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Appraisal of two early twentieth century composite masonry-concrete structures: the Civic Theatre in Schio (Italy, 1907) and the Carraresi's Castle in Padua (Italy, XIII century)

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Abstract

In this contribution two examples of buildings constructed using composite masonry-concrete are illustrated: the Civic Theatre in Schio (Vicenza, Italy) and the Carraresi's Castle in Padua (Italy). Their reinforced concrete (R.C.) elements were built at the beginning of the 20th century, a few decades after the invention of reinforced concrete. The theatre, in the original 1907 project, had already been conceived as a composite structure. The castle of Padua, built in the XIII century, has undergone a series of historical transformations, including the introduction of the r.c. elements in the north wing at the beginning of the twentieth century. Both are early examples of the use of the first patented technique for building r.c. structures: the Hennebique system . The Civic Theatre in Schio soon after its construction underwent a decline in its activity, until the complete closure and disuse at the end of the Seventies. The castle of Padua at the beginning of the 19th century, during the French domination, was transformed into a prison. Then, in 1990, the structure ceased to function as a prison and went through about twenty years of disuse which led to the current damaged conditions. The restoration and reuse of both of these structures, thanks to their cultural and architectural value, was proposed and supported by many historians, experts in architecture and fellow citizens. Therefore, both the Municipalities of Schio and Padua are planning to develop projects for their reuse. However, the change in the use and current norms require a series of studies and analyses in order to collect enough information for safety assessment. The comparison between the structure of the theatre and that of the castle is useful in order to gain more knowledge as to the materials and structural behaviour of these early r.c. structures, which nowadays present several problems mainly related to the degradation of the materials and to inadequate choice of structural solutions. In this work, the main results and key observations made during inspections and in situ and laboratory tests are presented. On the basis of collected information, inspections and tests carried out, the level of knowledge achieved could be considered adequate (Confidence Factor of 1,20, according to O.P.C.M. 3431 and EN 1998-3:2005 EC8) for both buildings. Following investigations, the results of the tests were used to check structures according to the original method of calculation (Hennebique system), to the Admissible Stresses method and to the Ultimate and Serviceability Limit State method. The safety assessment, required by changes in the use and by current norms, showed that both structures examined need strengthening repairs. Thus, in general, it is possible to say that most of the historic R.C. buildings need repairs to verify nowadays safety requirements.

Keywords: historic concrete, tests, Hennebique system, Admissible Stresses, Limit States, assessment, checks, confidence factors.

1. Introduction

The history of modern historic concrete started around the end of the 19th century. The primitive plain concrete itself was already employed in ancient Egypt. It became the major-construction material in the Roman age. At that time, the concrete was made from lime and small stones, with use of pozzolana as known. The lime contributes to the hardening process of concrete by the exposure in the air; whereas the pozzolana reacts with lime even in water. The pozzolana constitutes also one of the aggregates and improves strength and durability of the concrete. In the past times the main problem of concrete was its small tensile strength. However, this issue was solved by developing reinforced concrete at the end of the 19th century (Newby F.[8]), which changed the scale of the structure drastically. Indeed, despite the introduction of reinforced concrete in construction has paved the way for a century of continuous technological innovation in the industry the mechanical behaviour of structures made with this material was not fully understood for a long time. The incomplete knowledge of structural behaviour, the lack of development of concrete technology and the difficulty to define the loading conditions, even if in a probabilistic way, with the current accuracy, are at the root of most of the problems of buildings and other r.c. structures realised in the historical period covering the first decades of the 19th century. Nowadays, understanding these issues is essential for planning proper interventions for the rehabilitation and structural improvement of this modern heritage according to current codes.

