

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.

Keywords: embodied energy; reinforced concrete; optimization

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 (IEA, 2005). 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 (OECD, 2003).

Currently, most efforts to reduce carbon dioxide (CO₂) 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 (WCSB, 2008). 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 (Yohanis and Norton, 2002), provided that a cradle to grave system boundary is employed (Goggins et al., 2010). 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) (Goggins et al., 2010)). Nevertheless, some reasonable estimates of the embodied energy of most common construction materials have been compiled (Reddy and Jagadish, 2003; CTBUH, 2009; Hammond and Jones, 2008).

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 (UNDP, 2007). Some studies have found that embodied energy’s share of total life-cycle energy can be as low 5 % and as high as 40 % (Sartori and Hestness, 2007), 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 (Yohanis and Norton, 2002). This is due to the fact that the 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 (CTBUH, 2009). 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 (Davidovits, 1993; Gartner, 2004; WBCSD-IEA,2010), and recycling (Thormark, 2002), 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 (ACI, 2008).

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.

2.1.1 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_r) 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.

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

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

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 per cubic meter, and ρ_s is the specific mass of steel.

In Eq. (2), E^S is the embodied energy per kilogram of steel and E^C is the embodied energy per cubic meter of concrete.

In this study, C^C was fixed at \$130/m³ while ratio R is treated as a variable. Table 3 presents some typical values of R from the literature. The variation in R in the table is due to (a) demand and supply-driven fluctuations in the prices of steel and concrete (material costs) from year to year, and (b) whether or not placement costs of concrete and installation costs of reinforcement are included.

The embodied energy values assumed in this study are $E^C = 3180$ MJ/m³ and $E^S = 8.9$ MJ/kg, for concrete with $f'_c = 34$ MPa and recycled reinforcement of $f_y = 420$ MPa, respectively

(CBPR, 2003). It is noted that other databases for common construction materials are available (Hammond and Jones, 2008).

2.2 Formulation of Optimization Problem and Solution Method

The explicit form of the optimization problem is given by:

Minimize

$$f(b, h, A_s, A_v) \text{ or } g(b, h, A_s, A_v)$$

Subject to

$$\hat{M}_u = \phi_b A_s f_s d \left(1 - \frac{\beta_1}{2} \frac{\varepsilon_{cu}}{\varepsilon_t + \varepsilon_{cu}} \right) \quad (3)$$

$$\max \left(0.25\sqrt{f'_c}, 1.4 \right) \frac{bd}{f_y} \leq A_s \leq 0.85 f'_c \beta_1 bd \left(\frac{\varepsilon_{cu}}{0.004 + \varepsilon_{cu}} \right) \quad (4)$$

$$\hat{V}_u = \phi_s \left(\frac{\lambda \sqrt{f'_c} bd}{6} + \frac{A_v f_{yt} d}{s} \right) \quad (5)$$

$$A_v \geq \max \left(\frac{\sqrt{f'_c}}{16}, \frac{1}{3} \right) \frac{bs}{f_{yt}} \quad (6)$$

$$300 \text{ mm} \leq b \leq 800 \text{ mm} \quad (7)$$

$$300 \text{ mm} \leq h \leq 800 \text{ mm} \quad (8)$$

In Eq. (3), $f_s = E\varepsilon_t \leq f_y$ is the tensile stress in the reinforcement and in Eqs. (3) to (5) $d = h - d'$ is the distance from the extreme compression fiber to the centroid of the longitudinal tension reinforcement. Additional variables found in the above equations have been defined either in the previous sections or in Table 2.

All constraints pertaining to RC member design, i.e. Eqs. (3) to (6), are based on the ACI 318-08M Code. For flexural loads, the strength design of a member is performed using Eq. (3), thus satisfying both strain compatibility and force equilibrium of concrete and reinforcement (i.e., factored flexural load effects = design flexural strength). Equation (4) shows the minimum and the maximum tensile reinforcement of the flexural member. For shear loads, the strength of a member is designed using Eq. (5) in which the design shear strength consists of strengths provided by both concrete (the first term in the right hand side of the equation) and reinforcement (the second term). Equation (6) imposes the requirement of a minimum amount of shear reinforcement. The last two constraints, Eqs. (7) and (8), define the lower- and upper-bound sizing constraints on section width b and depth h .

