



Article

State of Conservation of Concrete Heritage Buildings: A European Screening

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Abstract: Historic concrete buildings are at risk. Limited knowledge of concrete technology until the 1960s led to more sensitive buildings than modern concrete buildings. In addition, the lack of sensibility regarding their heritage value and insufficient protection is leading to remorseless demolition. Still, concrete has proved to be a resilient material that can last over a century with proper care. There is not yet an estimation of the status of historic concrete buildings in Europe. Until now, a few attempts have been done to secondarily, and subjectively, gauge their conservation status. This paper is the result of a joint investigation studying forty-eight historic concrete buildings distributed in four countries. They were surveyed by expert teams according to a predefined methodology. The study aims to identify recurrent damages and parameters affecting the conservation state. It also aims to serve as the first trial for an objective and measurable methodology, to apply it with a statistically significant number of cases. Damages related to the corrosion of reinforcement and moisture-related processes were the most recurrent. The use of plasters, flat roofs, and structural façade walls show a positive effect in protecting the concrete. The state of conservation has a great variability across countries.

Keywords: assessment; concrete; damage processes; decay patterns; historic structures



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1. Introduction

Reinforced concrete (RC) started to be used in Europe in the late 19th and early 20th centuries. The new material was eagerly adopted in some countries to construct new buildings; whereas in others, concrete boomed in a later period. In Genova, Italy, for instance, the Hennebique silos (1901–1906) (Figure 1a) exhibited an early mastery in the use of concrete systems in a large-scale building with a system patented nine years before [1]. Whereas, in the same period, in the Netherlands, RC buildings tended to be of less entity and complexity like the Calve building in Delft (1908) (Figure 1b) as concrete had not yet found its niche in the country.

After WWII, reinforced concrete became widely accepted as a construction system. Developments in concrete technology, the favor of architects towards the functionalist aesthetic, and examples of large RC buildings (e.g., Unite d'Habitation of Le Corbusier in 1953) propelled the use of RC buildings in post-war Europe [2,3]. However, not all European countries followed the same path.

Cyprus, for instance, started late in the tenacious use of concrete. When the island was a British colony (1922–1960), RC was introduced to modernize the Cypriot landscape (Pyla and Phokaides, 2009). However, it was not until the decade of the 1960s, with the

island's independency from the British Empire, when the concrete 'boom' started with the construction of many private and public buildings (Figure 1c).

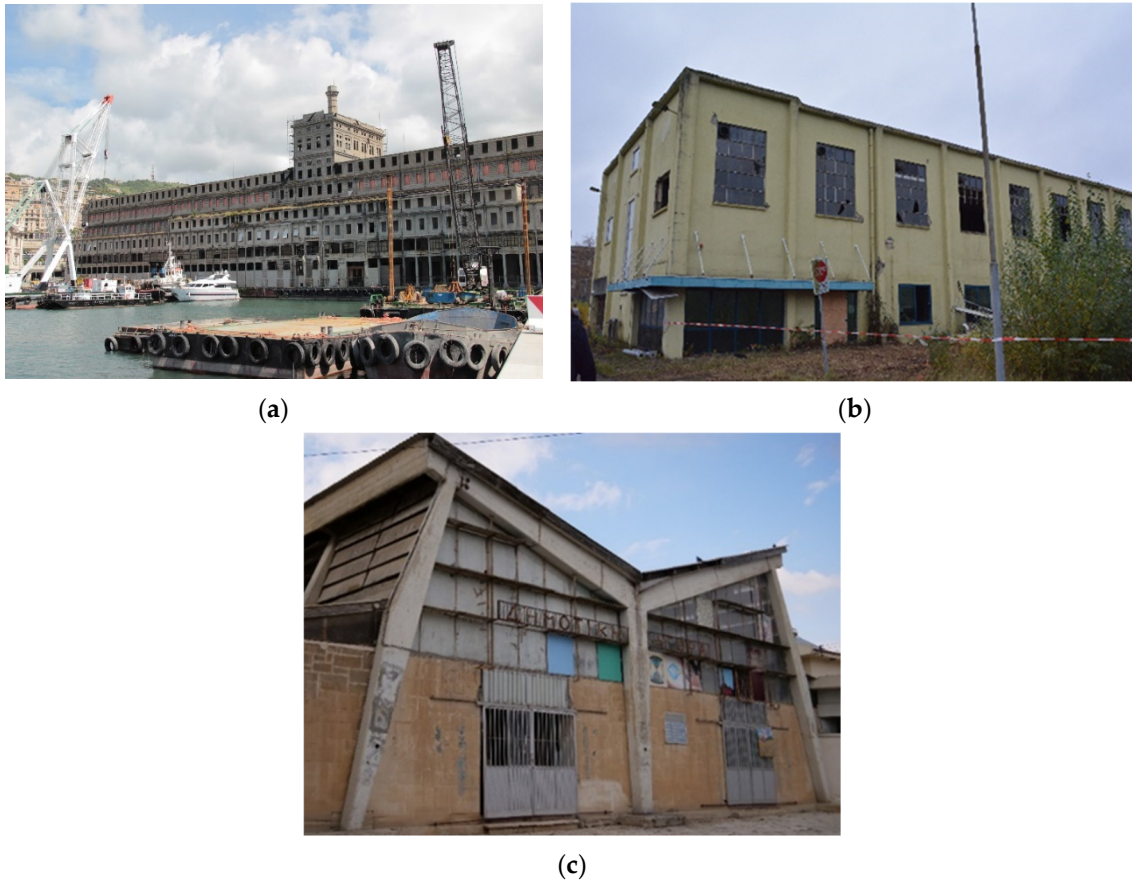


Figure 1. Historic concrete buildings. (a) Hennebique Silos in Genova (1901–1906). Source: Authors 6; (b) Calve Building (1908) in Delft, the Netherlands. Demolished in 2019. Source: Author 1; (c) Athienou Municipal Market (1951–1955) in Cyprus. Source: Authors 3 and 4.

