Minimising energy in construction: practitioners' views on material efficiency

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Abstract

The built environment accounts for 39% of global energy related CO_2 emissions, and construction generates 13% of global GDP. Recent success in reducing operational energy and the introduction of strict targets for near-zero energy buildings mean that embodied energy is becoming the dominant component of whole life energy consumption in buildings. One strategy that may be key to achieving emissions reductions is to use materials as efficiently as possible. Yet research has shown that real buildings use structural material inefficiently, with wastage in the order of 50% being common. Two plausible mechanisms are 1) that some engineers hold individual misconceptions, or 2) that inefficiency is a cultural phenomenon, whereby engineers automatically and unquestioningly repeat previous methods without assessing their true suitability. This paper presents a survey of 129 engineering practitioners that examined both culture and practice in design relating to material efficiency. The results reveal wide variations and uncertainty in both regulated and cultural behaviours. For the first time, we demonstrate that embodied energy efficiency is not a high priority, with habitual over-design resulting in more expensive buildings that consume more of our material resource than necessary. We show wide variability in measures that engineers should agree on and propose research through which these culture and individual issues might fruitfully be tackled within the timeframes required by climate science.

Keywords: structural design, material utilisation, efficiency, embodied energy, design methods

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1.   Introduction

Global warming is partly caused by increasing greenhouse gas (GHG) concentrations in the atmosphere, particularly carbon dioxide. About half of cumulative anthropogenic CO_2 emissions between 1750 and 2010 occurred in the last 40 years [1]. Emissions from fossil fuels and industrial processes represent 65% of all greenhouse gas emissions [1]. To limit future impacts of climate change, and to meet the emissions targets set by the Paris Agreement [2] significant reductions in GHG emissions are necessary. Indeed, some scenarios will require extraction of CO_2 from the atmosphere [3]. The European Union low carbon road map requires an 80% reduction in domestic emissions by 2050 compared to 1990 [4] and the UK Climate Change Act 2008 includes similar targets [5].

The built environment is estimated to account for around 36% of global final energy use and 39% of energy related CO_2 emissions [6]. In 2015, the manufacturing of materials for building construction accounted for 11% of global energy related CO_2 emissions [7] - around half of all world steel production is used in buildings and infrastructure [8, 9]. About 13% of global GDP is generated by construction [10] and activity in this sector creates the underpinning buildings and infrastructure that make all other sectors productive.

Lifetime carbon emissions associated with a building or asset are composed of 1) emissions arising from energy consumption during use (operational emissions) and 2) emissions associated the building materials and maintenance (embodied emissions) [11]. Assuming a 60-year building lifespan, whole life embodied carbon emissions in new office and residential buildings in the UK are already estimated at 67% and 69% respectively [12]. Success in reducing operational energy consumption means that embodied energy is now the dominant component of whole life energy consumption [13-16], as illustrated in Figure 1.

One strategy that may therefore be key to achieving global emissions reductions is to use materials as efficiently as possible [9, 17] and thereby minimise energy in construction.
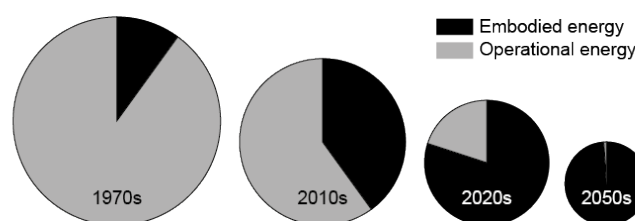
Figure 1: The increasing importance of embodied energy (approximate data for UK built environment) [17-19]

48 **2.   Structural design**

49 In limit state (or load and resistance factor) design, minimum performance requirements are established by

50 codified rules for structural elements [20] at ultimate and serviceability limit states (ULS and SLS), with

51 partial factors being used to ensure reliability. Codes do not establish upper limits to these criteria that an

52 element may not exceed. There is therefore no requirement for structural designers to be efficient in their use

53 of embodied energy, creating the potential for code-satisfying but materially-inefficient structures.

54 *2.1. Structural utilisation*

55 Defining a structural utilisation ratio (UR) as that between an actual performance value and the maximum

56 allowable performance value which is deemed limiting for a structural member [21] provides a mechanism

57 by which material efficiency can be measured. Examining 10,000 steel beams in real buildings, Moynihan

58 and Allwood [22] demonstrated average utilisation ratios of 0.40 at ULS, meaning that more than half of the

59 structural steel could have been removed whilst still meeting the specified strength and serviceability criteria.

60 Based on designs for 3,500 steel beams from 27 office and educational buildings, an apparent reluctance to

61 design beams above utilisation ratios of 0.80 was observed in work by Dunant *et al* [21]. In addition, 63% of

62 the beams considered by Dunant *et al* [21] were dominated by serviceability, rather than strength,

63 requirements. Orr *et al* [23] demonstrate that utilisation in structural concrete is also often low, with the

64 potential to achieve material savings of 30-40% through design optimization [23].

65 Utilisation ratios include an underlying assumption of sensible choices in structural form. For example, a

66 floor beam bent about its minor axis may exhibit a utilisation ratio of 1.00. However, simply rotating the

67 beam by 90º to bend about its major axis could reduce the elastic utilisation by 90% [24]. Throughout this

68 paper, it is assumed that sensible choices of structural form are made in the design stage.

69 *2.2. Loading*

70 In limit state design characteristic load values are modified by partial factors to arrive at design loads. Both

71 loads and partial factors may be determined using statistical methods (for example where loading is normally

72 distributed by taking a confidence interval, normally chosen as 95% [25]), but in practice are more often

73 based on calibration to our long experience of building tradition [20].

74 Global design codes typically take characteristic (unfactored) imposed floor loading for offices in the region

75 of 2.0–3.0kN/m^2 [26]. Assuming 0.75kN static force per person [27] this is a range of approximately 2.7 to

76 4.0 people per square metre of floor space. Characteristic values used by designers are often much higher

77 than code requirements. Cook and Craig [28] found characteristic values of imposed loading in offices being

78 requested by clients at up to 5.00kN/m^2 (6.7 people/m^2). Similarly, letting agent specifications for 365,000m^2

79 of office space over 12 buildings in London (average age 6 years) demonstrates an area weighted average

80 characteristic imposed floor loading excluding partitions of 3.37kN/m^2 [26]. The design value for office floor

81 loading has not changed significantly since a value of 3.6kN/m^2 (75psf) was defined in the Laws of New

82 York State 1862 [29] and 4.8kN/m^2 (100psf) was defined in the 1909 London Building Code [30].

83 In the space planning of office buildings, workplace densities are usually taken in the range of 8-13m^2 per

84 workspace [31] ($\approx$0.13-0.08 people/m^2 or 0.094kN/m^2 - 0.058kN/m^2). These recommendations are often

85 upper limits. The Occupier Density Study [32] examined 381 office buildings (2.5 million m^2) and found

86 workplace densities in the range of 4.5 – 42m^2 per workspace (0.167kN/m^2 - 0.018 kN/m^2). These values are

87 just a few percent of characteristic values for which the floor may have been designed [33].

88 Collecting data from real buildings, CIRIA [34] demonstrated that in existing buildings imposed loading did

89 not exceed 2.63kN/m^2 in 99.9% of cases and did not exceed 1.77kN/m^2 in 99% of cases [34]. Surveys of

90 floor loading in real buildings regularly demonstrate average real loading in the order of 0.50kN/m^2 [35-39].

91 These values are in contrast to assumptions made in design codes and by designers. The disconnect between

92 real and design loading is noted by Fitzpatrick *et al* [40] who state "loadings significantly higher than the

93 code figure have almost become the norm because of the perception that to have more capacity…would a

94 useful tool in marketing". This supports earlier work by Woolson *et al* [39] who stated "live loads assumed

95 in design … were largely matters of tradition and had scant scientific basis".

