Contribution to sustainable seismic design of reinforced concrete members through embodied CO_2 emissions optimization

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Abstract. *The embodied CO_2 emissions of reinforced concrete (RC) structures can be significantly reduced by structural optimization that maximizes structural efficiency. Previous studies dealing with design of RC structures for minimum CO_2 emissions do not address seismic design provisions. This is the case despite the fact that in many countries around the world, including most of the top-10 countries in CO_2 emissions from cement production, RC structures have to be designed against earthquake hazard. To fill a part of this gap, this study, using exhaustive search, examines optimum designs of RC beam and column members for minimum embodied CO_2 emissions according to Eurocode-8 for all ductility classes and compares them with optimum designs based on material cost. It is shown that seismic designs for minimum CO_2 footprint lead to less CO_2 emissions but are more expensive than minimum cost designs. Their differences strongly depend on the assumed values of the environmental impact of reinforcing steel and concrete materials. Furthermore, it is concluded that seismic design for high ductility classes can drive to significant reductions in embodied CO_2 emissions.*

Keywords: Sustainable, environmental, embodied, CO_2 emissions, optimization, seismic design, reinforced concrete, Eurocodes

Running Head: Sustainable seismic design of concrete members

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1 Introduction

Sustainable development is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs. To meet this aspiration, strong actions are required to support the three diverse and sometimes conflicting pillars of sustainability: environmental, economic and social [1].

Climate change is one of the most important threats to sustainable development in the 21st century. It is expected to slow down economic growth, impact human health and increase risks from climate-related natural hazards [2]. Anthropogenic greenhouse gas (GHG) emissions have been the dominant cause of the observed climate change [2]. The built environment is one of the main contributors of GHG emissions [3].

Reinforced concrete (RC) is ubiquitous in the built environment. Its environmental impact consists of embodied emissions of reinforcing steel and concrete. Embodied emissions of reinforcing steel are related to the energy used to melt scrap metal and reform it [1]. Embodied emissions of concrete are attributed mostly to cement production. Cement emissions are generated by fuel combustion and carbon oxidation during clinker production. It is estimated that cement is responsible for roughly 8% of global CO_2 emissions) [4].

Clearly, embodied CO_2 emissions of reinforced concrete can be reduced by recycling or using novel materials such as low carbon cements and clinker substitutes [1]. In addition, structural optimization methodologies can be applied to maximize material efficiency and minimize the environmental impact of RC structures.

A significant number of research studies focus on optimum design of RC structures for minimum environmental impacts. Yeo & Gabbai [5] investigated optimum designs of RC beams for minimum embodied energy. They concluded that optimization 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 cost-optimized members. They also find that the exact reduction depends strongly on the cost ratio of steel reinforcement to concrete. Medeiros and Kripka [6] 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 footprints and they are 1% more expensive than minimum cost-based designs. Furthermore, studies [7-9] comparing optimum designs of RC frames for minimum CO_2 footprint and construction cost report that the former lead to 4-15% less CO_2 emissions than then latter. They also conclude that the actual reductions depend on the cost and environmental impact ratios of reinforcing steel to concrete materials [9].

All previous studies do not consider seismic design of RC structures. 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) [4], RC structures need to be designed against earthquake hazard. Optimum seismic design of RC structures has been the focus of several research studies especially the last two decades. An overview to structural seismic design optimization frameworks can be found in Fragiadakis and Lagaros [10]. Early efforts to optimise earthquake resistant structures were based on traditional seismic design approaches. More recent studies investigate optimum performance-based seismic design (PBSD) methodologies that provide better control of structural damage [11-14]. The author [15] developed optimum seismic designs of RC frames according to traditional [16] and PBSD methodologies [17]. It is found that PBSD provides always better damage control and it is significantly less expensive in regions of low to moderate seismicity. However, it is accompanied by significant computational cost that it could undermine the optimization procedure.

All previous optimum seismic design studies set construction or life-cycle costs as design objectives. Indeed, the environmental impact of RC structures designed for seismic resistance has very little been explored. Hossain and Gencturk [18] developed a detailed framework for the assessment of the life-cycle environmental impact of RC buildings accounting also for the emissions produced for repairing RC members after damaging earthquakes. Tapia and Padgett [19] 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.

It can be concluded from the previous discussion that optimum seismic design of RC structures for minimum embodied environmental impact has very little been explored. To fill a part of this gap, this study develops seismic designs of RC beam and column members for minimum cradle to site CO_2 emissions and compares them with optimum designs based on material cost. The aim is to investigate good practices for minimizing embodied CO_2 emissions in seismic design of RC members and examine the trade-offs between cost and environmental impact of seismically designed RC members. In this manner, the environmental and economic pillars of sustainability in the context of seismic design of RC members are properly addressed. Furthermore, the developed framework can be extended to deal explicitly with the social requirement of sustainable design by using appropriate methods to assess the social impact of RC members [20].