Similarly, the initial use of reinforced concrete started with an industrial character [1,4], as the examples aforementioned. A few countries, however, began to explore new uses immediately. In the Czech Republic, concrete was conceived as a polyvalent material and soon began to be used in a wide range of buildings. Palaces, churches, and even stores, like the Wenke department store in Jaromer built in 1911, were constructed in the Czech Lands. The diversity and variation of concrete evolution and uses in Europe became part of its scientific appeal and heritage. Unfortunately, this vibrant variation usually results in different forms and speeds of concrete degradation.

Depending on the area and age, historic concrete can vary in terms of composition, structure, and construction [5]. As a result, buildings of similar age in different countries may not degrade in the same way or at the same pace. In recent years, there have been different attempts to make a screening of the conservation state of concrete buildings. In 2014 and 2016, the European project REDMONEST [6] studied the state of conservation in three countries—Spain, France, and Belgium. The results of France were published in [7], obtaining that of the 800+ buildings studied, 60% were in fair or good condition. The assessment was performed through a questionnaire filled by '169 architects and curators'. Each building was classified into five levels of conservation, from 'good' to 'endangered'. The project also revealed that the roof, facades, and structure comprised the majority of the damage. The most frequent types of damage were black crust, biological growth, erosion, and carbonation-induced (C-I) corrosion. In the screening, there was not a quantitative

study on the amount of damage or the severity of the buildings, which can lead to some subjectivity in the classification of the conservations state.

A more recent European project, Innova Concrete, performed a similar screening in 2020. With the help of the associations DOCOMOMO Iberico and ICOMOS, the 100 most significant cultural heritage buildings made of concrete in Europe were in some way assessed [8]. The screening gathered basic information of each building and provided an estimation of the conservation state from ‘poor’ to ‘good’. It is not specified what parameters were taken into account and if they were measurable in order to have objective data. Therefore, it is a subjective estimation as different countries and professionals can have different ideas of what is good or poor condition, especially for historic concrete.

In the European JPI research project CONSECH20, 48 historic concrete buildings have been investigated in four different countries by the authors. The countries—Netherlands, Cyprus, Italy-Genova, and the Czech Republic—have divergent geographical, climatic, cultural, political, and economic characteristics. As a way to objectively assess the conservation state of the buildings, an experimental method was created. Visual surveys were carried out with pre-defined templates and terminology to gather information on the building and quantify the type, extent, and severity of the damage.

The aim of this paper is threefold: (a) develop a methodology for the survey, as defined in Section 1; (b) identify recurrent types of damage in concrete heritage buildings and their probable causes (results in Section 3.1); and (c) attempt to find indicative parameters affecting the degradation process and trends in maintenance, renovation, and reuse among the different countries (results in Sections 3.2 and 3.3). The results for each bundle are discussed (Section 3) before distilling the conclusions in Section 4.

2. Materials and Methods

The criteria for the selection of the historic concrete buildings were the following:

- Buildings built before the 1960s—older than 50 years old.
- Buildings with representative visible and exposed concrete elements indoors and outdoors.
- Overall condition. Two variables were considered: Restored buildings with a good fair condition, and in-need-of-repair buildings.

The main characteristics of the sample are summarized in Table 1.

Table 1. General characteristics of the buildings used as screening cases in CONSECH20.

Country	Number of Buildings	Age (Mean)		Listing		Ownership	
			CoV	Listed	Non-Listed	Private	Public
Cyprus	13	69.38	19%	10	2	46%	54%
Czech Republic	10	89.6	16%	8	3	60%	40%
Italy	10	83.3	17%	8	2	10%	90%
Netherlands	15	88.67	19%	9	6	67%	33%
Total	48	82.52	21%	35	13	48%	52%
Country	Condition		Currently Abandoned Buildings		Avg. Level of Damage Severity		
	Restored	Non-restored	N	%		CoV	
Cyprus	31%	69%	6	46%	23.77	65%	
Czech Republic	20%	80%	2	20%	22.1	75%	

Table 1. Cont.

Country	Number of Buildings	Age (Mean)		Listing		Ownership	
		CoV		Listed	Non-Listed	Private	Public
Italy	20%	80%		5	50%	21.4	76%
Netherlands	40%	60%		3	20%	4.27	86%
Total	29%	71%		16	33%	16.83	92%

A scheme of the methodology can be found in Figure 2. The survey for each building was carried out by a designated team in each country. Each team was specialized in damage assessment, conservation, and concrete degradation. Starting from the visible damage, each team recorded the most common damage types and evaluated the possible cause(s) of each damage. For this task, the Damage Atlas of the online tool MDCS was used [9], which defines illustrative examples and explains the characteristics and plausible causes of the different damage types.

