THE ACTIONS OF AXIALS LOADS ON MASONRIES - ULTRASONIC VERIFICATIONS AND STATISTICAL ANALYSIS OF OBTAINED DATA

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Abstract: Among the different non-destructive tests used to carry out an exhaustive survey about the mechanical and durability characteristics of a masonry made of solid tile-bricks, the ultrasonic method has experienced a wide diffusion thanks to its low costs and to its easiness of use; the method essentially consists in detecting the propagation velocity of ultrasonic pulses propagating through a solid to be acoustically characterized. The solid considered in this theoretical and experimental survey has been obtained from a meaningful statistical sample of masonry units made of solid tile-bricks blocks bound together by cement mortar.
The experimentation made use of one set of masonry panels, prepared for this purpose, consisting of solid bricks of UNI type (size of block cm 5.5 x 12 x 25 produced in Italy), arranged according to the thickness or according to a "one-head" pattern scheme .
The total height of the samples of the set is 48 cm inclusive of cement mortar layers, the mortar having been prepared according to the Italian regulations. The issues which came out during the statistical analysis of the experimentation results are basically of inductive nature: the purpose is to move from a limited and incomplete knowledge of the values of the propagation velocity quantity measured on the masonry, to get the most suitable definition of the possible distribution of all the values that can be reached by velocity under stress conditions imposed by the strength applied on the masonry at the moment of measuring the ultrasonic wave. The strength is generated by a press used to simulate the conditions imposed on the axial strength of the specimens under investigation.
The purpose of this work is to present a procedure for the interpretation of the data in order to assess the compressive stress state by using the ultrasonic velocity variable obtained from masonry samples expressly prepared for this experiment.

Introduction: Among existing non-destructive tests suitable to carry out an exhaustive survey about the mechanical characteristics of wall facings, the ultrasonic method has been fairly well disseminated thanks to his low costs and its user-friendly operation; the procedure mainly consists in detecting the velocity of propagation of ultrasound impulses spreading inside a solid to be acoustically characterized. For the purpose of this work, the solid was made by a fixed number of panels of solid brick masonry connected to each other by means of cement mortar.
The ultrasonic investigation is presented and proposed as a predicting tool to extend to the measurements of the simple compressive stress state in the panels assessed during failure tests, the corresponding values of the velocities of longitudinal propagation measured simultaneously through the definition of a functional link. The paper intends to propose an interpretation procedure able to assess the compressive stress state of given masonry elements by using the pulse velocity variable obtained on a series of masonry samples specifically prepared of this kind of experimentation.

Results: Six masonry panels have been expressly prepared for the experimentation. Each panel has been prepared according to the scheme (figure 1) foreseeing the arrangement of seven courses of solid bricks UNI-type placed according to the brick thickness, therefore resulting in a one-head positioning after the interposition between courses of a layer of equivalent gauged mortar of type M3 prepared according to what provided for by the Italian standards on masonries (D.M. of 20/11/1987) for this type of mortar.[1]
Wall panels with geometrical dimensions BxLxH of cm 12.0 x 52,0 x 48,0, levelled on their upper and lower parts through the interposition of a layer of distribution and levelling mortar

have individually undergone to simple compressive test through the application of a centered load generated by a 2000 KN press in order to determine the ultimate compressive load.

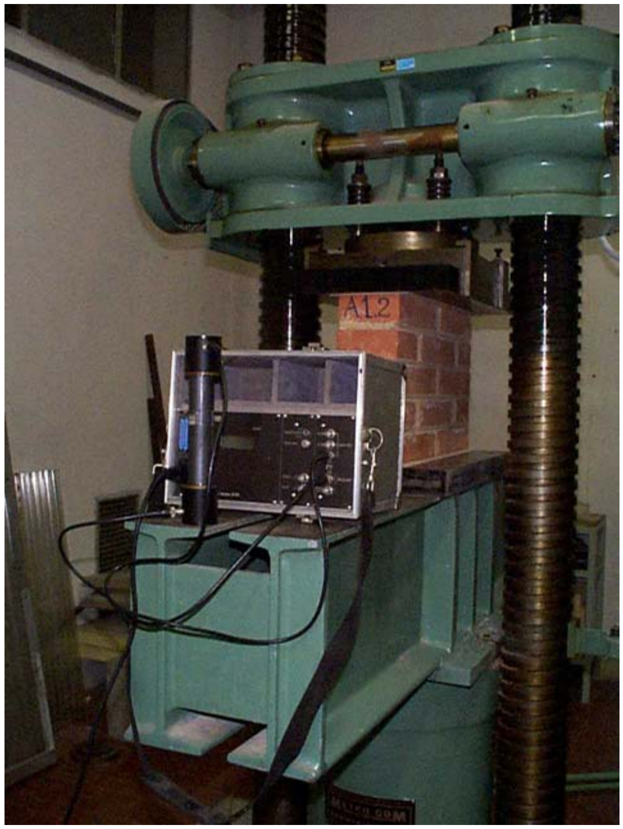

Figure 1. Preparation of the masonry panel for breaking test after having obtained the ultrasonic velocity data

