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Employing generative design for sustainable construction

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Abstract

Generative design is the alteration of an object's shape to optimize its function. Currently, the scope of generative design is limited in the structural civil engineering field. Structural design still follows conventional methods compatible with conventional construction processes. These processes restrict the flexibility in design resulting in structural elements having excess materials to satisfy critical structural capacity requirements. This introduces additional costs and higher environmental impacts. New tools, such as concrete and steel 3D printers, are emerging to enable more complex geometries in construction allowing higher flexibility in design options. Inspired by the above, this paper aims at developing a design engine that provides optimal design solutions to reinforced concrete beams with sufficient structural capacities while using less materials and resources. Based on ACI code design guidelines, a cantilever beam was structurally analyzed to relate geometry parameters to structural capacity. Optimization was achieved by minimizing the depth and the steel reinforcement ratio at each segment along its length. Hence, concrete and steel at each location would take their optimal quantities. This results in lighter and more economic structures conforming to the structural capacities required by the codes. The engine is based on three objective functions that solve for the minimum values of beam depth and reinforcement at each section which optimize cost and CO₂ emissions individually or simultaneously. MATLAB was used to design the optimized beam and to calculate the percentage decrease in cost and CO₂ emissions between the optimized and conventional beam. A significant reduction ranging between 40% and 52% of cost and between 39% and 51% of CO₂ emissions per beam is achieved. If the design engine developed was utilized in parallel with the 3D printing construction method, structures with optimized quantities, materials, and shapes would be developed. Thus, minimizing drastic effects on the environment and achieving reduced costs.

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1. Introduction

Generative design is being addressed in the automotive and architectural fields by changing an element's shape to optimize its function. However, the structural engineering field lags in this area where structural engineers continue to use methods established approximately 100 years ago [1,2]. Generative design systems aim to create design processes that produce more efficient shapes by exploiting current computing and manufacturing capabilities [3]. Such systems are inspired from nature by accepting and rejecting design options to get a form that uses precise amounts of materials

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where required, to eventually create optimized structures that meet or exceed traditional capabilities [4]. Similar processes of imitating nature's strategies are called biomimicry [5].

Optimization approaches with defined objectives and constraints are employed through computer algorithms to achieve such structural improvements [6]. Optimization techniques fall into three categories: mathematical, optimality, and heuristic programming methods, each of which has its applications and limitations [6].

With the quick advancement in 3D printing technologies, shape optimization has become the interest of not only manufacturers but also anyone who has access to a 3D printer [7]. One of the main advantages that concrete 3D printing provides over the conventional construction method is that the concrete does not need an existing formwork [8]. In fact, optimized concrete structures are best constructed using 3D printing technology where the designed geometry meets structural requirements while consuming the least possible construction resources [7]. As for steel 3D printing, Arc welding is considered the most efficient additive manufacturing technique [9]. These methods are mainly entitled to push the boundaries and constraints of the design world that are available for engineers and architects [8].

This research aims at generating an optimized structural element (singly reinforced cantilever beam) by reducing materials' quantities; thus, reducing its environmental footprint and cost. The scope was set to develop an engine that provides optimal design solutions to reinforced concrete beams having sufficient structural capacities and utilizing fewer resources. The variables studied are the depth of concrete and the steel reinforcement ratio. Moreover, employing 3D printing for the construction process in such context was examined.

To achieve the study objectives, an optimization process was applied to a cantilever beam to explore its effects on design parameters and consequently cost and CO₂ emissions. For comparison purposes, the implications were checked for a non-optimized cantilever beam.

2. Methodology

The project is divided into two parts: developing a design engine and evaluating the 3D printing construction process. To develop the design engine, the following methodology was adopted: defining the design variables, performing theoretical structural analysis, building the engine through MATLAB coding, and realizing the outputs.

2.1. Problem description and design steps

Two cantilever beams were studied. The first is the reference beam, which is designed by the traditional methods, while the second is the beam with varying cross section, which is designed considering optimization techniques as shown in Fig. 1 (a) and Fig. 1 (b) respectively.

Focusing on the optimized beam design, the structure was analysed by basic flexural design methods to determine the required concrete depth h and steel reinforcement ratio at each section (considering a uniform incremental length x across the entire length L as presented in Fig. 1 (b)). Shear design was performed to determine the area of shear reinforcement needed for each region. Deflection checks based on maximum permissible deflections suggested in Table 9.5 (b) in the ACI code were conducted [10]. Long term deflection is reduced by adding compressive steel [10]; however, after checking deflection, it was realized that there is no need to add compressive steel.

