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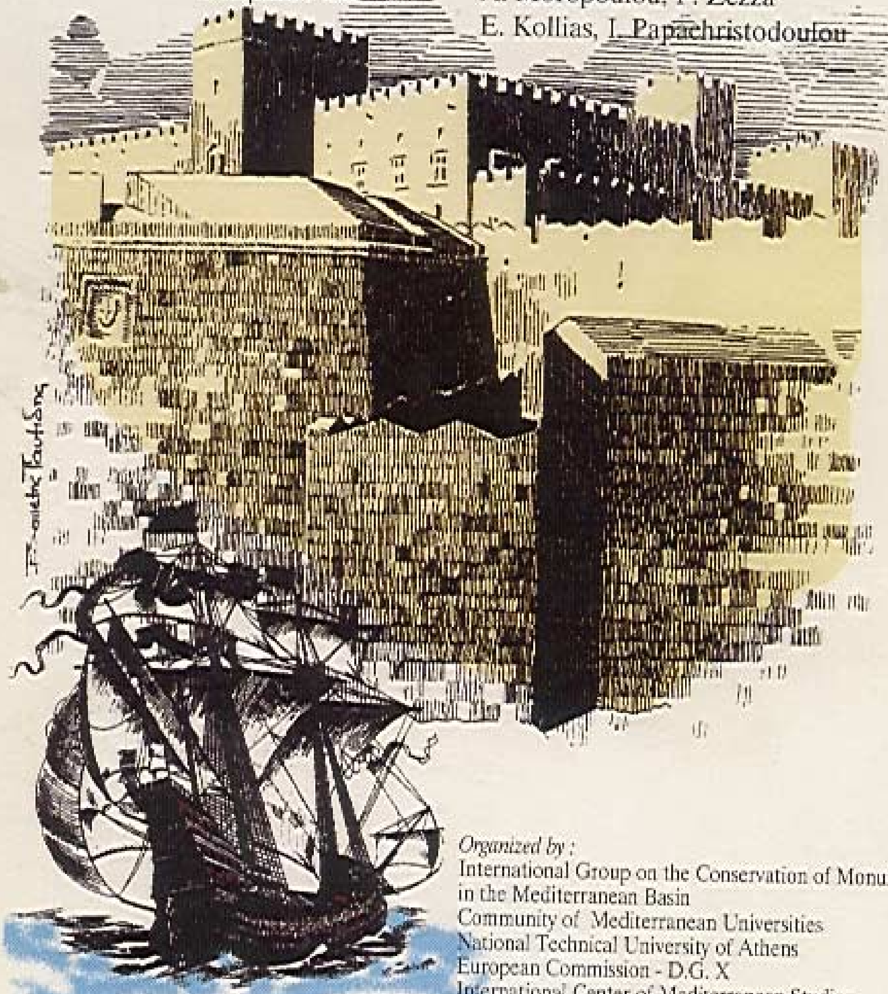

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AN APPLICATION OF THE SONIC METHODOLOGY IN THE TOWER MASONRY STRUCTURAL CONTROL ON THE "SFORZA CASTLE" IN GALLIATE

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Abstract

The use of CND (Non Destructive Controls) has a great importance in the renovation field, due to the possibility of accomplishing researches in preventive and diagnostic stage on buildings historical-artistic interest. The application carried out on south-east tower of Galliate castle, which is based on the utilization of indirect surveying technique, was aimed at the experimental data re-elaboration, in order to correctly evaluate the static condition of the case study. The compressive stresses affecting the wall structure were related to propagation velocity of ultra-sounds recorded. The method which allowed us to emphasize the dependence between the causes and the effects was the regression analysis; therefore, by using a statistical elaboration, the "dependence curves" were obtained. The performed experiment allowed us, first to express remarks consideration with respect to the static condition of the case study, secondly to implement an evaluation control methodology, in structural terms, of monumental buildings individual parts.

