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Effectiveness of design codes for life cycle energy optimisation

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ABSTRACT

The built environment is materially inefficient, with structural material wastage in the order of 50% being common. As operational energy consumption in buildings falls, due to continued tightening of regulations and improvements in the efficiency of energy generation and distribution, present inefficiencies in embodied energy use become increasingly significant in the calculation of whole life energy use. The status quo cannot continue if we are to meet carbon emissions reduction targets. We must now tackle embodied energy as vigorously as we have tackled operational energy in buildings in the past.

Current design methods are poorly suited to controlling material inefficiency in design, which arises as a risk mitigation strategy against unknown loads and uncertain human responses to these loads. Prescriptive codes are intended to result in buildings capable of providing certain levels of performance. These performance levels are often based on small tests, and the actual performance of individual building designs is rarely fully assessed after construction. A new approach is required to drive the minimisation of embodied energy (lightweighting) through the collection of performance data on both structures and their occupants.

This paper uses an industry facing survey to explore for the first time the potential use of performance measurement to create new drivers for *lighter* and *more usable* designs. The use of ubiquitous structural, human, and environmental sensing, combined with automated data fusion, data interpretation, and knowledge generation is now required to ensure that future generations of building designs are lightweight, lower-carbon, cheaper, and healthier.

1. Introduction

The structural design of buildings is wasteful [1]. It has been demonstrated [2] that structural engineers regularly over-specify material. This situation arises as a risk mitigation strategy against unknown loads and uncertain human responses to these loads. This paper uses an industry facing survey to explore the potential use of sensing technology to measure performance, creating new drivers for *lighter* and *more usable* designs. Measurement, feedforward and feedback loops, and prototyping, are established practice in aerospace, ICT, medical, automotive and power generation industries, and are used to improve performance by learning from in-service behaviour. Reductions in design uncertainties for these industries have led to significant economic and environmental cost savings, for example through reduced weight and fuel consumption.

In stark contrast, the global construction industry has no similar virtuous circle for design, despite being worth $8.5tr annually [3], and creating and maintaining the built environment that emits about half of the planet's carbon emissions [4]. Structural engineering remains the only engineering discipline that does not consistently measure in-service performance of its designs to drive improvements in both operation and future design. The status quo, where structural material wastage in the order of 50% is common [2,5], cannot continue if we are to meet carbon emissions reduction targets [6,7]. Examples of this wastage are described later. Legislation requiring all new European buildings to be nearly zero operational energy by 2020, and improvements in the efficiency of energy generation and distribution [8], means that embodied energy may soon comprise the entirety of a building's whole life energy use [9,10].

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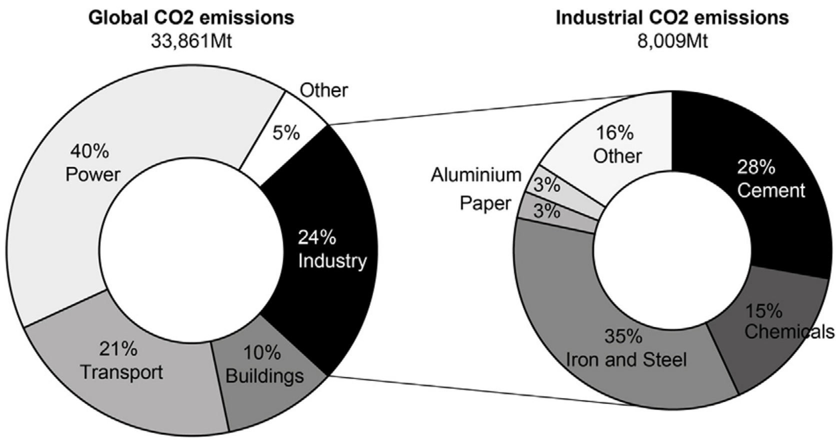

Fig. 1. Global CO_2 emissions in 2013 demonstrating the importance of key building materials [17].

