Energy and Buildings 140 (2017) 61–67

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Effectiveness of design codes for life cycle energy optimisation

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ARTICLE INFO

Article history:
Received 1 November 2016
Received in revised form 28 January 2017
Accepted 29 January 2017
Available online 1 February 2017

Keywords:
Performance-based design
Built environment
Whole life cycle

ABSTRACT

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

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

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

1. Introduction

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

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

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http://dx.doi.org/10.1016/j.enbuild.2017.01.085
0378-7788/

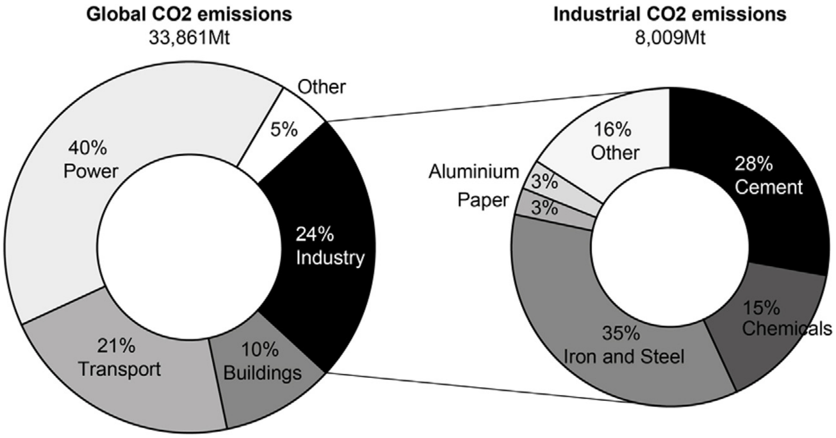

Fig. 1. Global CO_2 emissions in 2013 demonstrating the importance of key building materials [17].

1.1. Material utilisation

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

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

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

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

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

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

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

Table 1
Comparison of vertical live loads.

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

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

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

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

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

1.2. Material emissions

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

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

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

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