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What can we learn from Structural Health Monitoring (SHM)? Part 1: Theory

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ABSTRACT

This paper is the first part of a two-part series and introduces the theoretical basis for Part 2: Case Study (Smith, 2024b), which presents the application of this theory to a building in London. The primary research objective was to provide a method to safely reduce Eurocode partial design factors to enhance material utilization, thereby decreasing material usage and embodied carbon while maintaining structural reliability. It is hypothesised that Structural Health Monitoring (SHM) can be used to increase certainty of the variability of the dead load justifying a reduction in the factor of safety, whilst maintaining codified structural reliability levels. The research addresses a critical issue: buildings necessary to accommodate the growing and urbanizing global population are responsible for 39% of global carbon emissions, encompassing both embodied and operational emissions. Consequently, reducing the embodied carbon in buildings is a vital component of the strategy to mitigate the effects of climate change. Traditionally, the factors of safety employed in structural design have remained largely unchanged for over a century, despite significant advancements in computational methods. Moreover, over-design in construction leads to an annual cost of £1 billion to the underperforming United Kingdom (UK) construction industry. This paper introduces a theoretical approach for reliability analysis, building on Eurocode 0, and extending it through Bayesian analysis. While the method has been applied to dead load, the approach is versatile and can be applied to other load types, such as imposed and wind loading. Similar approaches have already been successfully implemented by others in the context of material strength factors of safety.

INTRODUCTION

This paper is part 1 of a 2 part series titled *What can we learn from Structural Health Monitoring (SHM)?* And summarises the theoretical background used as the basis for this research. The carbon crisis is now pushing building design down a pathway of improvement in relation to carbon emissions. It is hypothesised that using Structural Health Monitoring (SHM) data as part of reliability and Bayesian analyses provides a methodology to design more efficiently, use less material, and reduce embodied carbon in buildings. Research to reduce carbon is being done in other areas, such as introducing new materials and carbon sequestration. However, Structural Health Monitoring (SHM) technology is already available and is part of industry best practices. Also, a codified method of applying reliability analysis already exists.

SHM is defined as *the integration of sensing devices to allow the loading and damage state of the structure to be monitored, recorded, analysed, localised, quantified and predicted in a way that non-destructive testing becomes an integral part of the structure* (Boller and Meyendorf, 2008).

A building's design efficiency is improved by making the structural elements, such as beams and columns, smaller and lighter (with less material) while safely carrying the applied loads, under the given conditions, for the working life of the structure. Efficiency is defined as *increasing the material utilisation* and is achieved in this approach by reducing partial design factors.

It is argued that SHM can give the designers more certainty in their understanding of structural analysis (structural behaviour) and the magnitude, distribution and variability of the design building loads. A fundamental engineering design principle is; that safety factors are lower (ie higher efficiency) in situations where certainty (confidence) is high and vice versa. Certainty is characterised by low variability. The most relevant example of this in practice is the partial factor applied to design actions derived from the (more certain) dead load is 1.35 compared to the (less certain) live load where the higher value of 1.5 is applied. With increased certainty, designers can arguably decrease safety factors, and this opportunity has been captured within the Eurocodes and is referred to as *Reliability Analysis*. Reliability Analysis in this context is the term used for the probabilistic structural design methods based on achieving a target reliability factor (β).

It is difficult to make changes to a structure during or immediately post-construction. In the short term, this research aims to use the results from SHM to assess the level of certainty around the structural modelling and the assumed design actions to derive updated partial design factors using reliability and Bayesian analyses. If the partial design factors are less than those used in the design, the difference represents surplus building capacity. This surplus capacity generates building flexibility which results in a lower carbon footprint.