96 Assuming higher than necessary ULS or SLS floor loading in design creates more expensive buildings [40]

97 that consume more of our material resources [17].

98 **3.   Motivation**

99 Once we accept that there is a problem with over-use of resources in construction, the important next

100 questions are how does this happen and what can be done about it? In particular, to 1) what extent are these

101 issues arising because professionals share systematic misunderstandings about fundamental engineering [41]

102 and 2) to what extent are they arising because of more cultural, practice-based processes whereby engineers

103 over-specify materials in a relatively unconscious manner because "that's how things are done". This paper

104 presents the results of a survey of 129 engineering practitioners that examined both culture and practice in

105 design relating to material efficiency to assess the relative contribution of these two possible explanations.

106 **4.   Survey**

107 *4.1. Design*

108 The survey was divided into seven sections, six of which asked questions relating to energy in construction

109 with the seventh used to gather population characteristics. Section 1 "General Questions" was designed to

110 provide baseline information on respondent's approach to design and their experience of the relationship

111 between design, construction, and client. All 11 questions in this section were on a 7-point Likert scale

112 ("Strongly Agree" – "Strongly Disagree"). In Section 2 "Loading", four numerical questions were used to

113 understand the relationship between loads chosen at design and the respondent's understanding of real

114 loading in office structures. This section was also designed to examine how respondents feel about changes

115 in imposed floor loading through two 7-point Likert and two numerical response questions. Section 3

116 "Serviceability" was designed to understand how often and which serviceability criteria govern designs,

117 along with how often the respondent would allow such criteria to be exceeded.

118 The purpose of Section 4 "Design" was to determine which effects are perceived to have the biggest

119 influence on material utilisation using a combination of 7-point Likert scales, given lists, and numerical

120 questions. Section 5 "Capacity" continued the examination of material utilisation with more detailed

121 questions on structural utilisation limits, using a combination of 7-point Likert scales, free text, and

122 numerical questions. Section 6 was designed to bring all the preceding sections together using "real life"

123 design examples to explore respondent's practice using numerical, free text, and given list questions.

124 Prior to distribution of the survey, a small number of academic and practitioner volunteers were invited to

125 trial the survey to ensure it could be completed in a reasonable time and to ensure there were no factual or

126 structural problems. This feedback was positive, and the final set of survey questions developed by the

127 authors is shown in Table 1. All questions in the survey as distributed were optional.
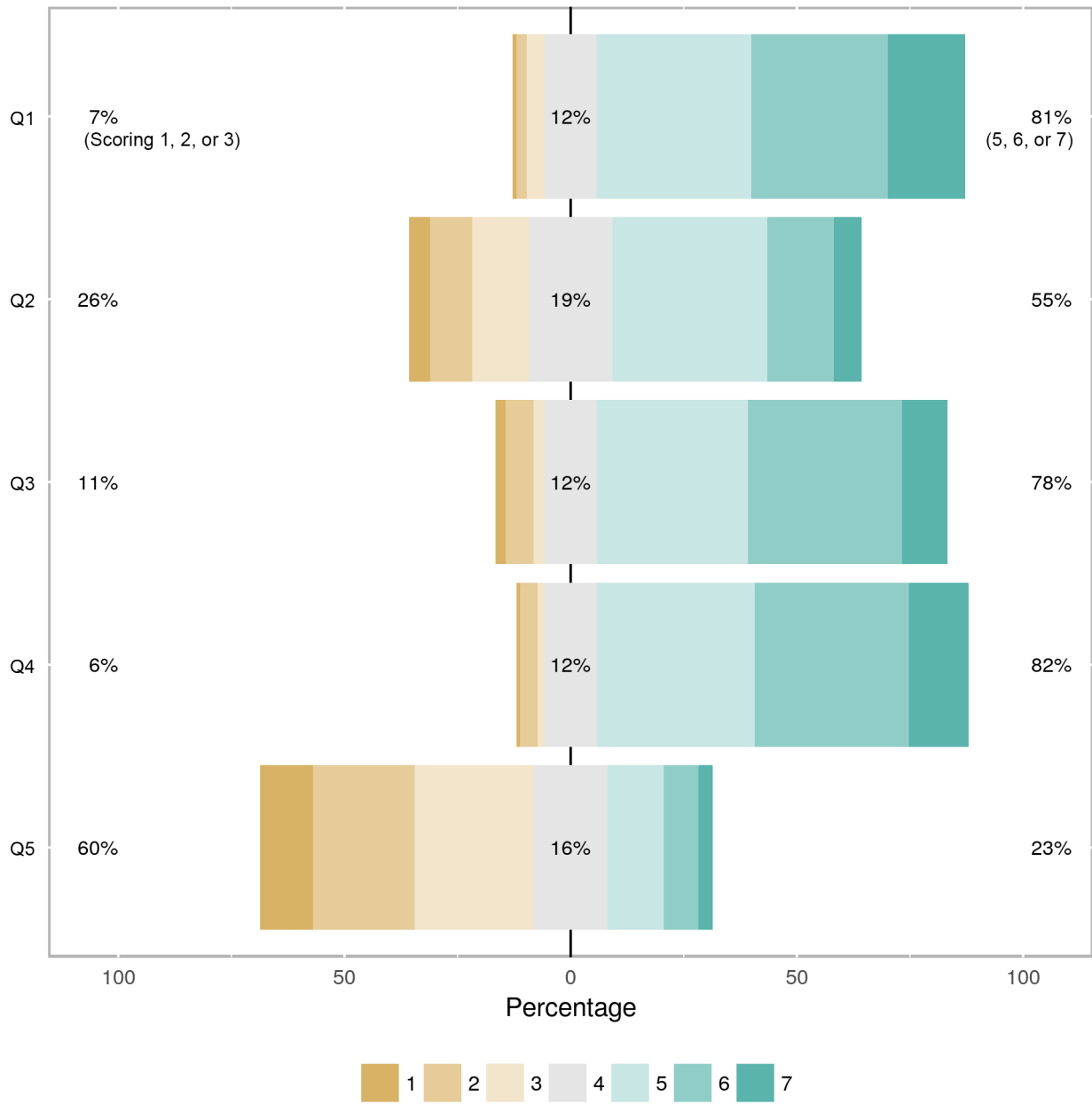
128 *Table 1. Survey questions*

#	Question	Type
Section 1: General Questions		
1	Maximising material utilisation is a key design criterion for me	A
2	The material utilisation of each structural element in my designs is normally close to 1.00	[See
3	The oversizing of structural elements during initial or concept design stages is normally appropriate	note
4	An easily constructed structure is more valued by the whole design team than a materially efficient structure	(1)]
5	Reducing the dimensions of structural elements agreed at concept design stage during detailed design is best avoided	
6	The potential for construction errors influences my structural member sizing decisions	
7	I simplify my structural designs to improve constructability	
8	My clients or design team normally require me to minimise total embodied energy	
9	The material utilisation of a structural design is normally presented to clients	
10	The best way to reduce total material consumption is to ensure that structural material utilisation is high	
11	Clients normally insist on low-carbon structural designs	
Section 2: Loading		
12	How often do you think that values for imposed vertical floor design loads given in your local design code of practice are appropriate?	A
13	In your experience how often are imposed design loads for floor plates decided by the client	A
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?	B
15	For the same building, what additional CHARACTERISTIC value for moveable partitions would you use?	B
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?	B
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?	B
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	B
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?	B
Section 3: Serviceability		
20	In your experience, how often does the serviceability limit state govern the size of structural elements?	A
21	In your experience which of the following SLS criteria most often governs the design of structural elements in buildings? [*Deflection, Vibration, Cracking, None*] [*Concrete, Steel, Timber*]	C
22	How frequently would you be comfortable with allowing the following structural serviceability limits to be exceeded in an office building throughout its lifetime? [*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*]	C
Section 4: Design		
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: [*Ease of construction, Material consumption, Cost to client, Design time, Other*]	C
24	Imagine you are undertaking the detailed design of a flexurally dominated floor beam. The flexural design effect of the actions ("E_d") 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 ("R_d") of the beam at mid-span (including partial factors) would you choose?	B
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?	A
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? *[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].*	C
Section 5: Capacity		
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.	A
28	Imagine that such a limit is introduced into a design code. The Design value of resistance ("R_d") for each element must be greater than the Design effect of the action ("E_d") AND less than "Beta" multiplied by "E_d", 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?	B
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?	D
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?	B
Section 6: Design examples		

#	Question	Type
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?	B
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?	B
33	Please provide a short justification for your decision	D
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?	B
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? *[Yes, No]*	C
36	Please provide examples of what you might assume or do differently in the design of your own house	D
Section 7: Population Questions Q37-42 (see §4)		
(1) Type A: 7-point Likert; B: Numerical; C: Given list; D: Free text.		