2 Optimum design of reinforced concrete members according to Eurocodes

2.1 Optimization problem formulation and solution algorithm

A single-objective optimization problem with discrete design variables is generally formulated as:

Minimize: $F_{tot}(\boldsymbol{x})$

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

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 problem, $F_{tot}(\boldsymbol{x})$ represents the objective function of the optimization problem. The vector $\boldsymbol{x}$ is the design solution and contains n number of independent design variables x_i (i=1 to n). Design variables x_i take values from discrete sets of values $\boldsymbol{D}_i=(d_{i1}, d_{i2}, \dots, d_{iki})$, 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 allowable discrete values of x_i. Furthermore, the solution should be subject to m number of constraints $g_j(\boldsymbol{x})\le 0$ (j=1 to m). In the subsequent sections, the objective function, design variables and design constraints in the context of the optimum seismic design of RC members are specified in detail.

Different algorithms exist to solve the afore-described optimization problem. These can be divided in two categories: gradient-based and metaheuristic such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO) and many others [21]. Alternatively, exhaustive search can be employed that examines all possible combinations of design variables and finds the combination that satisfies all design constraints and minimizes the objective function. Clearly, this is the least efficient method in terms of computational cost. Nevertheless, exhaustive search is adopted in this study because it is guaranteed to track global optima and it is computationally affordable for small scale optimization problems.

2.2 Objective function

In optimization of RC members, typically, the objective function $F_{tot}(\boldsymbol{x})$ is set to be the total material economic cost $C_{tot}(\boldsymbol{x})$. Alternatively, the goal of the optimization solution can be the minimization of the total embodied CO_2 emissions $E_{tot}(\boldsymbol{x})$. In both cases, the objective function is taken as the sum of the corresponding contributions of concrete $F_c(\boldsymbol{x})$, steel $F_s(\boldsymbol{x})$ and formwork $F_f(\boldsymbol{x})$. Hence, it is written as follows:

$$F_{tot}(\boldsymbol{x}) = F_c(\boldsymbol{x}) + F_s(\boldsymbol{x}) + F_f(\boldsymbol{x}) \rightarrow F_{tot}(\boldsymbol{x}) = V_c(\boldsymbol{x}) \cdot F_{co} + m_s(\boldsymbol{x}) \cdot F_{so} + A_f(\boldsymbol{x}) \cdot F_{fo} \quad (2)$$

In Eq. (2), 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. F_{co}, F_{so} and F_{fo} are the unit prices of the materials. If the material unit economic costs (expressed in Euros per material unit quantities) are used as unit prices (see columns 2-3 of Table 1), then Eq. (2) yields the total economic cost (i.e. $F_{tot}(\boldsymbol{x})=C_{tot}(\boldsymbol{x})$). Alternatively, if the material unit environmental impacts (expressed in $kgCO_2$ per material unit quantities) are used (see columns 4-7 of Table 1), then Eq. (2) calculates the total embodied CO_2 emissions (i.e. $F_{tot}(\boldsymbol{x})=E_{tot}(\boldsymbol{x})$). Furthermore, $F_s(\boldsymbol{x})$ can be taken as the sum of the contributions of longitudinal $F_{sl}(\boldsymbol{x})$ and transversal $F_{sw}(\boldsymbol{x})$ steel reinforcement.

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 [22]. The unit environmental impact values of concrete and steel are taken from [23]. This study reports typical cradle to site embodied CO_2 emissions and the range (low to high) of their possible values considering different material production practices. The value of E_{fo} is taken from [7].

Table 1: Material unit costs and environmental impacts

Material	Economic Unit Cost	Units	Environmental Unit Impact			Units
			Low	Typical	High	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Concrete C25/30	101.0	(€/m^3)	142.0	228.0	319.0	(CO_2Kg/m^3)
Steel B500c	1.07	(€/kg)	0.43	0.87	1.77	(CO_2kg/kg)

Formwork	15.7	(€/m^2)	8.9 for columns; 3.1 for beams	(CO_2Kg/m^2)

2.3 Design parameters and variables

In optimization problems, the input data are divided in design parameters that keep constant values and design variables that change during the optimization solution. Herein, design parameters are the RC members' material properties, length *L*, concrete cover and end forces as shown in Fig. 1. For simplicity and to focus on seismic effects, antisymmetric member end forces and no element distributed loads are assumed in this study.

Furthermore, design variables are the cross-sectional characteristics shown again in Fig. 1. Rectangular beam sections and square column sections are examined in this study. Beam section design variables (Fig. 1a) are the height h_b and width b_b, the diameter d_{bb} and number of main bars n_b at the top and the bottom (assumed the same due to antisymmetric loading conditions), the diameter d_{bwb}, spacing s_b and number of legs n_{wb} of transverse reinforcement parallel to beam section height.

Square column section design variables (Fig. 1b) are the height (and width) h_c, the diameter d_{bc} and number n_c of main bars per side, assumed herein the same for all column section sides for simplicity, the diameter d_{bwc}, spacing s_c and number of legs n_{wc} of transverse reinforcement assumed again the same in both column section directions for simplification purposes.

