Education (Department for Education 2023)
- *Identifying problematic RAAC planks*, prepared by the Royal Institute of Chartered Surveyors (RICS, 2023)
- *Reinforced Autoclaved Aerated Concrete (RAAC) – Guidance on Listed Buildings*, prepared by Purcell (Thomson et al., 2024).

As discussed in the previous section, RAAC panels should not be modified in any way and fixings should not be installed in RAAC panels, as this significantly increases the risk of collapse. A greater awareness of these risks would reduce the likelihood of RAAC panel collapses occurring.

## 5.2 RAAC panel identification

A key method for reducing the risk of RAAC panel collapse is identifying where RAAC panels are located. Cross-disciplinary work has already been undertaken across public, private and commercial estates to identify RAAC panels.

RAAC panel identification directly reduces the probability of panel collapse by helping to inform the maintenance regime for the building and reducing the likelihood that works to the building result in unintentional adverse loading of the panel. Beyond this, identification allows the risk to be quantified and further inspections, monitoring or mitigation to be implemented as necessary.

With regards to the values presented in Sections A and B of this report, a greater understanding of the distribution, condition and use of RAAC panels in England would greatly reduce the uncertainty within the estimated probabilities of RAAC panel collapse and the probability of people being below the RAAC panels at the time of collapses.

Guidance on identifying RAAC panels is provided in the documents listed in subsection 5.1.

### 5.2.1 Desk studies

Desk studies can be used in a limited way to identify whether a building does not include RAAC. However, as discussed in RR1212 - Reinforced Autoclaved Aerated Concrete (RAAC) in England: Assessment of number of RAAC panels, RAAC can be present in a broader range of buildings than might be expected given recent publicity of RAAC.

Buildings built in England after 2000 are deemed highly unlikely to contain RAAC. Whether a building was built after this date can often be confirmed through planning records and archive satellite images.

WSP is aware that some building owners and structural engineering/building surveying companies have been identifying buildings constructed in the 1990s as not containing RAAC based on desk studies alone. This is not advised. While buildings constructed in the 1990s are less likely to contain RAAC, some examples have been found in the UK. There is also the risk that buildings constructed in the 1980s, where RAAC was more broadly used, may be incorrectly recorded as constructed in the 1990s.

Another common misconception is that buildings constructed before 1950 will not contain RAAC. This is untrue. RAAC was used in a wide range of building renovations and was marketed for this purpose due to its low weight and the ease with which it could be modified with hand tools on site.

Other misconceptions surrounding RAAC include that it is only found in flat roof construction and was primarily used in public sector buildings. WSP has found extensive examples of RAAC being used in pitched roof construction, alongside in wall and floor construction, across a broad array of building sectors.

For buildings built prior to 2000, visual site inspections are recommended to determine if RAAC is present. It should be noted that RAAC is often obscured by fixed or sealed finishes and intrusive investigations may be required to expose structural elements in order to determine that RAAC is not present. Alongside this, it is common for the form of construction to vary across a building, reflecting modifications to the building over time or varying material availability at the time of construction.

## 5.3 RAAC panel inspection

As discussed in the previous section, RAAC panels often exhibit signs of distress prior to collapse. Visual RAAC panel inspection can allow these signs of distress to be identified and further steps taken to reduce the risk that the RAAC panel collapses whilst people are below it.

Alongside visual inspection, measurements of the end bearing can be taken and used to inform the assessment of risk posed by individual RAAC panels.

The frequency with which inspections should occur needs to be informed by:

- The risks associated with accessing and inspecting RAAC panels (such as working at height).
- Any disruption to safety critical activities which may result from accessing the RAAC panels.
- The condition of the RAAC panel.
- The likelihood that a RAAC panel collapse will occur whilst people are below it.

For example, it would seem prudent to inspect RAAC panels in buildings which have high occupant densities and/or occupancy rates, such as hospitals, more frequently than areas which are rarely accessed, such as electrical substations. Similarly, buildings which house critical infrastructure may require more frequent inspections due to the potential wider consequences and impact any RAAC panel collapse may have.

