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DUCTILITY, PERFORMANCE AND CONSTRUCTION COST OF R/C BUILDINGS DESIGNED TO EUROCODE 8

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Abstract: This paper evaluates three, regular and irregular, reinforced concrete (RC) buildings designed to Eurocode 8 (EC8) for a peak ground acceleration ranging from 0.16-0.36g in terms of their respective seismic performance and construction cost as a function of their Ductility Class. The structures are alternatively designed for two classes of medium and high ductility (DCM and DCH) and two values of the behaviour factor *q* (q_{min}, q_{max}). The structural, non-structural and overall construction cost is comparatively assessed and the performance of the alternative designs is further assessed through nonlinear static (i.e., pushover) analysis according to EC8-Part 3. It is shown that the decisions made on the Ductility Class adopted have higher financial impact on irregular buildings, however, this influence is smoothed in terms of total construction cost. It is also shown that the building performance is primarily affected by the decisions made regarding the behaviour factor used in design and to a lesser extent on the Ductility Class itself.

Introduction

Modern seismic code provisions for buildings rely on energy dissipation through inelastic deformations during the design earthquake due to the necessity to compromise life safety requirements with economic considerations. To avoid demanding nonlinear analysis in the framework of everyday design purposes, an equivalent lateral load or modal response spectrum analysis is permitted, using spectral accelerations that result from a response spectrum, appropriately reduced by a, so called, behaviour factor (*q* in Europe) or force reduction factor (*R* in the U.S.). Ultimately, the structural system is designed for a lower level of strength, relying that stable energy absorption will be made feasible through specific geometric and minimum reinforcement requirements along with the associated detailing rules. Fundamental requirements (i.e. collapse prevention, damage limitation, minimum level of serviceability) are also achieved through capacity design for the enhancement of global ductility. According to Eurocode 8 (CEN 2004) in particular, the above philosophy is materialised for reinforced concrete buildings through the choice of the Ductility Class, i.e., Low (DCL), Medium (DCM) and High (DCH), each corresponding to different structural and detailing requirements. Notably, the Lower ductility class is only recommended by National Annexes in low seismicity areas or for base-isolated structures.

Clearly, the choice of the ductility class might affect the cross-sections of the structural members, loads and action effects (through both the modification of response spectrum and dynamic characteristics), as well as numerous design parameters, which not only lead to a diversified seismic behaviour of the structure, but are also often counteracting in terms of economic impact. In simple terms, the adoption of DCH is indeed associated with a lower level of seismic forces through the typically higher permissible values of the behaviour factor q, at least for identical structural systems with similar levels of regularity. On the other hand, high ductility objectives are inevitably related to more strict reinforcement and detailing rules thus yielding the cost-efficiency of the overall design quite unpredictable.

Several studies have comparatively assessed the performance of buildings designed to EC8 for different ductility classes (Fardis 2009; Booth 2012; Fardis et al. 2012) often further

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investigating the associated construction cost. The majority of these studies assess the inelastic behaviour of frame (Panagiotakos and Fardis 2004; Athanassiadou 2008) or both frame and dual (Kappos 1998; Kappos and Antoniadis 2007) earthquake resisting structural systems. This assessment is typically performed in-plane with only few exceptions (Anagnostopoulou et al. 2012). The main outcome of this research is that even in cases where large differences are indeed observed in material quantities and detailing for the alternative design approaches, this did not translate into remarkable differences in structural performance. Other studies (Carvalho et al. 1996) revealed that a difference was detected in the longitudinal-to-transverse steel ratio, which was found to depend primarily on the structural system, with a ratio fluctuation from 75%-25% for DCM, 60%-40% for DCH frame systems and a rather stable ratio for wall systems. However, the total material quantities (steel and concrete) required were approximately identical independently of the ductility class adopted. This observation was also verified by other researchers (Kappos 1998), which examined the effect of ductility class (DCL, DCM, DCH) on the in-plane performance of two, symmetric, ten-storey RC buildings with frame and dual structural systems. It was again concluded that the effect of ductility class on building cost is rather negligible and that the seismic performance of all buildings studied was equally satisfactory, with the anticipated exception of relatively extended column hinging and inadequate shear capacity of walls in the lower ductility systems.

It has to be noted herein, that according to Eurocode 8, the behaviour factor q depends not only on the structural system and the Ductility Class adopted but also on the degree of regularity in plan and height, while it represents a *maximum permissible* and not a *recommended* value. As a result, given the present challenging architectural forms, the actual seismic performance and the associated cost of three dimensional, dual building systems cannot be easily assessed in advance. Along these lines, the scope of this work is to study further the impact of Ductility Class on the construction cost and performance of such spatial buildings of different degrees of regularity, designed with distinct behaviour factors along the two principal directions, within the permissible minimum and maximum limits.

