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Citation: Mergos, P.E. (2018). Seismic design of reinforced concrete frames for minimum embodied CO2 emissions. Energy and Buildings, 162, pp. 177-186. doi: 10.1016/j.enbuild.2017.12.039

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Seismic design of reinforced concrete frames for minimum embodied CO_2 emissions

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Abstract.

Optimum structural design of reinforced concrete (RC) frames has been the focus of extensive research. Typically, previous studies set economic cost as the main design objective despite the fact that RC structures are major contributors of CO_2 emissions. The limited number of studies examining optimum design of RC frames for minimum CO_2 emissions do not address seismic design considerations. However, in many countries around the world, including most of the top-10 countries in CO_2 emissions from cement production, RC structures must be designed against earthquake threat. To bridge this gap, the present study develops optimum seismic designs of RC frames for minimum cradle to gate embodied CO_2 emissions and compares them with optimum designs based on construction cost. The aim is to identify efficient design practices that minimize the environmental impact of earthquake-resistant RC frames and examine the trade-offs between their cost and CO_2 footprint. To serve this goal, an RC frame is optimally designed according to all ductility classes of Eurocode 8 and for various design peak ground accelerations (PGAs), concrete classes and materials embodied CO_2 footprint scenarios. It is found that the minimum feasible CO_2 emissions of RC frames strongly depend on the adopted ductility class in regions of high seismicity, where low ductility seismic design can generate up to 60% more CO_2 emissions than designs for medium and high ductility. The differences reduce, however, as the level of seismicity decreases. Furthermore, CO_2 emissions increase significantly with the design PGA. On the other hand, they are less sensitive to the applied concrete class. It is also concluded that, for medium to high values of the ratio of the unit environmental impact of reinforcing steel to the respective impact of concrete, the minimum CO_2 seismic designs are very closely related to the minimum cost designs. However, for low values of the same ratio, the minimum cost design solutions can generate up to 13% more emissions than the minimum CO_2 designs.

Keywords: Seismic design; Eurocode 8; environment; embodied; CO_2 emissions; optimization; reinforced concrete; genetic algorithms

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1 Introduction

Natural hazards (e.g. earthquakes, floods, windstorms) and climate change are threatening sustainable development in the 21st century [1]. Reinforced concrete (RC) structures play a vital role in protecting human societies from natural disasters. On the other hand, they contribute significantly to greenhouse gas emissions that have been the dominant cause of the observed climate change. This is mainly due to the embodied environmental impact of cement, which is responsible for roughly 8% of global CO_2 emissions [2], and reinforcing steel. The previous observations underline the need for optimum structural design of RC structures that minimises their environmental impact as well as vulnerability to natural hazards.

In standard engineering practice, optimum structural design is pursued either with the aid of the designer's experience or a manual trial-and-error process. However, for complex problems, these approaches are often inadequate and automated structural optimization methodologies are required. Early automated optimization efforts of RC structures focussed on construction cost [3]. It was not until rather recently that research studies examined design of RC structures for minimum environmental impact. Paya *et al*. [4] developed multi-objective optimum designs of RC frames where, among others, construction cost and environmental impact were set as conflicting design objectives. The environmental impact was expressed in terms of the Eco-indicator 99 [5]. It is reported that 5% increase in the minimum construction cost can lead to 24% reduction in the environmental impact. In a later study, Paya *et al*. [6] examined optimum designs of RC frames for minimum material cost and embodied CO_2 emissions. They found that these two design objectives are strongly related. The minimum CO_2 designs are only 3% more expensive and produce 4% less CO_2 emissions than the optimum cost designs. Yeo & Gabbai [7] investigated optimum designs of RC beams for minimum embodied energy. They observed that minimum embodied energy design 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 minimum cost designs. Camp and Huq [8] examined CO_2 and material cost optimization of RC frames. They found that a modest 2% increase in cost over the minimum cost design can result in 8-10% reduction in CO_2 emissions. Medeiros and Kripka [9] examined optimum designs of RC columns under uniaxial bending and compression loads for different environmental assessment parameters including CO_2 emissions. They found that designs for minimum CO_2 emissions produce 1% less CO_2 footprint and they are 1% more expensive than minimum cost-based designs. Furthermore, Yeo and Potra [10] investigated the potential of additional reductions of CO_2 emissions of RC frames when setting as single design objective the CO_2 footprint instead of construction cost. They concluded that the CO_2-based designs result in a footprint that is 5-15% lower than the design for minimum cost. Furthermore, they observed that the actual amount of reduction strongly depends on the ratio of the unit cost of reinforcing steel to the unit cost of concrete and the ratio of the unit environmental impacts of these two materials [10].

The previous optimization efforts do not address seismic design of RC frames. However, in many countries around the globe, including most of the top-10 countries in CO_2 emissions from cement production (e.g. India, Iran, Turkey, Japan) [2], RC structures need to be designed against earthquake hazard. An overview of the existing seismic design optimization frameworks can be found in Fragiadakis and Lagaros [11]. The more recent studies on optimum seismic design of RC structures focus on performance-based design (PBSD) methodologies [e.g. 12-16]. However, all previous research efforts on optimum seismic design of RC structures set construction and/or life-cycle economic costs as design objectives [11].

Indeed, the environmental impact of RC structures designed for seismic resistance has very little been explored. Tsimplokoukou *et al*. [17] and Romano *et al*. [18], recommend a sustainable seismic design methodology, where the results of an environmental life-cycle assessment in terms of environmental units are added to the results of a life-cycle performance-based structural assessment expressed in monetary values by transforming the former to equivalent monetary values. Furthermore, Hossain and Gencturk [19] developed a detailed framework for the assessment of life-cycle environmental impact of RC buildings accounting also for the emissions produced for repairing RC members after damaging earthquakes. Moussavi Nadoushani and Akbarnezhad [20] examined 15 different lateral force resisting systems, including moment resisting frames and shear walls, for buildings located in regions of moderate seismicity concluding that the selection of the structural system influences significantly the life-cycle environmental impact. Belleri and Marini [21] showed that in the case of an old existing building, located in a region of high seismicity, which underwent only energy refurbishment the expected annual environmental impact due to seismic risk is almost equal to the respective annual operational impact after thermal refurbishment. Furthermore, Tapia and Padgett [22] developed a multi-objective optimization framework for retrofit of bridges under natural hazards, including earthquakes, where life-cycle cost and environmental impact are set as design objectives. However, an existing steel bridge is used as case study. The author [23] examined seismic designs of single RC beam and column members for minimum embodied CO_2 emissions according to Eurocode 8 [24] for all ductility classes (Low, Medium and High). It is found that seismic designs for minimum CO_2 footprint drive to less CO_2 emissions but are more expensive than designs for minimum cost. The differences depend significantly on the values of the unit environmental impacts of reinforcing steel and concrete materials. Furthermore, it is observed that CO_2 emissions increase importantly with the magnitude of seismic forces and that higher ductility classes (Medium and High) produce slightly higher CO_2 emissions for the same level of seismic forces due to the need for additional transverse steel reinforcement and capacity design considerations.