The Civic Theatre in Schio and the Carraresi's Castle in Padua could be considered the early example of r.c. structures in Italy. For them a specific procedure of study was elaborate. First of all, preliminary investigations were led concerned the design and construction rules of the Hennebique system, the development of the reinforced concrete properties across the two centuries and the available structural codes at the time of construction. The studies included archival documentation on the history of the building, as well as on its design and construction. In-depth critical survey were carried out by means of visual inspections, based on the available detailed geometrical survey. Comprehensive on-site investigations by means of non-destructive and minor destructive techniques allowed gathering useful data on the state of conservation of the structures and the properties of soil, masonry, reinforced concrete element and wood structures of the roof.

The assessments of the r.c. structural elements of the theatre and of the castle were carried out following the Hennebique design principles, using the records found into the original design report, in order to understand the structural and constructive assumptions adopted by the designer, or following the structural code at the time of the construction. Finally, the results of the original calculations were compared to those obtained with modern design procedures. This allowed evaluating the safety level of the buildings and estimating the reliability of the original design procedure.

2. Case studies

The analysed buildings are composite masonry-concrete structure. The Civil Theatre of Schio was designed in 1907 as a composite structure, while the castle of Padua dates to the 13th century. Initially the castle structure was entirely made of masonry, but at the beginning of the 20th century it underwent transformations that led to the addition of horizontal and vertical r.c. structures. The two buildings are characterized by very different structural configurations, by the use of different building types, by the presence of r.c. slabs as well as r.c. and hollow tiles mixed floors. The theatre is located in the centre of Schio, about thirty kilometres to north-west from Vicenza, while the Carraresi's castle is located in the historic centre of Padua.

Historical background of the Civic Theatre of Schio

The Civic Theatre in Schio (Vicenza, Italy) was built during the first years of the 20th Century. It has a rectangular plan with an approximate surface of 1300 m², it is 15 m tall and is composed by three structural portions: foyer and dance hall; stalls; stage and backstage spaces (Figure 1). The external load bearing vertical structures and those that separate the three portions of the building are made of stone masonry walls. Both the horizontal and the vertical load bearing structures of the stalls are made of reinforced concrete, designed and built according to the Hennebique patent (Nelva and Signorelli [7]) by the Porcheddu company from Turin. At that time Porcheddu was the only patentee in Italy. This building is thus an early example of reinforced concrete structure in Italy. The year of construction coincides with the year of publication of the first national code on reinforced concrete (D.M.10/01/1907 [11]).

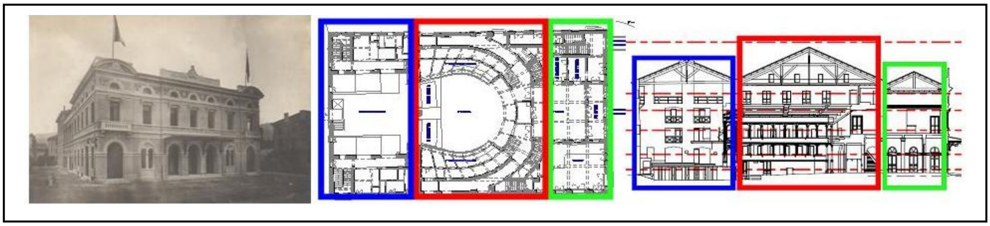

Figure 1: Civic Theatre of Schio: historical photo and the three structural portions

In 1915 Italy came into the war, the Civic Theatre closed and it was used as a warehouse of military Subsistence. For unknown reasons, in 1916 the ceiling of the hall collapsed because of a fire, but in 1919 the theatre was rebuilt and resumed its regular activities. From the Seventies to 1982 the structure completely declined, but between 1982 and 1987 some maintenance works were carried out. In 1994/97 the Town Hall Administration got involved with the restoration of the main facade, the maintenance of the cover and the restoration of the hall and the atrium of Ridotto (Zironda [10]).