Where possible, removing ceiling grids or fixed finishes below RAAC panels can allow formal inspections to be carried out with minimal disruption, as well as allowing informal inspection of the RAAC panels by building users, who may identify that visually identifiable deterioration of the panels has occurred. However, for RAAC roof panels in poor condition, it has been noted that fixed finishes or ceiling grids may reduce the risk of harm occurring, as debris from spalling is caught by the finishes or ceiling grid below.

Regular inspection of RAAC panels is considered an effective method of reducing both the likelihood of RAAC panel collapse, as mitigation measures can be implemented prior to collapse, and the likelihood of collapse occurring whilst people are below the panels, as an exclusion area can be established below the RAAC panels in poor condition.

Guidance on inspecting RAAC panels, alongside methodologies for assessing the risks of individual RAAC panels, is provided in the IStructE guidance referenced in subsection 5.1.

## 5.4 Deflection monitoring

Measuring the mid-span deflection of RAAC panels can be used to inform the assessment of risk posed by individual RAAC panels, alongside providing a metric for monitoring the condition of RAAC panels over time. There are a range of technologies for collecting and processing deflection measurements.

Deflection measurements can allow RAAC panels which are deteriorating to be identified and may allow the identification of deterioration which cannot normally be seen. As with the RAAC panel inspections discussed above, regularly collecting deflection measurements from RAAC panels can be an effective method of reducing the likelihood of RAAC panel collapse and the likelihood of any collapse occurring whilst people are below the panel.

The frequency in which deflection measurements are collected needs to be informed by the risks associated with accessing and inspecting RAAC panels (such as working at height), any disruption to safety critical activities which may result from accessing the

RAAC panels, the condition of the RAAC panel, and the likelihood that a RAAC panel collapse will occur whilst people are below the RAAC panel.

Guidance on deflection monitoring of RAAC panels is provided in the IStructE guidance referenced in Section 5.1.

## 5.5 Non-destructive testing

Non-destructive testing (NDT) can allow the deterioration of RAAC panels to be detected and quantified. However, at present, there are limited examples of its application in the large-scale management and monitoring of RAAC panels. As such, the impact of NDT on the likelihood of RAAC panel collapse cannot be quantified at present.

## 5.6 Temporary propping

Temporary propping reduces the likelihood of RAAC panel collapse by providing alternative load paths and methods of support to the panel. Careful consideration must be given to avoiding punching shear of the RAAC panel induced by the head of the prop, where RAAC panels are present above, and the foot of the prop, where RAAC panels are present below. Temporary props are likely to induce significant levels of disruption and are not intended as a long-term remedial measure.

In the short term, where a RAAC panel is at imminent risk of collapse, carefully considered temporary propping will significantly reduce the likelihood of that panel collapsing and potentially impacting people below the RAAC panel at the time of the collapse.

## 5.7 End-bearing support of RAAC panels

Additional end-bearing support of RAAC panels in the form of timber or steel beams or angles installed at the end of RAAC panels, as shown in Figure 18, provides an effective means of reducing the probability of RAAC panel collapse occurring.

As discussed in the previous section, end bearing failure is believed to be the primary mechanism which induces RAAC panel collapse. Installing end-bearing support would result in a significant reduction in the probability that RAAC panel collapse occurs. However, end-bearing support does not prevent all types of RAAC panel collapse from occurring, as it is still possible for failure to occur elsewhere along the length of the RAAC panel.

The need for end-bearing support needs to be assessed against the current end-bearing provided for the RAAC panel, the risk/consequences of RAAC panel collapse in the vicinity of the panel, and the risks associated with the works needed to install the additional end bearing support.

*End bearing support*

*Full grillage support*

**Figure 18. End bearing support and full grillage support of RAAC panels**

Further commentary on end-bearing support of RAAC panels is provided in the IStructE guidance referenced in Section 5.1.

