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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.

*Keywords:* Performance-based design; built environment; whole life cycle.

# 37 **1 Introduction**

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

48 In stark contrast, the global construction industry has no similar virtuous circle for design,  
49 despite being worth \$8.5tr annually [3], and creating and maintaining the built environment  
50 that emits about half of the planet's carbon emissions [4]. Structural engineering remains the  
51 only engineering discipline that does not consistently measure in-service performance of its  
52 designs to drive improvements in both operation and future design. The status quo, where  
53 structural material wastage in the order of 50% is common [2, 5], cannot continue if we are  
54 to meet carbon emissions reduction targets [6, 7]. Examples of this wastage are described  
55 later. Legislation requiring all new European buildings to be nearly zero operational energy  
56 by 2020, and improvements in the efficiency of energy generation and distribution [8], means  
57 that embodied energy may soon comprise the entirety of a building's whole life energy use  
58 [9, 10].

## 59 **1.1 Material utilisation**

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

$$62 \quad E_{d,ULS} \leq R_d \quad (1)$$

63

$$E_{d,SLS} \leq C_d \quad (2)$$

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

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

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

83 In addition to standardisation of cross sections, structures may be designed for unrealistic  
84 vertical loads. Mitchell and Woodgate [11] surveyed 32 office buildings (160,000m<sup>2</sup>), dividing  
85 floor plates into a range of bay sizes for analysis. They found mean loading of 0.57kN/m<sup>2</sup>  
86 and 95% percentile loading of 0.96kN/m<sup>2</sup> in bays with a mean size of 192m<sup>2</sup>. Slightly higher  
87 loading was found at the ground (average 0.62kN/m<sup>2</sup>) and basement floors (average

88 0.75kN/m<sup>2</sup>). These loads are significantly less than what is assumed in design [12]. Similar  
89 results have been reported around the world, Table 1.

90 **Table 1: Comparison of vertical live loads**

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

91  
92 In the UK, city centre offices are routinely designed for a vertical floor live loading of 5kN/m<sup>2</sup>,  
93 a figure that was first specified over 100 years ago [16] and is far in excess of the 2.5kN/m<sup>2</sup>  
94 that is required for most office space by the present Eurocodes [12]. There is thus a culture  
95 of inefficiency being driven by a perception of letting requirements that does not reflect best  
96 design practice. The use of such a high floor loading is often mentioned alongside ‘flexibility’  
97 for future use of the space, yet we routinely design our columns and foundations for much  
98 smaller loads - the UK National Annex to BS EN 1991-1-1 [12] allows the load in a column to  
99 be reduced by 50% in structures of more than 10 storeys.

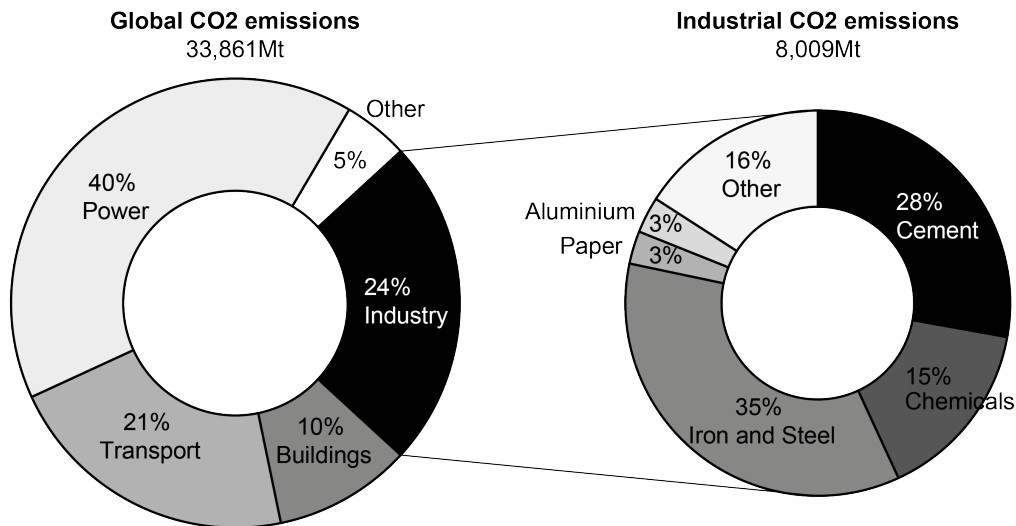
100 It could be argued that it is unlikely that all floors in a building would be loaded equally, yet in  
101 city centres, where rents are high and single buildings are let out floor by floor to different  
102 companies, it is not unreasonable to suggest that each floor plate might see approximately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