Historical background on the Carraresi's Castle in Padua

The castle's towers were built during the domination of Ezzelino III da Romano when in 1237 he came in Padua and imposed his dictatorship. In 1256 Ezzelino was defeated by the Lega and in 1338 the Carraresi domination started. In 1374, Francesco da Carrara started the castle's construction, in which the pre-existing towers were incorporated. In 1405 the Carraresi's domination was substitute by the Serenissima one and until 1709 the castle became a military depot and a barn. Then, at the beginning of the 19th century, during the French domination, it was transformed into a prison. In 1899 hygiene requirements related to the transformation of three dormitory-rooms to infirmary led to the construction of three floors with the Hennebique system. In the following year, works were executed by the Porcheddu company. During the First World War, the north wing was severely damaged because of bombings and then, during the Fifties, the double leaf wall was replaced with a reinforced concrete frame. Prison works went on in time and inside the building two different workshops were settled: the north wing was used as a furniture factory, the south wing as a mechanical production lines for the construction of bicycles (Bressan [3]).

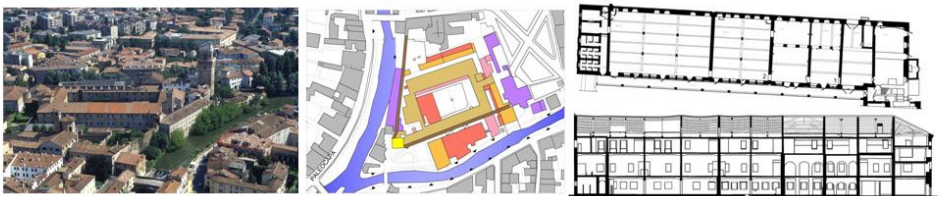

Figure 2: Castle of Padua: photo, plan and section

Finally, since 1990 the structure is no more a prison and its disuse, during approximately twenty years, has taken a part in the current damage state.

3. In situ and laboratory investigations

Several on site inspections were planned and then carried out on both buildings to improve the level of knowledge. Thus, details useful for the assessment of the structural behaviour were verified, and their state of conservation was assessed. Investigations were planned to minimize obtrusiveness on existing structures and to favour crosschecking of results among tests at different level of invasivity. Visual inspection constituted the first step for identifying the most significant elements on which carrying out tests for the characterization of the vertical and horizontal structures and where to gain the data we need. In particular, the main tests were:

- soil drillings for recognizing available stratigraphy and identifying property of the foundation soil;
- borehole corings in the most representative portions of the r.c. structures for verifying stratigraphy and for laboratory mechanical, chemical and petrographic analyses;
- flat-jack tests on walls (single and double), for estimating stress values and for evaluating the elastic modulus and compressive strength at elastic limit of masonry in the most representative portions of the walls;
- local scarification for studying details;
- non-destructive tests with magnetic scanner to detect reinforcing bars in concrete;
- non-destructive tests with sclerometer for a first appraisal of compression strength of r.c. elements;
- resistographic tests in the main roof structures to evaluate the strength of timber elements and their conditions.

R.C. structures

The vertical and horizontal r.c. structures of the two buildings belong to different historical periods. In particular, the Theatre of Schio has a unique construction system (Hennebique), whereas the castle, in addition to the Hennebique system presents at least two other constructive technologies. The reinforcement bars in all cases are smooth, so the element which makes possible to identify the different construction eras is the type of stirrups. Tests performed with scanner detected flat stirrups (typical of Hennebique system), stirrups with a “serpentine” shape, as illustrated in the second beam section of Figure 3 and stirrups with two arms as we use today. The techniques used to identify those details were scanner and local scarifications (Belluco [2])(Figure 4).

