12th International Conference on Structural Analysis of Historical Constructions
SAHC 2020
P. Roca, L. Pelà and C. Molins (Eds.)

CONSERVATION OF 20TH CENTURY CONCRETE HERITAGE STRUCTURES IN CYPRUS: RESEARCH AND PRACTICE

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Keywords: Concrete Heritage, Structural Assessment, Displacement Pushover, CONSECH20

Abstract. *The conservation of 20th century concrete heritage structures poses a major challenge worldwide. Whilst these structures possess a remarkable architectural value and a rather experimental character in terms of the use of materials and technologies, at the same time there is admittedly lack of recognition of their cultural and historical value by the wide public. More often than not, such buildings are left to deteriorate and often they are even demolished. This paper follows the workings of the project "CONSErvation of 20th century concrete Cultural Heritage in urban changing environments" (CONSECH20). The aforementioned international interdisciplinary project aims to investigate concrete constructions built until 1965 in four different European countries (Cyprus, Italy, The Netherlands and the Czech Republic), in terms of their architectural, social and historical value, and to address their restoration and re-use potential. The paper initially presents the significance of 20th century concrete heritage structures in general, and describes the methodology proposed in order to ensure the protection of such buildings from demolition, and facilitate their restoration and re-use (if and where possible) for the benefit of the society. The focus is on the structural assessment and restoration of 20th century concrete heritage buildings in Cyprus, following the methodologies described by modern codes for the assessment and retrofit of existing concrete structures. A new practical analysis approach is described and compared to the force-control approach of the pushover analysis of Eurocode 8:3, which significantly overestimates the demands for seismic upgrading. The two aforementioned approaches are examined for a specific case study concrete heritage building in Nicosia, Cyprus.*

1 INTRODUCTION

Concrete has a long history of use as a construction material. However, it was not until the 20th century that it became a major building material, used in the construction of innovative and groundbreaking structures worldwide [1,2]. Whilst these structures undoubtedly possess a remarkable architectural value, and a rather experimental character in terms of the use of materials and technologies, their significance in terms of engineering technology and architectural design is not always recognized. This is also highlighted by ICOMOS, the

International Council on Monuments and Sites, in its Madrid document [3], where it is stated that '*the architectural heritage of the 20th century is at risk from a lack of appreciation and care*'. In fact, more often than not, 20th century concrete heritage structures are left to deteriorate through lack of maintenance and often they are even demolished. Hence, the conservation of 20th century concrete heritage structures poses a major challenge worldwide.

This paper follows the workings of the project "CONSErvation of 20th century concrete Cultural Heritage in urban changing environments" (CONSECH20), aiming to highlight the urgent need for the protection of 20th century concrete heritage structures. It elaborates on the structural assessment and restoration of 20th century concrete heritage buildings, following the methodologies described by modern codes for the assessment and retrofit of existing concrete structures. It also outlines existing conservation policies for such buildings in Cyprus. The paper recognizes the difficulties that arise in preserving historic Reinforced Concrete (R.C.) structures, not only because of the architectural variety of these buildings, and the experimental nature in the use of technologies and materials, but also because of the lack of regulations, good quality materials and testing procedures, or indeed knowledge of seismic design, at the time of their construction.

Regarding the latter, in the cases of R.C. historic structures in seismic prone areas, the simulation and assessment of their structural capacity is of crucial importance, since the outcome of the assessment process will also determine the requirements for retrofit and upgrading, in terms of strength and ductility, as well as the magnitude of damage, in terms of deformation, likely to develop in a future seismic event. The Codes used for structural assessment, such as EC8-Part 3 [4], use a force-controlled pushover approach to determine the target displacement of an existing structure, that is found to be problematic when applied to historic concrete structures. The problem lies in the methods and modelling technics that are adopted for assessing the existing capacities of old structures. Erroneous results yield in excessive restoration and upgrading demands. This paper focuses on three major issues that could be adjusted in the code-described procedure for the assessment of historic R.C. structures: (a) the non-linear pushover analysis must use the post-peak performance of a structure, (b) the nonlinearity introduced by hinges should take into consideration possible brittle shear, or other failures, and (c) the connection of the building's walls to the diaphragm should take into consideration possible formation of plastic hinges on the diaphragm and complete disconnection of the slab with the walls. A new practical analysis approach is hereby used and compared to the force-controlled approach of the pushover analysis of EC8-Part 3 [4], taking into account the three issues mentioned above. The two aforementioned approaches are examined for a specific case study concrete heritage building in Nicosia, Cyprus.