Overview of the buildings studied

Three dual earthquake resistant RC buildings (i.e., two residential and one educational) are examined (hereafter denoted as Building I, II and III), constructed in the cities of Thessaloniki, Lefkada and Larissa, respectively, in Greece (Figure 1). Buildings I and III had been designed to the Greek Seismic Code of 2000 (Earthquake Planning and Protection Organization (EPPO) 2000), while Building II to an older version of the same code. They are all redesigned according to EC8, adopting for comparison purposes, identical material properties (i.e., concrete class C20/25 and class B500c steel).

Building I is a five-storey, regular in plan and height building with pilotis and basement on soil type B designed for a peak ground acceleration of 0.16g. The maximum permissible behavior factor $q=q_{max}$ was adopted for the two Ductility Classes (DCM/DCH) and the two principal directions, X and Y and was found equal to $q_{DCMx} = q_{DCMy} = 3.00$ and $q_{DCHx} = q_{DCHy} = 4.40$.

Building II is irregular both in plan and in elevation. It consists of four storeys, basement walls and a loft at 2.5m in the ground floor, with a slab covering approximately 40% of the plan area. Its initial design and actual damage during the 2003 Lefkada earthquake has been studied elsewhere (Sextos et al. 2011) but the breadth of the available data and its refined post-earthquake assessment established a particularly reliable structural system of minimum epistemic uncertainty that was deemed worth to be re-designed. Belonging in the highest seismicity zone in Greece, the structure was designed for a peak ground acceleration of 0.36g. The behavior factor $q=q_{max}$ for the two Ductility Classes (DCM/DCH) for the two directions was taken equal to $q_{DCMx} = q_{DCMy} = 2.40$ and $q_{DCHx} = q_{DCHy} = 3.52$. It is noted herein that the initial, maximum permissible value of the behaviour factor, q_0, was penalized by a 20% reduction due to its irregularity.

Building III is a three storey RC structure resting on stiff soil conditions, which is irregular both in plan and in elevation and is designed to a peak ground acceleration of 0.24g. The building is classified as wall-equivalent dual system in the x-x direction and frame-equivalent dual system in y-y direction, with subsequently distinct values of behavior factor q for the two Ductility Classes (DCM/DCH) and the two directions equal to q_{DCMx} = 2.64, q_{DCMy}= 2.76 and q_{DCHx} = 3.96, q_{DCHy}= 4.14, respectively. Constructed as a part of the Larissa Polytechnic Campus it is considered of great importance (category III according to EC8, γ_I = 1.2). Notably, due to the complexity of the structure, the more strict detailing rules prescribed by DCH led to larger cross-sections and consequently the fundamental period of the DCH structure was found lower compared to the one computed for the DCM case (T=0.30sec and T=0.33sec, respectively).

Modelling aspects for response spectrum and nonlinear static (pushover) analysis
The modal response spectrum analysis and the nonlinear static (i.e., pushover) was carried out with the aid of the commercial software SAP2000 (CSI 2014) for Buildings I and II and with Fespa software (LH Software 2014) for Building III. Three dimensional linear finite elements were used for beams and columns and shell elements for walls and slabs. A secant stiffness equal to 50% of the uncracked gross section was considered for all members according to EC8. The first ten modes were taken into account in the response of each building, resulting in a minimum cumulative modal mass of 95% activated at each principal horizontal direction. Material partial factors of γ_c=1.5 and γ_s=1.15 for concrete and steel, respectively, were assumed, according to the requirements of the code (§5.2.4). For the purposes of inelastic analysis, a point-hinge model was used for all RC members in the form of lumped plasticity at the ends of the beams, at the top and bottom of the columns and at the bottom of the walls at the ground level, after appropriate transformation of the wall shell elements into equivalent linear elastic elements connected to the beams rigidly. A built-in three-component model, which has the ability to account for changes in flexural capacity in two directions (M_y-M_z) due to changes in the axial load (N) was used for the columns, while the simpler one-component model was used for the beams. Regarding the walls, an external fiber model was first implemented for the analysis of critical regions, with appropriate constitutive laws for steel and concrete and the flexural response was approximated with bi-linearized moment-curvature response using the software program RCCOLA.net, subsequently converted into a bi-linearized moment-rotation relationship (Kappos and Panagopoulos 2010). The acceptance criteria, in terms of plastic rotation θ, were extracted from ASCE – FEMA (FEMA-356 2000) (§6.5.2.2.2 Table 6-7, §6.5.2.2.2 Table 6-8) for beams and columns, respectively, while Eurocode 8 part 3 (CEN 2006) was implemented for the required chord-rotation relationships. Pushover analysis was conducted assuming a modal distribution of the lateral forces according to the first two modes, each one along the two principal horizontal directions. Given that capacity design prescribed in the initial design of the three structures, shear brittle failure was not considered.