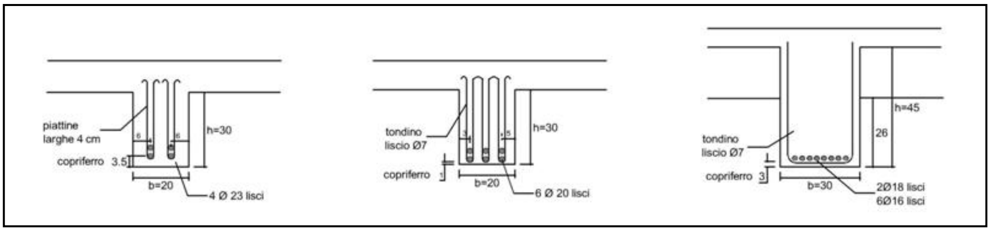

Figure 3: The three typology of stirrups

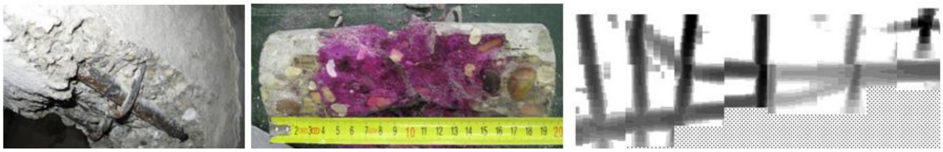

Figure 4: Local scarification, carbonation test and magnetic scanner

As regards the on site mechanical characterization of concrete, in both buildings non-destructive testing with sclerometer were performed. This technique, in the case of the theatre of Schio was accompanied by ultrasonic investigations, to perform the Sonreb method correlation. The results are shown in

Table 1.

Quantitative analysis of concrete properties were carried out in laboratory by means of compression tests performed on cores of material taken from slabs, beams and pillars.

Mechanical tests were complemented with phenophtalein chemical tests, for the detection of carbonation phenomenon, and, in the case of the castle, also with petrographic analyses and study of the mineralogical composition of concrete through diffractometric analysis with X rays of powders (XRPD) (Figure 5).

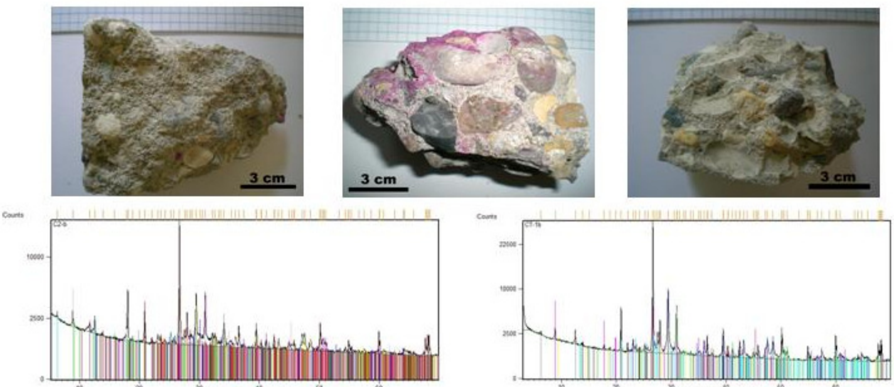

Figure 5: Petrographic analyses

	tests no.	r.c. structural element	rebound index	speed of propagation [m/s]	time [μs]	distance [cm]	R_{ck} [N/mm^2]
Theatre of Schio	S1	beam	41,7	2900	42	12,5	15,2
	S2	pillar	48,6	4347	42,8	18,5	51,0
	S3	pillar	46,8	4107	44,9	18,5	44,7
	S4	beam	47,3	4576	40,4	18,5	53,5
	S5	beam	45,6	2714	66,6	18,5	16,0
Castle of Padua	00.109	beam	36,1	-	-	-	34
	00.109	beam	36,6	-	-	-	35
	00.109	slab	37,7	-	-	-	28
	00.110	beam	31,3	-	-	-	25
	00.110	beam	40,6	-	-	-	41
	01.036	beam	42	-	-	-	46
	01.035	beam	36,5	-	-	-	35
	01.035	beam	27,2	-	-	-	18
	01.035	slab	30,7	-	-	-	15
	01.032	beam	30,7	-	-	-	25
	01.032	slab	26,4	-	-	-	9
	02.049	beam	39,2	-	-	-	40