1.1. Material utilisation

In the design of structural members, the ultimate (Eq. (1)) and serviceability (Eq. (2)) limit states must be satisfied:

$$E_{d,ULS} \leq R_d \tag{1}$$

$$E_{d,SLS} \leq C_d \tag{2}$$

where $E_{d,ULS}$ is the design value of the effect of actions such as internal force, moment or a vector representing several internal forces or moments; R_d is the design value of the corresponding resistance; $E_{d,SLS}$ is the design value of the effects of actions specified in the serviceability criterion, determined on the basis of the relevant load combination; and C_d is the limiting design value of the relevant serviceability criterion.

Eq. (1) and Eq. (2) provide no upper limit on *how much* greater than the effect (E_d) the compliance of a member (R_d or C_d) should be. This creates the potential for code-satisfying but materially-inefficient structural elements, a scenario that is frequently encountered [8]. In examining 10,000 steel beams in real buildings, Moynihan and Allwood [2] demonstrated average utilisations of less than 50% of their capacity. Significant material savings could have been made within the requirements of *existing* European design codes. Work by Orr et al. [5] demonstrates that utilisation of structural concrete is also often low, with the potential for material savings of 30–40% through design optimisation.

In construction, the use of as few different cross sections as possible is preferred by contractors to simplify logistics, resulting in an increase in overall material usage [2]. In a large floor plate, for example, beam depths may be determined everywhere by a worst case loading scenario in one position. This ensures that whilst one member may, in an infrequent design situation, be working close to its capacity, the vast majority of elements will never be utilised to a significant extent.

In addition to standardisation of cross sections, structures may be designed for unrealistic vertical loads. Mitchell and Woodgate [11] surveyed 32 office buildings (160,000m^2), dividing floor plates into a range of bay sizes for analysis. They found mean loading of 0.57 kN/m^2 and 95% percentile loading of 0.96 kN/m^2 in bays with a mean size of 192m^2. Slightly higher loading was found at the ground (average 0.62 kN/m^2) and basement floors (average 0.75 kN/m^2). These loads are significantly less than what is assumed in design [12]. Similar results have been reported around the world, Table 1.

In the UK, city centre offices are routinely designed for a vertical floor live loading of 5 kN/m^2, a figure that was first specified over 100 years ago [16] and is far in excess of the 2.5 kN/m^2 that is required for most office space by the present Eurocodes [12]. There is thus a culture of inefficiency being driven by a perception of letting requirements that does not reflect best design practice. The use of such a high floor loading is often mentioned alongside 'flexibility' for future use of the space, yet we routinely design our columns and foundations for much smaller loads – the UK National Annex to BS EN 1991-1-1 [12] allows the load in a column to be reduced by 50% in structures of more than 10 storeys.

Table 1
Comparison of vertical live loads.

Average live load (kN/m^2)	Survey area (m^2)	Survey location	Reference
0.33	28,818	Ghana	Andam [13]
0.47	34,420	USA	Culver [14]
0.46	11,720	India	Kumar [15]

It could be argued that it is unlikely that all floors in a building would be loaded equally, yet in city centres, where rents are high and single buildings are let out floor by floor to different companies, it is not unreasonable to suggest that each floor plate might see approximately the same load. The crucial point is that this will be far less than 5 kN/m^2, which is useful for the building owner if all the columns have been sized for a smaller total loading. Tellingly, column reduction factors may not be used if loads "*have been specifically determined from knowledge of the proposed use of the structure*" [12].

Two opportunities therefore exist to drive the lightweighting of new structures:

1. To design them for realistic loads;
2. To design their members with much higher utilisation factors.

1.2. Material emissions

Nearly two-thirds of industrial CO_2 emissions arise from the production of cement, iron and steel, and aluminium, all of which are ubiquitous in the construction of buildings and structures, Fig. 1.

Allwood et al. [8] describe four major strategies for reducing material demand through material efficiency:

a) Longer-lasting products;
b) Modularisation and remanufacturing;
c) Component re-use and
d) Designing products with less material.