5.   Results

There were 129 responses to the survey. All questions were optional. Data on the respondents' background was collected at the end of the survey (Section 7) but is presented initially here for context. Eighty nine percent (115 out of 126) of respondents identified as Structural Engineers, and 5% (7/126) as Civil Engineers. Eighty four percent (108/128) of respondents identify as male, 13% as female (17/128). Seventy four percent of survey respondents were from the UK (93/126), with the remainder from USA (8/126), Sri Lanka (5/126), Hong Kong and Australia (4/126), with fewer than four responses each from Ireland, India, China, South Africa, United Arab Emirates, Azerbaijan, Greece, Denmark, and Canada. Twenty-six percent (33/129) of respondents were Graduates, 25% (32/129) Senior Engineers, 11% (14/129) Associates, 16% Directors (20/129). 56% (72/129) were between 25-44, 30% (38/129) were between 45-64, and 8% (10/129) were younger than 24. Sixty percent of respondents had more than ten years of experience, 25% had between 2 and 4 years of experience. Ten percent (13/128) of respondents were involved in feasibility studies, 7% (9/128) in pre-design client discussions, 45% (58/128) in detailed design, and 38% (48/128) in concept design.

Likert (Type A, Table 1), Numerical (Type B), and some Given List (Type C) responses are presented in Figure 2 - Figure 7 and Table 2 to support subsequent analysis. Responses for Q26, 29, 33, 35 and 36 are presented alongside later analysis due to the large amount of free text involved in these questions.

Q1   7%   12%   81%
(Scoring 1, 2, or 3)   (5, 6, or 7)

Q2   26%   19%   55%

Q3   11%   12%   78%

Q4   6%   12%   82%

Q5   60%   16%   23%
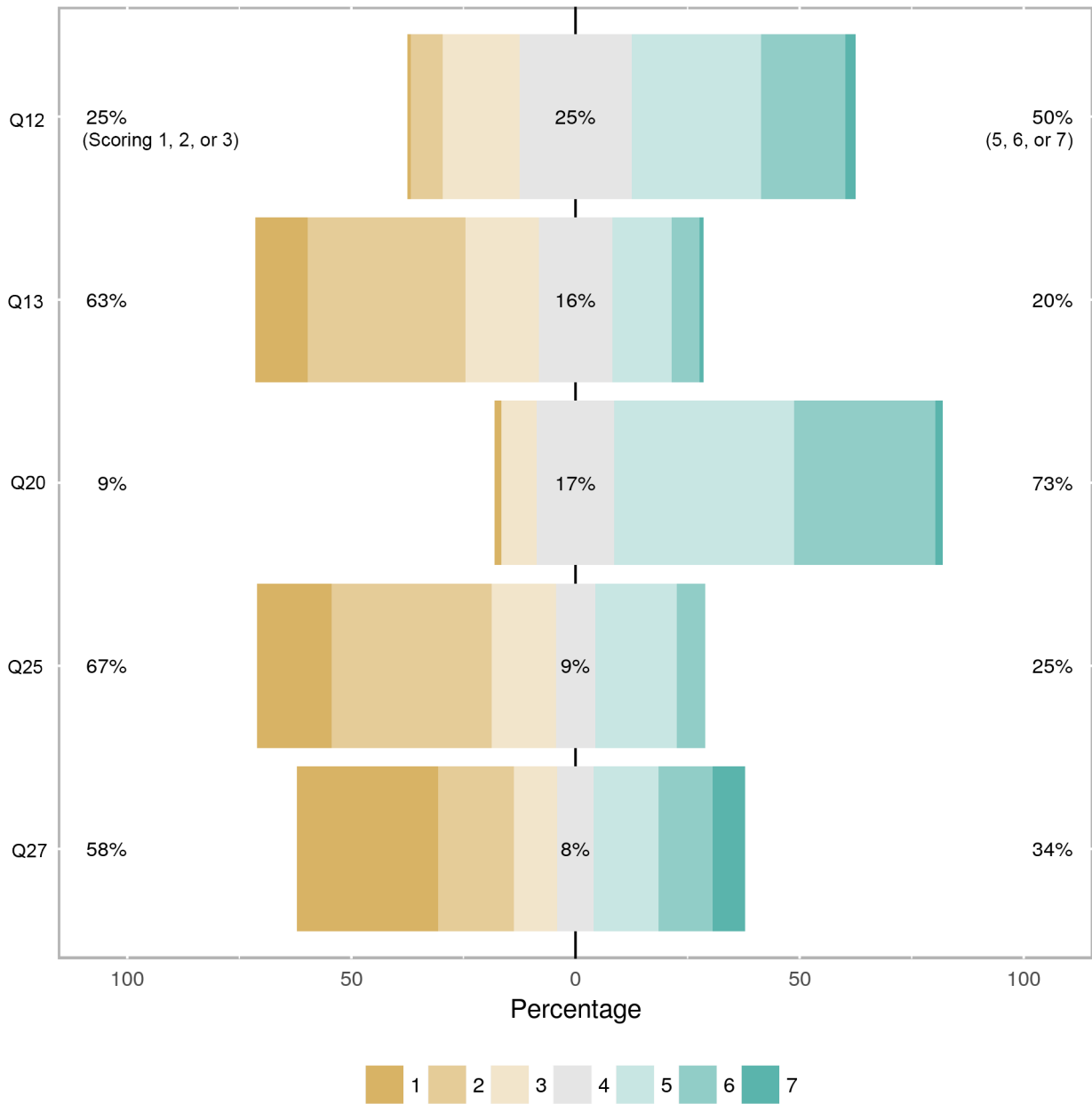
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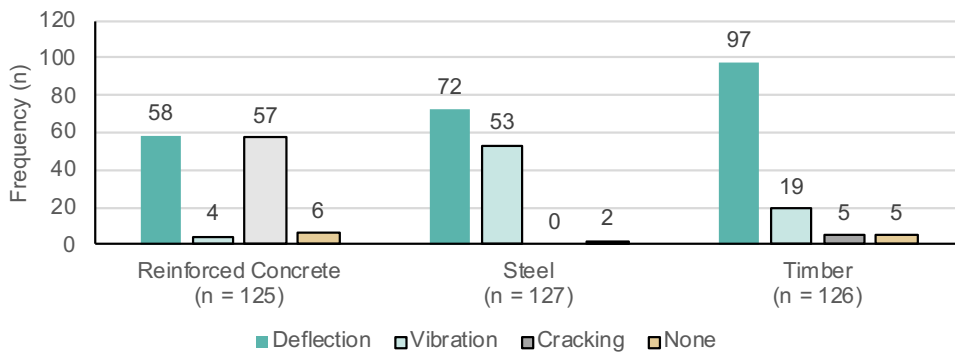147   *Figure 2: Likert responses to Q1-Q5 (where 1 = Strongly Disagree, 7 = Strongly Agree)*