Table 1: Sclerometer and ultrasonic tests results

		r.c. structural element	R_{ck} [N/mm²]	carbonation depth [mm]
Civic Theatre of Schio	1S3	slab	15,4	55
	2S1	slab	21,4	45
	3S1	slab	15,7	60
	4SLB	slab	9,9	total
	2T3	beam	27,1	67
	3TL	beam	26,7	66
	4TL	beam	28,1	40
Castle of Padua	C1	slab	32,9	35
	C2	slab	26,6	45
	C3	slab	52,1	15
	CP1	pillar	29,7	20
	CT1	beam	40,3	100
	CT3	beam	35,5	45

Table 2: Compressive strength of cores

As illustrated in

Table 1 and in

Table 2, in the Civic Theatre of Schio compressive strength of beams in the hall and in the gallery are higher (26,7÷28,1 MPa) than values found in slabs (15,4÷21,4 MPa). In particular, the gallery slab has the lowest compressive strength (9,9 MPa) because of the total carbonation, inadequate texture and particle-size distribution (Figure 6). Investigations on the beams and columns of the gallery were not possible because they have a too small section size (Capozzo [4]).

Figure 6: Civic Theatre of Schio: slab cores

The best values of compressive strength were found in the Hennebique elements of the Castle of Padua ($R_{ck,beam}$= 52,1-R $_{ck, slab}$ = 40,3 MPa) although they were built first of all.

4. Assessments

A bibliographic research on the original calculation reports was performed for both buildings. In the Porcheddu archive of Turin (Archivio Porcheddu [1]) drawings and information regarding the structures built with the Hennebique method were found, for other structural r.c. elements it was not possible to retrieve any data on the procedure of calculation.

First of all, the calculation reports were studied in order to understand procedures for beam design and to find correlations between shear and bending moment, section size, quantity and arrangement of reinforcement bars. Then, the assessment of different types of structural elements were carried out firstly by using the original method of calculation (determined or perceived). Then, the method of Admissible Stresses (AS), according to D.M.14/02/92 [12] was considered. Whereas, in the case of the Castle of Padua, also verifications to the Ultimate Limit State (ULS) and to the Serviceability Limit State (SLS) were carried out according to the Semiprobabilistic Limit State methods illustrated in the D.M. 14/01/2008 ([15]). The load conditions were distinguished at nowadays and at the state of project.

Hennebique system

For each beam and slab the original calculation report gave, on average, the following information: the load per meter carried by the beam; formulas for determining bending moment and shear; the values of compression zone height, of lever arm and of the distance between the tensile reinforcement bars and neutral axis with formulas to find them; quantity of tensile reinforcement bars, quantity of the necessary longitudinal reinforcement bars and diameters; number of stirrups and their step; width, thickness and axial length of stirrups. This method of calculation was then repeated for the most significant structural elements. In the Theatre of Schio, structural elements located on the side of the stage and the beams of the gallery were verified; in the castle of Padua, some structural elements belonging to each of the identified historical period were assessed.

The reproduction of the Hennebique calculation method solved some initial uncertainties. It was found that:

- geometric section was established a priori, and reinforcement bars were adapted to the available arm;
- the resultant of forces within the compressed edge was always and still placed in the above slab centre of gravity neglecting the contribution of the concrete rib between neutral axis and slab;
- the effective width of the slab which worked with the beam below was probably considered equal to the distance between beams;
- the distance between the reinforcement bars and the beam edge was considered a priori equal to 5 cm both at the tensile edge and at the compressed one;
- for shear calculation, after finding the maximum acting shear, it was assumed that this would be held up half by longitudinal bent bars and half by stirrups. So the shearing concrete strength was completely neglected. After imposing the maximum value of shearing stress borne by the reinforcement bars (usually the Porcheddu company used a limit of 0,7 N /mm²) it was possible to obtain the amount of bars needed through the following formula :

$$A_S = \frac{T}{2\sigma_s} \qquad (1)$$

where: A_s is the reinforcement bars area, T is the maximum shear value, σ_s is the admissible shear stress in the steel for each number of stirrups arms;
- stirrups spacing depended on shear actions: at higher stress, in fact, spacing is smaller. As for spacings following the first, by analysing sequences for different beams, it seemed that the k-th Δx spacing increased following this law:

$$\Delta x_k = \Delta_{k-1} + k \ \text{ per } \ k = 0, n \qquad (2)$$

where k is the increase in centimetres compared to the previous step.