To design structural components with less material, a full understanding of the performance requirements of that component is required. Whilst this data collection is commonplace in other industries, measuring and understanding the performance of build-

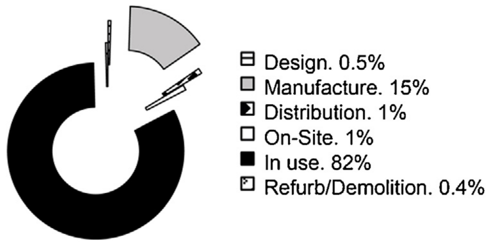

Fig. 2. CO_2 emissions the construction industry has the ability to influence (after [4]).

ings and structures is highly challenging. It is relatively easy to obtain strain gauge data for a beam, but much more difficult to interpret this data stream into design knowledge that could be utilised in the design of future buildings.

1.3. The importance of embodied energy in the construction market

The minimisation of operational energy has been the focus of both design regulations [18] and research [9], but relatively little attention has been paid to minimising embodied energy [5]. Arup [19] note that whilst the embodied energy of a building or structure was previously operational energy for another industry, not counting embodied energy puts the construction industry at risk of 1) using energy saving products where the energy required in manufacture far outweighs savings in use; 2) seeing materials arriving on site as 'carbon free'; 3) reducing pressure to minimise material wastage; and 4) increasing the likelihood of demolition and reconstruction rather than refurbishment, as the embodied carbon of an existing structure is not highly valued.

Fig. 2 presents the broad areas of a building's life cycle, highlighting the proportion of CO_2 emissions the construction industry has the ability to influence [4]. The current importance of in-use energy is clear, and this sector has received significant research attention in recent years. As operational energy falls, the proportion of whole life energy coming from manufacture (embodied energy) is due to increase in proportion rapidly making the minimisation of embodied energy (lightweighting) an urgent design criterion.

1.4. The performance gap

Building codes establish minimum requirements for safety through the specification of prescriptive criteria that regulate acceptable materials of construction, identify approved structural and non-structural systems, specify required minimum levels of strength and stiffness, and control the details of how a building is to be put together. Although these prescriptive criteria are intended to result in buildings capable of providing certain levels of performance, the *actual performance* of individual building designs is not assessed *after construction* as part of the traditional code-based design process. As a result, we do not know how well our buildings perform. The performance of some buildings could therefore be better than the minimum standards anticipated by the code, while the performance of others could be worse [20]. We are unable to frequently update codified design requirements despite the vast numbers of buildings that are constructed each year, which have the potential to provide exactly the data required to ensure that design standards truly inform best practice.

1.5. Environmental assessment

Methods for the environmental assessment and rating of buildings do not yet require the minimisation of embodied energy through structural efficiency of building design. LEED [21] '*materials and resources*' credits are given based efforts to minimise life cycle emissions from the "extraction, processing, transport, maintenance, and disposal of building materials [21]", but does not require the structural design to be efficient in its use of these materials. In the BREEAM [22] system, only one credit out of a possible 150 is given to "*measures to optimise material efficiency in order to minimise environmental impact of material use and waste*" [22]. A greater emphasis on achieving materially efficient design could be assisted by future revisions to these popular performance assessment methods.

2. Exploring alternative approaches

Whole life environmental, economic and social costs are rarely taken into account in codified design methods. The concept of minimising embodied energy is far less advanced within both industry and research, where focus remains on improving operational energy efficiency [19,23–26]. The importance of undertaking a life cycle analysis to select the optimum construction solution increases when this design is correlated against the total energy use of the building.

A key purpose of codes of practice is to offer guidance on dealing with uncertainties in the design and construction process of structures. Developments in sensing technology now offer opportunities to measure what happens in real-life structures, and may thereby enable an alternative design approach that employs measurements to minimise and better manage uncertainties in the built environment.

In the future, big data pertinent to every structure could potentially be used to update the information in existing design codes of practice. This transformation will facilitate the design of fit for purpose, resilient structures, with minimal whole life environmental, economic and social costs and will contribute to minimise the gap that is found in buildings from a structural and energy perspective. To assess the appetite from industry for such a shift in thinking an international survey was undertaken.

