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Mechanical characterization of stone masonry structures in old urban nuclei

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MECHANICAL CHARACTERIZATION OF STONE MASONRY STRUCTURES IN OLD URBAN NUCLEI

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ABSTRACT

Ancient stone masonry residential buildings generally have very poor mechanical properties. It is then a common practice, especially in seismic zones, to subject them to heavy and costly strengthening interventions, without adequately controlling the extent these interventions are actually needed. This paper presents the first results of a comprehensive research project, aimed at establishing the actual mechanical characteristics of the more common types of masonry in old urban nuclei in the province of Trento, and to choose the best strengthening interventions. From the scientific point of view, it is relevant to point out that the flat-jack technique was applied for the first time to the considered type of masonry. For this reason calibration with in-situ large scale conventional compression tests was performed.

INTRODUCTION

The work presented in this paper is part of a comprehensive research project sponsored by the Bureau for Public Housing of the Province of Trento (ITEA), whose activity of providing public residential buildings consists now mainly in restoring old masonry buildings in the historical centres of the province. The research has been carried out in collaboration with ISMES, ENEL Research Centre, and the University of Padua.

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Such types of masonry structures generally have very poor mechanical properties. This is due to the use of “poor” materials, i.e. natural, badly bonded (round and roughly dressed stones), and very weak mortars. Strengthening interventions are badly needed for these reasons, especially in seismic zones.

Howerer, the empirical approach on which such interventions are designed and made is no longer acceptable since the techniques and materials which are usually utilized, irrespectively of the cultural and historical value of the building, are very costly. The effectiveness of these interventions also varies depending on the way they are applied.

The project has been carried out in order to provide practical answers to such problems, taking into account the specific characteristics of the masonry typologies and the expected intensities of natural events (especially earthquakes) of the region in wich ITEA operates. The work programme in fact, essentially consists of the evaluation, through in-situ experimental investigations, of the actual mechanical characteristics and structural behaviour of the cited masonry elements and structural systems subjected to vertical and horizontal actions, both before and after they have been repaired and strengthened using different materials and techniques.

Such investigations are in fact absolutely necessary for establishing an engineered approach to the design of structural restoration, by adequately modelling the behaviour of the materials and structures. This modelling should be simple enough to be used in the common practice, but soundly based on experimental data. In this way the actual need and extent of the interventions can be evaluated, and the most appropriate repair and strengthening materials and techniques can be chosen, taking into account the actual characteristics of the existing masonries.

Another important scope of the research is also the immediate transfer of knowledge from research to pratcice. For this reason, the project is scientifically led by the University of Padua and recognised research institutions like ISMES and ENEL’s Research Center, but carried out in co-operation and direct participation with the technical staff of ITEA.

The most important problem which was to be solved at the beginning of the research programme was the establishment of a reliable and economically feasible methodology for the assessment of the mechanical properties of the described type of masonry. The most efficient method which has been so far proposed is based on inspections through core drilling and bore-hole video surveys and evaluations of the state of stress, deformability and strength of masonry through the flat jack technique.

The so far adopted flat jack technique is well calibrated in the case of regular brick and stone masonry. Its application in the case of the studied masonry type, wich is much less homogeneous and without regular mortar joints, required the development and calibration of new specifically designed device and techniques.

This was a very successful phase of the project, in terms of laboratory set up and calibration of new research devices and techniques, through extensive in-situ destructive tests, as well as in furnishing significant information on the mechanical properties of the above mentioned masonry types. The principal results of this research are presented and discussed in this paper.

DESCRIPTION OF THE BUILDINGS AND MASONRY TYPOLOGIES

The territory where the research was conducted extends over a large mountainous region in the north-east part of Italy. However, most of the population lives in the largest valley, along the river Adige. In all such centres the historical nucleus still represents an important (frequently the most important) residential part. In fact, economical, social and cultural reasons make it more and more convenient and attractive to rehabilitate old masonry buildings.

A typical example of an historical nucleus of the region is shown in Fig. 1. In Fig. 2 a and b the typical plant layout and sections of an old masonry building block are displayed.