Effect of ductility class and behaviour factor on the construction cost
Having designed the three buildings according to the principles described above, a detailed estimation of the required quantities (primarily concrete and steel) was performed and the breakdown of structural, non-structural and additional cost was made as summarized in Tables 1-4. It is evident that the adoption of a different Ductility Class did not result into any substantial increase in the required reinforcement of Building I, primarily due to the inherent regularity of the structure and the relatively low seismic zone (a_g=0.16g) which have resulted in most members being designed with the minimum required dimensions and reinforcement. Though not presented herein, it is also mentioned that some non-negligible differences (up to

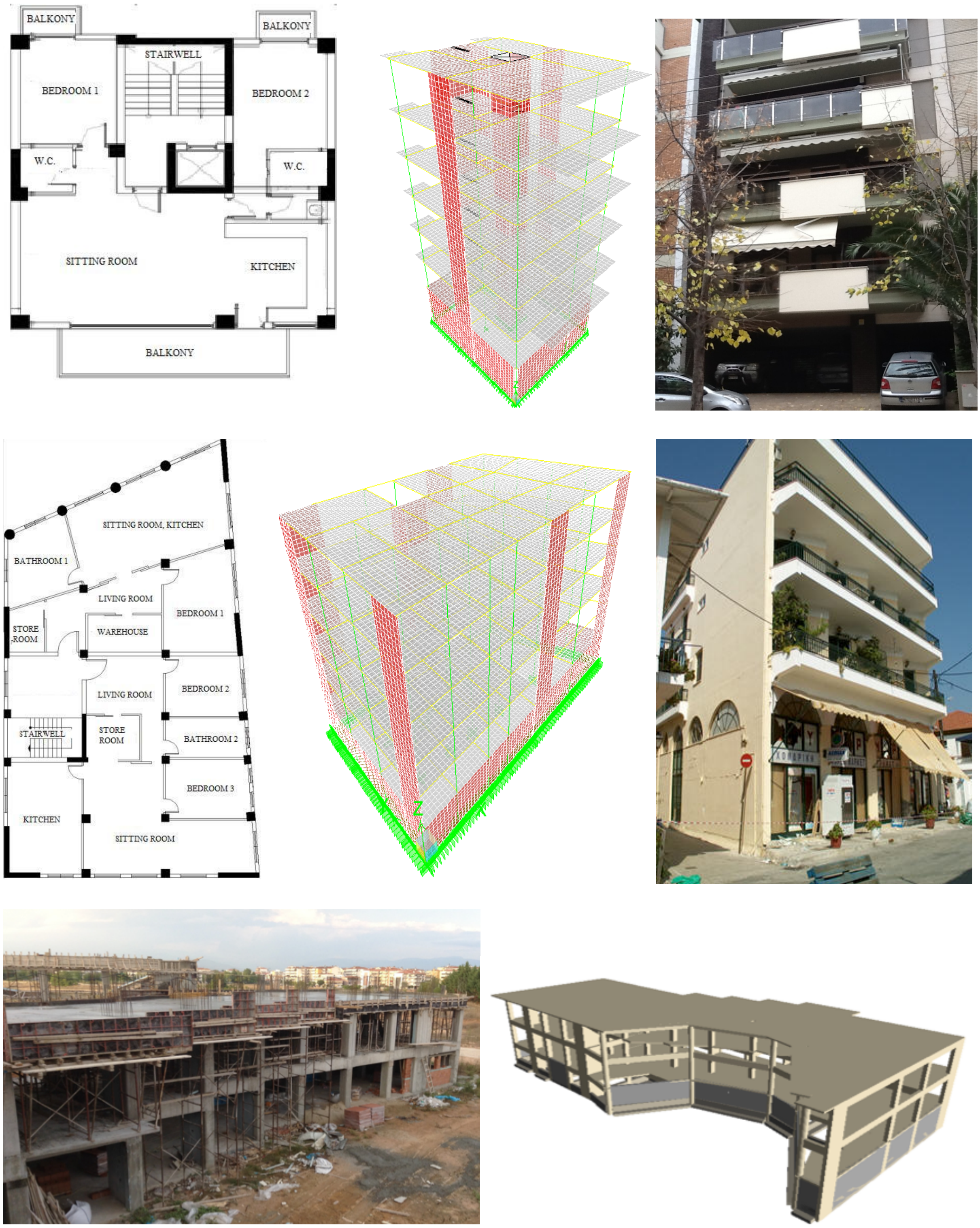

Figure 1. Overview of the three RC buildings studied

28.5%) were indeed observed in terms of the steel reinforcement weight of the beams, however, the total amount of the required reinforcement was not significantly affected (differences up to 4%). This is further reflected on the overall construction cost (Table 1) where it is clearly shown that the selection of Ductility Class does not influence the construction cost of the regular building, at least when exposed to low-to-moderate levels of seismic hazard.