3. RESULTS

3.1 Feasible Design Domains

Figure 1 shows the domain of feasible beam designs and also includes contours of constant total section cost (Fig. 1(a)) and contours of constant total section embodied energy (Fig. 2(a)). The infeasible region, represented by the colorless region in each plot, corresponds to the region where one or more of the constraints are not satisfied. Comparing Figs. 1(a) and 1(b), it is evident that the lowest cost regions do not necessarily correspond to the lowest embodied energy regions.

It is of interest to take this comparison one step further and examine differences in the contributions of concrete and steel to the total cost versus their contributions to the total embodied energy. Figure 2 shows contours of the contributions of the concrete and reinforcement (longitudinal plus shear) to the total cost (in Figs. 2(a) and 2(b), respectively) and also shows similar contours for the total embodied energy (in Fig. 2(c) for concrete and Fig. 2(d)

for reinforcement). A comparison of Figs. 2(a) and 2(c), and Figs. 2(b) and 2(d), reveals that contribution of concrete to the total embodied energy is significantly larger than its contribution to the total cost and vice-versa for steel.

3.2 *Optimized Designs*

Consider the case where the section width is $b = 400$ mm and the cost ratio is $R = 0.8$. Figure 3 shows the sections of minimum concrete, steel, and total cost, along with the sections of minimum concrete, steel, and total embodied energy, as a function of the section height h . The sections for minimum total cost and minimum total embodied energy over all values of h are identified with a dotted line and arrow in Figs. 3(a) and 3(b), respectively. The heights for the optimized sections are 590 mm for cost and 462 mm for embodied energy, respectively. These results show that the minimum embodied energy section has a smaller volume of concrete and a larger amount of reinforcement in comparison to the minimum cost section.

The differences in the section height and the corresponding amount of reinforcement can cause the optimized members to behave differently. When the maximum usable compressive strain of concrete reaches 0.003, the tensile strain of the reinforcement is higher than 0.005 for the cost optimized sections, but is close to 0.005 for the embodied energy optimized sections. This implies that higher ductile structural behavior can be expected for the cost optimized sections. However, the ductility for the embodied energy optimized sections is sufficient as well.

Now consider repeating the identification of the minimum cost and embodied energy sections described above for each value of the section width b in the range $[0, 800]$ mm. As before, $R = 0.8$. Figure 4 shows the section height h corresponding to the minimum total cost and total embodied energy sections as a function of the section width b . The embodied energy optimized sections have lower section heights than the cost optimized sections, which implies that the

former sections use a larger amount of reinforcement and have a smaller concrete volume in comparison to the latter. Figure 5 shows the difference in the total cost and total embodied energy for both the minimum cost sections and the minimum embodied sections as functions of the section width b . The results show that optimization for embodied energy can achieve around a 10 % reduction in embodied energy at an added cost of roughly 5 %. Note that the achievement of this embodied energy reduction is based on the relative cost ratio of concrete to reinforcement being $R = 0.8$.

3.3 Effect of Cost Ratio R

In order to investigate the effect of changing R on the embodied energy reduction shown in Fig. 5, R is varied between 0.6 and 1.2, and the difference in both cost and embodied energy between the cost and embodied energy optimized sections is plotted in Fig. 6. Also shown for reference are the cost ratios from Table 3. The reference values are seen to span the range of cost ratios considered. The figure shows that as the relative cost of steel reinforcement increases from $R = 0.6$ to $R = 1.0$, the optimized embodied energy design can achieve a reduction in embodied energy up to approximately 16 %. Over the same range, the embodied energy optimized section also increases the cost by approximately 9 %. When the relative cost ratio R goes beyond unity, the differences between embodied energy reduction and cost addition reduce.