2 STRUCTURAL ASSESSMENT AND RESTORATION OF 20TH CENTURY CONCRETE HERITAGE BUILDINGS

Factors considered critical for the deterioration or loss of historic R.C. structures are environmental changes, changes in the surrounding landscape, natural disasters (i.e. earthquakes, floods etc.), and often demolition and replacement by skyscrapers, as many of these structures are not yet designated by the appropriate bodies as listed and their fate is thus decided by individuals who are not always sympathetic to historic structures. Moreover, even when efforts are made to restore these buildings, failure to recognize their architectural value and blind application of the provisions of codes designed for the retrofit of ordinary structures, or indeed insufficient knowledge of the correct restoration practices, often results in architectural geometrical alterations (especially problematic in structures of the modern movement with specific geometries), or in more adverse deterioration after the repair (usually in cases of faulty repair techniques in corroded members).

2.1 Modelling of historic concrete structures

In recognition of the great likelihood of damage of existing sub-standard buildings, Codes for their structural assessment and upgrading have been developed worldwide [4–9]. In the case of listed R.C. structures in seismic prone areas, the use of elastic analysis, which is given as an option by the codes, results in high demands for structural upgrading, that usually require alteration of the architectural character of these structures. The safety of the users must nevertheless be established, while the historic form of each individual structure must be preserved. This sometimes leads to the overlooking of code provisions [10]. In the case of historic structures, correct simulation and structural assessment is of utmost importance, since the results of the structural analysis will define the displacement demand in a future seismic event.

Possible assessment analysis procedures, as described by EC8-Part 3 [4], are linear (lateral force and modal response spectrum) and non-linear (push-over and time history analysis). Linear analysis models are penalizing the structure, since by assuming linear properties of the members, the capacity in terms of loads is increased and the deformation is decreased. The linear procedure that does not take into consideration the formation of plastic hinges at the beams and columns cannot predict the actual response and the redistribution of forces in the structure, due to the failure of certain members. Especially in the case of the modal analysis, the validity of the results is disputed, since the response is a CQC or an SRSS combination of the various modes; the drifts in the lower floors are thus underestimated and the change in the stiffness of the structure due to the variation of the axial load is neglected [11].

For the nonlinear static pushover analysis, two possible variations may be used. One is the monotonically increasing lateral loads (EC8-Part 3) and the other is the monotonically increasing lateral displacements at the floor levels. The application of forces at the floor levels in programs such as SAP2000 [12] exhibits limitations when the analysis is performed for structures that include various brittle mechanisms of failures at the members of the structure. The sudden failure of a member may result in negative stiffness of the structure and the inverted matrix of stiffness cannot be used to deduct the displacements caused by the forces. This results in non-convergence issues and abrupt termination of the analysis, leading to underestimation of displacement and overestimation of the load capacity [13]. On the contrary, displacement-based procedures can overcome the non-convergence issues, redistributing the forces correctly through the structure and estimating reliably the sequence of failures of the members.

The non-linear model used for the analysis must capture the proper dynamic characteristics of the structure, as the modes of vibration and the corresponding periods define the seismic excitation of a structure. As per EC8-Part 3 (Par. 4.3.1) the proper model must use the stiffness of the elements by incorporating the effect of cracking, such that stiffness corresponds to the initiation of yielding of the reinforcement. The cross-section of each element may therefore be used to compute the Moment (M_y)-Curvature (φ_y) diagram of each cross-section and calculate the cracked stiffness of the member as $EI_{cr}=M_y/\varphi_y$. The M-φ is used thereafter in the plastic hinges to control the load-bearing capacity after yielding, as well as the redistribution of lateral loads.