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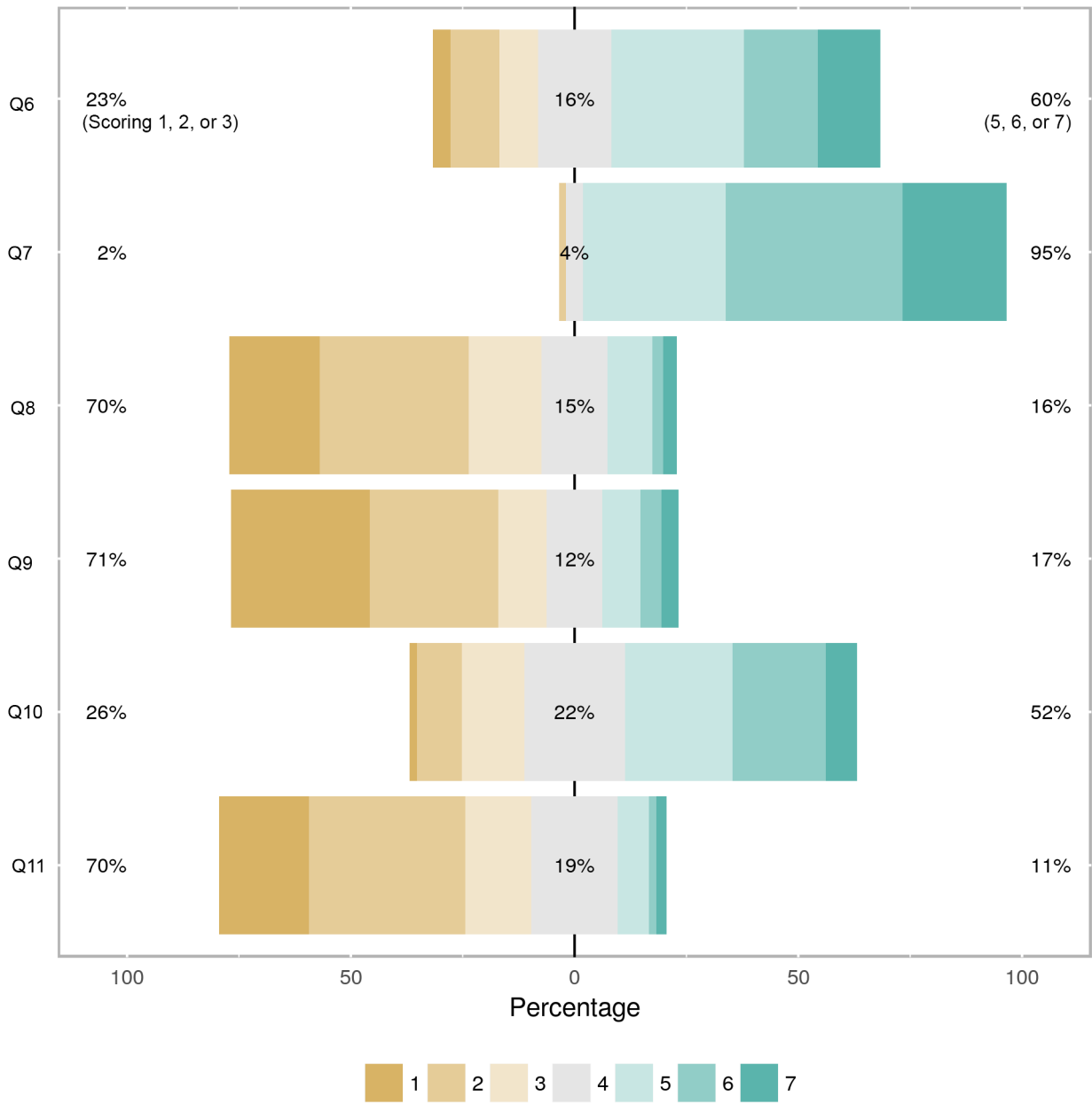
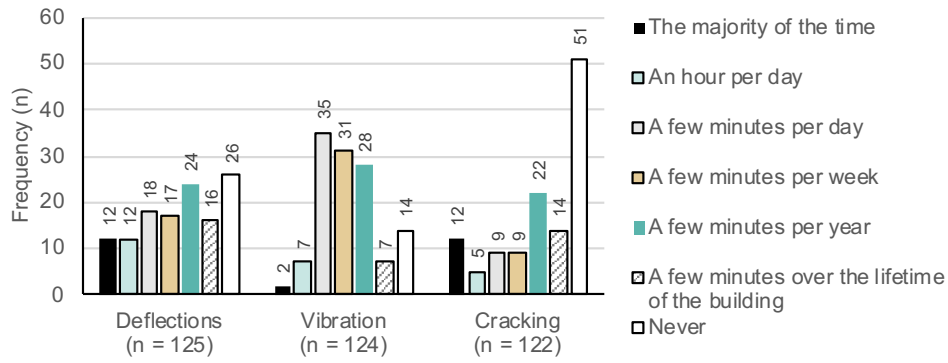*Figure 3: Likert responses to Q6-Q11 (where 1 = Strongly Disagree, 7 = Strongly Agree)*

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Figure 4: Likert responses: Q12, 13, 20, 25 (where 1 = Never, 7 = Always) and Question 27 (where 1 = Not at all; 7 = Completely)
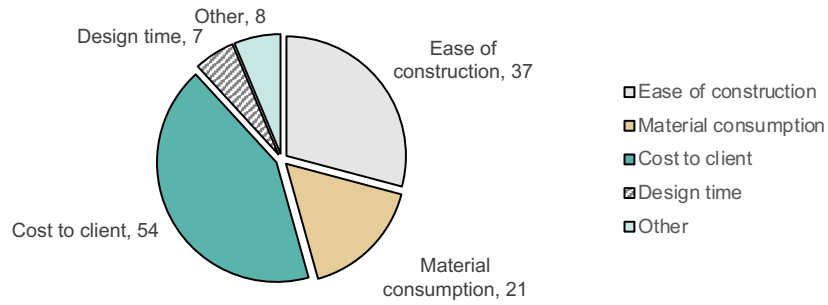

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Figure 5: Q21 responses

Figure 6: Q22 responses

Figure 7: Q23 responses (n = 127)

Table 2: Questions Type B (see Table 1)

Question	n	Minimum	Maximum	Average	Median	Units
14	124	1.00	10.00	3.08	3.00	kN/m^2
15	124	0.50	3.50	1.08	1.00	kN/m^2
16	122	0.30	10.00	1.70	1.50	kN/m^2
17	122	1.00	20.00	3.05	2.50	kN/m^2
18	121	-30	50	-0.21	0.00	%
19	121	-50	100	-6.33	0.00	%
24	118	1.00	400	216	210	kNm
28	120	1.00	1,000,000	8,346	1.50	-
30	119	0.00	1.00	0.75	0.80	-
31	117	80	500	248	250	mm
32	124	1	120	25	10	-
34	119	1	60	8	6	-

6.   Analysis

6.1. Sample representativeness

To examine the representativeness of the sample, the subset of respondents identifying as working in the UK

(74%, 93/126) were examined against UK statistical data [42]. Rest of World (ROW) data is provided, but is

not compared to official statistics due to small overseas samples. The gender balance is in-line with UK

industry, with only a marginally higher percentage of female respondents (Table 3). The age profile of

respondents (Table 4) is largely comparable to UK data for people working in the engineering sector (SIC) in

166   an engineering role (SOC) – the "UK data – SICxSOC" [42]. The survey saw a slightly larger number of

167   respondents in both 25-34 and 55+ age brackets compared to the wider industry.