An analogous observation was made for Building II, regarding the required quantities (steel and concrete) and the associated structural cost. Due to the increased demand caused by the higher seismicity of the area and the irregularity of the structure, the differences were more pronounced in this case. Furthermore, a closer observation of the results reveals that the DCH design lead to a reduced amount of longitudinal reinforcement but additional transverse reinforcement compared to DCM, thus highlighting a significant, though suppressed in terms of total quantities, impact of the ductility class, which has also been mentioned by several researches in the past (Kappos 1998; Athanassiadou 2008); the clear trend being that the percentage of longitudinal steel decreases, while that of the transverse steel increases with increasing (i.e., more demanding) ductility class. The aforementioned differences led to non-negligible differences on steel reinforcement weight between the two ductility classes (up to 28%), yet as already mentioned in terms of total quantities (concrete and steel) these differences were diminished (10%). Comparison of the total cost of Building II, shown in Table 2 indicates that both ductility classes specified in EC8 are essentially equivalent (differences up to 3%) primarily due to the fact that the structural cost generally corresponds to 1/3 of the total construction cost.

Building III on the other hand, presented more distinct sensitivity to the design decisions made primarily due to its significant irregularity, its complexity and also the alternative assumptions made regarding the adoption of the maximum or minimum permissible value of the behaviour factor. Notably, the requirement in steel reinforcement weight in the columns was increased by up to 55.8% for DCH and maximum q, and further to 85% for DCH and minimum q=1.5. On the contrary, this increase was only 6% for beams and 35% for structural walls for the case of q_{max}, and 15% and 18% for q_{min}. Overall, shifting from DCM to DCM increased the structural cost by 8.1% and the total construction cost by a mere 1.5%. It was only when the transition from DCM to DCH was combined with the adoption of the minimum permissible value of q_{min}=1.5 that the structural cost was increased by 24.3% and the total construction cost by 4.5%. A more detailed breakdown of material quantities for the case of Building III is illustrated in Figure 2 where the above trends are clearly highlighted. Similar results were deducted in a pertinent study (Mitropoulou et al. 2010) in which the influence of the behavior factor in EC8 was checked in terms of construction and total life cycle cost. It was inferred that the initial cost was not excessive for a design for q=1, since it varied from 3% to 15% for q=2 to q=4, respectively.

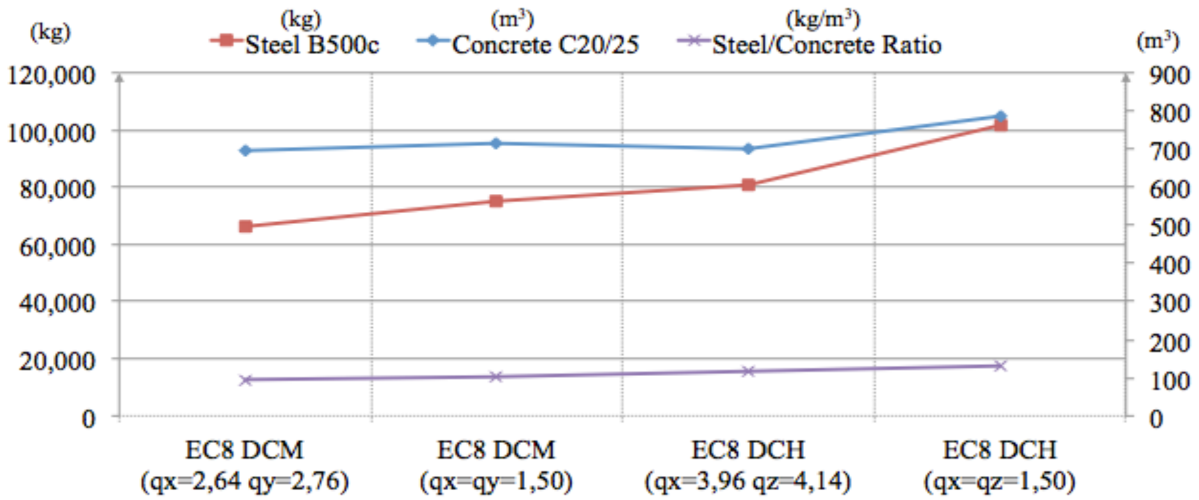

Figure 2. Material cost for different design approaches of Building III.