1. Description of the tower, object of intervention

The south-east tower of the "Sforza Castle" in Galliate rises out ground with a form represented in horizontal section by a figure comparable to an upset "L"; the establishment of the tower, with a cross section of the same typology as the described shape, develops vertically upon a height of approximately 19.35 m; the value is measured with reference to a vertical line drawn from the higher end point of the corner merlon, facing the homonymous square, and the main point of reference of the elevations placed at the level of the ground floor of the external scarp walls in elevation, which constitute the externally visible base and lying in the contiguous ditch, of the same tower. The horizontal sections used to explain the distribution of the utilizable spaces at the different levels of the tower and to represent the consistence of the resistant areas of the masonries under prevalent actions of the vertical loads can be referred to at four similar dispositions of form, respectively located aft the cellar floor (elevation level, plane moat; -5.20 m), of the ground floor of the Castle (elevation level, horizontal level of the superior line of moulding of crowning of the impost plane of the curtain faceworks: 0.00 m), of the passage connecting trench guard floor on the contiguous south curtain facework (elevation level, trampling plane of the communication trench and contiguous floor on the tower; +5.10 m) and at last, of the trampling plane of the communication trench of the terrace storey of the tower (elevation level +11.00 m). The geometry of the above - mentioned cross sections is resumed in the Table 1.1 which points out in detail evidence, floor to floor, the resistant area of the bearing walls.

	Gross area m^2	Net area m^2	Resistant area m^2
Cellar floor	147.20	72.00	75.20
Cellar floor *	130.00	72.00	58.20
Ground floor	125.30	70.70	54.60
Passage connecting trench guard floor	113.10	54.00	59.10
Terrace storey	121.58	102.00	19.58 **

Table 1.1- Geometric features of the horizontal cross section of the south-east tower of Sforza Castle in Galliate.

(*) Estimated values without computing the horizontal occupation area of the projection of the slope.

(**) Area of the impost section of the battlement which projects on the brackets

The global morphology of the construction and its configuration are mainly referred to by a single object consisting of a truncated prismatic base on which develops in elevation a single body formed by two similar parallelepipeds jointed and placed on a base (represented by an upset "L") with oblique symmetry; inclusively the tower occupies on the whole of 2449 m^3 of which 1054 m^3 are consist only of vertical masonries of the "sack" type.

The wall structure making up the tower, consisting of the elevated vertical parts and the sloping parts which are typical of the basement, is mainly composed, for what concerns the vertical loadbearing masonries, by two facings, an internal and an external one, each of them being 27 cm thick and consisting of brick blocks, laid according to a Gothic laying, and of an air space having a variable thickness according to the topometric position of the wall. The air space is filled with a lime mortar, bricks and river stones mix and it represents the variable element for the different thicknesses of the walls realized at the internal offsets which are found along the height of the tower's internal spaces; for what concerns, instead, the basement's loadbearing structures elements, the most important feature is the slope of the wall's external bank which assumes a 0.20 value for all the brick facings which face the moat surrounding the whole Castle. The building technique of the external perimetrical walls, which originally had a defensive function, is known as the "sack" masonry. The facings employed in these masonries, before performing a loadbearing function, provided the caissons for the following building phase which was carried out by filling the air space with a mix made of inerts consisting of river stones weakly bound with lime mortar. The variability of the walls thicknesses along the tower's height may be resumed by using some values that can be obtained both at recent openings (entrance portal to the Asilo bridge, window under the bridge's arch) and at ancient openings (loopholes that still may be found at different heights); these thickness values may be more or less resumed according to the following values, respectively: 2.60 m at the vault impost reveals of the bridge leading to the tower; 2.10 m at the level of the loophole situated on the south-facing side adjacent to the guard communication trench of the curtain overlooking it and, as last value, 0.05 m related both to the battlements (Figure 1.1) and to the upper outrising parts, that is to say the masonry overhanging the corbels which support the battlements.

To completely describe the present state of the different structures included in the angular body of the tower it is also important to mention the original fitting of the barrel vaults which contributed in creating the planks for the levellings of the two floors, which are still used as routes for pedestrians giving access to the inside of the Castle; it is also necessary to consider the recent restructuring of the crumbling wooden floor at the level of the battlements which has been replaced by a reinforced concrete slab.

Finally, in order to provide a complete explanation and understanding of the facts that led to the fortification phenomenon, the first document relating about the date of construction of the Castle and containing details about its reasons, its scopes and the necessity of building it, is the diploma issued by Berengarius I on July 19th 911[1] which establishes the origin of the defensive settlement.

2. Experimentation in situ with ultrasound techniques

The indispensable interventions of preservation restoration, which have been recently started under the co-ordination of the *Soprintendenza per i Beni Ambientali ed Architettonici del Piemonte*, were predominantly aimed at the re-settlement and re-arrangement of the many-centuried roofings, which originally stood on the towers and on the curtains of the main bodies belonging to the

Castle's portions which, over different periods, became a municipal property. Now, these interventions have allowed for the execution of a preliminary survey aimed at the sonic-tensional characterization of the masonries situated on the edges of the southern and eastern external boundary lines of the homonymous angular tower. It was possible to lead an exhaustive experimental phase of this work by operating on two different surfaces accessible from the tower: the former, being located at the foot of the external basement and determined by the two longer sides of the cellar's plan, is 1.70 m high and has an overall surface of 49.13 m^2 (Figure 2.1); the latter, being inside the tower and being situated in the room accessible from the adjacent storey of the guard communication trenches, develops vertically along the two walls with windows of the tower along a 1.50 m height from the walkway surface, on a 28.80 m^2 overall area.