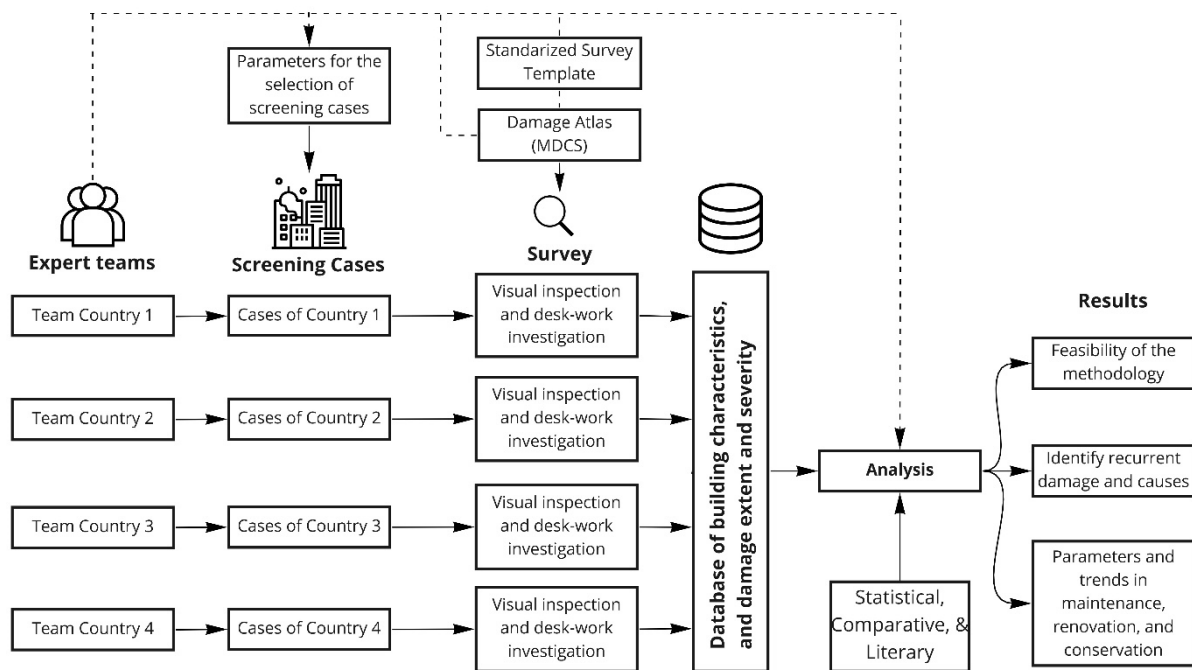


Figure 2. Flow chart of the proposed methodology.

In parallel to the on-site survey, a background investigation was performed about the history of each building and its characteristics (age, location, exposure, type of structure, type of use, façade, roof, exposed elements, finishes over concrete, materials, etc.).

The information was then conveyed into a standardized spreadsheet template, one per building, to be used for all partner institutions. The template was designed to gather the relevant parameters of the building to assess its significance and state of damage and conservation. It was divided in four main sections, (1) general information with location, year of construction, dimensions, number of stories, exposure, etc.; this also included the type of protection, ownership, and past and current uses; (2) characteristics of its structure (typology, material, reinforcement, exposure, etc.); (3) damage assessment (identifying the type of damage, location, extent and severity); and (4) a value assessment to identify scientific and social relevancies. The template was based on the synthesis of different templates for the visual assessment of existing buildings [10–14]. To guarantee

uniform and comparable data, and avoid misinterpretations, the parameters and values were previously agreed upon and programmed to be selected from a dropdown menu.

Depending on the extent and severity of each damage, a numerical value was assigned. The sum of the individual values resulted in a total value defined as the *Level of Damage Severity and Extent*, which was related to its state of conservation. Therefore, buildings with higher values were, in general, in a worse state of conservation than buildings with lower values.

3. Results

The results of the investigation are divided into three sets:

- The recurrent damage types and most probable causes.
- The effect of different parameters on the severity of the damages observed.
- Trends in maintenance/renovation/reuse in different countries.

3.1. Recurrent Damage Types, Damage Processes, and Correlation

Among the types of damage defined for concrete in MDCS (Figure 3), the most recurrent ones were: spalling and delamination (16.42%), individual cracks (11%), corrosion of reinforcement-rust layers (8%), disintegration of cement matrix (6%), and biological-growth-related damages (discoloration and moist spots, 3.85% each). These five types of damages formed around 50% of the damages found across the countries, although the orders of magnitude have slight variations as shown in Figure 4.

Damage Group	1. Disintegration		2. Cracks	
Damage sub-Group	Loss of cohesion	Layering	Non-connected cracks	Interconnected cracks
<i>Individual Damage</i>	Pop Outs	Scaling	Parallel cracks	Map-cracking
	Erosion / Disintegration of cement matrix	Spalling	Individual cracks	Crazing
	Dusting	Delamination (exfoliation)		Interconnected cracks (forming a geomatric pattern)
	Crumbling			
	3. Surface chages and blemishes		4. Biological growth	
Chromatic alterations	Superficial irregularities		Deposit	
Discoloration	Bug holes		Soiling	Higher plants
Fading	Honey combing / Rock pockets		Staining	Mosses
Moist spots	Inhomogeneity (segregation)		Graffiti	Biofilm
Linear colour change (cold joint)			Encrustation (leaching)	Algae
			Efflorescence	Lichens
				Liverworts
				Moulds
5. Deformation	6. Mechanical damage	7. Corrosion of reinforcement	8. Deformation of reinforcement	
Displacement		Rust layers		
Bending		Pitting		
Bulging		Loss of rebar diameter		
Leaning				
Deviation in plane				

Figure 3. Types of damage classified in eight groups as defined in MDCS.

As the number of individual damage types was large, 41 types, similar damages were grouped in eight categories (as shown in Figure 3) based on their shared nature (e.g., different types of cracks were grouped as Cracks) aiming to identify clear patterns. The most recurrent grouped damage were Corrosion of reinforcement, Disintegration, and Cracks (Table 2).