The study considers a singly reinforced cantilever beam with varying depth h (m) and steel reinforcement ratio ρ as shown in Fig. 1 (b).

Fig. 1. (a) traditionally designed beam; (b) optimized beam.

The length L (m) and width b (m) of the beam are user defined parameters. The structure is subjected to a uniformly applied load including superimposed dead load SDL , live load LL and self-weight of the beam. The total dead load DL is the sum of the SDL and self-weight. Based on typical applications, the considered SDL and LL are 200 (kg/m²) and 250 (kg/m²) respectively. The load combination employed is $1.2 \times DL + 1.6 \times LL$ [10]; however, since the self-weight is varying along the length of the beam the constant distributed load C (kg/m), excluding self-weight, would be as calculated in (1).

$$C = TA \times (1.2 \times SDL + 1.6 \times LL) \quad (1)$$

The corresponding ultimate design loads: bending moment M_u and shear force V_u acting on the critical section of the beam were calculated. A sample equation for a beam divided into two sections is shown in (2) and (3).

$$M_{u(2)} = \frac{1}{2} C [x_{(1)} + x_{(2)}]^2 + \gamma b (h_{(1)}) (x_{(1)}) \left(x_{(2)} + \frac{x_{(1)}}{2} \right) + \gamma b (h_{(2)}) (x_{(2)}) \left(\frac{x_{(2)}}{2} \right) \quad (2)$$

$$V_{u(2)} = [C + 1.2 \gamma b (h_{(2)})] \quad (3)$$

Where $x_{(1)}$, $h_{(1)}$, $x_{(2)}$ and $h_{(2)}$ represent the length and depths of sections one and two respectively. All remaining variables and parameters mentioned in (2) and (3) in addition to other parameters are described in Table 1.

2.2. Design variables and parameters

The design variables are the beam depth and the ratio of steel reinforcement. The parameters that are set as inputs into the code include: L , b , increment length x , and TA . Table 1 includes all the design parameters, defined as constants during the optimization process. The values are those used by common reinforced concrete design practice or as depicted by the ACI code [10]. Also, Table 1 includes the necessary design equations used to calculate parameters referred to in other sections of the paper [10].

Table 1. Design parameters and corresponding values and equations.

Parameter	Value	Parameter	Equation
Concrete compressive strength	$f'_c = 280 \times 10^4$ (kg/m ²)	Effective depth of the beam	$d = h - 0.05$ (m)
Reinforcement yield strength	$f_y = 4200 \times 10^4$ (kg/m ²)	Area of flexural steel reinforcement	$A_s = \rho \times b \times d$ (m ²)
Specific mass of reinforced concrete	$\gamma = 2500$ (kg/m ³)	Nominal moment capacity	$M_n = A_s \times f_y \times \left(d - \frac{\rho \times (h - 0.05) \times f_y}{2 \times 0.85 \times f'_c} \right)$ (kg.m)
Specific mass of steel	$\rho_s = 7.8 \times 1000$ (kg/m ³)	Spacing of shear reinforcement	s (m)
Strength reduction factor for shear	$\phi = 0.75$	Nominal shear strength provided by concrete	$V_c = 2 \sqrt{f'_c} \times b \times d$ (kg)
Strength reduction factor for flexure	$\phi = 0.9$	Nominal shear strength	$V_n = \frac{V_u}{\phi}$ (kg)
	$\beta_1 = 0.85$	Nominal shear strength provided by shear reinforcement	$V_s = V_n - V_c$ (kg)
Tributary area	TA (m)	Area of shear reinforcement	$A_v = \frac{V_s}{d \times f_y} \times s$ (m ²)
Concrete cover	5 cm		

2.3. Optimization problem and solution method

Two MATLAB optimization solvers were used: “fmincon” and “gamultiobj”. “fmincon” function follows the Lagrangian Multiplier Method (mathematical programming method) which is capable of performing optimization for constrained complex engineering problems [11], whereas “gamultiobj” uses a controlled elitist genetic algorithm (heuristic method) that favors fitter individuals [12]. “fmincon” performs constrained nonlinear multi-variable optimization that requires an initial estimate to find a constrained minimum of an objective function [13,14]. Two objective functions were considered separately: one minimizes cost and the other minimizes CO₂ emissions to yield

optimized depth and reinforcement values. Another scenario of considering both objectives simultaneously was also evaluated. Such a scenario is not permissible using Lagrangian optimization, therefore a genetic algorithm which allows multi-objective optimization was used [12].

The objective functions corresponding to the minimization of cost and CO₂ emissions are (4) and (5) respectively. Table 2 summarizes cost estimates that are based on common practice in Lebanon, and CO₂ emissions in reference to [15].

