Viewpoint

Embracing probability: could big data spell the end of safety factors as we know them?

Arthur Coates calls on structural engineers to push for the adoption of post-monitoring sensors to provide better data on building performance and, ultimately, more accurate loading predictions.

Big data

We are fascinated by data; our phones collect information on everything we do, where we travel, our heart rate, our sleeping patterns and now even fertility. Over the past decade, data has become one of the most valuable commodities globally. The combined market capitalisation of Amazon, Microsoft and Apple in 2020 exceeded the gross domestic product of the UK, the world's sixth largest economy[1].

Contrastingly, the construction industry, in particular structural engineering, has been very slow in its uptake of data analysis techniques. There are sensors on watches that can measure our blood oxygen levels, but very rarely are structural loads measured in practice.

What data is useful to structural engineers?

The handful of buildings that measure performance in service[2,3] typically utilise strain gauges and accelerometers, which help an engineer's understanding of the serviceability performance of the structure. These are usually only implemented on unique, high-profile projects where the equipment is funded by research institutions.

However, this data is not always meaningful. Although we have a good understanding of how individual structural elements move in controlled loading applications, there is no indication of the magnitude or nature of the applied loading in real building scenarios. We may know that a truss has moved, say, *x* mm since construction, as on the new Google office development in London[4], but inferring imposed loads from deflections means making broad assumptions about stiffness. As such, drawing a conclusion on the efficacy of a structure under realistic loading scenarios is a complex task. To tackle this, we must collect useful data on the actual imposed loads on buildings.

There are various ways in which this could be carried out. Sensors exist in everything now; there are four different types of motion sensor in an iPhone[5]. Using infrared heat maps, personal Internet of Things devices, such as smart watches, or even monitoring CO_2 levels[6] would help analyse movements of people around buildings and other infrastructure, granting us an insight into how they are loaded over time. The most sustainable building in the world in 2016, The Edge in Amsterdam, comes very close to this reality, where occupancy can be measured using Bluetooth to the individual's smart device[7]. Unfortunately, this data is not fed back to the structural engineers.

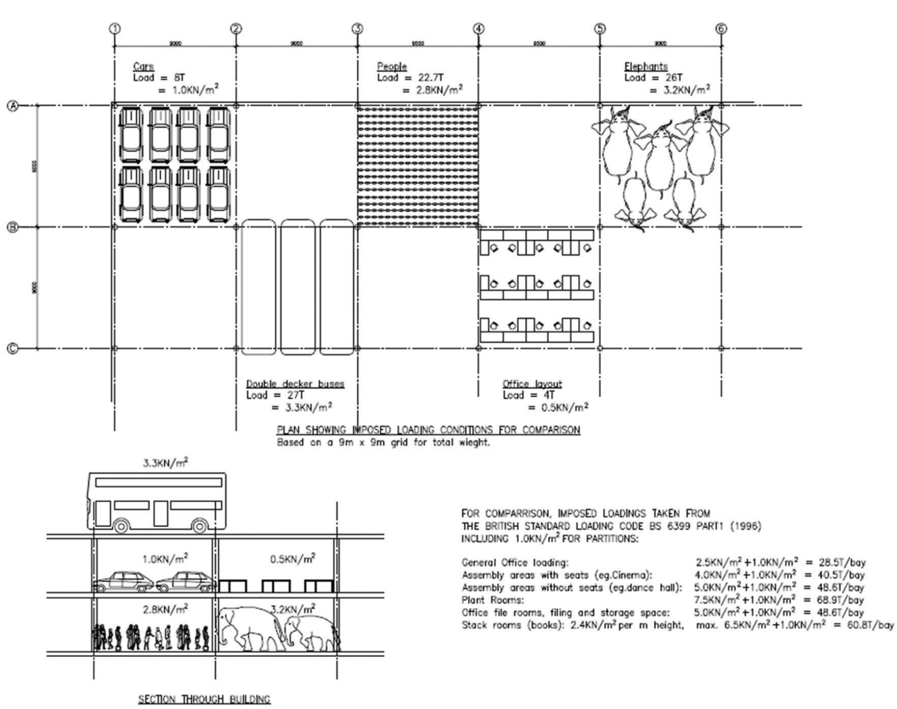
Understanding wind loading on buildings is also an important task. London's Highpoint tower set a precedent with a series of pressure sensors installed on the building to understand how the correlating wind speed affected building sway[8].