Figure 1 - Typical nucleus of old masonry residential buildings

A variety of typologies of materials and structural elements, frequently built in several succesive historical periods, determine the complexity of the architectural features of the individual buildings and the block.

Some of the most important characteristics of the studied buildings can be easily categorized since they are typical and mainly connected to such aspects as the use of the buildings and the site where they stand.

Such a categorization has been made, and the selected buildings represente the most common of such categories. Therefore, investigations are being conducted on residential buildings and rural facilities. The first type of buildings were in fact more carefully built and maintained, utilizing mortars, which are of particularly good quality. Buildings made of round and cut stones (in the shapes they are naturally quarried) are also considered. The first types are mostly used near the river Adige, while the second are mostly utilized in the smaller and higher valleys.

Another important structural aspect, which mainly depends on the use of the buildings, is connected to the floor structure characteristics. As can be seen in Fig. 2 a and b, where an ensemble of residential and rural buildings (strictly connected as they were in the traditional rural centres) is shown, the lower storey of the first type of buildings are largely vaulted.

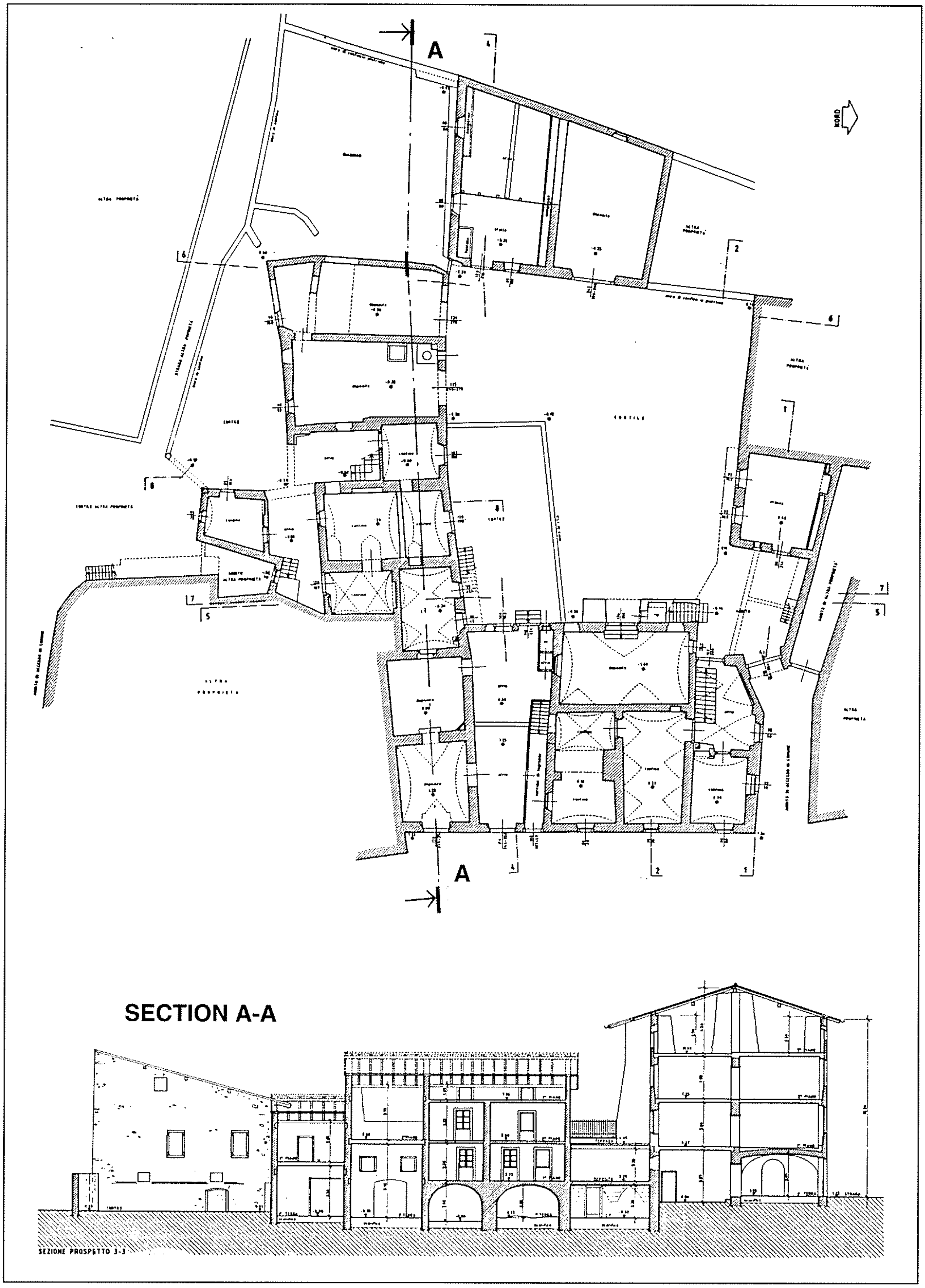

Figure 2 - Typical old masonry building block

