UNIVERSITY OF CAMBRIDGE

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MEICON

Minimising Energy in Construction

Survey of Structural Engineering Practice

Report

Dr John Orr

EP/P033679/2
www.meicon.net

Foreword

A personal reflection from the industrial chair of MEICON

The purpose of **MEICON** can be summarised as trying to help engineers create the greatest good for the greatest number, at least in terms of structural materials. It is aimed at engineering's common practice, targeted at its low-hanging fruit, rather than its extremes. Of course, its purpose is better to use those materials, to improve life on the planet. Here lies its philosophical strength and its social value.

Engineers encountering this first **MEICON** report as it was being drafted have been overwhelmingly positive. Some celebrated it as "the most useful and stimulating 15 minutes" they had spent in a long time. Its uplifting message is that there really is plenty that can be done to improve material efficiency, emerging from the realisation it's not really that hard if the environment is fertile. So, there is plenty of scope for clients to engage actively with their engineers, working constructively together with the ultimate aim of doing better projects, more efficiently, more valuably, to create mutual satisfaction.

Because **MEICON** reveals much about engineers' custom and practice, it encourages us to consider if engineering could use a professional code of conduct, its own "Hippocratic Oath". If so, an engineer might pledge to "dedicate my life to the service of humanity". After all, this is the exact pledge made by many doctors. An engineer might also promise, as a doctor does, that "The health and well-being of my Patient will be my first consideration". For engineers, of course, the planet we occupy is the "Patient", and the insightful use of engineering materials is the engineer's treatment of choice.

While engineering like this is a life-enhancing activity, the survey in this report reveals understandable conflicts as engineers try to give of their best, under the pressures of commercial and professional life. This is no surprise. So **MEICON** has begun its work by looking behind the scenes to diagnose what professional structural engineers actually do in practice, and the results are revealing.

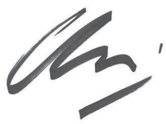
The survey results show statistically significant variations in both regulated and cultural practice as engineers strive to serve their many masters and mistresses. Many engineers tell us they frequently add more capacity into elements than is required, at the expense of material efficiency even as they continue to trust their design codes. They explain their reasons: sometimes it's because they want to anticipate changes before construction, or because they feel the need to accommodate future changes of use in a building, worried they may have no fee to cover the studies involved.

MEICON suggests the need for modernising the industry so that clients begin to incentivise those who design for materially efficient structures and enable design teams to achieve them. By demonstrating their value in this way, engineers will stay relevant in the longer term.

The report contains much on the potential for resource reduction without in any way compromising performance standards. It also begs the question of the unintended consequences of some dominant practices. To take an environmental example: using 20% less concrete needs 20% fewer concrete trucks, reducing emissions-based bronchial health problems in a city. This would happen naturally when engineers design their beams and columns just for the performance they need. Bronchial health will improve simply as the beneficial by-product of using less material.

MEICON has begun to highlight target areas for clear improvements in “good practice” in both regulation and culture. These yield financial, environmental and societal returns at such a scale that voluntary action, already the province of engineers, will not be enough on its own. The procurement environment also needs to evolve. Through delving into real engineering practice, it is already clear that low fees do not encourage low material use in practice. Better for commissioners to take the holistic view, challenging and enabling the good designer to require the least material, recognising anyway that design fees are a small part of most project costs, far outweighed by material and environmental performance savings. In rough terms, every 10% wasted just on the material resource content of a building structure adds at least 1% to the overall cost of the project. This is roughly equivalent to the engineer’s entire design fee. So a 20% reduction in material would cover the engineer’s fee and give the client the same sum again as a double saving. For government clients, these savings can be redirected for hospitals, schools, infrastructure, healthcare, pensions. For private clients the financial benefits to their shareholders are equally clear.

The construction industry is poised to change significantly, and engineers can be washed along as disruptive, emergent change takes place around them, or grasp the opportunity to lead that change themselves. The final chapter of this report poses Industry and Research Questions, designed for engineers to engage with **MEICON** so that the value and impact of engineering choices can be embraced by all at the design stage – because better decisions would surely be made if they were. If this project is a call to arms, you may be asking: What can I do to help? The answers begin in the first few pages of the report: “At a Glance” – you are invited to read on and respond accordingly. This is merely the beginning of the story. The potential benefits of a collective response would be transformative for everyone and we hope you will be moved to act.



Chris Wise RDI, FREng, FICE, HonFRIBA, FIStructE
Senior Director, Expedition Engineering
Chair of the Useful Simple Trust

Summary

This report presents preliminary findings arising from work undertaken as part of the research project *Minimising Energy in Construction* (**MEICON**)[a].

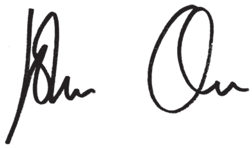
The long-term vision of **MEICON** is for the built environment to be designed cost-effectively, based on whole life cycle energy consumption using minimum material resource for appropriate performance. Our immediate ambition is to use feasibility studies to identify and address sources of wasted embodied energy, value-less cost, and performance over-design in the construction industry to transform sector wide design practice and define the research areas that will underpin this transformation.

As a first step, an online survey was undertaken to examine current culture and practice in structural engineering design as it relates to embodied energy. This report combines analysis of these survey responses with initial explorations of some of the issues that surround the minimisation of embodied energy. **Chapter 1** provides the highest-level outcomes in a condensed format. **Chapter 2** provides the underlying data and analysis.

The results of the survey reveal wide variations and uncertainty in both regulated and cultural behaviours. We find that embodied energy efficiency is not yet a high priority in design, resulting in buildings that consume more of our material resource than may be necessary. The wide spread of responses to the majority of questions demonstrates a lack of consensus across the sector when considering questions of material efficiency, illustrating both the scale and potential opportunity for the sector to lead in solving the challenges ahead.

Our findings are supplemented throughout the report by new questions that have arisen during this initial study. These are grouped into eighteen “Industry Questions” and twenty-one “Research Questions”, each of which will require a collaborative, sector-wide effort to solve.

We therefore call upon you to join us and help us to solve these challenges as we move towards minimal energy construction. Visit **www.meicon.net/survey2018** to find out how you can help.



Dr John Orr MEng (hons) PhD CEng MIStructE FHEA

Principal Investigator

University of Cambridge

Dr Alex Copping	*University of Bath*
Mr Michal Drewniok	*University of Cambridge*
Prof Stephen Emmitt	*University of Bath*
Prof Tim Ibell	*University of Bath*

Chris Wise RDI FREng FICE HonFRIBA FIStructE

Industrial Steering Committee Chair

Expedition Engineering

Richard Boyd	*Arup*
Oliver Broadbent	*ThinkUp*
Kate Leighton	*AECOM*
John Nolan	*Nolan Associates*
Mike Otlet	*OPS Structures*
Nick Russell	*Thomasons*
Faith Wainright	*Arup*

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Definitions

The following definitions are used in this report:

Building information modelling (BIM): The process involving the generation and management of digital representations of physical and functional characteristics of buildings and structures [1].

Circular economy: A system where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised by slowing, closing and narrowing energy and material loops [2, 3].

Characteristic values of an action: The unfactored principle representative values of an action, modified by partial factors to obtain "Design" values [4].

Deconstructability: The ability for a building or structure to be taken apart at any stage during its life cycle.

Design effect of actions (E_d): The factored effect of actions (where actions are applied loads, imposed deformations, or imposed accelerations) on structural members. For example internal forces, moments, stresses, strains.

Design rationalisation: The sizing of multiple similar structural elements based on worst-case load levels in one member [5].

Design resistance (R_d): The factored capacity of a member or component, or a cross-section of a member or component of a structure, to withstand actions.

Design working life: Period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary [6].

Embodied carbon: the carbon required to initially produce a building. Here, it includes carbon associated with the abstraction, processing, and manufacture of materials of the building as well as their transportation and assembly on site[1] [7, 8].

Embodied energy: the energy required to initially produce a building. Here, it includes the energy used for the abstraction, the processing, and the manufacture of the materials of the building as well as their transportation and assembly on site[1].

[1] Embodied carbon and Embodied energy can also be measured to include maintenance and repair, but this is not the focus of this particular report.

Lightweighting: The process of minimising material consumption in design such that an appropriate level of performance against relevant limit state design criteria is achieved, and no more.

Limit states: States beyond which the structure no longer fulfils the relevant design criteria [6].

Operational carbon: The emissions of carbon dioxide during the operational phase of a building [9].

Operational energy: energy associated with the operational phase of a building [9].

Overdesign: The overly conservative design of structural elements.

Reliability: The ability of a structure or a structural member to fulfil the specified requirements, including the design working life, for which it has been designed. Reliability is usually expressed in probabilistic terms [6].

Reuse: Taking a component from a structure and using it again in the same way as originally intended.

Repurpose: Taking a component from a structure and using it again, but to fulfil a different function or purpose from that originally intended.

Serviceability limit states (SLS): States that correspond to conditions beyond which specified service requirements for a structure or structural member are no longer met [6].

Ultimate limit state (ULS): States associated with collapse or with other similar forms of structural failure [6].

Utilisation Ratio (UR): The ratio between an actual performance value and the maximum allowable performance value which is deemed limiting for a structural member [5].

We and **Us**: The community of people who, at any stage of a building's life cycle, have the ability or potential to impact on its total embodied energy.

Chapter 1: At a glance

1 Initial findings (IF)

Our initial findings, based on analysis and interpretation of a 36-question online survey that received 129 responses are:

IF1: There is a lack of consensus when considering material efficiency, demonstrated by most questions receiving responses across the entire possible spectrum (see **Q1**-**Q36**).

IF2: Ease of construction is more highly valued than material efficiency, and simplified designs usually favoured (see **Q4** and **Q7**). Member sizing is also influenced by a perceived risk of construction errors (**Q6**).

IF3: Clients do not ask for materially efficient structures (**Q8**, **Q9**, **Q11**) and there is no strong incentive for design teams to achieve them.

IF4: Estimates of average imposed floor loading are significantly greater than are measured in surveys of real buildings (**Q16**).

IF5: We face no significant penalties if structures are significantly overdesigned, and this may even be viewed as a positive attribute (**Q19**, **Q23**, **Q24**, **Q26**).

IF6: Using design codes to introduce upper limits on over design of members was not viewed as being feasible due to “increased complexity”. (**Q28-30**).

IF7: The number of sets of calculations undertaken in design may be less than 10% of the possible total (**Q32**) primarily due to grouping of members to save calculation time (**Q33**).

IF8: 40% of respondents would approach the design of their own house in a different way to their day-to-day work (**Q34-35**).

IF9: The design value for office floor loading that we use has not changed significantly since 4.8kN/m^2 was defined in 1909 (§4.4.1, **p.62**).

IF10: Vibration design is often undertaken using 10% of characteristic loads, demonstrating awareness of “realistic” loads for some limit states (§4.5, **p.65**).

IF11: The value savings that are possible by rethinking material efficiency are potentially similar to the entire fee income of all UK structural engineering design firms (§5.3.2, **p.80**).

2 Industry Questions (IQ)

Based on the survey data and analysis, a series of questions are identified where action and thought from industry is required if we are to address sources of wasted embodied energy, value-less cost, and performance over-design in construction. Please consider each question in turn, and engage with the **MEICON** team on those which most interest you.

IQ1: Could we collectively define benchmark structural utilisation values against which new structural designs could be compared, to drive material efficiency?

IQ2: How might a calculation of material use per m^2 best be presented to clients, to drive material efficiency?

IQ3: How might designers demonstrate they are contributing to meeting Construction 2025 targets?

IQ4: What might the benefit be of design code floor loading values being based on data gathered from a systematic global survey of loading levels in buildings?

IQ5: What might the unintended consequences be of changing live load values at ULS based on measured data?

IQ6: What might the unintended consequences be of changing live load values at SLS based on measured data?

IQ7: How might real time building loading information be integrated into building management systems to provide “traffic light” load levels to aid facility management?

IQ8: What measurements might be required to define realistic serviceability limit state acceptability criteria, to ensure that SLS design levels are appropriate and do not unreasonably dominate over strength design?

IQ9: What discussions are required with clients to understand allowable periods during which SLS requirements might not be met?

IQ10: How can digital tools be developed and used to better join up design, procurement, and construction, to avoid the need to “build in” spare capacity “just in case”?

IQ11: To what extent does connection design dominate overall member utilisation?

IQ12: How might we collectively design and build exemplar structures that achieve benchmark material consumption values (IQ1 and IQ2) to demonstrate full scale feasibility, with lessons learned being shared with the whole community?

IQ13: Would it be feasible to introduce both upper limits to member capacity, and target “average utilisation” factors across all members in a structure? What might the unintended consequences of this be?

IQ14: How might we agree on a “ratchet” of increasingly stringent design requirements, allowing time to adjust design culture whilst recognising the imperative need to reduce carbon emissions?

IQ15: Is there a perception that utilisation ratios of 1.00 ($E_d = R_d$) are dangerous? If so, why?

IQ16: To what extent might design calculations and checking of calculations be automated, using techniques such as machine learning?

IQ17: How can we save design data for future interventions in the building? Might it be feasible to embed embodied energy data, structural capacity, and energy use data in land registry records, for example?

IQ18: Who needs to participate at which design stage to ensure material efficiency and embodied energy are key design drivers?

3 Research Questions (RQ)

In addition to specific industry focused recommendations, a series of key research questions for academia and industry to tackle collaboratively are identified:

RQ1: How do we align the incentives of clients, architects, engineers, legislators, and contractors such that minimum embodied energy structures are the preferred outcome on all projects?

RQ2: How can continuous measurement of floor loading in real buildings be used to provide certainty to the statistical basis for SLS loading, and how can this data be used to understand the extent to which loading conditions are “peaky” so that decisions about SLS requirements can be made?

RQ3: What is the real envelope of floor loading for which most designs should be undertaken?

RQ4: What might the benefits and consequences be of reducing material and load partial safety factors?

RQ5: How should partial safety factors for workmanship change as construction becomes increasingly automated?

RQ6: How will design and construction automation, along with target values of material efficiency, affect the economics of structural engineering, particularly fee levels?

RQ7: Structural frames account for a small amount of project cost, but a large amount of embodied carbon. What is the value proposition for reducing material use if the cost impact is small?

RQ8: How can the implications of concept design decisions on material use and life cycle use be better understood by and illustrated to design teams?

RQ9: How might Failure Mode Effects Analysis (FMEA) be feasibly applied to the design of buildings to incorporate more detailed consideration of the consequences of failure and an appropriate level of risk?

RQ10: How can structural models be checked in an automated fashion? How can we reduce error rates in structural engineering design? Should there be a partial safety factor for analytical errors in all structural design, and how might this change over time as automation increases?

RQ11: To what extent can automation of construction and digital design be used to drive a cultural change to instil better confidence in construction competence?

RQ12: What is the roadmap to achieving a separation between ULS and SLS design, such that active control can be introduced appropriately?

RQ13: How might serviceability be more appropriately defined such that (whilst maintaining current ULS criteria) SLS is rarely the dominant limit state for most structures? What might the unintended consequences of this be?

RQ14: How can mass-customisation of building components be embedded into design, procurement, and construction processes to maximise value?

RQ15: What prototype demonstrator buildings are required to demonstrate to our community what better looks like?

RQ16: How might a construction contract that requires minimal embodied energy design be drafted?

RQ17: Can the success of the Merton Rule in renewables [10] be replicated to reduce embodied energy?

RQ18: What barriers exist to making material utilisation a more fundamental part of points-based methods of building assessment? Should we have a “MOT” for buildings?

RQ19: What is the role of big data, computer science, and machine learning in changing the process of design?

RQ20: How do people interact with buildings? How does this change when they are lightweight? Are there any unintended consequences of lightweighting that change the user experience?

RQ21: What should be taught in Universities to prepare new engineers for the demands of design. What disciplines will be needed to work collaboratively in the future design office?

4 Next steps

4.1 Vision

Our long-term vision is for the built environment to be designed cost-effectively, based on whole-life cycle energy consumption using minimum material resource for appropriate performance in a circular economy.

4.2 What you can do now

- *Analyse* your personal practice as it relates to embodied energy. Consider:
  - How often do you measure embodied energy? What are your own benchmarks for design efficiency? What barriers do you experience to achieving minimal embodied energy structures?
- *Analyse* your own responses to the survey questions against the findings.
- *Review* your personal practice by comparing it with those of your colleagues, both inside and outside your organisation. Include your choices of loading, serviceability criteria, extent of calculations across multiple elements and the importance of 'what-if' factors. Create a database of embodied energy per m^2 values for your projects.
- *Form* an action learning group to share experiences of trying to implement these principles in your design work. Share your findings with colleagues, examine differences, and identify best practice.
- *Feedback* your anonymised findings to the **MEICON** team (www.meicon.net) to help us collate international benchmarks.
- *Consider* our "Industry Questions". Choose those that interest you most. Discuss them with colleagues and clients, write an initial response in three bullet points, and circulate your ideas company-wide to generate discussion.
- *Examine* our "Research Questions". Choose those you feel able to help answer and enter your details at www.meicon.net to join a new research team.
- *Analyse* how your company's sustainability strategy addresses material efficiency in design. How might **MEICON** be used to help improve it?
- *Agree* to making at least one change to your practice based on these results.

4.3 Your input

This research is collaborative and requires the input of our community – please engage with the **MEICON** team by joining us at workshops and events. Full information is available on the project website, www.meicon.net.

Chapter 2: In detail

1 Introduction

Buildings and construction are estimated to account for nearly 40% of energy-related CO_2 emissions [11], Figure 1. About 13% of global GDP is generated by the construction industry, which creates and maintains our built environment [12]. Construction underpins the buildings and infrastructure that make all other sectors productive and their workers healthy. Past success in reducing *operational* energy consumption and the introduction of strict targets for near-zero energy buildings [13] mean that *embodied* energy is now approaching 100% of total energy consumption [14] (Figure 2).

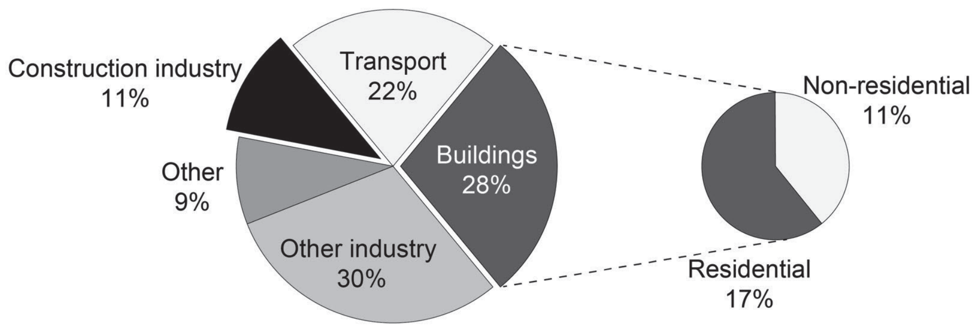

Figure 1: Share of global energy-related CO_2 emissions by sector, 2015 [11]

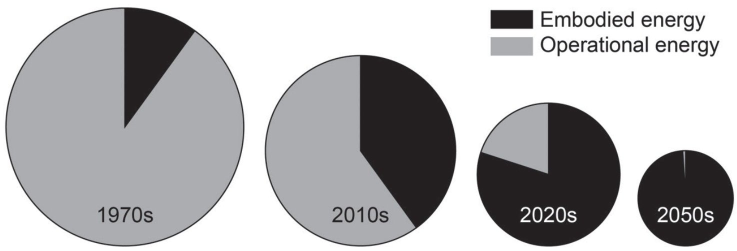

Figure 2: The increasing importance of embodied energy (approximate data for UK built environment) [15-17]

To meet the emissions targets set by the Paris Agreement [18] arising from the 21st Conference of the Parties, enhancements in the material production and use across different industries is necessary. The UK National Carbon Plan [19] proposes that by 2050 buildings will have near-zero emission footprints, meaning that embodied energy will soon outweigh operational energy use. The European Union has stated [20] requirements to reduce domestic emissions by 80% by 2050 (and 25% by 2020) when compared to 1990 levels.

However, the European cement industry has already identified that current technologies will not do enough to meet 2050 emissions reductions goals [21]. A focus on embodied energy minimisation (or structural lightweighting), which could reduce concrete consumption by 40% [22], driven by new analysis, optimisation, and automated construction methods will play a crucial role in meeting these targets, addressing our national need for ambitious research that can provide breakthrough technologies.

The importance of this fundamental shift in focus is highlighted by analysis of recently constructed steel and concrete buildings, in which it was demonstrated that embodied energy *wastage* in the order of **50%** is common [14, 22]. Inefficient overdesign of buildings and infrastructure must be tackled to minimise embodied energy demand and to meet future energy efficiency targets.

Achieving growth and *minimising* embodied energy will require a step change in procurement, design and construction that puts embodied energy at the centre of a holistic whole-life cycle design process.

The UK government has stated [1] that the construction industry should achieve, by 2025, a **33%** reduction in initial *and* whole life cost of assets, **50%** reduction in overall time from inception to completion of newbuild and refurbished assets, a **50%** reduction in greenhouse gas emissions, and a **50%** reduction in the import-export trade gap. These ambitious targets must be met at the same time as the global construction market is expected to grow in value by over 70% [1].

UK productivity has flat-lined since 2007 and now sits 17% below the G7 average [23]. UK construction sector productivity is poor, and this performance is replicated around the world (Figure 3). In addition, UK construction faces a looming workforce shortage with 1 in 5 workers expected to retire by 2023 [24]. This presents an opportunity for real change driven by new constructive solutions developed in an open source research-led manner to enable future competitive construction tendering.

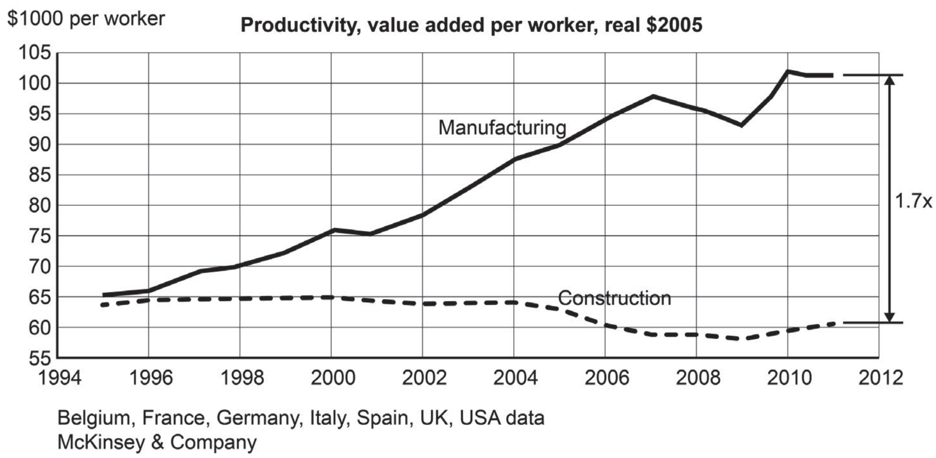

Figure 3: Productivity data for construction compared to manufacturing [25]

Finally, we face significant population pressures. Our global population is expected to reach 9.7billion by 2050, with 67% of us living in cities [26]. China alone could add 350million people to its urban population by 2030 [27]. Yet Europe's and Japan's population will both be smaller in 2060 than they are today, and the total population of China is expected to fall by 400million between 2030 and 2100 [26]. Depopulation of cities will occur alongside reductions in total populations for some countries. This presents a complex problem for the design of the built environment, in which buildings and infrastructure constructed today are expected to be in use for 60-120 years: providing structures that are resilient, healthy, and productive in the medium term, but demountable and potentially reusable in the long term.

To achieve the required levels of innovation in analysis, design, and automation of construction will require significant new investment in large structural engineering research projects.

MEICON has identified a series of areas where feasibility studies are required to define these large-scale research needs to enable significant energy savings in the construction industry before 2025. **MEICON** will identify a series of 'low-hanging fruit' research areas, in priority order, for embodied energy savings, and work with our industrial partners to develop feasible pathways to implementation in the construction industry.