The method employed for the sonic characterization of the masonry facings, previously identified on the tower, is essentially based on the measurement of the time needed by ultrasonic waves (in this experimentation, the frequency being 54 KHz) to cover the distance between the transmitting and the receiving probe, positioned on a solidary contact on the material means to be examined, where generates the propagation motion of the ultrasonic waves produced by the transformation of the electric impulses by means of a special instrument consisting, in this monitoring session, by the ultrasound equipment model E46, manufactured by Controls s.p.a..

Among all possible applications of the general method for the use of ultrasounds in non-destructive tests, the technique employed to measure the temporal quantity was the one called homeosuperficial or otherwise known as indirect technique, according to which the test is executed with both probes (transmitting and receiving) positioned on the same surface at previously defined distances - chosen by considering the energy aspects - which, in this survey, resulted to be 1.00 m, 1.50 m and 2.00 m, respectively, and realized by means of locators which were placed on a calibrated rod, used as a movable base.

As regards the practical application of the homeosuperficial technique to the vertical walls of the tower, first of all the attention was drawn, on the whole, to the six horizontal brick courses, positioned on three different heights of the wall facing belonging to one of the previously indicated surfaces, and chosen for the sonic characterization; then, by making the calibrated rod with locators placed at 0, 100, 150, 200 cm, progressively slide along each horizontal course - spatially determined by its respective springing height - the individual fixed reference points, placed at known relative distances, were fixed on the masonry in order to measure propagation times; these points, positioned on the masonry and lined up along the course to be surveyed, coincided, each time, at each progressive shifting of the movable base, with the corresponding locators marked on the calibrated rod. By acting as illustrated above, it was possible to analyse the ultrasounds propagation times, as a whole, on 143 points located on the tower's masonries and distributed in the following way: 104 were located on 35 progressive horizontal measuring bases which were spatially determined on the tower's external basement; 39 points were located on 13 localized horizontal bases, inside the tower, in the room facing on the guard communication trench The transit times values, measured on each base, have been included in a diagram as a function of the three invariable relative distances, chosen to mark the reference points on the movable rod. These diagrams (an example is given in Figure 2.2), are a diagrammatic representation of the survey's results.

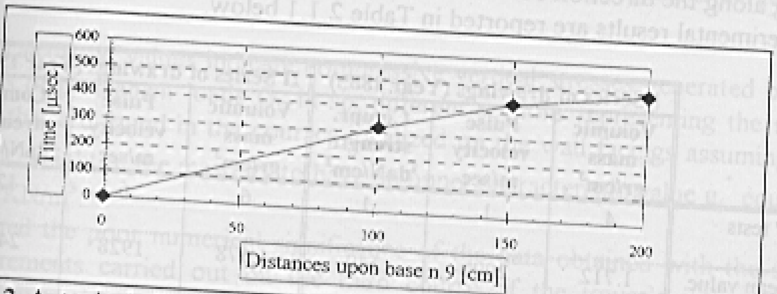

Fig. 2.2 A typical diagram of the transit times obtained by indirect method measuring on fixed points of a moving base horizontally disposed, along the second course (h=100) situated inside the room of the south-east tower of the Sforza Castle in Galliate.

2.1 Other kinds of checks and tests

While performing the sonic monitoring survey on internal and external walls of the south-east tower of the Sforza Castle in Galliate it was possible to make an on-site sampling of a limited amount of solid bricks from the two distinct masonry portions of the monumental group that presumably date back to as many production and installation periods. These periods, that can help establishing the age of the blocks belonging to the two groups of samples which have been taken from different positions of the tower, can be chronologically dated. the former dates back to 1885 when the part including the eastern curtain was restructured at the same time as the refuge was being built; the latter may date back to 1969: the material recovered in this case was sampled from the bricks used for the restructuring of the tower's top battlement on the occasion of the latest restoration intervention (*Restauro Chierici*).