168   *Table 3. Gender profile of the survey respondents*

Gender	UK – survey (n = 93)	UK data - SIC x SOC [42]	ROW – survey (n = 36)
Female	14%	10%	11%
Male	83%	90%	89%
Prefer not to say	3%	-	0%

169   *Table 4: Age profile of the survey respondents*

Age	UK- Survey (n = 93) (%)	UK data - SIC x SOC [42]	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%

170   *6.2. Sample power*

171   The total population of professionals who have the potential to impact embodied energy of structures is

172   difficult to define precisely but is in the order of hundreds of thousands. The survey was distributed via email

173   lists to approximately 3,000 recipients working in construction, engineering, and design in the UK and

174   around the world. These email lists were chosen based on the experience and contacts of the authors. It is not

175   possible to know how many times the email was forwarded by these recipients, many of whom operate in

176   large multinational companies. The survey link received 725 clicks, and the survey received 129 full

177   submissions. Of the 725 click throughs, 303 were from the UK, resulting in 93 survey submissions from the

178   UK. The next largest click through country was the USA, with 176, but this resulted in only eight

179   submissions.

180   A chi-square analysis of the Likert scale questions (Figure 2, Figure 3 and Figure 4) was undertaken to

181   determine if the split between respondents scoring agree (5-7) and disagree (1-3) was large enough for

182   conclusions to be drawn about it. In all cases, neutral responses (scoring 4) were treated as participants

183   expressing no opinion. The results, Table 5, show that in all questions responses were sufficiently far from

184   being distributed evenly across the two remaining categories of agree and disagree that we can conclude that

185   people collectively seem to express a majority view in one direction or the other on every question.

186   *Table 5: Chi-Square analysis for Likert scale questions*

Question	Disagree	Neutral	Agree	Disagree as % of non-neutral responses	Agree as % of non-neutral responses	Chi-square	p
1	7	12	81	8%	92%	80.27	< .0001

Question	Disagree	Neutral	Agree	Disagree as % of non-neutral responses	Agree as % of non-neutral responses	Chi-square	p
2	26	19	55	32%	68%	13.39	.0002
3	11	12	78	13%	87%	65.07	< .0001
4	6	12	82	7%	93%	84.67	< .0001
5	60	16	23	71%	29%	21.28	< .0001
6	23	16	60	27%	73%	21.28	< .0001
7	2	4	95	2%	98%	115.02	< .0001
8	70	15	16	82%	18%	43.74	< .0001
9	71	12	17	81%	19%	42.75	< .0001
10	26	22	52	33%	67%	11.18	.0008
11	70	19	11	86%	14%	55.44	< .0001
12	25	25	50	33%	67%	10.75	.001
13	63	16	20	75%	25%	28.74	< .0001
20	9	17	73	11%	89%	64.44	< .0001
25	67	9	25	74%	26%	24.73	< .0001
27	58	8	34	63%	37%	8.08	.004

187 To assess whether the sample was large enough to address these questions, we conducted power analysis for

188 the worst-case chi-squared test in the table (Question 12) in which 25% of participants abstained, leaving

189 only 97 in the analysis. Power analysis for comparing numbers distributed across two categories showed that

190 97 participants is sufficient to study chi-square effect sizes down to w = 0.29 with statistical power of .80.

191 w = 0.29 is equivalent to a 36%:64% split across the two categories of agree and disagree, which in this

192 specific example (Q12) would mean 35 people in one category and 62 in the other. As Q12 had a more

193 extreme split than this, we can be reasonably certain that all our questions had sufficient responses to reach

194 useful conclusions about whether people generally agreed or disagreed, given that for no question was the

195 result tighter than for Q12.

196 For numerical response questions, the margin of error, *m* (Eq.2) is calculated and the results are shown in

197 Table 6.

198 $$m = 1.96 \frac{\sigma}{\sqrt{n}} \quad (2)$$

199 Where σ = standard deviation; n = sample size.

200 *Table 6: Margin of error by question*

Question	Margin of error	Question
14	19%	
15	8%	
16	21%	

Question	Margin of error	**Question**
17	36%	
18	238%	Values from -50 to +50, Median = 0, σ = 13%
19	335%	Values from -50 to +100, Median = 0; σ = 19%
24	834%	Standard deviation 46kNm
24	546%	Q24 excluding seven values below 200kNm (see §6.6) (standard deviation 30kNm)
28	1,630,000%	
28	16%	Q28 excluding ten responses >5 (see §6.7).
30	4%	
31	1017%	Range 80-500mm, Median = 250mm
32	549%	Range 1-120; Median = 10.
34	135%	Range 1-60; Median = 6

201 A low margin of error (and thus agreement between respondents) is seen in Q15 (characteristic value for

202 moveable partitions) and Q30 (minimum value of material utilisation). Much larger differences appear when

203 considering respondent estimates of average (Q16) and maximum (Q17) floor loading in real offices.

204 Questions 18 and 19 both have median values of 0.00 (no change in design code of practice loadings) but

205 exhibit a very wide standard deviation and thus high very margins of error. Question 28 shows a 1,630,000%

206 margin of error due to five very large responses. Question 24, which examined the design of an imaginary

207 beam, had a standard deviation of 46kNm and thus again a very high margin of error. Such large errors can

208 be interpreted as a lack of consensus between professional engineers, and is seen also in responses to Q31,

209 Q32, and Q34.

210 *6.3. Section 1: General Questions*

211 Respondents stated that maximising material utilisation is a key design criterion (Q1: 81%, 105/129, scoring

212 5, 6, or 7, where 7 is "Strongly Agree") and that the material utilisation of their designs is normally close to

213 1.00 (Q2: 55%, 71/129, scoring 5, 6, or 7). This is however contrary to what has been measured in large

214 surveys of real buildings, where material utilisation is usually closer to 0.50 [21, 22]. There exists a strong

215 correlation between Q1 and Q2, with Spearman Rank +.56.

216 Oversizing of structural elements at early design stages is considered by the respondents to be normally

217 appropriate (Q3: 78%, 100/129, scoring 5, 6, or 7) and they further agree that ease of construction is more

218 valued by the design team than material efficiency (Q4: 82%, 106/129, scoring 5, 6, or 7). Oversizing at

219 concept stage does not appear to theoretically preclude later changes in geometry, as respondents show a

220 willingness to change structural sizes during detailed design in Q5, where 60% (78/129 scoring 1, 2, or 3) of

221 respondents disagreed that reducing the dimensions of structural elements agreed at concept design stage

222 during detailed design is best avoided. Respondents also note that the potential for construction errors

223 influences these sizing decisions (Q6: 60%, 77/128, scoring 5, 6, or 7). In Q7 95% of respondents agree

224 (122/129 scoring 5, 6, or 7) that designs are simplified to improve constructability, while Q8 highlights that

225 there is little demand from client or design team for embodied energy to be minimised (70%, 90/129, scoring

226 1, 2 or 3). These factors are linked by Q9, where 71% of respondents (91/129 scoring 1, 2, or 3) disagreed

227 that material utilisation of structural design is normally presented to clients and only 11% (14/129, Q11) of

228 respondents agree (scoring 5, 6 or 7) that clients insist on low-carbon structural designs.

229 Q1 (median $\tilde{x} = 5$) was correlated to Q10 ($\tilde{x} = 5$) with a Spearman rank of .50. This correlation, with a

230 critical significance level of $\alpha = 0.05$, and 129 pairs of data, is statistically significant ($p < .0001$). The

231 correlation demonstrates good consistency in responses. Designers who want to reduce material consumption

232 make maximising material utilisation a key part of their design process. Strong correlations between Q8 and

233 Q11, and Q9 and Q11 are reasonably well expected. They show there is no contradiction between answers in

234 these questions. Low scores in Q8 ($\tilde{x} = 2$) are matched with low scores in Q9 ($\tilde{x} = 2$) and Q11 ($\tilde{x} = 2$).