## 5.8 Grillage support of RAAC panels

To further reduce the risk of RAAC panel collapse, a steel or timber grillage can be installed below the RAAC panel, as shown in Figure 18. This provides alternative load paths and acts to support the RAAC panel, should collapse occur.

This grillage can act as a full support, where the load from the RAAC panels is distributed to the grillage, or as a failsafe, where the grillage acts to support the RAAC panels, if collapse should occur.

Grillage supports will significantly reduce the risk of RAAC panel collapse and the risk of people below the panel being impacted by any collapse. Unlike providing additional end-bearing, grillages support the full length of a RAAC panel and will reduce the likelihood of any RAAC failure mechanism from occurring. However, as the majority of RAAC panel collapses known to WSP have been related to end bearing failure, the additional reduction in the likelihood of RAAC panel collapse where a full grillage is provided is likely to be limited.

Further commentary on grillage support of RAAC panels is provided in the IStructE guidance referenced in subsection 5.1.

## 5.9 Restricting access to areas including RAAC panels

As has been widely publicised, one method of managing the risks from RAAC panels is to restrict access to areas containing RAAC panels.

Restricting access is likely to lead to only an incidental reduction in the likelihood of RAAC panel collapse. However, it will significantly reduce the likelihood that someone is below the RAAC panels if a collapse were to occur.

Consideration should also be given to the potential for RAAC panel collapse to cause damage or the collapse of floors located below the RAAC panels. This is an elevated risk where RAAC panels are present as intermediary floors within a single building.

The need to restrict access to areas including RAAC panels must be informed by a balanced assessment of the risks posed by the RAAC panels in those areas and is not considered a viable or suitable long-term approach to managing the risks posed by RAAC panels.

### 5.9.1 Restricting rooftop access

Where RAAC roof panels are identified it is strongly recommended that access to the roof above those panels is strictly managed. The load bearing capacity of RAAC panels is typically lower than other commonly encountered forms of roof construction. This issue can be exacerbated for RAAC panels due to the risk of further weakening of the panels due to the factors discussed in Section C.

The likelihood of RAAC collapse occurring due to adverse loading can be reduced by clearly indicating that RAAC is present in the roof structure, indicating the additional risks posed by the RAAC panels, carrying out RAAC specific risk assessments for works on the roof and controlling access to the roof. However, this reduction in likelihood may be partially offset by reduced maintenance of the roof and there is a possibility that it may increase the risk of ponding water and vegetation forming on the rood.

## 5.10 RAAC panel removal

Removing RAAC panels will lead to a short-term increase in the likelihood of RAAC panel collapse and collapse occurring whilst people are below the panel while works are undertaken. However, in the long-term, the removal of RAAC panels reduces the risk of RAAC panel collapse to zero.

## 5.11 Section D summary

This section has presented an overview of strategies for managing, monitoring and mitigating the risks posed by RAAC panels.

As a baseline, the most effective method of reducing the likelihood of RAAC panel collapse and people being below the RAAC panel at the time of collapse is the identification of RAAC. If RAAC remains unknown there is an enhanced risk that deterioration may be occurring, that adverse loading may be applied to the RAAC, or that deterioration to the RAAC indicating imminent collapse may go unidentified. With regards to the analysis presented in Sections A and B, whilst the identification of RAAC will not directly reduce the likelihood of collapse occurring, a catalogued record of RAAC use across the building stock will reduce some of the uncertainty in the values estimated.

Some of the dangers surrounding the use of desk studies and media coverage have been highlighted.

A hierarchy of methods for reducing the likelihood of RAAC panel collapse is presented below:

1. RAAC panel removal
2. Grillage support
3. End bearing support
4. Temporary propping
5. Visual RAAC panel inspection combined with deflection monitoring
6. Visual RAAC panel inspection
7. RAAC awareness and training

Non-destructive testing has been excluded from the above list as its current efficacy is unknown. Restricting access to areas below RAAC panels has also been excluded as it does not meaningfully reduce the likelihood of RAAC panel collapse from occurring.