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

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

110 **1.2 Material emissions**

111 Nearly two-thirds of industrial CO<sub>2</sub> emissions arise from the production of cement, iron and  
112 steel, and aluminium, all of which are ubiquitous in the construction of buildings and  
113 structures, Figure 1.



114

115 **Figure 1: Global CO<sub>2</sub> emissions in 2013 demonstrating the importance of key building materials [17]**

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

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

122 To design structural components with less material, a full understanding of the performance  
123 requirements of that component is required. Whilst this data collection is commonplace in  
124 other industries, measuring and understanding the performance of buildings and structures  
125 is highly challenging. It is relatively easy to obtain strain gauge data for a beam, but much  
126 more difficult to interpret this data stream into design knowledge that could be utilised in the  
127 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.

Figure 2 presents the broad areas of a building’s life cycle, highlighting the proportion of CO<sub>2</sub> 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.

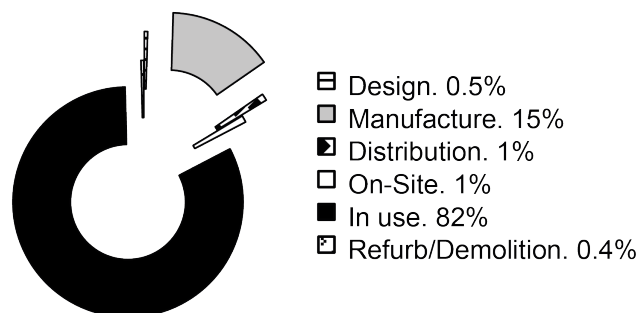


Figure 2: CO<sub>2</sub> emissions the construction industry has the ability to influence (after [4])



#### 147 **1.4 The performance gap**

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

#### 161 **1.5 Environmental assessment**

162 Methods for the environmental assessment and rating of buildings do not yet require the  
163 minimisation of embodied energy through structural efficiency of building design. LEED [21]  
164 '*materials and resources*' credits are given based efforts to minimise life cycle emissions  
165 from the "extraction, processing, transport, maintenance, and disposal of building materials  
166 [21]", but does not require the structural design to be efficient in its use of these materials. In  
167 the BREEAM [22] system, only one credit out of a possible 150 is given to "*measures to*  
168 *optimise material efficiency in order to minimise environmental impact of material use and*  
169 *waste*" [22]. A greater emphasis on achieving materially efficient design could be assisted by  
170 future revisions to these popular performance assessment methods.

## 171 **2 Exploring alternative approaches**

172 Whole life environmental, economic and social costs are rarely taken into account in codified  
173 design methods. The concept of minimising embodied energy is far less advanced within  
174 both industry and research, where focus remains on improving operational energy efficiency  
175 [19, 23-26]. The importance of undertaking a life cycle analysis to select the optimum  
176 construction solution increases when this design is correlated against the total energy use of  
177 the building.

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

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

### 189 **2.1 Survey**

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

194 The survey took into consideration:

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

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

205 **Table 2: Survey questions**

	<b>Question</b>	<b>Response</b>
<b>1</b>	Your sector	Given list: <i>Industry</i> <i>Academia</i>
<b>2</b>	Your region of work	Given list: <i>Europe, North America, South America, Asia, Oceania, Africa</i>
<b>3</b>	Your position	Given list: <i>Graduate, Associate, Associate Director, Director, Executive Officer</i>
<b>4</b>	How satisfied are you with current design codes?	Given list: <i>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)</i>
<b>4(a)</b>	If you selected a rating of less than 6, please list two reasons why you feel that current design codes are inappropriate	Free text
<b>4(b)</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
<b>5</b>	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 <i>From 1: Not at all to 7: Completely</i>
<b>6</b>	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	Given list <i>From 1: Not at all to 7: Completely comfortable</i>