The scopes of the theoretical/experimental programme were essentially aimed at the characterization of the static behaviour of the masonry which was assessed in terms of global safety coefficients, equivalent to the ratios between the effects of vertical permanent actions and the corresponding resistance capacity of the sections that are deemed to be the most meaningful as concerns the checks to be done. In order to make a correct assessment of the data gathered by means of the sonic measurements, a programme involving complementary tests has been prepared and realized for each individual artificial element available in order to define the physical and mechanical properties of each group of elements recovered during the sonic monitoring survey. In particular, in order to meet the above mentioned minimum requirements, the following parameters were obtained for the two groups of samples:

-volumic mass and nominal dimensions of the brick (270 x 134 x 62 mm),

-ultrasounds transit time and velocity, using the direct method in transparency, along a horizontal trajectory coinciding with the brick's greatest dimension;

-compressive strength under uniaxial compression of the brick with a stress acting along the direction of vertical loads.

Experimental results are reported in Table 2.1.1 below.

	I Series of drawings (Year 1885)			**II Series of drawings (Year 1969)**		
	Volumic mass gr/cm^3	**Pulse velocity m/sec**	**Compr. strength daN/cm^2**	**Volumic mass gr/cm^3**	**Pulse velocity m/sec**	**Compr. strength daN/cm^2**
N° tests	4	1	1	6	6	12
Mean value	1.712	2090	540	1.578	1928	240
Standard deviation	0.087	-	-	0.059	213	31
Coefficient of variance	0.05	-	-	0.04	0.11	0.13

Table 2.1.1- Experimental results of tests carried out on the masonry.

3. Statistical Analysis of experimental results

The numerical values of the pulse velocity measurements, obtained with the indirect method, have been subsequently processed according to statistical analysis methods, by using distinct phases related to the different purposes to be achieved.

For subsequent developments, before progressing the analytical processing of the sonic data, it is useful to draw the attention to how measurements were made during the acquisition of pulse velocity: each horizontal section of the wall facing, lying at the same height as the course where the corresponding horizontal pulse velocities were acquired, is the place where a stress state takes place; according to our purposes, we have assumed this stress state to be essentially due to the action of vertical permanent loads (steady load of the overlooking structural parts).

The analysis of these vertical permanent loads has then allowed to calculate, on the basis of nominal dimensions and specific weights, the stress states σ, under compression on the different localization heights of the courses belonging to the wall facings, inside or outside the tower, concerned by the sonic characterization. The results obtained are reported in Table 3.1.

	Height cm	Stress daN/cm^2
1st course (place inside tower)	50	$\sigma_1 = 1.35$
2nd course (place inside tower)	100	$\sigma_2 = 1.26$
3rd course (place inside tower)	150	$\sigma_3 = 1.16$ *
4th course (battlement tower)	170	$\sigma_4 = 4.64$
5th course (battlement tower)	120	$\sigma_5 = 4.74$
6th course (battlement tower)	70	$\sigma_6 = 4.83$

Table 3.1- Values of the stressing states along the courses of the masonry
(*) Course not considered in the following treatment for shortage of the data of the available sonic measurements.

The calculated values indicate compressive vertical stresses generated by the actions of permanent loads G_k in six different sections representing the stress states that are found in the courses localized on the wall facings assuming the specific weight of the masonry to have an upper characteristic value g_s^* equal to 19.00 KN/m^3.

Granted the poor numerical significance of the data obtained with the sonic measurements carried out on the third course of the tower's internal wall facing, we obtained, however, five samples of data about indirect pulse velocities that, considering how they were acquired (horizontal trajectories along horizontal courses), can be considered as affected by a stress state σ_i existing in the relative horizontal section.

To complete the exposition of the pulse velocities data, the five samples have been considered separately and for each one we have calculated the most meaningful statistical indexes.

Tables 3.2 and 3.3 report the main parameters estimated for each sample and obtained from the respective populations assumed being distributed according to a Gaussian distribution: in particular, as regards the statistical variable "pulse velocity" v_p, it is possible to read: the number of measurements executed, the value of the mean of velocities, the range of the sample, in terms of maximum and minimum value, the mean square deviation, estimated with the moment criterion (standard deviation) and, finally, the coefficient of variance, meant as the ratio between mean square deviation and the mean of the velocities.

Assuming that the populations of pulse velocities, to which correspond the five assigned samples, are all distributed according to a normal distribution and estimating, according to the moment criterion, the parameters M(v) and S(v) (average and mean quadratic deviation), it is possible to trace, on the normal probabilistic chart, the five straight lines that individuate these distributions, by means of the reduced variable u of the cumulative standardized normal distribution function which linearly graduates one of the two reference vertical axis of the probabilistic chart.