Similarly, the Met Office has created the Virtual Met Mast system[9] which uses site-specific wind data to help optimise the location and design of wind turbines. Obtaining wind data from crane anemometers could be a good starting point in creating a localised, yet universal, dataset for future structural design.

The problem with imposed loads

In statistical terms, data represents a reduction in uncertainty. As the famous saying by Grace Hopper goes: 'One accurate measurement is worth a thousand expert opinions'. Data offers unique pieces of information which allow us to understand whether our past decisions were correct, and equally to make informed decisions

FIGURE 1: Imposed loading comparisons



© PRICE & MYERS

in the future.

Assessment of imposed floor loads has been the repeated focus of many efforts historically[10–12]. Despite this research, there has been little impact on most built projects[13]. Recent studies by MEICON[14,15] demonstrated the almost ludicrous magnitude of current imposed loads for commercial buildings (Figure 1). This is reinforced by a recent occupancy study from the British Council of Offices which found that the average density of office space is only one person for every 9.6m²[2,16], equivalent to 0.1kN/m².

On top of unlikely loading requirements, a partial safety factor, γ_f, is usually applied (Figure 2). Typically, this adds an additional 50% for imposed loads when assessing strength parameters using BS EN 1990[17].

But what does a partial safety factor represent? In simple terms, it is a measure of the uncertainty in our belief about loading. And there lies the problem: engineers have no idea how buildings are loaded in reality. Our estimation of loading may not be wrong, but it is arbitrary given we do not make the effort to understand whether this estimation is true.

In the growing agenda of carbon efficiency in design, it is imperative that structural engineers improve best practice by challenging historic assumptions. This article will focus on the assumptions around the uncertainty in the variability of actions on structures. Ultimately, the question is: is the current safety factor framework of limit state design still appropriate?

Limit state design

The safety factor framework that we use in the UK is prescribed by the limit state design process within Eurocodes. Engineers must design structures to satisfy strength and stiffness criteria, or *limits*.

Given variable loads can be difficult to estimate for the design life of a building, designers use a nominal characteristic load, a constant value, for design based on historic upper limits (such as from BS EN 1991-1[18]). These are derived assuming an acceptably low probability of exceedance (Figure 3) and then a constant partial safety factor is applied.

These *limits* have been constructed deterministically; precedence shows us that buildings can withstand these characteristic imposed loads; therefore, we assume we can continue to use these design loads in the future. Even BS EN 1990 states that imposed loads and safety factors are based on 'calibration to a long experience of building tradition'.

Whether we are aware of it or not, we make decisions every day on what imposed loads to use in the design of buildings, whether strictly following codes of practice or not. Choosing to design an office building for 2.50kN/m² is a decision we make. Equally, applying a safety factor of 1.5 on top of this is a decision on how uncertain we feel.

Without feedback, we cannot understand the uncertainty within our decision-making. Research studies seem to suggest that we are just reinforcing poor, ill-informed decisions. But how close are we?

Education in probability and inference

Structural engineers should have a better appreciation of the uncertainty in loads and the associated reliability of a structure, i.e. its probability of failure. This was argued nearly 20 years ago by McRobie, who declared that 'structural engineers [should] be educated'[20] in Bayesian theory; the notion of considering probability as a belief.

The fundamental concept of Bayesian theory is of conditional probability: we can make an updated and refined *posterior* probability, given *prior* information. What this means in terms of the loading on structures is that we can continually update our belief of the load exceeding *x* – say, 2.50kN/m² for an office – given *y* loading has occurred in the past. The more data we have, the less uncertain our prediction becomes over time.

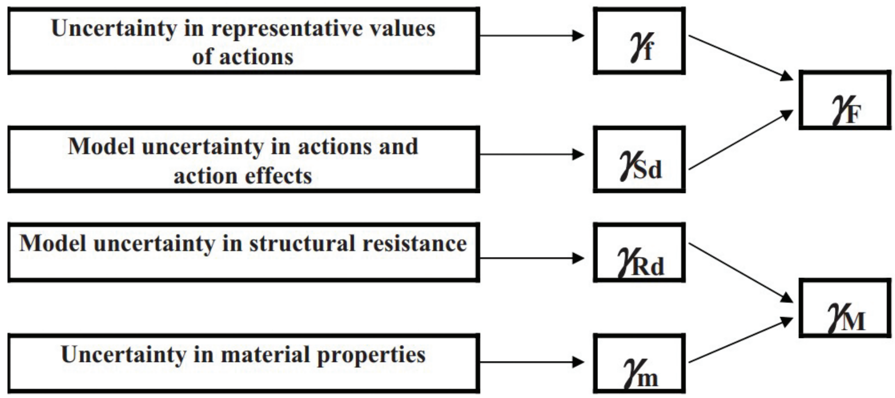


FIGURE 2: Uncertainty factors from BS EN 1990[17]

This raises the question of whether the past deterministic methods of using safety factors in design are now still appropriate, when probabilistic methods of analysis are available and the ways to collect and interpret data exist.