	Question	Response
	using measured data from vibrations, deflections, and loadings in real buildings, to inform future design projects.)	
7	How frequently do you measure the as-built versus as-designed performance of your projects?	Given list <i>From 1: Never, to 7: Always</i>
8	How often do you utilise the post-construction performance of one or more structures to inform subsequent designs?	Given list <i>From 1: Never 7: Always</i>
9	Which, if any, of the following actions and conditions have you attempted to measure in buildings that you have designed?	Given list <i>Select at least 1 option: Fatigue, Vibration, Live loading, Durability, Cracking, None, Other</i>
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

206

## 207 2.2 Survey results

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

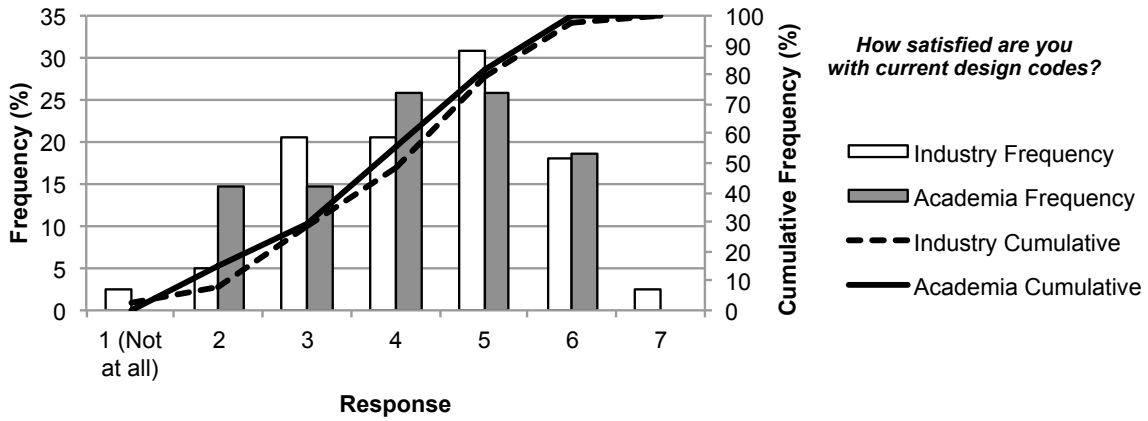
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**Table 3: Summary of region of work and role of respondents**

Region of work <sup>1</sup>	Industry (% <sup>2</sup> )	Region of work <sup>1</sup>	Academia (% <sup>2</sup> )
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 <sup>3</sup>	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]

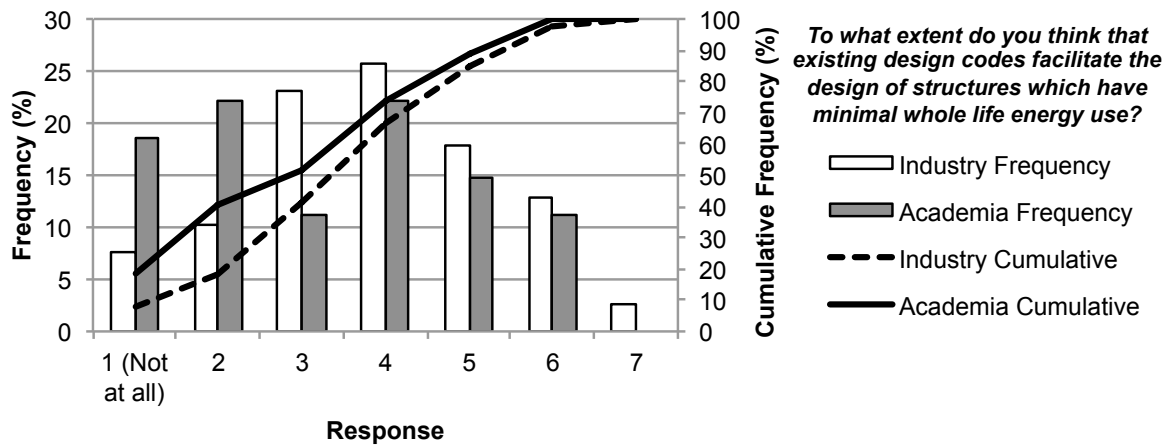
Notes: <sup>1</sup> Region of work allowed multiple regions to be chosen, percentage given in terms of number of valid survey responses. <sup>2</sup>Participants could select more than one region of work. <sup>3</sup> Positions for academia were mapped to positions in industry in broad terms using a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