Statistics remind us that, by virtue of this method, the functions of probability F(v) of a certain type (in our case the normal distribution) can all be represented through straight lines; on the chart, then, the values of F(v)'s are read on a vertical axis by adopting a particular graduation obtained by introducing the dimensionless variable u (3.2) that is known as reduced variable of the cumulative standardized normal distribution function and that verifies the well-known property:

$$Q(u) = F(v) \tag{3.1}$$

In this specific case, to create the normal probabilistic chart, a graduation of v values was chosen on the axis of abscissas, in order to include the extreme values of the group of data:

	Number of individual values	Mean of the velocities m/sec	Max. velocity m/sec	Min. velocity m/sec	Standard deviation m/sec	Coeff. of variance
1st course	15	3412	4003	2534	404	0.118
2nd course	15	3479	4112	2963	401	0.115
3rd course	9	-	-	-	-	-
All data	39	3460	4112	2534	396	0.114

Table 3.2- Statistical parameters of the sonic measurements carried out inside the south-east tower.

	Number of individual values	Mean of the velocities m/sec	Max. velocity m/sec	Min. velocity m/sec	Standard deviation m/sec	Coeff. of variance
4th course	35	3546	4103	2254	380	0.107
5th course	34	3458	4142	2054	478	0.138
6th course	35	3621	4284	2900	373	0.103
All data	104	3543	4284	2054	414	0.116

Table 3.3- Statistical parameters of the sonic measurements carried out on the base of the south-east tower.

The values of reduced variable u have been inserted, in linear scale, on the axis of ordinates with $u \in [-3; +3]$; so, by using an appropriate table[III] , which attributes the values of Q(u) for the cumulative standardized normal distribution function, the values of cumulated probability corresponding to the whole values of u in the interval [-3; +3] were marked on an axis parallel to the axis of the reduced variable u.

The group of data of the sample was reported on the normal probabilistic chart following points $[v_i, F(v_i)]$, that is to say, using the linear scale of the reduced variable u, by marking the points $[v_i, u_i]$, where u_i is the fractile corresponding in table[III] to the value $F(v_i)$ of cumulated frequency. By estimating unknown parameters M(v) and S(v) the actual distributions of normal probabilities were (then deduced; these probabilities hold true for what concerns populations of velocity of each individual sample and can be represented through straight lines of the following type:

$$u = \frac{v - M(v)}{S(v)} \tag{3.2}$$

Parameters M(v) and S(v) are calculated by using the moment criterion, for an N number of measurements, as a function of the values of first and second rank moments of the sample, corresponding to the moments of the sample, corrected against distortion, through the following relations:

$$M(v) = v_m \tag{3.3}$$

$$S(v) = s(v)\sqrt{\frac{N}{N-1}} \tag{3.4}$$

Since in our case we knew on the whole the data of 104 and 39 observations, carried out both on the basement and inside the tower, it was interesting to compare each distribution of probability, estimated for each course of the tower's basement and interior, with those obtained through values M(v) and S(v), globally deduced from the two global data samples belonging to the two sets of measurements. So, the following data were obtained:

$v_{m,basement}$ = 3543 m/sec   S(v) = 414 m/sec
$v_{m,internal}$ = 3460 m/sec   S(v) = 396 m/sec

Each estimate of parameters M(v) and S(v) corresponds to an equation straight line of type (3.2), that can be easily drawn on the probabilistic chart as the line connecting the two points [(M(v)-S(v)), -1] and [M(v), 0] whose co-ordinates are read on the axis of casual variable v and reduced variable u.

By adopting the above criteria, it was possible to draw on the normal probabilistic chart, the straight lines representing the functions of probability $F_i(v)$ for the five samples consisting of the sets of values of sonic velocities, measured along each individual internal course of the tower (straight lines $u_{[1]}$ and $u_{[2]}$) and on the courses of the external basement (straight lines $u_{[4]}$, $u_{[5]}$ and $u_{[6]}$).

We here after report each equation obtained for each of the indicated straight lines:

$$u_{[1]} = \frac{v - 3412}{404} \quad \text{1st course, inside tower} \tag{3.5}$$

$$u_{[2]} = \frac{v - 3479}{401} \quad \text{2nd course, inside tower} \tag{3.6}$$

$$u_{[4]} = \frac{v - 3546}{380}$$ 4th course, external basement (3.7)

$$u_{[5]} = \frac{v - 3458}{478}$$ 5th course, external basement (3.8)

$$u_{[6]} = \frac{v - 3621}{373}$$ 6th course, external basement (3.9)

The distributions they represent are affected by their respective stress states σ_i, created by the action of permanent loads acting in the corresponding sections (see Figures 3.1, 3.2).