In addition, it is assumed that the design variables take values from discrete values sets in accordance with construction practice. Section dimensions h_c, b_c, h_b, b_b take values multiples of 50mm starting from 300mm. Numbers of main bars n_c, n_b, and legs of shear reinforcement n_{wc} and n_{wb} take any integer value greater than one. Transverse reinforcement spacing s_c and/or s_b take values between 80mm and 300m with a step of 20mm. Longitudinal bar diameters d_{bc}, d_{bb} take values from (12, 14, 16, 18, 20, 25)mm and transversal bar diameters d_{bwc}, and d_{bwb} from (8, 10, 12)mm discrete values sets.

Generally, three different section properties per RC member are used. Two for the member critical end regions and one section for the rest part of the member. However, due to the assumed antisymmetric response, the same design variables for the two end sections are used. Furthermore, for simplicity reasons, it is assumed that the end and intermediate sections have the same design variables apart from the spacing of the transverse reinforcement. The latter is taken different to account for the more demanding detailing and seismic design requirements in the end regions of RC members. In total, 8 independent design variables for beams and 7 variables for columns are used in this study.

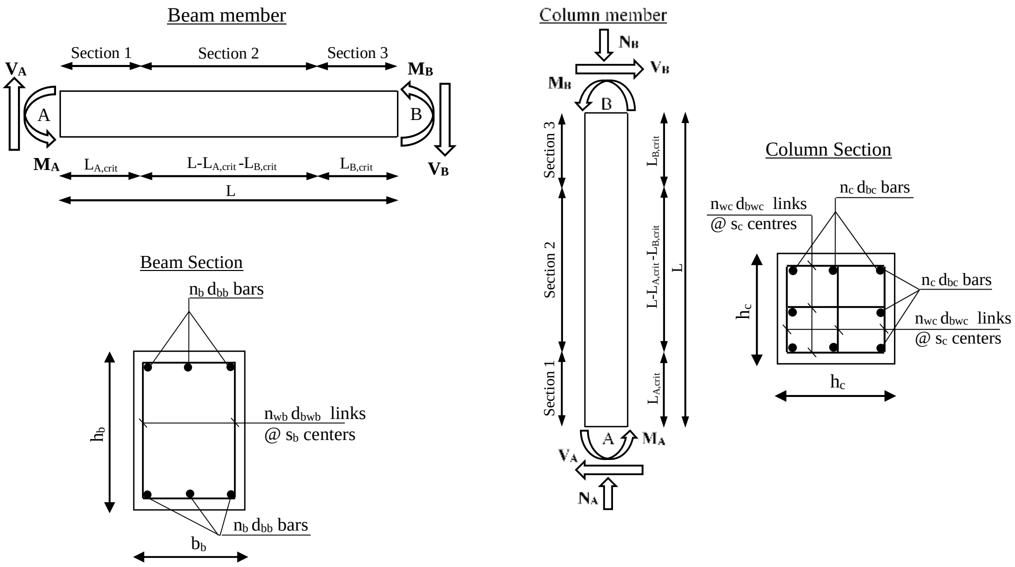


Fig. 1: Design variables: a) column members; b) beam members

2.4 Design constraints

Design constraints are defined herein in accordance with the requirements of Eurocode-2 (EC2) [24] and Eurocode-8 (EC8) [16]. It is recalled that seismic design to EC8 can be performed either without provisions for energy dissipation and ductility (Ductility Class Low – DCL) or with provisions for energy dissipation and ductility (Ductility Classes Medium and

High – DCM and DCH). DCM and DCH allow for smaller seismic loads compared to DCL, but require more demanding rules for increasing ductility capacities.

Generally, structural design constraints $g_j(\boldsymbol{x})$ can be classified into Engineering Demand Parameter (*EDP*) and Structural Design Parameter (*SDP*) constraints. The first category represents the requirement that *EDPs* (i.e. forces, displacements, rotations, drifts) remain below a capacity value EDP_{cap}. In this study, *EDPs* are the internal forces at member ends. End moments M_A and M_B (Fig. 1) are treated as known (design parameters). For DCL, shear forces are calculated by equilibrium using end moments M_A and M_B. For DCM and DCH, the capacity design shear forces are used in accordance with EC8 provisions to preclude brittle shear failures. Corresponding capacities EDP_{cap} are calculated by using characteristic material strengths divided by partial safety factors equal to γ_c=1.50 for concrete and γ_s=1.15 for reinforcing steel and using standard EC8 procedures. For bending moments of column members, moment capacities are calculated for the axial load demand under examination.