4. CONCLUSIONS

This paper presents, via a simple example, an illustration of the potential benefit of structural optimization for embodied energy in reinforced concrete structures. For the values of the embodied energy and cost assumed herein, results indicate that optimization of structural member design for embodied energy results in decreases on the order of 10 % in embodied

energy at the expense of an increase on the order of 5 % in cost relative to a cost-optimized member. The exact reduction in embodied energy depends significantly on the value of the cost ratio R of steel reinforcement to concrete. Note that the cost ratio R must take into account not only the material costs of the concrete and steel, but also construction costs such as the placement costs of concrete and installation costs of reinforcement.

Future work involves the optimal design of reinforced concrete buildings for sustainability using multi-objective optimization, in which the cost and embodied energy objective functions are treated simultaneously. In addition, CO₂ emissions or green house gas emissions will be considered as an alternative indicator for the sustainable design of structures.

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Table 1. Design variables and corresponding ranges

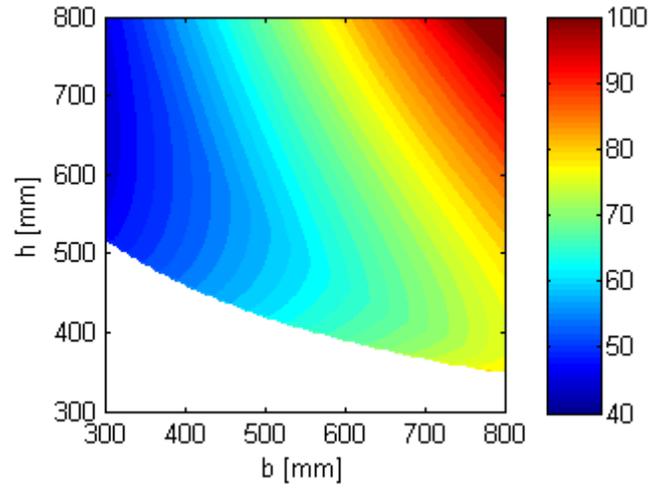
Variable	Range
Width of compression face of member (b)	$300 \text{ mm} \leq b \leq 800 \text{ mm}$
Height of member (h)	$300 \text{ mm} \leq b \leq 800 \text{ mm}$
Area of longitudinal tension reinforcement (A_s)	Given M_u and (b, h), each value is calculated as per ACI 318-08M
Area of shear reinforcement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

Table 2. Design parameters and corresponding values

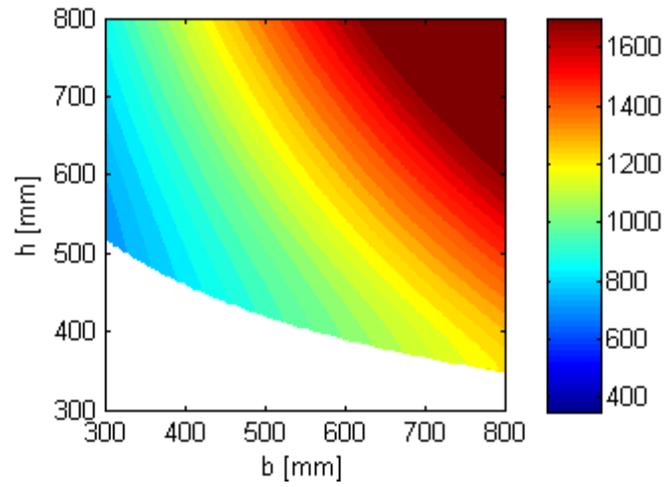
Parameter	Value
Factored moment	$M_u = 400 \text{ kN} \cdot \text{m}$
Factored shear force	$V_u = 220 \text{ kN} \cdot \text{m}$
Concrete compressive strength	$f'_c = 34 \text{ MPa}$
Longitudinal reinforcement yield strength	$f_y = 420 \text{ MPa}$
Shear reinforcement yield strength	$f_{yt} = 300 \text{ MPa}$
Modulus of elasticity of steel	$E = 2 \times 10^5 \text{ MPa}$
Specific mass of concrete	$\rho_c = 2400 \text{ kg/m}^3$
Specific mass of steel	$\rho_s = 7850 \text{ kg/m}^3$
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	$L = 7 \text{ m}$
Concrete cover (includes radius of fictitious bar having area A_s)	$d' = 65 \text{ mm}$
Longitudinal spacing of shear reinforcement	$s = 150 \text{ mm}$