In 2001, Calgaro and Gulvanessian[21] claimed that BS EN 1990 was the first operational code that recognised the possibility of using probabilistic design methods. Yet 20 years on, many engineers do not realise that Annexes B and C explicitly describe these methods using reliability analysis.

A probabilistic approach could replace the current safety factor framework, if enough data exists. If I am certain how a building is loaded, then the factor of safety can be justifiably reduced.

Using a Bayesian approach, we can rationally combine the codified certainty levels with objective data to modify our beliefs in a systematic way. For instance, I believe the current office loading requirement of 2.50kN/m² is too conservative. Using current levels of uncertainty from BS EN 1990 as a starting point, i.e. $\gamma_q = 1.5$, I could update this characteristic load with data collected from previous buildings. This would result in either a more accurate imposed load requirement – say, 2.00kN/m² – or a more accurate level of reliability – say, $\gamma_q = 1.1$ – or even a balance of both options. The tools for doing this are in our hands and eventually we should be able to iterate and refine our safety factors to a minimum.

In many buildings, the dead load far exceeds the imposed loading. Therefore, using the alternative method proposed by Smith[22], we could measure the dead load of buildings at completion and use any surplus capacity created from the safety factors to unlock the 'loading credit' for future building expansions, generating significant carbon savings.

How are other industries embracing probabilistic methods?

Whether we admit it or not, the construction

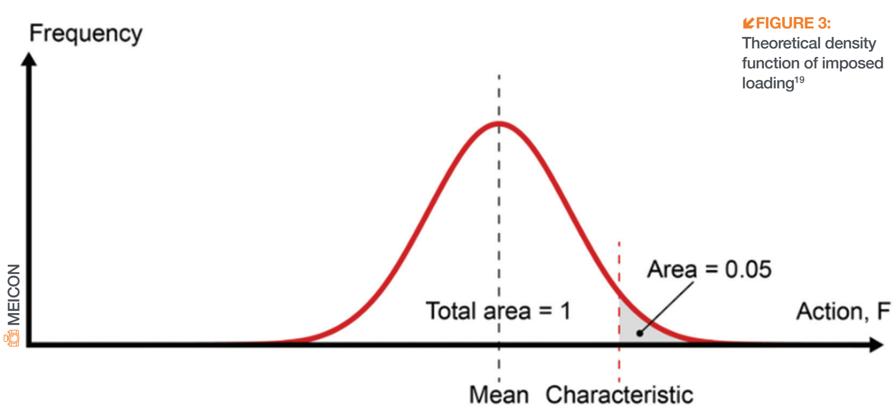


FIGURE 3: Theoretical density function of imposed loading[19]

industry is decades behind the innovation shown by other sectors[23]. Within the automotive industry, the emergence of self-driving cars has shown the opportunity for real-time probabilistic methods in statistically diverse environments. Autonomous cars make extremely important decisions based purely on prior data, i.e. is it currently safe for me to change lanes?

Similarly, within the insurance industry, risk can now be priced and insurance sold using real-time data. A specialist drone insurance company[24] recently introduced an insurance product that models hyper-localised meteorological data and transport conditions, as well as mining Twitter to assess potential crowding influences at street level, in real time. This results in an extremely accurate, short-term risk profile.

Although the manufacturing landscape of replicative products, such as cars, is currently very different to that of bespoke infrastructure, similar probabilistic methods could be used for the real-time analysis of building structures through current sensor and artificial intelligence technology.

What might the future look like for structural monitoring systems?

As there is a push for smarter, more tech-enabled buildings, we should harness this innovation to begin collecting data on the loading and structural performance of all buildings.

Embedding sensors in frames could help build an intelligent risk profile over a building's design life. This could determine, in real time, how reliable structures are; almost like a Fitbit or telematics-style 'black box' for buildings, continually monitoring its health **(Figure 4)**.

With the cost of access to customised monitoring systems and services dramatically reducing[25], engineers should provoke clients into considering these measures at an early stage. The value may not all be in the design of new buildings, but more in the assessment of existing buildings and how they could be adapted and restored for the future. In that sense, the 'return on investment' on probabilistic structural monitoring systems would be more suited to institutions with long-term viewpoints, such as governments or large-scale asset managers.