235 The responses to Section 1 demonstrate that embodied energy efficiency is currently a low priority in the

236 design process.

237 *6.4. Section 2: Loading*

238 Responses to Questions 12-19 show a remarkable spread in answers, with this range demonstrating a lack of

239 consensus across industry. In the case of imposed floor loading, which can be measured with relative ease

240 using data from multiple buildings over long periods of time to inform accurate and reliable design codes,

241 the spread in responses highlights our failure to measure and learn from the real in-service performance of

242 structures.

243 In Q12 50% (64/128) of respondents agree (scoring 5, 6, or 7) that values for imposed vertical floor design

244 loads given in their local design code of practice are appropriate. Twenty five percent (32/128) disagreed,

245 scoring 1, 2, or 3. In Q13 63% (81/128) of respondents agree that floor loads are not decided by clients.

246 Three questions were used to examine the relationship between loads chosen at design and loads that exist in

247 real structures. Q14 asked respondents to identify the characteristic floor areas load they would chose when

248 designing a multi-storey office building in a city centre. Q16 and Q17 asked respondents to estimate the

249 average and maximum loads that the same office would see over a 60-year life cycle. Those scenarios are

250 compared in Table 7.

251 Table 7. Floor load responses

	Characteristic floor load for design (kN/m²) [Q14]	In-service average floor load over 60 years (kN/m²) [Q16]	In-service maximum floor load over 60 years (kN/m²) [Q17]
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/m² and maximum (Q17) = 5kN/m²; (2) maximums for Q16 and Q17 from the same respondent, who entered a characteristic (Q14) value of 5kN/m².			

252 The 46 respondents who chose 2.5kN/m² in Q14 are examined in more detail in Table 8. The maximum

253 values for Q16 and Q17 in this sample were given by different respondents (see notes to Table 8). The

254 maximum in Q17 was 7.50kN/m² which is the same as the design loading that is often applied over c.5% of

255 an office floor area. Four respondents entered an average in service floor load (Q16) greater than their

256 chosen characteristic value for design (Q14).

257 Table 8. Floor load responses sample - 38% of all respondents who chose characteristic load for office building at 2.5kN/m².

	Characteristic floor load for design (kN/m²) [Q14, n = 46]	In-service average floor load over 60 years (kN/m²) [Q16, n = 46]	In-service maximum floor load over 60 years (kN/m²) [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/m² for Q17; (2) This respondent gave a value of 1.5kN/m² for Q16.			

258 Questions 18 and 19 of the survey were designed to examine how respondents feel about changes in imposed

259 floor loading. Forty-nine percent (59/121, Q18) do not expect imposed floor loading in their own design

260 code of practice to change in the next decade (median response 0%). Forty percent (48/121, Q19) of

261 respondents would not change imposed design loading, and 46% (56/121, Q19) respondents would reduce

262 imposed design loading, if they were solely responsible for doing so.

263 Examining responses to Q11 and Q19 it was found that respondents entering scores of 1 ("Strongly

264 Disagree" 20%, 26/129), or 2 (35%, 45/129) in Q11 had a group median response to Q19 of -10%. The

265 sample median to Q19 was 0%.

266 A correlation (Spearman Rank +0.44) is found between Q12 and Q19. Respondents who think floor loading

267 is appropriate would not change it (or would increase it), while respondents who chose low values in Q12

268 (i.e. "Never") were more likely to choose negative values for Q19 (i.e. to reduce floor loading). As an

269 example, ten respondents chose values of 1 or 2 in Q12 (floor loading is not appropriate). This group's

270 median response to Question 19 was -22.5% (compared to the sample median of 0%). This demonstrates

271 both consistency of the respondents, and a subset of respondents who do believe change in loading is

272 required. Of this subset of ten respondents, their responses to Q11 have a median of 2, the same as the

273 sample median for all respondents. This suggests that even if clients do not insist on low-carbon designs, the

274 designer may feel that there is an issue with the values of floor loading being used in design.

275 *6.5. Section 3: Serviceability*

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

277 In Q20 the survey respondents identify that the serviceability limit state often governs structural element

278 sizing. Seventy-three percent of respondents (93/127) scored Q20 with 5, 6, or 7 (7 being "Always"). This

279 response is clearly dependent on structural typologies, and the SLS limits being considered, which could be

280 examined in greater detail in future work. In general, the survey results show that structures are often

281 governed by serviceability.

282 The focus on SLS highlights the need for accurate load levels, such that serviceability limits do not lead to

283 unnecessary overdesign. In addition, the SLS limits themselves must be realistic and based on measured data

284 – for example what level of vibration, or deflection, is acceptable in various structural typologies. In

285 vibration analysis, it is recognized that imposed floor loading values used for strength design are

286 inappropriate. Taking an imposed load of 10% of the design value is a widely-used figure in practice and is

287 chosen as a realistic value of imposed loading in normal usage [27].

288 The median response to Q16 ("…what do you think the average area load on the floor of the office would be,

289 over the life of the structure, as measured during office hours?") of $1.50kN/m^2$ is much larger than found in

290 surveys of real buildings [31, 32, 40]. Therefore serviceability limit state calculations are potentially being

291 undertaken on what might amount to extreme loading, which is not the purpose of the SLS.

292 In Q21 (see Figure 5), respondents suggest that for steel buildings, deflection and vibration govern design;

293 for reinforced concrete structures deflection or cracking dominate; and for timber deflection dominates.

294 Q22 (see Figure 6) examined how often designers would be happy for SLS limits to be exceeded in office

295 buildings. It is interesting that respondents were happy for the SLS limits to be exceeded at all, since this is

296 non-compliant with limit state design. Sixty percent (75/124) of respondents are comfortable with allowing

297 vibration limits to be exceeded a few minutes per week or more. Forty-seven percent (59/125) are

298 comfortable with allowing deflection limits to be exceeded for a few minutes per week or more. Only 21%

299 (26/125) would never allow deflection limits to be exceeded (Q22). Forty-two percent (51/122) of

300 respondents would "Never" be comfortable with exceeding Cracking SLS. This may reflect the irreversible

301 nature of cracking, as compared the more often reversible limits of deflection and vibration.

302 Each SLS option (Cracking, Deflection, Vibration) received responses in all time categories, implying that

303 flexibility in serviceability limits would be beneficial to designers. Realistic serviceability loading, and

304 realistic serviceability limits, go hand in hand. Without an understanding of the effect of a serviceability load

305 on the performance of a structure, it is understandable for designers to be conservative. Therefore,

306 measurement of loading and corresponding SLS performance is essential if SLS loads are to be reduced.

307 This first step may be followed by future research to target reductions in ULS loading.

308 *6.6. Section 4: Design*

309 Question 23 demonstrates that "Cost to client" has the most significant influence (54/127, 43% responses) on

310 design. Ease of construction (37/127, 29%) and Material consumption (21/127, 17%) follow behind. This is

311 a positive finding as designers should have a good grounding in what is feasible on site. However, we must

312 also consider the extent to which links between structural engineering consultants, and on-site contractors,

313 are made given the material use and productivity data presented in the literature review.

314 Question 24 (Table 2) asked Engineers to choose the resistance of a beam required to carry a bending

315 moment of 200kNm. The question did not require answers to be greater than 200kNm and seven responses

316 were given of less than 200kNm. Excluding these responses, the average response was 224kNm, equivalent

317 to a utilisation of 89%. Most respondents (82/118, 69%) chose a resistance of >200kNm, despite there being

318 no need to do this. In this response, we see evidence of a culture in which overdesign, albeit mainly modest,

319 is standard practice, despite the education of structural engineers being explicit about inherent

320 conservativeness of design codes of practice.