It can be concluded from the previous discussion that the available studies on optimum seismic design of RC frames have not considered explicitly embodied environmental impact as design objective. To fill part of this gap, the present study develops various optimum seismic designs of an RC frame for minimum cradle to gate embodied CO_2 emissions and examines their properties and characteristics. To serve this goal, a computational framework for the optimum design of RC frames is employed based on genetic algorithms that are able to track global optima of complex problems with discrete design variables. The aim here is to explore and identify efficient design practices that minimize embodied CO_2 footprint of seismically designed RC frames. Furthermore, the CO_2-based designs are compared with designs for minimum cost to investigate the trade-offs between cost and CO_2 footprint of earthquake resistant RC frames.

2. Optimum seismic design of RC frames

2.1 General

The standard formulation of a single-objective optimization problem with discrete design variables is the following:

Minimize: $F(\boldsymbol{x})$

Subject to: $g_j(\boldsymbol{x}) \leq 0,\ j = 1\ to\ m$ (1)

Where:

$$\boldsymbol{x} = (x_1, x_2, \dots, x_n)$$

$$x_i \in D_i = \left(d_{i1}, d_{i2}, \dots, d_{ik_i}\right), i = 1\ to\ n$$

In this formulation, $\digamma(\boldsymbol{x})$ is the objective function and $\boldsymbol{x}$ is the design solution vector that comprises of n independent design variables x_i (i=1 to n). The design variables x_i take values from discrete values sets $\boldsymbol{D}_i=(d_{i1}, d_{i2}, \ldots, d_{iki})$, where d_{ip} (p=1 to k_i) is the p-th possible discrete value of design variable x_i and k_i is the number of possible discrete values of x_i. Furthermore, the solution should be subject to m number of constraints $g_j(\boldsymbol{x})\leq 0$ (j=1 to m). The specification of the optimization problem components in the case of optimum seismic design of RC frames examined in this study is described in the following sections.

2.2 Objective function

Typically, the objective function in optimum design of RC frames $\digamma(\boldsymbol{x})$ is set to be the material cost $C(\boldsymbol{x})$. Alternatively, as discussed in the introduction section, the environmental impact $E(\boldsymbol{x})$, expressed herein in terms of embodied CO_2 emissions, can be used. In both cases, the cost/environmental impact is calculated as the sum of the contributions of concrete $\digamma_c(\boldsymbol{x})$, formwork $\digamma_f(\boldsymbol{x})$ and steel $\digamma_s(\boldsymbol{x})$. The latter can be taken as the sum of the contributions of longitudinal and transversal steel reinforcement.

The previous are summarized in Eq. (2), where V_c (m^3) is the concrete volume, m_s (kg) the mass of steel reinforcement and A_f (m^2) the area of the formwork. $\digamma_{co}$, $\digamma_{so}$ and $\digamma_{fo}$ are the unit prices of concrete, steel and formwork respectively. When the unit economic costs (expressed in Euros per material unit quantities) are set as unit prices (columns 2-3 of Table 1), then Eq. (2) determines the economic cost $C(\boldsymbol{x})$. Alternatively, if the material unit environmental impacts (expressed in $kgCO_2$ per material unit quantities) are used (columns 4-7 of Table 1), then Eq. (2) calculates embodied CO_2 emissions $E(\boldsymbol{x})$.

$$\digamma(\boldsymbol{x}) = \digamma_c(\boldsymbol{x}) + \digamma_s(\boldsymbol{x}) + \digamma_f(\boldsymbol{x}) \rightarrow \digamma(\boldsymbol{x}) = V_c(\boldsymbol{x}) \cdot \digamma_{co} + m_s(\boldsymbol{x}) \cdot \digamma_{so} + A_f(\boldsymbol{x}) \cdot \digamma_{fo} \quad (2)$$

Table 1 presents the unit prices adopted in this study for the economic cost and CO_2 emissions. The economic values are based on the Hellenic Ministry of Public Works [25]. The unit environmental impact values of concrete and steel are taken from [26]. In this study, cradle to gate embodied CO_2 emissions are specified that include the impacts of the extraction of the raw material and factory production. Therefore, impacts due to delivery to the site, operational and end of life impacts are not taken into consideration. It is found therein that the embodied environmental impact of concrete and reinforcing steel materials present significant variations. In the case of concrete, the variations come from either the specification of the concrete mix or from the different processes used to make Portland cement clinker. The variations of reinforcing steel embodied CO_2 values depend primarily on its recycled content. To envelope all possible scenarios, a range of values (low – typical – high) is provided in [26], as shown in Table 1. In addition, the unit environmental impact value of formwork is taken from [6].

Table 1: Material unit costs and environmental impacts

Material	Economic Unit Cost	Units	Environmental Unit Impact			Units
			Low	Typical	High	
Concrete C25/30	101.0	(€/m^3)	142.0	228.0	319.0	(kgCO_2/m^3)
Concrete C32/40	116.0	(€/m^3)	161.0	264.0	377.0	(kgCO_2/m^3)
Steel B500c	1.07	(€/kg)	0.43	0.87	1.77	(kgCO_2/kg)
Formwork	15.7	(€/m^2)	8.9 for columns; 3.1 for beams			(kgCO_2/m^2)

2.3 Design parameters and variables

In optimization problems, the input data are divided in design parameters that are assumed fixed and design variables that change values during the solution process. In this study, for the sake of simplicity, geometry (i.e. storey heights and member lengths), material properties and loading of RC frames are treated as design parameters. Therefore, the present study examines solely sizing optimization of RC frames, where only beam and column members cross-sectional characteristics need to be specified (Fig. 1).

For the square column sections assumed in this study (Fig. 1a), these characteristics are the cross-sectional dimension h_c, the diameter d_{bc} and number n_c of main bars per side and the diameter d_{bwc}, spacing s_c and number of legs n_{wc} of transverse reinforcement. For rectangular beam sections (Fig 1b), these characteristics are the cross-sectional dimensions h_b and b_b, the diameter d_{bt} and number of main bars n_{bt} at the top and the diameter d_{bb} and number of main bars n_{bb} at the bottom, the diameter d_{bwb}, spacing s_b and number of legs n_{wb} of transverse reinforcement parallel to beam section height.

As a first approach, all these characteristics can be used as design variables. However, this approach leads to a high number of design variables, even for very simple RC frames, undermining the computational efficiency and accuracy of the optimization problem. Alternatively, only cross-sectional dimensions can be used as design variables x_i and reinforcing steel characteristics may then be determined following standard structural design methodologies. The latter approach is straightforward in the context of seismic design according to Eurocode-8, as opposed to more advanced seismic design methodologies [16], because in the case of Eurocode-8 structural analysis depends only on cross-sectional dimensions. Therefore this approach is adopted in the next of this study.