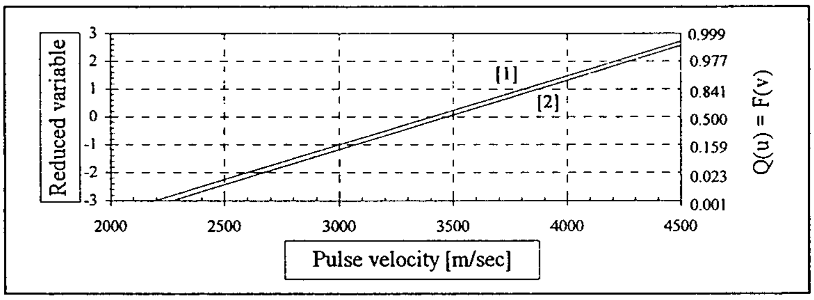

Figure 3.1- Normal probabilistic chart. Representation of the distribution functions for the two velocity samples measured on the wall courses inside the tower.

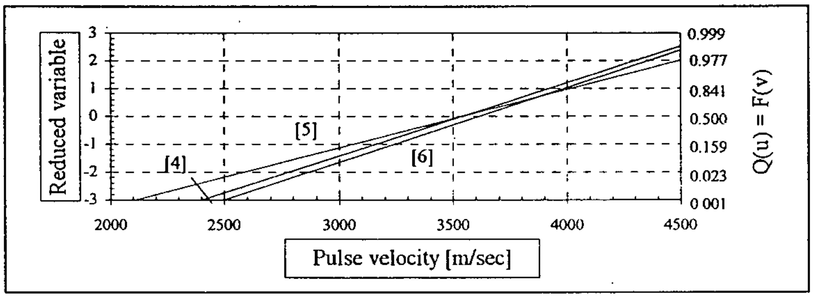

Figure 3.2- Normal probabilistic chart. Representation of the distribution functions for the three velocity samples measured on the wall courses of the tower's basement.

As previously pointed out, together with the representation of the functions of probability for the five samples obtained through the analysis of the gathered data, it was possible to group together the data in two groups of values of the measured velocities inside the tower and on its basement, respectively, for the two obtained global samples, characterized by their own mean stress states $\sigma_{m,internal}$ = 1.26 daN/cm^2, $\sigma_{m,basement}$ = 4.74 daN/cm^2; the straight lines, that on the normal probabilistic chart represent the corresponding functions of probability $F_i(v)$, have the following equation (see Figure 3.3):

$$u_{[internal]} = u_{[7]} = \frac{v - 3460}{396} \qquad (3.10)$$

$$u_{[basement]} = u_{[8]} = \frac{v - 3543}{414} \qquad (3.11)$$

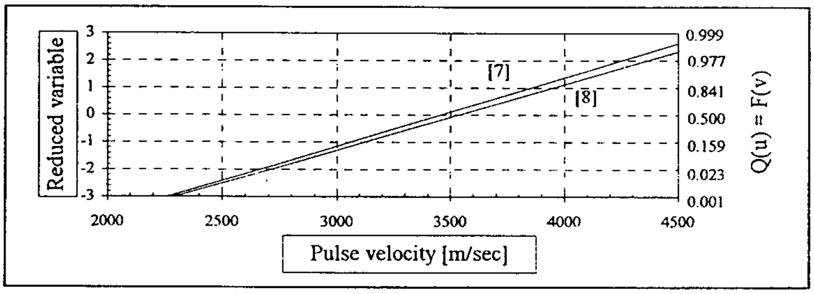

Figure 3.3 - Normal probabilistic chart. Representation of the distribution functions for the two global velocity samples measured on the wall courses of the tower's basement and interior.

With reference to the mentioned global samples, it was possible to make some initial remarks:

- for each distribution, the probability that velocity lies within the interval M(v)-2S(v) equals 0.954, therefore, it is possible to consider fractiles of rank 0.023 and 0.977, corresponding to the values of probability of the respective normal distributions $F=F_i(v)$, as smaller and greater representative values for velocities in the extreme areas of distributions. These velocity values, obtained by inserting values +2, -2 assigned to the reduced variable u in the respective equations of straight lines (3.10) and (3.11), are summarized in Table 3.4.

This table presents an added column to indicate the condition "null propagation velocity" when the compressive stress reaches the characteristic breaking strength f_k of the wall facing.