321 Question 25 asked how frequently elements in completed designs have a resistance equal to the design effect

322 of actions (i.e. utilisation of 1.00). Zero respondents chose "Always", and 52% (66/126) of respondents

323 chose 1 ("Never") or 2. That is somewhat contradictory to Q2, where 55% (71/129) of respondents chose

324 scores of 5-7 (with 7 being "Strongly Agree") to "*Material utilisation of each structural element in my*

325 *designs is normally close to 1.0*". Of the 29 respondents who chose a beam capacity of 200kNm (utilisation

326 of 1.00) in Q24, their median answer in Q25 was 3, only one step above the group response.

327 The dominant reason given in Q26 for *not* having a utilisation of 1.00 was given as "The span, loading, or

328 layout might change before construction" (30%, 38/126), followed by "I like to build in a bit of spare

329 capacity just in case" (19%, 24/126), and "The building might change use later in its life" (17%, 21/126).

330 Only 12 respondents chose "I am uncomfortable with the design effect of the actions being equal to the

331 design resistance of the element".

332 *6.7. Section 5: Capacity*

333 Section 5 examined the feasibility of limiting over-design of structural elements through design codes by

334 introducing a "Beta" limit, given by Eq.(1):

335 $$E_d \leq R_d \leq \beta E_d \qquad\qquad (1)$$

336 Where E_d = Design effect of action; R_d = Design value of resistance; $\beta \geq 1.00$.

337 The idea of introducing such a bound to design resistance was considered to be largely unfeasible (Q27,

338 median response 3, with 31% (39/125) scoring 1, "Not at all"). This is significant as in other questions the

339 extreme responses tended not to be used – here there appears to be a stronger feeling that the proposed

340 "Beta" value is not something that should be adopted.

341 Q28 then asked to imagine that such a limit had been introduced, and respondents were to state what value of

342 "Beta" they would be happy with (numerical response ≥ 1.00). The median response was 1.50 (average

343 8,346 skewed by one outlier response of 1×10^6). Of the 120 responses, ten were greater than 5.00. Excluding

344 these ten responses, the median response was 1.45 (average 1.69). Participants were asked to identify in Q29

345 if there might be any unintended consequences of such a limit. The responses, given as a free text answer,

346 fell into three broad categories: 1) business risks including possibility of legal action; 2) designer

347 uncertainty; and 3) implications of tighter design. The most popular response (29%, 32/110) was "increased

348 complexity". Nineteen percent (21/110) identified "less flexibility" as a further consequence.

349 Q30 (n = 119) asked participants to think about average utilisation factors across a design. A numerical

350 answer was again required but had to be ≤ 1.00. The median response was 0.75 (average 0.80). This median

351 response corresponds to a 25% overcapacity. There is a significant spike in response at a utilisation of 0.50

352 (12%, 14/119), and 7% (8/119) entered a value less than 0.50. One respondent chose 0.00. Table 9 compares

353 the responses of Q24, Q28, and Q30, which ask a similar question in different ways. Q24 is a specific beam

354 design choice, Q28 is an individual element upper limit, and Q30 is an average minimum utilisation for a

355 design.

356 Table 9. Comparison of Q24, Q28, and Q30, all given as a material utilisation (E_d/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				

357 From this it is apparent that imposing a specific limit on every element would be difficult to achieve,

358 whereas an average utilisation may be more feasible. In fact, the average utilisation proposed by respondents

359 to the survey is high when compared to that measured in real buildings. A strong negative correlation is

360 found (Spearman Rank -0.56) between Q28 and Q30. The two questions have slightly different concepts

361 behind them, but a logical response to Q30 would be the inverse of Q28, which is seen in this correlation.

362 *6.8. Section 6: Design Examples*

363 Question 32 provided an example floor plate subject to a uniform load over its area and asked respondents to

364 identify how many sets of calculations they would undertake to size the beams (Figure 8). The floor plate

365 was taken from a real building example given in Moynihan and Allwood [14] although it was not identified

366 as such to participants.
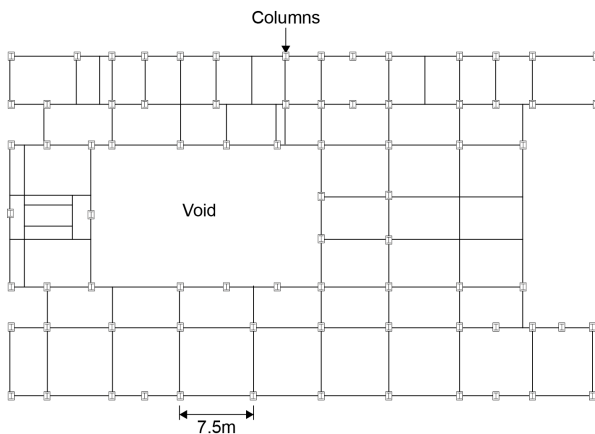
367

368 *Figure 8: Floor plate given in Q32 after [14]*

369 The median response was that ten sets of calculations would be undertaken, and the average was 24 sets of

370 calculations. Three respondents chose "1" and seven chose "120". In Q33 the dominant reason (60%,

371 68/113) given for this was rationalisation or grouping of the members.

372 Question 34 asked participants to identify how many different sections depths they would expect to see in an

373 as-built structure and received a median response of 6 sets (average 8). In Q35 participants were asked if

374 they would do anything differently if designing their own house – 63% (81/129) responded "No". Of the

375 remaining 37% (48/129) who responded in the positive, examples of what might be done differently given in

376 Q36 include "Control of loading" (14/44, 32%), "Greater certainty" (8/44, 18%) and "Higher utilisation"

377 (7/44, 16%). Interestingly, 7% (3/44) stated "Lower utilisation" suggesting that some would be more

378 conservative with the design for their own house.

379 **7.   Discussion**

380 In this section key research areas are explored in light of the survey data and its analysis, and "Research

381 Questions" (RQ) which require further research are posed.

382 In the UK, we have an established tradition of imposed loading levels in offices of around 4kN/m^2.

383 Regardless of whether this is appropriate for use today, any change in loading levels must be accompanied

384 by wider cultural changes, since the value of a lower floor load capacity may not immediately be clear to our

385 community. When comparing lettable areas one with an imposed characteristic floor load of 1kN/m^2 could

386 be viewed as substandard to one with 4kN/m^2 – even if 1) the maximum load the office would ever see in its

387 lifetime of use by a client could be demonstrated to be less than 0.25kN/m^2 (for instance); 2) the structure

388 was designed for easy retrofit should greater capacity be required for some alternative bespoke use in the

389 future; and 3) actual failure would occur at a load much greater than 1kN/m^2. We find in the survey that an

390 abundance of capacity may be viewed in a positive light, yet from a material efficiency perspective this

391 should not always be the case. We therefore must consider what design loading levels we should be using

392 that endow appropriate long-term value on our buildings and infrastructure.

393 **RQ1:** How do we align the incentives of clients, architects, engineers and contractors such that minimum

394   embodied energy structures are the preferred outcome on all projects?

395 **RQ2:** How can continuous measurement of floor loading in real buildings be used to provide certainty to

396   the statistical basis for design loading?

397 Question 24 presented a highly idealised beam design question, where flexure was specified as the dominant

398 design condition, and a capacity of E_d = 200kNm was required. Sixty-nine percent (82/118) of our

399 respondents chose a value of R_d for this imaginary beam that was greater than 200kNm. One quarter

400 (29/118) chose a value of R_d equal to 200kNm. In our conversations with practitioners, the addition of a "bit

401   of fat" to design appears to be commonplace. Setting a maximum utilisation in design software of 0.80,

402   designing 10 out of 100 possible beams, or choosing the "next size up" from catalogues of parts are all

403   understandable decisions when viewed in isolation. The cumulative outcome of this culture of design is seen

404   most plainly in building structures with average member utilisations of 0.50 or less [7].