Along with the preparation of the panels, also other specimens have been prepared to determine the most meaningful mechanical characteristics of each individual constituent material of the wall facing by proceeding in accordance to what indicated at paragraph 2.1.1. of the Annex to the above mentioned D.M.
Before breaking the masonry samples, the available masonry panels where subjected to ultrasonic characterization. To this end, the panels were subjected to three different loading steps: no load, 200 and 400 KN; at each loading step, the ultrasounds propagation velocity was measured through indirect technique (probes placed on the same wall face) applied with horizontal trajectories on a base of cm 34,7 + D, D being the 5 cm diameter of the probes.
For each loading condition, the results expressed in terms of propagation velocity of the ultrasound impulses, are listed in the table below (1). In particular, for the statistical variable "pulse velocity" it is possible to read the number of measurements carried out, the value of the mean of velocities, the amplitude of the sample in terms of minimum and maximum value, the standard deviation and, finally, the coefficient of variatiance, considered as the ratio between standard deviation and the mean.

Load	Number of individual values	Min velocity m/sec	Max. velocity m/sec	Mean of the velocities m/sec	Standard deviation m/sec	Coeff. of variance
	22	2880	3680	3252	201	0,061
200 KN	19	2960	3880	3364	219	0,065
400 KN	19	3100	3890	3395	274	0,080

Table 1 – Statistical parameters of the ultrasonic measurements carried out in the different loading conditions

Discussion: The numerical values of the propagation velocity, obtained with the indirect method, have been processed through a statistical analysis.
Before illustrating the different phases of the processing of the data of ultrasonic velocities, it is useful to draw attention to the procedures used to obtain the pulse velocities. By using a 2000 KN press acting simultaneously to the measurement of the main velocity of propagation of the ultrasonic impulses, each sample was subjected to two successive external vertical load increments; to go further into details, during the simultaneous ultrasonic and tensional experiment, each tested panel was subjected to an initially null load which was incremented by a load intensity of 200 KN during the intermediate phase, to reach a 400 KN intensity at the last step of increment of the vertical load before bringing the panel to failure.
The compression break load of each of the six panels was determined during the final phase of the experimental cycle. The obtained average value was 58696 daN, corresponding to an average compressive strength of the masonry $f_{m,wall} = 94$ daN/cm^2. Following the above procedure, it was possible to identify the consequent compressive stress states induced by external loads into the panels; thinking in terms of efforts achieved the compressive stress, the loads have been expressed as per cent quantities of the average compressive strength of the masonry of reference panels; such a value is expressed by the average value of compressive strengths obtained through the tests performed until failure of each of the six panels used for the determination of the average break load.
The relations obtained, characterised by different acquisitions of ultrasonic data, are given below:

Masonry samples with no load $\sigma(1) = 0$

Masonry samples under a 200 KN load $\sigma(2) = 0{,}34\ f_{m,wall}$ (32 daN/cm^2)

Masonry samples under a 400 KN load $\sigma(3) = 0{,}68\ f_{m,wall}$ (64 daN/cm^2)

Each tensile state of independent stress $\sigma(1)$, $\sigma(2)$, $\sigma(3)$ imposed on the wall panels, corresponds to a statistical sample of pulse velocities, from which it is possible to deduce the law of distribution of probability of the respective population.
Supposing that the populations of pulse velocities corresponding to the three assigned samples are all distributed according to a normal distribution law, and having estimated according to the highest likelihood criterion parameters M and S that draw a distinction between a normal distribution and another normal distribution, it is possible to draw on the probabilistic chart the three straight lines representing these distributions by means of the reduced variable u of the

standardized normal distribution function linearly graduating one of the two reference vertical axes of the normal probabilistic chart [2].
In the statistic field, the probabilistic chart is known as a special chart where the probability curves of a certain type (in this case, the normal distribution) are all represented by straight lines.
To better understand the meaning of the normal probabilistic chart and how it is constructed, we can choose on the abscissa axis a linear scale for velocity v values in order to include the extremes of the samples whose F(v) representation is desired.
The values of the probability function F(v) are read on a vertical axis by adopting a particular graduation obtained through a transformation, by introducing the adimensional variable:

$$(1.1) \quad u = \frac{v - M(v)}{S(v)}$$

which is named reduced variable of the standardized normal distribution function which, statistically, has:

$$(1.2) \quad Q(u) = F(v)$$

and where an estimation of parameters M(v) and S(v) is given by the average value v_m and the mean square deviation s(v) of the sample respectively. In the Cartesian plane (v,u) the (1.1) represents a straight line; if on an axis of ordinates parallel to the axis of u (linearly graduated from -3, +3), for each value of u the corresponding value of Q(u) is reported, as obtained from specific tabulation tables of the standardized normal distribution function, an axis is obtained, whose non linear graduation is symmetric with respect to value 0,5 and, given the asyntotic nature of the normal distribution, values 0 and 1 of Q(u) can not be comprised on this vertical axis.
For each statistic sample, the series of velocities measurements is carried on the normal probabilistic chart. It ensues that, in the diagram, where the probabilities Q(u) graduated as specified above are carried on the axis of ordinates, the points (v_i, F(v_i)) relevant to a normal distribution can't but be arranged along a straight line, more precisely, along the straight line that on the corresponding diagram (v,u) has equation 1.1.
Therefore, as regards the samples under examination, after estimating the parameters of distribution M(v) = v_m and S(v) = s(v) according to the highest likelihood criterion, the three straight lines that represent these distributions on the normal probabilistic chart, have the following equation: (see Figure 2.)

$$u(1) = \frac{v - 3252}{201} \qquad u(2) = \frac{v - 3364}{219} \qquad u(3) = \frac{v - 3395}{274}$$

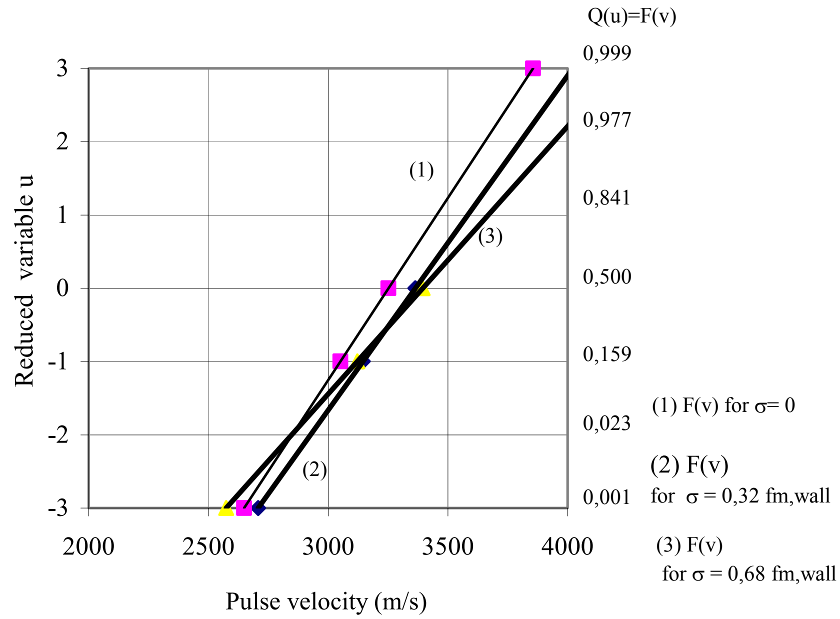

Figure 2 – Normal probabilistic chart. Representation of the distribution functions for the three velocity samples measured on the wall courses of the masonry panels.

and are influenced by the respective three stress states σ_1, σ_2, σ_3.

By recalling the properties of the probability functions F(v) for the three distributions, it is possible to draw the first remarks:

- for each distribution, the probability that velocity be included in the interval M(v) – 2S(v) equals 0,954, therefore, fractiles of rank 0,023 and 0,977, corresponding to the values of probability of the respective normal distributions F = F(v) can be considered as representative lower and higher values of velocities by the extremes of the distributions. Such velocity values, obtained by placing the values +2.-2 assigned to the reduced variable u, in the respective equations of straight lines 1,2,3, are recapitulated in the table below (2) where an additional column was included to indicate the null pulse velocity condition when the compressive stress reaches the average breaking strength of the wall panels.

