Energy and Buildings 102 (2015) 337–346

Contents lists available at ScienceDirect

Energy and Buildings

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

Effects of structural system on the life cycle carbon footprint of buildings

Zahra S. Moussavi Nadoushani, Ali Akbarnezhad*

School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia

ARTICLE INFO

Article history:
Received 8 March 2015
Received in revised form 27 May 2015
Accepted 28 May 2015
Available online 1 June 2015

Keywords:
Life cycle carbon
Embodied carbon
Structural materials
Lateral load resisting systems

ABSTRACT

The criteria used conventionally in selection of structural system characteristics include mainly performance related and economic criteria and the environmental impacts including life cycle carbon footprint are rarely taken into consideration. This paper highlights the importance of considering the life cycle carbon footprint in selection of the structural system for buildings by illustrating the significant effect that variations in the structural system characteristics including type of the lateral load resisting system, material and height of the structure may have on the carbon footprint of structures. A set of 15 alternative steel and concrete structural systems including moment resisting frames, braced frames, shear wall systems and dual systems are designed for 3, 10 and 15 storey buildings. The carbon footprint of each individual design is estimated by considering the emissions incurred in material extraction, transportation, construction, operation and end-of-life phases using a computational method. The results indicate considerable differences between the life cycle carbon of different structural systems and between the carbon emissions incurred in different life cycle phases of a particular structural system, confirming the importance of considering the life cycle carbon footprint in selection of structural system characteristics.

1. Introduction

The design of structures usually starts by making a number of important decisions including selection of the structural system. The three most important characteristics of a structural system generally include the lateral load resisting system, material of the structure and height of the structure. Such decisions are usually made by structural engineers, in close collaboration with architects and owners, by taking into account a number of selection criteria which address the performance, costs, construction rate and architectural requirements as well as any other requirements outlined by project stakeholders. However, despite their emphasized importance in the scientific literature [1–3], the environmental impacts of the structure are not generally considered in the structural system selection process. One of the important environmental impacts associated with a building which has received little attention in the structural design field is the considerable amount of carbon emissions incurred throughout the building's life cycle. The share of the construction industry in the total annual global greenhouse gas (GHG) emissions has been estimated to be as high as 30% which is significant and demands preventive measures [4]. The GHG emissions are usually reported in carbon equivalent (CO_2-e) units and, for simplicity, are generally referred to as carbon emissions. The emissions associated with a building occur in different phases of its life cycle including material extraction, transportation, construction, operation and end-of-life phases. The carbon emissions incurred in the operation phase are generally expressed as operating carbon while those incurred in material processing, transportation and construction phases are reported as embodied carbon.

There is currently a lack of awareness about the effects of the structure on the life cycle carbon of buildings. The focus of relevant literature has been solely on comparing the carbon footprint of a particular structure made with two different materials (rather than different structural frames, materials and heights) in only a single phase of the building life cycle (rather than comparing the total life cycle carbon), i.e. material manufacturing and construction phase (embodied carbon) or operation phase (operating carbon). By relying on the results of a few studies, the impact of structures on the operating carbon has been assumed to be generally insignificant [5–8]. Consequently, the focus of previous studies has been placed mainly on the effects of structures on the embodied carbon of buildings including the carbon emissions associated with manufacturing and transportation of materials and carbon emissions incurred during the construction phase [3]. Dimoudia and Tompa [9] showed that the highest share in the embodied energy of a

* Corresponding author. Tel.: +61 29385 9504.
E-mail address: a.akbarnezhad@unsw.edu.au (A. Akbarnezhad).