Habitual over-design has been estimated to cost between £0.7 to 1.4 billion per year in structures alone (Orr and Wise, 2018). There is much debate over whether the current structural design methods produce designs that are too safe; these arguments are diverse and multi-dimensional. This research aims not to make buildings less safe; instead, buildings should be designed safe enough. Others have expressed this sentiment, including Chris Wise in his IASBE Milne Lecture; Enough is enough (2010). Later again, Wise (2018) recommended that the words '*…and no more*' should be added into design codes for an estimated saving of £1.4 billion per year. In some cases, overdesign serves to futureproof structures, and the Bazalgette super sewer in London is a fine example. Future-proofing infrastructure capacity is typically a sound investment. However, future-proofing should be carried out intentionally and sustainably, rather than as a happy consequence of habitual over-design.

STRUCTURAL DESIGN IN ACCORDANCE WITH THE EUROCODES

There are various approaches available to design buildings — the conventional method, as set out in the European design codes, specifies Limit State Design (LSD) using partial design factors. A design according to Eurocode starts with assuming values for the load intensity and variability, and then the designer carries out a structural analysis on that basis. The designer then uses partial design factors to obtain a measure of the maximum expected load (design action). Likewise, the minimum expected strength (resistance) is calculated. Designers use the partial factors dictated by the Eurocodes to calculate these maximum and minimum values. With these two parameters (load and resistance), the designer can perform a simple pass or fail test on a particular structural element (beam, column etc) to ensure that the minimum strength consistently exceeds the maximum load. This approach relies on the code writers' judgement of the degree of certainty (variability) of the load and strength. This approach is easy to use but is typically conservative in its assumptions.

PROBABILISTIC DESIGN & RELIABILITY ANALYSIS

As an alternative to LSD, a design based on probabilistic methods can be applied. The Eurocode then passes off the responsibility and states that the relevant authority can give specific conditions for use (BS EN 1990:2002+A1:2005 Section 3.5 (5)). Probabilistic design methods encompass the mathematics of probability within the calculation, meaning the designer must have an idea of the mean load and its expected variability. The Eurocode goes on to describe the basis for partial factor design and reliability analysis nominating the reliability index (β) and form factor (α) (BS EN 1990:2002+A1:2005 Annex C).

When first introduced, the advantages of β-value in combination with probabilistic theory as part of structural reliability analysis was that it produced similar values to the familiar safety factors, this meant

that the β-value could be interpreted without recourse to sophisticated probabilistic concepts which are unfamiliar to most engineers (Reid, 1999). In his paper, Reid proceeds to write that the β-value has significant potential as a device to implement improvement in engineering design practice. Reid's view is closely aligned with the goals of this research. Beeby & Jackson (2016) have done extensive work using reliability analysis to improve the design of steel in reinforced concrete.

Reliability analysis differs from the conventional design approach as it considers the expected variability of both the load and the strength to arrive at an acceptable probability of failure. It is harder to apply because the designer must have a general knowledge of statistics and a detailed understanding of the probability distributions of the building loads and strength. But, reliability analysis is beneficial because the partial factors can be naturally reduced when the designer has more certainty.

Reliability Analysis provides a mechanism for including measured data to calculate the mean and variation of both the load and the strength to generate less conservative partial design factors. This approach means the strength of the building can be more closely tailored to the applied loads, reducing over design, and therefore reducing overall building cost and embodied carbon. It can be combined with either the existing partial design factor methods or as part of a complete reliability analysis where the probability distributions of all the design variables are known.

This methodology was chosen as it is widely available and applicable to the UK construction industry. However, despite its availability, reliability analysis is seldom used in industry. At no stage during either informal interviews or research were any examples found where this approach had been used to determine partial design factors.

Reliability Index ($\boldsymbol{\beta}$) is a measure of structural reliability which is related to the Probability of Structural Failure (P_f) over the building life by:

$$P_f = \Phi(-\boldsymbol{\beta}) \qquad \text{(BS EN 1990:2002+A1:2005 Equation C.1)}$$

Where Φ is the cumulative distribution function of the standardised normal distribution, the relationship between P_f and $\boldsymbol{\beta}$ is given in Table 1 below.