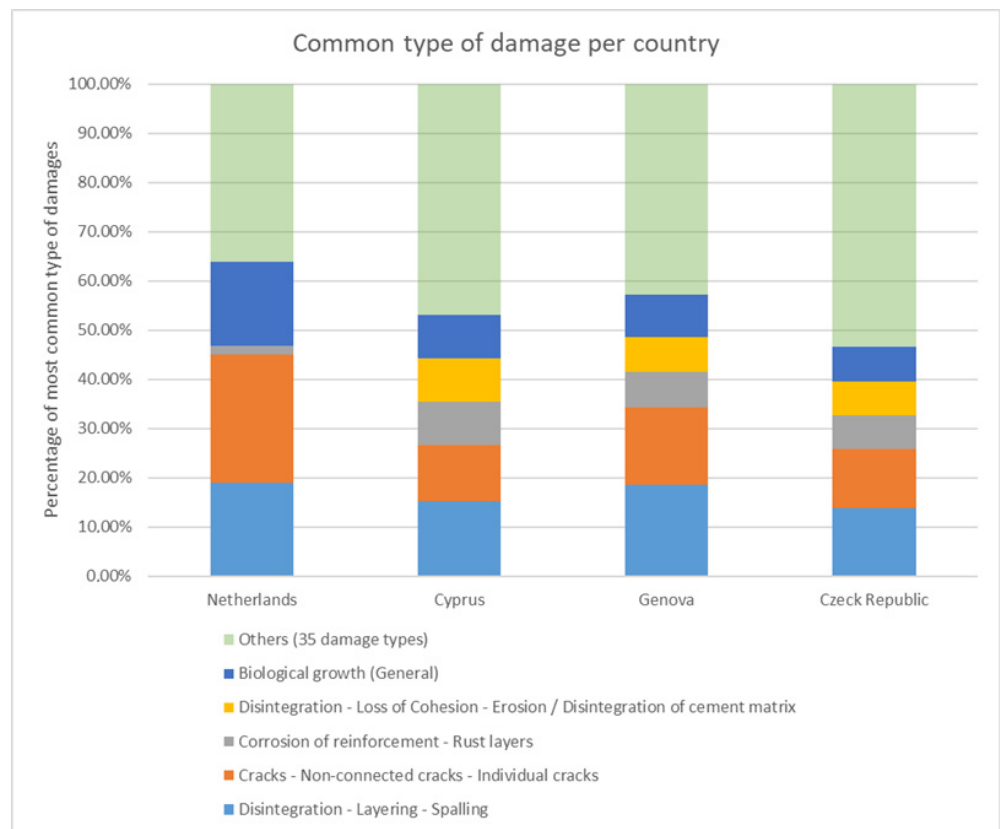


Figure 4. Damage types per country.

Table 2. Types of damage found in the buildings investigated, percentage, and incidence.

Groups of Damage	Number of Damage Cases Reported	% of the Cases Reported	Incidence in Buildings ¹
Disintegration	80	30.77%	18.15%
Surface changes and blemishes	56	21.54%	8.85%
Cracks	46	17.69%	14.17%
Corrosion of reinforcement	41	15.77%	19.44%
Biological growth	34	13.08%	8.93%
Deformation	2	0.77%	1.04%
Mechanical Damage	1	0.38%	2.08%
Deformation of reinforcement	0	0.00%	0.00%
Total	260		

¹ Percentage of buildings having the specified type of damage.

Regarding the hypothetical causes of damage, the most recurrent were carbonation-induced corrosion (29%), biological growth (24%), and surface condensation (12%). When alike, damage processes were grouped in four categories with the following results: Moisture related (35%), Structural damage (13%), Environmental related (17%), and Corrosion (35%).

The correlation between the damage and the potential cause/s is summarized in Figure 5. The most relevant results were that Cracks were predominantly related to corrosion and structural damage, and Disintegration was primarily linked to corrosion, moisture, and environmental processes. The rest of the correlations did not provide significant findings.

Hypothetical Causes of Damage

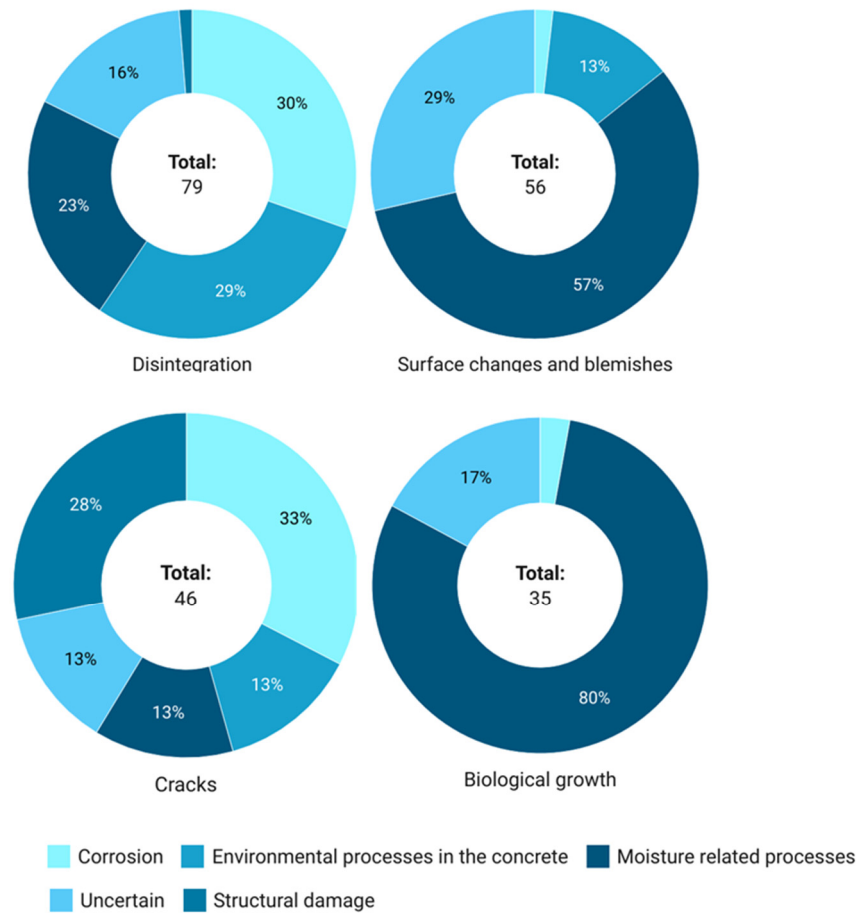


Figure 5. Hypothetical causes of damage per type of damage group.