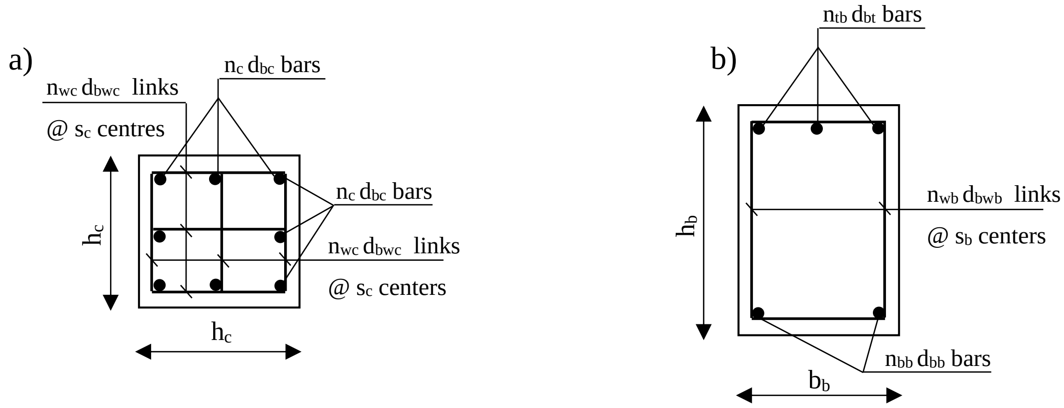


Fig. 1: Cross-sectional characteristics: a) column sections; b) beam sections

2.4 Design constraints and solution strategy

Design constraints $g_j(\boldsymbol{x})\leq 0$ represent herein the design provisions of Eurocode-2 (EC2) [27] and Eurocode-8 (EC8) [24]. A detailed description of these constraints can be found in [16]. First, design solutions are checked to verify that they comply with construction practice limitations (e.g. the width of beams cannot be greater than the width of adjoining columns) and that they satisfy Damage Limitation (DL) limit state for non-structural components as well as the limitations for P-delta effects. Next, steel reinforcement demands are calculated for the Ultimate Limit State (ULS) according to EC2 and EC8 provisions. Then, using exhaustive search or any other optimization algorithm, steel reinforcement characteristics are selected to satisfy, in the most efficient way, both steel reinforcement demands and the detailing rules of EC2 and EC8 including checks for confinement when necessary. If an appropriate steel reinforcement configuration is found then the design solution is branded feasible and the value of the objective function is returned to the optimizer. Otherwise, the design is not feasible and a penalty term is added to the value of the objective function. The afore-described procedure is illustrated in Fig. 2.

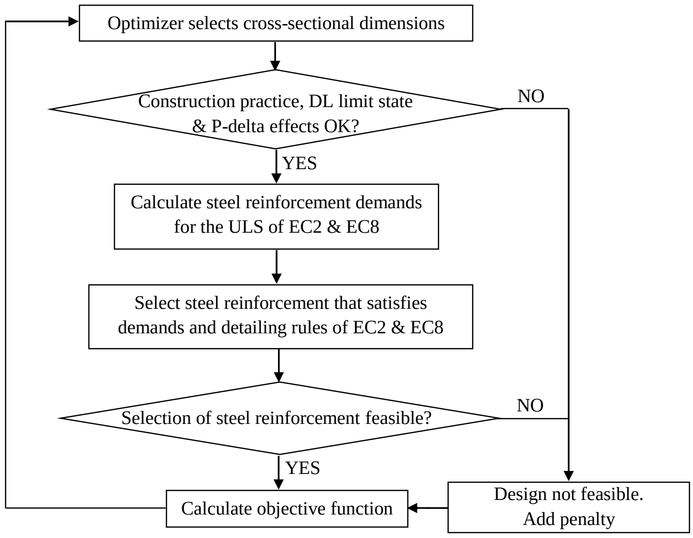


Fig. 2: Optimum seismic design to EC8 flowchart

2.5 Optimization algorithm

Different algorithms can be used to solve the optimization problem of Eq. (1). Metaheuristic optimization algorithms are nature-inspired search procedures that discover optima by randomization and local search [28]. They are well suited to structural engineering problems as they do not require calculation of derivatives [28, 29]. Furthermore, they are almost guaranteed to provide near global optimal solutions even to problems, where classical methods are trapped in local optima [28, 29].

Genetic Algorithms (GAs) [30] are metaheuristic optimization algorithms imitating Darwin's theory of evolution. GAs gradually modify populations (generations) of candidate solution vectors $\boldsymbol{x}$ (individuals) until the improvement of next generations is below a pre-specified tolerance. Individuals of next generations (children) are formed from selected individuals of previous generations (parents) based on their objective function values.

In this study, the mixed-integer GA as implemented in MATLAB-R2017a [31] is employed. This algorithm handles both continuous and discrete design variables by using special crossover and mutation functions [32]. In addition, it considers nonlinear constraints by adopting the penalty function approach [33].

3. Numerical applications

3.1 Introduction

In the following, different optimum seismic design solutions of a three-storey two-bay (Fig. 3) RC frame for minimum embodied CO_2 and/or economic cost are developed and compared. The frame is part of a building of ordinary importance that rests on soil class B following the classification of EC8 [24]. Concrete cover is assumed to be 30mm. Uniform distributed loads of 22.5kN/m act along beam members of all storeys for the quasi-permanent load combination of EC8. Furthermore, point loads of 67.5kN and 135kN are applied at the exterior and interior joints respectively for the same load combination. The quasi-permanent weight of all storeys is equal to 540kN.

Due to symmetry and for the sake of simplicity, one square cross-section is assumed for both exterior columns and one square cross-section for the interior column. Furthermore, the same rectangular cross-section is assumed for both beams of each storey. A different beam section is used, however, for each of the frame storeys. For simplicity, it is assumed that steel reinforcement does not vary along member lengths. In total, 8 independent design variables are employed in this case study representing the afore-mentioned cross-sectional dimensions of the RC frame.

For the optimum designs, it is assumed that cross-sectional dimensions take values starting from 300mm and increasing by 50mm. Transverse reinforcement spacing of beam and columns takes values between 75mm and 300mm with a step of 25mm. Numbers of main bars and legs of shear reinforcement may take any integer value greater than one. Furthermore, the diameters of the longitudinal bars are assumed to take values from the following discrete set (14mm, 16mm, 18mm, 20mm and 25mm) whereas diameters of transverse reinforcement take values from (8mm, 10mm, 12mm) in accordance with standard construction practice.