Table 3. Cost ratio variation

Reference	R	Comments
Paya-Zaforteza et al. (2009)	1.10	$f'_c = 35 \text{ MPa}$, $f_y = 400 \text{ MPa}$ Material costs only (2007 prices)
Sahab et al. (2005)	0.91	$f'_c = 35 \text{ MPa}$, $f_y = 460 \text{ MPa}$, $f_{yt} = 250 \text{ MPa}$ Material & placement costs (2001 prices)
Guerra et al., 2009	0.80	$f'_c = 28 \text{ MPa}$, $f_y = 420 \text{ MPa}$ Material & placement costs (year unknown)

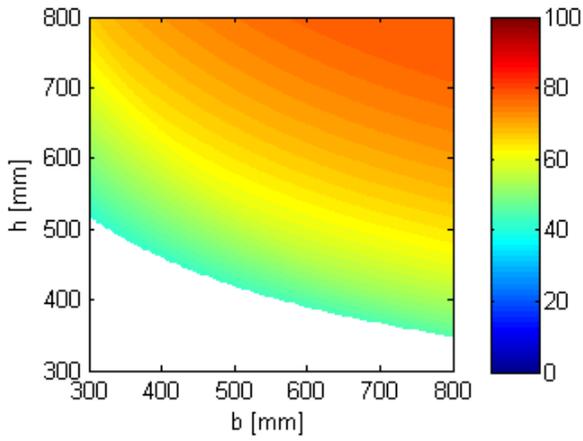


(a) Total section cost [\$]

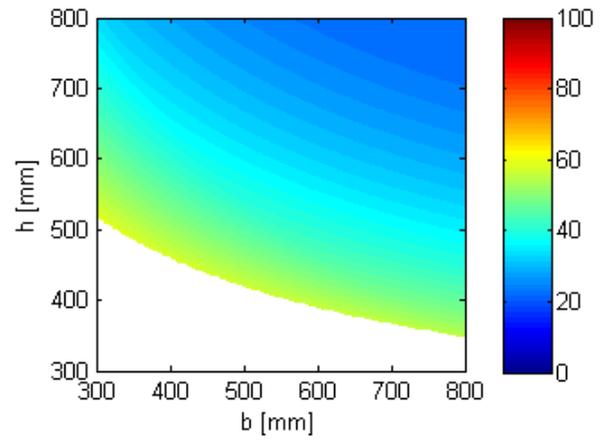


(b) Total embodied energy [MJ]

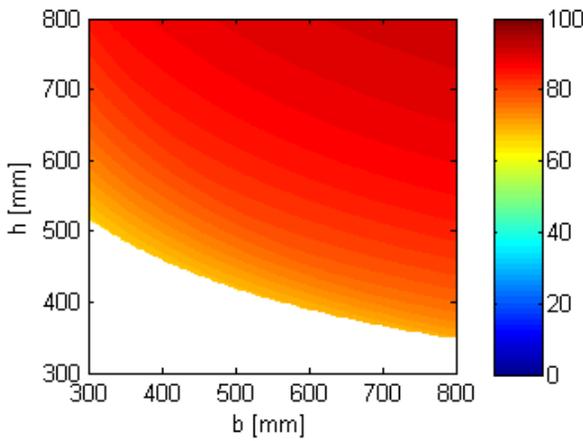
Fig. 1. Domain of feasible designs ($R = 0.8$)



