



# City Research Online

## City St George's, University of London

**Citation:** Mergos, P.E. (2018). Contribution to sustainable seismic design of reinforced concrete members through embodied CO2 emissions optimization. *Structural Concrete*, 19(2), pp. 454-462. doi: 10.1002/suco.201700064

This is the accepted version of the paper.

This version of the publication may differ from the final published version. To cite this item please consult the publisher's version.

**Permanent repository link:** <https://openaccess.city.ac.uk/id/eprint/18081/>

**Link to published version:** <https://doi.org/10.1002/suco.201700064>

**Copyright and Reuse:** Copyright and Moral Rights remain with the author(s) and/or copyright holders. Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, unless otherwise indicated, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way. For full details of reuse please refer to [City Research Online policy](#).

# Contribution to sustainable seismic design of reinforced concrete members through embodied CO<sub>2</sub> emissions optimization

Panagiotis E. Mergos \*

*Research Centre for Civil Engineering Structures, Department of Civil Engineering, City,  
University of London, London EC1V 0HB, United Kingdom*

**Abstract.** *The embodied CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> footprint lead to less CO<sub>2</sub> 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<sub>2</sub> emissions.*

**Keywords:** Sustainable, environmental, embodied, CO<sub>2</sub> emissions, optimization, seismic design, reinforced concrete, Eurocodes

**Running Head:** Sustainable seismic design of concrete members

---

\* Corresponding author. Panagiotis E. Mergos, Lecturer in Structural Engineering, Research Centre for Civil Engineering Structures, City, University of London, London, EC1V 0HB, UK.  
E-mail address: [panagiotis.mergos.1@city.ac.uk](mailto:panagiotis.mergos.1@city.ac.uk), Tel. 0044 (0) 207040 8417

## **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 21<sup>st</sup> 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<sub>2</sub> emissions) [4].

Clearly, embodied CO<sub>2</sub> 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<sub>2</sub> emissions. They found that designs for minimum CO<sub>2</sub> emissions produce 1% less CO<sub>2</sub> 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<sub>2</sub> footprint and construction cost report that the former lead to 4-15% less CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions and compares them with optimum designs based on material cost. The aim is to investigate good practices for minimizing embodied CO<sub>2</sub> 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:  $F_{tot}(\mathbf{x})$

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

Where:

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

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

In this problem,  $F_{tot}(\mathbf{x})$  represents the objective function of the optimization problem. The vector  $\mathbf{x}$  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  $D_i=(d_{i1}, d_{i2}, \dots, d_{ik_i})$ , 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  $g_j(\mathbf{x}) \leq 0$  ( $j=1$  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  $F_{tot}(\mathbf{x})$  is set to be the total material economic cost  $C_{tot}(\mathbf{x})$ . Alternatively, the goal of the optimization solution can be the

minimization of the total embodied CO<sub>2</sub> emissions  $E_{tot}(\mathbf{x})$ . In both cases, the objective function is taken as the sum of the corresponding contributions of concrete  $F_c(\mathbf{x})$ , steel  $F_s(\mathbf{x})$  and formwork  $F_f(\mathbf{x})$ . Hence, it is written as follows:

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

In Eq. (2),  $V_c$  (m<sup>3</sup>) is the concrete volume,  $m_s$  (kg) the mass of steel reinforcement and  $A_f$  (m<sup>2</sup>) 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.  $F_{tot}(\mathbf{x})=C_{tot}(\mathbf{x})$ ). Alternatively, if the material unit environmental impacts (expressed in kgCO<sub>2</sub> per material unit quantities) are used (see columns 4-7 of Table 1), then Eq. (2) calculates the total embodied CO<sub>2</sub> emissions (i.e.  $F_{tot}(\mathbf{x})=E_{tot}(\mathbf{x})$ ). Furthermore,  $F_s(\mathbf{x})$  can be taken as the sum of the contributions of longitudinal  $F_{sl}(\mathbf{x})$  and transversal  $F_{sw}(\mathbf{x})$  steel reinforcement.