Table 1. Structural and total construction cost for alternative design approaches (Building I)

	DCM		DCH		
Cost category	Total (Euro)	%	Total (Euro)	%	Comparison DCH/DCM
Structural Cost (concrete, reinforcement)	138.897,93	25,6 %	140.507,79	25,8 %	**+1.1** %
Non-structural cost (installations, doors and windows, plaster etc)	196.935,65	36,3 %	196.935,56	36,1 %	0.00 %
Additional costs (contracting cost, unpredictable costs, tax)	206.480,50	38,1 %	207.470,30	38,1 %	0.48 %
Total	542.313,99	100,0 %	544.913,65	100,00%	**+0.5** %

Table 2. Structural and total construction cost for alternative design approaches (Building II)

	DCM		DCH		
Cost category	Total (Euro)	%	Total (Euro)	%	Comparison DCH/DCM
Structural Cost (concrete, reinforcement)	288.851,54	32,3 %	297.842,69	32,8 %	**+3.1** %
Non-structural cost (installations, doors and windows, plaster etc)	265.117,26	29,6 %	265.117,26	29,1 %	0.00 %
Additional costs (contracting cost, unpredictable costs, tax)	340.596,63	38,1 %	346.126,66	38,1 %	1.62 %
Total	894.565,43	100,0 %	909.084,61	100,00 %	**+1.6** %

Table 3. Structural and total construction cost for alternative design approaches (Building III) with the adoption of the maximum permissible behaviour factor q.

	DCM		DCH		
Cost category	Total (Euro)	%	Total (Euro)	%	Comparison DCH/DCM
Structural Cost (concrete, reinforcement)	192.550,13	18,6%	208.072,37	19,8%	**+8.1** %
Non-structural cost (installations, doors and windows, plaster etc)	366.710,47	35,4%	366.710,47	34,9 %	0.00 %
Additional costs (contracting cost, unpredictable costs, tax)	476.724,31	46,0 %	476.724,31	45,3%	0.00 %
Total	1.035.984,91	100,0 %	1.051.507,15	100,0 %	**+1.5** %

Table 4. Structural and total construction cost for alternative design approaches (Building III) with the adoption of the minimum permissible behaviour factor $q_x=q_y=1.5$.

	DCM ($q_x=q_y=q_{min}=1.5$)		DCH ($q_x=q_y= q_{min}=1.5$)		
Cost category	Total (Euro)	%	Total (Euro)	%	Comparison DCH/DCM
Structural Cost (concrete, reinforcement)	204.395,38	19,5 %	239.068,45	22,1 %	**+17.0** % **(+24.2%*)**
Non-structural cost (installations, doors and windows, plaster etc)	366.710,47	35,0 %	366.710,47	33,9 %	0.00 %
Additional costs (contracting cost, unpredictable costs, tax)	476.724,31	45,5 %	476.724,31	44,0 %	0.00 %
Total	1.047.830,16	100,0 %	1.082.503,23	100,0%	**+3.3** % **(+4.5%*)**

* equals to additional 24.2% structural cost and additional 4.5% total cost, compared to DCM with q_{max}

Effect of Ductility Class and behaviour factor on structural performance
Having designed the three buildings for different Ductility Classes and values of behaviour factor and computed the associated cost of construction, their obtained capacity was comparatively assessed with the aid of nonlinear static (i.e., pushover) analysis. Figures 3-5 illustrate the Capacity Curves of all buildings for DCM (in red) and DCH (in black). Dotted lines represent the cases where the minimum permissible value of q_{min}=1.5 was adopted in the design in contrast to the conventional use of q_{max}. At first, (Figure 3) it is made clear that the achieved capacity of Building I is independent of the Ductility class in both directions, as already anticipated by the negligible effect that this decision had on the geometry and required reinforcement of most structural members; them being designed according to the minimum requirements due to the relatively low seismicity and the overall symmetry and regularity of the structure which in turn resulted into increased overstrength and reduced sensitivity to the variations of the design base shear.

Capacity of Building II is also found in accordance with the first observations drawn at the stage of design and cost analysis (Figure 4). In fact, nonlinear analysis in both directions revealed that design for DCM and subsequently for a lower behavior factor (q_{DCM}=2.40) provided the structure with 5% higher strength, compared to the DCH case (q_{DCH}=3,52), apparently at the cost of ductility. Accordingly, the DCH structure, in which the detailing requirements were more demanding, presents larger ultimate displacement by approximately 15%. It is also noted that the failure mechanism is distinct in the two cases, as failure of the DCM structure occurs due to the exceedance of the ultimate plastic rotation of a structural wall, whereas failure of the DCH designed building is attributed to a column-related kinematic mechanism.