Need for alternative justification processes

Although it is likely the use of probabilistic methods will remain an abnormal form of justification, a further suite of 'diversification' clauses could be introduced for building regulations approval. This could build on the imposed load reduction factors, like Annex A1 of BS EN 1990, or the lowering of safety factors through alternative justification.

Testing whole structural systems to better understand relative stiffnesses would help reduce the uncertainty in the variation of load paths,

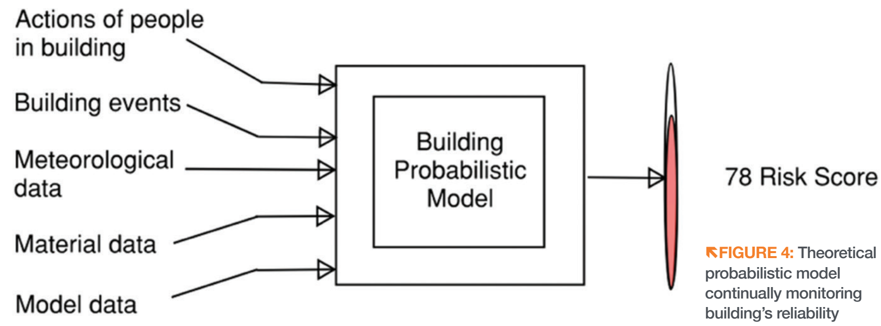


FIGURE 4: Theoretical probabilistic model continually monitoring building's reliability

thereby reducing the need for factors of safety in local element design. After all, the uncertainty in modelling assumptions is the other part of the partial safety factor, γ_f.

On the other hand, with known imposed loads currently so low and associated factors of safety so high, could we convince building control bodies to accept utilisation ratios above 1.0, where imposed loading governs? Alternatively, could we just get rid of safety factors and design structures for plastic failure scenarios instead, like in the seismic design of many regions globally?

Methods of alternative approval should exist, or additions be made to current codes of practice, to allow engineers to make free and informed decisions on structural performance.

Potential consequences of reducing imposed loads

Of course, reducing the loading requirements and/or safety factors on buildings is a ripe opportunity for engineers to reduce material usage. However, it will require a re-think of other elements of structural design.

For instance, engineers will need to carefully consider the resultant serviceability performance, if actual loads in reality remain unchanged. Although most buildings can accommodate some structural movement, engineers will need to fully engage with movement and tolerance reports, rather than just detailing a 25mm deflection head to partitions.

It is not clear whether secondary elements like fire stopping details, service ducts and brittle finishes are designed for current movement limits or take advantage of much reduced actual movements. Using monitoring systems and making data-backed decisions will improve performance in this area.

Not yet touched upon is our judgement on consequence. Although probabilistic methods remove the subjectivity in decision-making, the concept of reliability requires an understanding of what happens if a structure fails.

Historically, this is how safety factors have been determined, with higher values for higher-consequence structural elements. The intended consequence must be considered holistically with regards to system robustness, rather than assessing imposed loads or factors of safety alone. Otherwise we are blindly 'tip-toeing towards the edge'[26].

Introducing a hierarchy of partial safety factors for individual element design, depending on their contribution to the overall stability and robustness, is an alternative design strategy similar to the 'critical component failure' analysis used by the aeronautical industry.

Conclusions

With more data, our predictions become more accurate, allowing us as designers to make better judgements. Engineers should have a basic education in probability and data analysis to understand the everyday decisions they make.

For too long, the engineering sector has spun a tale of the 'margin of limited success' in design. The actual problem is of engineers expending a huge amount of time on extremely detailed analysis models with no understanding of where the loads stem from. Now is the time to explore the other strand of design by tackling the loads, and associated uncertainty, that we design structures for. As Dunham said in 1947, there is a 'lack of economy in providing strength throughout the structure that will not be used in 99% of the building'[10].

In the current climate emergency, it is our duty to tackle the problem of wasting material in structures where it may not be necessary. Although the wide-scale use of post-monitoring sensors in structures may be a long way off, we should push for their adoption in early-stage client meetings. In the meantime, we should always challenge the imposed loading requirements of buildings; and if they are deemed essential by clients, we should thoroughly consider whether significant factors of safety are always necessary.

Acknowledgements

With special thanks to David Illingworth of London Structures Lab and Ben Smith of the University of Cambridge for their input.