Table 1 presents the unit prices adopted in this study for the economic cost and CO<sub>2</sub> 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<sub>2</sub> 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 <sup>3</sup> )	142.0	228.0	319.0	(CO <sub>2</sub> kg/m <sup>3</sup> )
Steel B500c	1.07	(€/kg)	0.43	0.87	1.77	(CO <sub>2</sub> kg/kg)

Formwork	15.7	(€/m <sup>2</sup> )	8.9 for columns; 3.1 for beams	(CO <sub>2</sub> Kg/m <sup>2</sup> )
----------	------	---------------------	--------------------------------	--------------------------------------

### 2.3 Design parameters and variables

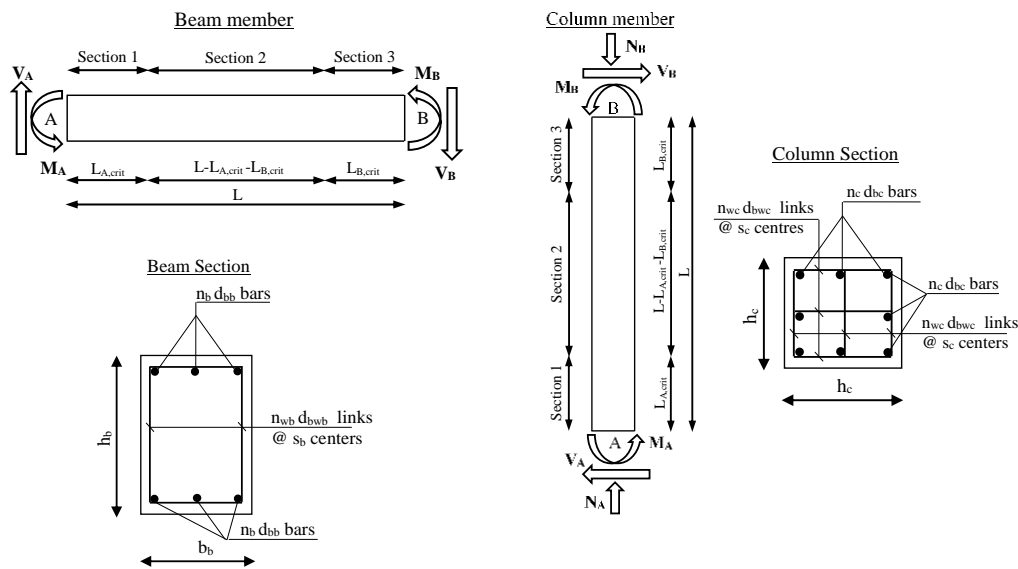
In optimization problems, the input data are divided in design parameters that keep constant values and design variables that change during the optimization solution. Herein, design parameters are the RC members' material properties, length  $L$ , concrete cover and end forces as shown in Fig. 1. For 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  $g_j(\mathbf{x})$  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  $\gamma_c=1.50$  for concrete and  $\gamma_s=1.15$  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  $f_{ck}=25\text{MPa}$  and reinforcing steel B500c with characteristic strength  $f_{yk}=500\text{MPa}$  for the longitudinal and transversal reinforcement are used. The concrete cover is 0.03m. The beam member has length of  $L=5\text{m}$  and it is subjected to antisymmetric end moments with magnitude  $M_{sd}=300\text{kNm}$ . The column member has length of  $L=3\text{m}$  and it is subjected to antisymmetric end moments  $M_{sd}=500\text{kN}$  and compressive axial load  $N_{sd}=500\text{kN}$ . 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  $\rho_l$ , the volumetric ratio of transverse steel parallel to the shear force  $\rho_w$  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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> solutions.