Contrary to the behaviour of new structures designed with the capacity design provisions, old structures, as indicated by previous earthquake events, suffer from brittle failures at the ends of the beams (such as shear failure), from the failure of the joint's cross-section, the punching shear in slabs without beams, while columns may exhibit shear failure, anchorage failure of the longitudinal reinforcement or failure of lap splices, even prior to the yielding of the beams [14]. The M-φ diagrams that should be used in the modelling of the structure must include all possible types of failures, even the brittle ones. This can be achieved by calculating the Moment in the beams and columns that corresponds to each type of failure, and using the weakest link to control the behavior of the hinges in the simulation.

One more subject that needs to be addressed for the correct evaluation of the structural response of old structures built without taking into consideration seismic provisions is the diaphragmatic function of the structural walls, which for new structures is considered by default. The distribution of lateral displacements and loads on the walls of the structures is achieved through their connection with the slabs. In older structures, slab reinforcement was the minimum required for vertical loads, resulting in severe cracking in the zones peripheral to the walls and eventual plastic hinge formation in the slabs and disconnection from the walls. In those cases, the disconnection of the walls leads to a sharp decrease of the stiffness and increase of the period, which in turn increases the lateral displacements that will be introduced by the seismic event on the structure and leads to its inevitable collapse.

2.2 Shear wall collectors in old R.C. structures

Diaphragms aim to support the vertical elements that carry the seismic actions, carry the seismic loads from the point of application to all the vertical elements of the load carrying system and connect the various elements in order to work as they were conceived [15]. Based on EC2 [16], diaphragms are designed for a factored combination of the vertical loads and not under seismic excitation. On the contrary, ACI 318 [17], as well as the ASCE/SEI 41-17 [10], take under consideration the dynamic influence of the seismic loads on the diaphragms, increasing stresses with appropriate factors and assigning appropriate detailing provisions for the collectors, i.e. the diaphragm's zones that transfer shear forces from the diaphragm to the elements of the lateral load resisting system. In these cases, design aims at preventing the formation of plastic hinges at the collector zones. This must be taken into consideration, especially in the cases of old structures, where appropriate detailing of those zones was not ensured. Those zones will most probably form plastic hinges when the diaphragm forces overcome the shear capacity.

The formation of plastic hinges in the diaphragms also results in the separation of the diaphragms from the lateral load bearing walls, leading to failure of the structural system, as was observed from various collapses during previous earthquakes [18,19]. The forces between a diaphragm and a shear wall can be computed either by finite element analysis, or by using free body cuts on the shear walls above and below the diaphragm with force equilibrium [20]. The diaphragms are allowed to be idealized as rigid when the span to depth ratio is less than 3 and no horizontal irregularities exist, while appropriate flexibility must be assigned in the diaphragm in all other cases, where usual values of the stiffness modifier are between 0.15-0.5 [20].

The design of the collector for shear transfer is based on the assumption that shear stresses are uniformly distributed on the interface between the diaphragm and the wall, as per ACI 318 [17] Par. 18.12.9.1:

$$V_n = A_{cv}\left(0.17\lambda\sqrt{f_c'} + \rho_t \cdot f_y\right) < 0.66\sqrt{f_c'} \cdot A_{cv} \tag{1}$$

Where ρ_t, is the uniformly distributed slab reinforcement perpendicular to the wall's flexural reinforcement and λ=1 for normal concrete. The values are referred to structures designed as per new Code provisions and proper detailing for capacity-based design as per ACI 318 [17]. In the cases of old sub-standard structures, with low reinforcement ratios of the slabs, the ACI equation seems to overestimate the real shear transfer capacity between the diaphragms and the walls, as reported by experimental research [21]. The shear force for failure of a lightly reinforced slab, with simultaneous yielding of the reinforcement in both directions, is described by the first term of Eq. 2, while the second term of the same equation represents the yielding of the reinforcement perpendicular to the slab's main flexural reinforcement with simultaneous crushing of the diagonal compressive strut.

$$V_n = min\{\, A_{cv} \cdot f_y\sqrt{\rho_t \cdot \rho_l}\ ;\ A_{cv} \cdot f_y \cdot \rho_t \sqrt{\frac{\lambda \cdot f_c}{\rho_t \cdot f_y} - 1}\} \tag{2}$$