2.1. Survey

A survey of professionals in the built environment was undertaken to establish industry satisfaction with current design codes of practice and their appetite for alternative design approaches which could integrate intelligent sensing, data processing, and performance based design in order to secure a sustainable built environment.

The survey took into consideration:

1. Areas in which the use of an alternative design approach would be beneficial, to both individual designers and to companies; and
2. Information that a designer has available related to the current life cycle performance of buildings.

To collect this data, an integrated survey was designed to collect data using two different methods: given list method and free form method [27]. The survey describes user experiences with different types of buildings and structures, focusing on suitability of current design codes and also on measurements and data analysis in buildings and structures. The survey questions are given in Table 2. The survey was completed online, and distributed to a target list of global professionals (practitioners and academics) in the construction industry.

Table 2
Survey questions Response.

	Question	
1	Your sector	Given list: *Industry* *Academia*
2	Your region of work	Given list: *Europe, North America, South America, Asia, Oceania, Africa*
3	Your position	Given list: *Graduate, Associate, Associate Director, Director, Executive Officer*
4	How satisfied are you with current design codes?	Given list: *From 1: Completely dissatisfied (You consider them to be extremely unrealistic or overly conservative) to 7: Completely satisfied (You consider them to deal suitably with the uncertainties in modelling civil engineering environments)*
4(a)	If you selected a rating of less than 6, please list two reasons why you feel that current design codes are inappropriate	Free text
4(b)	Can you list two examples of structures designed using codes of practice which have subsequently failed to meet client requirements on performance?	Free text
5	To what extent do you think that existing design codes facilitate the design of structures which have minimal whole life (embodied and operational) energy use?	Given list *From 1: Not at all to 7: Completely*
6	How comfortable would you be with the implementation of a design approach that uses measurements from real buildings to justify design decisions? (For example by using measured data from vibrations, deflections, and loadings in real buildings, to inform future design projects.)	Given list *From 1: Not at all to 7: Completely comfortable*
7	How frequently do you measure the as-built versus as-designed performance of your projects?	Given list *From 1: Never, to 7: Always*
8	How often do you utilise the post-construction performance of one or more structures to inform subsequent designs?	Given list *From 1: Never 7: Always*
9	Which, if any, of the following actions and conditions have you attempted to measure in buildings that you have designed?	Given list *Select at least 1 option: Fatigue, Vibration, Live loading, Durability, Cracking, None, Other*
10	What challenges have you met when trying to interpret sensor data to understand building/structure/infrastructure performance?	Free text
11	In your experience, where can the use of sensing data and measurements make a difference for clients?	Free text

2.2. Survey results

The whole process resulted in 78 survey submissions, of which 12 were incomplete responses. Of the 66 valid responses, 39 (60%) were from industry and 27 (40%) from academia. A summary of region of work and jobs of the respondents is given in Table 3. Region of the world and seniority of position were required questions to provide a sufficiently detailed profile of respondents to the survey. The results from the given list method presented in Table 2 are presented in Figs. 3–8 .

Table 3
Summary of region of work and role of respondents.

Region of work[1]	Industry (%[2])	Region of work[1]	Academia (%[2])
Europe	82% [32]	Europe	67% [18]
North America	10% [4]	North America	15% [4]
South America	5% [2]	South America	0% [0]
Asia	15% [6]	Asia	4% [1]
Oceania	3% [1]	Oceania	4% [1]
Africa	3% [1]	Africa	11% [3]
Position	**Industry (%)**	**Position[3]**	**Academia (%)**
Graduate	10% [4]	Post-doc	18% [5]
Associate	13% [5]	Lecturer	22% [6]
Associate Director	15% [6]	Senior Lecturer	4% [1]
Director	33% [13]	Reader	15% [4]
Executive Officer	8% [3]	Professor	37% [10]
Other	21% [8]	Other	4% [1]

Notes: [1] Region of work allowed multiple regions to be chosen, percentage given in terms of number of valid survey responses. [2] Partcipiants could select more than one region of work. [3] Positions for academia were mapped to positions in industry in broad terms using a British career progression model.