1.1 Structural design

In structural design, minimum performance requirements are established by codified design rules for all structural elements. These set out how to calculate the design effect (E_d) of actions (e.g. wind, imposed loads, or temperature) on an element for which the resistance (R_d) of that element must be greater than or equal to. A similar relationship is used for serviceability calculations. These requirements establish how strong and stiff each element should be. However, they do not establish *upper limits* on these criteria that each element may not exceed. In other words, there are no requirements for designers to be efficient in their use of embodied energy. This creates the potential for *code-satisfying* but *materially-inefficient* structural elements, a scenario that is frequently encountered [17]. In examining 10,000 steel beams in real buildings, Moynihan and Allwood [14] demonstrated average material utilisations of less than 50% of capacity. Dunant *et al* [5] further show that 35-45% of the steel by mass for the steel frame is not required in terms of structural efficiency. Based on designs for 3,500 steel beams from 27 office and educational buildings, an apparent reluctance to design beams above utilisation ratios of 0.80 was observed [5]. 63% of the beam designs considered by Dunant *et al* [5] were dominated by serviceability, rather than strength, requirements.

The evidence shows that significant embodied energy savings could be made within the frameworks of *existing* European design codes. Work by Orr *et al* [22] further demonstrates that the utilisation of structural concrete members is also often very low, with the potential to achieve material savings of 30-40% through design optimisation.

In the calculation of design effects of actions (E_d) and corresponding resistances (R_d), partial safety factors are used to ensure the reliability of the resulting design [4] by reducing the characteristic material properties (X_k) and increasing the characteristic value of actions (F_k) to provide design values (Figure 4). Partial safety factors are not intended to make poorly designed structures safe.

Structures where $E_d = R_d$ (for strength) **and** $E_d = C_d$ (for serviceability) are entirely code compliant, highly optimised, and provide the required levels of reliability - but are rarely seen. Instead, structures often consistently demonstrate that $E_d << R_d$ and embodied energy is unnecessarily wasted. Serviceability criteria are one aspect of design that must be examined in detail. Working within *existing codified design rules* to ensure immediate impact **MEICON** proposes to reduce this performance gap.

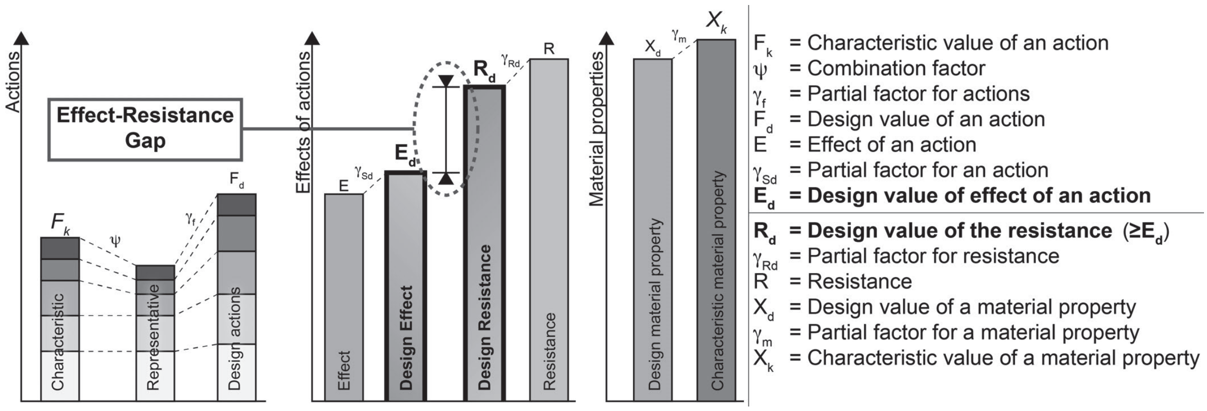

Figure 4: The "effect-resistance gap"

We must tackle the underlying reasons and sources of this wastage to minimise embodied energy. This includes addressing the rationality of loading models and their statistical basis. **MEICON** may not tackle the partial (γ) or combination (ψ) factors that lie on either side of these equations; whilst they offer opportunities for material savings, the low hanging fruit in structural engineering is to be found the design inefficiency and culture that leads to $E_d << R_d$. This challenge must be embraced to provide results within the timeframes required by climate science.

1.2 Structural geometry

Exploitation of structural geometry may occur at two levels of complexity: 1) choices of structural form and overall geometry; 2) sizing and shaping of individual members within a building. Choices made early in the design phase of a structure can have significant impacts on total material consumption [28].

Design rationalisation, in which many structural elements are sized based on the load levels in the worst-case member, is common and causes significant wastage [14]. To design structures in which the effect-resistance gap is minimised (i.e. E_d and R_d as close to each other as possible, everywhere) under an envelope of loading will ultimately require the exploitation of geometry.

Utilisation ratios are calculated with an underlying assumption of sensible choices of structural form. As an example, a floor beam bent about its minor axis may exhibit a utilisation ratio of 1.00. However, simply rotating the beam by 90º to bend about its major axis would reduce the elastic utilisation by 90% [29]. Understanding how sensible choices of structural form are made in the design stage is therefore a key part of ensuring materially efficient designs.

The capability to manufacture variable section steel beams exists [15, 30]; as does the ability to cast concrete into any geometry [31]. Both levels of geometrical exploitation now require feasibility studies to establish research needs associated with their efficacy. *What shape should structures be to work efficiently? How does this affect construction? Can components be made composite to improve efficiency whilst maintaining the need for whole life deconstructability? Is there still a place for on-site casting of concrete?*

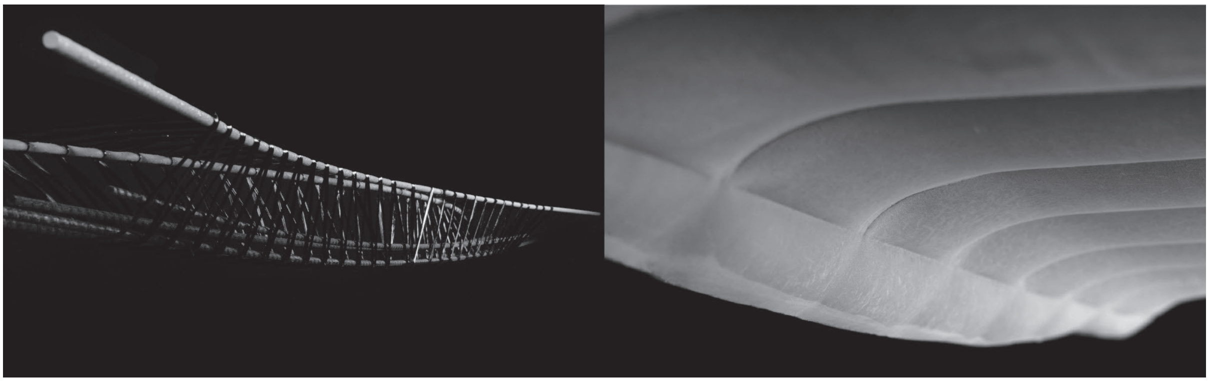

Figure 5: Left: Internal reinforcement for optimised concrete structure [32]; Right: Flexibly formed optimised concrete T-Beam [33]

1.3 Construction

About 36 million people are employed in the European construction market [34], yet the construction industry is highly disparate, with 94% of construction companies operating in Europe having fewer than nine staff [35]. The employees of these 9.2M small- and micro-companies make up 46% of the European construction workforce [35]. This disparate industry is heavily influenced by its construction heritage. Flat slabs, for example, are popular with clients, engineers and contractors for many reasons, not least because they are seen as quicker, more affordable and lower risk than alternatives. However, they consume vast amounts of concrete (floor plates typically make up around 60% of the material in a building) and are rarely optimised.

The construction and use of buildings generates around a **third** of all material waste in the EU, giving rise to environmental pressures at every life-cycle stage [36]. Prevention of waste at the *design stage* is essential for the efficient use of resources. This must be matched by an ability to recycle and reuse these materials at later stages, and by incorporating recycled building components into new constructions. This requires a fundamental change in construction attitudes and practices. It may preclude some current construction practices, including for example the in-situ casting of continuous concrete frames which are difficult to demolish for effective reuse. The need for research into whole-life design of structures to consider both operational and embodied energy has been identified at UK and EU level [36, 37], yet the built environment is only at the very start of a journey towards a circular economy [38]. This transition requires immediate research, and will take many years, making the feasibility studies of **MEICON**, in which the critical research requirements are defined, timely. The potential future economic benefits are significant: a mere 1% rise in *global* construction industry productivity could save about $100bn *per year* [39].

1.4 Design culture

Unlike jet engines, which are leased from their manufacturer, constantly monitored, maintained and updated, the construction of buildings is largely unlinked to whole life costs. Short term views are taken by designers and contractors, who neither occupy nor rent the structures they design. Anecdotal evidence from our industrial partners suggests that over-sizing of structural members is often undertaken ‘just in case’ loads or layouts change during the design phases. This strategy, understandable perhaps when hand calculations were required, is outdated. Evidence from large studies suggests that utilisation ratios are rarely taken above 80% [5], even when highly automated design is available [40].

MEICON sets out to inform design culture, providing evidence for new design decision making processes to make better use of automation in structural design, and linking this directly with Building Information Modelling (BIM) as a key enabler of the transformation being sought.

1.5 **MEICON** Project Phase 1

In response to the above challenges, the EPSRC funded **MEICON** project began in 2017 to tackle the “low hanging fruit” that will lead to significant change in structural design. Phase 1 of this project was to examine current culture and practice in structural engineering design relating to embodied energy. This was undertaken through an online survey which asked questions about current design practice.

The remainder of Chapter 2 details the design of the survey, the data collected, and the analysis and discussion of this data that lead to initial findings (IF). In §4 Industry Questions (IQ) are posed, and in §5 Research Questions (RQ) are posed, alongside the relevant analysis. All data presented here are available on the project website, www.meicon.net.

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2 Survey design

2.1 Introduction

The initial **MEICON** survey was divided into seven sections, six of which asked questions relating to **MEICON** with the seventh used to gather population characteristics. All questions were optional, and were grouped as follows:

Table 1: Question grouping

Section	Title	Number	Data
1	General Questions	11	§3.2
2	Loading	8	§3.3
3	Serviceability	3	§3.4
4	Design	4	§3.5
5	Capacity	4	§3.6
6	Design examples	6	§3.7
7	Population	7	§3.1

The following definitions were provided in the introduction to the survey:

- “Embodied energy” refers to the energy required to initially produce a building. It includes the energy used for the abstraction, the processing, and the manufacture of the materials of the building as well as their transportation and assembly on site.
- “Material utilisation” is the ratio between an actual performance value and the maximum allowable performance value (for example, the maximum design effect of an action on a beam ("E_d") divided by the beam’s design resistance ("R_d")).
- "Design effect of actions" ("E_d") Is the factored effect of actions (where actions are applied loads, imposed deformations, or imposed accelerations) on structural members. For example internal forces, moments, stresses, strains.
- "Design resistance" ("R_d") Is the factored capacity of a member or component, or a cross-section of a member or component of a structure, to withstand actions.
- "Characteristic" values of an action are un-factored, and are modified by a partial factor to obtain "Design" values.

2.2 Survey questions

Section	Question	Response type
1	Maximising material utilisation is a key design criterion for me	7-point Likert (Strongly disagree – Strongly agree)
	The material utilisation of each structural element in my designs is normally close to 1.00	
	The oversizing of structural elements during initial or concept design stages is normally appropriate	
	An easily constructed structure is more valued by the whole design team than a materially efficient structure	
	Reducing the dimensions of structural elements agreed at concept design stage during detailed design is best avoided	
	The potential for construction errors influences my structural member sizing decisions	
	I simplify my structural designs to improve constructability	
	My clients or design team normally require me to minimise total embodied energy	
	The material utilisation of a structural design is normally presented to clients	
	The best way to reduce total material consumption is to ensure that structural material utilisation is high	
	Clients normally insist on low-carbon structural designs	
2	How often do you think that values for imposed vertical floor design loads given in your local design code of practice are appropriate?	7-point Likert Never - Always
	In your experience how often are imposed design loads for floor plates decided by the client	7-point Likert Never - Always
	Imagine you are designing a new multi-storey office building for a financial services firm in the centre of a city. What CHARACTERISTIC value of imposed vertical floor design load in the office spaces would you use, excluding any allowance for moveable partitions?	Numerical
	For the same building, what additional CHARACTERISTIC value for moveable partitions would you use?	Numerical

Section	Question	Response type
	The same building is put into service, and is used as an office space for 60 years. What do you think the AVERAGE area load on the floor of the office would be, over the life of the structure, as measured during office hours?	Numerical
	The same building is put into service, and is used as an office space for 60 years. What do you think the MAXIMUM area load on the floor of the office would be, over the life of the structure, as measured during office hours?	Numerical
	Thinking about your local design code of practice, what percentage change in vertical loading values do you expect to see in the next ten years	Numerical
	Imagine you are solely responsible for rewriting your local structural design code. What percentage changes, if any, in imposed design loading would you introduce?	Numerical
3	In your experience, how often does the serviceability limit state govern the size of structural elements?	7-point Likert Never - Always
	In your experience which of the following SLS criteria most often governs the design of structural elements in buildings?	*Matrix:* [Reinforced Concrete, Steel, Timber] [Deflection, Vibration, Cracking, None]
	How frequently would you be comfortable with allowing the following structural serviceability limits to be exceeded in an office building throughout its lifetime?	*Given list:* • The majority of the time • A few minutes per day • An hour per day • A few minutes per week • A few minutes per year • A few minutes over the lifetime of the building • Never
4	You are asked to design the floor plate in a multi-storey building. Which one of the following has the biggest influence on your final design:	*Given list:* • Ease of construction • Material consumption • Cost to client

Section	Question	Response type
		• Design time • Other
	Imagine you are undertaking the detailed design of a flexurally dominated floor beam. The flexural design effect of the actions ("Ed") on the beam at mid-span is 200kNm (including partial factors). The beam is to be a fabricated steel section. What value for the flexural design resistance ("Rd") of the beam at mid-span (including partial factors) would you choose?	Numerical
	Thinking about your professional practice, how frequently do elements in your completed structural designs have a design resistance that is EQUAL to the design effect of actions on the element?	7-point Likert Never - Always
	Thinking about your professional practice, which of the following would be the prime reason for an element to have a design resistance that is greater than the design effect of the actions on the element?	*Given list:* • The span, loading, or layout might change before construction. • I am uncomfortable with the design effect of the actions being equal to the design resistance of the element. • I don't trust the factors of safety in design codes • I like to build in a bit of spare capacity just in case. • The building might change use later in its life. • Other
5	How feasible do you think it would be to introduce into design codes a limit on how much greater the Design Resistance of a structural element could be as compared to its required capacity? This would prohibit engineers from designing elements with a capacity greater than this upper limit.	7-point Likert Not at all - Completely
	Imagine that such a limit is introduced into a design code. The Design value of resistance ("Rd") for each element must be greater than the Design effect of the action	Numerical (must be ≥1.00)

Section	Question	Response type
	("Ed") AND less than "Beta" multiplied by "Ed", where "Beta" is a number ≥1.00. This relationship is shown in the equation below. What value of "Beta" would you be happy, as a structural designer, to see in a design code?	
	What might the unintended consequences of a limit to the design value of resistance relative to the design effect of the actions be, in your opinion?	Free text
	Imagine instead that an average material utilisation across all structural elements is introduced as a codified design requirement. What minimum value of material utilisation should be achieved by structural designers?	Numerical (must be ≤1.00)
6	How deep (in mm) would you expect a two-way spanning flat slab in an inner-city office building to be, if the column spacing below it is 7m x 7m?	Numerical
	Imagine you are designing the steel beams in a floor plate of the multi-storey office building shown below. This floor plate is repeated multiple times. There are a large number of beams with varying spans. The floor load is constant across the area. Thinking about the beams only, approximately how many sets of calculations would you probably undertake to size the beams across the floor plate?	Numerical
	Please provide a short justification for your decision	Free text
	Thinking about your experience of the structural engineering profession more generally, how many different section depths would you expect to see in the as-built structure, regardless of the number of calculations performed?	Numerical
	Imagine you are the structural designer for your OWN house. Would your approach to assumed loads and individual sizing of members be any different from your day-to-day professional role?	*Given list:* • Yes • No
	Please provide examples of what you might assume or do differently in the design of your own house	Free text

Section	Question	Response type
7	Your profession	*Given list:* • Structural Engineer • Civil Engineer • Contractor • Architect • Other
	Country	*Given list:* (all countries in the world)
	Your position	*Given list:* • Graduate • Senior Engineer • Associate • Associate Director • Director • Executive Officer • Other
	Your role	*Given list:* • Feasibility studies • Concept design • Detailed design • Pre-design client discussions
	Your gender	*Given list:* • Male • Female • Prefer not to say
	Your age	*Given list:* • 16-24 • 25-34 • 35-44 • 45-54 • 55-64 • 65-74 • 75-84 • 85+
	Total number of years experience in the profession	*Free text*

3 Survey responses

This section presents the full survey response data as collected in the first window period from 1st August 2017 – 25th October 2017. Data on the respondents' background was collected at the end of the survey (Section 7) but is presented first here for context. There were 129 responses to the survey. All questions were optional, and the number of responses is noted alongside each question (*n*). The number who didn't respond is given by 129 – *n*, for each question.

The survey data presented below, with any identifying comments removed, may be downloaded from the data archive at https://doi.org/10.17863/CAM.25734. Analysis of this data is presented in §4.

3.1 Section 7: Survey population

Questions relating to the respondent background were asked at the end of the survey but are presented initially here for context. The same layout is used in the analysis presented in §4.

3.1.1 Your profession (n = 129)

Table 2

Choice		**Responses**	**%**
Structural Engineer		115	89%
Civil Engineer		7	5%
Contractor		1	1%
Architect		0	0%
Other:	Academic	2	2%
	Student	3	2%
	Bridge Engineer	1	1%
		129	**100%**

Of the 129 responses, 89% were from people identifying as structural engineers. "Academic" was deliberately not included due to the focus of the survey. Six people chose "Other", and their responses are shown in Table 2.

3.1.2 Country (n = 126)

Table 3

Country	**Responses**	**%**
United Kingdom	93	74%
United States	8	6%

Country	Responses	%
Sri Lanka	5	4%
Hong Kong	4	3%
Australia	4	3%
Ireland	3	2%
India	2	2%
China	1	1%
South Africa	1	1%
United Arab Emirates	1	1%
Azerbaijan	1	1%
Greece	1	1%
Denmark	1	1%
Canada	1	1%
	126	**100%**

3.1.3 Your position (n = 129)

Table 4

Response		Number	%
Graduate		33	26%
Senior Engineer		32	25%
Associate		14	11%
Associate Director		8	6%
Director		20	16%
Executive Officer		3	2%
Other	Principal Engineer	3	2%
	Academic	5	4%
	Sole Practitioner	6	5%
	Undergraduate	2	2%
	Manager	3	2%
		129	**100%**

The survey saw a good spread of responses, with concentrations at Graduate/Senior Engineer and Director level. Responses under “other” were grouped into five categories with at least two responses in each.

3.1.4 Your role (n = 128)

Table 5

Response	Number	%
Feasibility studies	13	10%
Concept design	48	38%

Response	Number	%
Detailed design	58	45%
Pre-design client discussions	9	7%
	128	**100%**

3.1.5 Your gender (n = 128)

Table 6

Response	Number	%
Male	108	84%
Female	17	13%
Prefer not to say	3	2%
	128	**100%**

Whilst gender balance reflects the industry, more could have been done in the undertaking of the survey to specifically target female responses for example by working with groups such as Women in Engineering.

3.1.6 Your age (n = 129)

Table 7

Response	Number	%
16-24	10	8%
25-34	49	38%
35-44	23	18%
45-54	20	16%
55-64	18	14%
65-74	7	5%
75-84	1	1%
85+	1	1%
	129	**100%**

3.1.7 Total number of years experience in the profession (n = 128)

Table 8

Response (years up to)	Number	%
0	1	1%
2	11	9%
4	21	16%
6	14	11%
8	3	2%

Response (years up to)	Number	%
10	15	12%
15	8	6%
20	12	9%
30	21	16%
40	13	10%
50	7	5%
60	2	2%
Total	**128**	**100%**

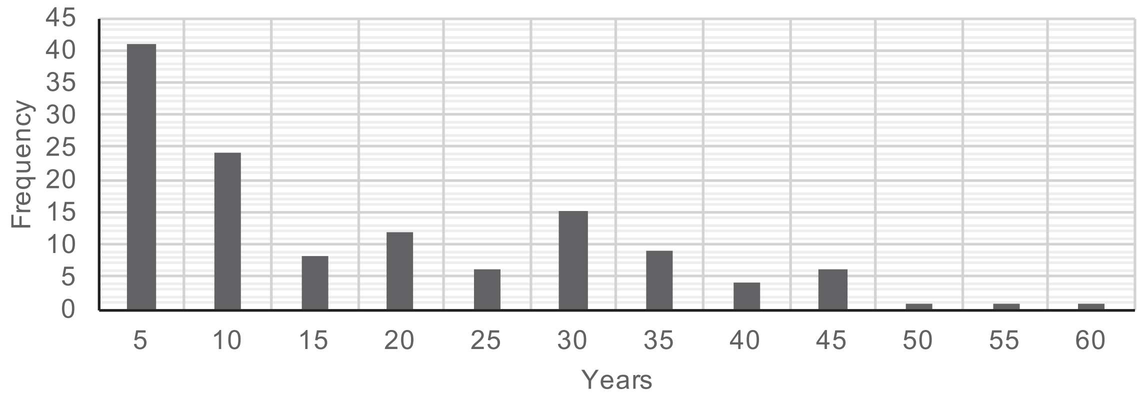

Figure 6: Histogram of years experience in the profession

The average number of years of experience was 16.6, standard deviation of 14 years.

3.2 Section 1: General Questions

Respondents were asked eleven General Questions, all of which were given on a 7-point Likert Scale graded from “Strongly Disagree” to “Strongly Agree”. The Median value is given beneath each plot. Analysis of these questions is presented in §4.