215



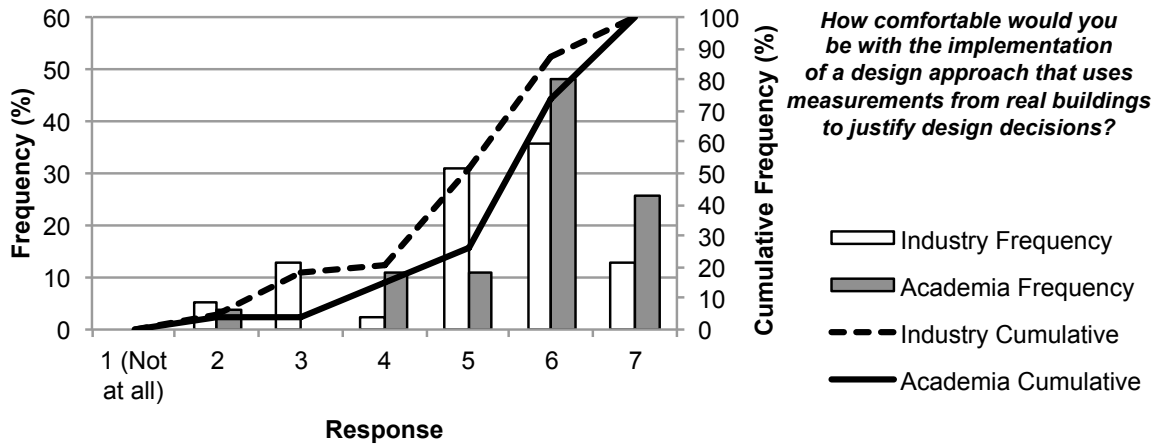
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217 **Figure 3: Responses to Q4 (Table 2)**



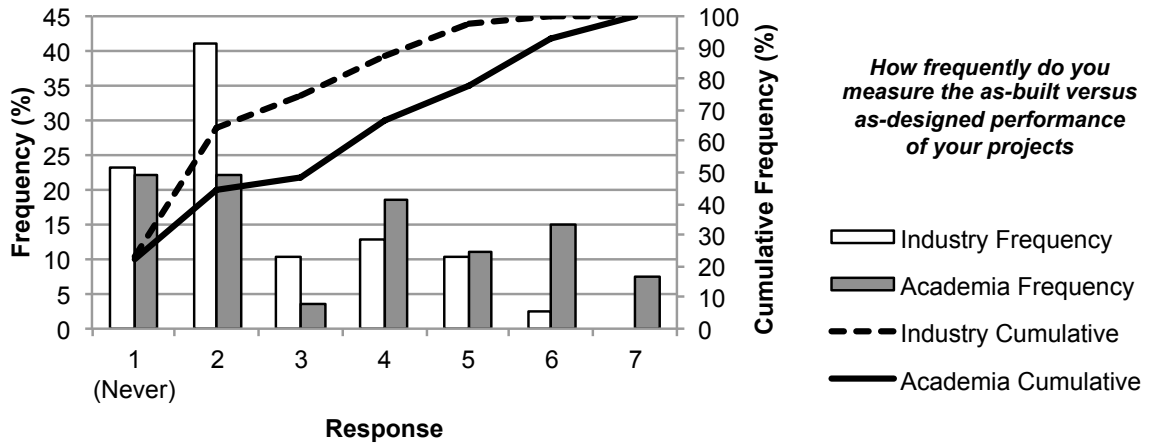
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219 **Figure 4: Responses to Q5 (Table 2)**