Table 1 - Relation between β and P_f (BS EN 1990:2002+A1:2005 Table C1)

P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
$\boldsymbol{\beta}$	1.28	2.32	3.09	3.72	4.27	4.75	5.20

By inspection of Table 1, one can see that in the range of $1 < \boldsymbol{\beta} < 4$:

$$P_f \approx 10^{-\boldsymbol{\beta}}$$

A design using Eurocodes leads to a structure with a $\boldsymbol{\beta}$ -value greater than 3.8 for a 50-year reference period. Assigning target acceptable risk levels is very challenging as it relies on what society deems to be an acceptable risk level, and these views can be notoriously fickle.

Back Analysed β -Value

Several authors have calculated a back analysed the reliability ($\boldsymbol{\beta}$ -value) based on the Eurocodes and have shown it to be significantly variable above and below the specified value, depending on a range of factors (Vrouwenvelder (2008), Gulvanessian and Holicky (2005) and Kohler & Fink (2012). If the reliability of a structure is already variable, rather than draconian prescription of partial factors, why not use a fixed $\boldsymbol{\beta}$-value as the basis for design in combination with building-specific probabilistic methods? The most apparent answer is that partial factors are simpler for codes to specify and easier to apply in practice, despite the inherent conservatism of this approach.

Eurocode 0 includes two different methods for conducting reliability analysis contained in Annexes B and C. Annex B describes a method for minor adjustments to partial factors based on different reliability classes and guidance on ensuring that a number of the general assumptions for quality are satisfied. In this way, the Eurocode aims to eliminate failures due to gross errors and to achieve the resistance assumed in the design. Annex C is more detailed and has been used as the basis for this research.

Eurocode 0 Annex C states that values partial factors can be determined in two ways, either:

a) based on calibration to a long experience of building tradition. This is the leading principle of the Eurocodes with the currently proposed combination of partial factors.

b) based on statistical evaluation of experimental data and field observations. This should be carried out within the framework of a probabilistic reliability theory.

In this way, the probability of the design actions exceeding the design resistance is low enough from an acceptable level of probability of failure, but not so low as to be uneconomical.

The design values of action effects (E_d) and resistances (R_d) should be defined such that the probability of having a more unfavourable value is as follows:

$P(E > E_d) = \Phi\ (+\alpha_E \beta)$ (BS EN 1990:2002+A1:2005 Equation C.6a)

$P(R \leq R_d) = \Phi\ (-\alpha_R \beta)$ (BS EN 1990:2002+A1:2005 Equation C.6b)

α_E and α_R (with $|\alpha| \leq 1$) are the values of the First Order Reliability Method (FORM) sensitivity factors. The value of α is negative for unfavourable actions and positive for resistances. Eurocodes nominate the same α_E and α_R values as specified in the international standard (ISO 2394:2015).

$0.16 < \sigma_E/\sigma_R < 7.6$ (BS EN 1990:2002+A1:2005 Equation C.7)

where σ_E and σ_R are the standard deviations of the action effect and resistance respectively, in expressions (C.6a) and (C.6b). This gives:

$P(E > E_d) = \Phi(-0.7\beta)$ (BS EN 1990:2002+A1:2005 Equation C.8a)

$P(R \leq R_d) = \Phi(-0.8\beta)$ (BS EN 1990:2002+A1:2005 Equation C.8b)

Partial Factor Design

The following method for partial factor design is described by Vrouwenvelder (2008). To obtain the relevant partial factor, the designer can simply divide the design value of an action by its representative or characteristic value (BS EN 1990:2002+A1:C7 (7)), as shown as follows:

$$\gamma = X_d / X_k$$

In the context of this research, based predominantly on dead load, it is reasonable to expect that the probability distribution is normal. In the case of a normal distribution, the following expressions hold:

$$X_d = \mu(1-\alpha.\beta.V) \text{ and } X_k = \mu(1-k.V)$$

Where,

V is the coefficient of variation ($V = \sigma/\mu$)

k is the fractile of the characteristic value

β is the reliability index; and

α is the Form sensitivity coefficient ($0 < \alpha < 1$)