SDPs are parameters related to the detailing of structural design solutions. *SDPs* can either be design variables themselves (e.g. cross-sectional dimensions, steel bar diameters) or simple functions of design variables like the volumetric ratios of steel reinforcement. Two cases of *SDP* constraints are possible. In the first case, a *SDP* should be smaller than or equal to a maximum permissible value SDP_{max}. In the second case, a *SDP* should be greater than or equal to a minimum permissible value SDP_{min}. In this study, all member *SDP* constraints reflecting detailing provisions of both EC2 and EC8 are taken into consideration. A detailed description of these constraints can be found in [15].

It is noted that consideration of the design constraints is straightforward in the framework of the exhaustive search optimization algorithm used in this study. More specifically, the design solutions that do not satisfy all design constraints are branded as unfeasible and are simply disregarded in the optimization solution.

3 Numerical examples

This section presents numerical applications of the optimum seismic design methodology of RC members described above. One beam and one column member are examined. In both cases, concrete class C25/30 with characteristic strength f_{ck}=25MPa and reinforcing steel B500c with characteristic strength f_{yk}=500MPa for the longitudinal and transversal reinforcement are used. The concrete cover is 0.03m. The beam member has length of L=5m and it is subjected to antisymmetric end moments with magnitude M_{sd}=300kNm. The column member has length of L=3m and it is subjected to antisymmetric end moments M_{sd}=500kN and compressive axial load N_{sd}=500kN. Shear forces are calculated according to §2.4. The RC members are designed according to EC8 for all ductility classes. The cost of concrete C25/30 and steel B500c are taken from Table 1. The environmental impacts are taken from the same table following the typical scenario for both materials. Exhaustive search is used to find the optimum solutions as described in §2.1.

Tables 2 and 3 present the characteristics of the optimum design solutions of the beam and column RC members designed for all ductility classes either for minimum cost or for minimum environmental impact. Apart from cross-sectional dimensions, the longitudinal reinforcement volumetric ratio per side ρ_l, the volumetric ratio of transverse steel parallel to the shear force ρ_w inside and outside the critical end regions, the material contributions to environmental impact and the total environmental impact and cost are presented.

Observing the properties of the optimum solutions, a number of conclusions can be extracted. It can be seen that sectional dimensions are smaller for the minimum CO_2 emissions with respect to the minimum cost solutions. The opposite is the case for the longitudinal reinforcement ratios. As a result, the environmental impact contributions of concrete and framework are smaller and the contribution of longitudinal steel higher for the CO_2 based solutions. This can be attributed to the fact that the assumed environmental impact ratio of concrete to steel is higher than the respective cost ratio. Therefore, it is less efficient to use concrete in terms of environmental impact with respect to economic cost. This conclusion is also verified by the fact that the steel mass to concrete volume m_s/V_c ratio, used widely in construction industry to quantify the amount of steel in concrete, is significantly higher in the case of minimum CO_2 solutions.

It is also shown that the CO_2 based solutions lead to savings in total CO_2 emissions but are more expensive than the minimum cost solutions. However, the differences are rather small. If r_{CO2} is defined as the ratio of CO_2 emissions of the minimum cost designs over the emissions of the minimum CO_2 designs then it is found that r_{CO2} ranges between 1.01 and 1.11 for both RC members and all ductility classes. This effectively means that the optimum cost solutions generate 1-11% more CO_2 emissions than the CO_2 based solutions. Similarly, if r_{cost} is the ratio of the cost of the minimum CO_2 designs with respect to the cost of the minimum cost designs then it is obtained that r_{cost} ranges between 1.01 and 1.05. This means that the minimum CO_2 designs are 1-5% more expensive than the minimum cost design solutions.

It is also evident that the volumetric ratios of the transverse reinforcement in the critical end regions increase as the ductility level increases. As a result, the environmental impact of transverse reinforcement is higher in the case of DCM and DCH with respect to DCL driving to higher total environmental impacts of these two ductility classes for the same M_{sd} values. However, the relative contribution of transverse reinforcement to the total environmental impact is rather small (2-9%) and the total environmental impacts of the different ductility classes are very close.

Table 2: Optimum beam solutions characteristics

Ductility Class	Design Objective	h_b	b_b	ρ_l	$\rho_{w,in}$	$\rho_{w,out}$	$\frac{E_c}{E_{tot}}$	$\frac{E_{sl}}{E_{tot}}$	$\frac{E_{sw}}{E_{tot}}$	$\frac{E_f}{E_{tot}}$	$\frac{m_s}{V_c}$	E_{tot}	C_{tot}
		m	m	%	%	%	-	-	-	-	kg/m^3	CO_2Kg	€
DCL	min Cost	0.55	0.30	0.92	0.11	0.11	0.58	0.32	0.03	0.08	156.1	327.0	354.5

DCL	min CO_2	0.45	0.30	1.49	0.11	0.11	0.48	0.43	0.02	0.07	245.8	322.0	363.4
DCM	min Cost	0.55	0.30	0.92	0.28	0.11	0.57	0.32	0.03	0.08	159.8	329.7	357.9
DCM	min CO_2	0.40	0.30	1.90	0.33	0.13	0.42	0.48	0.03	0.07	316.3	324.2	373.6
DCH	min Cost	0.55	0.30	0.92	0.28	0.11	0.57	0.31	0.04	0.08	161.7	331.0	359.5
DCH	min CO_2	0.40	0.30	1.90	0.42	0.15	0.42	0.48	0.04	0.07	322.3	327.4	377.4