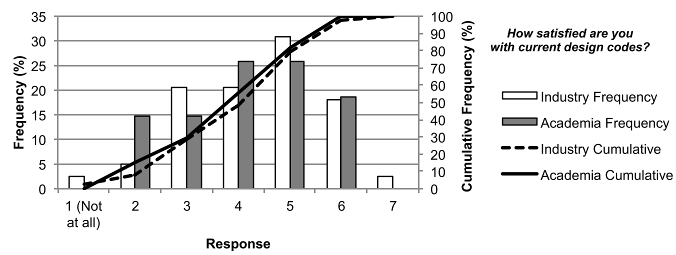

Fig. 3. Responses to Q4 (Table 2).

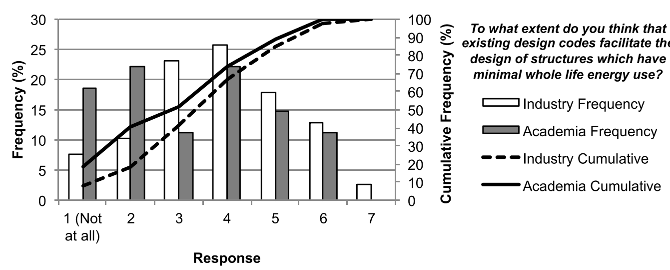

Fig. 4. Responses to Q5 (Table 2).

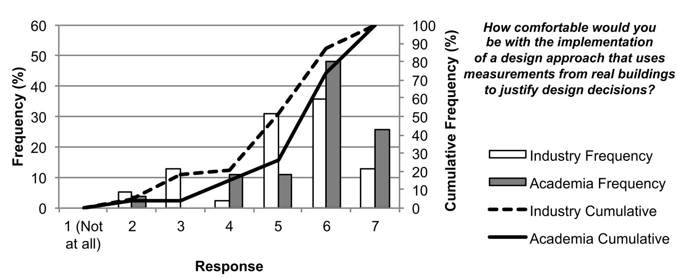

Fig. 5. Responses to Q6 (Table 2).

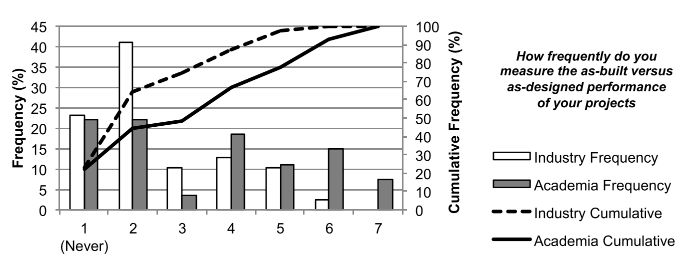

Fig. 6. Responses to Q7 (Table 2).

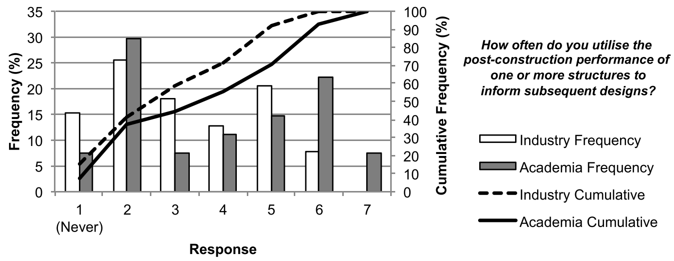

Fig. 7. Responses to Q8 (Table 2).

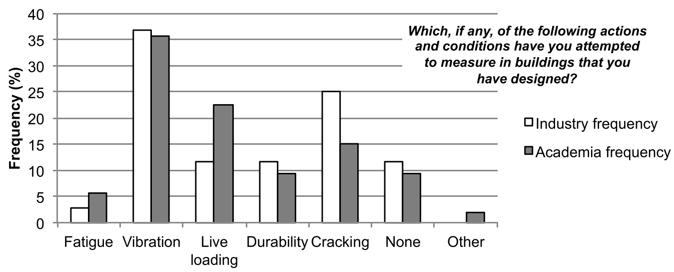

Fig. 8. Responses to Q9 (Table 2).