2.3 Displacement Pushover Analysis

Recent studies [13] have shown that using a displacement based approach, instead of a lateral load pattern of increasing intensity, can increase the validity of the prediction of failure of structures, as it does not require a positive-definite stiffness matrix for convergence. The pushover analysis resistance curve in this approach is obtained by applying a drift demand pattern, based on the fundamental mode of translational vibration of the structure. The procedure of assessment proposed by Fotopoulou et al. [13] is adapted for structures with coupled translational and rotational mode shapes. In order to perform a Displacement Pushover analysis, the fundamental mode shapes of the structure must be determined. Especially in the cases where a structure has irregularities in plan and elevation, a proper 3D model must be used, including the true stiffness of the beams, columns and walls, in order to determine the torsional moments due to stiffness irregularities. The primary modal shapes of the structures in the two directions (including torsion when coupled), give the displacements in X and Y directions of each node in relation to the Center of Mass (C.M.) node on the roof of the structure. Based on the differential translation of each node to that of the C.M., incremental translations can be imported simultaneously to all the vertical elements of the structure, according to the mode shapes of vibration. For each incremental displacement of the Top C.M. node (Δ_i), the displacements of each column and wall are derived (D_{ci}) and the corresponding drifts (θ) are distributed between the beams and the columns connected on each joint, based on their relative stiffness. The drift of each column is determined as $\theta_c=\lambda/(\lambda+1)\cdot\theta_{bc}$, where $\lambda=EI_b\cdot h_c/(EI_b\cdot h_c)$, with λ being corrected in each next step, assuming the value of 1 when the column has yielded. The Shear-Drift curve of each vertical member is then used to derive the shear that is developed at each incremental step. The Shear-Drift curve of each member is determined based on both ductile and brittle possible modes of failure. The sum of the shear forces of the vertical elements in the base floor of the structure is the Base Shear of the structure.

3 CONSERVATION OF 20TH CENTURY CONCRETE HERITAGE BUILDINGS IN CYPRUS: POLICY AND RESEARCH

In the Cypriot society, as indeed in many other societies at present, the dominant view is that only traditional masonry structures constitute part of the country's architectural heritage, due to their long span life and straightforward legal protection by the local Town Planning and Housing Department (TPH). The construction of R.C. structures in Cyprus began in the 1930s. The non-recognition of the social and historical value of these buildings by the general public, as well as the constant changes in the urban environment, are rapidly leading to their deterioration and often their demolition; thus a significant part of the history and architecture of Cyprus is lost. Some of the R.C. buildings built by 1960 are still in use, albeit in bad condition. Others have undergone interventions, which have led to the alteration of their original character. The aforementioned highlight the significance of the protection of 20th century concrete heritage structures in Cyprus and renders CONSECH20 timely.

3.1 Listing and Conserving 20th Century R.C. heritage buildings in Cyprus

The Republic of Cyprus (RoC) protects historic buildings, monuments and sites through two main legal instruments. The first instrument is 'The Antiquities Law', a law dating back to 1905, through which 'Ancient Monument' objects, buildings or sites considered to be of public interest by reason of their historic, architectural, traditional, artistic or archaeological value are listed. In 1972, the 'Town and Country Planning Law' was introduced and since then has become the foundation regarding the protection primarily of vernacular architecture. In essence, Article 37 - '*Protection Decree*' of the aforementioned Law, allows for the issuing of preservation orders by the Minister of Interior, on the recommendation of the Department of TPH. These Decrees declare as 'listed' individual buildings or structures, groups of buildings or sites of special social, architectural, historical or other interest. There are over 100 preservation orders issued until today, covering more than 5,000 buildings across the RoC. The majority of these buildings belong to the vernacular architecture, with a much smaller number of buildings belonging to the 'modern architecture' [22]. There are no restrictions regarding the age of the building to be recommended for listing through a Protection Decree, or indeed the type of construction material used. Once listed, these buildings are protected, in the sense that their demolition, as well as any alterations which could change their original character, become illegal. Legal owners of listed buildings have the responsibility and obligation to submit any planned alterations to the competent Section (i.e. the Conservation Section) of the TPH and get permission before actually implementing these changes.