3.2. Building Characteristics Influencing Damage Severity and Extent

The average age of the buildings was 85 years old, with the youngest being 53 years old. Some of them were restored in the past, amending environmental damage to some degree. For a fair comparison among buildings to determine the level of damage severity and extent, it would not be exact to compare restored buildings with buildings that did not undergo significant restoration interventions, from now on ‘non-restored buildings’. Thus, only non-restored buildings (34 buildings) were taken into account for this comparative analysis.

The non-restored buildings were analyzed to find relations between the level of damage, age, and building characteristics. For example, a building characteristic is the type of roof. The buildings with the same type of roof are compared to the other roof types, also considering the age. When a representative number of older buildings with the same type of roof have a better state of conservation than younger buildings, then there is an indication that that particular type of roof has a positive effect. When the opposite happens, i.e., younger buildings have a worse state, then a negative effect is implied, since it seems to accelerate building degradation.

To evaluate whether the calculated trend was relevant, three factors were considered: (1) Representativeness: The building characteristic was present in at least 20% of the buildings; (2) variability of the sample: The coefficient of variation (CoV) of the level of damage extent and severity was below average; (3) age similarity: The CoV of the age of the buildings for a given characteristic was low ($\leq 20\%$). In this paper, only the relevant building characteristics that suggested an effect are presented and summarized in Table 3. The relevant characteristics influencing positively or negatively the state of conservation of the buildings are shown in Table 4.

The presence of Structural bearing walls in the facades suggests a positive effect. In fact, the average age of this type of building (94.28 years) is higher compared to the rest, but still their state of conservation is remarkably better (half of the level of severity for infill walls for instance). Although, structural bearing wall buildings were concentrated in the Netherlands (66%) where the buildings were, in general, in a better state of conservation. Flat roofs seem to have a positive effect in the prevention of environmental damage compared to other types of roofs, but they were the predominant type of roof across all countries (20 out of 34). Proprietary and non-standard structural systems suggest a negative effect, but the number of examples of this typology is extremely limited—only four buildings. Thus, this result should be taken with a grain of salt. Lastly, the existence of a sacrificial plaster in the exposed concrete elements suggests a positive protective effect. The older buildings with plaster show less damage than younger ones.

Table 3. Parameters affecting the state of conservation of historic concrete buildings.

Building Characteristics	No. of Buildings		Level of Severity		Age	
	N	Representativeness of the Sample	Avg. Level of Severity	CoV Severity	Age (mean)	CoV Age
Type of Façade						
Infill wall	11	22.92%	21.18	61%	83.36	22%
Curtain wall	5	10.42%	16.6	99%	85.4	12%
Structural bearing wall	7	14.58%	10.43	127%	94.28	16%
Other	11	22.92%	26.45	68%	81.54	26%
Type of Roof						
Flat	20	41.67%	16.8	91%	87.8	19%
Gable	3	6.25%	12	74%	93.66	4%
Hip	1	2.08%	28	0%	72	0%
Dome	3	6.25%	13.33	136%	73.66	37%
Combination	3	6.25%	32	20%	86	27%
Butterfly	1	2.08%	36	0%	65	0%
Other	3	6.25%	36	57%	82.67	27%
Type of Structure						
Concrete frame	16	33.33%	17.75	73%	82.68	18%
Concrete load-bearing walls	2	4.17%	3.50	141%	94.00	17%
Hybrid structure	7	14.58%	20.14	70%	83.43	26%
Proprietary	4	8.33%	29.75	66%	103.50	11%
Other	5	10.42%	25.80	91%	78.40	26%
Concrete elements exposed?						
No	7	14.58%	18.28	73%	86	17%
Yes, with coating	1	2.08%	40	0%	85	0%
Yes, with plaster	18	37.50%	15.44	96%	91.5	18%
Yes, without coating or plaster	6	12.50%	32.33	51%	75.16	24%
Other	2	4.17%	20	99%	58	2%
Environment						
Industrial	14	29.17%	17.64	87%	85.14	22%
Maritim	3	6.25%	30.67	82%	93.67	5%
Rural	5	10.42%	12.2	105%	85.2	22%
Urban	12	25.00%	23.33	63%	83.5	18%

The environment is believed to be one of the leading causes of concrete degradation [15]. This non-physical characteristic was also studied by comparing different environments. Buildings in urban areas showed more extent and severity of damage than buildings in industrial areas (refer to Table 3). The highest severity of damage was found in buildings in maritime areas, although the number of buildings was limited to only three. A relation was also expected between specific types of damage, depending on the environment. However, the relative distribution of the types of damage was similar across all environments studied (refer to Figure 6). Disintegration was the most common damage,

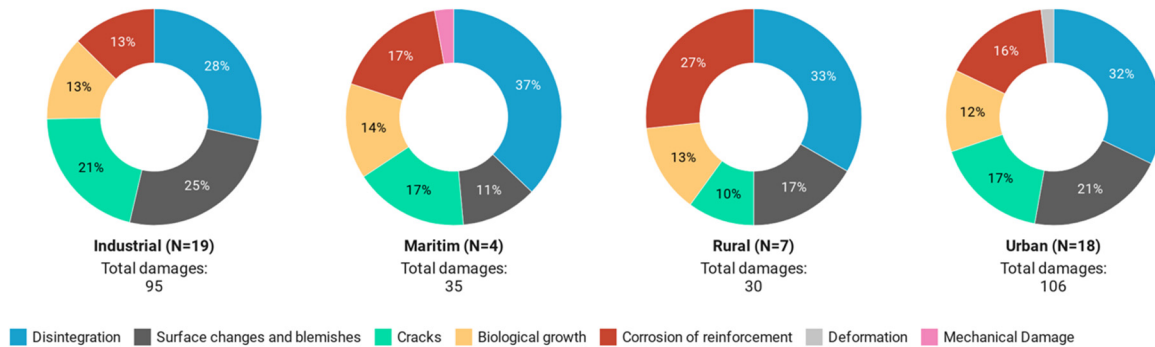
followed by surface changes and blemishes in most environments. Corrosion, cracks, and biological growth appeared in lesser numbers.