3.2.1 Question 1: Maximising material utilisation is a key design criterion for me (frequency, n = 129)

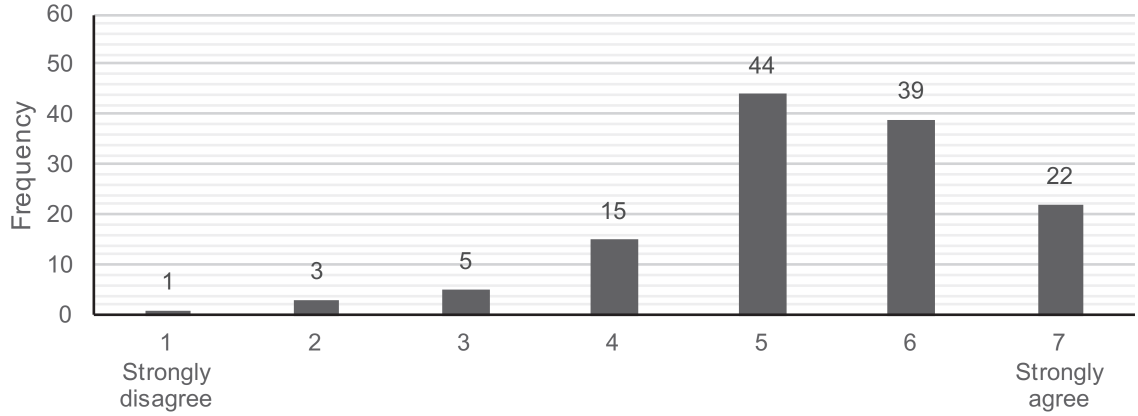

Figure 7: Q1

Median = 5

3.2.2 Question 2: The material utilisation of each structural element in my designs is normally close to 1.00 (n = 129)

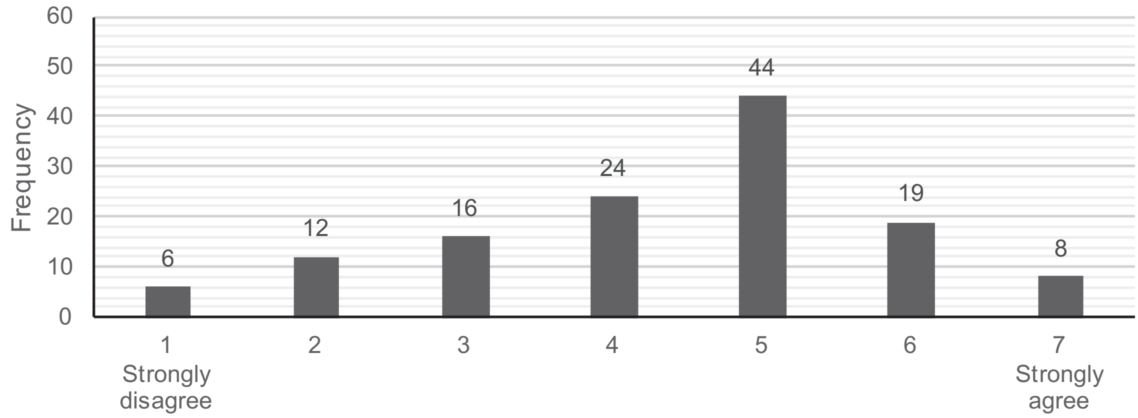

Figure 8: Q2

Median = 5

3.2.3 Question 3: The oversizing of structural elements during initial or concept design stages is normally appropriate (n = 129)

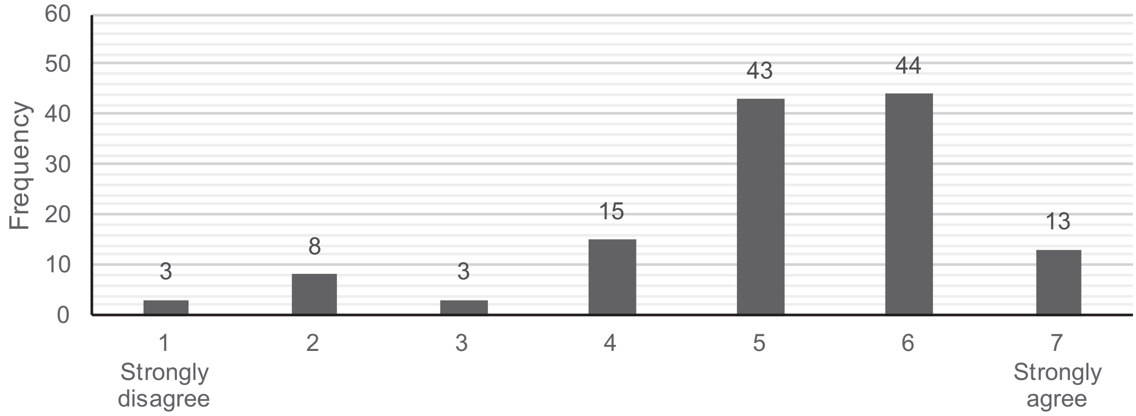

Figure 9: Q3

Median = 5

3.2.4 Question 4: An easily constructed structure is more valued by the whole design team than a materially efficient structure (n = 129)

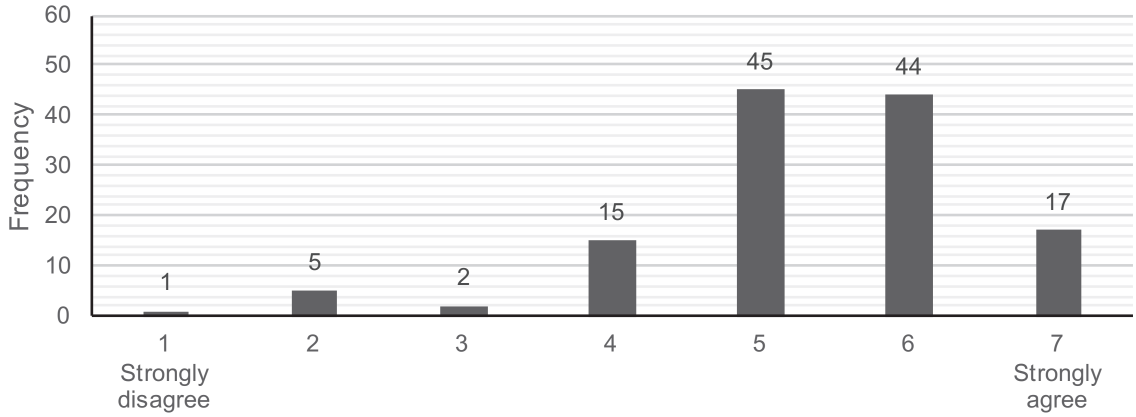

Figure 10: Q4

Median = 5

3.2.5 Question 5: Reducing the dimensions of structural elements agreed at concept design stage during detailed design is best avoided (n = 129)

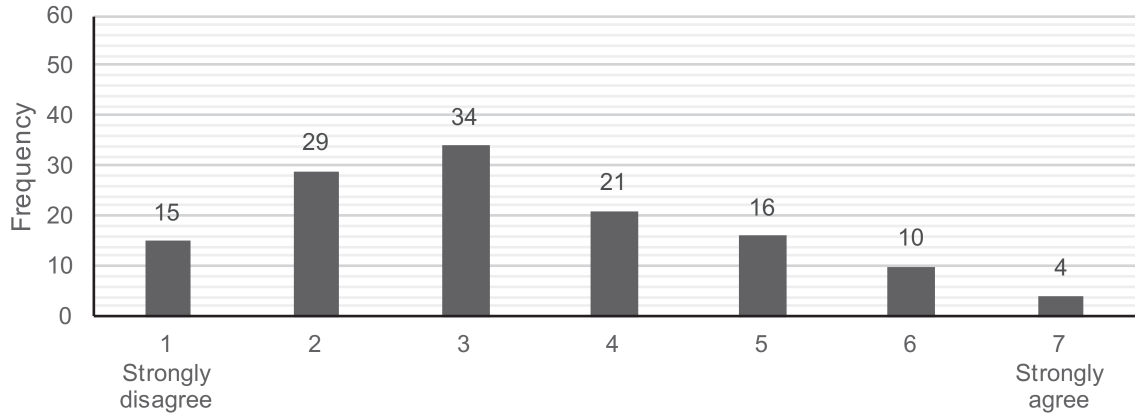

Figure 11: Q5

Median = 3

3.2.6 Question 6: The potential for construction errors influences my structural member sizing decisions (n = 128)

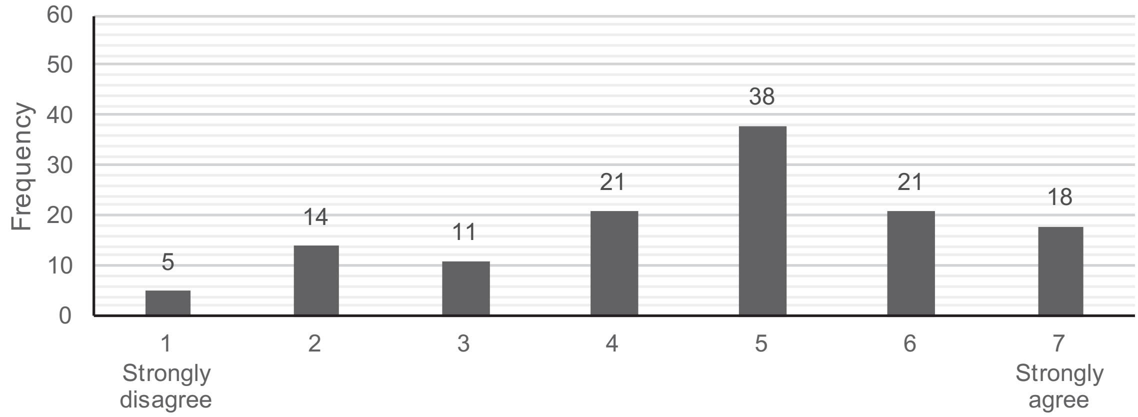

Figure 12: Q6

Median = 5

3.2.7 Question 7: I simplify my structural designs to improve constructability (n = 129)

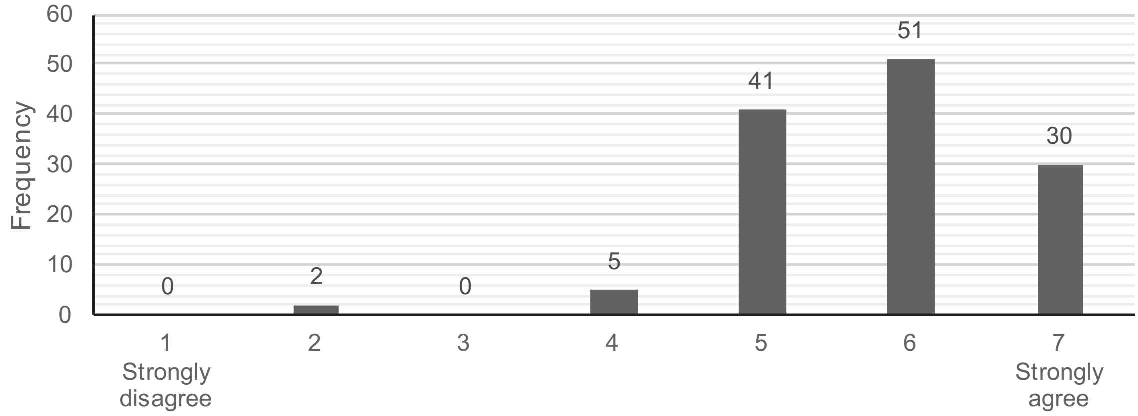

Figure 13: Q7

Median = 6

3.2.8 Question 8: My clients or design team normally require me to minimise total embodied energy (n = 129)

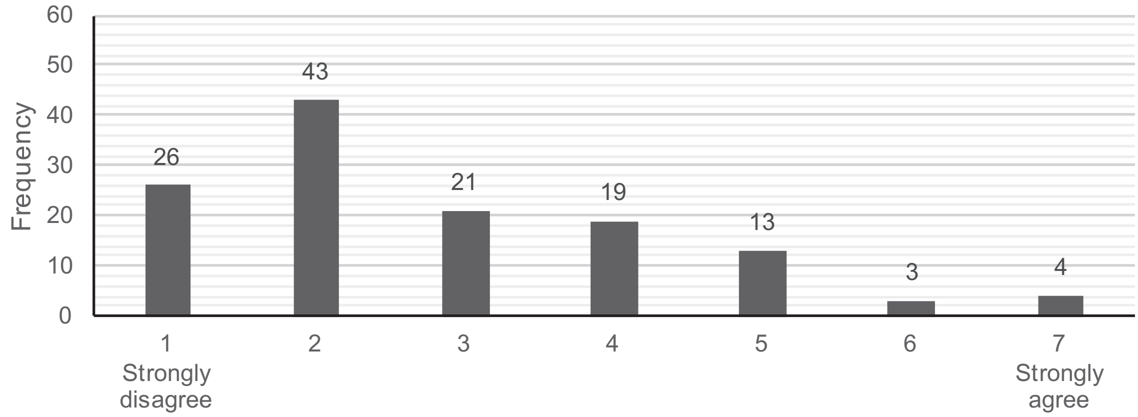

Figure 14: Q8

Median = 2

3.2.9 Question 9: The material utilisation of a structural design is normally presented to clients (n = 129)

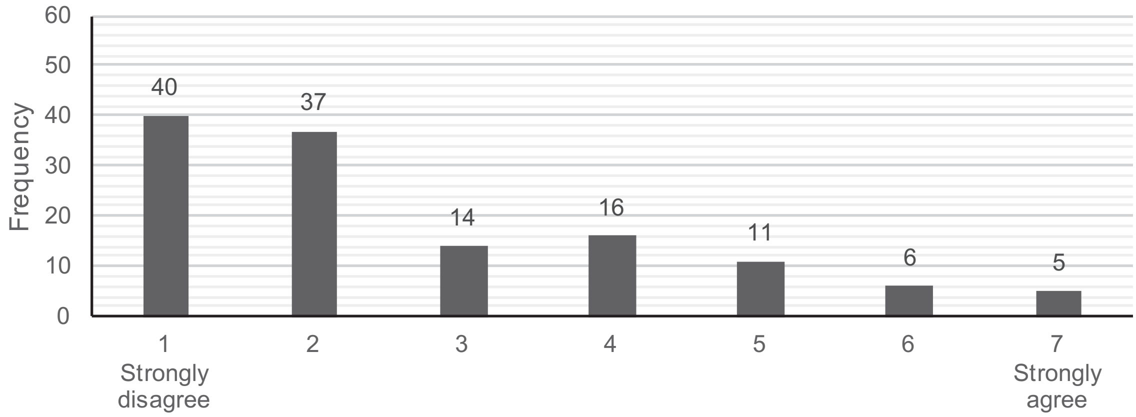

Figure 15: Q9

Median = 2

3.2.10 Question 10: The best way to reduce total material consumption is to ensure that structural material utilisation is high (n = 129)

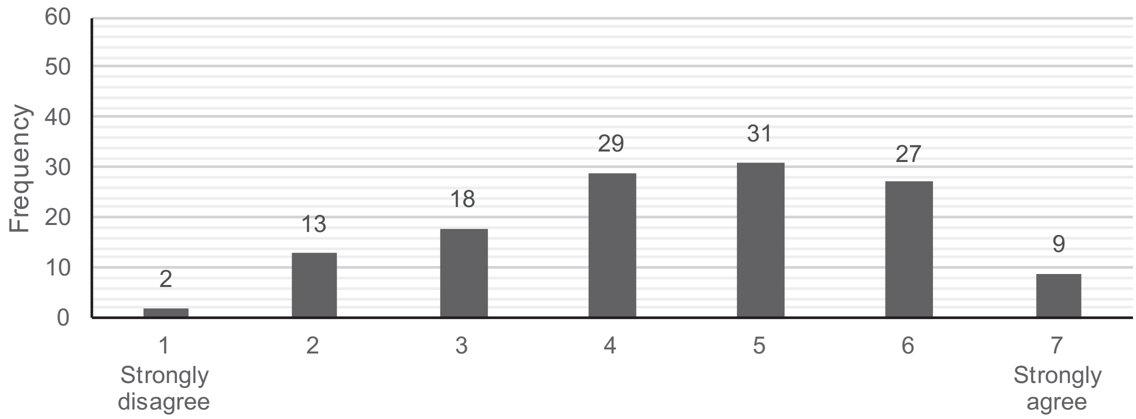

Figure 16: Q10

Median = 5

3.2.11 Question 11: Clients normally insist on low-carbon structural designs (n = 129)

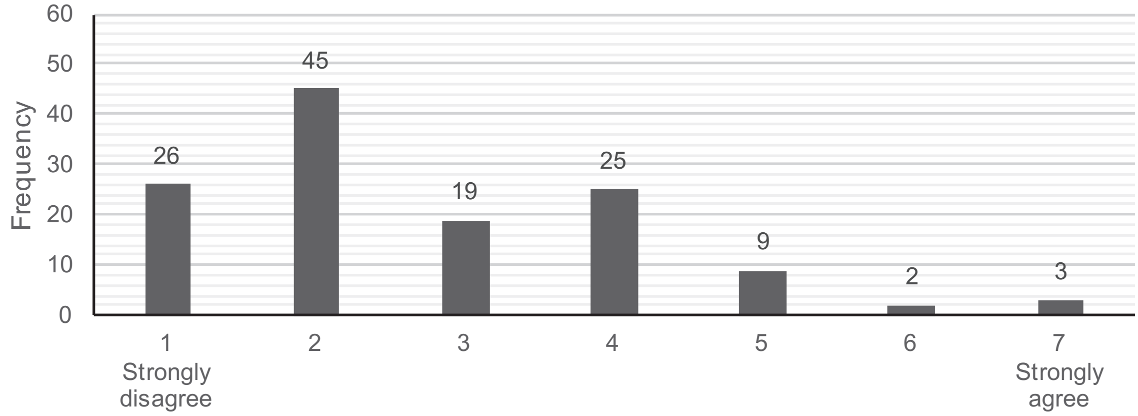

Figure 17: Q11

Median = 2

3.3 Section 2: Loading

In this section participants were asked eight questions, two of which were graded on a 7-point Likert scale, four of which asked for numerical responses relating to floor loading values, and two of which asked for percentage change responses relating to imposed floor loading given in future design codes. Analysis of these questions is presented in §4.

3.3.1 Question 12: How often do you think that values for imposed vertical floor design loads given in your local design code of practice are appropriate? (frequency, n = 128)

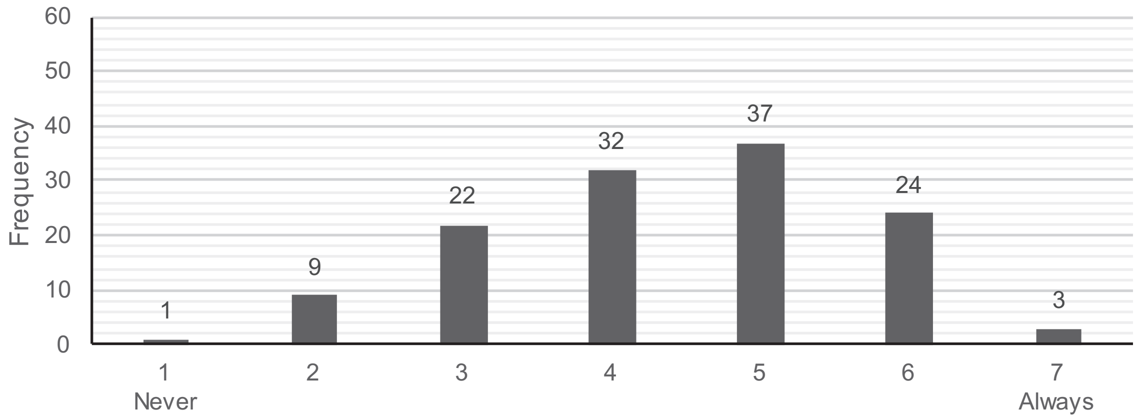

Figure 18: Q12

Median = 4.50

3.3.2 Question 13: In your experience how often are imposed design loads for floor plates decided by the client? (n = 128)

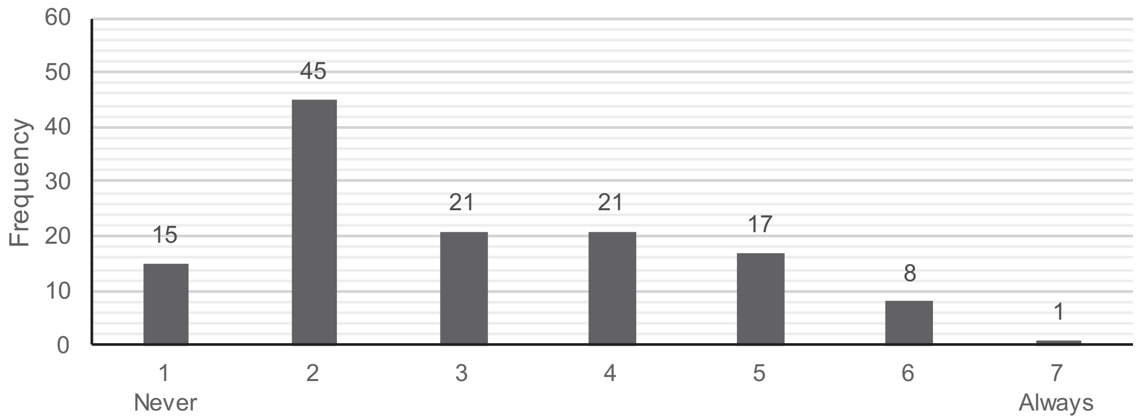

Figure 19: Q13

Median = 3

3.3.3 *Question 14: Imagine you are designing a new multi-storey office building for a financial services firm in the centre of a city. What CHARACTERISTIC value of imposed vertical floor design load in the office spaces would you use, excluding any allowance for moveable partitions? (n = 124)*

This question allowed the participants to enter their response as a number. The histogram distribution of responses is shown below.

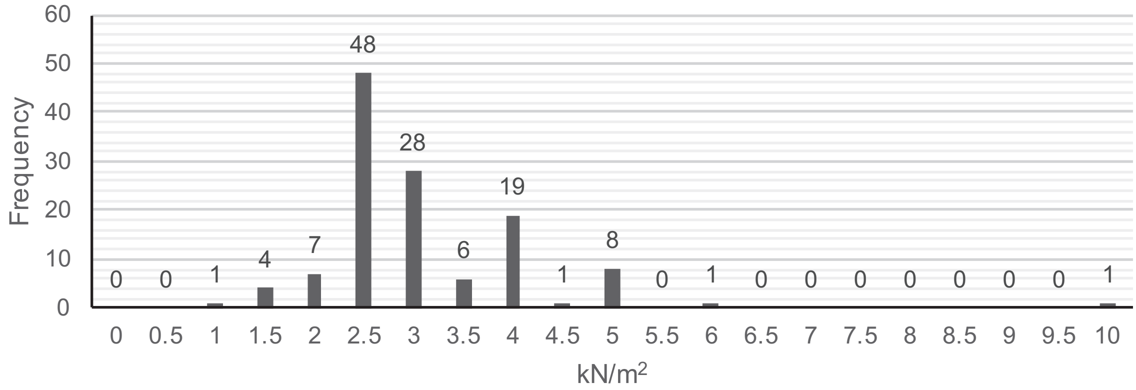

Figure 20: Q14 histogram

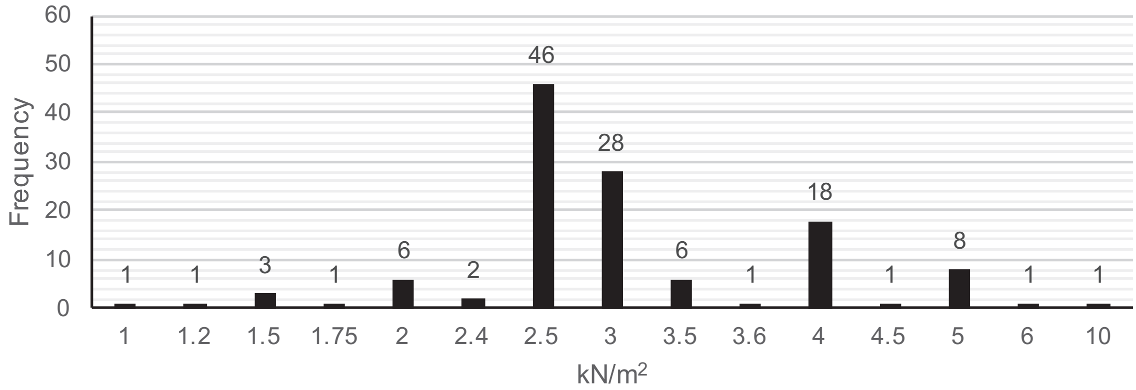

Figure 21: Q14 responses grouped by answer, note irregular x-axis

Average = 3.08kN/m^2
Median = 3.00kN/m^2

3.3.4 Question 15: For the same building, what additional CHARACTERISTIC value for moveable partitions would you use? (n = 124)

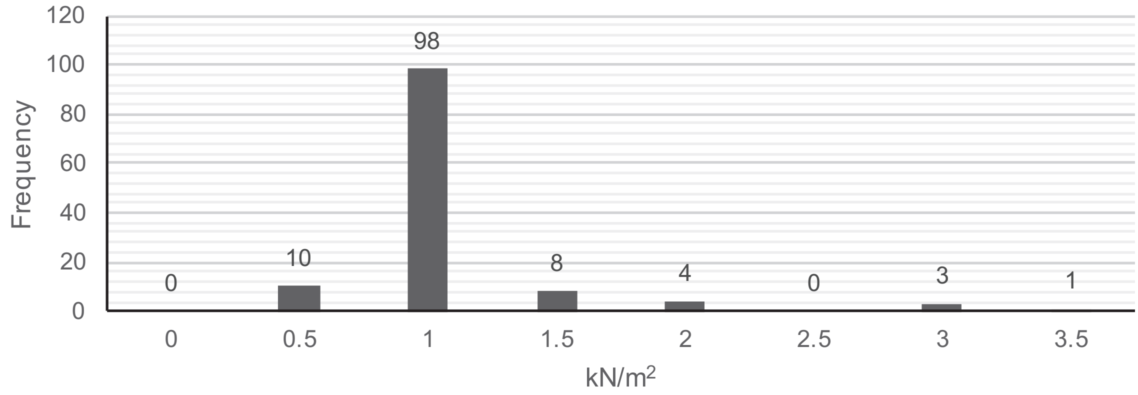

Figure 22: Q15

Average = 1.08kN/m^2
Median = 1.00kN/m^2

3.3.5 Question 16: The same building is put into service, and is used as an office space for 60 years. What do you think the AVERAGE area load on the floor of the office would be, over the life of the structure, as measured during office hours? (n = 122)