A hierarchy of methods for reducing the likelihood of people being below the RAAC panel and impacted by any collapse is presented below:

1. RAAC panel removal
2. Restricting access to areas below RAAC panels
3. Grillage support
4. End bearing support
5. Temporary propping
6. Visual RAAC panel inspection combined with deflection monitoring
7. Visual RAAC panel inspection
8. RAAC awareness and training

The lists provided above are generalised across all occupied buildings in England. The individual ranking of methods for reducing the likelihood of collapse or people being below the RAAC panel at the time of collapse will be highly sector and building specific and will need to account for factors such as the frequency with which the area containing RAAC is accessed, the condition of the RAAC panels, the risk factors presented in Section C, how the building is used, and the disruption which each monitoring or mitigation measure would cause, among others.

# 6 Conclusions

This report has presented an analysis and commentary on the risks posed by RAAC panels in England. The results presented are intended to help guide and inform the wider strategy for managing RAAC panels in England, as well as dispel some commonly held misbeliefs regarding RAAC panels.

In **Section A** of this report, the average number of RAAC panel collapses and the probability of RAAC panel collapse occurring has been calculated for a range of RAAC panel collapse rates as the exact figure is not known. Current evidence would suggest that the number of RAAC collapses occurring each year is low.

If the RAAC panel collapse rate is 1 in 10 million per year, the lowest RAAC failure rate considered plausible given historic patterns of RAAC panel collapses, there is between an 11.8% and a 28.4% probability of observing a RAAC panel collapse in a given year. The probability of observing two or more RAAC panel collapses in a single year for the same RAAC panel collapse rate is between 0.8% and 6.3%.

If the collapse rate of RAAC panels is 1 in 2.5 million there is approximately equal probabilities that zero RAAC panels collapse in a given year (median result 37.7%) or one RAAC panel collapse occurs in a given year (median result 35.6%). The median probability of observing two RAAC panel collapses in a year is 17.9%, the median probability of observing three RAAC panel collapses is 5.8% and the median probability of observing four or more RAAC panel collapses of approximately 1.8%.

If the collapse rate of RAAC panels is 1 in 0.5 million there are equal probabilities of observing fewer than four RAAC panel failures in a year and observing four or more RAAC panel failures in a year. There is a meaningful probability that nine or more RAAC panel collapses may occur in a year.

A RAAC panel collapse rate of 1 in 2.5 million results in a median prediction that there is an average of 0.97 RAAC panel collapse per year, approximately equal to the currently observed rate of an average of one RAAC panel collapsing per year. This is as expected given that the median estimate is that there are approximately 2.5 million RAAC panels in England.

On the assumption that the RAAC panel collapse rate is broadly equal across all building sectors, it is likely that the majority of RAAC panel collapses will occur in commercial settings, specifically warehouses and factories.

In **Section B** of this report, the probabilities of people being below RAAC panels in England at the time of collapse have been estimated.

For the purposes of this initial assessment of the risk posed by RAAC and acknowledging the broad uncertainties surrounding the consequences of RAAC panel collapses, conservative assumptions regarding occupant densities and the area impacted by RAAC panel collapse have been made.

Based on these broad assumptions, alongside the assumptions and limitations of earlier parts of this work, it is estimated that the probability of a single person being below a RAAC panel at the time of collapse in a single year is between 1.6% and 21.8%. It is estimated that the probability of two people being below RAAC panels at the time of collapses in a single year is approximately a third of this, between 0.3% and 7.9%.

Within these broad estimates, and on the balance of previous evidence on the occurrence rate of reported RAAC panel collapses, the probability of observing one person being below a RAAC panel at the time of collapse in a year is estimated to be on the lower side of the range given above, with an estimated probability of between 4.0%. and 9.5% (dependent on the number of RAAC panels in England).