As far as Building III is concerned, the interpretation of the results requires more careful investigation. A first, quite anticipated observation is that indeed, design for the minimum permissible value of the behaviour factor q_{min}=1.50 as opposed to the assumption of $q=q_{max}$ has led to substantial increase in the building strength in both directions, as it is evident in Figure 5. More precisely, the strength of the structure designed for q=1.50 exceeded the strength of the conventionally designed structure ($q=q_{max}$) by 54% to 76%, depending on the direction of assessment. On the contrary, it is found that the selection of the ductility class does not influence the performance of the structure as much as the selection of the value of the behavior factor. The most interesting observation though is that for the cases that the same assumption was made with respect to the behaviour factor (i.e., DCM vs. DCH for q_{max} or q_{min}), it is the DCH that exhibits the higher strength, even though it is associated with higher values of behaviour factor (q_x=3.96, q_y=4.14) compared to the DCM building (q_x=2.64, q_y=2.76) and has been designed for subsequently lower level of design seismic forces. This fact can be attributed to the larger section dimensions and the significantly higher amount of reinforcement that were required for the DCH case, as a result of the various secondary rules prescribed. Particular reference is made to clause §5.6.2.2 aiming to control longitudinal reinforcement diameters but implicitly enforcing disproportional increase of the member dimensions in order to be satisfy the maximum bar diameter requirement (Avramidis et al. 2015). This is a rather controversial issue that has triggered an extensive debate within the professional community, which should be addressed and hopefully amended in the foreseen revision of the Eurocode 8. It is also reported that the reinforcement required for the irregular Building III when designed for DCH was in many instances very dense while the particularly demanding detailing rules were often found difficult to be implemented on site.

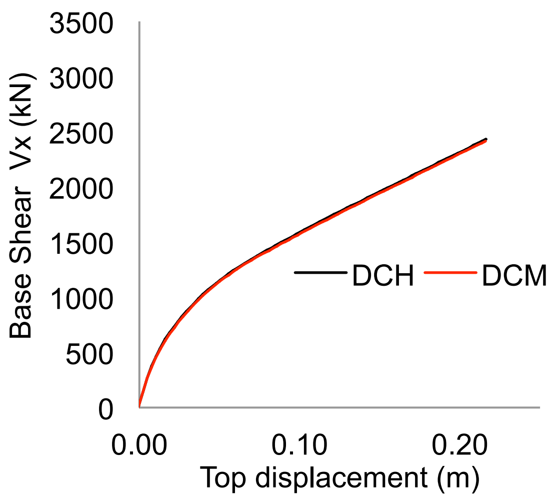

Figure 3. Capacity Curves for DCM and DCH of Building I along the x-x (left) and y-y (right) direction.

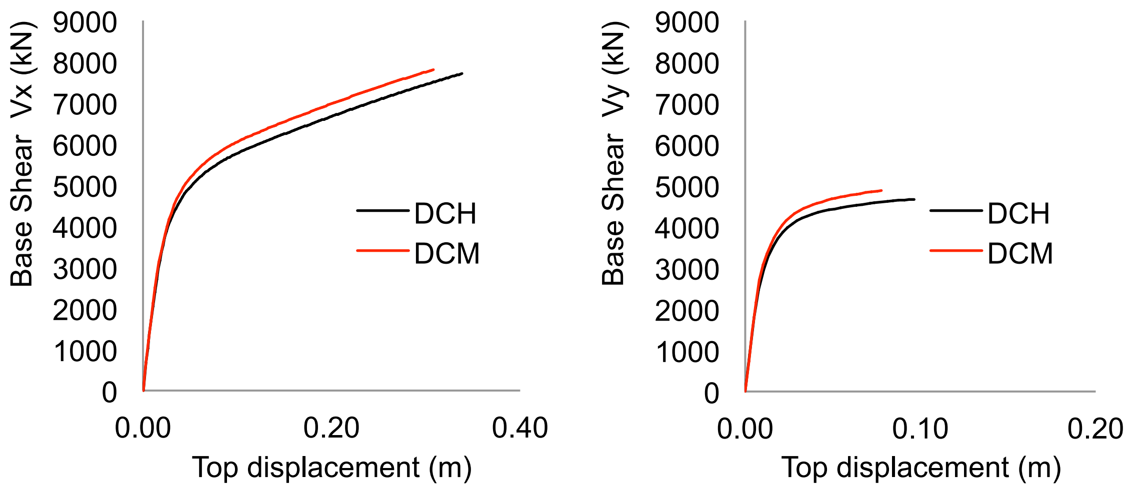

Figure 4. Capacity Curves for DCM and DCH of Building II along the x-x (left) and y-y (right) direction.