3.2. Selecting 20th century concrete heritage structures for CONSECH20

Following a more global trend, there has been a rise in the interest 20th century concrete buildings have been receiving in the RoC over the past decade, in particular. In 2009 for example, the Town and Planning Department of the RoC funded the research and production of a publication titled 'Learning from the Heritage of the Modern'. Additionally, the Docomomo Cyprus list [23], including significant projects constructed roughly between 1920-

1980, was prepared by a team of architects. The goal of the list was to showcase the impact of modern architecture in modernization processes and the shaping of the built environment. It is also important to mention that there is an emerging research hub on architectural modernism in Cyprus. In this framework, the international interdisciplinary project "CONSErvation of 20th century concrete Cultural Heritage in urban changing environments" (CONSECH20) is currently in progress, aiming to investigate concrete constructions built until 1965 in Cyprus (and in three other European countries - Italy, The Netherlands and the Czech Republic), in terms of their architectural, social and historical value, and to address their restoration and re-use potential. The project is focusing on representative case studies of 20th century historic concrete buildings, the selection of which is based on certain criteria. In Cyprus, a preliminary extensive list of what could be considered as "concrete heritage buildings" has been prepared using information from relevant bibliography, as well as from various archival sources (both public and private). This list amounts to approximately 160 buildings.

In order to shortlist these buildings and perform a more in-depth analysis, a number of additional criteria were taken into account, such as representative architectural styles, materials, construction system, decorative techniques, aesthetic quality, and damage mechanisms (Table 1, Fig. 1). Starting from the period of construction, only structures built before 1965 were selected. This allowed the inclusion of key-structures built after the independence of the island in 1960. Given the social focus of CONSECH20, there was special interest on public, municipal and state-owned buildings of social and architectural significance. Both listed and non-listed buildings were included in the list. Similarly, buildings which have undergone successful interventions, which could constitute good lessons from the past, as well as buildings which are in need of restoration, have been included in the list.

Table 1: Examples of case studies selected in Cyprus in the framework of CONSECH20

Building Name	Year	Structural System	Current Use	Listed	State of the Building
Melkonian Institute	1926	Proprietary	Abandoned	Yes	Needs restoration
Pavilion at Halasultan Tekke	1960	R.C. Frame	Abandoned	No	Needs restoration
Carob Store	1960	Prefab	Industrial	Yes	Needs restoration
Ledra Palace Hotel	1947-49	R.C. Frame	Under UN occupancy	Yes	Needs restoration
Mangoian Shops and Apartments	1951-52	R.C. Frame	Education /Spectacle	Yes	Successful Past Interventions
Alexandros Demetriou Tower	1957-59	R.C. Frame	Commercial/ Residential	Yes	Successful Past Interventions
Tourist Pavilion	1960-62	Hybrid	Abandoned	No	Needs restoration
Old Municipal Market	1965	R.C. Frame	Abandoned	Yes	Needs restoration
Athienou Municipal Market	1955	R.C. Frame w/o slabs	Abandoned	Yes	Needs restoration
Technical School Nicosia	1953	R.C. Frame	School	No	Past Interventions not Successful
Kyperounta Sanatorium	1938-40	R.C. Frame	Hospital	No	Needs restoration