	σ = 0	σ = 0,34 f m,wall (32 daN/cm2)	σ = 0,68 f m,wall (64 daN/cm2)	σ = f m,wall (94 daN/cm2
	v (m/sec)	v (m/sec)	v (m/sec)	v (m/sec)
F(v) = 0,977	3654	3802	3943	0
u = 2				
F(v) = 0,500	3252	3364	3395	0
u = 0				
F(v) = 0,023	2850	2926	2847	0
u = - 2				

Table 2 – Values of the pulse velocities depending by parametric values of distributing functions and corresponding compressive stresses measured on the masonry panels.

Since the random antecedence link between the variables holds good, the analysis of regression was used to analyse more thoroughly the statistic dependence between "causes" (acting stress states) and "effects" (pulse velocity of ultrasonic waves). For each of the three reference statistic samples $F_1(v)$, $F_2(v)$, $F_3(v)$, influenced by their respective stress states σ_1, σ_2, σ_3, it is possible to assign predetermined values of marginal probability (0.023, 0.500, 0.977) to the respective distribution functions and therefore determine the corresponding values of pulse velocities with a prefixed rank p; such values v_k associated to values σ_k have originated points σ_k, v_k belonging to the investigated relation of functional dependence between the observed physical quantities [3].
Having stated that the pulse velocity is null when the compressive stress state reaches the average breaking strength of the masonry panels, the interpolation of stresses-velocities points (velocities being ordered according to identical probability values obtained from the respective distribution functions, as shown in Table 2) allowed to establish a functional link (curves of stressing possibility) obtained with curves of dependence of the second rank between stress states and velocities of the ultrasonic impulses.

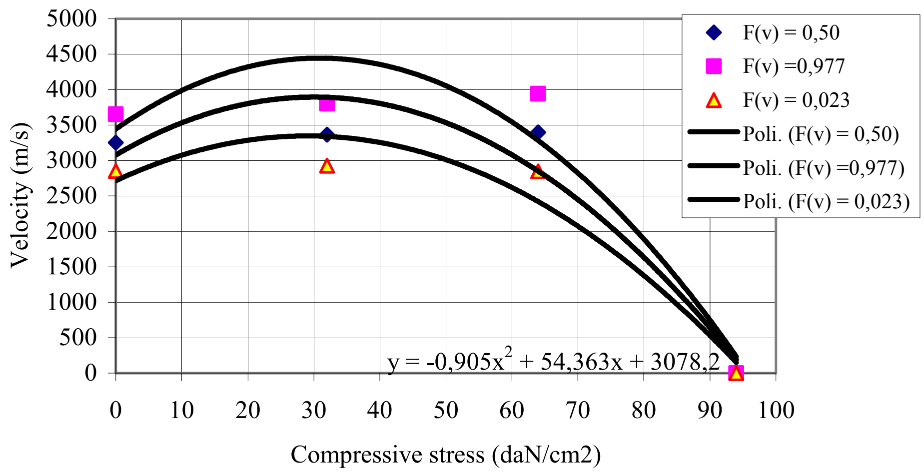

Figure 3. Curves of stressing possibility for the masonry panels tested

Considering how they have been obtained, such curves (Figure 3) are characterised by marginal probability values F (v) of 0,023, 0,500, 0,977 respectively, and they admit maximum points obtained by setting to zero the corresponding derived functions, whose ordinates divide the respective diagram in two areas; one with increasing velocity and the other with decreasing velocity, which outlines two different behaviours of the masonry: in fact, in the former area, increasing velocities are conceptually justified by admitting the compacting and settling and compacting of the particles making up the masonry's blocks, while in the latter area (with decreasing velocities) the behaviour of the masonry may be explained by the formation and propagation of microcracks, that diffuse up to failure. The propagation of these microcracks is related to the generation, in the masonry, of traction stress states, together with poor strength of the brick tile material against this stress; to put it clearer, even if compression remains the dominant stress state for wall courses, the formation of microcracks and therefore the consequent decrease of pulse velocity, must be necessarily related to the presence of traction stresses and not directly to the compression stress states taken into account.

Conclusions: The ultrasonic survey of the performed experiment, together with the statistical analysis of the velocity data can be proposed as a combined method of non-destructive control that can be applied to the masonry facings having drawn the curves of stressing possibilities under compression that are specific of the reference masonries.
The method is based on the use of ultrasonic survey associated in a balanced way with a destructive experimental survey performed on masonry panels to be subjected to breaking tests by simple compression.
The method consists in establishing a procedure through the statistical analysis of the acquired experimental quantities, combining and synthesizing the meaning of acting “causes” and “effects” through the definition of dependence curves, known as “stressing possibility curves” which are representative of the field of variability of normal tensions σ and of the velocities of propagation v detected on the reference panels.

References:

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