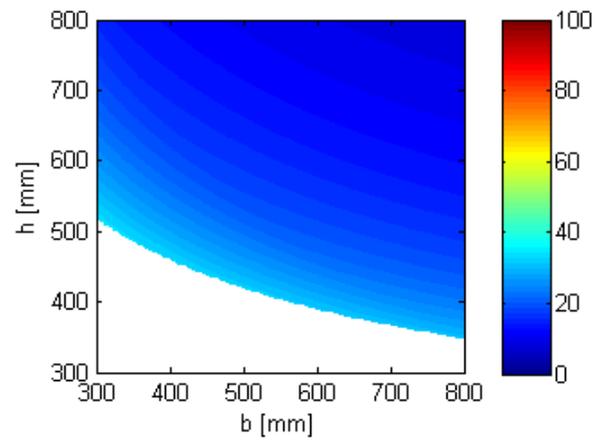
(a) Concrete in cost [%]



(b) Reinforcement in cost [%]

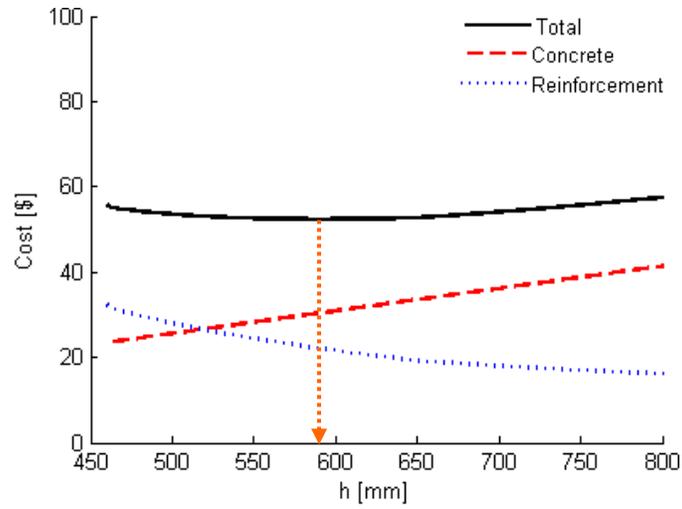


(c) Concrete in embodied energy [%]

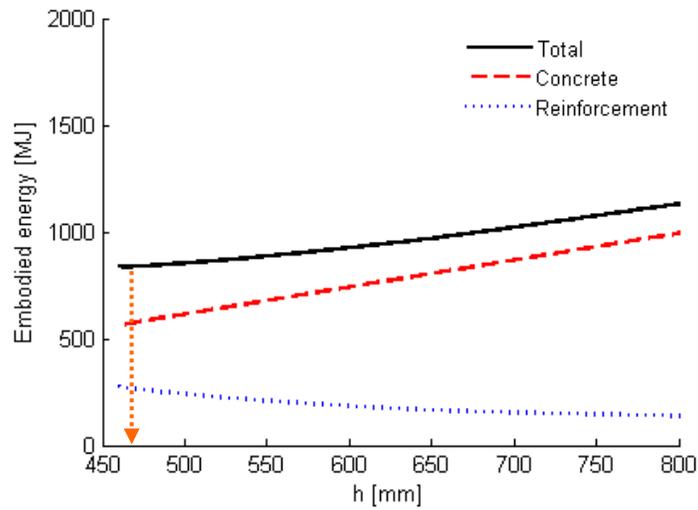


(d) Reinforcement in embodied energy [%]

Fig. 2. Contributions of concrete and reinforcement to the total cost and total embodied energy ($R = 0.8$)



(a) Cost



(b) Embodied energy

Fig. 3. Variation in cost (a) and embodied energy (b) with h for $b = 400$ mm ($R = 0.8$)

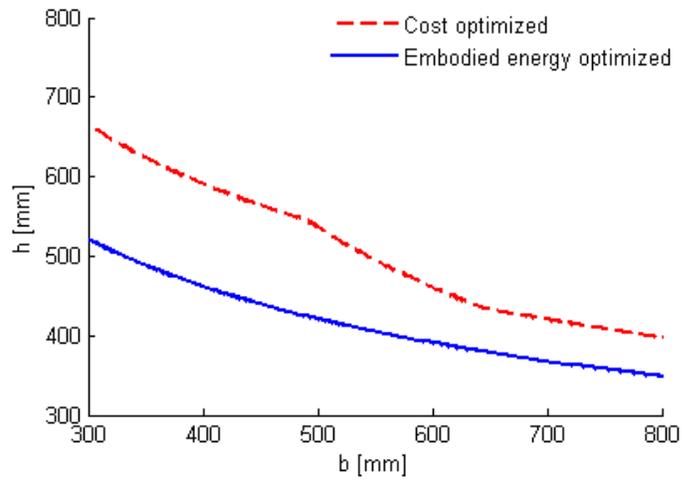


Fig. 4. Variation in section height h with section width b for cost optimized and embodied energy designs ($R = 0.8$)