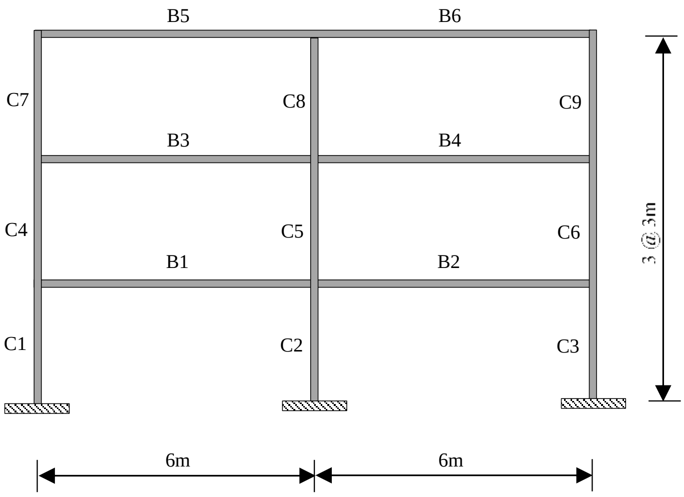


Fig. 3: Examined three-storey two-bay frame

In the following, the RC frame is optimally designed according to all ductility classes of EC8 for various design Peak Ground Acceleration (PGA) values, concrete classes, material CO_2 footprint scenarios and design objectives. Due to the regularity of the low-rise frame under investigation, the lateral force method of analysis is used to calculate seismic responses. In all cases, the optimization results reported herein were obtained by using the GA algorithm in MATLAB with 50 individuals per generation. Iterations were terminated when the mean relative variation of the best fitness value was negligible for more than 50 generations. MATLAB-R2017a [31] default options were used for GA operations. Ten independent GA runs for each design problem were conducted and the minimum objective function solutions are provided herein. It is worth noting that in all cases the GA runs for the same design problem returned objective function solutions that didn't vary more than 1%. This shows the level of accuracy of the obtained optimum solutions.

3.2 Seismic design methodology

In this section, the RC frame of Fig. 3 is optimally designed according to EC8 for ductility class high (DCH), medium (DCM) and low (DCL). All designs are performed for 0.40g design PGA value. Concrete C25/30 and reinforcing steel B500C in accordance with EC2 [27] specifications are used. Concrete and reinforcing steel costs and CO_2 emissions are taken from Table 1 following the typical environmental impact scenarios. Designs for both minimum cost and CO_2 footprint are examined.

Figs. 4a and 4b present optimization histories of the minimum CO_2 and material cost solutions. It can be seen that all solutions terminate when the objective functions remain practically constant for more than 50 generations. Fig. 4c shows the minimum CO_2 impacts derived by following the different design approaches. It is shown that DCL produces the highest and DCH the lowest emissions. DCM solution generates CO_2 emissions very similar to DCH. It is interesting to note that DCL produces 60% more CO_2 emissions than DCH. This is explained by the fact that seismic forces for DCH and DCM are significantly reduced with respect to DCL by the application of the behavior factor q that accounts for ductility capacity of structures [24]. As shown in [23], CO_2 emissions of RC members are drastically reduced as design seismic forces decrease. On the other hand, the use of additional transverse reinforcement, to achieve higher ductility capacity for DCM and DCH, does not increase significantly CO_2 footprint due to the small contribution of transverse reinforcement to the total CO_2 emissions [23]. As a result, embodied CO_2 can be significantly lesser for higher ductility classes. Similar conclusions can be drawn in the case of minimum material costs as shown in Fig. 4d.

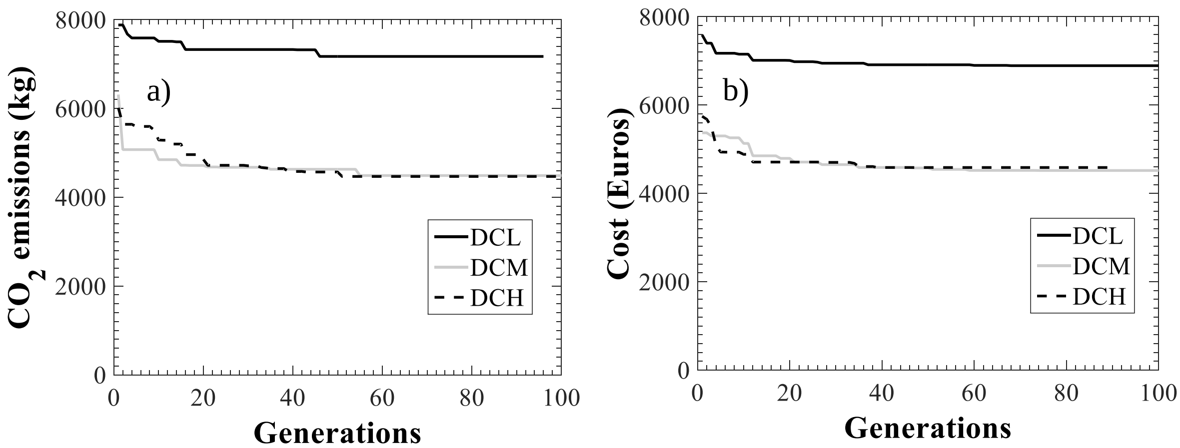
It is customary to express CO_2 emissions of buildings in terms of $kgCO_2$ per gross floor area. In this case study, the total floor area of all three storeys of the concrete building attributed to the examined structural frame is equal to $108m^2$. Therefore, the CO_2 emissions of the frame under examination in terms of $kgCO_2$ per gross floor area are equal to $66.4kgCO_2/m^2$, $41.6kgCO_2/m^2$ and $41.4kgCO_2/m^2$ for DCL, DCM and DCH respectively. It is clarified that these values do not include the impact of the RC slabs so they are smaller than similar values published elsewhere for complete structural systems (e.g. [26]). Furthermore, these values should be treated with caution when dealing with isolated RC frames because they strongly depend on the magnitude of the applied loads and the structural layout of the building under investigation. Perhaps, a more meaningful normalization for earthquake resistant RC frames would be to divide the total environmental impact of the structural frame by its total seismic mass. In the case study under examination, the total seismic mass is 165.1t. Therefore, the environmental impacts of the RC frames per total seismic mass are equal to $43.4kgCO_2/t$, $27.2kgCO_2/t$ and $27.0kgCO_2/t$ for DCL, DCM and DCH respectively.

Fig. 4e presents the contributions of the different materials of the RC frame to the minimum CO_2 emissions. Concrete contributes the highest part with around 50% contribution in all designs. Next comes the longitudinal reinforcement and then the formwork. As described in the previous paragraph, the contribution of transverse reinforcement, despite increasing with the level of ductility class, is always minor. The contribution of steel reinforcement is highest in the case of DCL.