Table 3: Optimum square column solutions characteristics

Ductility Class	Design Objective	h_c	ρ_l	$\rho_{w,in}$	$\rho_{w,out}$	$\frac{E_c}{E_{tot}}$	$\frac{E_{sl}}{E_{tot}}$	$\frac{E_{sw}}{E_{tot}}$	$\frac{E_f}{E_{tot}}$	$\frac{m_s}{V_c}$	E_{tot}	C_{tot}
		m	%	%	%	-	-	-	-	kg/m^3	CO_2Kg	€
DCL	min Cost	0.50	0.62	0.14	0.14	0.49	0.32	0.04	0.15	193.5	350.9	325.2
DCL	min CO_2	0.45	0.91	0.19	0.19	0.41	0.41	0.04	0.14	287.4	338.8	332.9
DCM	min Cost	0.55	0.50	0.23	0.12	0.54	0.25	0.05	0.15	144.8	380.2	335.9
DCM	min CO_2	0.45	0.91	0.33	0.19	0.40	0.41	0.05	0.14	295.3	343.0	338.1
DCH	min Cost	0.50	0.79	0.33	0.20	0.46	0.32	0.07	0.14	227.4	373.1	352.4
DCH	min CO_2	0.45	0.91	0.56	0.22	0.39	0.39	0.09	0.13	320.8	356.5	354.6

4 Parametric study

This section examines the effects of different design parameters on the optimum seismic design solutions of RC members. More particularly, the effects of M_{sd} and the material unit costs and environmental impacts are investigated. The numerical examples presented in section §3 serve as the basis of the parametric studies of this section.

4.1 Design bending moment M_{sd}

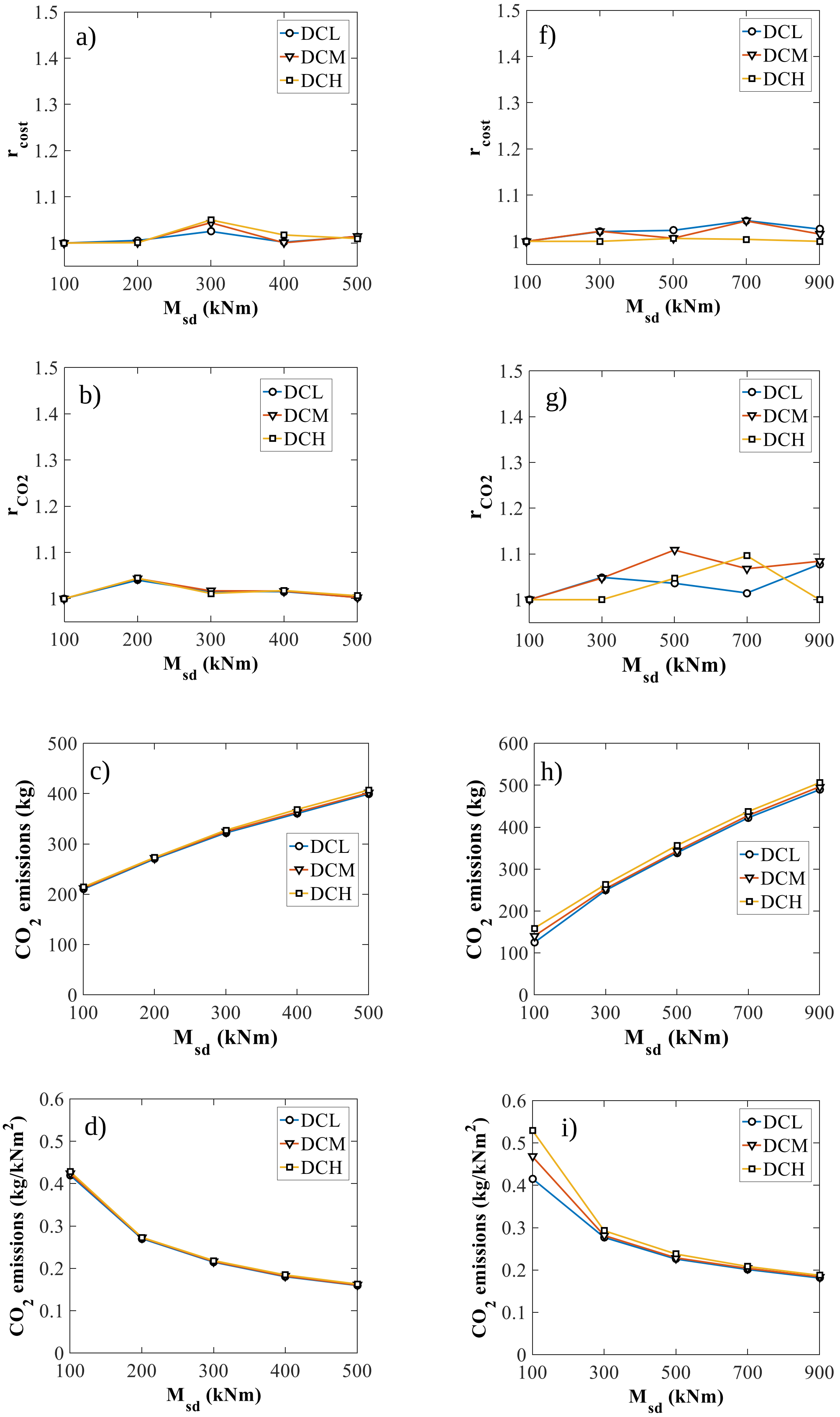
This section investigates the effects of M_{sd} on the optimum beam and column seismic design solutions. The following M_{sd} values M_{sd}=100, 200, 300, 400 and 500kNm for the beam and M_{sd}=100, 300, 500, 700 and 900kNm for the column RC members are examined. All other design parameters of section §3 remain unchanged.

