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Sustainable design of reinforced concrete structures through embodied energy optimization

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ABSTRACT

As the world struggles to reduce energy consumption and greenhouse gas emissions, much attention is focused on making buildings operate more efficiently. However, there is another, less recognized aspect of the built environment: the embodied energy of buildings, which represents the energy consumed in construction, including the entire life cycle of materials used. Architects and structural engineers extensively perform designs of buildings with steel and reinforced concrete–materials that, to different degrees, are energy intensive. This presents an opportunity to use structural optimization techniques, which have traditionally been employed to minimize the total cost or total weight of a structure, to minimize the embodied energy. With this in mind, an analysis is carried out to determine the implications, from the point of view of cost, of optimizing a simple reinforced concrete structural member, in this case a rectangular beam of fixed moment and shear strengths, such that embodied energy is minimized. For the embodied energy and cost values assumed, results indicate a reduction on the order of 10% in embodied energy for an increase on the order of 5% in costs.

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1. Introduction

The building and construction sector accounts for the largest share in the use of natural resources by land use and materials extraction. Worldwide, buildings are responsible for between 25% and 40% of total energy use [1]. According to studies carried out by the Organization for Economic Cooperation and Development (OECD), the residential and commercial building sectors are responsible for approximately 30% of primary energy consumed in OECD countries, and for about 30% of the greenhouse gas emissions of these countries [2].

Currently, most efforts to reduce carbon dioxide (CO_2) emissions during a given building's service life are focused on reducing the energy required to operate and maintain it (i.e., the operating energy). In fact, numerous energy efficiency measures that significantly reduce energy consumption during a building's operation have been widely accepted and implemented by design professionals and the building industry [15]. It is important to realize, however, that the use phase represents only one chapter in the life-cycle story of buildings. Indeed, the processing and manufacture of building materials cause enormous off-site impacts prior to a given building's use. These impacts occur upstream during the source (raw material acquisition), transport, process (manufacturing), and distribution life-cycle stages. The embodied energy of individual building materials is used to quantify this upstream energy capital. Note that in addition to the upstream energy usage, the embodied energy also accounts for energy used during on-site construction and energy used in the replacement of materials and components during the building's useful life. It also accounts for energy used for demolition [3], provided that a cradle to grave system boundary is employed [4]. Unfortunately, the quantification of embodied energy for any particular building material is an inexact science (the accuracy and completeness of embodied energy analysis is very much dependent on the method used) and requires a "long view" look at the entire manufacturing and utilization process (using, e.g., Life Cycle Assessment (LCA) [4]). Nevertheless, some reasonable estimates of the embodied energy of most common construction materials have been compiled [5–7].

In aggregate terms, the embodied energy of building materials can account for a fairly significant share of the total energy use of a country. In the case of the United Kingdom and Ireland, estimates suggest that 10% of the total energy consumption is embodied in materials [8]. Some studies have found that embodied energy's share of total life-cycle energy can be as low 5% and as high as 40% [9], with the significant variation in large part due to the fact that embodied energy varies from country to country. Furthermore, these percentages will increase as attempts to develop net-zero energy buildings (ZEB) progress [3]. This is due to the fact that the

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net-zero energy goal pertains largely to the operating energy, rather than to the life-cycle energy.

With the exception of Portland cement, materials used in typical concrete mixes have relatively low embodied energy values. However, because concrete is the most widely used material in construction, the total amount of embodied energy in reinforced concrete structures is enormous. The global production of concrete increased from 40 million cubic meters in 1900 to 6.4 billion cubic meters in 1997 [6]. It is also noted that concrete is typically not recycled for direct reuse in most structures.

For reinforced concrete structures, embodied energy reduction can be achieved not only by the use of novel building materials, such as low-carbon cements and clinker substitutes [10,11,16], and recycling [12], but also through the more efficient use of materials resulting from the optimization of RC (reinforced concrete) structural designs. In current practice, structural designs are typically optimized for total cost or total weight. From the view point of sustainability, however, optimized designs for embodied energy are essential as well.

The main objective of this paper is to explore, via a simple example, the implications, from the point of view of cost, of using the total embodied energy as the objective function to be minimized. For comparison, the implications from the point of view of embodied energy are also examined for the case in which the total cost is used as the objective function. For each case, the role of the ratio of the cost of steel to that of concrete on the conclusions is also ascertained.

2. Methodology

2.1. Problem description

Consider a continuous reinforced concrete beam of length $L = 7$ m with a rectangular cross-section of area bh, where b is the width and h is the height. The beam is assumed to have a factored design moment and a factored design shear force, at their critical locations, of $M_u = 400$ kN m and $V_u = 220$ kN, respectively. In addition to the moment and shear force due to the factored loads, the beam is subjected to a moment M_{sw} and shear force V_{sw} due to self-weight. The design of the beam, including the design of the longitudinal and shear steel reinforcements, is based on the restrictions and guidelines found in the ACI 318-08M Code [13].