	F(v) = 0,977 u = +2	F(v) = 0,500 u = 0	F(v) = 0,023 u = -2
$\sigma_{m,internal}$ = 1.26 daN/cm^2	4252	3460	2668
$\sigma_{m,basement}$ = 4.74 daN/cm^2	4371	3543	2715
$\sigma = f_k$ = 56 daN/cm^2	0	0	0

Table 3.4- Values of the pulse velocities (expressed in m/sec) depending by parametric values of distributing functions and corresponding compressive stresses.

Failing experimental data, which are difficult to obtain on historical facings, the breaking strength was deduced on the basis of the characteristics of each of the components employed to build the masonry (f_{bk} = 176 daN/cm^2, characteristic strength of the blocks obtained from the experimental data shown in Table 2.1.1 by applying to the sample the known relation $f_{bk} = f_{bm} - K_s$; assumed type of mortar: M4 - Point 2.3.1.1 of Ministerial Decree 20-11-1987[III].

The linear interpolation between the extremes of the corresponding class of the block's reference value of characteristic strength related to the type of supposed mortar allowed to assign to the masonry a characteristic strength f_k=56 daN/cm^2. To analyse more deeply the statistical dependence between the "causes", represented by the extent of the stress state acting in the masonry, and the "effects" produced on the sound pulse velocity, holding true the casual priority bound existing between the two variables, the analysis of regression is a method that can establish a statistical link between the two variables. In our case, to make our previous remarks more concrete, it was necessary to look for a functional relationship between the values of simple compression stress state σ_i and the mean values of indirect pulse velocity v_p.

It was possible, for each of the two reference global samples, corresponding to the mean stress states of the tower's masonry, to assign predetermined values of marginal probability (0.023, 0.500, 0.977) to the respective functions of distribution and therefore determine the corresponding values of pulse velocities according to order (rank) p, which was fixed in advance; these values v_k, combined with values σ_k , representative of the masonry compression stress states, which in turn affected the two functions of probability, originated points $[\sigma_k, v_k]$ of the functional dependence relation between the observed physical quantities we were looking for; these points, according to our purposes, were interpolated with second-rank curves having known marginal probability values.

With reference to what we have already pointed out, in order to complete the choice of interpolating points and once asserted that the pulse velocity is null when the compressive stress state reaches the masonry mean breaking strength, the interpolation of stresses-velocities points (velocities being ranked with the same values of probability obtained from the respective distribution functions, as illustrated in Table 3.4) allowed to establish a functional link (curves of stress possibility/compressive stress), obtained with second-rank dependence curves, between the results of compression tests on the blocks that characterized the procedure followed to determine the historical masonry mean strength and the velocities of the ultrasonic impulses measured on the tower at the same time as the action of permanent loads. These curves (Figure 3.4), considering how they were obtained, are characterized by marginal probability values F(v) of 0.023, 0.500 and 0.977, respectively, and have the following expression:

- for u =+2 $v = -2.18244\ \sigma^2 + 47.2900\ \sigma + 4195.88$
- for u = 0 $v = -1.69837\ \sigma^2 + 34.0408\ \sigma + 3419.80$
- for u =-2 $v = -1.21430\ \sigma^2 + 20.7916\ \sigma + 2643.73$

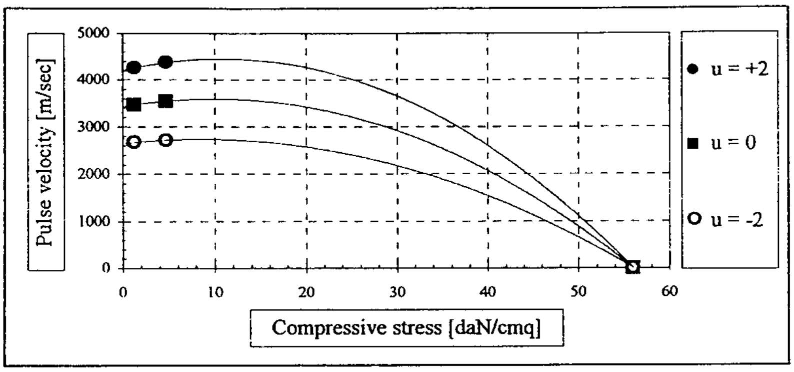

Fig. 3.4- Curves of stressing possibility for the south-east tower of the Sforza Castle in Galliate.