It is also shown that the CO<sub>2</sub> based solutions lead to savings in total CO<sub>2</sub> emissions but are more expensive than the minimum cost solutions. However, the differences are rather small. If  $r_{CO_2}$  is defined as the ratio of CO<sub>2</sub> emissions of the minimum cost designs over the emissions of the minimum CO<sub>2</sub> designs then it is found that  $r_{CO_2}$  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<sub>2</sub> emissions than the CO<sub>2</sub> based solutions. Similarly, if  $r_{cost}$  is the ratio of the cost of the minimum CO<sub>2</sub> 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<sub>2</sub> 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	$h_b$	$b_b$	$\rho_l$	$\rho_{w,in}$	$\rho_{w,out}$	$\frac{E_c}{E_{tot}}$	$\frac{E_{sl}}{E_{tot}}$	$\frac{E_{sw}}{E_{tot}}$	$\frac{E_f}{E_{tot}}$	$\frac{m_s}{V_c}$	$E_{tot}$	$C_{tot}$
		m	m	%	%	%	-	-	-	-	kg/m <sup>3</sup>	CO <sub>2</sub> Kg	€
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 <sub>2</sub>	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 <sub>2</sub>	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 <sub>2</sub>	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	$h_c$	$\rho_l$	$\rho_{w,in}$	$\rho_{w,out}$	$\frac{E_c}{E_{tot}}$	$\frac{E_{sl}}{E_{tot}}$	$\frac{E_{sw}}{E_{tot}}$	$\frac{E_f}{E_{tot}}$	$\frac{m_s}{V_c}$	$E_{tot}$	$C_{tot}$
		m	%	%	%	-	-	-	-	kg/m <sup>3</sup>	CO <sub>2</sub> Kg	€
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 <sub>2</sub>	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 <sub>2</sub>	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 <sub>2</sub>	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 $M_{sd}$

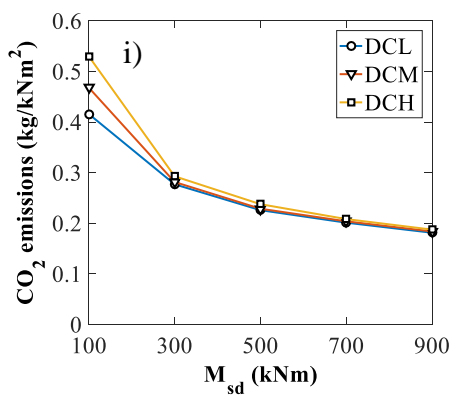
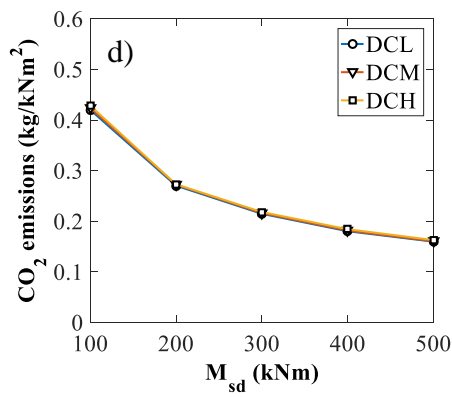
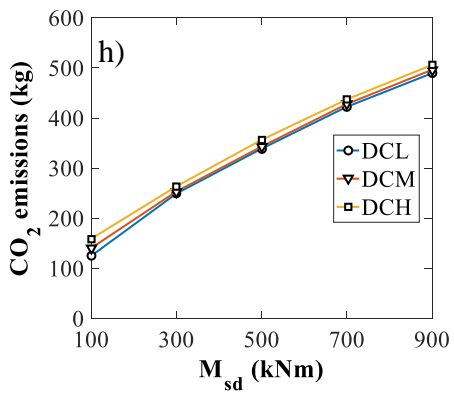
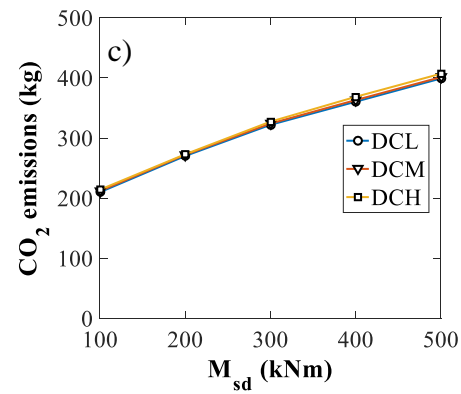
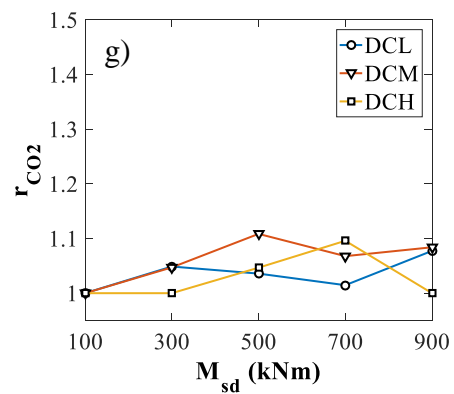
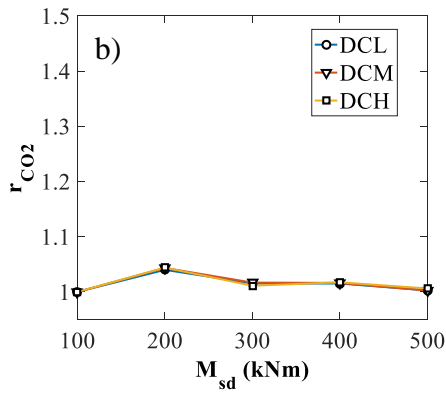
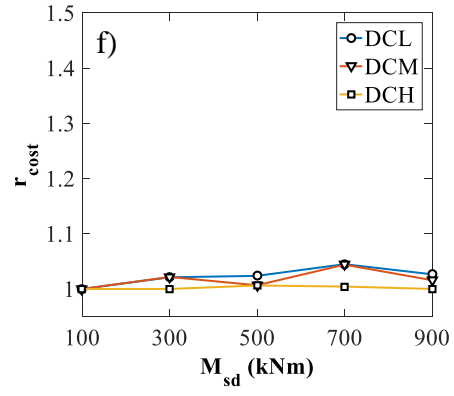
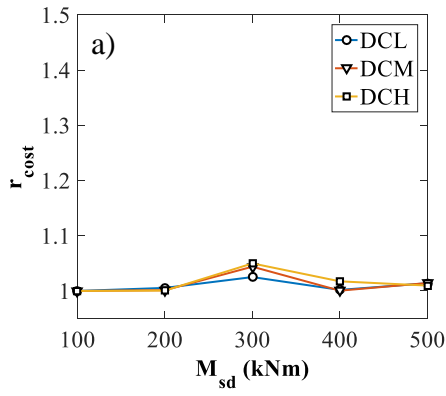
This section investigates the effects of  $M_{sd}$  on the optimum beam and column seismic design solutions. The following  $M_{sd}$  values  $M_{sd}=100, 200, 300, 400$  and  $500\text{kNm}$  for the beam and  $M_{sd}=100, 300, 500, 700$  and  $900\text{kNm}$  for the column RC members are examined.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