If a normal distribution does not fit the sample, the above expressions would need to be revised. For simplicity, if we assume that k = 0, as is often the case for loads as the representative value normally corresponds to a return period equal to the design life, then $X_k = \mu_k$ and then the partial design factor can be calculated as follows:

$$\gamma_i = 1 + |\alpha_i|\beta V_i$$

Following on from this:

$\alpha_{E}.\beta.\sigma_{E} = 0.7 \text{ x } 3.8 \text{ x } \sigma_{E} = 2.66\sigma_{E}$

$\alpha_{R}.\beta.\sigma_{R} = 0.8 \text{ x } 3.8 \text{ x } \sigma_{R} = 3.04\sigma_{R}$

By inspection of this relationship, the partial factor increases for higher reliability and variability. Similarly, if the variability is zero, the partial design factor reverts to unity. The coefficient of variation (V) should follow from field observations or laboratory test results. The coefficient should also include the uncertainties due to the limited amount of data (statistical uncertainty), measurement errors, and the lack of accuracy due to approximation in the calculations (model uncertainty).

Back Calculation of Assumed Variability

Using this approach and the partial factors nominated in Eurocodes, the following calculations derive the assumed variability within the Eurocode.

Assuming the dead load (G) is dominant :

$\gamma_{G} = 1 + 0.7 \text{ x } 3.8 \text{ x } \sigma_{E} = 1.35$ then, $\sigma_{E} = 0.1316$ This result forms a central part of this research.

$\gamma_{Q} = 1 + 0.28 \text{ x } 3.8 \text{ x } \sigma_{E} = 1.5$ then, $\sigma_{E} = 0.4700$

These results show the assumed variability within Eurocode for the live load is 3.6 times greater than the dead load. This result aligns with the fundamental engineering philosophy that in areas of greater certainty, the partial factors can be justifiably reduced.

Target Certainty

Moynihan (2014) identified that buildings from his study generally had 30% surplus capacity mainly attributed to standardisation and constructability. In a similar vein, research by Xuereb and Parkin (2016) indicated that SHM could provide at least 15% surplus building capacity on an eight-storey steel-composite commercial building. Based on this research, the target surplus building capacity was set at 30% of the dead load. The justification for this target value is; that the dead load is straightforward to calculate based on the density and dimensions of the permanent building elements. Calculations for the dead load are carried out by a computer operated by an experienced and qualified engineer, based on a highly accurate building model, so the dead load calculations should be accurate and reliable.

This resulting research target was a design partial factor $\gamma_{g} = 1.05$ reduced from 1.35 ie 30%. Commonly in design, the characteristic value is set as the mean plus 5%; indicating this would be an appropriate lower bound starting point. But, to achieve this, the SHM data would need to prove a variability on the calculation of dead load better than σ_{E}=0.0188.

This research target is represented by the green distribution in Figure 1 below. The yellow distribution represents the Eurocode assumption of a variability σ_{E}=0.1316 and the corresponding design partial factor $\gamma_{g} = 1.35$. Based on this improved certainty, the black curve representing the resistance distribution shifts to the left, requiring less resistance to carry the load, smaller structural elements and less embodied carbon. As the structure is already built, the client could take this surplus capacity, equivalent to 30% of the dead load, and use it for future building expansions, justifying the cost of the SHM system.