Table 4. Factors influencing positive and negative trends in building state of conservation.

Effect of Building Characteristics on State to Conservation	
Positive Effect	Negative Effect
Structural bearing wall facades *	Other than flat, gable and dome roofs *
Flat roofs	Proprietary structures *
Plaster on exposed elements	No plaster in exposed elements *
Private ownership	Public ownership
Adjacent to other buildings *	Maritime and urban environments
Industrial or rural environments	Sport and recreation, and strategic/public services
Original use as Industrial, office and religious	Non-restored buildings
Restored buildings *	

* The parameter complies with relevancy criteria.

Types of Damage per Environment



*N' denotes number of buildings

Figure 6. Types of damage per environment.

The position of the building within the urban context may also have an influence on the degradation process. The results indicated that adjoining buildings showed a better state of conservation compared to the rest of the positions examined, suggesting a positive effect. The isolated position, on the other hand, did not display a positive or negative effect.

The original requirements depending on the use of the building can have regional differences and this can have an implication in their state of conservation. Thus, the original use of the buildings was analyzed. Slight negative trends were found in buildings originally used for Sports and Recreation, and for Strategic and Public services. On the other hand, buildings showing a better conservation state were Office and Business, Religious, and Industrial.

Whether the building had changed its original use or not did not have a noticeable impact on the state of its conservation. Most of the industrial buildings had been converted or abandoned. Educational and Sport and Recreational buildings have been abandoned in Cyprus (CY). In Genova (IT), the only buildings that did not fall into abandonment were religious and “others” (Figure 7).

Change of Use per Country

Change of building use per country

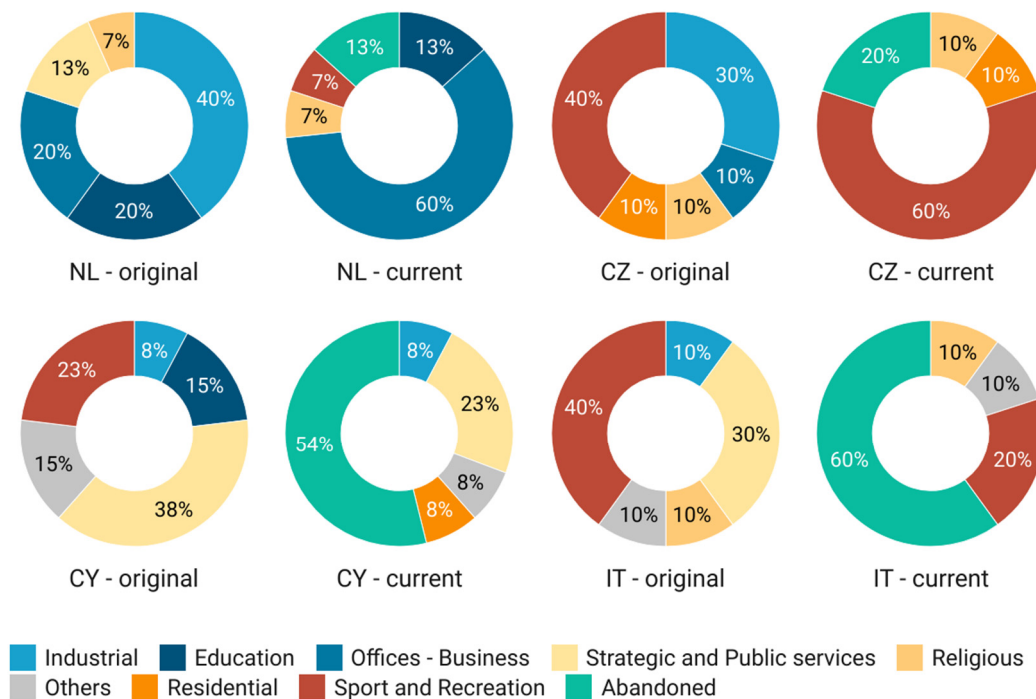


Figure 7. Change of building use per country.

3.3. Trends in Maintenance, Renovation and Reuse in Different Countries

By comparing the state of conservation of non-restored buildings, a trend in building maintenance could be observed among countries. In Figure 8, the non-restored buildings of each country are displayed in terms of Age (X axis) and Level of damage extent and severity (Y axis). The large scatter of the results does not allow for precise conclusions, but some trends can be extracted. Buildings in the Netherlands showed a better state of conservation, having the lowest level of damage across all ages. Cyprus had, on average, higher damage—even in younger buildings. The Czech Republic had scattered results but there seems to be a tendency for a better state of conservation of older buildings. On the contrary, Genova had an opposite trend, where the younger buildings were in a better state than older buildings.

Four different parameters were studied to shed light on the level of maintenance and care of each country: Earlier restorations, abandonment, protection (monumental status), and ownership.

Non-restored buildings accounted for 71% of the buildings studied, showing a similar percentage (from 60 to 80%) in all countries (Figure 9). As expected, restored buildings showed a lower level of damage severity than non-restored buildings.

Abandoned buildings accounted for 33% of all buildings, but this percentage differed among countries. In the Netherlands and the Czech Republic, abandoned buildings represented 20%, while in Genova and Cyprus, they represented 50 and 46%, respectively.

On average, 73% of all buildings had some type of monumental protection. The protection could be local, provincial, or national. Interestingly, the level of damage severity was higher in listed buildings, compared to non-listed, in all countries except Cyprus (Figure 10).