The values of strength calculation used in the Hennebique method for the homogeneous iron and concrete, equal respectively to 100 and to 2,5 N/mm^2, permitted to have a very high safety factor, equal to 4 for iron and 5 for concrete (Table 3)(Capozzo [4]).

Safety factors	
D.M. 10/01/1907(as Hennebique system)	D.M.09/01/1996 Admissible Stresses
$\frac{R_{c,failure}}{\sigma_{c,calc}} = \frac{12 \div 15 N/mm^2}{2{,}5 N/mm^2} \cong 5$	$\frac{R_{ck}}{\sigma_{c,adm}} = \frac{15 N/mm^2}{6 N/mm^2} \cong 2{,}5$
$\frac{R_{s,failure}}{\sigma_{s,calc}} = \frac{370 \div 450 N/mm^2}{100 N/mm^2} \cong 4$	$\frac{R_{s,failure}}{\sigma_{s,adm}} = \frac{540 N/mm^2}{260 N/mm^2} \cong 2$

Table 3: Comparison between safety factors

In the Civic Theatre of Schio the original calculation report was used for studying the Hennebique method theory. The Castle of Padua was assessed against two load combinations. One includes an overload of 6 kN/m² (combination 1) set out by norms for reusing the castle as library and the other combination considers the current state characterized by dead loads only (combination 2).

$$N_1 = \gamma_G G_k + \gamma_Q Q_k \tag{3}$$

$$N_2 = G_k \tag{4}$$

where: γ_G and γ_Q are partial factors for actions, G_k are dead loads and Q_k are live loads.

The Hennebique calculation method considering the current load condition (only self-weight) led to a positive assessment of most of all elements analysed, with the exception of those located in areas which have undergone changes of dead loads over time. Instead safety assessments were not satisfied using combination 1. The results subdivided for steel and for concrete are illustrated in Table 4.

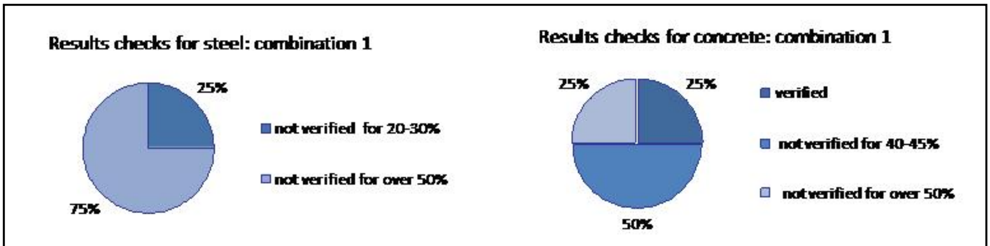

Table 4: Castle of Padua: assessment of R.C. elements with the Hennebique method

Admissible Stresses

The assessments to the Admissible Stresses according to the D.M.14/02/92 [12] were performed on the main elements of the Theatre of Schio and the north wing of the Castle of Padua. However, in the first case, checks were conducted only at the project state (Q_k= 4 kN/m²), whereas in the castle checks were relating to both the current state (only self-weight) and the project state (Q_k= 6 kN/m²).

The theatre of Schio presented some critical zones. In particular, the gallery had very low mechanical properties (R_{ck} =9,9 MPa) which did not comply with safety requirements. Moreover, the Serviceability Stresses were over the Admissible Stresses mainly in beams and slabs modified during the building construction (Table 5).

In the castle of Padua, checks were almost all satisfied. Structural deficiency held on in main beams on the ground floor and in beams on the first floor where original dead loads were changed over time (Table 6).