Furthermore, Fig. 4f presents the materials cost contributions of the minimum cost designs. It is shown that the concrete cost percentile contributions are significantly smaller than the respective CO_2 contributions and the opposite is the case for the formwork contributions. This is justified by the unit prices of the economic cost and environmental impact of the concrete and formwork shown in Table 1. Interestingly, however, the sum of the contributions of concrete and formwork, which both depend solely on the cross-sectional dimensions, is similar in minimum CO_2 and cost designs. As a result, the contribution of steel reinforcement (both longitudinal and transverse) is also equivalent in the two optimum designs.

Figs. 4g and 4h present the ratio of steel mass (kg) to the concrete volume (m^3) of the minimum CO_2 and cost design solutions respectively. This ratio is used widely in construction practice to quantify the amount of steel in concrete. It can be seen that the DCH has the highest amount of steel reinforcement per m^3 of concrete. This is mainly due to the additional transverse reinforcement required to achieve the increased level of ductility capacity. It is also interesting to observe that the m_s/V_c ratios are higher in the case of optimum CO_2 designs. This can be justified by the fact that steel is less expensive with respect to concrete in terms of CO_2 than in terms of material cost (Table 1 – Typical scenario). Therefore, the optimization solver seeks for design solutions with more amount of steel per m^3 of concrete in the case of minimum CO_2 designs. It is also worth mentioning that the variations between the design approaches are quite significant with the ratios ranging between 138kg/m^3 and 202kg/m^3.

Table 2 presents the cross-sectional dimensions of the different design solutions examined in this section. It is interesting to note that the CO_2 and cost-based designs are characterised by similar dimensions. The same holds for the DCM and DCH designs. On the other hand, the DCL solutions are using significantly larger dimensions that may cause problems to the architectural design of the building leading to additional CO_2 emissions. However, architectural design considerations are out of the scope of the present study.



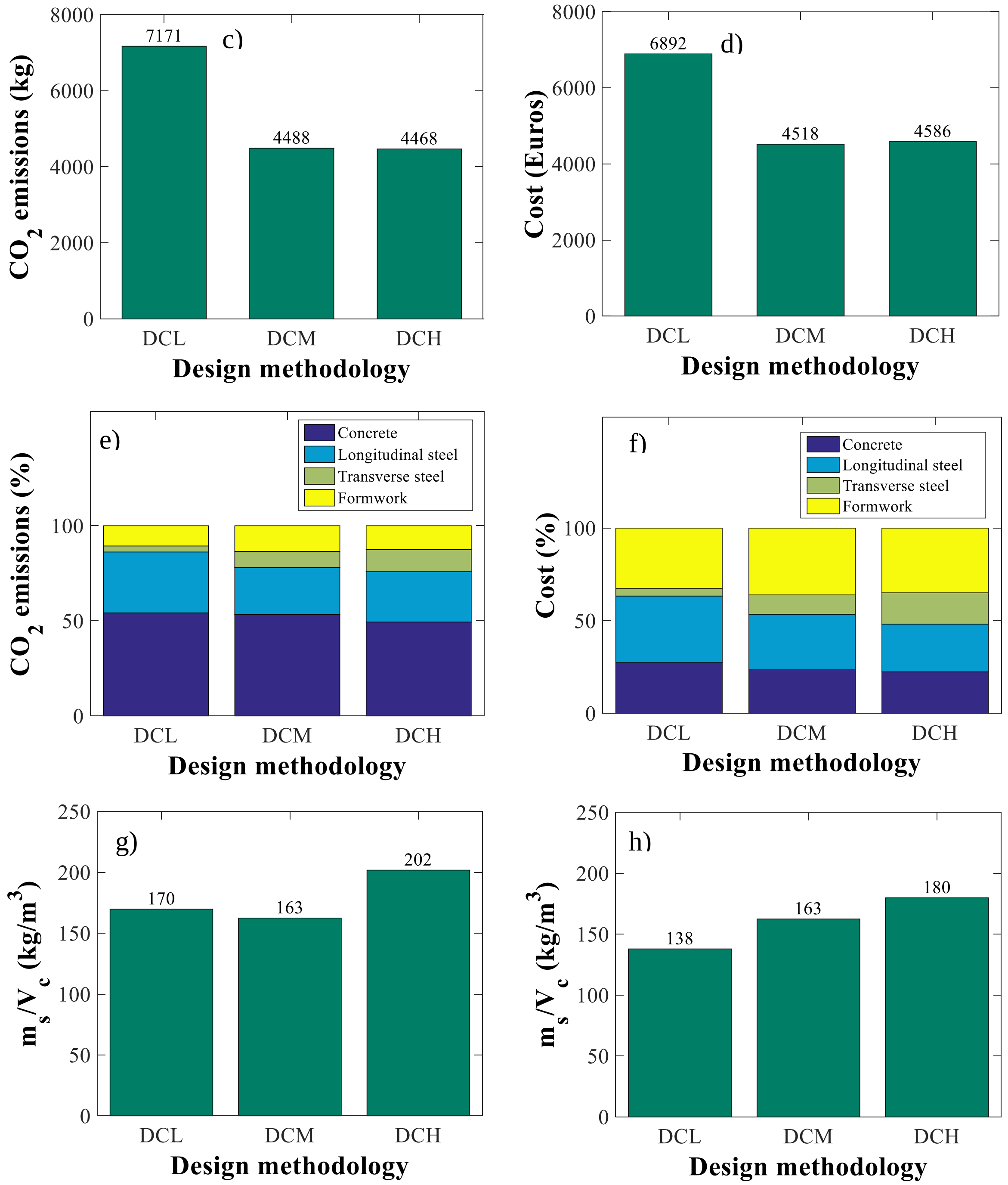


Fig. 4: Optimum designs according to different seismic design methodologies: a) optimization history of minimum CO_2 design; b) optimization history of minimum cost design; c) minimum CO_2 emissions; d) minimum costs; e) contributions to minimum CO_2 emissions; f) contributions to minimum costs; g) m_s/V_c ratios of minimum CO_2 solutions; h) m_s/V_c ratios of minimum cost solutions.

Table 2: Cross-sectional dimensions of different design solutions

Cross-sectional dimensions		$h_c = b_c$ (m)		h_b / b_b (m / m)		
Members		C1, C3, C4, C6, C7, C9	C2, C5, C8	B1, B2	B3, B4	B5, B6
Ductility Class	Design Objective					
DCL	CO_2	0.50	0.60	0.70 / 0.40	0.90 / 0.35	0.65 / 0.30
DCM	CO_2	0.45	0.45	0.65 / 0.30	0.35 / 0.30	0.40 / 0.30
DCH	CO_2	0.35	0.50	0.75 / 0.30	0.40 / 0.30	0.30 / 0.30
DCL	Cost	0.55	0.65	0.80 / 0.40	0.90 / 0.35	0.55 / 0.30
DCM	Cost	0.45	0.45	0.65 / 0.30	0.35 / 0.30	0.40 / 0.30
DCH	Cost	0.40	0.50	0.65 / 0.30	0.40 / 0.30	0.35 / 0.30

3.3 Design PGA

Herein, the RC frame of the previous section is optimally designed to all ductility classes of EC8 and for three different values of the design PGA: 0.20g, 0.30g and 0.40g representing different seismicity levels. The same material properties, costs and environmental impacts as in §3.2 are used.