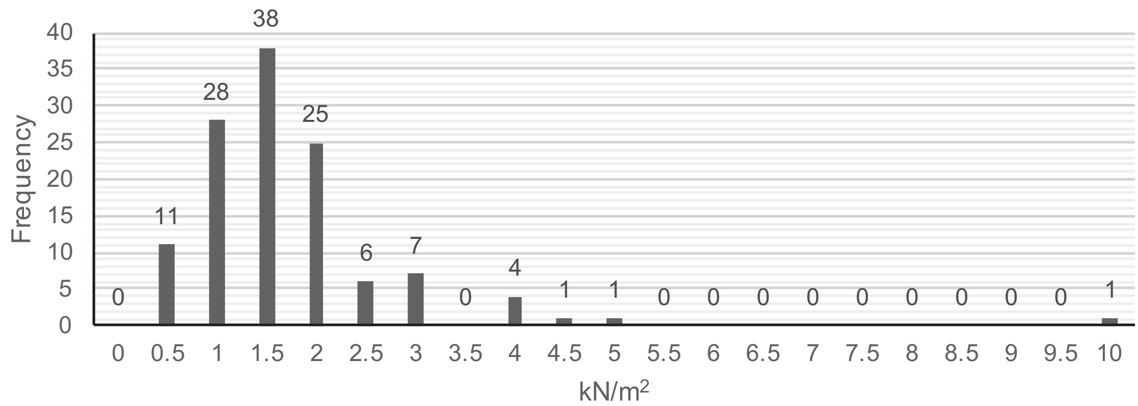

Figure 23: Q16 histogram

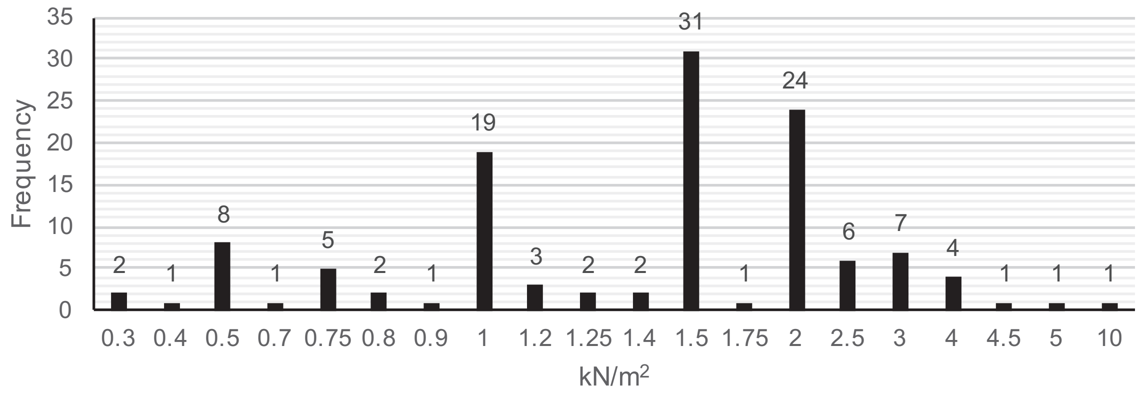

Figure 24: Q16 responses grouped by answer, note irregular x-axis

Average = 1.70kN/m^2
Median = 1.50kN/m^2

3.3.6 Question 17: The same building is put into service, and is used as an office space for 60 years. What do you think the MAXIMUM area load on the floor of the office would be, over the life of the structure, as measured during office hours? (n = 122)

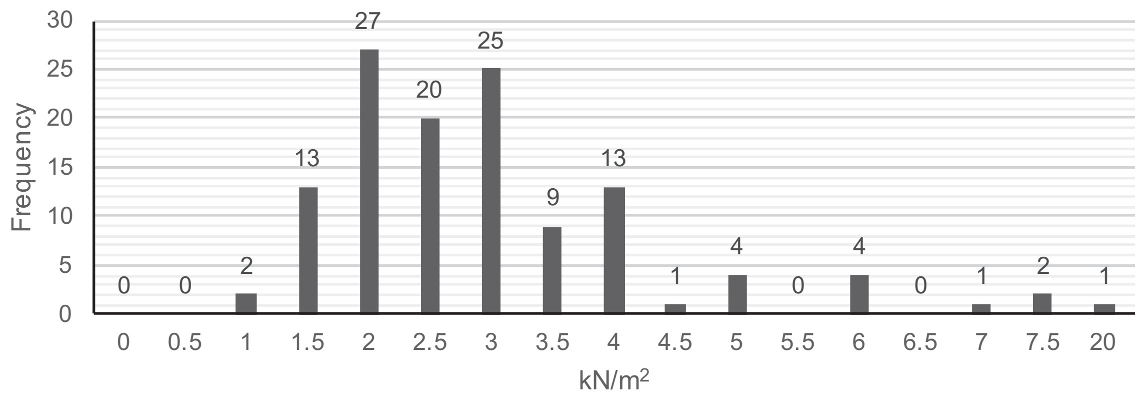

Figure 25: Q17, noting the gap between the final two groups (7.5 and 20)

Average = 3.05kN/m^2
Median = 2.50kN/m^2

3.3.7 Question 18: Thinking about your local design code of practice, what percentage change in vertical loading values do you expect to see in the next ten years? (n = 121)

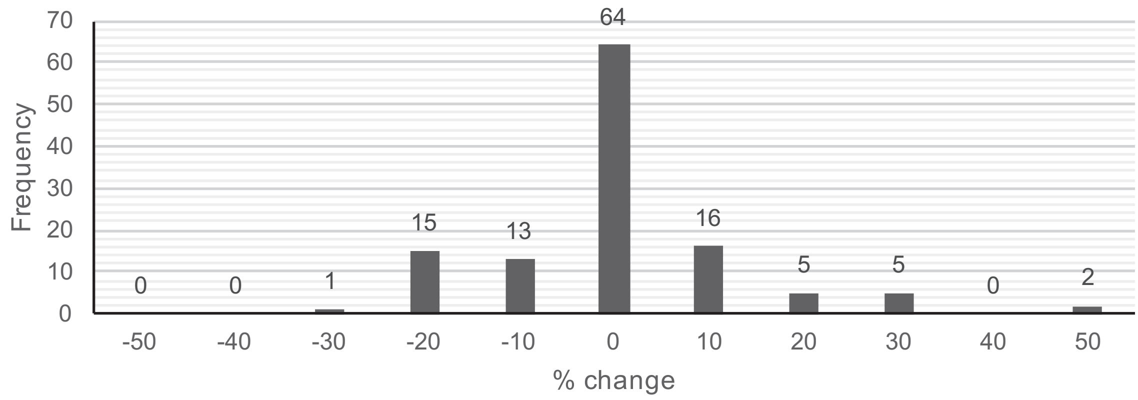

Figure 26: Q18

Average = -0.21%
Median = 0%

3.3.8 Question 19: Imagine you are solely responsible for rewriting your local structural design code. What percentage changes, if any, in imposed design loading would you introduce? (n = 121)

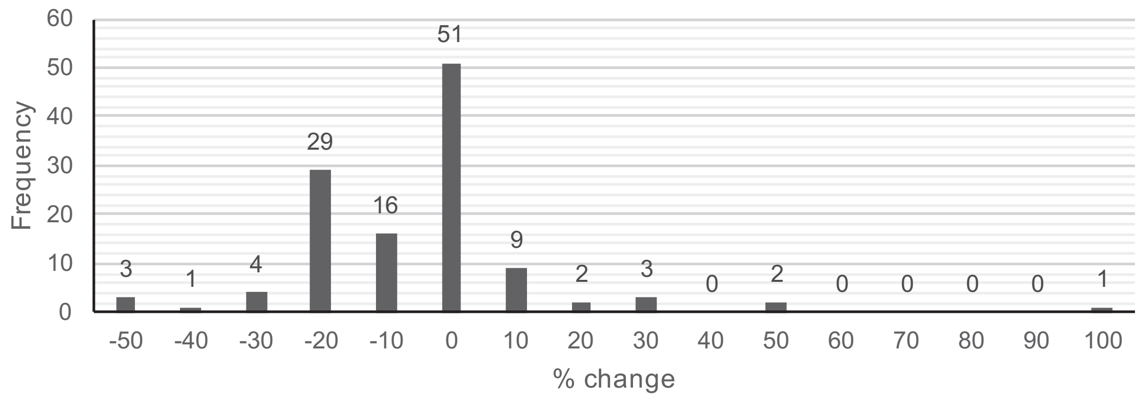

Figure 27: Q19

Average = -6.3%
Median = 0%

3.4 Section 3: Serviceability

Three questions were asked about serviceability, one with a 7-point scale, one covering SLS limits, and one covering acceptable duration of exceedance of SLS limits. Analysis of these questions is presented in §4.

3.4.1 Question 20: In your experience, how often does the serviceability limit state govern the size of structural elements? (frequency, n = 127)

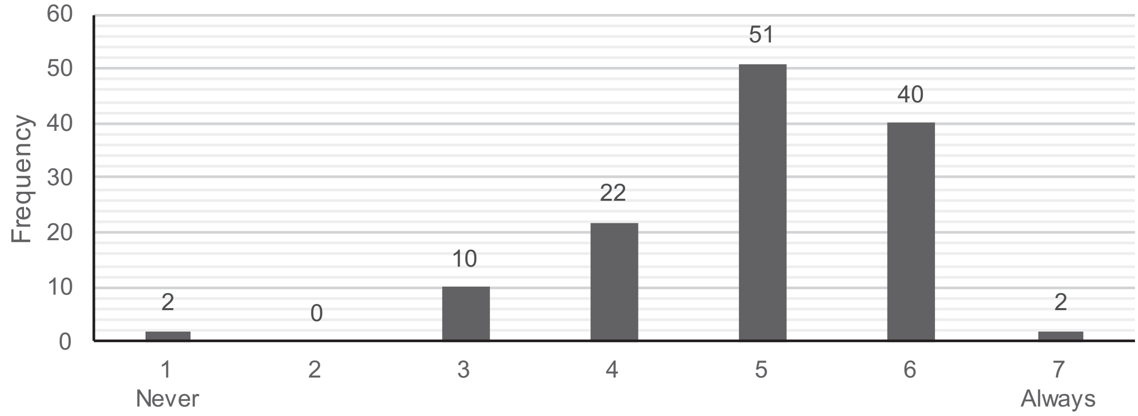

Figure 28: Q20

Median = 5

3.4.2 Question 21: In your experience which of the following SLS criteria most often governs the design of structural elements in buildings? (n = 127)

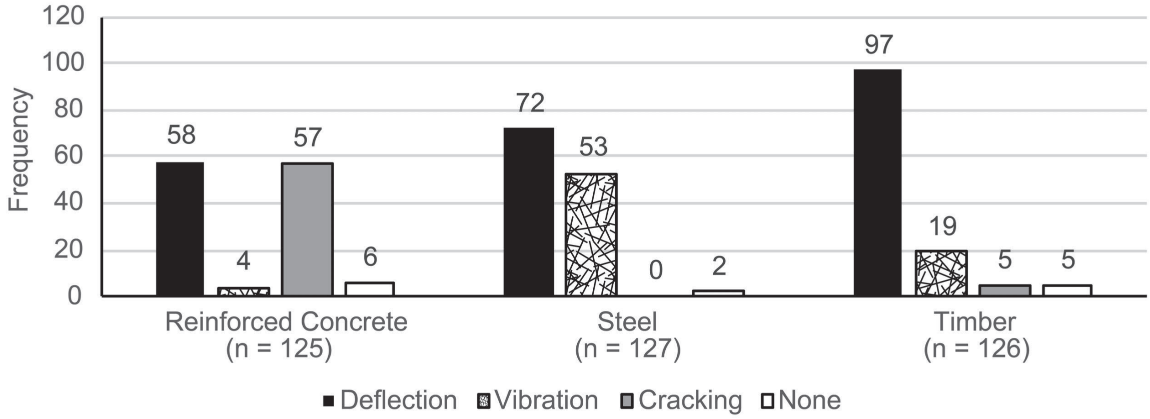

Figure 29: Q21

3.4.3 Question 22: How frequently would you be comfortable with allowing the following structural serviceability limits to be exceeded in an office building throughout its lifetime?

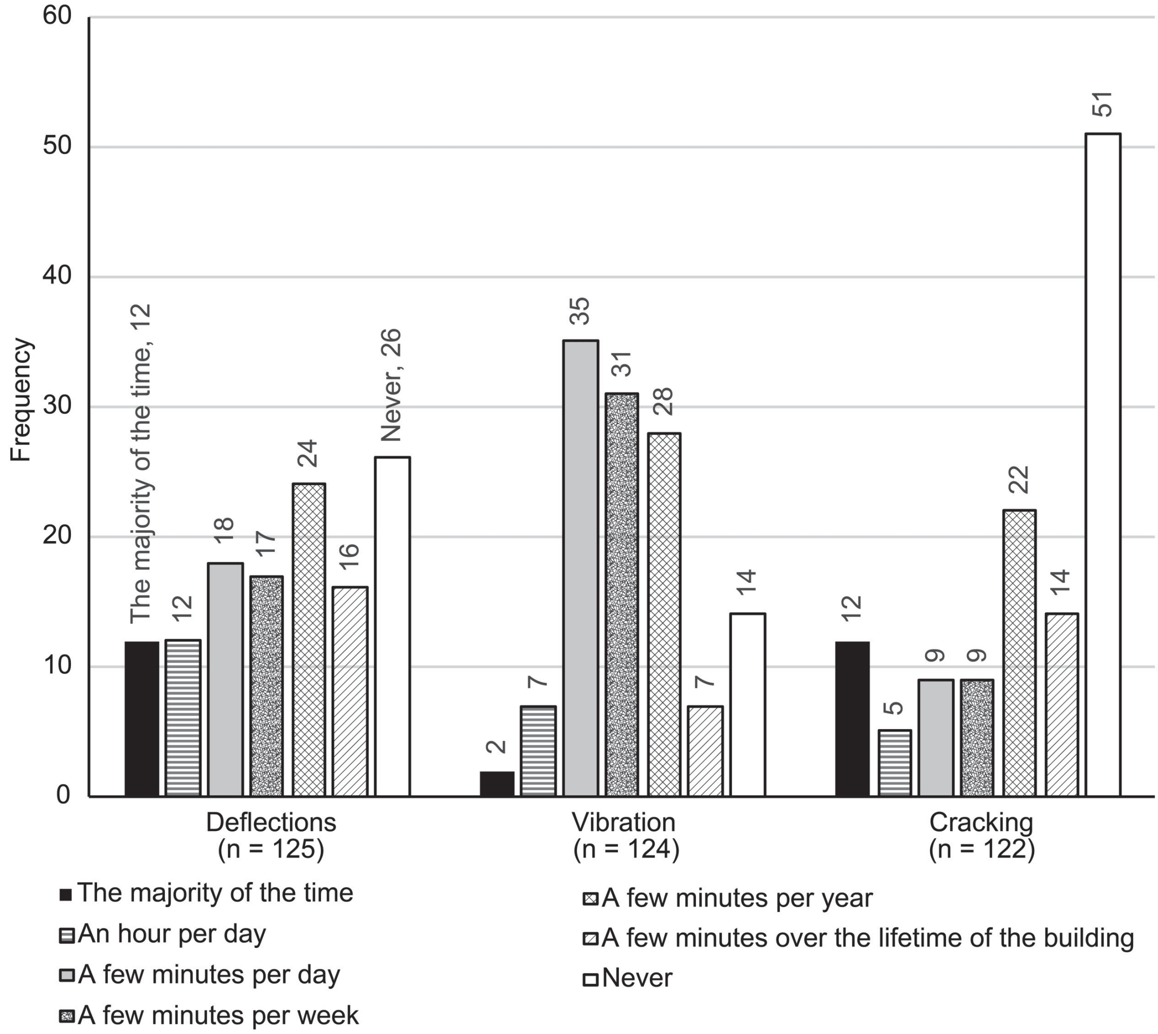

Figure 30: Q22

3.5 Section 4: Design

This section of the survey asked four questions relating to realistic design scenarios and in particular focused on how the relationship between design resistance and the effect of design actions. Analysis of these questions is presented in §4.

3.5.1 Question 23: You are asked to design the floor plate in a multi-storey building. Which one of the following has the biggest influence on your final design: (frequency, n = 127)

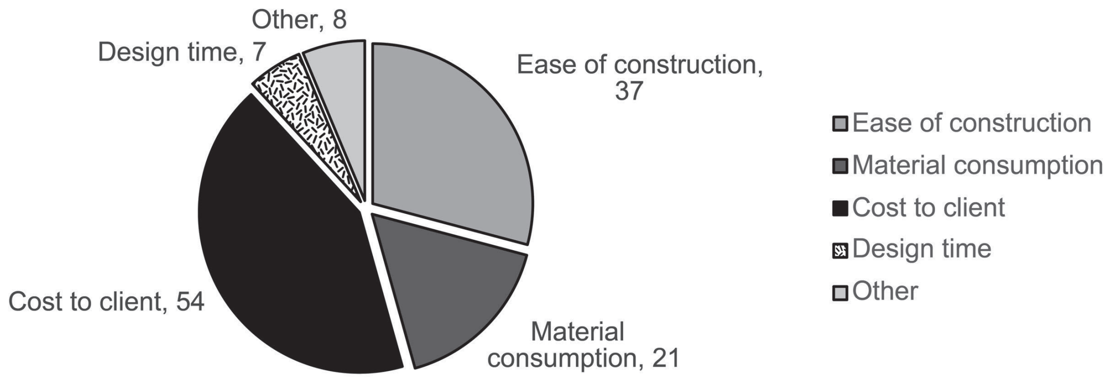

Figure 31: Q23

Of the responses under other, three respondents noted that “it depends”. Other responses include “structural depth zone”, “sustainable design life”, “risk vs cost”, “ease of construction seems = cost to client”.

3.5.2 *Question 24: Imagine you are undertaking the detailed design of a flexurally dominated floor beam. The flexural design effect of the actions ("Ed") on the beam at mid-span is 200kNm (including partial factors). The beam is to be a fabricated steel section. What value for the flexural design resistance ("Rd") of the beam at mid-span (including partial factors) would you choose? (n = 118)*

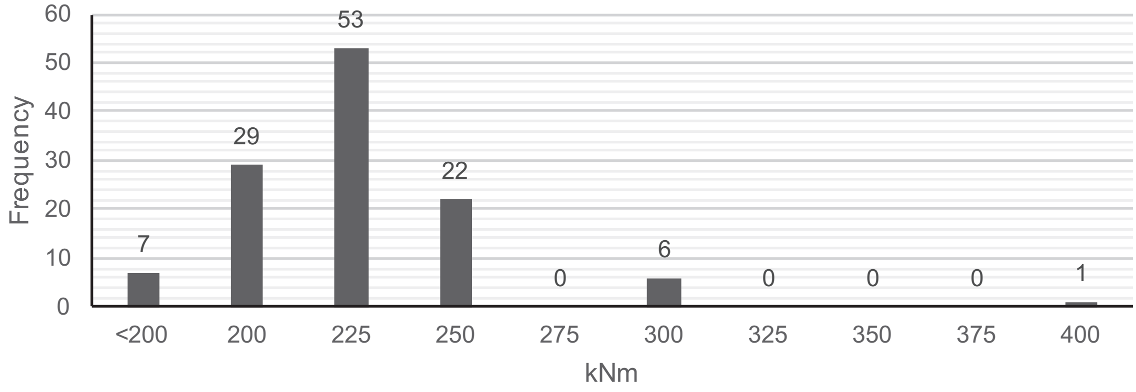

Figure 32: Q24

Average = 216kNm
Median = 210kNm

Seven response to this question had a value of less than 200kNm, which would make them non-compliant with the design scenario. The responses in question had values of: 1.2, 1.5, 10, 140, 180, 190, and 190. Excluding these values, the following is found:

Average = 224kNm
Median = 215kNm

3.5.3 Question 25: Thinking about your professional practice, how frequently do elements in your completed structural designs have a design resistance that is EQUAL to the design effect of actions on the element? (n = 126)

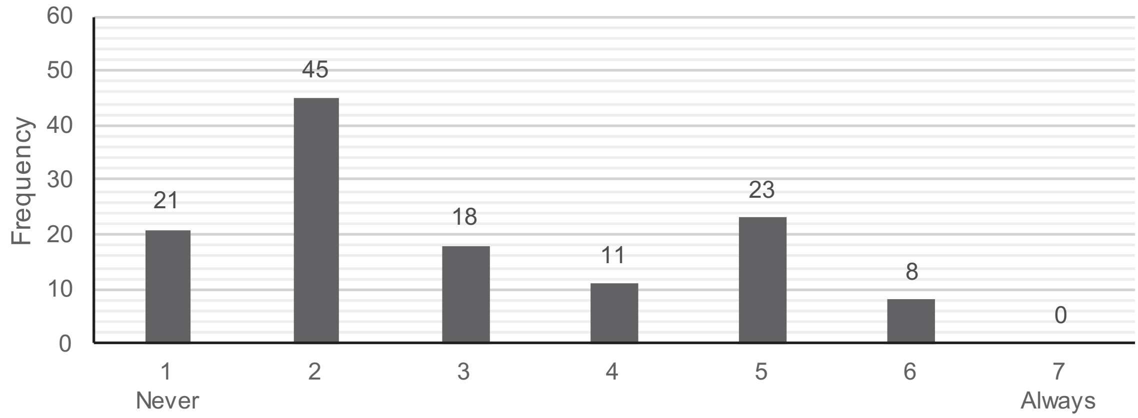

Figure 33: Q25

Median = 2

3.5.4 Question 26: Thinking about your professional practice, which of the following would be the prime reason for an element to have a design resistance that is greater than the design effect of the actions on the element? (n = 126)

Table 9

Response (years up to)	Number	%
The span, loading, or layout might change before construction.	38	30%
I am uncomfortable with the design effect of the actions being equal to the design resistance of the element.	12	10%
I don't trust the factors of safety in design codes	0	0%
I like to build in a bit of spare capacity just in case.	24	19%
The building might change use later in its life.	21	17%
Other	31	25%
	126	**100%**

The large number of responses under “other” is split into the following, based on free-text responses:

Table 10

Other response, grouped as:	Number	%
Constructibility	9	7%
Workmanship	3	2%
Standardisation	12	10%
Uncertainty	2	2%

Other response, grouped as:	Number	%
Fee	2	2%
Multiple of the listed factors	3	2%
	31	**25%**

3.6 Section 5: Capacity

Section 5 asked participants four questions relating the utilization of structural elements in buildings. Analysis of these questions is presented in §4.

3.6.1 Question 27: How feasible do you think it would be to introduce into design codes a limit on how much greater the Design Resistance of a structural element could be as compared to its required capacity? This would prohibit engineers from designing elements with a capacity greater than this upper limit. (frequency, n = 125)

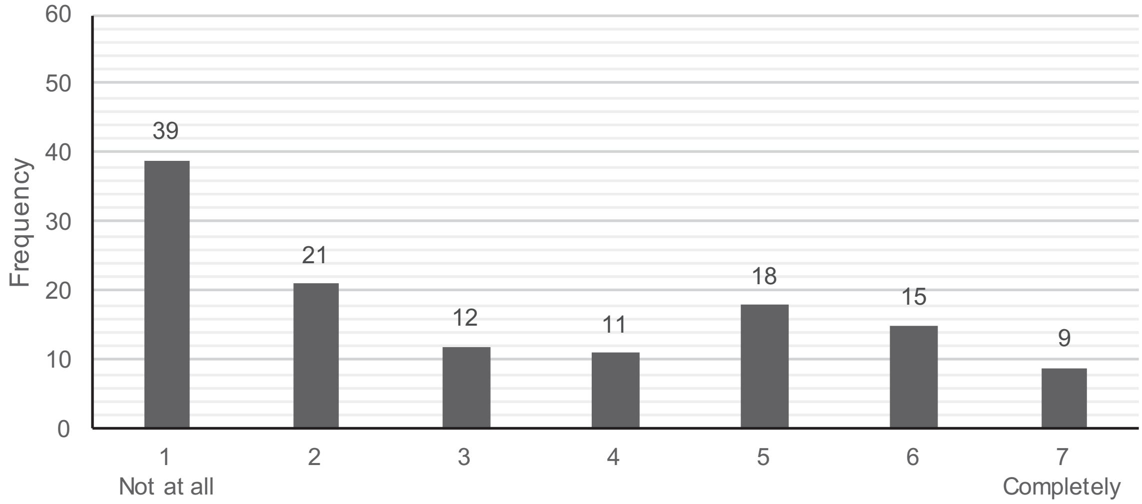

Figure 34: Q27

Median = 3

3.6.2 Question 28: Imagine that such a limit is introduced into a design code. The Design value of resistance ("Rd") for each element must be greater than the Design effect of the action ("Ed") AND less than "Beta" multiplied by "Ed", where "Beta" is a number ≥1.00. This relationship is shown in the equation below. What value of "Beta" would you be happy, as a structural designer, to see in a design code? (n = 120)

$E_d \leq \mathbf{R_d} \leq \beta E_d$

E_d = Design effect of action
R_d = Design value of resistance
$\beta \geq 1.00$

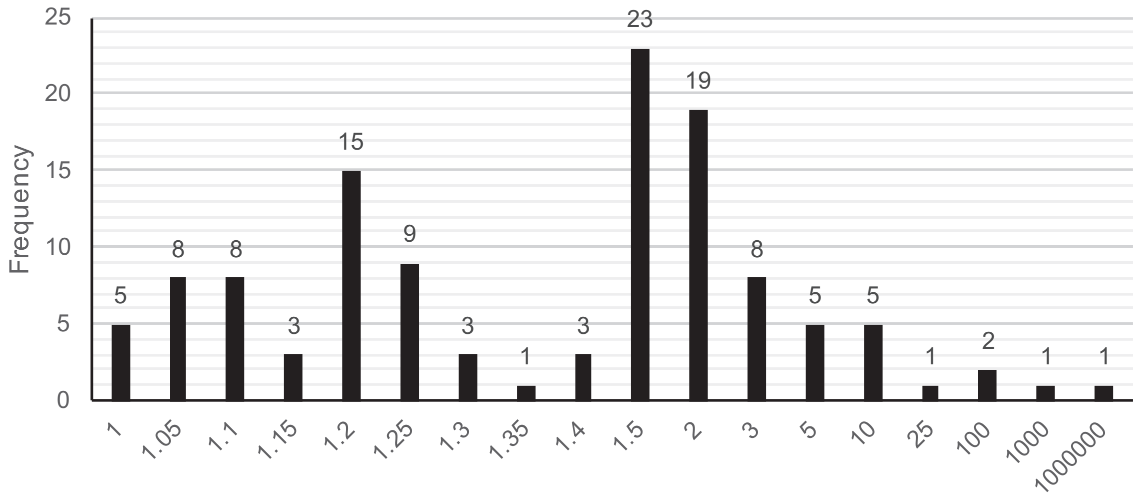

Figure 35: Q28 responses grouped by answer, note the irregular horizontal axis

Median = 1.50

Any numerical value ≥1.00 was a valid response. The average for this question is skewed by the three responses 100, 1000 and 1,000,000 and is therefore not reported. Ten responses were greater than 5.00.