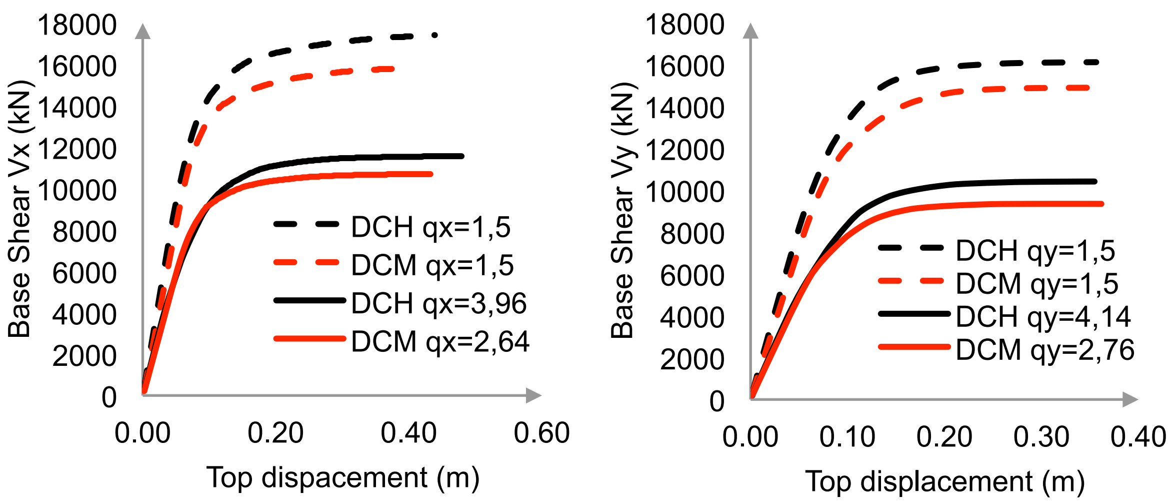

Figure 5. Capacity Curves for DCM and DCH of Building III along the x-x (left) and y-y (right) direction.

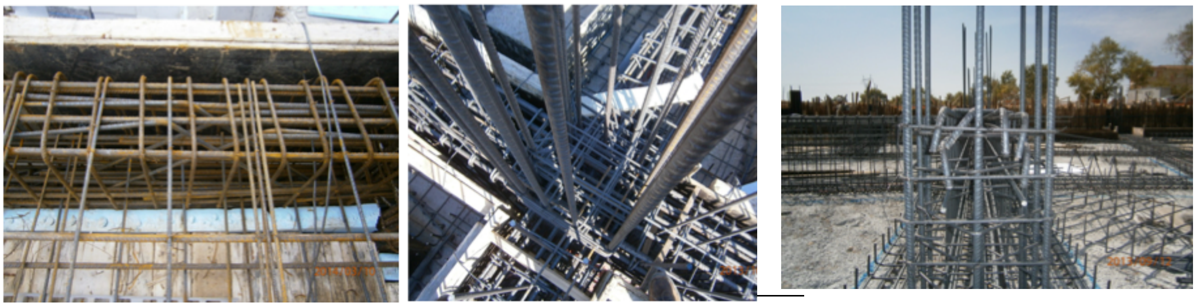

Figure 6. Construction and detailing issues related to designing for DCH.

Conclusions

The aim of the present study is to evaluate the performance and the construction cost of RC buildings with dual structural systems designed according to EC8 for different Ductility Classes (DCM/DCH) and for different behavior factors within the range of the minimum and maximum permissible limits (q_{min}/q_{max}) in accordance to §5.2.2.2. The buildings have been deliberately selected to represent structural systems with different degrees of irregularity and have been designed to three different levels of peak ground acceleration. The main conclusions drawn are summarized in the following:

The choice of the ductility class (DCM/DCH) has no significant effect on the total amount of the reinforcement required and on the total cost of *regular*, dual structural system in low-to-moderate seismicity areas, as most of the cross section dimensions and the corresponding reinforcement are dictated by the code-prescribed minimum requirements. The same observation is naturally further reflected on the inelastic response of such structures, which was found practically identical for the two Ductility Classes studied.

Dual structural systems that present a level of *irregularity* both in plan and in elevation (as Buildings II and III) are indeed affected by the decision of the Ductility Class and this is evident both in terms of the required quantities for different structural members (i.e., beams, columns and walls) and the longitudinal to transverse reinforcement ratios. However, again, the overall impact of the Ductility Class on the total construction cost is rather minor as the latter is dominated by the non-structural and additional costs, which consist approximately 65% of the total budget.