As illustrated in Fig. 2, the  $r_{cost}$  and  $r_{CO_2}$  ratios vary slightly with  $M_{sd}$ .  $r_{cost}$  varies between 1 and 1.05 and  $r_{CO_2}$  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<sub>2</sub> designs are the same as both are governed by the minimum detailing requirements.

Regarding the minimum embodied CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions.

When CO<sub>2</sub> emissions are normalized to the product  $M_{sd} \cdot L$ , the normalized values in (kgCO<sub>2</sub>/kNm<sup>2</sup>) 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<sub>2</sub> 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.



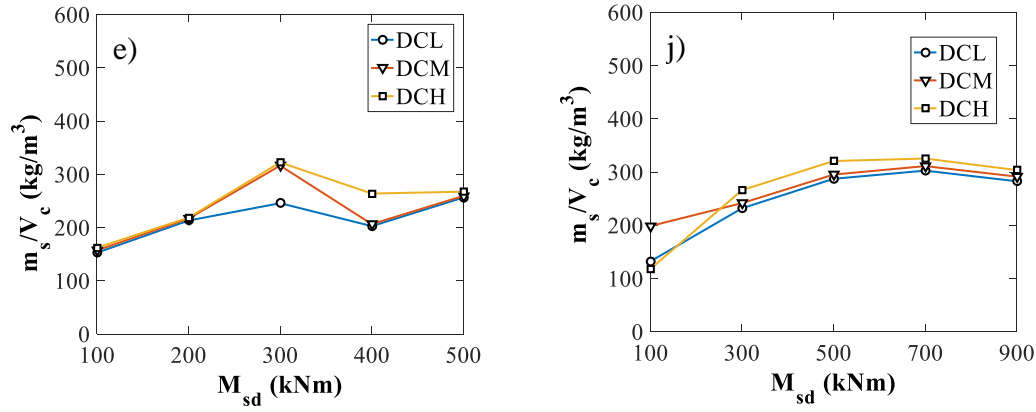


Fig. 2: Variation of optimum solution properties with  $M_{sd}$  for: a-e) beam; f-j) column RC members