2.3. Survey analysis

The analysis to the quantitative data from the survey shows that, generally, both industry and academia have similar views to the potential use of ubiquitous sensing technology to measure performance as the basis for future drivers of *lighter* and *more usable* designs.

2.3.1. Given list responses

In response to the question "*How satisfied are you with current design codes?*" it can be said that Industry is slightly happier with design codes than Academia – 48% of Industry answered less than 4 and 58% of Academia answered less than 4.

Regarding the question "*To what extent do you think that existing design codes facilitate the design of structures which have minimal whole life energy use?*" answers from practitioners and academics are similar. Half of the industrial respondents agree that current design codes of practice do not facilitate the design of structures which have minimal whole life energy use.

Around 80% of the industry and academia are comfortable or completely comfortable (providing a score greater than 5) with the concept that measurements from real buildings should be used to inform subsequent designs. However, the majority does not measure the as-built versus as-designed performance of projects, and the majority does not utilise the information collected from post-construction performance of structures to inform subsequent designs.

About one in five practitioners and academics surveyed never measure as built versus as-designed performance of projects, with the vast majority of both sets of professionals giving a score less than 4.

Besides this, the results from the fifth question "How often do you utilise the post-construction performance of one or more structures to inform subsequent designs?" show that 15% of the industry never utilise post-construction performance and around 70% gave a score less than 4. In responses from academia, a low 7% never utilise post-construction performance and about half gave a score less than 4. Regarding the types of measurements that are usually made in buildings, the majority only measure vibration and cracking of structures. Durability and live loading represent a mere 8% each.

All of the data support the view that academia and industry should work together to change present design methods, as the same changes are desired by both sectors. This change must be led by significant joint research projects that are undertaken both in the laboratory and 'in the wild', to validate and develop the design protocols that future building design will rely on.

2.3.2. Free form responses

The full data set of the surveys (redacted for confidentiality) is provided in the data archive (see data access statement). In the following section a summary of responses to the four free form questions is collated and summarised.

There were 29 responses from industry and 20 responses from academia to Q4(a). The most frequently reported criticism of design codes from industry was their conservatism ("*Loading codes are overly conservative*"; "*conservatisms become so high in some cases that they are inappropriate*"). Codes were described as "*out-dated*" and "*difficult to interpret*", with respondents commenting on the difficulty of applying "idealised" code methods to "real-world" engineering. Overly complex code methods were also mentioned as a key barrier to innovation ("*Overly complex and prescriptive, which inhibits creativity and innovation, as well as encouraging mistakes*").

Responses from Academia were also concerned with overly conservative codes ("*Overly conservative and encourages engineers to blindly follow rules rather than the laws of physics*"). The empirical basis of many design codes was also identified as a key limitation of codes ("*Based on empiricism; source of design rules often unclear*") along with the sources of these empirical equations ("*Much of the information used in design is informed by data collected in labs on scaled models*", "*Experimental testing is poorly addressed!*"). Codes were identified as requiring more real world-data ("*They do not cover situations encountered in real life*", "*lack of sufficient feedback loop of information on structural performance from as built structures*").

These responses highlight the need for design methods that are 1) based on real world measured performance from tests on realistically sized elements; 2) provide an appropriate level of conservatism; and 3) do not prevent or limit engineering creativity. Academia and industry are in broad agreement in these three areas.

A further concern arises from structures that nominally satisfy the design code, but then fail in-service due to unforeseen loading or structural behaviour. There were 24 responses from industry and 14 responses from academia to Q4(b). The majority of responses mentioned serviceability level failures ("*vibrations*", "*accelerations due to wind loading*", "*deflection limits*"). Only a small number of structures were named in the survey, with one respondent noting "There are cases but couldn't mention them due to client confidentiality". This highlights a key barrier within civil structural engineering in which poor performance is infrequently reported, meaning that the industry as a whole struggles to learn from past mistakes. Only in extreme circumstances do serviceability level issues get widely reported for major structures [28,29], and whilst full structural collapse remains infrequent such events are widely reported [30]. In the UK, a well established confidential reporting mechanism exists for structural-related failures [31], with the goal of improving best practice.