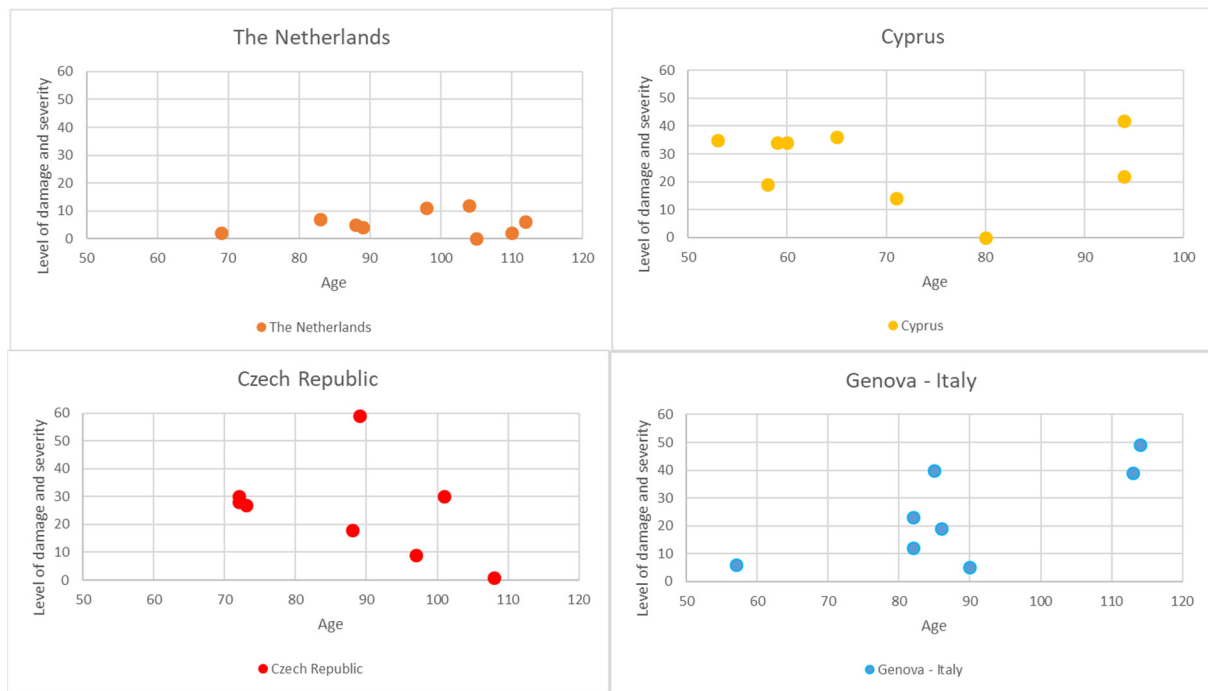


Figure 8. Age (X axis) and Level of damage (Y axis) of the non-restored buildings in each country.

Restored and Non-Restored building per Country

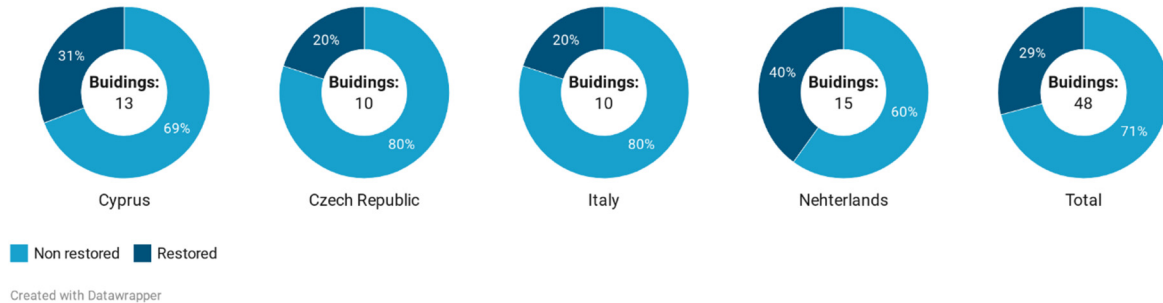


Figure 9. Restored and non-restored buildings per country.

Generally, there is an even number of private and public buildings in the sample, although there are significant differences in their state of conservation among countries. Considering all the buildings, restored and non-restored, the Netherlands and Czech Republic have similar ratios, 67–33% and 60–40% ratios of private–public buildings, respectively. On the contrary, the buildings in Genova were predominantly public ones (90%). Cyprus had an even ratio, 46–54% of private to public buildings. There is not a clear indication between the level of damage and the ownership; although, private buildings tend to be in a better condition than public ones (Figure 11).

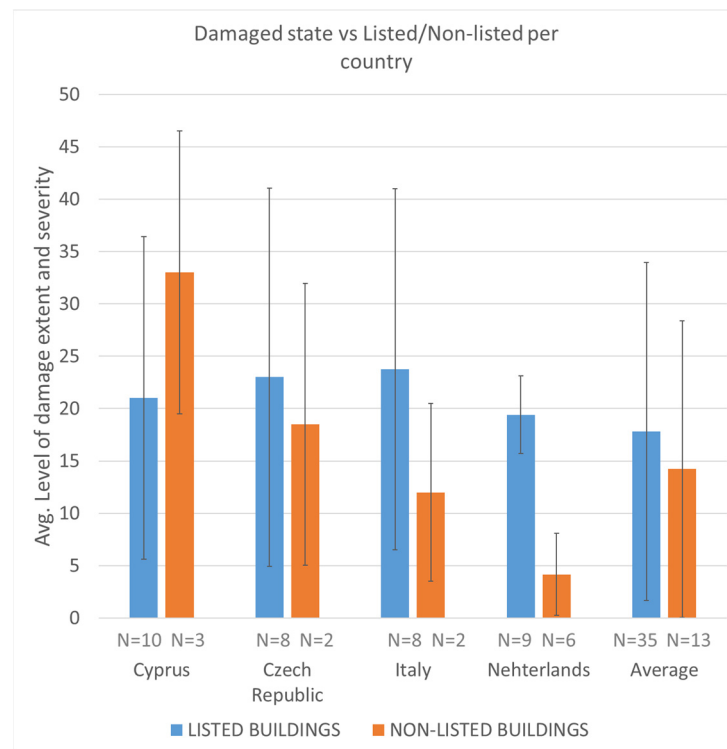


Figure 10. Level of damage severity vs. Building protection per country.