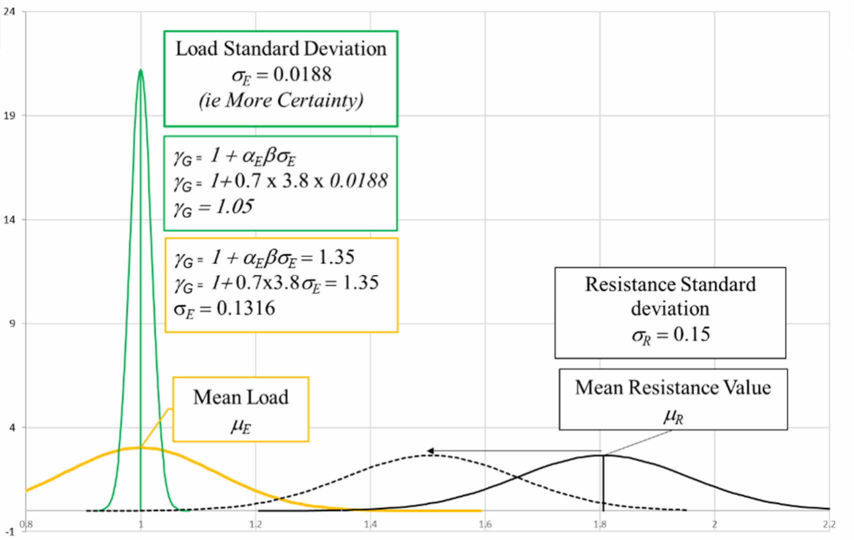

Figure 1 - Revised Factors of Safety Showing the Benefits of Greater Certainty

Bayesian Statistics

Bayesian analysis is a statistical method for combining prior probability distributions (the inbuilt Eurocode assumptions) with new information (SHM data) to create a posterior probability distribution representing the new belief. In applying Bayesian statistics, the designer can more rationally combine two different sources of data rather than choosing either one.

The method for combining the two probability distributions is as follows.

1. Prior: The probability distribution was established using the Eurocode expectation that the measured/predicted values would have a mean value of 1 (meaning the measured is equal to the predicted) and a standard deviation of $\sigma_E = 0.1316$ (as derived the above). The design value would then be the predicted value multiplied by the Eurocode load factor of 1.35. For the Bayesian calculations, σ_E will be renamed $\sigma_0 = 0.1316$, now representing the variability of the prior distribution. As derived above, the subsequent partial factor on dead load would be $\gamma_g = 1.35$, which is the value found in the Eurocodes. In mathematical terms this would be expressed as: $\text{Norm}(\mu_0, \sigma_0^2) = \text{Norm}(1, 0.1316^2)$, with N number of data points, say 100.

2. New Information: The target for the research is that the mean of the measured/predicted values will still equal 1, but the standard deviation will be $\sigma_E = 0.0188$ (carried down from above), representing the higher degree of certainty in the structural analysis derived from the SHM. For the Bayesian calculations, this value will be renamed $s = 0.0188$ representing the normal distribution of the new sample data. The subsequent partial factor on dead load would be $\gamma_g = 1.05$ (as derived above). In mathematical terms, this would be expressed as: $\text{Norm}(m, s^2) = \text{Norm}(1, 0.0188^2)$, with n number of data points, say 216.

