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Regularity and optimisation practice in steel structural frames in real design cases

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A B S T R A C T

Large amounts of energy and carbon are embodied in the frames of buildings, making efficient structural design a key aspect of reducing the carbon footprint of buildings. Similarly to a previous study which analysed real structures had observed that the unused mass of steel framed building could amount to nearly 46% of the total mass due to over-specification of the sections, we find a value of 36%. We observe that this value correlates with the design method, with software-aided design bringing significant improvements and with the design stage, where most of the optimisation seems to occur between the preliminary and tender stage.

We find that neither the regularity of the structure nor the cost, independent of the measure used, correlate with the mean utilisation ratio (UR). Conversely, we observe an apparent reluctance to design beams above a 0.8 capacity UR. This reluctance explains most of the unused mass in buildings. The rest of unused mass consists in cores, trimmers and ties (6%), some of which bear loads not captured in this analysis but are otherwise necessary for stability reasons, and in edge secondary beams (3%) which design is constrained, and should not necessarily be considered as 'unused' mass.

1. Introduction

The efficiency of many technical systems in common use is reaching their theoretical efficiency limits. This is notably the case of buildings which can now be designed to be operationally carbon neutral as they operate (Cotterell and Dadeby, 2012). However, the growing needs for construction has an impact through the carbon and energy embodied in the buildings, notably the frames. With the threat of global warming, new objectives (Rhodes, 2016) have been established for developed and developing countries for carbon release. Further improvement of the operational performance aspects of new buildings cannot help significantly to reach the targets. There is therefore a pressing need to find new ways to reduce embodied carbon.

This is a particular concern as the embodied carbon in buildings can represent as much as 70% of the whole life carbon (Dimoudi and Tompa, 2008; Nadoushani and Akbarnezhad, 2015) for warehouses and sheds, and can still reach 20% in office buildings. The strategies for the reduction of this embodied carbon are different depending on the material used for the frame: concrete, steel or timber. The choice of material for the building frame depends amongst other considerations on the function of the building and the economic constraints associated with its construction. Lowered carbon footprint of concrete-framed building requires finding new supplementary cementitious materials, as the current production of slag and fly ash is fully exploited, or of insufficient quality (Snellings, 2016). In the case of steel-framed buildings, improvements in the energy and carbon efficiency of the steel production process are unlikely as they are already close to their limit (Cullen et al., 2012). In this work, we focus on the design of the structural frame of steel-framed buildings.

A different approach to lowering the carbon footprint of buildings is to improve the structural design. Strategies for efficient design of buildings depend on the choice of the structural system. This is a complicated decision which depends on the capabilities of the design firms, the norms and codes (including seismic), the time allotted, the budget and the preferences of the client. Therefore, although it is not feasible to assess the quality of a design in terms of the fundamental choices made, it is possible to measure how closely the specifics of the design match an ideal, figured by an exact adherence to the code. In this work, therefore, we do not assess the design itself. The codes themselves can affect the absolute efficiency of the design. Modern codes such as the Eurocode define limit states for elements instead of working stresses. This paradigm is much more efficient than the working stress

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design methods used previously, for example, the change in the Canadian code resulted in structures which were 15% lighter (Kennedy, 1984). The Eurocode, in its latest iteration, is one of the most advanced codes, introducing provisions for plastic design — which is uncommon — but also has small safety factors. Some of the provisions on plastic design were already found in the British Standard. With respect to the safety factors, the reliability of steel elements has been well established over a century of experience and improvements (Byfield, 1996). Therefore, the ideal structure following the Eurocode is also quite close to a 'optimal' structure making maximum use of the materials whilst still being extremely safe. Although the design of efficient structural systems, notably using plastic provisions, is a complex topic — portal frame structures are usually very efficient structures — it is possible to study how *optimised* a structure is. For a given topology of beams and columns, with the loads specified, it is possible to establish the lightest elements required to build the structure according to the code. The choice of connexions, whether nominally pinned or moment bearing affects the overall efficiency of the design, *but has no bearing on how optimised it is*. Optimum design according to codes has been studied since computer modelling became possible (Saka, 1990).

Despite structures built exactly to the code being safe, the engineers seem to frequently design well within the limits of the code. A previous study by Moynihan and Allwood (2014) analysed 79 steel-framed buildings, and the utilisation ratios of all beams and columns were collected. They concluded that 46% of the steel mass in beams and columns are not load bearing. They have suggested a number of factors which can explain this: rationalisation, *i.e.* using the same section across the building frame, chosen to match the highest requirements; elements from older buildings designed with pen-and-paper are not optimised because this process would have been too time-consuming; UK universal beams and sections cannot satisfy requirements exactly — nonetheless, many fabricated elements were found to have relatively low utilisation ratios where section properties could be allocated to suit the structural performance. In general, this ground-breaking study both identified a great potential for savings and opened questions relating to the design process which led to this performance gap.