Industry respondents to Q4(b) highlighted that "*The majority of structures are over designed*" and "*are inefficient*" meaning that this "*overdesign provides overcapacity which compensates for...mistakes or misunderstandings*". Another respondent highlighted that structural performance is only one type of failure, with "*missed opportunities for resource effectiveness and economy, constrained by code*".

Responses from Academia to Q4(b) also focused on serviceability ("*vibration*", "*aeroelastic instability*", "*dynamic responses*", and "*fatigue*"). The issue of confidentiality ("*many not in public domain*") was again raised.

There were 25 responses from Industry and 18 responses from Academia to Q10 ("*What challenges have you met when trying to interpret sensor data to understand building/structure/infrastructure performance?").* Key themes in responses from industry include the length of time required ("*extended period of time to get any useful data*"), and the time and expense of processing the data ("*time required to process data meaningfully*", "*Lack of staff that understand this data and are able to interpret this in a meaningful manner*"). The interpretation of data was identified as a key challenge ("*difficult to convert into an easily usable form*", "*noise from oversensitivity*", "*Elimination of false readings*"), along with the cost ("*Nobody wants to pay*") and the fact that the building owner or maintenance company may not have the capacity to interpret sensor data to inform their day-to-day work.

Key themes in responses from academia focused on the difficulties of managing and interpreting large amounts of data ("*too much data*", "*loss of information in processing*", "*noise*", "*hard to find reliable information*", "*we have even less experience as a profession in interpreting data from real life than designing based on code*"). The difficulties of installing sensing systems was also highlighted ("*Getting permission to collect data*", "*Exact details and positioning of sensors required*", "*cost*"). The issue of permission is a key criterion for future design methods. If the structural engineering profession is to achieve a design process that can learn from real, measured behaviour, then much work is required to convince our clients that the sharing of such data is in their long-term interest. Only with a full understanding of how structures behave and the impact that they have on the health of the building occupants, will structural engineers and designers be able to make informed design decisions. This process will drive both sustainability (reduced material consumption by understand what shape our structures really should be to achieve serviceability and ultimate limit state performance) and productivity (improved internal design of the human-structure interaction).

Q11 (*In your experience, where can the use of sensing data and measurements make a difference for clients?*) received 29 responses from industry and 20 responses from academia. Industry responses included the potential for savings in embodied energy ("material use") through reduced conservatism, and all stages of a building life cycle from design, construction ("*construction costs*"), maintenance ("*assessment of the performamce of the structure, which leads to proactive...maintenance*"), and retrofit ("demonstrating adequate performance of the building (hence delaying demolition)"). The importance of sensor design was highlighted, with benefits "*only when designed with the end use in mind"*.

The potential for sensor data to reduce uncertainty was highlighted as a benefit to clients ("*Obtaining...sensing...data to improve prediction methods can only be of help to clients*"), but in contrast it was also noted that: "*Clients are often concerned about using this sort of data and putting their particular project at risk if it is constructed*". Convincing clients of a reduction in floor loading from the often used $4\,kN/m^2 + 1\,kN/m^2$ for partitions was highlighted, with "*very little appetite to change this (even though it is very conservative) as a lesser loading allowance is seen as a 'worse' product"*. This highlights the non-engineering challenges of data collection and interpretation.

One response saw little benefit to clients at all, "*unless they build multiple similar buildings*", which of course does happen, particularly for office and residential developers. Even more significantly, the potential for sensors in multiple different buildings to inform vertical and lateral loading requirements is very large – turning the detailed building-specific data into generalised design principles. This presents a huge challenge.

Responses from Academia to Q11 again focused on the potential for data collection to drive material efficiency. Concerns on client attitudes were again highlighted ("*Few clients build sufficiently regularly that the data is useful to inform their own future project*"). It is worth noting that many University campuses are engaged in significant building projects, making University Estates Departments a key target for a sensing based design approach. The use of data to inform maintenance and building operation was highlighted ("Use of their own data can save energy use and refurb costs") and use of *others*' data was suggested as a further route to impact ("*Use of OTHERS' sensing data can save material = cost during design.*").