A feasible design from the point of view of ultimate strength design is one in which $\hat{M}_u/\phi_b \leq M_n$ and $\hat{V}_u/\phi_s \leq V_n$, where $\hat{M}_u = M_u + M_{sw}, \hat{V}_u = V_u + V_{sw}, M_n$ and V_n represent the nominal moment and shear strengths, respectively, and ϕ_b and ϕ_s are the corresponding strength reduction factors. Defining a feasible section as one that satisfies all ACI 318-08M Code requirements, the objectives in this study are to determine (a) the feasible design that minimizes the total embodied energy and (b) the feasible design that minimizes the total cost.

2.1.1. Design variables

The design variables in this study are the width of the beam b, the height of the beam h, the total area of the longitudinal reinforcement A_s, and the total area of the shear reinforcement A_v having spacing $s = 150$ mm. Listed in Table 1 are the design variables considered and their ranges. No specific ranges can be given *a priori* for A_s and A_v as these are determined by, among other factors, the values of h and b. Finally, note that A_s and A_v are treated as continuous variables. The discrete case, in which both bar selection and bar positioning are design variables, is not considered here for the sake of simplicity.

Table 1
Design variables and corresponding ranges.

Variable	Range
Width of compression face of member (b)	300 mm ≤ b ≤ 800 mm
Height of member (h)	300 mm ≤ b ≤ 800 mm
Area of longitudinal tension reinforcement (A_s)	Given M_u and (b, h), each value is calculated as per ACI 318-08M
Area of shear reinforcement within distance s (A_v)	Given V_u, s, and (b, h), each value is calculated as per ACI 318-08M

2.1.2. Design parameters

The design parameters, defined as constants during the optimization process in this study, are listed in Table 2. The strength reduction factor for flexure ϕ_b is determined by the net tensile strain of the bottom longitudinal reinforcement. When the section is classified as compression-controlled (i.e., the compression strain of concrete reaches the crushing strain $\varepsilon_{cu} = 0.003$, while the net tensile strain of the reinforcement (ε_t) remains less than or equal to 0.002), the stress of the bottom longitudinal reinforcement is in the elastic range and the minimum value of $\phi_b = 0.65$ is specified. When the section is classified as tension-controlled (i.e., the compression strain of concrete reaches 0.003, while the net tensile strain of the reinforcement is greater than or equal to 0.005), the bottom reinforcement yields and the maximum value of $\phi_b = 0.90$ is specified. For the intermediate values of the strain, the strength reduction factor is determined by linear interpolation. For a beam member, the net tensile strain shall not be less than 0.004, which corresponds to $\phi_b = 0.812$. This specification limits the maximum reinforcement in a beam. Further details are presented in the ACI 318-08M Code.

2.1.3. Objective functions

The objective functions are given below in Eqs. (1) and (2). Objective function f corresponds to the total cost of the beam per unit length, while objective function g corresponds to the total embodied energy per unit length.

$$f(b, h, A_s, A_v) = C^C\left[\rho_s\left(A_s + \frac{A_v}{s}\right)\frac{R}{100} + \left(bh - A_s - \frac{A_v}{s}\right)\right] \tag{1}$$

$$g(b, h, A_s, A_v) = \rho_s\left(A_s + \frac{A_v}{s}\right)E^S + L\left(bh - A_s - \frac{A_v}{s}\right)E^C \tag{2}$$

In Eq. (1), C^C is the cost of concrete per cubic meter, R is the ratio of the cost of 100 kg of reinforcement steel and the cost of concrete

Table 2
Design parameters and corresponding values.

Parameter	Value
Factored moment	$M_u = 400$ kN m
Factored shear force	$V_u = 220$ kN m
Concrete compressive strength	$f_c' = 34$ MPa
Longitudinal reinforcement yield strength	$f_y = 420$ MPa
Shear reinforcement yield strength	$f_{yt} = 300$ MPa
Modulus of elasticity of steel	$E = 2 \times 10^5$ MPa
Specific mass of concrete	$\rho_c = 2400$ kg/m^3
Specific mass of steel	$\rho_s = 7850$ kg/m^3
Lightweight concrete factor	$\lambda = 1$ (for normal weight)
Strength reduction factor for shear	$\phi_s = 0.75$
Strength reduction factor for flexure	$0.812 \leq \phi_b \leq 0.9$
Ratio of depth of the Whitney stress block and the depth to the neutral axis	$\beta_1 = 0.81$
Maximum useable compression strain in the concrete	$\varepsilon_{cu} = 0.03$
Section length	$L = 7$ m
Concrete cover (includes radius of fictitious bar having area A_s)	$d' = 65$ mm
Longitudinal spacing of shear reinforcement	$s = 150$ mm

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