Table 2. Cost and CO₂ footprint of concrete and reinforcing steel.

Material	Cost	CO ₂	Quantity
Concrete ($f_c' = 40$ MPa)	80 (\$/m ³)	518.23 (kg/ m ³)	$b \times h \times increment$ (m ³)
Steel	600 (\$/ton)	7.4×1000 (kg/ton)	$f_s \times \rho \times b \times d \times increment$ (ton)

$$f_1 = (Cost_c \times Volume_c) + (Cost_s \times Mass_s) \quad (4)$$

$$f_2 = ((CO_2)_c \times Volume_c) + ((CO_2)_s \times Mass_s) \quad (5)$$

Where subscripts c and s correspond to concrete and steel respectively.

Serviceability and strength constraints based on the ACI code were considered for the optimization process [10]. Serviceability constraints include maximum allowable deflection (m): $\frac{L}{480}$ (6). Strength constraints include: flexural strength according to moment capacity (7), minimum and maximum requirements for flexure reinforcements (8), (9), (10) and (11). The minimum height h_{min} of concrete considers minimum reinforcement and cover. As recommended in [16] the maximum height h_{max} of concrete is the width multiplied by 2.5.

$$|M_u| < 0.9 \times M_n \text{ (kg.m)}; \quad \forall increments \left(\frac{x}{L} \right) \quad (7)$$

$$h_{min} = 0.1 \text{ (m)} \quad (8)$$

$$h_{max} = 2.5 \times b \text{ (m)} \quad (9)$$

$$\rho_{min} = \text{minimum of} \left(\frac{3 \times \sqrt{f_c'}}{f_y} \text{ or } \frac{200}{f_y} \right) \quad (10)$$

$$\rho_{max} = \frac{0.85 \times \beta_1 \times f_c'}{f_y} \left(\frac{87000}{87000 + f_y} \right) \quad (11)$$

The variables in these equations were defined in text of section 2.1 and Table 1.

3. Results of optimal design

The optimization process was explored for several cantilever beams having varying lengths L and widths b and subject to different loads. Additionally, non-optimized solutions characterized by a constant cross section were obtained for beams with similar parameters for comparison purposes. The results corresponding to a sample structure of a 4 (m) long beam having a width b of 0.3 (m) and carrying an area of 8 (m²), will be elaborated in this section. The geometry resulting from the optimization process differed among the different objective functions. In each of these, the depth h and the ratio of reinforcement ρ converged to the optimal solution that minimizes the respective objective functions. Table 3 summarizes the obtained results.

All objective functions considered yield a much lower concrete volume than that obtained through the traditional approach but a higher total mass of steel reinforcement. These optimum results were also associated with a significant lower cost and CO₂ footprint. The different total volume and mass are a consequence of different combinations of depth h and ratio of reinforcement ρ at each section to minimize each respective objective function. It can be noticed that the objective function minimizing cost alone results in the least total concrete volume and the largest reinforcement

mass, while that minimizing the CO₂ footprint results in a higher concrete volume but lower reinforcement. Results emerging from the multi-objective function solution compromise the outcomes.

Additionally, as the increment size decreases a more optimized solution is achieved as observed in Table 3 and Fig. 2. For example, the results of the cost objective function improved by 9% in terms of volume reduction and 23% in terms of reinforcement mass reduction when the increment size was reduced from 1 (m) to 0.01 (m). This reduction was also associated with a reduction of cost and CO₂ footprint by approximately 25% each. All the outputs of the optimization process related to the flexure design are represented in Table 3 below for the non-optimum solutions and for each objective function and increment size. Results for shear and deflection were also obtained as a part of this study but are not presented in the table. Fig. 2 below shows the variation of cost and CO₂ footprint as the size of the increment increases or as the number of sections that subdivide the beam decreases. A significant reduction in cost and CO₂