As illustrated in Fig. 2, the r_{cost} and r_{CO2} ratios vary slightly with M_{sd}. r_{cost} varies between 1 and 1.05 and r_{CO2} between 1 and 1.11 for both the beam and column designs. These variations do not seem to follow a specific trend and they should be attributed to the discrete nature of the design variables adopted in this study. Interestingly, for the minimum M_{sd} values, all ratios are equal to unity. This is the case because the optimum cost and CO_2 designs are the same as both are governed by the minimum detailing requirements.

Regarding the minimum embodied CO_2 emissions, it can be seen that they increase sharply with M_{sd}. The rate of emissions increase slightly decreases as M_{sd} increases. For the same M_{sd} values, the DCH solutions produce the highest and the DCL the lowest CO_2 emissions. This could be attributed to the higher transverse reinforcement requirements of the former optimum designs. However, the differences between the ductility classes are almost negligible because transverse reinforcement does not contribute significantly to the total CO_2 emissions. Taking into consideration the fact that M_{sd} values are importantly reduced when designing for higher ductility classes (in the order of 2-4 times), it can be concluded that seismic design for higher ductility classes may lead to important savings in CO_2 emissions.

When CO_2 emissions are normalized to the product $M_{sd}{\cdot}L$, the normalized values in ($kgCO_2/kNm^2$) decrease as M_{sd} increases. Furthermore, the normalized values tend to stabilize for high M_{sd} values. This drives to the conclusion that designs for smaller M_{sd} values are less efficient in terms of environmental impact per unit seismic design moment. This is especially the case for M_{sd} values close to zero where minimum detailing requirements govern the design solutions.

Regarding the ratio m_s/V_c of the minimum CO_2 solutions, it increases for small but it becomes almost constant for higher M_{sd} values. Generally, the DCH solutions demonstrated the highest m_s/V_c ratios, for a given M_{sd} value, followed by the DCM optimum designs.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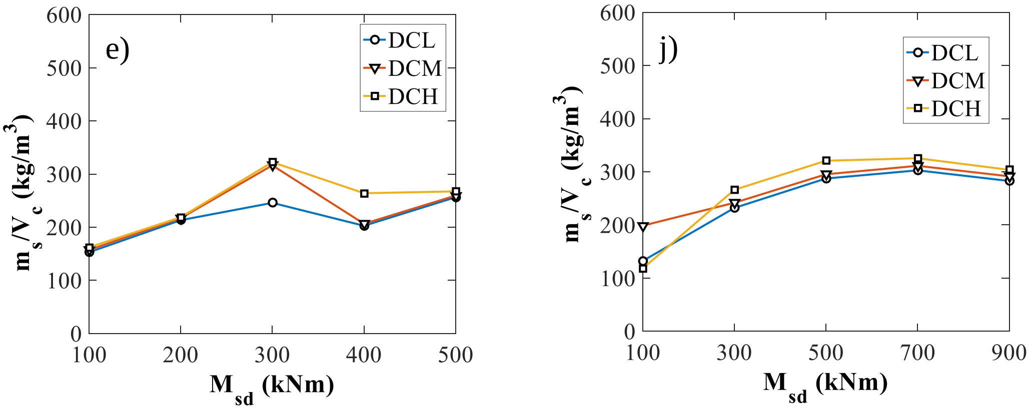


Fig. 2: Variation of optimum solution properties with M_{sd} for: a-e) beam; f-j) column RC members