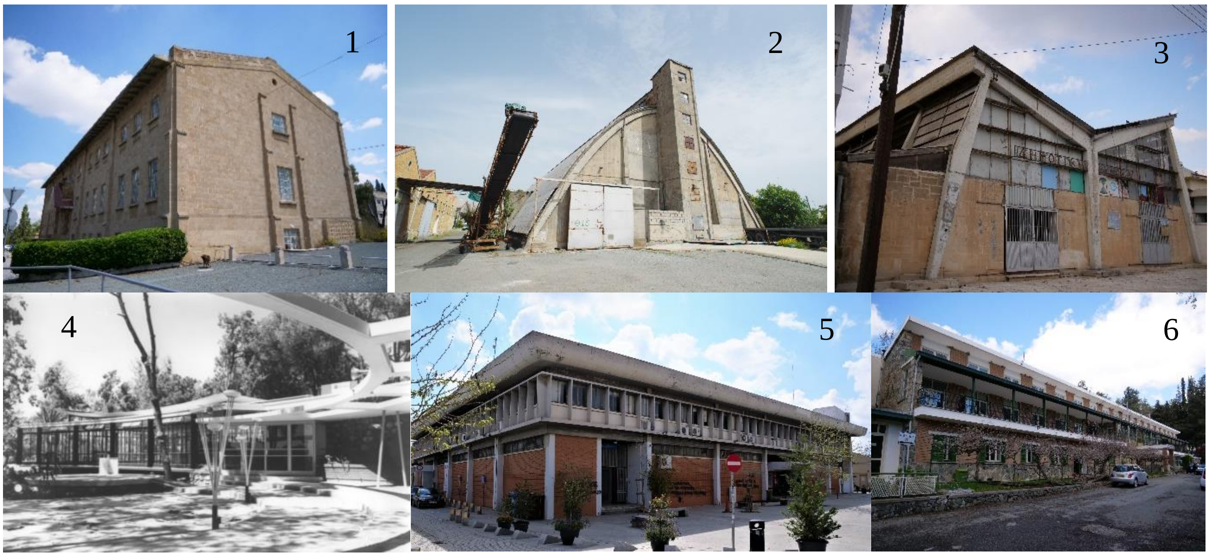

Figure 1: Buildings that will be examined in the framework of CONSECH20 project. 1. Melkonian Institute, Nicosia; 2. Carob Store, Limassol; 3. Athienou Municipal Market; 4. Tourist Pavilion, Limassol; 5. Old Municipal Market, Nicosia; 6. Kyperounta Sanatorium

For the screened case studies, the type of structural system, as well as the general state of conservation, have been noted. The type of construction was also recorded (cast in place, prefabricated). Finally, the original and the current location of the building were documented (i.e. urban, industrial, maritime, rural, etc.), alongside the original and current use (residential, industrial, offices, etc.).

3.3 Displacement pushover on selected case study

Cyprus is a seismic prone area. Up till 1979, there was no regulation in Cyprus concerning design against seismic action, while in 1979 “Short Seismic Measures” were introduced, that were not mandatory. The first “Cyprus Seismic Code” was made mandatory in 1994, while in 2012 the Eurocodes replaced local Codes.

Given that historic concrete structures in Cyprus were designed only for gravity loads, any restoration procedure must take into consideration both the safety of the public, as well as the historic fabric. In order to limit excessive restoration requirements, correct assessment of the structural capacity of existing heritage structures, especially against earthquake loading, must be adopted; therefore, the Displacement Pushover analysis is incorporated.

This section reports on an example of the Displacement Pushover analysis, performed on one of the listed buildings selected in the framework of CONSECH20. The structure in reference is the Old Municipal Market in Nicosia, Cyprus. The Market was built in 1965, following a demand from the Greek Cypriot community after the division of the old city of Nicosia in 1963, which meant that Greek Cypriot retailers lost their original retail space, located in the North of the city. In the last couple of decades, the use of the market declined and the Municipality of Nicosia has been exploring new uses for the space. Between July 2018-2019, the building was offered as a multi-use space to a group of young artists etc. It has now been decided that the market will be renovated to host RISE Centre of Excellence.

The structure consists of four parts, separated by structural joints. In this paper, only the west part is analysed (Fig. 2). The latter comprises of a two storey R/C moment frame with 3 walls at one side of the plan, leading to eccentricity. The ground floor height is 4.45 m and the 1st floor is 3.10 m. More information on the structural system may be found in Georgiou et al. [24,25].