http://dx.doi.org/10.1016/j.enbuild.2015.05.044
0378-7788/

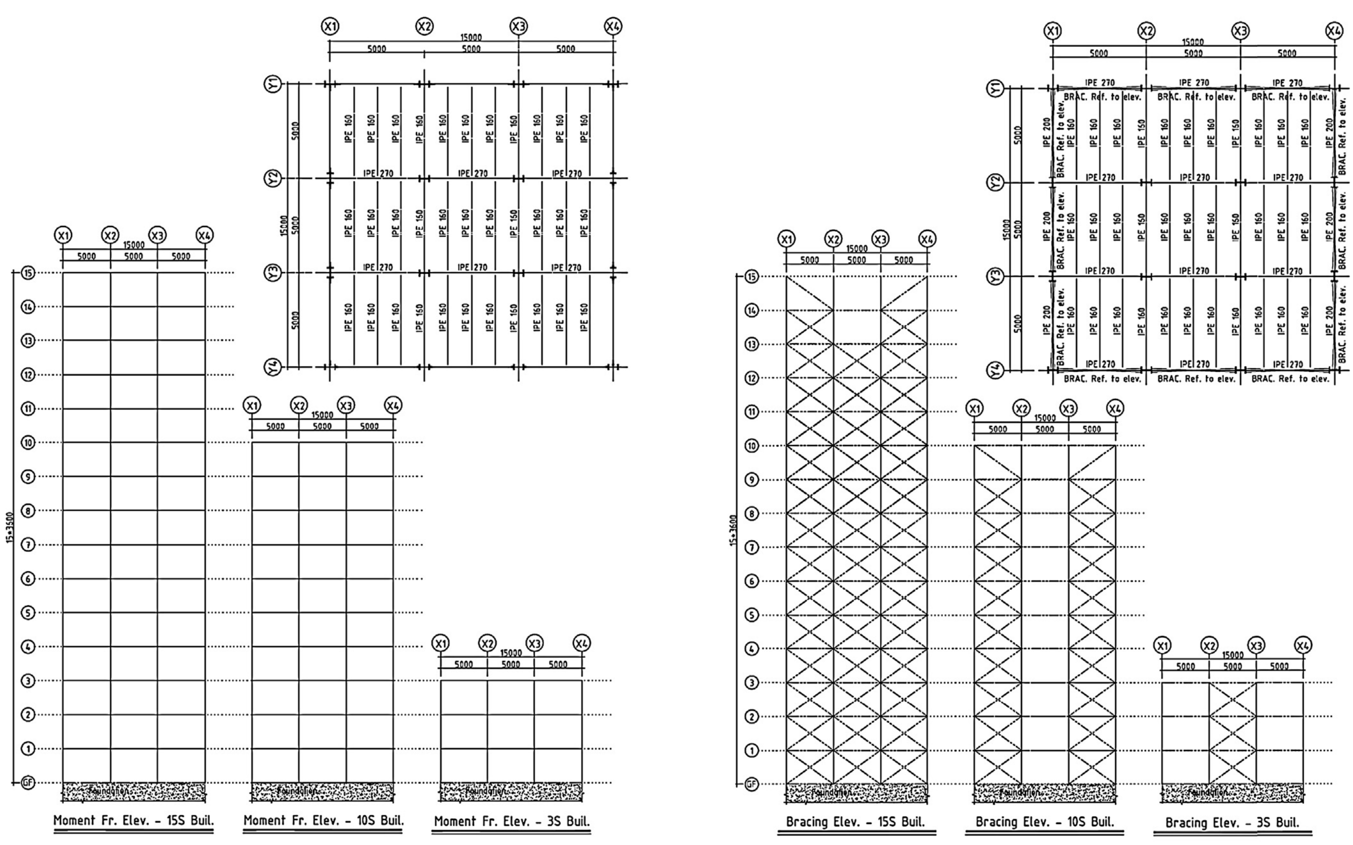
number of contemporary office buildings made with different materials belonged to the structural materials (concrete and reinforcement steel), accounting for 59.57–66.73% of the total embodied energy of the building [9]. Ji et al. [2] showed that the embodied carbon of a concrete structure, associated with manufacturing, transportation and on site construction, can vary by up to 40% depending on the grade of the concrete and reinforcing rebar used. Furthermore, Cole [10] reported considerable differences between carbon emissions associated with on-site construction of alternative wood, steel and concrete structural building assemblies. However, all the above studies were focused on the impact of the structure on the carbon emissions incurred in one or two phases of the building life cycle rather than the total life cycle impact.

On the other hand, while considerable effort has been made to investigate the effects of material type on the embodied carbon of structures, the effects of other important characteristics of the structural system including type of the lateral load resisting system and height of the structure have not been investigated. To the best of our knowledge, the overlapping effects of structural load resisting system and material has been only highlighted in a previous study by Collings et al. [11] which was conducted on structural systems used for bridges rather than buildings. Collings et al. [11] showed that in a similar trend to its costs, the carbon footprint of a bridge increases with an increase in the span length and addition of special architectural features, highlighting the importance of considering the carbon footprint in the design of bridge structures. There is currently a lack of understanding about the overlapping impacts of characteristics of the structural systems used for the buildings including the lateral load resisting system, material of the structure and height of the structure on the life cycle carbon footprint of the building.

This paper aims to; (1) highlight the importance of considering the life cycle carbon footprint in designing the structural system for buildings by illustrating the effect that variations in the structural system characteristics including type of the lateral load resisting system, material and height of the structure may have on the carbon footprint of structures; (2) highlight the importance of considering the total life cycle carbon footprint rather than the carbon emissions incurred in a single phase of the building life cycle, i.e. embodied carbon only or operation carbon only, in selection of structural system for a particular building. The effect of the choice of structural system on the life cycle carbon of the structure is investigated by considering the carbon emissions incurred in all phases of a typical building's life cycle including material extraction and processing, transportation, construction, operation and end-of-life phases. Five different structural systems were designed for three different building heights. All the resulting 15 alternative structures were then subjected to process-based analysis to determine their associated life cycle carbon emissions. The results are compared to evaluate the variations in the carbon emissions incurred in different phases of the building life cycle as well as the life cycle carbon footprint of the building with changes in the lateral load resisting system, structural material (concrete vs. steel) and height of the building.

2. Methodology

Different structural design alternatives were generated for a case building by varying the type of material, i.e. steel vs. concrete, the lateral load resisting system, i.e. sway vs. non-sway, and height of the structure. As shown in Figs. 1 and 2, the case building has a square shape plan with three bays in orthogonal directions, each



(a) (b)

Fig. 1. (a) Steel moment resisting frames and (b) braced frames (plans and elevations).