No allowance has been made in these estimates for potential changes in the RAAC collapse rate, due to either continued structural degradation of the RAAC panels or due to targeted interventions or increased awareness. A discussion of the cumulative probability of one or more people being below RAAC panels at the time of collapses over a range of time frames has been presented, and the challenges of quantifying the long-term risks from RAAC discussed.

Assuming the prevalence and collapse rate of RAAC panels is broadly similar across non-residential building sectors, the building sectors where people are most likely to be below RAAC panels when collapse occurs are shops and healthcare. People being below RAAC panels at the time of collapses is more likely to occur in shops due to the higher numbers of shops built in the period of concern in England relative to other building sectors and a higher than average occupant density during occupied hours. In healthcare buildings the higher likelihood of people being below RAAC panels at the time of collapses is due to the assumed 24-hour occupation rate and the relatively high proportion of RAAC panels located within Best Buy Hospitals if the number of RAAC panels in England is low.

While it is estimated that a majority of RAAC panels may be located in warehouses and factories, these building sectors have relatively low occupant densities, greatly reducing the likelihood of people being below RAAC panels at the time of collapses in these sectors.

The potential consequences of simultaneous collapse of RAAC panels have been discussed. As it is expected that the majority of RAAC panel collapses occur in sectors which are sparsely populated, and the current probability of RAAC panel collapse has been deemed to be low, it has been shown that under most scenarios simultaneous RAAC panel collapse results in only small increases in the probabilities that one or more people are below RAAC panels at the time of collapses in a year.

Causes and mechanisms of RAAC panel collapse were presented in **Section C**. Anecdotal evidence suggests that a lack of sufficient end bearing is a primary mechanism by which RAAC panel collapse occurs and is symptomatic of the majority of the RAAC panel collapses in England studied to date.

**Section D** presented an overview of strategies for managing, monitoring and mitigating the risks posed by RAAC panels.

As a baseline, the most effective method of reducing the likelihood of RAAC panel collapse and the likelihood that people are below the RAAC panels at the time of collapses is the identification of RAAC. If RAAC remains unknown there is an increased risk that deterioration may be occurring, that adverse loading may be applied to the RAAC, or that deterioration to the RAAC indicating imminent collapse may go unidentified.

# 7 References


ASHRAE (2021*). Standard 62.1-2019*. Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

BSO (2023). *Office Occupancy: Density and Utilisation.* London, UK. British Council for Offices.

Building Research Establishment (2013), *Housing in the UK National comparisons in typology, condition and cost of poor housing.* London, UK. Available at: https://www.brebookshop.com/samples/327290.pdf

Department for Education (2021), *Review of time in school and 16 to 19 settings.* London, UK. Available at: https://www.gov.uk/government/publications/review-of-time-in-school-and-16-to-19-settings

Department for Education (2023), *Reinforced autoclaved aerated concrete: identification guidance.* London, UK. Available at: https://www.gov.uk/government/publications/reinforced-autoclaved-aerated-concrete-estates-guidance

House of Commons Library (2022), *Shop opening hours and Sunday trading.* London, UK. Available at: https://researchbriefings.files.parliament.uk/documents/SN05522/SN05522.pdf

House of Commons Library (2023), *The School Day and Year.* London, UK. Available at: https://commonslibrary.parliament.uk/research-briefings/sn07148/

Office for National Statistics (2023), UK Workforce Jobs SA : C Manufacturing (thousands). London, UK. Available at: https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/timeseries/jwr7/lms

Liddell, Martin, Read, Rob, Palmer, Matthew, Robertson, David and Goodier, Chris (2022) *Reinforced Autoclaved Aerated Concrete (RAAC) investigation and assessment–further guidance*. London, UK. Institution of Structural Engineers.