Arthur Coates
CEng, MIStructE
Arthur is a Senior Engineer at London Structures Lab. He is passionate about using new technology to help tackle the climate emergency and previously led the Climate Action Group at Price & Myers.

REFERENCES

1) Bloomberg website (2020) [Online] Available at: www.bloomberg.com (Accessed: March 2021)

2) Blair A., Bartram C. and Clark E. (2018) 'Structural design of the new Exhibition Road Quarter at the Victoria & Albert Museum, London', *The Structural Engineer,* 96 (6), pp. 12–19

3) Fast P. and Jackson R. (2018) 'The TallWood House at Brock Commons, Vancouver', *The Structural Engineer,* 96 (10), pp. 18–25

4) Illingworth D. (2020–21) *Conversations with Arthur Coates*

5) Azo Sensors (2012) *The Sensors Used in an iPhone* [Online] Available at: www.azosensors.com/article.aspx?ArticleID=66 (Accessed: March 2021)

6) Atamate website (2021) [Online] Available at: www.atamate.com (Accessed: March 2021)

7) BRE (2016) *The Edge, Amsterdam* [Online] Available at: www.breeam.com/case-studies/offices/the-edge-amsterdam/ (Accessed: March 2021)

8) Margnelli A., Greco L., Gkoktsi K. *et al.* (2018) 'Wind-induced response of tall buildings: Case study of a slender tall building in London', *13th UK Conference on Wind Engineering*, Leeds, UK

9) Met Office (s.d.) *Site selection* [Online] Available at: www.metoffice.gov.uk/services/business-industry/energy/site-selection (Accessed: March 2021)

10) Narver D., Freeman N. and Dunham J. (1947) 'Design Live Loads in Buildings-Discussion', *Transactions of the American Society of Civil Engineers,* 112 (1)

11) Fitzpatrick A., Mathys J., Taylor A. and Johnson R. (1992) *An assessment of the imposed loading needs for current commercial office buildings in Great Britain*, London: Stanhope Properties

12) Alexander S.J. (2002) 'Imposed floor loading for offices: a re-appraisal', *The Structural Engineer,* 80 (23), pp. 35–45

13) Winslow P. (2017) 'Machines for living – true performance-based design', *The Structural Engineer,* 95 (3), pp. 10–13

14) Drewniok M. and Orr J. (s.d.) *Demonstrating Floor Loading: Report* [Online] Available at: www.meicon.net/floor-loading (Accessed: March 2021)

15) MEICON (s.d.) *Mythbusters* [Online] Available at: www.meicon.net/mythbusters (Accessed: March 2021)

16) British Council for Offices (2018) *Office Occupancy: Density and Utilisation, London: BCO*

17) British Standards Institution (2002) *BS EN 1990:2002+A1:2005 Eurocode. Basis of structural design*, London: BSI

18) British Standards Institution (2002) *BS EN 1991-1-1:2002 Eurocode 1. Actions on structures. General actions. Densities, self-weight, imposed loads for buildings,* London: BSI

19) Orr J. (2019) *Design Uncertainty: Report* [Online] Available at: www.meicon.net/uncertainty (Accessed: March 2021)

20) McRobie A. (2004) 'The Bayesian View of Extreme Events', *Henderson Colloquium*, University of Cambridge, UK, 5 July

21) Calgaro J.-A. and Gulvanessian H. (2001) 'Management of reliability and risk in the Eurocode system', *Safety, risk, and reliability – trends in engineering*, International Conference, Malta, 22–23 March

22) Smith B.S. (2020) *A quantitative study of building SHM data with the goal to improve design efficiency using reliability analysis,* Cambridge: University of Cambridge

23) Farmer M. (2016) *The Farmer Review of the UK Construction Labour Model: Modernise or Die* [Online] Available at: www.constructionleadershipcouncil.co.uk/wp-content/uploads/2016/10/Farmer-Review.pdf (Accessed: March 2021)

24) Flock (2020) *Drone insurance for a connected world* [Online] Available at: www.flockcover.com (Accessed: March 2021)

25) Microsoft (2018) *2019 Manufacturing Trends Report* [Online] Available at: https://info.microsoft.com/rs/157-GQE-382/images/EN-US-CNTNT-Report-2019-Manufacturing-Trends.pdf (Accessed: March 2021)

26) Beal A.N. (2011) 'A history of the safety factors', *The Structural Engineer*, 89 (20), pp. 20–26

HAVE YOUR SAY

tse@istructe.org

@IStructE
#TheStructuralEngineer