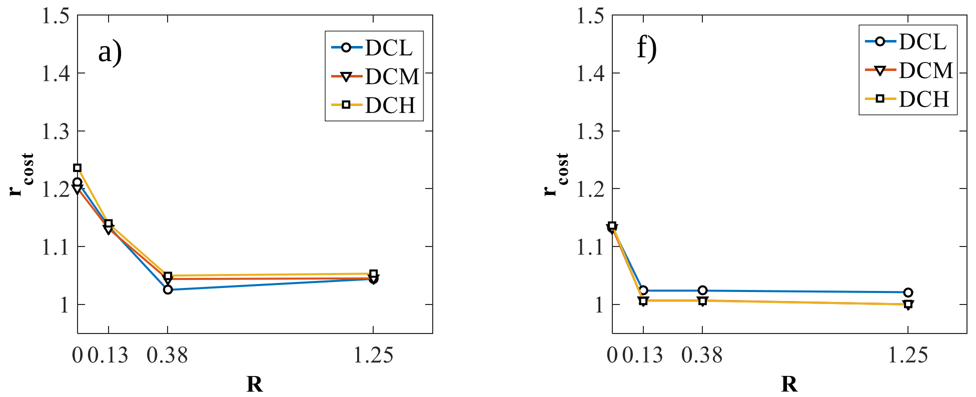
4.2 CO_2 emissions of reinforcing steel and concrete materials

To investigate the influence of the unit environmental impacts of concrete and reinforcing steel on the properties of the optimum solutions, the ratio *R* is used in this study [5]. *R* is defined as the ratio of the CO_2 footprint of 100kg of reinforcement steel to the CO_2 footprint of concrete per m^3. Next, three different scenarios are examined with regards to the combinations of environmental impacts of C25/30 concrete and reinforcing steel based on 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). Furthermore, to consider the fact that values of reinforcement steel CO_2 emissions even smaller than the low limit given in [23] have been reported in literature [9, 25] a scenario with high concrete CO_2 impact and zero reinforcing steel CO_2 footprint (R=0) is also examined herein. The latest scenario is used to envelope all scenarios with R<0.13. The results presented in the following are based on the numerical examples of section §3, where only the unit environmental impacts of concrete and steel are altered.

As shown in Fig. 3, the ratios r_{cost} and r_{CO2} vary significantly with *R*. r_{cost} varies between 1 and 1.24 and r_{CO2} between 1 and 1.55 for both the beam and column designs. The highest values are observed for R=0, followed by R=0.13 (high concrete - low steel impact scenario). For example, for R=0.13, the minimum cost column design for DCM produces 27% more emissions than the respective minimum CO_2 design. This difference is rather important and should be taken into consideration in optimum seismic design of RC members. It is also interesting to note that r_{cost} and r_{CO2} vary sharply between R=0 and R=0.38 but they change slightly between R=0.38 and R=1.25. Similar conclusions hold for all ductility classes.

Regarding the minimum embodied CO_2 emissions, it can be deducted that they become maximum in the R=1.25 (high concrete – low steel impact) scenario. In all cases, DCH designs produce the most CO_2 emissions followed by DCM. It is interesting to note that the differences in CO_2 emissions between ductility classes increase as R increases. This becomes more evident in Figs (5d, 5i) that present the ratios of CO_2 emissions of ductility classes DCM and DCH to DCL for the beam and column RC members respectively. These ratios increase as R increases. This is attributed to the fact that DCM and DCH require more transverse reinforcement and the environmental impact of steel increases as R increases.

Furthermore, the ratios m_s/V_c of the minimum CO_2 solutions decrease sharply as R increases. This is justified by the fact that the concrete becomes less and steel more expensive in terms of environmental impact as R increases. Therefore, more concrete and less steel are preferred in the optimum solutions as R increases.