Fig. 5a presents the variations of the minimum CO_2 emissions as a function of the design PGA. It can be seen that the emissions increase with the design PGA for all design methodologies. However, the rate of increase is not the same for all design approaches. More particularly, DCM and DCH emissions increase at a much smoother rate than DCL with PGA. Consequently, despite the fact that all ductility classes generate similar emissions for the low PGA value as they are governed by minimum detailing requirements, DCM and DCH produce significantly less emissions for higher PGA values. Therefore, it can be concluded that design for high ductility classes is more beneficial in regions of high seismicity than in regions of low seismicity. Fig. 5b shows the costs of the optimum cost solutions. It is evident that they display very similar trends to the optimum CO_2 values.

Figs. 5c and 5d present the contributions of concrete to the total CO_2 emissions and cost respectively for the different design PGA values. It is interesting to observe that these ratios do not vary considerably with the design PGA for all seismic design methodologies. However, they are significantly different for the two design objectives (CO_2 and cost) as discussed in the previous section.

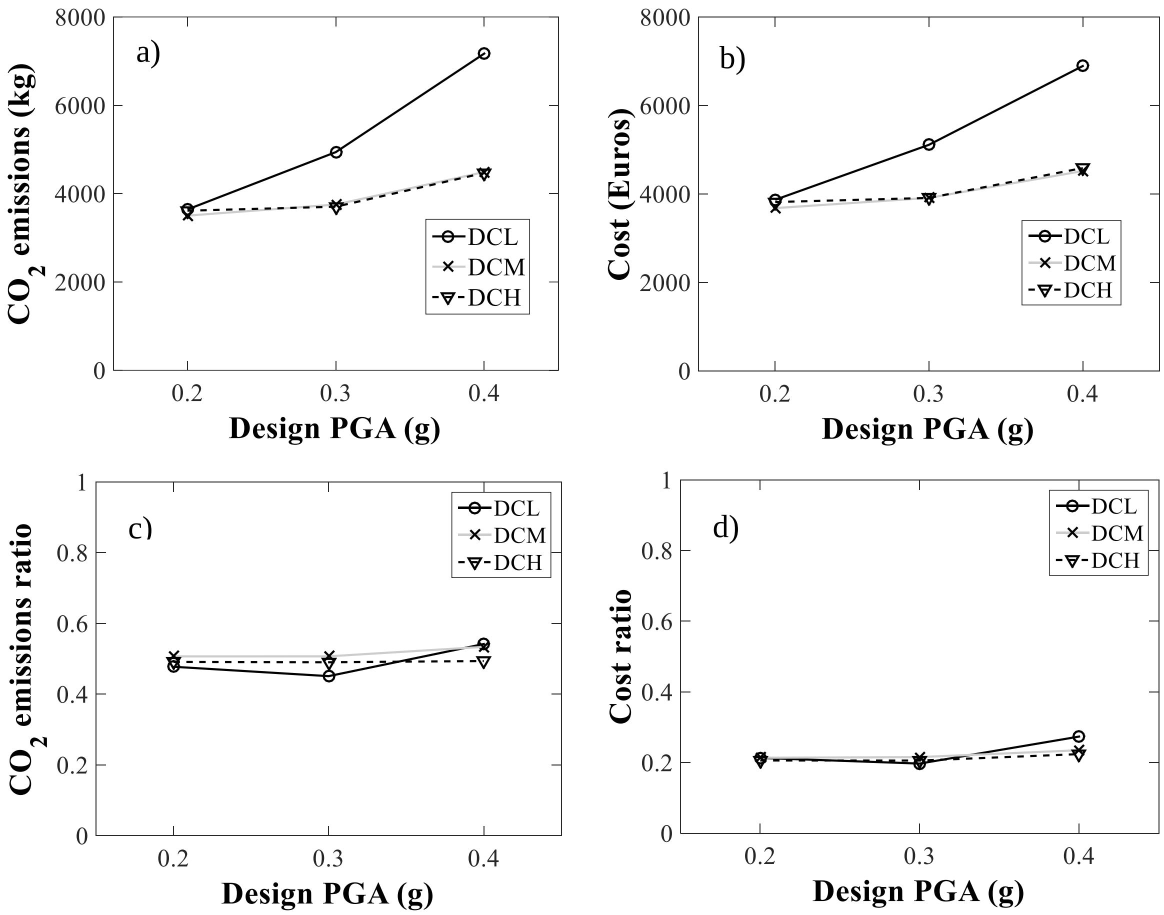


Fig. 5: Optimum designs for different design PGAs a) minimum CO_2 emissions; b) minimum costs; c) contribution of concrete to minimum CO_2 emissions; d) contribution of concrete to minimum costs.

3.4 Material embodied emissions

In this section, the influence of unit environmental impacts of concrete and reinforcing steel on the properties of the optimum design solutions is examined. To serve this goal, the ratio *R* is used herein [10]. *R* is defined as the ratio of CO_2 footprint of 100kg of reinforcing steel to the CO_2 footprint of 1m^3 of concrete. Furthermore, three different scenarios are considered regarding the combinations of environmental impacts of C25/30 concrete and B500c reinforcing steel using the values presented in Table 1: Typical concrete – typical steel impact (*R*=0.38); high concrete – low steel impact (*R*=0.13) and low concrete - high steel impact (*R*=1.25). These scenarios envelope all possible combinations of concrete and steel environmental impacts. The results presented in the following are based on the numerical examples of section §3.2, where only the unit environmental impacts of concrete and steel are altered.

Fig. 6a presents the ratio of CO_2 footprint of the minimum cost solutions over the CO_2 footprint of the respective minimum CO_2 solutions, namely r_{CO2}, for the three different environmental impact scenarios. It can be seen that this ratio ranges between 1.0 and 1.13.

This effectively means that the minimum cost designs produce up to 13% more emissions than the minimum CO_2 solutions. It is also evident that r_{CO2} is rather sensitive to R. It obtains maximum values at R=0.13 and decreases considerably up to R=0.38. After this R value, r_{CO2} remains practically constant and almost equal to 1. The latter means that the minimum CO_2 and minimum cost designs produce almost the same CO_2 emissions. It is also interesting to note that the higher r_{CO2} values are reported for DCL. This is explained by the fact that greater cross-sections are used for this ductility class due to the higher seismic design forces and because less strict detailing rules are required for this ductility class. These facts give more flexibility to the optimizer to select alternative cross-sectional solutions.