3.6.3 Question 29: What might the unintended consequences of a limit to the design value of resistance relative to the design effect of the actions be, in your opinion? (n = 110)

Question 29 was a free text response with 110 answers. They are grouped as per the following table.

Table 11

Response	Number	%
Increased complexity	32	29%

Response	Number	%
Less flexibility at all stages	21	19%
Serviceability problems and failures	13	12%
Connection problems, sizing for visual reasons	9	8%
Design to the upper limit	9	8%
Unforeseen failures	7	6%
Cost increases	4	4%
None	3	3%
Other	12	11%

The “other” category includes numerical answers that do not answer the question asked. All free text answers can be found in the data archive.

3.6.4 Question 30: Imagine instead that an average material utilisation across all structural elements is introduced as a codified design requirement. What minimum value of material utilisation should be achieved by structural designers? (n = 119)

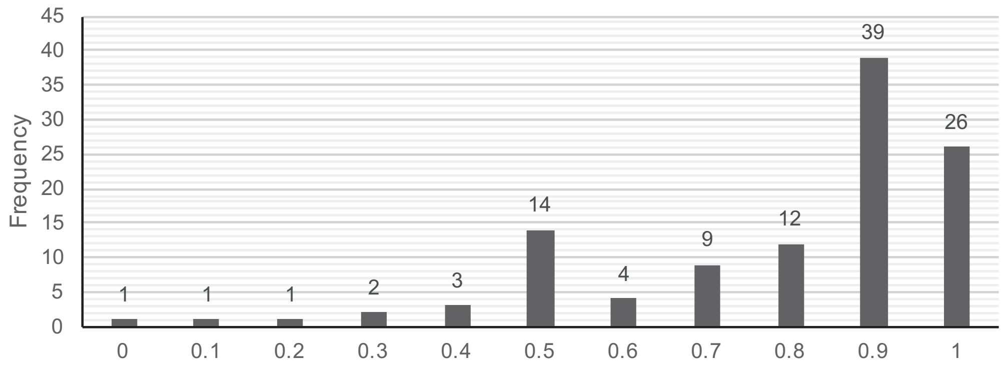

Figure 36: Histogram of responses, Q30

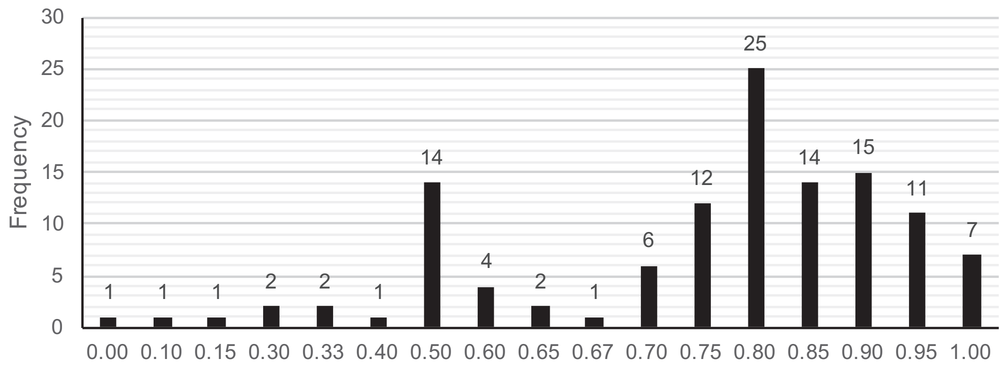

Figure 37: Q30 responses grouped by answer, note the irregular horizontal axis

Median = 0.80
Average = 0.75

3.7 Section 6: Examples

In this section examples of design were explored, with respondents asked to think about their own work, and the work of others in the profession. Six questions were asked. Analysis of these questions is presented in §4.

3.7.1 Question 31: How deep (in mm) would you expect a two-way spanning flat slab in an inner-city office building to be, if the column spacing below it is 7m x 7m? (n = 117)

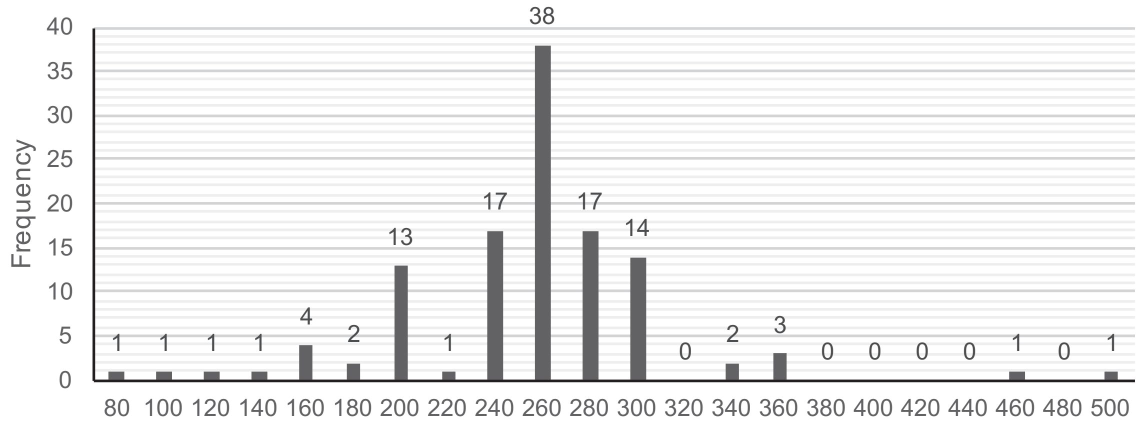

Figure 38: Q31 histogram of responses

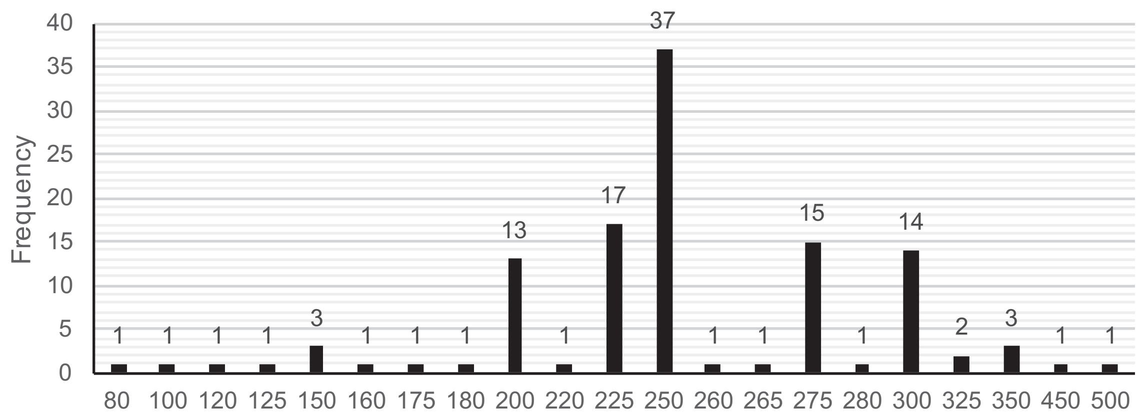

Figure 39: Q31 responses grouped by answer, note the irregular horizontal axis

Median = 250mm

3.7.2 Question 32: Imagine you are designing the steel beams in a floor plate of the multi-storey office building shown below. This floor plate is repeated multiple times. There are a large number of beams with varying spans. The floor load is constant across the area. Thinking about the beams only, approximately how many sets of calculations would you probably undertake to size the beams across the floor plate? (n = 124)

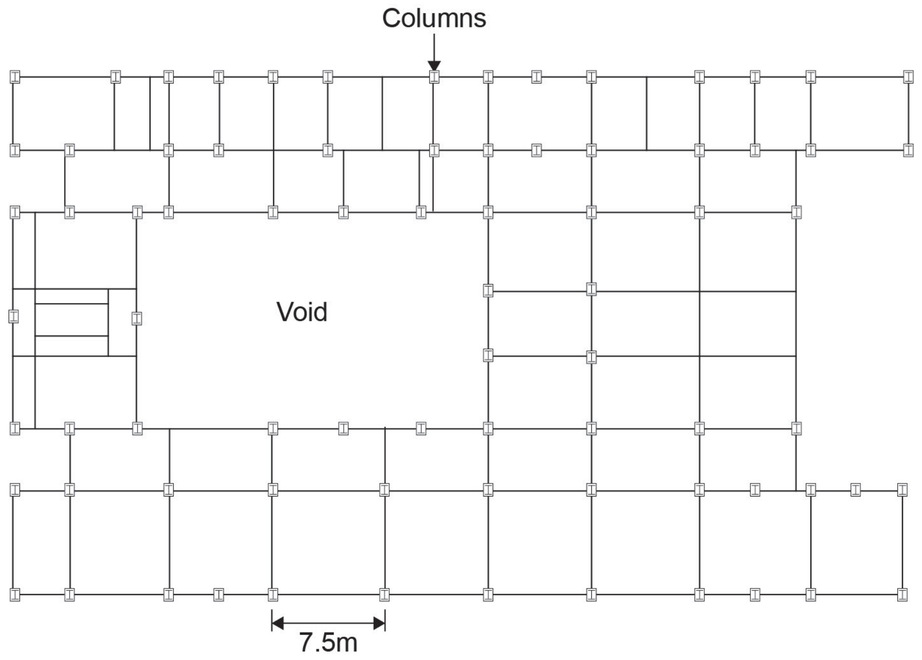

Figure 40: Floor plate shown for Q32

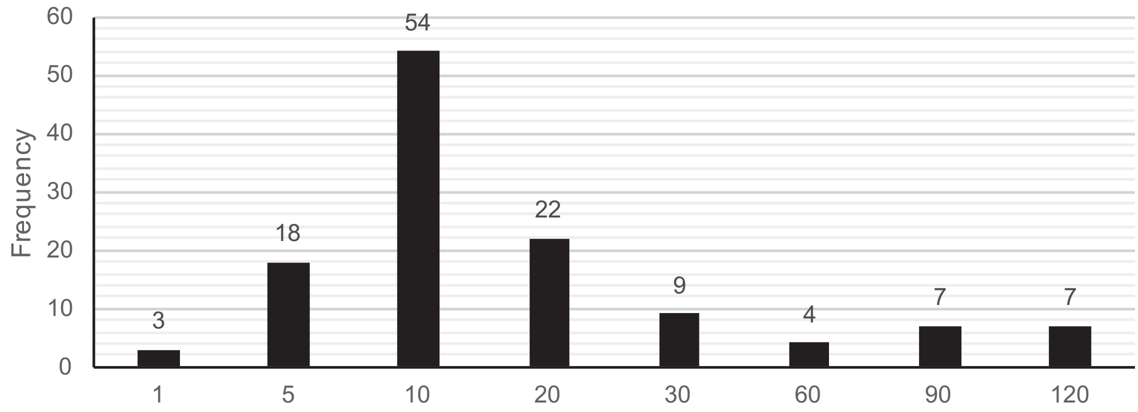

Figure 41: Q32 responses grouped by answer (note that the choices above were given in the question)

Average = 24.4
Median = 10.0

3.7.3 *Question 33: Please provide a short justification for your decision [relating to Q32]. (n = 113)*

Responses to this question were grouped per the following table, with the vast majority of answers relating to the need to rationalise. Answers tended to describe how this would be done, rather than providing justification of *why*.

Table 12

Response	**Number**	**%**
Rationalisation/Grouping	68	60%
Save design/calculation time	13	12%
Group to simplify construction	12	11%
Fabrication	6	5%
Automate design	6	5%
Connections	2	2%
Other	6	5%
	113	**100%**

3.7.4 *Question 34: Thinking about your experience of the structural engineering profession more generally, how many different section depths would you expect to see in the as-built structure, regardless of the number of calculations performed? (n = 119)*

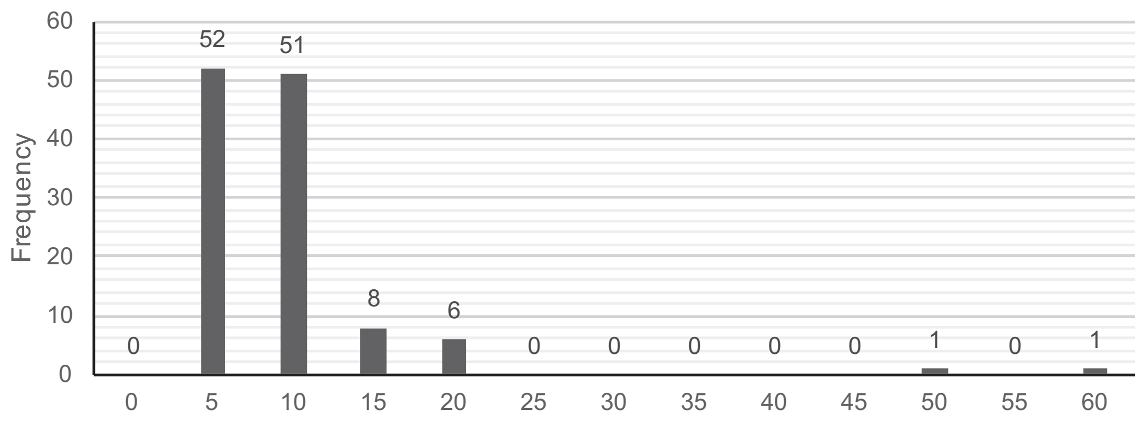

Figure 42: Q34 presented as a histogram with equal bins

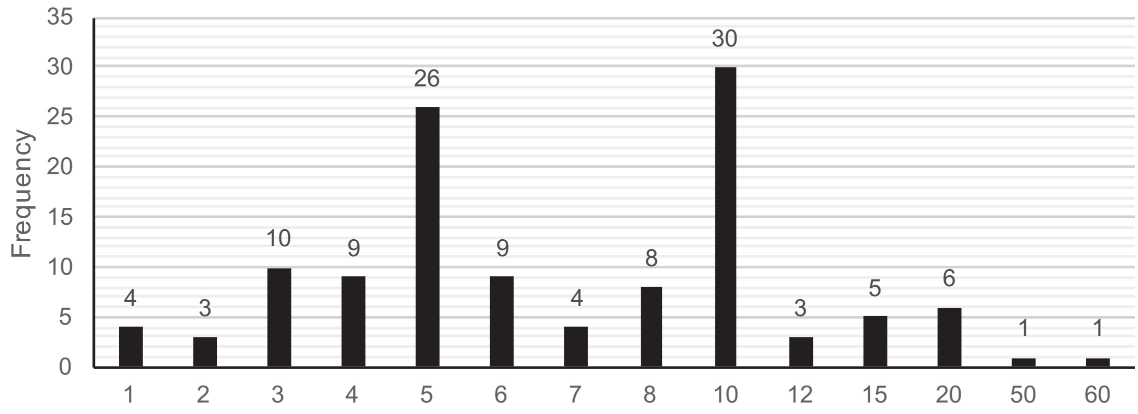

Figure 43: Q34 grouped by answer frequency

Median = 6.00
Average = 8.34

3.7.5 Question 35: Imagine you are the structural designer for your OWN house. Would your approach to assumed loads and individual sizing of members be any different from your day-to-day professional role? (n = 129)

Table 13

Response	Number	%
Yes	48	37%
No	81	63%

3.7.6 Question 36: Please provide examples of what you might assume or do differently in the design of your own house. (n = 44)

Table 14

Response	Number	%
Control of Loading	14	32%
Greater certainty	8	18%
Higher utilisation	7	16%
Budget is mine	4	9%
Lower utilisation	3	7%
Control of SLS	2	5%
Other	6	14%
	43	**100%**

4 Survey Analysis

4.1 Introduction

Section 4 presents analysis of the survey data. It is divided according to the sections of the survey. At appropriate points in the text, "Industry Questions" (**IQ**) are posed. These questions arise from the responses to the survey and are given as open questions to be answered over the course of **MEICON**. Please reflect on them in light of the survey data and provide the **MEICON** team with your own insights into how they might each be addressed. As all questions were optional the number of responses is given for each question.

4.2 Survey Section 7: Population

The survey respondents were predominantly men (108 of 128 responses, 84%) working in the UK (93/126, 74%) as Structural Engineers (115/129, 89%). This group represents 57% (74/129) of respondents. Respondents were well distributed in terms of role within the industry, with 26% (33/129) of respondents working at Graduate level, 25% (32/129) as Senior Engineer, 11% (14/129) as Associate, and 16% (20/129) as Director (Table 4). 45% (58/128) of participants work at Detailed Design stage, and 38% (48/128) work at Concept Design (Table 5). On average respondents had 16.6 years of experience (range 0 to 60, standard deviation 14 years, from 128 responses).

4.2.1 Sample representativeness

To examine the representativeness of the sample, the subset of respondents identifying as working in the UK (n = 93) are examined against UK statistical data. Rest of World (ROW) data is provided alongside for information, but it is not feasible to compare this to official statistics due to small samples in each country (Table 3). The gender balance of survey respondents is in-line with the broader UK industry, with only a marginally higher percentage of female respondents, Table 15. The age profile of respondents (Table 16, Figure 44) is largely comparable to UK data for people working in the engineering sector (SIC) in an engineering role (SOC) – the "SIC x SOC" data shown below. The survey saw a slightly larger number of respondents in both 25-34 and 55+ age brackets compared to the wider industry.

Table 15

Gender	UK – survey (n = 93)	UK data - SIC x SOC (1)	ROW – survey (n = 36)
Female	14%	10%	11%
Male	83%	90%	89%

Gender	UK – survey (n = 93)	UK data - SIC x SOC (1)	ROW – survey (n = 36)
Prefer not to say	3%	-	0%
Notes: (1) http://www.engineeringuk.com/media/1355/enguk-report-2017.pdf			

Table 16

Age	UK- Survey (n = 93) (%)	UK data - SIC x SOC (1)	ROW – Survey (n = 36)
<25	6%	8.6%	11%
25-34	39%	24.7%	36%
35-44	17%	25.5%	19%
45-54	17%	25.8%	11%
55+	20%	15.4%	22%
Notes: (1) http://www.engineeringuk.com/media/1355/enguk-report-2017.pdf			

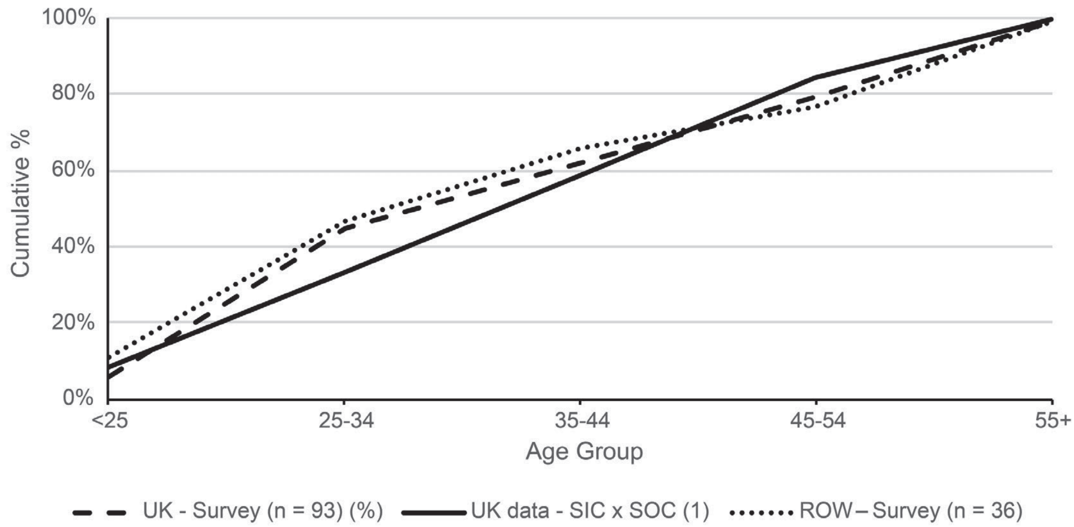

Figure 44: Cumulative age distribution comparison

4.2.2 Sample power

The total population of professionals who have the potential to impact embodied energy of structures is an unknown at this stage. The Institution of Structural Engineers has 27,000 members and the Institution of Civil Engineers 90,000 members, worldwide [41]. In the calculation of survey power, the population size is irrelevant unless the size of the sample exceeds a few percent of the total population you are examining.

The survey had 129 responses. With a 95% confidence level, it is calculated that the results have a confidence interval of 8.65%. This means we can be 95% confident that results presented in the survey are within ±8.65% of the response of the population.

It is recognised that this survey is a preliminary study, and that the confidence interval above is larger than would be ideal. To reduce the confidence interval to ±5% would have required 384 responses to the survey questions.

In the following analysis it is further recognised that accuracy also depends on the type of question and spread of answers. For example, in a Yes/No question, if 99% answer yes and 1% no, then the chance of error is small. If the split is 51%/49%, then the chance of error is much greater. It is easier to be sure of answers grouped at the extremes.

4.3 Survey Section 1: General questions

In Section 1 respondents state that maximising material utilisation is a key design criterion (Q1: 81%, 105/129, scoring 5, 6, or 7, where 7 is “Strongly Agree”), and that the material utilisation of their own designs is normally close to 1.00 (Q2: 55%, 71/129, scoring 5, 6, or 7). This is contrary to what has been measured in large surveys of real buildings, where material utilisation is usually closer to 0.50 [5, 14], see also §1. There exists a strong correlation, as expected, between Q1 and Q2 (Spearman Rank = +0.56).

The oversizing of structural elements at early design stages is considered by the respondents to be normally appropriate (Q3: 78%, 100/129, scoring 5, 6, or 7) and they further agree that ease of construction is more valued by the design team than material efficiency (Q4: 82%, 106/129, scoring 5, 6, or 7). Oversizing at concept stage does not appear to theoretically preclude later changes in geometry, as respondents show a willingness to change structural sizes during detailed design in Q5, where 60% (78/129 scoring 1, 2, or 3) of respondents disagreed that reducing the dimensions of structural elements agreed at concept design stage during detailed design is best avoided. Respondents also note that the potential for construction errors influences these sizing decisions (Q6: 60%, 77/128, scoring 5, 6, or 7). In Q7 95% of respondents agree (122/129 scoring 5, 6, or 7) that designs are simplified to improve constructability, while Q8 highlights that there is little demand from client or design team for embodied energy to be minimised (70%, 90/129, scoring 1, 2 or 3).