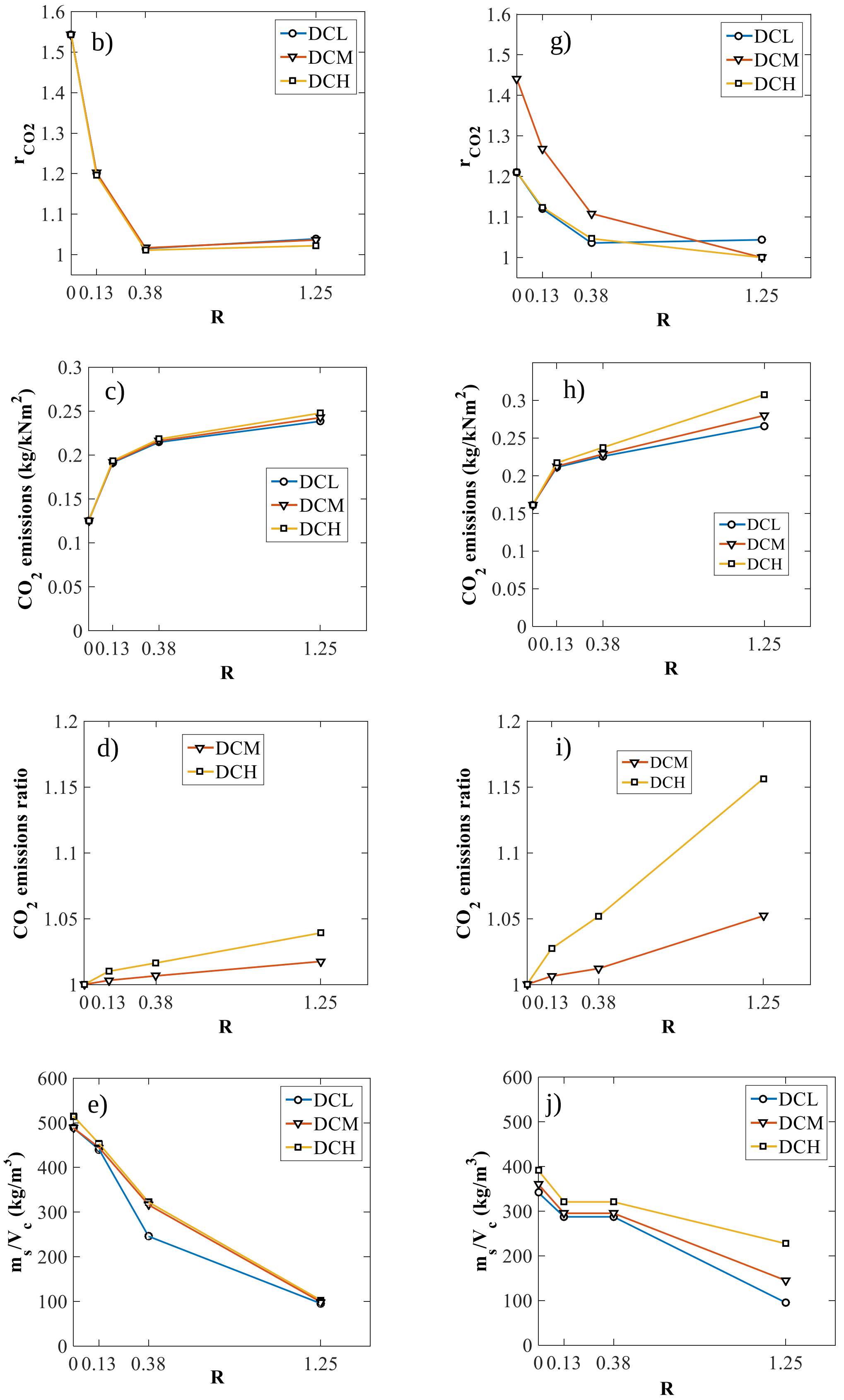


Fig. 3: Variation of optimum solution properties with *R* for: a-e) beam; f-j) column RC members

5 Summary and Conclusions

Reinforced concrete members are major contributors of CO_2 emissions. Their environmental impact can be reduced by recycling or using novel materials. Alternatively, structural optimization can be employed that maximizes material efficiency and minimizes embodied CO_2 emissions.

Previous studies dealing with structural design of RC structures for minimum CO_2 emissions do not address seismic design. This study examines optimum seismic designs of RC beam and column members for minimum embodied CO_2 emissions in accordance with EC8 provisions for all ductility classes.

For the typical concrete and reinforcing steel environmental impact scenarios, it is found that the optimum CO_2 solutions have smaller cross-sectional dimensions and larger longitudinal steel reinforcement and m_s/V_c ratios than the minimum cost designs. It is also shown that the CO_2 based solutions lead to additional reductions in total CO_2 emissions but are more expensive than the minimum cost solutions for the same seismic forces. Nevertheless, the differences are rather small and the ratios r_{cost} and r_{CO2} range roughly between 1.0 and 1.1. This effectively means that the optimum CO_2 designs perform well in terms of economic cost and vice versa. The previous conclusion is not the case, however, for the high concrete – low reinforcing steel impact scenario, where r_{cost} may take values up to 1.25 and r_{CO2} up to 1.55.

Comparing the minimum CO_2 designs of different ductility classes, it is observed that they differ mainly in the transverse reinforcement requirements in the critical end regions, which increase as the level of ductility class increases. Therefore, DCM and DCH designs produce more CO_2 emissions than DCL for the same seismic moments. However, the contribution of transverse reinforcement to the total CO_2 emissions is rather small. Hence, the differences in total CO_2 emissions between ductility classes are minor. Considering that M_{sd} values are importantly decreased when designing for higher ductility classes and that CO_2 emissions sharply increase with M_{sd} values, it can be concluded that seismic design for high ductility may drive to important reductions in embodied CO_2 emissions.

Regarding the m_s/V_c ratios of the optimum CO_2 design solutions, they decrease sharply with the R ratio because the relative cost of steel increases. On the other hand, they are not very sensitive to the applied M_{sd} values. More particularly, they increase with M_{sd} for small M_{sd} values but they tend to stabilize for higher M_{sd} values.

All previous conclusions hold for individual RC beams and column members. Unarguably, future research is required to examine whether these conclusions can be extended to the seismic design of complete RC frames and, more generally, different types of RC structures.

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