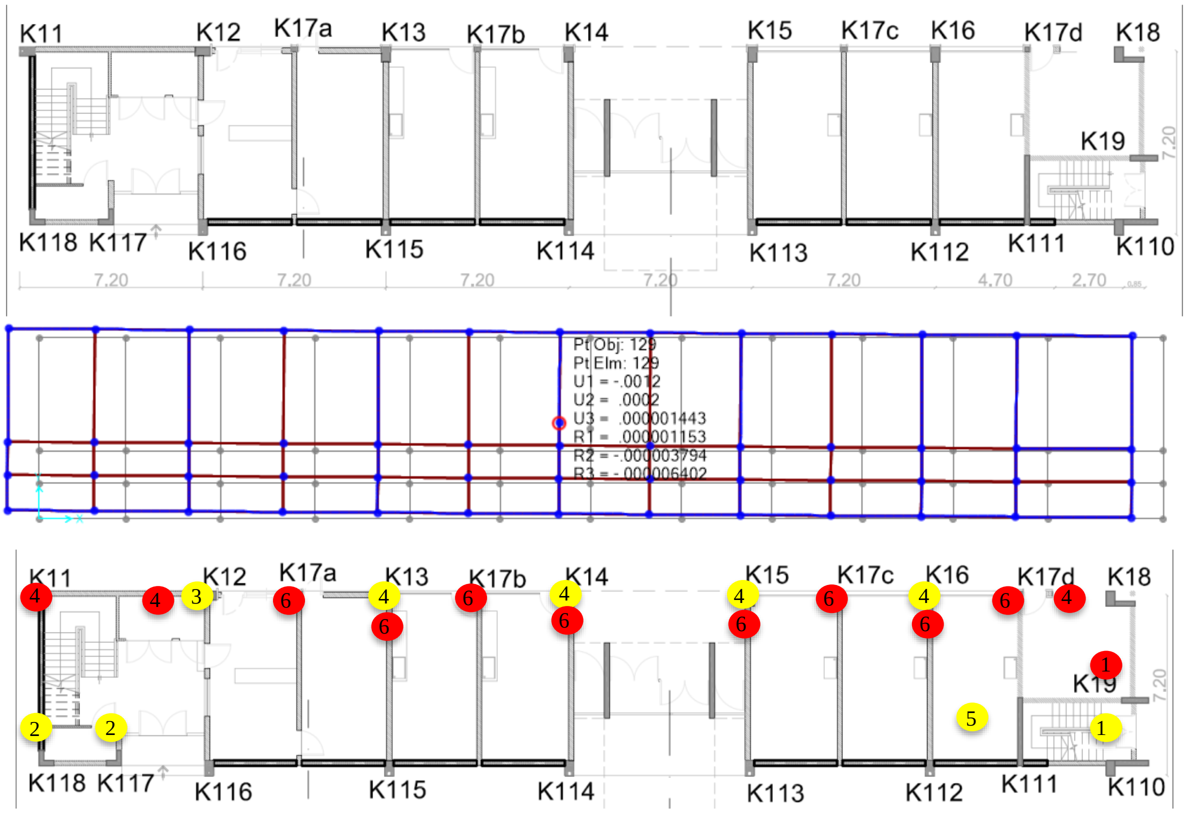

Figure 2: (Top) West part ground column denomination, (Middle) 2nd mode translational in the x-axis with a period of T_2=0.77 sec, 93% of translational mass participation and (Bottom) Displacement control pushover progressive failures in X-direction

Figure 2 also shows the 2nd mode shape of the structure, derived from a 3D model in SAP2000 [12]. Equations 1 and 2 were used to calculate the shear forces that can be transferred by the two walls acting on the X-direction of the structure, K18 and K110. In the special case of the K110 wall, which is not connected directly to the slabs, due to the adjacent staircase, but only to beams, the shear that can be transferred to the wall is the one delivered by the adjacent beam. The relation between the slab's shear and the shear at the base of the wall in the ground floor is estimated as [25]:

$$V_n = V_{wall} \cdot \left(\frac{h_{gr}^3}{h_{fl}^3} \cdot \left(\frac{1}{\Phi_{gr}} - 1 \right) - 1 \right) \tag{3}$$

Table 2 shows the capacity shear of the diaphragm connected to wall K18, as well as the wall shear forces for failure of the collector in K18 and the connecting beam in K110. The above results are used in the Displacement Pushover analysis of the structure and are compared to the same analysis, without taking into account the disconnection of the slabs from the walls.