These factors are linked by Q9, where 71% of respondents (91/129 scoring 1, 2, or 3) disagreed that material utilisation of structural design is normally presented to clients and only 11% (14/129, Q11) of respondents agree (scoring 5, 6 or 7) that clients insist on low-carbon structural designs. Engineers should not wait for clients to ask for such information, and instead should always calculate and present such data, compared to benchmarks for various building typologies, to their clients. Q10 shows that respondents agree (52%, 67/129, scoring 5, 6, or 7) that increasing material utilisation is a good way to reduce material consumption, and calculating such data is a first step towards achieving our Construction 2025 goals.

Question 1 "The best way to reduce total material consumption is to ensure that structural material utilisation is high ($\tilde{x} = 5$)" was correlated to Question 10 "Maximising material utilisation is a key design criterion for me ($\tilde{x} = 5$)" with a Spearman rank of 0.50. This correlation, with a critical significance level of $\alpha = 0.05$, and 129 pairs of data, is statistically significant. The correlation demonstrates good consistency in responses. Designers who want to reduce material consumption make maximising material utilisation a key part of their design process.

Strong correlations between Questions 8 and 11, and 9 and 11 (Question 8: "My clients or design team normally require me to minimise total embodied energy." Question 9: "The material utilisation of a structural design is normally presented to clients". Question 11 "Clients normally insist on low-carbon structural designs") are reasonably well expected. They show that there is no contradiction between answers in these questions. Low scores in Q8 ($\tilde{x} = 2$) are matched with low scores in Q9 ($\tilde{x} = 2$) and Q11 ($\tilde{x} = 2$).

The responses to Section 1 show that embodied energy efficiency is currently a low priority in the design process.

IQ1: Could we collectively define benchmark structural utilisation values against which new structural designs could be compared, to drive material efficiency?

IQ2: How might a calculation of material use per m^2 best be presented to clients, to drive material efficiency?

IQ3: How might designers demonstrate they are contributing to meeting Construction 2025 targets?

4.4 Section 2: Loading

Responses to Questions 12-19 show a remarkable spread in answers. This range of responses demonstrates a lack of consensus across industry. In the case of imposed floor loading, which can be measured with relative ease using data from multiple buildings over long periods of time to inform accurate and reliable design codes, this represents a key challenge for the **MEICON** project to address.

Three questions were used to examine the relationship between loads chosen at design and loads that exist in real structures. Q14 asked respondents to identify the characteristic floor areas load they would choose when designing a multi-storey office building in a city centre. Q16 and Q17 asked respondents to estimate the average and maximum loads that the same office would see over a 60-year life cycle. Table 17 shows a comparison between these scenarios.

Table 17: Floor load responses

	Characteristic floor load for design (kN/m^2) [Q14] (n = 124)	In-service average floor load over 60 years (kN/m^2) [Q16] (n = 122)	In-service maximum floor load over 60 years (kN/m^2) [Q17] (n = 122)
Average	3.08	1.70	3.05
Maximum (1)	10.00 (1)	10.00 (2)	20.00 (2)
Minimum (1)	1.00	0.30	1.00
Median	3.00	1.50	2.50
Notes: (1) this respondent entered average (Q16) = 3kN/m^2 and maximum (Q17) = 5kN/m^2; (2) maximums for Q16 and Q17 from the same respondent, who entered a characteristic (Q14) value of 5kN/m^2.			

The 46 respondents who chose 2.5kN/m^2 in Q14 are examined in more detail in Table 18. The maximum values for Q16 and Q17 in this sample were given by different respondents (see notes to Table 18). The maximum response to Q17 in this sample (7.50kN/m^2) is the same as the design loading that is often applied over c.5% of an office floor area (see also Table 19). Of the 46 respondents in this sample, only one entered an average in service floor load (Q16) greater than their chosen characteristic value for design (Q14). Across all responses (Q16, n = 122) there were a total of four respondents who entered an average in service floor load (Q16) greater than their chosen characteristic value for design (Q14).

Table 18: Floor load responses, sample

	Characteristic floor load for design (kN/m^2) [Q14, n = 46]	In-service average floor load over 60 years (kN/m^2) [Q16, n = 46]	In-service maximum floor load over 60 years (kN/m^2) [Q17, n = 46]
Average	2.50	1.36	2.69
Maximum	2.50	4.50 (1)	7.50 (2)
Minimum	2.50	0.30	1.00
Median	2.50	1.50	2.00
Notes: (1) This respondent gave a value of 6kN/m^2 for Q17; (2) This respondent gave a value of 1.5kN/m^2 for Q16.			

Questions 18 and 19 of the survey were designed to examine how respondents feel about changes in imposed floor loading. Forty-nine percent (59/121, Q18) do not expect imposed floor loading in their own design code of practice to change in the next decade (median response 0%). Forty percent (48/121, Q19) of respondents would not change imposed design loading, and 46% (56/121, Q19) respondents would reduce imposed design loading, if they were solely responsible for doing so

Examining responses to Question 11 (“Clients normally insist on low-carbon structural designs”) and Question 19 (“Imagine you are solely responsible for rewriting your local structural design code. What percentage changes, if any, in imposed design loading would you introduce?”), it was found that respondents entering scores of 1 (“Strongly Disagree” 20%, 26/129), or 2 (35%, 45/129) in Q11 had a group median response to Q19 of -10%. The sample median to Q19 was 0%.

A correlation (Spearman Rank = +0.44) is found between Q12 (“How often do you think that values for imposed vertical floor design loads given in your local design code of practice are appropriate?”) and Q19 (“Imagine you are solely responsible for rewriting your local structural design code. What percentage changes, if any, in imposed design loading would you introduce?”). Respondents who think floor loading is appropriate would not change it (or would increase it), while respondents who chose low values in Q12 (i.e. “Never”) were more likely to choose negative values for Q19 (i.e. to reduce floor loading).

As an example, 10 respondents chose values of 1 or 2 in Q12 (floor loading is not appropriate). Their median response to Question 19 was -22.5% (compared to the sample median of 0%). This demonstrates both consistency of the respondents, and a subset of respondents who do believe change in loading is required.

Of this subset of 10 respondents, their responses to Q11 have a Median of 2, the same as the sample median for all respondents. This suggests that even if clients do not insist on low-carbon designs, the designer may feel that there is an issue with the values of floor loading being used in design. Of further interest in this subset, it includes the respondent to Q28 who chose a value to the upper limit of resistance (“Beta”) of $1x10^6$.

4.4.1 Floor loading

The London City Council (General Powers) Act 1909 [42] set a floor loading requirement for office structures as 100 pounds per square foot (inclusive of partitions), which is equivalent to $4.8kN/m^2$. The legacy of this is still seen today in office floor area specifications as $4kN/m^2$ + 1 kN/m^2 for partitions.

Surveying letting agent data from $365,000m^2$ of office space over 12 buildings in London with an average age of 6 years reveals an area weighted average imposed floor loading of $4.48kN/m^2$ (including partitions), Table 19. This is not far from the values given in 1909, and is higher than both BS EN 1991-1-1 [43], which suggests office area loading of between $2.0kN/m^2$ and $3.0kN/m^2$, and the BCO Specification for Offices which suggests $2.5kN/m^2$ for above ground office floors [44].

Table 19: Letting agent data for 12 office buildings in London

Property name	Year	Rentable area (sq m)	Imposed load (kN/m^2)[1]	Over area (m^2)	Imposed load (kN/m^2)	Over area (m^2)	Source
Aldgate Tower	2014	29,190	4.00	27,731	7.50	1460	http://bit.ly/2CDUMWb
2 London Wall Place	2018	17,652	4.00	17,652			http://bit.ly/2CvMDzA
1 London Wall Place	2018	28,800	4.00	28,800			http://bit.ly/2EaQCST
99 Bishopsgate	1995	31,250	5.00	31,250			http://bit.ly/2lUnKXk
100 Bishopsgate	2018	81,633	4.50	73,470	7.50	8163	http://bit.ly/2m0V5Rm
Leadenhall Court	1988	10,126	6.00	10,126			http://bit.ly/2CWztgh
Principal Place	2017	55,742	4.00	52,955	7.50	2787	http://bit.ly/2F3R7PR
The Grove		2,323	5.00	2,323			http://bit.ly/2CIpQnG
The Avenue	2017	6,624	4.00	6,293	7.50	331	http://bit.ly/2CIq8eg
The Shard	2016	54,813	4.50	54,813			http://bit.ly/2m1SruK
240 Blackfriars	2014	22,018	4.00	22,018			http://bit.ly/2m1atNv
One Creechurch Place	2016	25,316	4.50	25,316			http://bit.ly/2CXuhst
Notes (1) Imposed loading including any allowance for partitions							

A more extensive analysis and exploration of floor loading is required, which should include practice outside of the UK and Europe. A significant research study to determine feasible methods to measure live loading in buildings is required to inform accurate loading models.

In Section 2 of the survey it is seen that we know quite well that real loads may be lower than what they design for, but do not find this sufficient reason to change loading codes. It would be valuable, therefore, to add to the data through systematic collection of actual floor loading in buildings. With such data engineers would be able to demonstrate that appropriate loads are being used during the bidding process.

It is also possible that many engineers do not realise what loading levels look like. As an example, the photo in Figure 45 shows the 50th Anniversary Celebration of the Golden Gate Bridge, where an estimated 300,000 people were on the structure at the same time. This is likely the most significant vertical load the bridge has ever seen. It amounts to 2.87kN/m^2 (60psf). Engineers must ask themselves if floor loading of this level would even be physically possible in most offices, how frequently such a situation would occur, and what the consequence of using a more realistic loading level might be. This aspect is explored in further detail in §5.2 on page 77.

IQ4: What might the benefit be of design code floor loading values being based on data gathered from a systematic global survey of loading levels in buildings?

IQ5: What might the unintended consequences be of changing live load values at ULS based on measured data?

IQ6: What might the unintended consequences be of changing live load values at SLS based on measured data?

IQ7: How might real time building loading information be integrated into building management systems to provide "traffic light" load levels to aid facility management?

Credit: PAUL SAKUMA/AP/REX/Shutterstock

Credit: DOUG ATKINS/AP/REX/Shutterstock

Figure 45: 50th Anniversary of the Golden Gate Bridge - live load estimated at 60psf (2.87kN/m²)

4.5 Section 3: Serviceability

Section 3 aimed to examine the role that serviceability considerations have in overall material consumption.

In Q20 the survey respondents identify that the serviceability limit state often governs structural element sizing. Seventy-three percent of respondents (93/127) scored Q20 greater than 5 (with 7 being always). This response is clearly dependent on structural typologies, and the SLS limits being considered, which could be examined in greater detail in future work. In general, the survey results show that structures are often governed by serviceability – and half of respondents are comfortable with allowing deflection and vibration limits to be exceeded for up to a few minutes per week.

The focus on SLS highlights the need for accurate load levels, such that serviceability limits do not lead to unnecessary overdesign. In addition, the SLS limits themselves must be realistic and based on measured data – for example what level of vibration, or deflection, is acceptable in various structural typologies.

In vibration analysis, it has long been recognised that imposed floor loading values used for strength design are inappropriate. To appropriately represent the behaviour of a floor in-service, an accurate understanding of the imposed load is required. It is worthwhile to quote here from SCI P354 [45] which states:

> *"…the actual imposed load being considerably less than the prescribed design loads on the floor. This discrepancy between design imposed loads and in situ loads in service means that it is advisable to consider only the imposed loads which may be reasonably assumed to be permanent during building use. Indeed, imposed loads may be ignored completely as a conservative design scenario. According to Hicks et al. [46], it is recommended that the allowance should not exceed 10% of the nominal imposed load."*

Taking an imposed load of 10% the design value is a widely-used figure in practice and is chosen as a realistic value of imposed loading in normal usage [45]. This suggests again that engineers are aware that imposed loads are unrealistic.

As a further note, in vibration analysis the static force exerted by the average person is taken as close to 746N [45]. Recommended loading density for common dynamic scenarios are 0.25 people per m^2 for aerobic and gymnasium activities, and 2 people per m^2 for social dancing. These correspond to loads of 0.19kN/m^2 and 1.49kN/m^2 respectively. The median response to Q16 ("…what do you think the average area load on the floor of the office would be, over the life of the structure, as measured during office hours?") of 1.50kN/m^2 is approximately equal to the value of 2 people per m^2.

Many serviceability limit state calculations are therefore potentially being undertaken on what might amount to quite extreme loading, which is not the purpose of the SLS.

We therefore need to initially explore realistic serviceability limits. For example, if we were to retain current imposed loading values for strength design, what reduction factors would be required to ensure that design for serviceability does not dominate over design for strength?

Q22 examined how often designers would be happy for SLS limits to be exceeded in office buildings. The responses are summarised in Table 20. It is interesting that respondents were happy for the SLS limits to be exceeded at all, since this is non-compliant with limit state design. Sixty percent (75/124) of respondents are comfortable with allowing vibration limits to be exceeded a few minutes per week or more. Forty-seven percent (59/125) are comfortable with allowing deflection limits to be exceeded for a few minutes per week or more. Only 21% (26/125) would never allow deflection limits to be exceeded (Q22). Forty-two percent (51/122) of respondents would “Never” be comfortable with exceeding Cracking SLS. This may reflect the irreversible nature of cracking, as compared the more often reversible limits of deflection and vibration.

Each SLS option (Cracking, Deflection, Vibration) received responses in all time categories, implying that flexibility in serviceability limits would be beneficial to designers. Realistic serviceability loading, and realistic serviceability limits, go hand in hand. Without an understanding of the effect of a serviceability load on the performance of a structure, it is understandable for designers to be conservative. Therefore, measurement of loading and corresponding SLS performance is essential if SLS loads are to be reduced. This first step may be followed by future research to target reductions in ULS loading.

Table 20: Responses to Q22

	Deflections	**Vibration**	**Cracking**
The majority of the time	10%	2%	10%
A few minutes per day	14%	28%	7%
An hour per day	10%	6%	4%
A few minutes per week	14%	25%	7%
A few minutes per year	19%	23%	18%
A few minutes over the lifetime of the building	13%	6%	11%
Never	21%	11%	42%

IQ8: What measurements might be required to define realistic serviceability limit state acceptability criteria, to ensure that SLS design levels are appropriate and do not unreasonably dominate over strength design?

IQ9: What discussions are required with clients to understand allowable periods during which SLS requirements might not be met?

4.6 Section 4: Design

This section of the survey asked four questions relating to realistic design scenarios and focused on how the relationship between design resistance and the effect of design actions – the "effect-resistance gap".

Question 23 demonstrates that "Cost to client" has the most significant influence (54/127, 43% responses) on design. Ease of construction (37/127, 29%) and Material consumption (21/127, 17%) follow behind. This is a positive finding as designers should have a good grounding in what is feasible on site. However, we must also consider the extent to which links between structural engineering consultants, and on-site contractors, are made given the material use and productivity data presented in the literature review.

Question 24 (n = 118) asked participants to choose the resistance (R_d) of a beam required to carry a bending moment of 200kNm. The question did not require answers to be greater than 200kNm, and seven responses were given of less than 200kNm. Excluding these responses, the average response was 224kNm (n = 111) equivalent to a utilisation of 89%. Twenty-nine respondents (25%) entered 200kNm, a utilisation of 1.00. Most respondents (69%, 82/118) chose a resistance of >200kNm, despite there being no need to do this. In this response, we see evidence of a culture in which overdesign, albeit mainly modest, is standard practice, despite the education of structural engineers being explicit about inherent conservativeness of design codes of practice.

Question 25 asked how frequently elements in completed designs have a resistance equal to the design effect of actions (i.e. utilisation of 1.00). The median response was 2 (with 1 being "Never" and 7 being "Always"). Zero respondents chose 7, and 52% (66/126) of respondents chose 1 ("Never") or 2. That contrasts with responses to Q2, where 55% (71/129) of respondents chose scores of 5-7 (7 being "Strongly Agree") to agree that "material utilisation of each structural element in my designs is normally close to 1.0". Of the 29 respondents who chose a beam capacity of 200kNm (utilisation of 1.00) in the design example given in Q24, their median answer in Q25 was 3, only one step above the group response.

The dominant reason given in Q26 for *not* having a utilisation of 1.00 was given as "The span, loading, or layout might change before construction" (30%, 38/126), followed by "I like to build in a bit of spare capacity just in case" (19%, 24/126), and "The building might change use later in its life" (17%, 21/126). Only 12 respondents chose “I am uncomfortable with the design effect of the actions being equal to the design resistance of the element”. One response to Q26 was:

> *“9" walls require 6"+ wide beam flanges to support them (or an extra steel plate!) so 203 wide (x203 deep UC) is required, whatever the loading!”*

In the design of steel structures, standard section sizes may in some situations define levels of overdesign. This is less immediately a problem in concrete designs, but there is a need to examine to the extent to which this is true in building structures. For example: are utilisation levels low in some sections simply because it is the smallest possible beam size that is readily available? We must also examine what this means for design – in other words, are there alternative structural layouts that maximise the designer’s ability to achieve high utilisation factors?

The intention of this section was to focus on the member design, and additional work is required to examine connection detailing. In discussions with industrial partners, it is not uncommon for a connection to be designed based on an envelope of all possible worst case resultant forces, which can lead to unrealistic combinations dominating design, and thus dominating the amount of material used. In future work, the effect of designing connections for an envelope of forces should be examined.

Some additional responses of interest, relating to fee levels, include:

> *“Fee levels not sufficient for optimisation. Although this is changing with a higher level of automation in design.”*
>
> *“time to refine is cost prohibitive due to low fees”*

IQ10: How can digital tools be developed and used to better join up design, procurement, and construction, to avoid the need to "build in" spare capacity "just in case"?

IQ11: To what extent does connection design dominate overall member utilisation?

4.7 Section 5: Capacity

Section 5 examined in more detail the feasibility of limiting over design of structural elements through design codes by introducing a limit on the value of R_d compared to E_d, as given by Eq.(1):

$$E_d \leq \mathbf{R_d} \leq \beta E_d \qquad (1)$$

E_d = Design effect of action
R_d = Design value of resistance
$\beta \geq 1.00$

The idea of introducing such a limit (a "Beta" value) on design resistance was considered to be unfeasible (Q27, median response 3 out of 7 (1 = "Not at all", 7 = "Completely"), 31% (39/125) responding "Not at all"). This is significant as in other questions the extreme responses have tended not to be used – here there is a strong feeling that this is not something that should be done.

Q28 then asked respondents to imagine that such a limit had been introduced. A numerical response was allowed but was only valid if ≥1.00. The median response was 1.50 (average 8,346, greatly skewed by one outlier response of 1x106). Of the 120 responses, ten were greater than 5.00. Excluding these ten responses, the median response was 1.45 (average 1.69).

Participants were then asked to identify in Q29 if there might be any unintended consequences of such a limit. The responses, given as a free text answer, fell into three broad categories: 1) business risks (including possibility of legal action); 2) design uncertainty (fudging to protect ourselves); and 3) implications of tighter design. The most popular response (29%, 32/110) was "increased complexity". Nineteen percent (21/110) of respondents identified "less flexibility" as a further consequence.

One response to Q29 stated:

> *"We should be setting limits on structural carbon by building type in tonnes/m^2. BIM technology allows this to be measured and is a more holistic and flexible approach to design that can be responded to in multiple ways one of which is optimisation of structural members"*

This approach would be feasible and should be supported by defining "benchmark" values of expected or target material use values for different building typologies.

Q30 asked participants to think about average utilisation factors across a design (with the utilisation factor being the inverse of a Beta value). A numerical answer was again required, but had to be ≤1.00. The median response was 0.75 (average 0.80). This median response corresponds to a 25% overcapacity. There is a significant spike in response at a utilisation of 0.50 (12%, 14/119), and 7% (8/119) entered a value less than 0.50. One respondent chose 0.00.

Discussions with industrial partners suggest that when automated software is used for (predominantly steel) design, target utilisation factors of 0.80 are entered. There appears to be no particular guidance or basis to this, but informal discussions with industry suggest this practice is quite commonplace. Further work is required to identify the source of such a limit, particularly when software is capable of automated design of all members, and what the unintended consequences of using such a limit might be on overall (average) utilisation factors.

Table 21 compares the responses of Q24, Q28, and Q30, which ask a similar question in different ways. Question 24 is a specific beam design choice, Q28 is an individual element upper limit, and Q30 is an average minimum utilisation for a design. The data is presented as a utilisation ratio to ease comparisons (β^{-1}).

Table 21: Comparison of Q24, Q28, and Q30, all given as a material utilisation ($E_d \div R_d$)

	Q24 (n = 118)	Q28 (n = 120)	Q28 (n = 110) (2)	Q30 (n = 119)
Median	0.93	0.67	0.69	0.80
Average	0.89	0.00(1)	0.59	0.75
Notes: (1) see text above (2) Q28 excluding ten largest numerical answers				

From this it is apparent that imposing a specific limit on every element would be difficult to achieve, whereas an average utilisation may be more feasible. In fact, the average utilisation proposed by respondents to the survey is high when compared to that measured in existing real buildings. This again underlines the general conclusion that the actual performance of designs is not well understood.

A strong negative correlation is found, as expected, between Question 28 ("Imagine that such a limit is introduced into a design code. The Design value of resistance ("Rd") for each element must be greater than the Design effect of the action ("Ed") AND less than "Beta" multiplied by "Ed", where "Beta" is a number ≥1.00. This relationship is shown in Eq.(1). What value of "Beta" would you be happy, as a structural designer, to see in a design code?") and Question 30 ("Imagine instead that an average material utilisation across all structural elements is introduced as a codified design requirement. What minimum value of material utilisation should be achieved by structural designers?"). The two numbers have slightly different concepts behind them, but a logical response to Q30 would be the inverse of Q28, which is seen in this correlation.

IQ12: How might we collectively design and build exemplar structures that achieve benchmark material consumption values (IQ1 and IQ2) to demonstrate full scale feasibility, with lessons learned being shared with the whole community?

IQ13: Would it be feasible to introduce both upper limits to member capacity, and target "average utilisation" factors across all members in a structure? What might the unintended consequences of this be?

IQ14: How might we agree on a "ratchet" of increasingly stringent design requirements, allowing time to adjust design culture whilst recognising the imperative need to reduce carbon emissions?

IQ15: Is there a perception that utilisation ratios of 1.00 ($E_d = R_d$) are dangerous? If so, why?

4.8 Section 6 – Design Examples

Section 6 examined some further specific design examples. Question 32 provided an example floor plate subject to a uniform load over its area and asked respondents to identify how many sets of calculations they would undertake to size the beams. The floor plate was taken from real building example given in Moynihan and Allwood [14], although it was not identified as such to the participants.

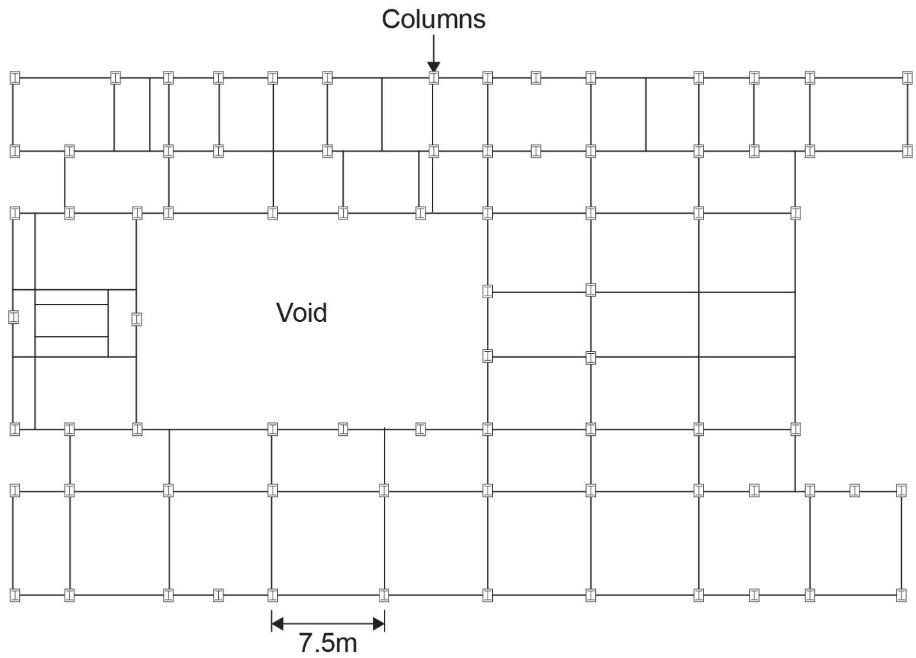

Figure 46: Floor plate shown for Q32

The median response was that ten sets of calculations would be undertaken (average 24). Three respondents chose “1” and seven chose “120”. The primary reason (60%, 68/113, of responses, Q33) given for this was rationalisation or grouping of the members.