Liddell, Martin, Palmer, Matthew, Rolf, Andrew, Atkins, Chris, Brown, Robin and Goodier, Chris (2023). *Reinforced Autoclaved Aerated Concrete (RAAC) investigation and assessment–further guidance*. London, UK. Institution of Structural Engineers.

Lush, David, Butcher, Kutcher, and Appleby, Paul (2013). *Environmental design: CIBSE guide A*. 8$^{th}$ Edition. Chartered Institute of Building Services Engineers, London, UK.

Ministry of Housing, Communities & Local Government (2018), *English Housing Survey 2017 to 2018: headline report*. London, UK. Available at: https://www.gov.uk/government/statistics/english-housing-survey-2017-to-2018-headline-report

Office for National Statistics (2022), *The night-time economy, UK: 2022.* London, UK. Available at: https://www.ons.gov.uk/businessindustryandtrade/business/activitysizeandlocation/articles/thenighttimeeconomyuk/2022

RICS (2023) *Identifying problematic RAAC planks.* London, UK. Royal Institute of Chartered Surveyors

Standing Committee on Structural Safety (2019), *SCOSS Alert – May 2019: Failure of reinforced autoclaved aerated concrete (RAAC) planks*. London, UK. Available at: https://www.cross-safety.org/uk/safety-information/cross-safety-alert/failure-reinforced-autoclaved-aerated-concrete-raac-planks

Thomson, Max, Baldwin, Alexandra, Mark, Louise, Wright, Jon, Waterman, Chris, and Tappin, Stuart (2024) *Reinforced Autoclaved Aerated Concrete (RAAC) – Guidance on Listed Buildings*. London, UK. Purcell.

# 8 Appendix A - Collapse scenarios calculation methodology

This appendix details the equations used in calculating the probability of different numbers of people being below RAAC panels at the time of collapses in a given year. These probabilities are calculated for *collapse scenarios*, defined here as the sum number of people who are below RAAC panel at the time of collapse in a given year.

The calculations presented here are based on integer partitions, differing ways of writing a value as a sum of positive integers.

## 8.1 Terminology and notation

With reference to collapses $P(n\ collapses)$ is used to notate the probability of *n* collapses occurring in a year. The value of *n* is taken as a discreet value between 0 and 20, denoted by *N*.

With reference to sectors, $P(sector)$ is used to notate the probability of the collapse occurring in a given building sector. The probability of *k* people being present in the sector at any given time is notated as $P(k\ people\ in\ sector)$.

## 8.2 Zero people below panel at time of collapses

There are two scenarios under which zero people are below RAAC panels at the time of collapses in a year:

- Scenario 1: Zero collapses occur in a year.
- Scenario 2: $n$ collapses occur in a year, all of which occur when zero people are below the panel.

Therefore, the probability of zero people being below RAAC panels at the time of collapses in a year is:

$$P(zero\ people\ below\ collapses) = P(Zero\ collapse) + \sum_{n>0}^{N}\left(P(n\ collapses)\left(\sum_{sectors} P(sector)P(zero\ people\ in\ sector)\right)^{n}\right)$$

## 8.3 One person below panel at time of collapses

There is one scenario under which one person is below RAAC panels at the time of collapses in a year:

- Scenario 1: $n$ collapses occur in a year, with a minimum of one collapse occurring, one of which occurs when a single person is below the panel and the rest of which occur when zero people are below the panel.

Therefore, the probability of one person being below RAAC panels at the time of collapses in a year is:

$$P(one\ person\ below\ collapses) = \sum_{n>0}^{N} \left( P(n\ collapses)\, n \left( \sum_{sectors} P(sector) P(zero\ people\ in\ sector) \right)^{n-1} \left( \sum_{sectors} P(sector) P(one\ person\ in\ sector) \right) \right)$$

## 8.4 Two people below panel at time of collapses

There are two scenarios under which two people are below RAAC panels at the time of collapses in a year:

- Scenario 1: $n$ collapses occur in a year, with a minimum of one collapse occurring, one of which occurs when two people are below the panel and the rest of which occur when zero people are below the panel.
- Scenario 2: $n$ collapses occur in a year, with a minimum of two collapses occurring, two of which occur when one person is below each panel and the rest of which occur when zero people are below the panel.