405   Throughout the survey, we see responses that place time and ease of construction at the centre of arguments

406   in favour of material inefficiency. Through our discussions with industry, it is apparent that there may be a

407   perception that significant extra design time is needed to safely achieve higher utilisation factors in structural

408   design. Dunant *et al* [21] found no correlation between price per square metre for steel structures and the

409   median utilisation ratio of their beams. This suggests that the available budget should not affect overall

410   material optimisation. If more engineering time could be spent at concept design stage, where the cost of

411   value improvement is low but value improvement opportunity is high [43], then perhaps choices that

412   maximise the ability to minimise embodied energy could more readily be made.

413   This paper has focused on structural frames. In a typical building the frame accounts for a relatively small

414   cost (c.10%) [44] but a large amount of embodied carbon. Kaethner and Burridge [45] analysed buildings in

415   the Concrete Centre Office Cost Study [44], and found that, on average, the superstructure accounted for

416   45% of the total embodied CO_2.

417   **RQ3:**   Structural frames account for a small amount of project cost, but a large amount of embodied carbon.

418   What is the value proposition for reducing material use if the cost impact is small?

419   The role of the structural engineer must be viewed in the context of a design process. The greatest potential

420   for influencing material efficiency is held at concept design stage. Once designs are "fixed" material

421   (in)efficiency is locked in, and the role of the engineer becomes one of making it work, rather than making it

422   work well. Nolan [46] provides further analysis of this aspect, identifying the procurement process as a key

423   barrier to achieving value in design.

424   **RQ4:**   How can the implications of concept design decisions on material use and life cycle use be better

425   understood by and illustrated to design teams?

426   The automation of structural design calculations is now relatively routine, using either bespoke or off-the-

427   shelf software. Higher levels of automation could help to drive designers towards more materially efficient

428 structures, if target utilisation factors can be set closer to 1.00. Q29 asked "*What might the unintended*

429 *consequences of a limit to the design value of resistance relative to the design effect of the actions be?*". Free

430 text responses included: "Waste of design time leading to inefficiencies in more important areas"; "more

431 cost, more errors, more change orders"; "Increased time to calculate = less time for job = more mistakes/

432 more people use fewer sections throughout building = average utilisation increases"; "increased design time -

433 looking for minima as well as maxima. increased complexity of construction - less standardisation."; "Too

434 many mistakes causing failures. Poor workmanship causing failures."

435 These responses highlight a need to understand errors in the design process. As a sector we are unaware of

436 the level of mistakes that currently exist in design calculations, and how they can be reduced. Although

437 automation of design appears to be desirable, the potential for errors exists if the underlying structural model

438 is poorly conditioned. The difficulty of properly examining finite element and other structural models, may

439 lead those who check designs to err on the side of caution, which itself could be a source of material

440 inefficiency.

441 **RQ5:** How can structural models be checked in an automated fashion? How can we reduce error rates in

442 structural engineering design?

443 The survey results show quite clearly that we value construction ease more highly than material efficiency

444 (Q4, Q6, Q7, Q26, Q29, Q33): Q23: 30% responses "Ease of construction", Q26: "Workmanship concerns,

445 either in element construction, or in construction of restraints envisaged etc" "the unpredictability of

446 contractors." "constructability and repeatability" "Conscious of the pressure from client/contractor at a later

447 date to verify structural capacity following the inevitable site error", Q29: "structures that are not buildable"

448 "difficulty of construction" "added construction cost" "Elements will be highly utilised and therefore doesn't

449 give much scope for layouts changing/construction mistakes", Q33: "Compromise between efficiency and

450 ease of design/fabrication/construction" "simplification would help the coordination and construction

451 process" "rationalise for ease of construction" "rationalisation of details to aide [sic] in construction, in terms

452 of both fabrication and supervisions".

453 In the past 40 years, the construction sector has demonstrably been unable to successfully improve

454 productivity [10]. The wider MEICON project aims to help industry to challenge strongly ingrained

455   perceptions of how things "should" be done and support novel research that can improve whole life

456   construction productivity through new methods for analysis, optimisation, and construction.

457   **RQ6:**   To what extent can automation of construction and digital design be used to drive a cultural change

458   to instil better confidence in construction competence?

459   **8.   Conclusions**

460   A 36-question online survey of design practice relating to embodied energy received 129 responses. The

461   results demonstrate that embodied energy efficiency is not currently a high priority in structural design, and

462   the wide spread of responses to the majority of questions demonstrates a lack of consensus across the sector

463   when considering questions of material efficiency. Two plausible mechanisms are that some designers

464   individually hold misconceptions about engineering, or that building inefficiency is a more cultural

465   phenomenon whereby engineers automatically and unquestioningly repeat previous methods without

466   assessing their true suitability.

467   The survey shows that ease of construction is more highly valued than material efficiency. Decisions relating

468   to member sizing are influenced by a perceived risk of construction errors (Q6). We find in our sample that

469   clients do not ask for materially efficient structures (Q8, Q9, Q11) and there is no strong incentive for design

470   teams to achieve them. At present, there appears to be no mechanisms against which material efficiency can

471   be benchmarked and performance measured. Collectively defining benchmark structural utilisation values

472   against which structural designs could be compared and understanding how calculations of material use per

473   m^2 might best be presented, to drive material efficiency, are key steps.

474   Questions 14 through 17 demonstrate that realistic vertical floor loading is poorly understood, and this has

475   significant impacts on the amount of material used to satisfy current serviceability limits. This is

476   compounded by the reality that designers face no significant penalties if structures are overdesigned, and that

477   overdesign is sometimes viewed as a positive attribute (Q19, Q23, Q24, Q26). This design culture, where

478   serviceability can govern over strength in terms of material usage, should be addressed by examining what

479   loading buildings should be designed for to provide acceptable serviceability performance, considering the

480   real effects of certain failure modes, whilst maintaining required reliability against structural failures. If

481   design based on the real performance of buildings is to be achieved, data gathered from a systematic global

482 survey of loading levels in buildings is essential. It is also essential to understand what the unintended

483 consequences of such a dataset might be for design.

484 Throughout the survey, serviceability is found to be a key design concern. Yet serviceability is poorly

485 understood, particularly with respect to human behaviour [47]. Measurements to define realistic

486 serviceability limit state acceptability criteria, to ensure that SLS design levels are appropriate and do not

487 unreasonably dominate over strength design, need to be defined.

488 Mechanisms by which limits to embodied energy wastage could be implemented were explored through

489 Q27-Q30. The use of an upper limit to over design of members, Eq. (1), was not viewed as being feasible

490 primarily to "increased complexity". When asked to propose a *minimum* utilisation factor the median

491 response of 0.80 (Q30) is identical to the *maximum* value found in surveys of real buildings by Dunant *et al*

492 [21]. This result is compounded by responses to Q32 and Q33, where it is found that the number of sets of

493 calculations undertaken in design may be less than 10% of the possible total, primarily due to grouping of

494 members to save calculation time. Unless groups are made of members identical in all respects, grouping of

495 similar members by definition results in over design of some of the group.

496 The survey results highlight the need to align the incentives of clients, policy makers, architects, engineers

497 and contractors such that minimum embodied energy structures are the preferred outcome on all projects.

498 Interdisciplinary research is required to explore how digital tools can be capitalised on to join up design,

499 procurement, and construction stages. In order to set such criteria requires an iterative approach, along with a

500 "ratchet" of increasingly stringent design requirements that allow time to adjust design culture within the

501 timeframe required by climate science. This paper demonstrates, for the first time, that there is plenty of

502 scope to work far more effectively to meet clients' performance requirements using only the material that is

503 needed, and no more.

504 **9. Acknowledgements**

10. Data access statement

All data used in this paper are available online at https://doi.org/10.17863/CAM.26422.

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