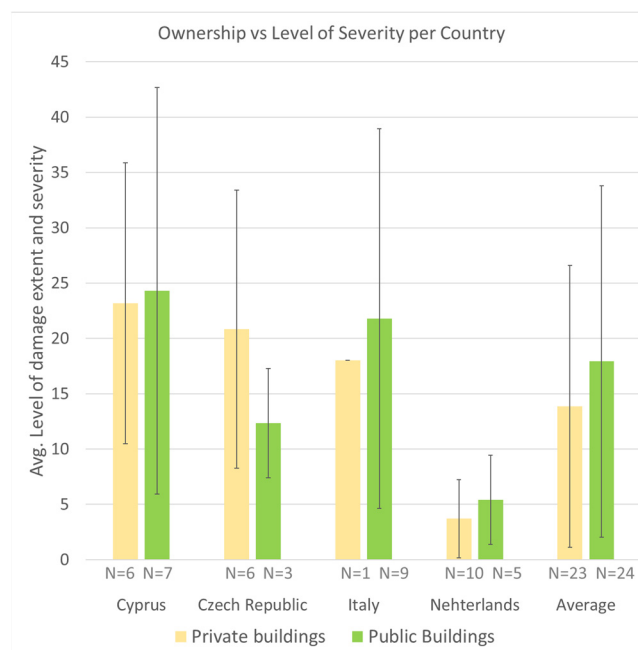


Figure 11. Level of damage severity vs. type of ownership per country.

4. Discussion

Many of the damage types found, such as corrosion, spalling, cracks, and biological growth have a common denominator: moisture. Biological growth thrives in moist environments on concrete surfaces [16]. Cracks are mainly related to corrosion of the reinforcement, which cannot happen without the presence of moisture in the concrete—in fact, the higher the moisture content in the concrete, the higher the corrosion rate [17]. In addition, the reduced concrete cover of the historic concrete and the coarser character of

the material—due to the higher w/c ratios and poorer compaction methods compared to contemporary concrete—can accelerate the carbonation rate destroying the passivity layer at the concrete–steel interface [18]. Still, carbonated concrete does not necessarily lead to deleterious corrosion as long as the moisture content is low [19].

Regarding the physical and non-physical characteristics of the buildings that may have a positive or negative effect on environmental damage, there is not a clear reason why flat roofs have a positive effect on the protection of concrete. One explanation can be that flat roofs tend to deviate water away from the edges of the building, reducing the amount of water that can ‘run off’ down the façade. This can reduce the moisture content in the exposed concrete elements in the façades. Aligning with this theory, a similar effect was observed in adjacent buildings, of which part of their façades are sheltered from rainwater.

The use of sacrificial plaster has proved to add protection against environmental damage to the concrete. The plaster reduces the rate of carbonation of the concrete, allowing less ingress of CO₂, and reduces the moisture content in the external layers of the material [20]. This protective layer has also shown protective effects, “however thin” the plaster was [19]. Whether the plaster was applied originally or not did not make a remarkable difference; the original plaster was slightly more protective than plaster applied in later interventions.

Other characteristics, such as original use and climate, did not have a substantial imprint on the overall building condition and varied among countries. Similarly, the trends in maintenance, renovation, and reuse among countries did not show clear results, but initial hypotheses can be made. The better state of conservation in buildings do not seem related to ownership, monumental protection, or earlier interventions—as there are restored buildings in a deficient state. This suggests that proper maintenance is the key to extend the lifespan of concrete buildings.

Concrete maintenance is still a pending subject in building science. In the last decade, different countries have conducted efforts to produce specific guidelines for concrete conservation of heritage buildings [21–24]. However, as identified in the meeting of concrete experts organized by the Getty Conservation Institute in 2014, long-term maintenance strategies and publications on the subject are still specific areas of need [25]. In the same line are the results published in [7]. The research emphasizes the ‘real’ need of better understanding the specific decays and how to develop and implement maintenance strategies. It also specifies that the target group, the people in charge of the maintenance of these buildings, need information and training on decay patterns and maintenance strategies.

5. Conclusions

This research has defined a methodology to be used as a first approach to objectively assess the state of conservation of historic concrete buildings across different countries. A clear terminology of damage types and measurable parameters, such as the extent and severity of the damage, have the potential to provide solid information to measure the state of a building. This methodology is expected to serve as the basis for larger European quantitative research involving a representative number of buildings across Europe. The goal of the proposed methodology is to gain a global understanding of the problems affecting historic concrete to prevent further degradation to the vast amount of younger concrete buildings.

To tackle the most recurrent types of damage and their respective causes, i.e., corrosion and moisture-related processes, the focus of the conservation and maintenance plans must be to prevent high moisture contents in the concrete. Using plaster has proven to be beneficial to significantly reduce the degradation of the concrete. Research on other types of barriers, such as surface treatments, should also be carried out to track their lifespan and efficiency.

Proper maintenance and continuous use of the building are directly linked to a sounder state of conservation. The dissemination and implementation of conservation and maintenance strategies for historic concrete must be further implemented by owners and actors involved in the conservation field. As further work of this research, workshops and sem-

inars will be given to professionals and non-professionals. The methodology and the complete information of the case studies will be openly available. With these actions, it is expected to open up new channels to reach wider audiences and to build up a solid body of information regarding the safeguard of historic concrete buildings.

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