The free-text responses from both Industry and Academia highlight some of the challenges and opportunities of using real-building data as the basis for future designs. In the following section this is explored further in the context of using sensing to achieve our carbon targets.

3. Future use of sensing

The results of the survey show that the majority of industry does not currently utilise widespread measurement of performance to inform subsequent designs (Fig. 6), but is indeed comfortable with the possibility of using measured data to justify design decisions (Fig. 5).

A significant body of work exists in the measurement of internal environment quality (temperature, humidity, VOCs, CO_2, productivity, health) but very little of this is correlated to the behaviour of the structure within which the people exist. Humans spend 90% of their time indoors, and yet we do very little to measure, learn from, and improve this environment [32,33]. An increasing association of sick building syndrome [34] with airtight buildings has the potential to inhibit moves towards greater energy efficiency [35,36]. Research is now required to link data from 1) building physics, 2) structural response, and 3) human behaviour in buildings and structures to provide holistic drivers towards lightweighting.

Direct measurements of loading from building contents may be achieved using room-based RFID scanning [37], while measuring the number and location of building occupants may require a number of technologies including i) infrared; ii) radio frequency; iii) ultrasound; iv) wearable ultra-wide band and inertial measurement units; v) point cloud scanning; and vi) tracking via WiFi [38] and magnetic field analysis [39]. These data must then be correlated with time stamped structural response data collected from strain gauges, accelerometers, and displacement gauges installed on the structure. Indirect measurements of loading, for example from wind, can be achieved by identifying the sensitivity and correlation matrices that link loading and structural response data sets [40,41].

Finally, research is required to understand the relationship between structural motion, physiology and user experience. The emerging serious issue of sopite syndrome (drowsiness induced by imperceptible building motion) identified by Lamb et al. [42] is one demonstration of the new importance of linking health with structural monitoring. Wearable technologies (measuring heart rate variability, temperature, blood pressure and accelerations) may be used to obtain objective user data, while subjective data may be collected through smartphone surveys that can provide periodic time-stamped self-assessments of biometrics, mood, alertness and productivity. Fusion of these data sets will ultimately allow building designers to understand how an applied motion (known structural behaviour) causes both physiological changes (objectively measured by wearables) and psychological and performance changes (measured by self-assessment).

The challenges of collecting, processing, interpreting, and analysing cross correlations between such data sets are not insignificant but will provide the step change in design practice that is required if we are to reduce design uncertainty and enable lightweighting of all future designs.

4. Conclusions

A survey was designed to collect designer level experiences, focusing on suitability of current design codes and on measurements and data analysis in buildings and structures. The results from both quantitative and free form data support a general opinion that design codes do not yet adequately deal with certain serviceability level issues and few codes directly account for real-world performance of structures.

This justifies current research moves by the authors towards performance based design approaches that use measurements from real buildings and their occupants to justify future design decisions. The survey also demonstrated the need for frequent updating of design codes to take into account recent knowledge about climate change and new material developments. There are missed opportunities for resource effectiveness and economy due to constraints of design codes. The strengthening of the link between waste reduction and resource efficiency could be enhanced if a better approach is implemented.

The majority of the survey participants do not utilise the information collected from post-construction performance of structures to inform subsequent designs. Where measurements are taken, a focus is on 'engineering' data such as vibration and cracking, rather than the much more difficult to measure interactions amongst structure, environment, and occupant health.

Current design does not regularly take into account the environmental impact of construction over the whole life cycle of a building or structure. The combination of reliable data measured from buildings, with optimisation algorithms and tools for performance-based design are required to achieve design optimisation and the minimisation of embodied energy. The use of ubiquitous sensing of human, structural, and environmental factors, combined with automated data fusion, data interpretation, and knowledge generation is now required to ensure that future generations of building designs are lightweight, lower-carbon, cheaper, and healthier. This paper provides the evidence base for the need for this transformative design approach.

Data access statement

All data created during this research are openly available from the University of Bath data archive at https://doi.org/10.15125/BATH-00333.

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