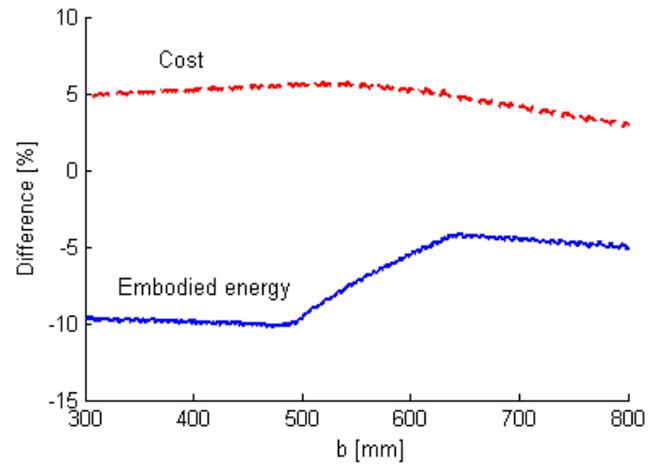


Fig. 5 – Variation in cost and embodied energy with section width b for cost optimized and embodied energy designs ($R = 0.8$)

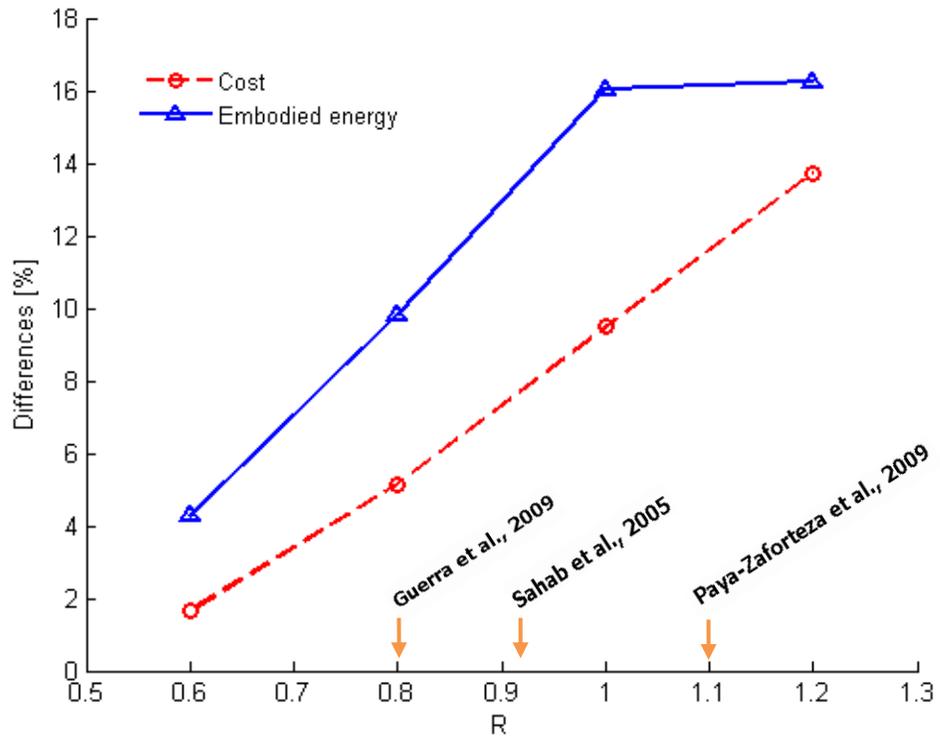


Fig. 6. Variation in percentage difference in cost and embodied energy with R ($b = 400$ mm)