Q32 asked participants to think about how many sets of calculations they might undertake in their own designs. Q34 asked participants to identify how many different sections depths they would expect to see in an as-built structure, with the median response of 6 (average 8).

In Q35 participants were asked if they would do anything differently if designing their own house. The majority responded in the negative (63%, 81/129). Of those who responded in the positive (48/129, 37%), examples of what might be done differently were “Control of loading” (32%, 14/44), “Greater certainty” (18%, 8/44) and “Higher utilisation” (16%, 7/44). Interestingly, 7% (3/44) stated “Lower utilisation” suggesting that some would be more conservative with the design for their own house.

IQ16: To what extent might design calculations and checking of calculations be automated, using techniques such as machine learning?

IQ17: How can we save design data for future interventions in the building? Might it be feasible to embed embodied energy data, structural capacity, and energy use data in land registry records, for example?

IQ18: Who needs to participate at which design stage to ensure material efficiency and embodied energy are key design drivers?

4.9 Survey Sections 1 – 6: Population effects

In this section brief comparisons of responses across Survey Sections 1 to 6, compared by Country, Age, and Years Experience are presented.

4.9.1 Country

Comparisons within the sample by country were not possible, as 74% of respondents were from the UK. It was however possible to compare UK (n = 93) and "Rest of World" (ROW) (n = 37) responses. Three respondents did not provide their country in the survey. See Table 3 for the full breakdown of respondent countries.

In Table 22, comparisons are made between UK and ROW median responses to questions with either Likert 1-7 or numerical responses. Overall, there is little difference between the two groups, and with the small sample size for ROW it is difficult to draw firm conclusions.

Question 1 suggests that maximising material utilisation is more important for ROW respondents, and ROW respondents more strongly agreed that the best way to reduce material consumption is to ensure structural utilisation is high (Q10).

ROW respondents scored local floor loading design codes as more appropriate (Q12) than UK respondents, and chose a slightly higher characteristic imposed floor loading for design (Q14) than UK respondents. The two groups had identical responses for Q16 (expected average floor loading over a 60-year service life) but the ROW respondents had a slightly lower median response for expected maximum floor loading in the same service life (2.50kN/m^2 compared to 2.75kN/m^2).

In Question 24, ROW respondents chose a median value of beam resistance of 203kNm (utilisation factor of 0.99) compared to the UK median response of 217.5kNm (utilisation factor of 0.92). Non-UK engineers also had a slightly higher median response to Q25 (how frequently $R_d = E_d$ in their designs) although both groups were at the low end of the scale, towards "Never". In a similar vein, ROW engineers had a slightly higher median response to Q27 (on the feasibility of a limit to design resistance), but again both groups thought this was not very feasible.

The two groups provide identical median responses to Q28 ("Beta" value as a limit to design resistance) and Q30 (average material utilisation), which suggests that the values here are representative of the industry quite broadly, and not just in the UK. This is a promising basis on which to begin this research.

Table 22: Comparisons between UK and ROW median responses to Likert or numerical response questions

Q	Question type	UK Median	ROW Median	UK-ROW	Sample Median
1	7-point Likert (Strongly disagree – Strongly agree)	5.00	6.00	-1.00	5.00
2		5.00	5.00	0.00	5.00
3		5.00	5.00	0.00	5.00
4		5.00	5.50	-0.50	5.00
5		3.00	3.00	0.00	3.00
6		5.00	5.00	0.00	5.00
7		6.00	6.00	0.00	6.00
8		2.00	2.00	0.00	2.00
9		2.00	2.50	-0.50	2.00
10		4.00	5.50	-1.50	5.00
11		2.00	2.00	0.00	2.00
12	7-point Likert (Never - Always)	4.00	5.00	-1.00	4.50
13		3.00	2.00	1.00	3.00
14	Numerical (kN/m^2)	2.50	3.00	-0.50	3.00
15	Numerical (kN/m^2)	1.00	1.00	0.00	1.00
16	Numerical (kN/m^2)	1.50	1.50	0.00	1.50
17	Numerical (kN/m^2)	2.75	2.50	0.25	2.50
18	Numerical (%)	0.00	0.00	0.00	0.00
19	Numerical (%)	0.00	0.00	0.00	0.00
20	7-point Likert (Never - Always)	5.00	5.00	0.00	5.00
24	Numerical (kNm)	217.50	203.00	14.50	210.00
25	7-point Likert (Never - Always)	2.00	3.00	-1.00	2.00
27	7-point Likert (Not at all - Completely)	2.00	3.00	-1.00	3.00
28	Numerical ("Beta")	1.50	1.50	0.00	1.50
30	Numerical (Utilisation Factor)	0.80	0.80	0.00	0.80
31	Numerical (mm)	250.00	225.00	25.00	250.00
32	Numerical (Calculations)	10.00	10.00	0.00	10.00
34	Numerical (Sections)	6.00	7.50	-1.50	6.00

4.9.2 Age

Responses are examined by age bracket for the UK sample (n = 93) in Table 23. In the initial 13 questions on a 7-point scale, the 55+ age bracket deviates most from the sample median (values in the table ≥±1 point from the sample median are highlighted). The differences are and in none of the initial questions is there a significant deviation noted by age bracket.

Responses to floor loading questions for design (Q14, Q15) and expected values in service (Q16, Q17) are largely comparable across the age brackets. However, examining expected (Q18) and desired (Q19) changes in floor loading, the 45-54 age bracket shows the largest difference to the sample median. This group expect floor loading to reduce by 7.5% in the coming decade, and if it was solely up to them would reduce it by 15% (compared to sample median values of 0% for both).

Table 23: Responses by age bracket for UK survey respondents (n = 93)

Q		UK 16-24 (n=6)	UK 25-34 (n=36)	UK 35-44 (n=16)	UK 45-54 (n=16)	UK 55+ (n=19)	UK sample (n=93)
1	7-point Likert (Strongly disagree – Strongly agree)	5	5	6	5.5	5	5
2		5	4.5	5	5	4	5
3		4.5	5	6	5	6	5
4		5	5	5.5	6	6	5
5		3	3	3	3	3	3
6		5.5	5	5	4.5	4	5
7		5.5	6	6	6	6	6
8		3	2	2	2	2	2
9		2	2	2	2	3	2
10		4.5	4	4	4.5	5	4
11		3	2	2	2	3	2
12	7-point Likert (Never - Always)	5	4	4	4.5	4	4
13		2.5	3	3	3.5	2	3
14	Numerical (kN/m^2)	2.5	3	2.75	2.5	2.75	2.5
15	Numerical (kN/m^2)	1	1	1	1	1	1
16	Numerical (kN/m^2)	1.15	1.5	1.5	1.4	1.5	1.5
17	Numerical (kN/m^2)	2.25	3	2.5	2.5	3	2.75
18	Numerical (%)	-2.5	0	0	-7.5	0	0
19	Numerical (%)	0	0	0	-15	0	0
20	7-point Likert (Never - Always)	4.5	5	5.5	5	5	5
24	Numerical (kNm)	220	220	210	210	210	217.5
25	7-point Likert (Never - Always)	2	2	2	3.5	3	2
27	7-point Likert (Not at all - Completely)	3	3	2	3	2	2
28	Numerical ("Beta")	2	1.45	1.5	1.25	1.5	1.5
30	Numerical (Utilisation Factor)	0.725	0.8	0.8	0.8	0.8	0.8
31	Numerical (mm)	250	250	275	250	250	250
32	Numerical (Calculations)	10	10	10	10	10	10
34	Numerical (Sections)	7.5	5	6	10	8	6

4.9.3 Responses correlated to years' experience

Analysis of survey responses shows no significant correlation (Pearson or Spearman Rank, Table 24) between years' experience and numerical answers. This supports the values shown for the UK sample in Table 23.

Table 24: Correlation of responses to years' experience

Q	Correlation to years' experience			Q	Correlation to years' experience	
	Spearman Rank	Pearson			Spearman Rank	Pearson
1	0.04	-0.06		15	-0.12	-0.09
2	0.11	0.12		16	-0.08	-0.14
3	0.05	-0.04		17	-0.01	-0.09
4	0.20	0.13		18	-0.10	-0.08
5	0.03	0.10		19	-0.13	-0.08
6	-0.24	-0.28		20	0.01	-0.01
7	0.19	0.16		24	-0.33	-0.22
8	-0.12	-0.06		25	0.22	0.20
9	0.01	0.05		27	-0.16	-0.12
10	-0.01	0.00		28	-0.10	0.00
11	-0.10	-0.04		30	0.23	0.20
12	-0.09	-0.03		31	0.08	0.09
13	-0.03	-0.02		32	-0.03	-0.06
14	0.04	0.05		34	0.07	0.07

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5 Discussion

5.1 Introduction

In this section key research areas that are explored that, based on the analysis of the preceding sections, require additional research. Taken together, these sections represent the first steps of the **MEICON** project. “Research Questions” (**RQ**) are posed for academia and industry to tackle collaboratively.

5.2 Loading

In the UK, and particularly in London, we have an established tradition of imposed loading levels in offices of around 4kN/m^2. Regardless of whether this is appropriate for use today, any change in loading levels must be accompanied by wider cultural changes, since the value of a lower floor load capacity may not immediately be clear to our community.

For example, when comparing lettable areas a space with an imposed characteristic floor load of 1kN/m^2 could be viewed as substandard to one with 4kN/m^2 – even if 1) the maximum load the office would ever see in its lifetime of use by a client could be demonstrated to be less than, for example, 0.50kN/m^2; 2) the structure was designed for easy retrofit should greater capacity be required for some alternative bespoke use in the future; and 3) the actual (failure) of the floor would occur at a load much greater than 1kN/m^2. In the survey it is seen that an abundance of capacity may be viewed in a positive light, yet from a material efficiency perspective this should not always be the case. We therefore must consider what design loading levels we should be using to give appropriate value our buildings and infrastructure.

MEICON proposes that it is the design community that should take the lead here. Without waiting to be asked, we must educate clients as to what is appropriate for design of floor space that includes allowances for future flexibility, unknown unknowns, and statistical variations in loading intensity. Office floor loadings are given a range of 2-3kN/m^2 in BS EN 1991 [43], but it is not clear why, or how a designer might choose between them, particularly since the higher limit is the recommended value and no distinction is made between types of offices. Why should one office space have a characteristic floor load 50% greater than another? One possible key to unpicking this puzzle is to develop an understanding of what actual loads are in buildings.

RQ1: How do we align the incentives of clients, architects, engineers, legislators, and contractors such that minimum embodied energy structures are the preferred outcome on all projects?

RQ2: How can continuous measurement of floor loading in real buildings be used to provide certainty to the statistical basis for SLS loading, and how can this data be used to understand the extent to which loading conditions are "peaky" so that decisions about SLS requirements can be made?

5.3 Design

Question 24 presented a highly idealised beam design question, where flexure was specified as the dominant design condition, and a capacity of E_d = 200kNm was required. Sixty nine percent (82/118) of our respondents chose a value of R_d for this imaginary beam that was greater than 200kNm. One quarter (29/118) chose a value of R_d equal to 200kNm. In our conversations with practitioners, the addition of a "bit of fat" to design appears to be commonplace, despite it being unnecessary. Setting a maximum utilisation in design software of 0.80, designing 10 out of 100 possible beams, or choosing the "next size up" from catalogues of parts are all understandable, if not desirable, decisions when viewed in isolation. However, the cumulative outcome of this culture of design is seen most plainly in building structures where average member utilisations barely reach 0.50 [14].

5.3.1 Design basis

It is worth returning to Figure 4 on page 18 to recall how characteristic actions and characteristic material properties are turned into design effects and design resistances. In most design, characteristic values are assumed to be normally distributed and a 95% confidence interval is chosen. This interval is the most widely used across scientific studies, despite it being an arbitrary choice [47]. The 95% confidence interval appears to have been adopted in structural design at around the time of writing the first design codes in the 1920s. This was then carried on as codes moved into limit state design.

The loads applied to any structure are likely to vary significantly both with time and location. Statistical methods are therefore employed to model the effect of the loads on a structure. A characteristic load is one with an acceptably low probability of being exceeded, typically taken to be 5%, as noted above. BS EN 1990 [4] defines characteristic values of actions as being those that have "a prescribed probability of not being exceeded on the unfavourable side during a reference period taking into account the design working life of the structure and the duration of the design situation", while characteristic material properties are specified as a 5% fractile [4].

Returning to Figure 45 on page 64, we might question what the actual chances of obtaining characteristic loads in real buildings are. Does a London office see a >3kN/m^2 floor load for 5% of its lifespan? For how long do you think an office floor really is loaded to its characteristic design load of 3kN/m^2 - which is equivalent to four people per square metre? (5% of 60 years is 3 years). We also note that floor loading is unlikely to be truly normally distributed, since for 14 hours a day most offices are normally empty of people.

The further reality of loading codes is that whilst a statistical basis for the values used is desired, it is not actually always the basis on which the data is derived – often there is no statistical data available. In these cases, characteristic values are simply nominal or target values prescribed in the codes and decided by committee on the basis of calibration against a long experience of building tradition. In other words, we use load values that have in the past not resulted in structural failures.

It is not the purpose of this report to delve further into statistical analysis, but we propose to consider in future work if there is a need to apply a 95% confidence interval on loads or material properties in all scenarios. Consider, for example the difference between floor overload causing a door not to fit, and the loss of a critical bracing member causing a roof to collapse. The use of appropriate characteristic loading values may open much greater material saving possibilities.

The origins of loading, as explored above, also warrant further investigation. Values for some actions appear to be more accurately determined than others – or at least are investigated in greater detail. As an example, consider the difference between determining wind loads and vertical imposed loads. Wind loads (for complex buildings) are routinely determined using physical models in sophisticated wind tunnel tests. The data from these tests are used directly in the design and represent the best knowledge for the structure being analysed. The same is not yet true for vertical loading, which is not measured in real structures, despite it being technological possible and simple to do so.

RQ3: What is the real envelope of floor loading for which most designs should be undertaken?

The four partial safety factors shown in Figure 4 on page 18, as used in the Eurocodes, could be examined in greater detail. Reducing partial factors representing uncertainty in representative values of permanent actions (γ_g) might offer immediate savings, on the basis that the deadweight of a structure and the density of the materials with which it is constructed should be very well understood. Partial factors for uncertainty in material properties (γ_m) might be revised to account for the improved quality of materials – reinforcing steel for example has a material partial safety factor of 1.15. What might the impact and unintended consequences be if this was reduced to 1.05, or 1.01?

BS EN 1990 [4] sets two ways in which partial (γ) and psi (ψ) factors may be determined: 1) “on the basis of calibration to a long experience of building tradition” or 2) "on the basis of statistical evaluation of experimental data and field observations carried out within the framework of probabilistic reliability theory". BS EN 1990 [4] notes in the text that route (1) is the leading principle for most γ and ψ factors currently in the Eurocodes. If we can successfully use measurement to define loading values, then the same research may be able to establish the information required to follow route (2) to appropriate values of these factors.

Material partial safety factors for masonry can be as high as 3.0 [48], partially determined by the level of workmanship and supervision during construction. Yet brick-laying robots are now available with an accuracy and speed exceeding that of a human, along with the ability to measure and record what has been built [49]. How will we decide on appropriate partial safety factors for robotic construction?

Many opportunities exist to reduce material consumption within existing design methods. As an example, the minimum cover over all concrete structures could be reduced by as much as 10mm (the value of Δc_{dev} in BS EN 1992-1-1 [50]) immediately if accurate cover measurement could be guaranteed [50]. Assuming the average thickness of all concrete members is 400mm, reducing this by 20mm ($2\Delta c_{dev}$) presents an immediate saving of 5% of UK concrete consumption (approximately 1.2 million m^3 of concrete, or 329,000tCO_2e[2] [7]). Not only does this reduce embodied energy, it saves weight – in our example, by 3.8 million tonnes. The knock-on effect of this is a reduction in foundation sizes, and further savings in material use.

RQ4: What might the benefits and consequences be of reducing material and load partial safety factors?

RQ5: How should partial safety factors for workmanship change as construction becomes increasingly automated?

5.3.2 Cost of overdesign

Throughout the survey, responses that place time and ease of construction at the centre of arguments in favour of material inefficiency are seen. Through discussions with industry, it is apparent that there may be a perception that significant extra design time is needed to safely achieve higher utilisation factors in structural design.

The BCSA [51] estimate the costs for the erection of a steel frame to be distributed as shown in Figure 47. The raw materials cost, although market dependent, is significant. Assuming raw materials account for 35% of the total, and steelwork design for 2%, a doubling of the design fee would only require a 6% reduction in

[2] Cement deliveries 2015 = 9.5 million tonnes. Assuming 75% is used in concrete gives 7.1Mt. At 300kg/m^3, this gives 23.8Mm^3 of concrete, 5% of which is 1.2Mm^3. Embodied carbon of C25/30 concrete is taken as 0.113kg $CO2_e$/kg, concrete density 2400kg/m^3, giving 329,000tCO_2e.

material costs to be fully offset. Assuming material costs are directly proportional to volume of material used, and based on the evidence given in this report, this is highly achievable. Further work is required to identify fully any links between design time and total cost, as the BCSA [51] report highlights that minimum weight may not lead to minimum cost – a balance is required between fabrication, erection complexity, erection time, and material use.

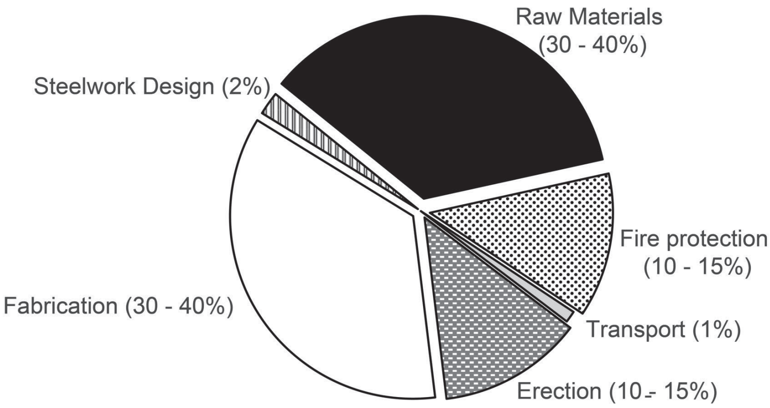

Figure 47: Steel frame costs, after BCSA [51]

Dunant *et al* [5] found no correlation between price per square metre for steel structures and the median utilisation ratio of their beams. This suggests that the available budget does not affect the overall optimisation of structures [5]. Therefore, we must consider how the vast computational power now available to designers may best be exploited. If more engineering time could be spent at concept design stage, where the *cost* of value improvement is low but value improvement *opportunity* is high [52], then perhaps choices that maximise the ability to minimise embodied energy could more readily be made.

Nolan [52] defines the “value gain” as the difference between the potential for value improvement and the cost of achieving value improvement (Figure 48). In this context, Value Engineering undertaken very early on at concept and schematic design stages has the greatest possible impact. Nolan [52] identifies the procurement process as one mechanism that prevents this early design involvement, causing significant lost value. The impact of the procurement process on material efficiency, particularly for large projects with Official Journal of the European Union (OJEU) requirements, requires significant futher research and consideration.

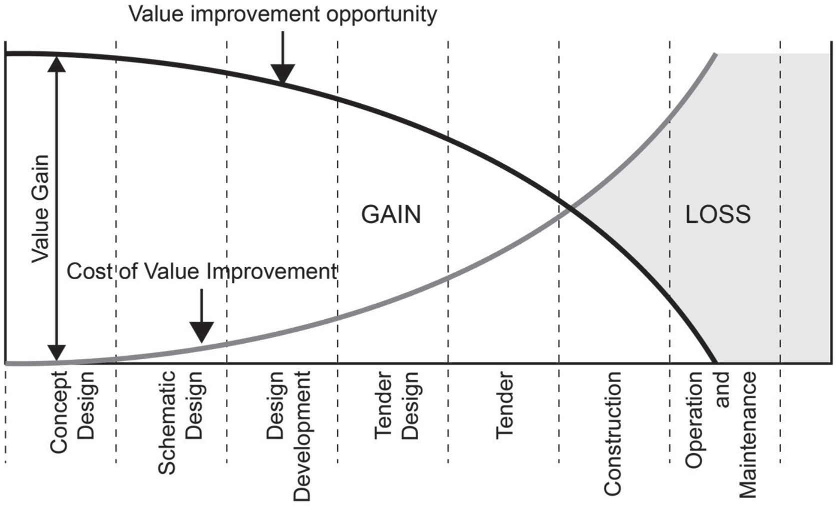

Figure 48: Value gain (following Nolan [52] and [53]).

As the construction sector introduces increased automation at the construction stage, the balance of optimisation may begin to change. Further work is required to identify how site automation, robotics, digital "passports" for individual building elements, and increased use of BIM may be harnessed to ensure that lightweight construction does become a cost-effective solution. Given the evidence of Figure 48, all of these considerations must be made in the context of the complexities of procurement.

We might further ask what incentives exist to save material for a structural engineer? If fees are based solely on achieving a design that works, and is not directly affected by material costs, then it is understandable that saving design time is an effective business strategy. The value in saving material using sits with the contractor and fabricator, where reducing material use by 30% directly affects the bottom line.

In 2015, UK demand for steel was approximately 10.4 million tonnes [54], half of which was used in construction [55]. Assuming rolled sections to be 12% of this total [56], produced at £1500/tonne [57], structural steelwork has an approximate value of £1.9bn. If demand was reduced by 25% (saving 302,000 tonnes of steel per year), and cost per tonne rose by 20% to account for any increases in production costs, the net saving would be in the order of £162 million per year. Wise and McCann [57], using similar analysis, identify a total of £3.7bn in savings that could be achieved by rethinking how we use materials.

The total value of professional Engineering Services fees is in the order of £3.9bn [58] per year (data from 2005-06). Of this, firms identifying as "Civil and Structural Engineering" had fee income of £1.1bn [58] (note that some firms undertaking structural engineering work who classify themselves as "interdisciplinary" would not fall into this total). The scale of the savings possible through better design and material efficiency in the same ballpark as total structural engineering fees. This presents a great opportunity for the sector.

In this report, the material efficiency of structural frames is considered. Yet in the context of a building, they account for a relatively small cost (c.10%) [59]. Despite this small cost, the structural frame brings with it a large amount of embodied carbon. Kaethner and Burridge [60] analysed example buildings proposed by the Concrete Centre Office Cost Study [59], and found that for office buildings, on average, the superstructure accounted for 45% of the total embodied CO_2.

RQ6: How will design and construction automation, along with target values of material efficiency, affect the economics of structural engineering, particularly fee levels?

RQ7: Structural frames account for a small amount of project cost, but a large amount of embodied carbon. What is the value proposition for reducing material use if the cost impact is small?

5.3.3 Design process

The role of the structural engineer must be viewed in the context of a design process. The greatest potential for influencing material efficiency is held at concept design stage. Once designs are “fixed” material (in)efficiency is locked in, and the role of the engineer becomes one of making it work, rather than making it work well. As explored above, Nolan [52] provides further analysis of this, identifying the procurement process as a key barrier to achieving value in design.

Students are taught both that design is an iterative process [61] and that collaboration between disciplines is one key to succesful design [62]. Many of our great precedents come from practitioners who may be described as engineers, designers, architects, and constructors [63-65]. In practice, design can often become “siloed” with relatively little interaction between stages and less ability to iterate ideas [66]. The experience of our partners suggests that more innovative projects by their nature result in more collaboration. An unfamiliar structural typology (e.g. shell structures) or material (e.g. ferrocement) may lead to greater interaction between architect, engineer, and contractor as each builds up their knowledge of the new process to ensure a successful outcome. The design of a “bread and butter” 12-storey concrete frame office block may lead to less collaboration, and less time invested in design decisions that impact material efficiency. This is a difficult cultural challenge, as it is the “bread and butter” structures that make up the bulk of our material use –rarely do teams get assembled to build complex ferrocement shells.

Examples of structures that perform similar functions but have significantly different embodied energy can be found in [28, 67]. Often these differences can highlight a design philosophy or conscious choice of architectural form. Outside of "iconic" projects, a common theme in our discussions with industry was the material consumption required to use transfer structures. In a tall building, one of the least structurally sensible places to put a very tall, wide, column free space is in the entrance lobby - yet this is commonplace. As a result, it is not uncommon to find extensive transfer structures above these entrance levels. Options including deep beams, or even deep slabs covering the entire floor plate [68] are commonplace.