#### 4.2 CO<sub>2</sub> emissions of reinforcing steel and concrete materials

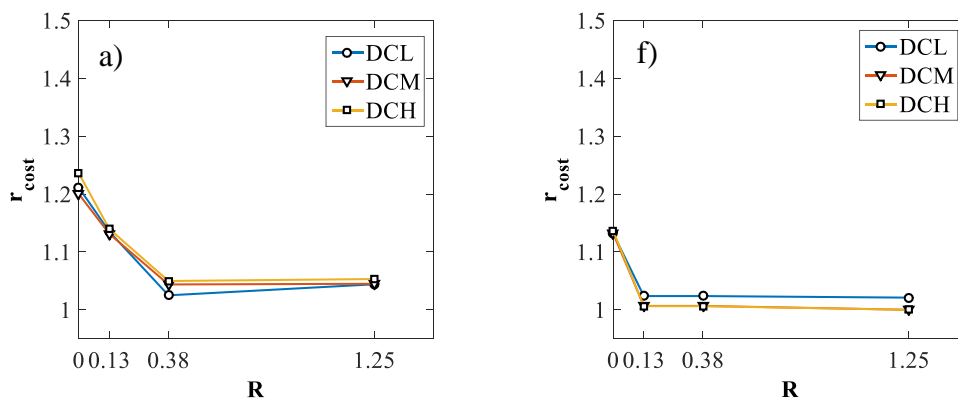
To investigate the influence of the unit environmental impacts of concrete and reinforcing steel on the properties of the optimum solutions, the ratio  $R$  is used in this study [5].  $R$  is defined as the ratio of the CO<sub>2</sub> footprint of 100kg of reinforcement steel to the CO<sub>2</sub> footprint of concrete per m<sup>3</sup>. 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<sub>2</sub> emissions even smaller than the low limit given in [23] have been reported in literature [9, 25] a scenario with high concrete CO<sub>2</sub> impact and zero reinforcing steel CO<sub>2</sub> 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.