3. When the prior and the new information are combined, a plausible candidate for the resulting posterior is:

$$\text{Norm.}(\mu_{\text{comb}}, \sigma^2_{\text{comb}})$$

$$\mu_{comb} = \frac{N\mu_0 + nm}{N + n}$$

$$\sigma_{\text{comb}} = \sqrt{\frac{(N-1)\,\sigma_0^2 + (n-1)s^2}{N + n - 1}}$$

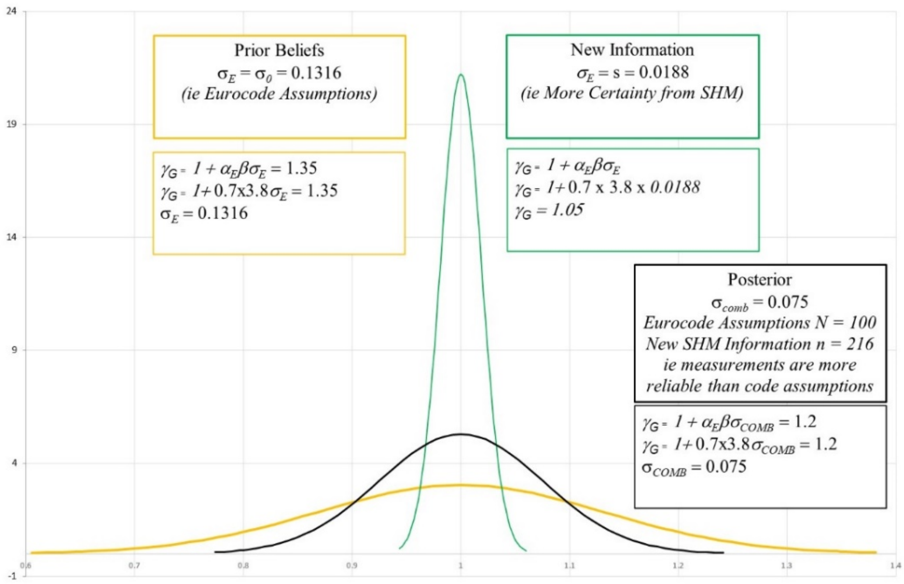

Figure 2 - Bayesian Combining of Posterior (Eurocodes) with Research Target

Mathematically, the values of N=100 and n=216 represent the number of samples in each data set. In practice, it is complicated to assign a sample number to the Eurocode assumptions. If N is chosen to be large compared to the sample size n, it means the designer is choosing to place greater emphasis on the prior knowledge (Eurocodes). Conversely, choosing N to be small compared to sample size n means

the designer is admitting the structural analysis models are flawed and is thus putting much greater emphasis on what the SHM data is reporting. Based on calulation, if $N/n \geq 10$, then the result is virtually equivalent to the prior belief. Similarly, if $N/n \leq 0.01$, then the result becomes equivalent to the new data.

Conclusion

This research aims to give the industry a method to exploit SHM data better to reduce embodied carbon in buildings. In the short term, by creating surplus capacity in future building expansions (flexibility). In the long term, by identifying the true certainty and quantifying the statistical parameters used in the design. This paper has set out the theoretical basis for using data derived from SHM to increase certainty and reduce partial safety factors. As the design process is slowly improved, at much later building iterations when the structural elements are as slim as they can be, buildings will become more dynamic and SHM will be more about assessing the building behaviour during everyday life (serviceability assessments), rather than the measurement of load and distribution. A building will have the same reliability, but its elements will become a lot smaller. By this time, the ‘Let it Move’ approach proposed by Winslow (2017) will become more commonplace.

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References

Andrews, C. (2018) ‘Wave Riders’, *Create*, pp. 54–61.

Beeby, A. and Jackson, P. (2016) ‘Partial safety factor for reinforcement’, *Structures*, 5, pp. 101–111. doi: https://doi.org/10.1016/j.istruc.2015.09.002.

Ben-Gal, I. (2008) ‘Bayesian Networks’, in *Encyclopedia of Statistics in Quality and Reliability*. American Cancer Society. doi: 10.1002/9780470061572.eqr089.

Boller, C. and Meyendorf, N. (2008) ‘State-of-the-art in Structural Health monitoring for aeronautics’, in *Proceedings of the International Symposium on NDT in Aerospace*.

Calgaro, J.-A. and Gulvanessian, H. (2001) ‘Management of reliability and risk in the Eurocode system’, in *Safety, risk, and reliability—trends in engineering. International Conference. Malta*, pp. 155–160.

Frangopol, D. M. (1998) ‘Probabilistic structural optimization’, *Progress in Structural Engineering and Materials*, 1(2), pp. 223–230. doi: 10.1002/pse.2260010216.

Gulvanessian, H. and Holicky, M. (2005) ‘Eurocodes: using reliability analysis to combine action effects’, *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 158(4), pp. 243–252. doi: 10.1680/stbu.2005.158.4.243.

Holicky, M., Diamantidis, D. and Sykora, M. (2015) ‘Determination of target safety for structures’, in *Proc. 12th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP12). Vancouver: Univ. of British Columbia*, p. 8.

Huang, J. *et al.* (2014) ‘Use of Bayesian statistics with the observational method’, *Australian Geomechanics Journal*. AUSTRALIAN GEOMECHANICS SOC, 49(4), pp. 191–198.

Huang, J. *et al.* (2016) ‘Updating reliability of single piles and pile groups by load tests’, *Computers and Geotechnics*. Elsevier, 73, pp. 221–230.