Furthermore, Fig. 6b shows the variation of the ratio r_{cost} with R. r_{cost} is the ratio of cost of the minimum CO_2 solutions over the cost of the minimum cost designs. It is seen that r_{cost} varies between 1.0 and 1.078. Therefore, the minimum CO_2 designs cost up to 8% more than the minimum cost designs. In general, similar conclusions for r_{cost} to r_{CO2} can be drawn.

So far in this study, the cost of carbon in monetary units has not been taken into account in the calculation of economic costs. In 2005, however, the European Union introduced the European Union Emissions Trading System (EU ETS) that converts CO_2 emissions into monetary values. Under the EU ETS, the European Member States allocate emissions allowances to their industrial operators, who are then able to trade them. Therefore, carbon prices are determined by the market and they are generally characterized by significant variability.

To investigate how the economic cost of carbon allowances can influence the economic comparison between minimum cost and minimum CO_2 designs, a carbon price of €8 per tonne of CO_2 emissions is used herein that is very close to the maximum carbon price of the EU ETS recorded in October 2017. Then, the total costs of the designs are calculated by adding materials costs and costs of carbon allowances. Next, the new r_{cost} ratios are calculated based on total costs. As expected, the revised r_{cost} ratios are reduced when carbon allowances are taken into account. This is due to the fact that minimum cost solutions produce more carbon emissions resulting in higher carbon costs than the minimum carbon solutions. However, these reductions are found to be negligible (e.g. the maximum r_{cost} reduces from 1.078 to 1.075). This is due to the rather small costs of carbon emissions with respect to material costs. Nevertheless, if carbon prices increase in the future then the differences are expected to be more significant.

Fig. 6c illustrates the variation of m_s/V_c ratios of the optimum CO_2 designs with R. It is shown that these ratios tend to decrease as R increases. This is expected since increase of R

means that the steel becomes more and the concrete less 'expensive' in environmental terms. Therefore, less steel and more concrete is used in the optimum design solutions. The highest variation is observed for the DCL designs, where m_s/V_c decreases by approximately 50% as R increases from 0.13 to 1.25.

Moreover, Fig. 6d shows the variation of the contribution of concrete to the total environmental impact of the minimum CO_2 designs. Clearly, the contribution of concrete decreases as R increases. This occurs because the unit environmental impact of concrete with respect to steel decreases as R increases. The decrease of m_s/V_c ratio due to R increase is not adequate to counteract this trend.

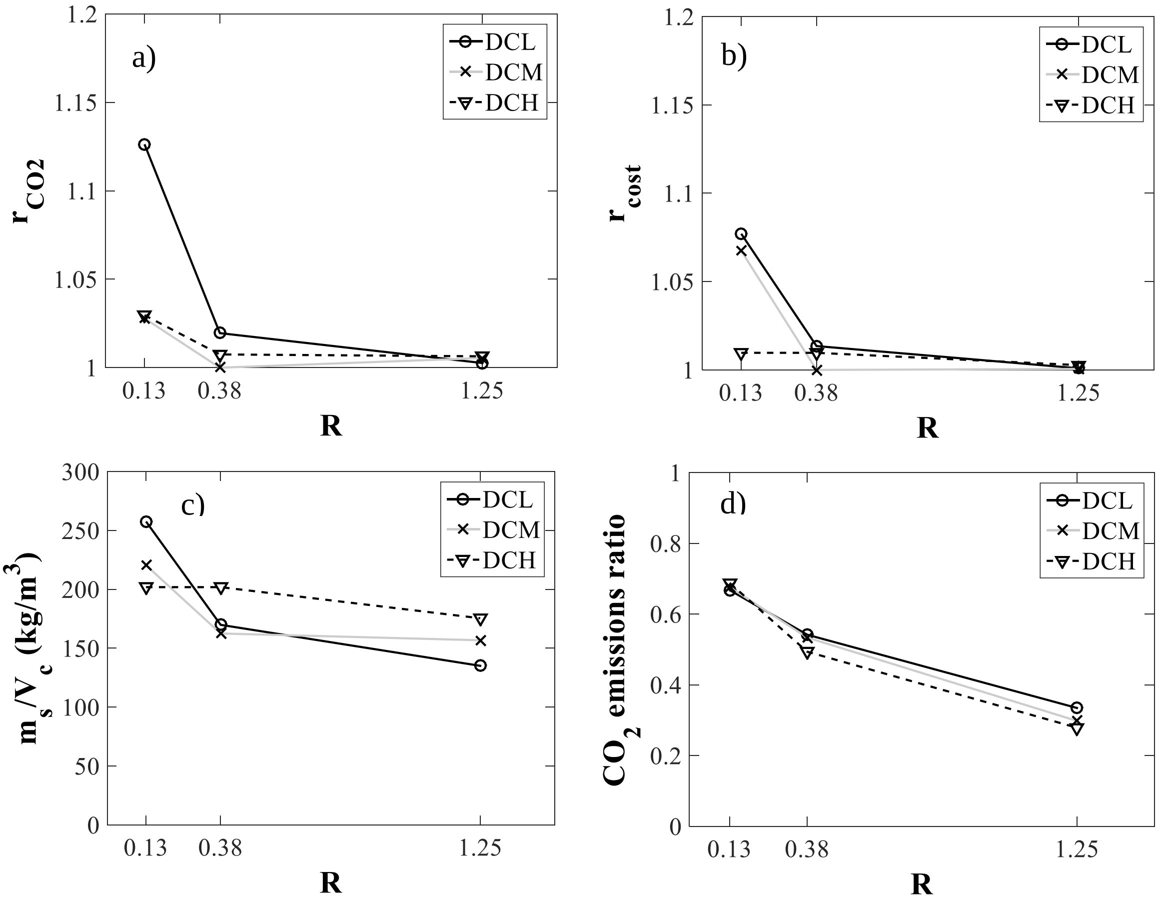


Fig. 6: Optimum CO_2-based designs for different R values a) r_{CO2}; b) r_{cost}; c) m_s/V_c ratios of minimum CO_2 solutions and d) contributions of concrete to minimum CO_2 emissions

3.5 Concrete class

Herein, the RC frame is optimally designed to all ductility classes of EC8 for 0.40g design PGA and assuming two different concrete classes: C25/30 and C32/40. In both cases, B500c reinforcing steel is used. Materials costs and CO_2 emissions are taken from Table 1 for the typical environmental impact scenarios.