		Depth (m)		Reinforcement Ratio		Concrete Volume (m ³)	Reinforcement Mass (tons)	%Cost Reduction	%CO ₂ Reduction
Conventional (Not Optimized)		0.481		0.007		0.577	0.028	-	-
Increment Size	Objective Function	Edge	Support	Edge	Support				
1	Cost	0.125	0.360	0.012	0.012	0.290	0.022	41.85	38.75
	CO ₂	0.141	0.428	0.008	0.008	0.340	0.017	40.19	39.86
	Cost + CO ₂	0.142	0.421	0.008	0.008	0.327	0.018	40.76	39.71
0.5	Cost	0.100	0.359	0.006	0.012	0.268	0.019	47.19	44.70
	CO ₂	0.100	0.427	0.006	0.008	0.312	0.015	45.78	45.72
	Cost + CO ₂	0.100	0.370	0.006	0.008	0.286	0.017	46.73	45.28
0.25	Cost	0.100	0.358	0.003	0.012	0.258	0.018	49.62	47.38
	CO ₂	0.100	0.426	0.003	0.008	0.299	0.014	48.29	48.36
	Cost + CO ₂	0.100	0.395	0.003	0.008	0.279	0.016	49.05	48.04
0.1	Cost	0.100	0.358	0.003	0.012	0.252	0.017	51.05	48.96
	CO ₂	0.100	0.426	0.003	0.008	0.292	0.014	49.78	49.91
	Cost + CO ₂	0.102	0.359	0.003	0.008	0.271	0.015	50.54	49.58
0.05	Cost	0.100	0.358	0.003	0.012	0.250	0.017	51.52	49.47
	CO ₂	0.100	0.426	0.003	0.008	0.289	0.014	50.27	50.42
	Cost + CO ₂	0.100	0.392	0.003	0.008	0.264	0.016	51.17	49.95
0.01	Cost	0.100	0.358	0.003	0.012	0.248	0.017	51.89	49.88
	CO ₂	0.100	0.425	0.003	0.008	0.287	0.013	50.66	50.83
	Cost + CO ₂	0.100	0.405	0.003	0.008	0.264	0.015	51.49	50.40

footprints is achieved ranging between \$23 and \$30 and 196 and 257 kg of CO₂ per beam.

Table 3. Design variables of results for optimized and non-optimized solution.

4. Discussion

According to Table 3, the optimized beam resulted in a cost decrease that ranged from 40% to 52%. If this optimization process is applied to all similar beams in a building, its impact would be more tangible. Additionally, if such optimization processes are adopted in the design of other types of structural elements in a building the effect on cost reduction would be substantial. Also Table 3 shows that the CO₂ percentage decrease ranged between 39% and 51%

Fig. 2. (a) change in cost with increment size; (b) change in CO₂ footprint with increment size.

using the CO₂ objective function. A traditionally designed beam produces around 550 kg of CO₂, whereas an optimized beam can decrease this amount to 249 kg; saving almost 301 kg of CO₂ per cantilever beam. Energy used in cement production accounts for 5% of the earth's greenhouse emissions [17]. Saving up to 45% of CO₂ emissions in the optimized design represents a significant benefit regarding greenhouse emissions. If the optimized beam was constructed using the conventional construction process, it would be time exhaustive and more complicated for laborers due to the complex beam geometry (Fig. 1 (b)). However, recent construction methods such as concrete and steel 3D printing facilitate the construction of such structures. Thus, the advantages related to time, quality and cost of such method are discussed along with its recent status in the construction industry.

Time is directly correlated with the interest paid to finance the project [18]. According to El Sakka & Hamzeh, a total of 60% reduction in construction time can be achieved if 3D printing methods were used [18]. In the conventional process, there is frequent labor movement to transport materials and resources such as forms and steel bars, thus generating waste. However, using 3D printing, such waste is eliminated since it is a form free process [18]. Additionally, due to its form free nature, concrete 3D printing minimizes defects such as honeycombing and segregation [18]. Hence, providing improved quality. Similar concrete defects cannot be addressed until formwork stripping occurs whereas in 3D printing such defects can be addressed in an extruded layer before casting the next one [18]. From a financial perspective, this construction method requires less labor because one 3D printer operator can substitute an entire crew [18]. However, this operator requires a certain set of skills and therefore would have a higher wage than a regular labor [18]. Also, since the construction process requires less time, a significant cut down in salaries and overhead costs would be achieved [18]. Yet, the high cost of concrete printers is a current disadvantage; thus, a thorough study should be performed on the direct cost of a concrete 3D printer to study the life cycle cost of this technology.

5. Conclusion

In this study, structural optimization was performed on a RC cantilever beam in order to design low cost and low carbon footprint RC structures. This was achieved by segmenting the beam and minimizing concrete and steel quantities at each section. Primary results yielded cost reduction ranging between 40% and 52%, while CO₂ reduction ranged between 39% and 51%. Also, considering the construction process, optimized structures can be executed by 3D printing construction methods which are considered to be more efficient and environmentally friendly. Current results seem very promising; a reason for efforts to be exerted to scale this work into entire buildings. Further research can follow this logic into other structural elements to eventually achieve optimized structures, and consequently realize greater economic and environmental advantages.

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