The results are compared in Fig. 3, for imposed displacements in the X-direction, where especially for wall K110, despite its great stiffness, the shear delivered is limited by the connecting beam. Therefore, the capacity of the structure as a whole is 25% less than that estimated by assuming diaphragmatic action of the walls to the rest of the vertical elements. Furthemore, by incorporating the procedure for determining the target displacement of the structure in the two cases, as per EC8-Part 1, Annex B, the period of the SDOF in the case of the K110 connection only to the beam is higher than that of the diaphragmatic connection, as shown in Fig. 3, leading to the conclusion that the actual structure, which has lower stiffness, will be requested to exhibit greater displacements for the design seismic action.

Table 2: Shear capacity of walls due to connection with diaphragm

	$\rho_{sl}=\rho_{st}$	V_n				V_{wall}
		ACI max	ACI	double yielding	yielding ρ_t	
K18	0.00452	678.87	403.77	228.91	888.81	287.38
K110	0	-	-	-	-	115.80

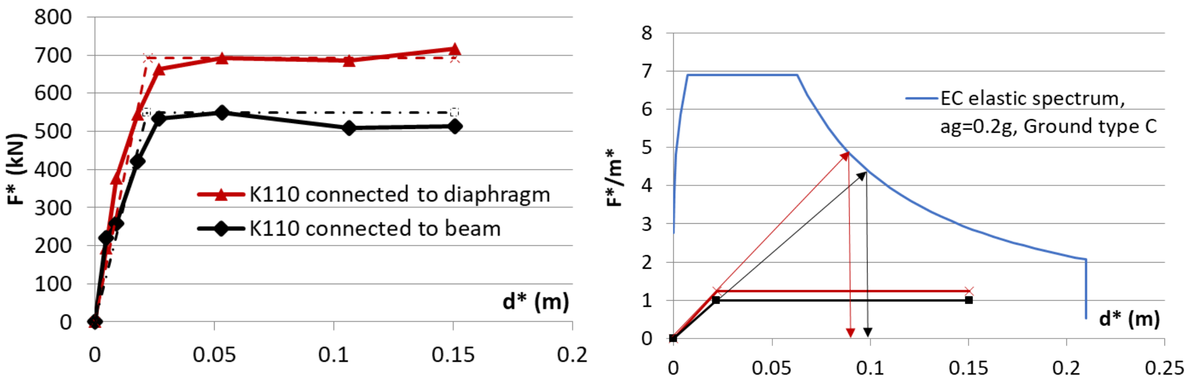

Figure 3: (Left) Base Shear-Control node X-displacement and (Right) Determination of target displacement based on EC8-Part 1, Annex B, in the cases of diaphragmatic connection of K110 and connection only with adjacent beam

4 CONCLUSIONS

- There are parallel accounts regarding the future of historic R.C. structures. On one hand, it is irrefutable that their protection has been delayed, based on a number of different rationales, starting from the uncertainty in R.C. conservation methods, and extending to cost, and of course the lack of (or the lag in) coercing political will towards their protection. On the other hand, there is a move towards the appreciation of such structures by a wider audience (from architects to engineers, as well as artists and beyond), which in turn pushes institutions to take real steps towards their protection. Time is of course of the essence.
- The social aspect of historic structures is essential and more needs to be done in order for conservation research to become really interdisciplinary. In Cyprus, many of the historic R.C. buildings have been found to have an interesting social background and importance, which can in turn be used in order to not only argue for their protection, but also to propose their restoration and rehabilitation, in combination with a use which

will enhance their social importance and appreciation by the wider society.

- Historic reinforced concrete structures present inherent challenges regarding their restoration, as possible methods of retrofit are limited by the demand to preserve the architectural concept. In order to limit excessive restoration requirements, correct assessment of their structural capacity, especially against earthquake loading, must be adopted.
- Ignoring the possibility of plastic hinge formation at the collector zones between the diaphragm and structural walls leads to overestimation of the base shear capacity and underestimation of the expected displacements.

Acknowledgements. The authors would like to acknowledge funding by the Republic of Cyprus through the Cyprus Research Promotion Foundation (Project P2P/JPICH_HCE/0917/0012). They would also like to thank Nicosia Master Plan for providing access to records and test results for the structure under study.

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