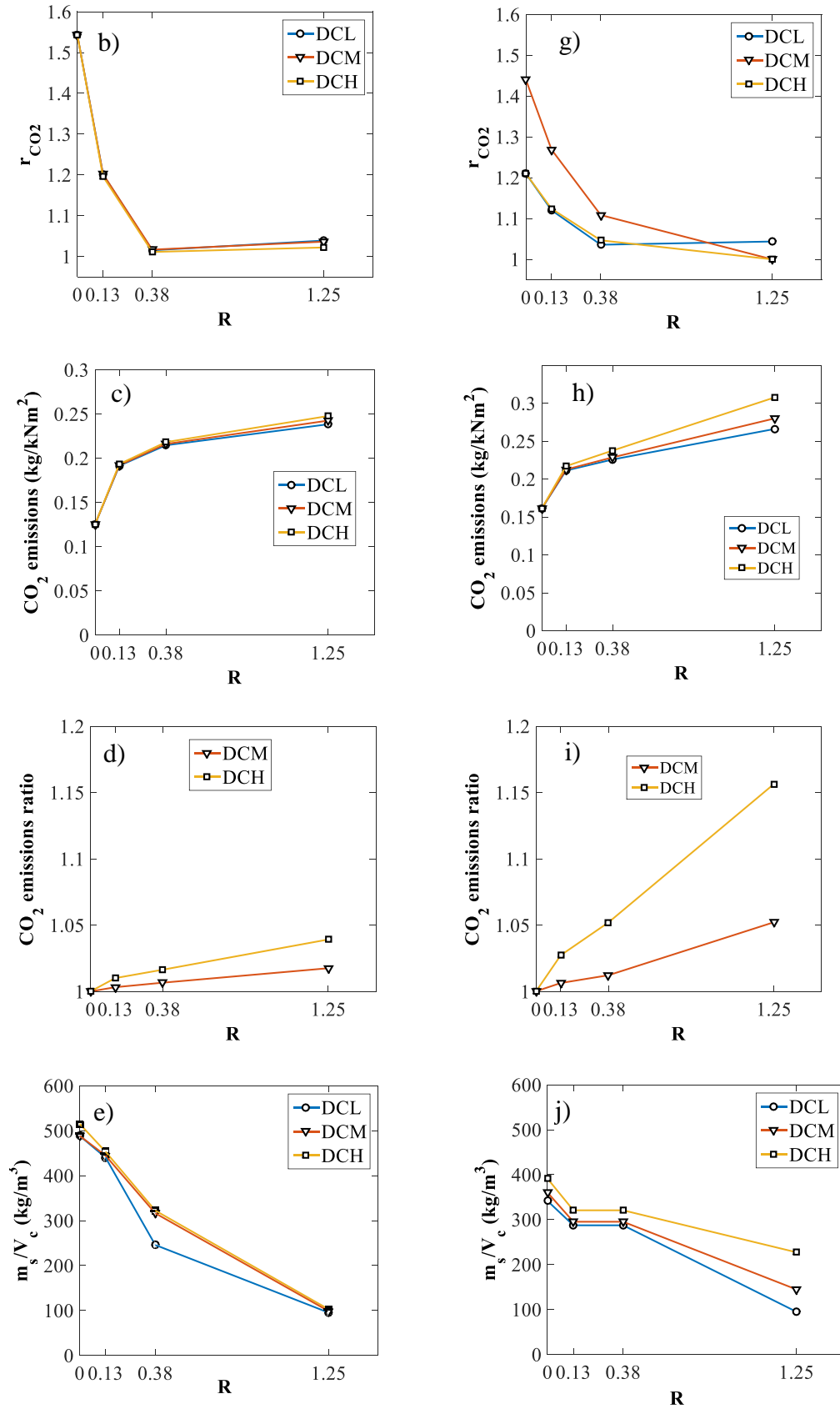
As shown in Fig. 3, the ratios  $r_{cost}$  and  $r_{CO2}$  vary significantly with  $R$ .  $r_{cost}$  varies between 1 and 1.24 and  $r_{CO2}$  between 1 and 1.55 for both the beam and column designs. The highest

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  $r_{CO_2}$  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 deduced 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<sub>2</sub> 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<sub>2</sub> emissions.

Previous studies dealing with structural design of RC structures for minimum CO<sub>2</sub> emissions do not address seismic design. This study examines optimum seismic designs of RC beam and column members for minimum embodied CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> based solutions lead to additional reductions in total CO<sub>2</sub> 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  $r_{CO_2}$  range roughly between 1.0 and 1.1. This effectively means that the optimum CO<sub>2</sub> 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  $r_{CO_2}$  up to 1.55.

Comparing the minimum CO<sub>2</sub> 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<sub>2</sub> emissions than DCL for the same seismic moments. However, the contribution of transverse reinforcement to the total CO<sub>2</sub> emissions is rather small. Hence, the differences in total CO<sub>2</sub> emissions between ductility classes are minor. Considering that  $M_{sd}$  values are importantly decreased when designing for higher ductility classes and that CO<sub>2</sub> 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<sub>2</sub> emissions.

Regarding the  $m_s/V_c$  ratios of the optimum CO<sub>2</sub> 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.