Therefore, the probability of two people being below RAAC panels at the time of collapses in a year is:

$$\begin{aligned} P(two\ people\ below\ collapses) &= \sum_{n>0}^{N} \left( P(n\ collapses) n \left( \sum_{sectors} P(sector) P(zero\ people\ in\ sector) \right)^{n-1} \right. \\ &\quad \left. \times \left( \sum_{sectors} P(sector) P(two\ people\ in\ sector) \right) \right) \\ &\quad + \sum_{n>1}^{N} \left( P(n\ collapses) \frac{n!}{2!\,(n-2)!} \left( \sum_{sectors} P(sector) P(zero\ people\ in\ sector) \right)^{n-2} \right. \\ &\quad \left. \times \left( \sum_{sectors} P(sector) P(one\ person\ in\ sector) \right)^{2} \right) \end{aligned}$$

## 8.5 Three people below panel at time of collapses

There are three scenarios under which three people are below RAAC panels at the time of collapses in a year:

- Scenario 1: $n$ collapses occur in a year, with a minimum of one collapse occurring, one of which occurs when three people are below the panel, and the rest of which occur when zero people are below the panel.
- Scenario 2: $n$ collapses occur in a year, with a minimum of two collapses occurring, one of which occurs when one person is below a panel and one when two people are below a panel. The rest occur when zero people are below the panel.
- Scenario 3: $n$ collapses occur in a year, with a minimum of three collapses occurring, each of which occurs when one person is below the panels. The rest occur when zero people are below the panel.

Therefore, the probability of three people being below RAAC panels at the time of collapses in a year is:

$$
\begin{aligned}
&P(\mathit{three\ people\ below\ collapses}) \\
&= \sum_{n>0}^{N}\left(P(n\ \mathit{collapses})n\left(\sum_{\mathit{sectors}} P(\mathit{sector})P(\mathit{zero\ people\ in\ sector})\right)^{n-1}\right. \\
&\times \left.\left(\sum_{\mathit{sectors}} P(\mathit{sector})P(\mathit{three\ people\ in\ sector})\right)\right) \\
&+ \sum_{n>2}^{N}\left(P(n\ \mathit{collapses})\frac{n!}{3!\,(n-3)!}\left(\sum_{\mathit{sectors}} P(\mathit{sector})P(\mathit{zero\ people\ in\ sector})\right)^{n-3}\right. \\
&\times \left.\left(\sum_{\mathit{sectors}} P(\mathit{sector})P(\mathit{one\ person\ in\ sector})\right)^{3}\right) \\
&+ \sum_{n>1}^{N}\left(P(n\ \mathit{collapses})\frac{n!}{2!\,(n-2)!}\left(\sum_{\mathit{sectors}} P(\mathit{sector})P(\mathit{zero\ people\ in\ sector})\right)^{n-2}\right. \\
&\times \left.\sum_{\mathit{sectors}} P(\mathit{sector})P(\mathit{one\ person\ in\ sector}) \sum_{\mathit{sectors}} P(\mathit{sector})P(\mathit{two\ people\ in\ sector})\right)
\end{aligned}
$$

## 8.6 Four people below panel at time of collapses

There are five scenarios under which four people are below RAAC panels at the time of collapses in a year:

- Scenario 1: $n$ collapses occur in a year, with a minimum of one collapse occurring, one of which occurs when four people are below the panel, and the rest of which occur when zero people are below the panel.
- Scenario 2: $n$ collapses occur in a year, with a minimum of two collapses occurring, one of which occurs when one person is below a panel and one when three people are below a panel, and the rest of which occur when zero people are below the panel.