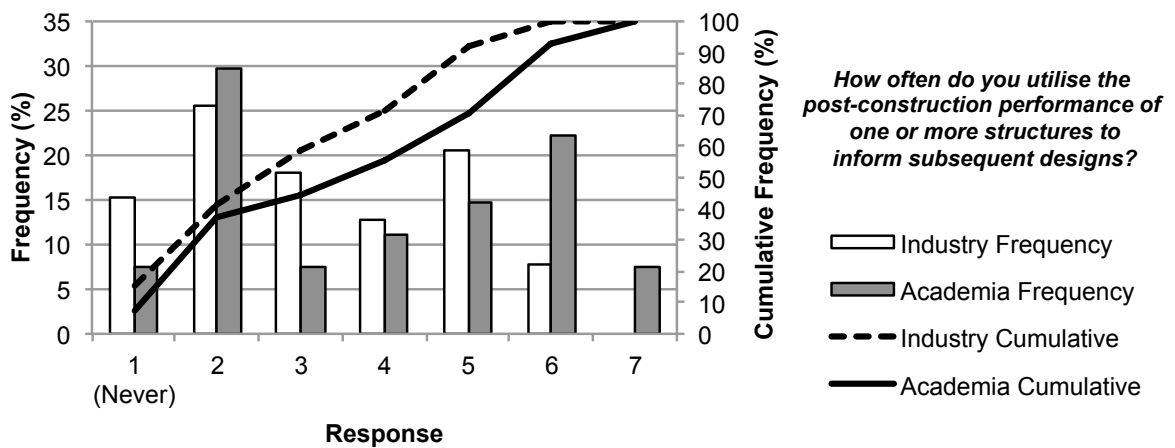
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221 **Figure 5: Responses to Q6 (Table 2)**



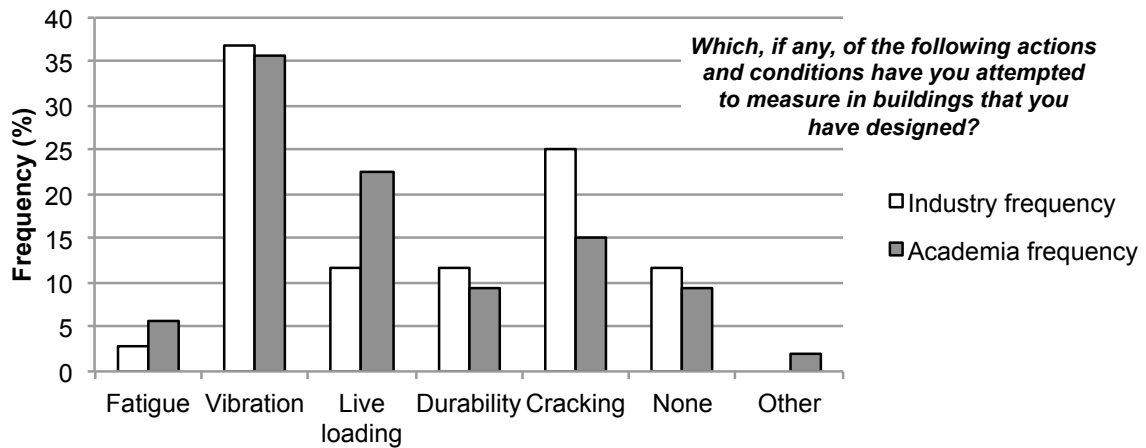
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223 **Figure 6: Responses to Q7 (Table 2)**



224

225 **Figure 7: Responses to Q8 (Table 2)**



226

227 **Figure 8: Responses to Q9 (Table 2)**

## 228 **2.3 Survey analysis**

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

### 232 **2.3.1 Given list responses**

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

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

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

245 information collected from post-construction performance of structures to inform subsequent  
246 designs.