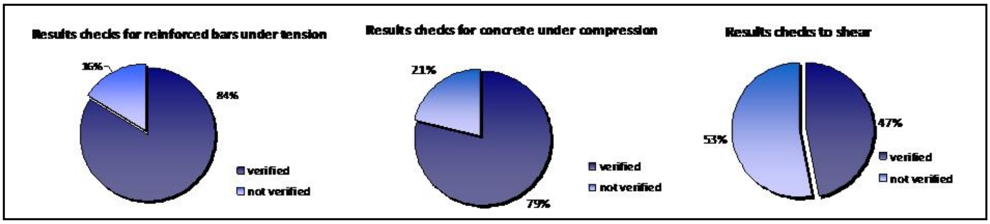

Table 5: The Civic Theatre of Schio: assessment of the admissible stresses

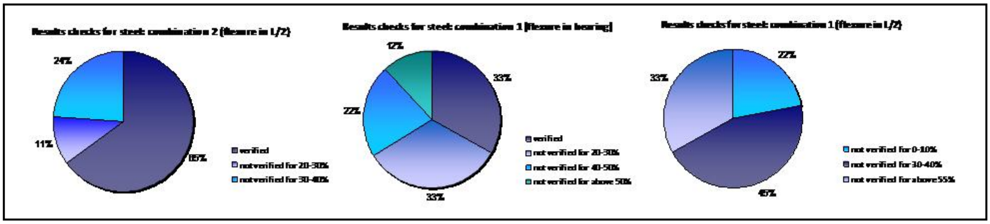

Table 6: The Castle of Padua: assessment of the admissible stresses

Limit States

The Limit States assessment was conducted only for the castle of Padua. The Ultimate Limit State was assessed against load combinations 1 (eq.3) and combination 2 (eq.4). The Serviceability Limit State assessment was led only for the elements which, subjected to the load combination 2, were verified by the ULS, but not by the Admissible Stresses method. The percentage of verified and not verified elements are presented in Table 7.

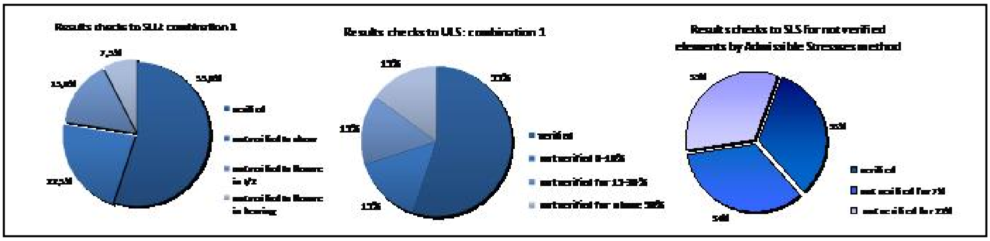

Table 7: ULS and SLS assessments

5. Conclusions

In the Theatre of Schio, the structures designed by the Hennebique method are almost all verified by the Admissible Stresses method. This result could be explained by two observations: the approximations of the Hennebique system were taken over by the use of high safety factors and also by oversize structures and the overload required by the theatre reuse is the same of the original one (Q_k= 4 kN/m²). However, localised structural weaknesses were found and hence further investigations will be necessary to quantify the real vulnerabilities and to determine appropriate repairs for the final reuse.

The combination of actions for the project state is more burdensome in the castle of Padua, where the placement of a library (Q_k = 6 kN/m²) was planned. At the ULS main problems are related to the behaviour of beams to shear. In fact in the Admissible Stresses method shear was carried by both stirrups and bent bars, whereas in the ULS only stirrups carry shear. Moreover, elements not verified by AS usually were verified by the ULS. Indeed the AS method considered only linear phase of materials, whereas during checks the ULS method also uses non-elastic properties of materials.

In the future it will be necessary to integrate these results with the seismic assessment. Horizontal actions of earthquake on these historic structures are going to underline further limits and weakness in particular because of shear stresses.

In general the reuse of an historic building (especially a public reuse) requires an increase of overload and the subsequent appropriate strengthening repairs for verifying the structures according to current norms.

Acknowledgement

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