- Scenario 3: $n$ collapses occur in a year, with a minimum of two collapses occurring, two of which occur when two people are below each panel, and the rest of which occur when zero people are below the panel.
- Scenario 4: $n$ collapses occur in a year, with a minimum of three collapses occurring, one of which occur when two people are below a panel and two of which occur when one person is under each other panel. The rest occur when zero people are below the panel.
- Scenario 5: $n$ collapses occur in a year, with a minimum of four collapses, four of which occur when one person is below each panel, and the rest of which occur when zero people are below the panel.

Therefore, the probability of four people being below RAAC panels at the time of collapses in a year is:

$$
\begin{aligned}
&P(four\ people\ below\ collapses)\\
&= \sum_{n>1}^{N}\left(P(n\ collapses)n\left(\sum_{sectors} P(sector)P(zero\ people\ in\ sector)\right)^{n-1}\left(\sum_{sectors} P(sector)P(four\ people\ in\ sector)\right)\right)\\
&+ \sum_{n>1}^{N}\left(P(n\ collapses)\frac{n!}{2!\,(n-2)!}\left(\sum_{sectors} P(sector)P(zero\ people\ in\ sector)\right)^{n-2} \times \left(\sum_{sectors} P(sector)P(two\ people\ in\ sector)\right)^{2}\right)\\
&+ \sum_{n>1}^{N}\left(P(n\ collapses)\frac{n!}{2!\,(n-2)!}\left(\sum_{sectors} P(sector)P(zero\ people\ in\ sector)\right)^{n-2} \times \sum_{sectors} P(sector)P(one\ person\ in\ sector)\right.\\
&\left.\times \sum_{sectors} P(sector)P(three\ people\ in\ sector)\right)\\
&+ \sum_{n>2}^{N}\left(P(n\ collapses)\frac{n(n-1)(n-2)}{3!}\left(\sum_{sectors} P(sector)P(zero\ people\ in\ sector)\right)^{n-2}\left(\sum_{sectors} P(sector)P(one\ person\ in\ sector)\right)^{2}\right.\\
&\left.\times \sum_{sectors} P(sector)P(two\ people\ in\ sector)\right)\\
&+ \sum_{n>3}^{N}\left(P(n\ collapses)\frac{n!}{4!\,(n-4)!}\left(\sum_{sectors} P(sector)P(zero\ people\ in\ sector)\right)^{n-4}\left(\sum_{sectors} P(sector)P(one\ person\ in\ sector)\right)^{4}\right)
\end{aligned}
$$

## 8.7 Five or more people below panel at time of collapses

The probability of five or more people being below RAAC panels at the time of collapses in a year is:

$$P(Five\ or\ more\ people\ below\ collapses) = 1 - \sum_{j}^{4} P(j\ people\ below\ collapses)$$

Reinforced autoclaved aerated concrete (RAAC) is a form of construction used in England between the 1950s and 1990s. RAAC panels were used for walls, floor and r oofs. RAAC was used across a range of different residential, commercial and government buildings. Recent years have seen a small number of RAAC panel failures. In HSE report RR1212, estimates are provided for the number of RAAC panels present in England.

This report uses estimates of the number of RAAC panels in England in combination with different collapse rates to estimate the probability of any collapses occurring whilst a person is below panels. As the precise number of RAAC panel collapses which happen each year is not known, it is known to be small, a range of different RAAC panel collapse rates are analysed.

As discussed in this report, there are a range of different risk factors which increase the likelihood of RAAC panel collapse, and a range of different monitoring and mitigation measures which can be used to reduce the likelihood that a RAAC panel collapses. As a baseline, the identification of RAAC is the most effective method of reducing the likelihood of RAAC panel collapse occurring with people under the panels. If RAAC remains unknown there is an increased risk that deterioration may be occurring, that adverse loading may be applied to the RAAC, or that deterioration to the RAAC indicating imminent collapse may go unidentified.

DOI: https://doi.org/10.69730/hse.25rr1213

Published by the Health and Safety Executive 02/25