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

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

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

### 262 **2.3.2 Free form responses**

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

266 There were 29 responses from industry and 20 responses from academia to Q4(a). The  
267 most frequently reported criticism of design codes from industry was their conservatism  
268 (*“Loading codes are overly conservative”; “conservatisms become so high in some cases*  
269 *that they are inappropriate”). Codes were described as “out-dated” and “difficult to interpret”,*  
270 with respondents commenting on the difficulty of applying “idealised” code methods to “real-



271 world” engineering. Overly complex code methods were also mentioned as a key barrier to  
272 innovation (“*Overly complex and prescriptive, which inhibits creativity and innovation, as well*  
273 *as encouraging mistakes*”).

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

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

287 A further concern arises from structures that nominally satisfy the design code, but then fail  
288 in-service due to unforeseen loading or structural behaviour. There were 24 responses from  
289 industry and 14 responses from academia to Q4(b). The majority of responses mentioned  
290 serviceability level failures (“*vibrations*”, “*accelerations due to wind loading*”, “*deflection*  
291 *limits*”). Only a small number of structures were named in the survey, with one respondent  
292 noting “There are cases but couldn't mention them due to client confidentiality”. This  
293 highlights a key barrier within civil structural engineering in which poor performance is  
294 infrequently reported, meaning that the industry as a whole struggles to learn from past  
295 mistakes. Only in extreme circumstances do serviceability level issues get widely reported  
296 for major structures [28, 29], and whilst full structural collapse remains infrequent such

297 events are widely reported [30]. In the UK, a well established confidential reporting  
298 mechanism exists for structural-related failures [31], with the goal of improving best practice.

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

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

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

318 Key themes in responses from academia focused on the difficulties of managing and  
319 interpreting large amounts of data (*“too much data”, “loss of information in processing”,  
320 “noise”, “hard to find reliable information”, “we have even less experience as a profession in  
321 interpreting data from real life than designing based on code”*). The difficulties of installing  
322 sensing systems was also highlighted (*“Getting permission to collect data”, “Exact details*

323 *and positioning of sensors required*", "cost"). The issue of permission is a key criterion for  
324 future design methods. If the structural engineering profession is to achieve a design  
325 process that can learn from real, measured behaviour, then much work is required to  
326 convince our clients that the sharing of such data is in their long-term interest. Only with a  
327 full understanding of how structures behave and the impact that they have on the health of  
328 the building occupants, will structural engineers and designers be able to make informed  
329 design decisions. This process will drive both sustainability (reduced material consumption  
330 by understand what shape our structures really should be to achieve serviceability and  
331 ultimate limit state performance) and productivity (improved internal design of the human-  
332 structure interaction).

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

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

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

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

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

### 365 **3 Future use of sensing**

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

370 A significant body of work exists in the measurement of internal environment quality  
371 (temperature, humidity, VOCs, CO<sub>2</sub>, productivity, health) but very little of this is correlated to  
372 the behaviour of the structure within which the people exist. Humans spend 90% of their time  
373 indoors, and yet we do very little to measure, learn from, and improve this environment [32,  
374 33]. An increasing association of sick building syndrome [34] with airtight buildings has the

375 potential to inhibit moves towards greater energy efficiency [35, 36]. Research is now  
376 required to link data from 1) building physics, 2) structural response, and 3) human  
377 behaviour in buildings and structures to provide holistic drivers towards lightweighting.

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

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

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

## 402 **4 Conclusions**

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

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

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

420 Current design does not regularly take into account the environmental impact of construction  
421 over the whole life cycle of a building or structure. The combination of reliable data  
422 measured from buildings, with optimisation algorithms and tools for performance-based  
423 design are required to achieve design optimisation and the minimisation of embodied  
424 energy. The use of ubiquitous sensing of human, structural, and environmental factors,  
425 combined with automated data fusion, data interpretation, and knowledge generation is now  
426 required to ensure that future generations of building designs are lightweight, lower-carbon,

427 cheaper, and healthier. This paper provides the evidence base for the need for this  
428 transformative design approach.

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## 432 **6 Data access statement**

433 All data created during this research are openly available from the University of Bath data  
434 archive at <http://doi.org/10.15125/12345> (*note: to be updated before publication*).

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