Jones, C. (University of B. (2019) *The Inventory of Carbon and Energy (ICE) Database*, *Circular Ecology*. Available at: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database (Accessed: 8 January 2020).

Kelly, R. and Huang, J. (2015) ‘Bayesian updating for one-dimensional consolidation measurements’, *Canadian Geotechnical Journal*. NRC Research Press, 52(9), pp. 1318–1330.

Kohler, J. and Fink, G. (2012) ‘Reliability based code calibration of typical Eurocode 5 design equations’, in *World Conference on Timber Engineering (WCTE) 2012*. Auckland, New Zealand, pp. 99–103.

McKinsey (2017) *Reinventing Construction: A Route To Higher Productivity*, *McKinsey & Company*. Available at: www.mckinsey.com/mgi. (Accessed: 6 May 2019).

Moynihan, M. C. and Allwood, J. M. (2014) ‘Utilization of structural steel in buildings’, *Proceedings: Mathematical, Physical and Engineering Sciences*. Royal Society, 470(2168), pp. 1–14.

Orr, J. and Wise, C. (2018) ‘Technical Lecture Series: Minimising Energy in Construction’. London: the Institution of Structural Engineers. Available at: https://youtu.be/R2Bhusyz-PQ.

Rackwitz, R. (2000) ‘Optimization: the basis of code-making and reliability verification’, *Structural safety*. Elsevier, 22(1), pp. 27–60.

Reid, S. G. (1992a) ‘Acceptable risk, engineering safety, DI Blockley, ed’. McGraw Hill.

Reid, S. G. (1992b) ‘Risk acceptance for novel engineering systems’, in *PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON OFFSHORE MECHANICS AND ARCTIC ENGINEERING*, p.

67.

Reid, S. G. (1999) ‘Perception and communication of risk, and the importance of dependability’, *Structural Safety*. Elsevier, 21(4), pp. 373–384.

Smith, B. S. and Hayward, T. (2021) ‘Case Study: Edinburgh St James – Bearing Pile Design’, in *Piling 2020*. Durham: The British Geotechnical Association (BGA).

Smith, B. S., Hayward, T. and Walford, C. (2021) ‘Case Study: Edinburgh St James – Embedded Retaining Wall Pile Design’, in *Piling 2020*. Durham: The British Geotechnical Association (BGA).

Smith, B. S. (2024b) ‘What can we learn from Structural Health Monitoring (SHM) - Part 2: Case Study’, *Australasian Structural Engineering Conference, Engineers Australia, Melbourne*.

Teimouri, H. (2016) ‘A Gaussian process–based approach to cope with uncertainty in structural health monitoring’, *Structural Health Monitoring*. Sage Publications, 16(2), pp. 174–184.

Vrouwenvelder, T. (2008) ‘Treatment of risk and reliability in the Eurocodes’, *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 161(4), pp. 209–214. doi: 10.1680/stbu.2008.161.4.209.

Winslow, P. (2017) ‘Machines for living--true performance-based design’, *The Structural Engineer: journal of the Institution of Structural Engineer*. Institution of Structural Engineers, 95(3), pp. 10–13.

Wise, C. (2010) ‘IABSE Milne Medal Lecture: Enough is enough’. London: International Association for Bridge and Structural Engineering (IABSE). Available at: http://istructe.adobeconnect.com/%0Ap87368980/.

Xuereb, K. and Parkin, I. P. (2016) ‘Adapting building structures to new uses in the future’, *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, 169(ES6), pp. 233–242. doi: 10.1680/jensu.15.00043.

Zheng, D. *et al.* (2018) ‘Embankment prediction using testing data and monitored behaviour: A Bayesian updating approach’, *Computers and Geotechnics*. Elsevier, 93, pp. 150–162.

BIOGRAPHY

Ben is a Technical Director, professionally qualified in both the United Kingdom and Australia, with extensive experience in providing engineering analysis & design and construction management across fast-paced environments. Ben has been fortunate to have had a distinguished career in the industry, leading the design and construction of iconic projects, across a number of sectors, both in the UK and internationally.