Comparison of the capacity curves of the three buildings studied for DCM and DCH reveals that the ultimate seismic performance in terms of the anticipated damage for different levels of seismic intensity, is only slightly dependent on the ductility class adopted. The above important observation is attributed to the fact that design for DCH is indeed associated with a lower design shear force but this is to some extent compensated by more strict detailing rules, minimum reinforcement ratios and geometric requirements. Overlapping the 12 capacity curves (3 buildings x 2 directions x 2 ductility classes) with the corresponding target displacements of the idealized equivalent SDOF systems defined according to the EC8-N2 method (which are not presented herein due to paper length limitations) further verifies that the code fundamental objective to provide compatible design alternatives with the same target probability of exceedence for the three performance limit states (“damage limitation”, “significant damage”, “near collapse”) is essentially met independently of the Ductility Class. On the other hand, it is evident that the behaviour factor adopted (i.e., $q_{min}<q<q_{max}$) substantially influences the strength of the building and subsequently its seismic performance, as the damage expected for a given return period of the earthquake is lower. Notably, this is achieved, without a proportional increase in the associated *total* construction cost.

Overall, it is the authors' view based on the results of this study, that designing for a the minimum value of the behaviour factor $q=q_{min}$, alongside with the application of all design and detailing rules prescribed in DCM is maybe the most tempting and cost-efficient combination of Ductility Class and behaviour factor, as it leads to an adequate amount of ductility and highest strength at the same time, without the practical implications of the particularly demanding detailing rules prescribed for the case of DCH.

REFERENCES

Anagnostopoulou V, Zeris C, Karayannis C (2012) Evaluation of the q Factor of Irregular RC Buildings Designed According to EC8. 15th World Conference on Earthquake Engineering, Lisbon, Portugal.

Athanassiadou CJ (2008) Seismic performance of R/C plane frames irregular in elevation. Engineering Structures 30:1250–1261.

Avramidis IE, Morfidis K, Athanatopoulou AM, et al. (2015) Eurocode Compliant Seismic Analysis and Design of RC Buildings. Concepts, commentary and worked examples with flowcharts. Geotechnical, geological and earthquake engineering series. Springer Netherlands.

Booth ED (2012) Creating a vision for the future of Eurocode 8. 15th World Conference on Earthquake Engineering, Lisbon, Portugal.

Carvalho E, Coelho E, Fardis MN (1996) Assessment of EC8 provisions for reinforced concrete frames. 11th European Conference on Earthquake Engineering, Paris. France.

CEN (2004) European Standard EN 1998-1. Eurocode 8: Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings", Committee for Standarization. European Committee for Standardization, Brussels, Belgium.

CEN (2006) European Standard EN 1998-3. Eurocode 8: Design of structures for earthquake resistance - Part 4: Silos, tanks and pipelines", Committee for Standarization. Brussels, Belgium.

CSI (2014) SAP2000: integrated building design software, v.17—user's manual. Berkeley, California, USA.

Earthquake Planning and Protection Organization (EPPO) (2000) Greek Seismic Code EAK2000 (amended in 2003), Athens, Greece (in Greek).

Fardis MN (2009) Seismic Design, Assessment and Retrofit of Concrete Buildings, based on Eurocode 8. Springer, Netherlands.

Fardis MN, Papailia A, Tsionis G (2012) Seismic fragility of RC framed and wall-frame buildings designed to the EN-Eurocodes. Bulletin of Earthquake Engineering 10:1767–1793.

FEMA-356 (2000) Prestandard and commentary for the seismic rehabilitation of buildings.

Kappos AJ (1998) Influence of ductility class on the seismic reliability and cost of EC8-designed structures. 11th European Conference on Earthquake Engineering, Paris, France.

Kappos AJ, Antoniadis P (2007) A contribution to seismic shear design of R/C walls in dual structures. Bulletin of Earthquake Engineering 5:443–466.

Kappos AJ, Panagopoulos G (2010) Fragility Curves for Reinforced Concrete Buildings in Greece. Structure and Infrastructure Engineering 6:39–53.

LH Software (2014) Computer Program FESPA for Windows, User's Manual, Athens, Greece.

Mitropoulou CC, Lagaros ND, Papadrakakis M (2010) Building design based on energy dissipation: a critical assessment. Bulletin of Earthquake Engineering 8:1375–1396.

Panagiotakos TB, Fardis MN (2004) Seismic Performance of RC Frames Designed to Eurocode 8 or to the Greek Codes 2000. Bulletin of Earthquake Engineering 2:221 – 259.

Sextos AG, Katsanos EI, Manolis GD (2011) EC8-based earthquake record selection procedure evaluation: Validation study based on observed damage of an irregular R/C building. Soil Dynamics and Earthquake Engineering 31:583–597.