As the Moynihan and Allwood study was the first of its type, we have followed a similar methodology, but with a more detailed analysis of design approach. We collected detailed information on the roles of elements, as well as the limiting factor of the design of each beam, the floor type and the design methodology for each project. The objective was to identify the design practices and goals which explain the UR but with a more detailed analysis of design approach and the underlying causes of the observations.

2. Materials and methods

We have analysed the floor plates (excluding supporting columns) of 30 buildings, 27 'real' at various stages of the design process and 3 'model' buildings found in design handbooks (Table 1). The beams represent about two-thirds of the mass of a typical steel frame. These steel-framed buildings are office/commercial or educational buildings. For each floor design, the details every beam for which we were able to gather sufficient information for were recorded. Their type, length, mass, and connection types were noted. Fabrication details such as the presence of cells in the web or the application of a pre-camber were also noted. Each beam role is also noted as being either a primary, secondary or a core/trimmer/tie. Edge beams are marked as such.

The case studies cover both traditional pen-and-paper (labelled 'None') and computer-aided optimisation (marked 'Full Frame') design methods, and different slab forms of construction: pre-cast, and composite metal deck both trapezoidal and re-entrant.

2.1. Evaluation of the UR in the case studies

Each floor beam has been recalculated using the CSC Fastrak software (CSC) according to the known design loads of the structures. The original digital plans were used when available, otherwise, they were redrawn. The software gives the utilisation ratios according to the bending moment, the deflection, the natural frequency, and the shear forces. The dominating UR of the beam is the largest of these four, which is deemed limiting. Based on this information, it is possible to measure the approximate over-design of each beam and the corresponding mass. It is also possible to relate the dominating UR to geometric and functional information. The role of parameters such as type of decking, design method (computer modelling or pen-and-paper) can then be related to the overall design.

Table 1

Overview of the case studies. Sectors are Commercial (C), Education (E), and Model (M). Floor systems are Trapezoidal (T), Pre-cast Decking (P) and Re-entrant decking (D). All case studies are from the UK.

#		Year	Stage	Storeys and height		Model	System
1	C	2005	As built	13	50.0	None	T
2	C	2009	Tender	17	66.0	None	R
3	C	2006	Construction	5	17.5	None	P
4	C	2013	Construction	3	12.0	None	R
5	C	2010	Construction	6	21.8	None	R
6	C	2008	Construction	3	11.0	None	R
7	C	2016	Preliminary	10	45.0	Unknown	T
8	C	2006	Construction	5	23.3	None	T
9	C	2001	Construction	3	11.4	None	T
10	E	2016	As built	3	11.8	Full frame	P
11	E	2017	Preliminary	2	8.0	Full frame	P
12	E	2017	Tender	2	9.0	Full frame	P
13	E	2012	Construction	3	11.6	Full frame	T
14	E	2016	Construction	2	7.7	Full frame	R
15	E	2006	Construction	3	9.3	None	P
16	E	2013	Construction	2	7.6	Full frame	T
17	E	2005	Construction	3	11.2	None	R
18	E	2013	Tender	5	11.2	None	R
19	E	2016	Construction	2	6.3	Full frame	T
20	E	2014	Construction	3	12.6	Full frame	T
21	E	2013	Construction	3	11.6	Full frame	T
22	E	2014	Construction	2	8.7	None	P
23	E	2016	Tender	3	11.4	Full frame	T
24	C	2014	Construction	1	5.9	Unknown	T
25	C	2016	Tender	13	54.9	Unknown	R
26	E	2018	Tender	4	17.2	Full frame	T
27	C	2016	Construction	2	5.7	None	P
28	M	—	—	8	26.8	Floor plate	T
29	M	—	—	8	26.8	Floor plate	T
30	M	—	—	8	26.8	Floor plate	T

The plans for all the case studies were entered in the software manually. The beams were re-calculated according to the standard which was used at the time, either the British Standard BS-5950 or the Eurocode EC3. However, as most of the design is dominated by bending, deflection or natural frequency, the results presented here are independent of the standard chosen as the formulas used in the British standard and Eurocode for these criteria are identical.

To ensure consistency, the following starting assumptions and restrictions apply:

1. The modelling was restricted to a single floor plate of each building, as opposed to a full frame analysis. Modelling a full frame would require many more assumptions to be made involving wind loading and stability systems, and would take significantly longer. By analysing a single plate only the vertical loads need to be established, which can generally be easily extracted from the design information. Any members determined to be part of the lateral stability system (such as in braced bays) have been omitted from the data collection, as have any members that form part of a portal frame. This decision also enables us to directly compare efficiencies between buildings with different numbers of stories.
2. Whilst gravity loads for the general floor finishes (Super-Imposed