There is a need for early design input to ensure that strategic decisions are made relating to the positioning of structural elements. Many good examples exist, where material has cleverly been arranged to support an architectural vision [69, 70].

RQ8: How can the implications of concept design decisions on material use and life cycle use be better understood by and illustrated to design teams?

5.3.4 Alternative approaches

Given the scale of the potential cost and energy savings to be made through material efficiency, alternative design bases could be explored. In many other branches of engineering, the consequences of failure for elements are explored in far greater detail and responded to in an appropriate way. Failure Mode Effect Analysis (FMEA) is widely used in automotive and aerospace industries. It is an approach that allows designers to identify all possible failures in a design, a manufacturing or assembly process, or a product or service.

Based on the severity of the failure, designers then determine what the response should be. As an example, if failure of one element would lead to total collapse, a second redundant system would likely be required (an alternative load path). If the consequence of failure was the inability to open a window for ten minutes, the designer might choose to do nothing.

RQ9: How might Failure Mode Effects Analysis (FMEA) be feasibly applied to the design of buildings to incorporate more detailed consideration of the consequences of failure and an appropriate level of risk?

5.3.5 Automation of design and checking

The automation of structural design calculations is now relatively routine, using either bespoke or off-the-shelf software. Higher levels of automation could help to drive designers towards more materially efficient structures, if target utilisation factors can be set closer to 1.00.

Question 29 of the survey asked “What might the unintended consequences of a limit to the design value of resistance relative to the design effect of the actions be, in your opinion?”. Several responses are worth highlighting here:

> *“Waste of design time leading to inefficiencies in more important areas”*
>
> *“more cost, more errors, more change orders”*
>
> *“Increased time to calculate = less time for job = more mistakes/more people use fewer sections throughout building = average utilisation increases”*
>
> *“increased design time - looking for minima as well as maxima. increased complexity of construction - less standardisation.”*
>
> *“Too many mistakes causing failures. Poor workmanship causing failures.”*

These responses highlight a need to understand errors in the design process. As a sector are we aware of the level of mistakes that currently exist in design calculations, and how can this be reduced. Although automation of design appears to be desirable, the potential for errors exists if the underlying structural model is poorly conditioned (incorrect or inappropriate use of releases or supports, for example). The difficulty of properly examining finite element and other structural models, may lead those who check designs to err on the side of caution, which itself could be a source of material inefficiency.

A similar concern is seen in a perception that increased design time is required, which may put pressure on both small and large companies. As shown in §5.3.2 on page 80, there is a sensible counter argument to this, where the value of a detailed design can lead to significant material (and cost) savings.

RQ10: How can structural models be checked in an automated fashion? How can we reduce error rates in structural engineering design? Should there be a partial safety factor for analytical errors in all structural design, and how might this change over time as automation increases?

5.3.6 Construction complexity

The survey results show quite clearly that construction ease is more highly valued than material efficiency (Q4, Q6, Q7, Q26, Q29, Q33). Our industry is famously slow to change, and thus has heavily ingrained methods of construction. This is seen perhaps most clearly in concrete and masonry. Concrete formwork has changed very little for 2000 years: timber boxes are assembled and used to hold wet concrete, while Brunelleschi’s dome at Santa Maria del Fiore, Florence, remains the world’s largest in masonry, with a span of 42m.

In the survey, many thoughts highlighting a need for ease of construction are seen. This might also be interpreted as construction that we are familiar with:

> *Q23: 30% responses "Ease of construction"*
>
> *Q26: "Workmanship concerns, either in element construction, or in construction of restraints envisaged etc" "the unpredictability of contractors." "constructability and repeatability" "Conscious of the pressure from client/contractor at a later date to verify structural capacity following the inevitable site error"*
>
> *Q29: "structures that are not buildable" "difficulty of construction" "added construction cost" "Elements will be highly utilised and therefore doesn't give much scope for layouts changing/construction mistakes"*
>
> *Q33: "Compromise between efficiency and ease of design/fabrication/construction" "simplification would help the coordination and construction process" "rationalise for ease of construction" "rationalisation of details to aide [sic] in construction, in terms of both fabrication and supervisions"*

In the past 40 years, the construction sector has demonstrably been unable to successfully improve productivity [12]. **MEICON** aims to help industry to challenge strongly ingrained perceptions of how things "should" be done and support novel research that can improve whole life construction productivity through new methods for analysis, optimisation, and construction. There is now a role for the automation of design, and construction, to drive required changes.

RQ11: To what extent can automation of construction and digital design be used to drive a cultural change to instil better confidence in construction competence?

5.3.7 Active control

The use of active building control systems to control serviceability under extreme loading offers the potential for whole life energy savings in the order of 70% [71]. Such a step may be required if we are to meet the UK Construction 2025 targets [1]. Whilst active control is quite widely used in vibration control, the full potential has not yet been realised. The work of Senatore *et al* [71] achieves a balance between a completely passive design (members must have sufficient embodied energy to carry all possible ULS and SLS) and a completely active design (low embodied energy, but high operational energy required to continuously actuate the structure to meet SLS requirements) by defining a load activation threshold [71], Figure 49.

By designing all the members to be strong enough for all possible ULS conditions, active control allows certain SLS criteria to be satisfied without requiring the use of additional material. The whole life energy is minimised via simultaneous optimisation of the structural layout and the actuation layout. Instead of relying only on passive resistance through material mass to counteract the effect of rarely occurring loads, an actuation system is optimally integrated to alter the flow of internal forces and to change the shape of the structure. The internal forces are controlled to achieve stress homogenization and the shape is changed to control deflections. This method has been successfully implemented for the design of planar and spatial truss structures of complex layout. Under normal service conditions, the structure would work without active control. In rare loads above the activation threshold, the mechanical devices (actuators) are activated to bring deflections (or some other SLS condition) back within required limits. Whole life embodied energy could be reduced by as much as 70% for slender structures with such technology [72].

Implementing such a design methodology would require fundamental change in structural engineering. Suitable to be combined with FMEA (§5.3.3, page 83), active control offers great potential for material efficiency, Figure 50.

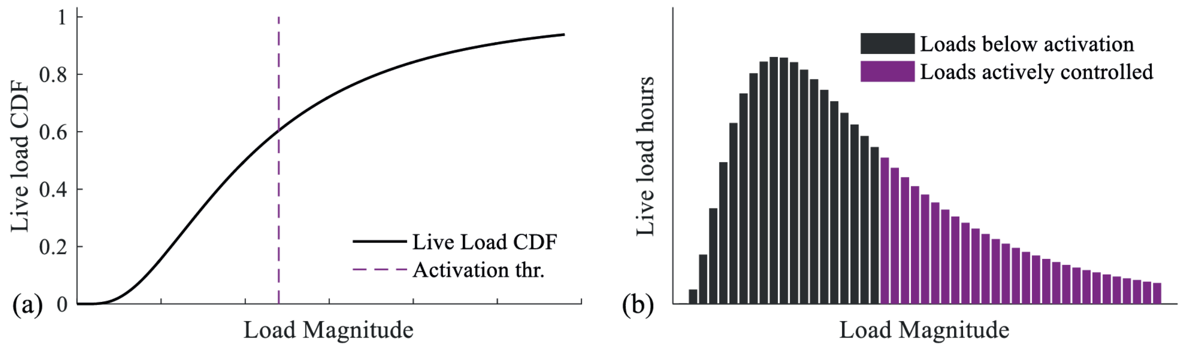

Figure 49: (a) Live load cumulative distribution; (b) live load hours [73]
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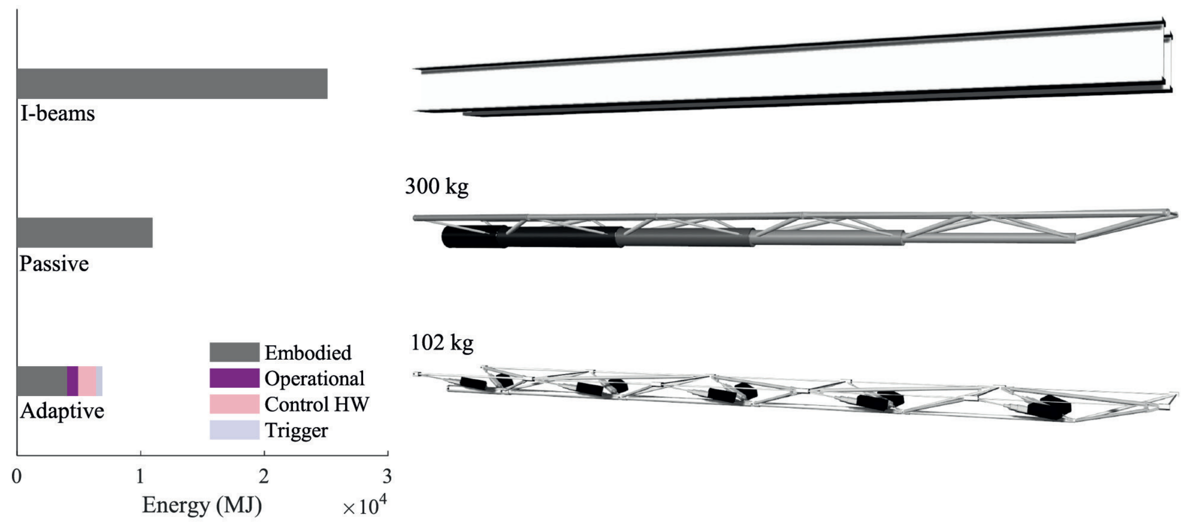

Figure 50: Energy comparison I-beams versus optimised passive structure versus adaptive structure [73]
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RQ12: What is the roadmap to achieving a separation between ULS and SLS design, such that active control can be introduced appropriately?

RQ13: How might serviceability be more appropriately defined such that (whilst maintaining current ULS criteria) SLS is rarely the dominant limit state for most structures? What might the unintended consequences of this be?

5.4 Standardisation

In our discussions about material efficiency it is often said that “each building is unique” and therefore it is hard to re-use design calculations from one building to the next. Standardisation of components, or the provision of an optimised “kit of parts” offer potential solutions. There are however significant issues with such an approach - who would hold the design risk for each item? Should a structural engineer “check” every standardised design to ensure they have executed their own professional due diligence? Would it prohibit architectural expression? Do we need to redesign every 8m span concrete beam supporting a floor load of $3kN/m^2$?

Instead, “mass customisation” may be a more fruitful design avenue, where every component of every structure can feasibly be completely unique. By combining automation of design with sophisticated robotic manufacture, this approach allows multiple unique elements to be included in every structure. It furthermore does not prohibit or limit the architecture, a key part of ensuring wellbeing and diversity of our built environment. Coupled with design and procurement processes that maximise value improvement opportunities by making clever decisions early on, this becomes a key part of minimal embodied energy structures.

RQ14: How can mass-customisation of building components be embedded into design, procurement, and construction processes to maximise value?

5.5 Final thoughts

Driving material efficiency in design requires complex cultural and technical research. We need clients who are willing to reconsider their methods of procurement, the teams they employ, and the working practices they use. This may initially be well suited to those involved in the design of repetitive elements (high speed rail, for example) or government bodies. There is a need for both carrots and sticks, and for exemplar structures that demonstrate what good looks like. There is a need to identify roadmaps with feasible pathways to achieving material efficiency.

This report has touched on a number of key areas yet more are still to be explored:

- Prototyping and living laboratories.

RQ15: What prototype demonstrator buildings are required to demonstrate to our community what better looks like?

- Legal frameworks.

RQ16: How might a construction contract that requires minimal embodied energy design be drafted?

- The Planning System.

RQ17: Can the success of the Merton Rule in renewables [10] be replicated to reduce embodied energy?

- Building sustainability assessment methods.

RQ18: What barriers exist to making material utilisation a more fundamental part of points-based methods of building assessment? Should we have a "MOT" for buildings?

- Data.

RQ19: What is the role of big data, computer science, and machine learning in changing the process of design?

- Occupant behaviour.

RQ20: How do people interact with buildings? How does this change when they are lightweight? Are there any unintended consequences of lightweighting that change the user experience?

- Education.

RQ21: What should be taught in Universities to prepare new engineers for the demands of design. What disciplines will be needed to work collaboratively in the future design office?

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6 Next steps

6.1 Vision

Our long-term vision is for the built environment to be designed cost-effectively, based on whole-life cycle energy consumption using minimum material resource for appropriate performance in a circular economy.

6.2 What you can do now

- *Analyse* your personal practice as it relates to embodied energy. Consider:
  - How often do you measure embodied energy? What are your own benchmarks for design efficiency? What barriers do you experience to achieving minimal embodied energy structures?
- *Analyse* your own responses to the survey questions against the findings.
- *Review* your personal practice by comparing it with those of your colleagues, both inside and outside your organisation. Include your choices of loading, serviceability criteria, extent of calculations across multiple elements and the importance of ‘what-if’ factors. Create a database of embodied energy per m^2 values for your projects.
- *Form* an action learning group to share experiences of trying to implement these principles in your design work. Share your findings with colleagues, examine differences, and identify best practice.
- *Feedback* your anonymised findings to the **MEICON** team (www.meicon.net) to help us collate international benchmarks.
- *Consider* our “Industry Questions”. Choose those that interest you most. Discuss them with colleagues and clients, write an initial response in three bullet points, and circulate your ideas company-wide to generate discussion.
- *Examine* our “Research Questions”. Choose those you feel able to help answer and enter your details at www.meicon.net to join a new research team.
- *Analyse* how your company’s sustainability strategy addresses material efficiency in design. How might **MEICON** be used to help improve it?
- *Agree* to making at least one change to your practice based on these results.

6.3 Wider research need

Structures are currently designed with uncertainty, which is a key factor in their resulting heavyweight nature. To reach the lightest possible structures for a set of optimisation criteria, where active control of serviceability is combined with the correct amount of material for strength, based on measured human and structural performance, requires a concerted interdisciplinary research program that will combine architecture, construction, computer science, artificial intelligence and machine learning, engineering and mathematics, Figure 51.

The benefits of this research will be evident through efficient construction, minimal whole life energy use, better internal environments for occupants, and establishing, for the first time, design based on certainty. Table 25 outlines our proposals for research in this area, to achieve data informed design, by 2030, that incorporates manufacture, assembly, operation, reuse, and demolition. Four key prosperity outcomes for the UK are targeted.

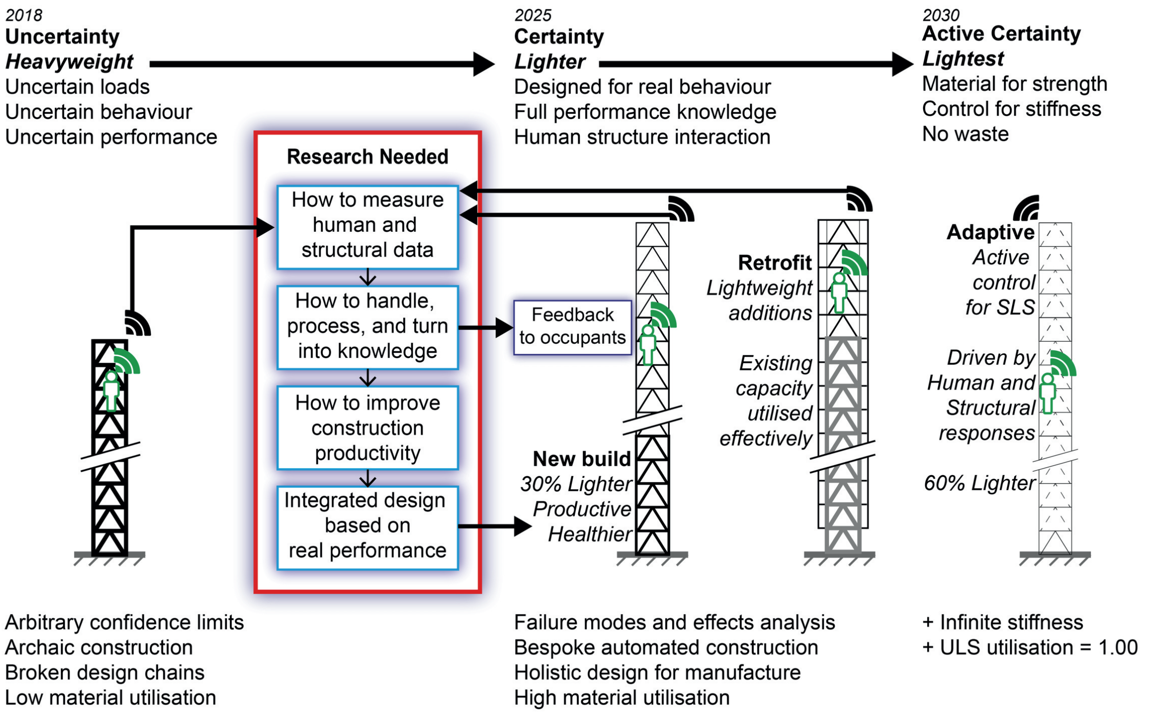

Figure 51: Research need to drive lightweighting

Table 25: Research requirements to achieve our 2030 goal (continued overleaf)

Prosperity outcome:		Learning from: Manufacture	Assembly	Function	Reuse	Deconstruction
Productivity	*2030 Goal*	• All buildings made from reused components • Automation of every stage of production to minimise human work and risk	• Automation of (on- and off-site) assembly using robotics and new construction methods to minimise human work and risk	• Using data to understand what designs make people healthy and productive. • Relationship between structural behaviour and human performance fully understood and informing designers	• Sensor data informs changes in use as actual performance of components is known. • If strengthening is required, actual load distribution is known • Re-use of components at the end of life	• Demolition without people • Recycle components into other forms, e.g. unusable concrete beams into aggregates • Know the properties and life load history, know what cannot be used again.
Productivity	*Research Map*	• Develop electronic passports for key building components carrying details of their load history, capacity, and manufacture. • Define how to automate the fabrication of structural components, using manufacturing-style processes including lean, and offsite construction. • Full scale demonstration buildings to establish feasibility.	• Design control systems and robotic technology allowing component tracking and installation with minimal human involvement. • Define how on-site assembly should inform and be linked to digital design • Use of robots and co-bots to de-risk construction • Full scale demonstration buildings to establish feasibility.	• Develop networks for ubiquitous sensing – human, structural, environmental • Define new data handling methods for operation that can link to building management. • Determine how knowledge can be extracted from this data • Define new protocols for continuous "learning from performance"	• Define how data collected over long periods of time can be interpreted to inform re-use and retrofitting • Establish reliable data storage methods (c.120 years) • Develop electronic passports for components	• Define new methods for automation of building component identification through embedded sensors and passports • Develop material separation and sorting technology to create databases of available materials for re-use in the manufacturing stage.
Resilience	*2030 Goal*	• Automated production of minimal embodied energy structures • Use of advanced composite materials that are suited to automation and highly durable • Integration of design with manufacture	• Improve reliability of construction by full recording of exactly how everything is built • Manage resources efficiently in the construction cycle – no waste on site	• Data from embedded sensors to provide picture of current state of stress, loading, and condition of the structure • Informs repair and maintenance Continuous data in a facilities management strategy	• Active SLS control for extreme loading scenarios in all buildings. • Response to extreme events informed by knowledge of actual behaviour • Use data to understand how to repair or strengthen	• Minimal building waste to landfill • Management of infrastructure and buildings as a material resource • Ensure demolition is only undertaken when required
Resilience	*Research Map*	• How to ensure automation of production enables **mass-customisation** and not mass-production of the same components • Definition of maximum and benchmark values of embodied energy for all building typologies, based on measured performance data • Full scale demonstration buildings to establish feasibility.	• Define which data have value and must be stored to inform reuse stages • Develop machine learning tools for co-bots and robots based on construction performance • Develop material separation and sorting technology to create databases of any waste materials arising from construction for re-use in the manufacturing stage of another project. • Full scale demonstration buildings to establish feasibility.	• Data handling, machine learning, and data storage methods to feed into building management systems, to inform how structures should be maintained and operated. • Use of self-sensing, self-healing materials that "maintain" themselves by exploiting material properties, and keep a record of their state to give continuous condition monitoring for building owners.	• Continuous sensing to drive active SLS control systems throughout structure (including data handling and robustness). • Sensing to record extreme events (loads and material response) to inform ULS design methods • Active control systems for SLS conditions beyond deflection and vibration control.	• Data control and handling methods to ensure reliability of component passports. • Define what information is essential to record during demolition to inform future re-use of components • Develop recycling methods for all building components that cannot be re-used (driving circular economy).

Prosperity outcome:		Learning from: Manufacture	Assembly	Function	Reuse	Deconstruction
Connectivity	2030 Goal	• Embedding sensors into structures to enable location tracking and condition monitoring in manufacture and assembly • Data automatically used to populate building models, identifying individual components through an electronic passport.	• Continuous monitoring of construction process to inform lean-principles based approach to construction methods • Data links with building models	• Using data from multiple buildings to inform design, based on measured performance • Link between human and structural factors • Understand precisely how structure is behaving and inform design methods • Understand e.g. effects of wind on multiple buildings in the same area • Data links with building models	• Response to changing environmental effects over time informed by performance data • Use of sensing in all structures to inform appropriate responses • Data links with building models	• Gathering of data during demolition – final extreme loading to inform actual capacity of built structures. • Data links with building models
Connectivity	Research Map	• Define the sensors that can be embedded within elements during manufacture to enable future health monitoring. • Define what data is valuable for assembly and operation, and what is not • Establish protocols for automated population of building models using data from component embedded sensors • Full scale demonstration buildings to establish feasibility.	• Define how data from thousands of components can be controlled and handled, interpreted and used, to inform future construction methods. • Full scale demonstration buildings to establish feasibility.	• Human participant trials in simulated buildings to define protocols for measurement of human-structure-environment interaction • Define proxies that are easy to measure in a non-intrusive way to enable widespread sensing of occupants • Define data handling and interpretation methods, including machine learning, to extract knowledge from data	• Define how building management systems can provide full record of occupant enjoyment of a building, to inform how future interventions might improve occupant wellbeing • Define data handling and storage to deal with often long life cycle between construction and reuse	• Define what information is essential to record during demolition to inform future re-use of components • Define protocols for "hand over" of building components from one project to another to minimise risk and ensure reliability of new designs.
Health	2030 Goal	• Minimise human involvement to improve health and safety of manufacturing	• Reduce risk of work to humans	• Transform buildings by putting occupant health, wellbeing, and productivity at the centre of design. • Data from occupant sensing to understand and inform future design • Management of interventions informed by data to improve indoor quality through appropriate actions	• Automation of repair and/reuse works	• Robotics to minimise risk to life
Health	Research Map	• Define the fabrication processes that can be fully automated • Determine how automated technologies are best used in construction, and what these new techniques would look like.	• Define the on-site processes that can be fully automated • Define new control systems to automate the installation of building components • Determine how robots, drones, and automated technologies can best be implemented and redefine construction methodologies based on this.	• Define how human data can be handled in non-intrusive manner to generate actionable data that positively informs future design methods. • Define protocols such that data from embedded sensors can provide live information of building health • Define protocols for continuous monitoring and improvement of internal environment to ensure healthy workspaces	• Define how data from human-structure-environment sensors is fed into method to propose positive interventions to the structure • Define methods by which structural health data is used in automated repair/retrofit scenarios	• Define methods to ensure building demolition can be undertaken with minimal human involvement • Define control and recognition systems such that components are extracted from a building without damage and are appropriately identified for reuse in new structures. • Automated link with database of available materials, linked to electronic passports.
AND embed outputs at each stage and from each stream into taught courses for engineering, architecture, psychology, physiology, computing, robotics, and other relevant sectors through a concerted effort to improve the underpinning knowledge of professionals entering the sector. Does the philosophy of overdesign start in Universities? How do we teach good design judgement?						

6.4 **MEICON** Project

The survey presented in this report underlines the importance of the feasibility level studies being undertaken in **MEICON**. In the current funded period, the project team aim to identify:

- Sources of wasted embodied energy
- Sources of value-less cost
- Sources of performance over-design

6.5 Your input

This research requires the input of the community – please engage with the **MEICON** team by joining us at workshops and events. Full information is available on the project website, www.meicon.net.

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7 References

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Contact
Dr John Orr
Department of Engineering
University of Cambridge
Trumpington Street
Cambridge CB2 1PZ

+44 (0)1223 332 623
jjo33@cam.ac.uk
www.meicon.net

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