## References

- [1] Georgopoulos, C. & Minson, A. (2014). *Sustainable concrete solutions*. John Wiley and Sons, Oxford.
- [2] Intergovernmental panel on climate change (IPCC) (2014). *Climate change 2014: Synthesis report*. Technical Report, Geneva, Switzerland.
- [3] Green Construction Board (2016). *Low carbon routemap for the UK built environment*. Technical Report, London, UK.
- [4] Olivier, J.G.J. *et al.* (2015). *Trends in global CO<sub>2</sub> emissions: 2015 Report*. Joint Research Centre, Hague, Netherlands.
- [5] Yeo, D. & Gabbai, R. (2011). Sustainable design of reinforced concrete structures through embodied energy optimization. *Energy and Buildings*, 43, 2028-2033.
- [6] Medeiros, G. & Kripka, M. (2014). Optimization of reinforced concrete columns according to different environmental impact assessment parameters. *Engineering Structures*, 59, 185-194.
- [7] Paya-Zaforteza, I., Yepes, V., Hospitaler, A., Gonzalez-Vidoso, F. (2009). CO<sub>2</sub>-optimization of reinforced concrete frames by simulated annealing. *Engineering Structures*, 31, 1501-1508.

- [8] Camp, C., Huq, F. (2013). CO<sub>2</sub> and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm. *Engineering Structures*, 48, 363-372.
- [9] Yeo, D. & Potra, F. (2015). Sustainable design of reinforced concrete structures through CO<sub>2</sub> emission optimization. *ASCE Journal of Structural Engineering*, 141, B4014002, 1:7.
- [10] Fragiadakis, M., Lagaros, N.D. (2011). An overview to structural seismic design optimisation frameworks. *Computers and Structures*, 89, 1155-1165.
- [11] Ganzerli, S., Pantelides, C.P., Reaveley, L.D. (2000). Performance-based design using structural optimization. *Earthquake Engineering and Structural Dynamics*, 29, 1677-1690.
- [12] Chan, C.M., Zou, X.K. (2004). Elastic and inelastic drift performance optimization for reinforced concrete buildings under earthquake loads. *Earthquake Engineering and Structural Dynamics*, 33, 929–950.
- [13] Lagaros, N.D. & Papadrakakis, M. (2007). Seismic design of RC structures: A critical assessment in the framework of multi-objective optimization. *Earthquake Engineering and Structural Dynamics*, 36, 1623-1639.
- [14] Fragiadakis, M., Papadrakakis, M. (2008). Performance-based optimum seismic design of reinforced concrete structures. *Earthquake Engineering and Structural Dynamics*, 37, 825-844.
- [15] Mergos, P.E. (2016). Optimum seismic design of reinforced concrete frames according to Eurocode 8 and *fib* Model Code 2010. *Earthquake Engineering and Structural Dynamics*, 46, 1181-1201.
- [16] CEN: EN 1998-1. Eurocode 8. *Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings*. Comité Européen de Normalisation, Brussels; 2004.
- [17] *fib*. *fib Model Code for Concrete Structures*. Berlin, Ernst & Sohn; 2010.

- [18] Hossain, K., Gencturk, B. (2014). Life-cycle environmental impact assessment of RC buildings subjected to natural hazards. *ASCE Journal of Architectural Engineering*, A4014001, 1-12.
- [19] Tapia, C. & Padgett, J.E. (2016). Multi-objective optimisation of bridge retrofit and post-event repair selection to enhance sustainability. *Structure and Infrastructure Engineering*, 12, 93-107.
- [20] Pons, O., Fuente, A. (2013). Integrated sustainability assessment method applied to structural concrete columns. *Construction and Building Materials*, 49, 882-893.
- [21] Lagaros, N.D. (2013). A general purpose real-world structural design optimization computing platform. *Journal of Structural and Multidisciplinary Optimization*, 49, 1047-1066.
- [22] Hellenic Ministry of Public Works (2013), *Readjustment and completion of invoices of public works*. Technical Report, Athens, Greece.
- [23] Kaethner, S.C., Burrige, J.A. (2012). Embodied CO<sub>2</sub> of structural frames. *Structural Engineer*, 90, 33-40.
- [24] CEN: EN 1992-1-1. Eurocode 2. *Design of concrete structures. Part 1-1: General rules and rules for buildings*. Comité Européen de Normalisation, Brussels; 2000.
- [25] Alcorn, A. (2003). *Embodied energy and CO<sub>2</sub> coefficients for NZ building materials*. Centre for Building Performance Research, Victoria University Wellington, Wellington.