Fig. 7a presents the minimum CO_2 emissions produced by all design methodologies using both concrete classes. It is evident that, in all cases, the designs with the lower concrete class (C25/30) generate less CO_2 emissions. This can be explained by the fact that the higher concrete class (C32/40) generates 16% more CO_2 emissions per m^3 than the lower one (C25/30) based on the values presented in Table 1.

Fig. 7b shows the costs of the optimum cost solutions for all design methodologies and both concrete classes. It can be seen that now the C32/40 designs require either lower or higher costs depending on the design methodology. Even in the cases of higher C32/40 costs (DCL) the differences are considerably smaller than the CO_2 emissions. At first sight, this observation seems unexpected because the cost of C32/40 is also approximately 15% higher than C25/30. However, the explanation can be given by the contributions of the different materials to CO_2 emissions and costs. As shown in Fig. 4, concrete contributes far more to total CO_2 emissions than total costs. Therefore, the increase of the unit prices of concrete has higher impact on the embodied emissions than economic cost. This impact cannot be counteracted by the reduction of steel demands due to the better mechanical properties of C32/40 apart from the case of DCH minimum cost design, where the contribution of concrete to the total cost is minor (Fig. 4f). These observations drive to the conclusion that in order to achieve less CO_2 emissions by the use of higher concrete classes the environmental impact of the latter must be decreased.

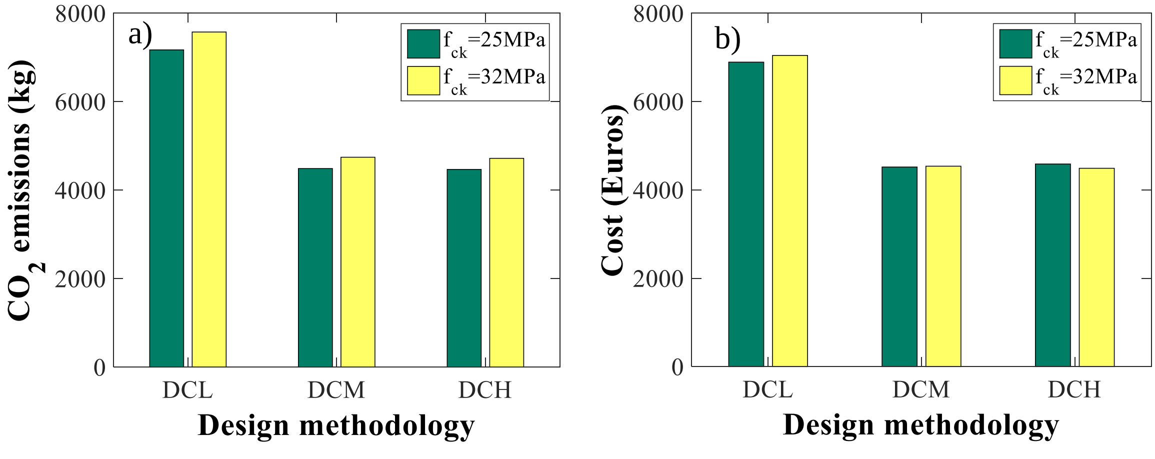


Fig. 7: Optimum designs for different concrete classes a) minimum CO_2 emissions; b) minimum costs

5 Summary and Conclusions

Reinforced concrete structures contribute significantly to global CO_2 emissions. This is mainly due to the embodied CO_2 emissions of cement and reinforcing steel. However, the environmental impact of RC structures can be drastically reduced by applying automated optimization techniques that maximize structural efficiency.

Previous studies aiming at minimizing embodied CO_2 emissions of RC structures do not consider seismic design. To fill part of this gap, this study investigates optimum seismic design of RC frames for minimum cradle to gate CO_2 emissions and compares it with minimum cost-based design. To serve this goal, a three-storey two-bay RC frame is optimally designed according to all ductility classes of EC8 for various design PGA values, concrete classes and material embodied CO_2 footprint scenarios. In total, 30 different designs of the RC frame are examined. The optimum designs are conducted by employing an optimization framework based on genetic algorithms. Ten independent GA runs are conducted for each RC frame design and the minimum objective function solution is selected. GA runs always converge to very similar solutions.

It is concluded that the adopted seismic design approach affects importantly the minimum feasible CO_2 emissions of RC frames. More particularly, in regions of high seismicity, DCM and DCH designs produce up to 60% lesser CO_2 emissions than DCL. This is due to the reduction of seismic forces via the use of the behaviour factor and the fact that the additional transverse reinforcement required does not increase significantly the embodied CO_2. As the level of seismicity decreases, however, the differences in CO_2 emissions between the optimum designs of different ductility classes tend to diminish.

It is important to clarify that the comparisons of this study examine only initial construction embodied CO_2 emissions. Environmental impacts related to repairs of damages caused by future earthquakes are not taken into consideration. The latter are expected to be higher in the cases of DCM and DCH with respect to DCL. Therefore, an extension of the present optimization framework to account for life-cycle embodied CO_2 emissions is interesting as it could modify the conclusions of the present study.

The concrete class also affects minimum CO_2 emissions in seismic design of RC frames. It is found that higher concrete classes, despite their better mechanical properties, lead to higher CO_2 emissions due to their higher unit embodied impact. However, the differences in CO_2 emissions between the optimum designs with different concrete classes are rather small.

Furthermore, it is observed that the differences between the optimum design solutions depend considerably on the ratio R of the unit environmental footprint of reinforcing steel to the respective footprint of concrete. More specifically, for medium to high values of R (R=0.38-1.25), it is found that the minimum CO_2 designs are very closely related to the minimum cost design solutions. This is a positive conclusion because both objectives should be considered in the design procedure. However, for low *R* values (*R*=0.13), it is observed that the minimum cost solutions generate up to 13% more emissions than the CO_2-based designs. The latter can be up to 8% more expensive than the minimum cost design solutions. It is worth mentioning herein that, with current carbon prices, carbon economic cost seems to have a negligible effect on the cost comparisons of minimum cost and CO_2 design solutions.

Regarding the amount of steel per m^3 of concrete in the minimum CO_2 designs, it is found that it varies for the different ductility classes and it decreases importantly as the unit environmental impact of reinforcing steel increases and/or the unit impact of concrete decreases.

For the contributions of the different materials, it is shown that formwork contributes the least to the CO_2 emissions of the optimum solutions. Interestingly, the respective contribution of concrete is similar for the different ductility classes and levels of the design PGA. However, it depends strongly on the unit environmental impacts of concrete and steel. It is found that for $R \leq 0.38$ concrete contributes more than 50% to the total CO_2 emissions.

Closing, it is emphasized that only cradle to gate embodied CO_2 emissions are addressed in this study. A holistic, cradle to grave, approach that considers also operational and end of life environmental impacts is necessary to get the full picture of life-cycle CO_2 emissions of RC buildings. The latter approach should be incorporated in a future extension of the proposed optimization framework.

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