They admit also peak-points, obtained by equalizing to zero the corresponding derived functions, whose ordinates divide the respective diagram in two areas, one with increasing velocity, the other one with decreasing velocity, allowing to point out two different behaviours of the masonry: as a matter of fact, in the former area, increasing velocities are conceptually justified by admitting the compaction and settling of the particles of which are made the masonry blocks, while in the latter area (with decreasing velocities), the masonry behaviour may be explained by the formation and propagation of microfissures that spread until failure[IV].Anyway, it is necessary to remark that the propagation of these microfissures is however linked to the beginning of tensile stress states in the masonry, together with poor or nearly null tensile strength of the examined material; to be more exhaustive, even if the predominant stress state found in the wall courses is the compressive state, the beginning of microfissures and consequently the decrease of ultrasound propagation velocity must necessarily be related to the presence of tensile stresses and not directly to the considered compression stress states. It is remarked that, by assuming the breaking state of the masonry as a reference, the global coefficient of safety γ existing between the masonry's characteristic strength and the action of permanent loads alone, results to be:

$$\gamma = \frac{R_k}{S_k} = \frac{56}{4.74} = 11.8$$

Such a value is far greater that the one that is normally demanded for this kind of structures (3*1.5=4.5), but if we admit that the peaks of the curves of stress possibility are points that outline an excessive state of microfissures, then, by simple reasoning on the central curve with marginal probability 0.500, the coefficient of safety with reference to this fissuring state takes on the value:

$$\gamma_f = \frac{10.02}{4.74} = 2.11$$

(being σ_f = 10.02 the abscissa corresponding to the relative peak for the central curve in Figure 3.4) and could be considered as a threshold for the considered service fissuring state.

4. Conclusions

The experiment executed on the masonries of the south-east tower of the Sforza Castle in Galliate, allowed to define a check methodology for the assessment of the static conditions of individual structural portions of a monumental building. The method, which is based on the ultrasonic survey combined in a well-balanced way with a necessarily limited sampling of undisturbed blocks to be submitted to crushing tests, consists in defining a procedure, by means of a statistical analysis of the obtained experimental quantities, able to combine and summarize the meaning of "causes" and "effects", through the definition of dependence curves, otherwise known as curves of stress possibilities for compressive stresses, which are representative of the variability range of normal stresses σ and of propagation velocities v measured on the monitored building.

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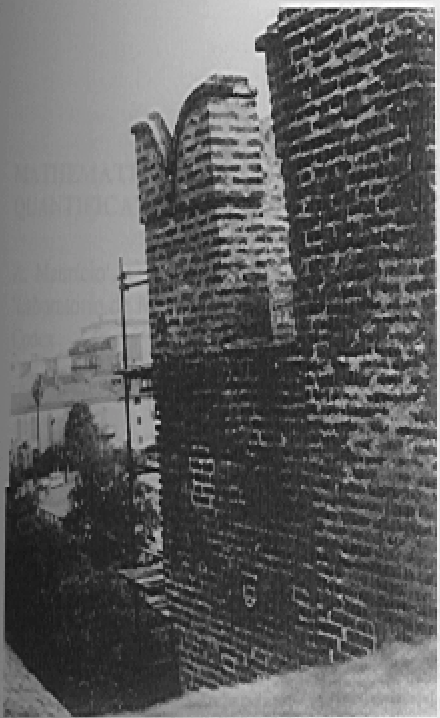

Fig. 1.1 - Crowing merlons of the south -east tower of the Sforza Castle in Galliate

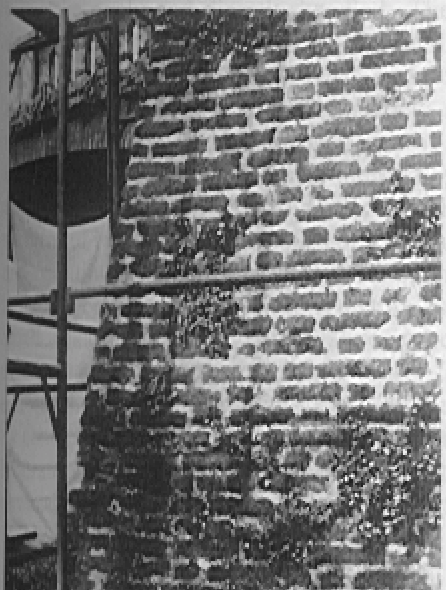

Fig. 2.1 - Base of the south -east tower of the Sforza Castle in Galliate, part of the area interested with sonic monitoring

Fig. 1.1 - Crowing merlons of the south-east tower of the Sforza Castle in Galliate

Fig. 2.1 - Base of the south-east tower of the Sforza Castle in Galliate, part of the area interested with sonic monitoring