The vaults are also made with masonry stone (mainly rubble and poorly bonded). The poor quality of masonry made it impossible to rely on a precisely defined structures behaviour as is the case of masonry vault units of solid clay. The stability of the structures under consideration depends on their degree of thickness, which influences the transfer of the internal forces to the foundations. This transfer is never the same and never precisely known. Under these conditions the vertical permanent loads are very high, and the horizontal thrusts (poorly known, in any case) can also be very high.

As a consequence of such a situation, and combined with the fact that the structures capable to equilibrate the horizontal thrusts (iron ties, buttresses) are frequently not adequate, the compressive stressess due to vertical loads and structural eccentricities can be locally very high even when seismic actions are not taken into account.

From here derives the importance of a careful characterization of the actual mechanical properties and state of stress of the masonry structures under consideration.

The other most important feature of the natural stone masonry is the bonding of units. It is worth noting first of all, that the shape and the dimensions of the units are never such as to allow the construction of single leaf walls. This, in the case of round stones, is practically impossible due to evident stability problems during the construction. But even the cut stones, obtaind from quarries, are so irregular in shape and dimensions that double withe type walls have always been constructed.

Figure 3 - Core drilling

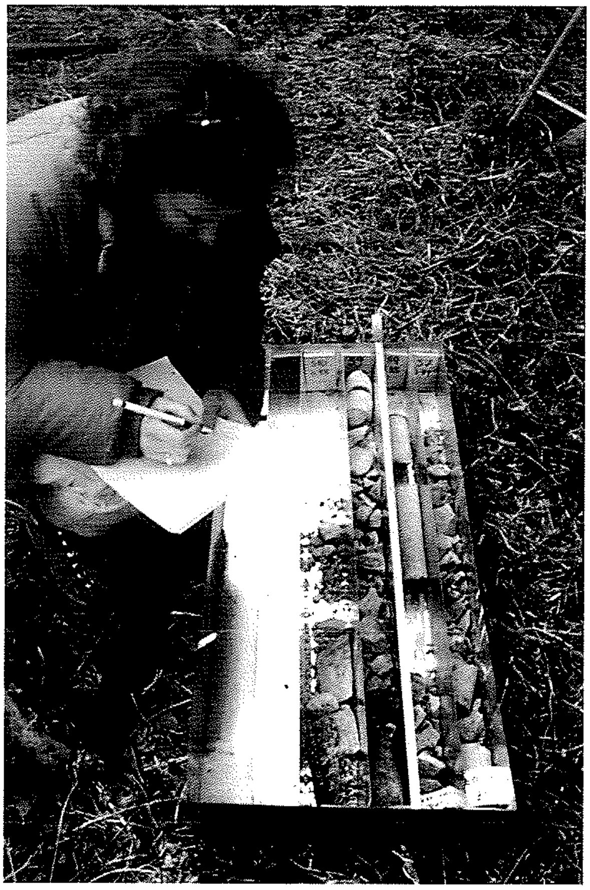

Figure 4 - Core drilled

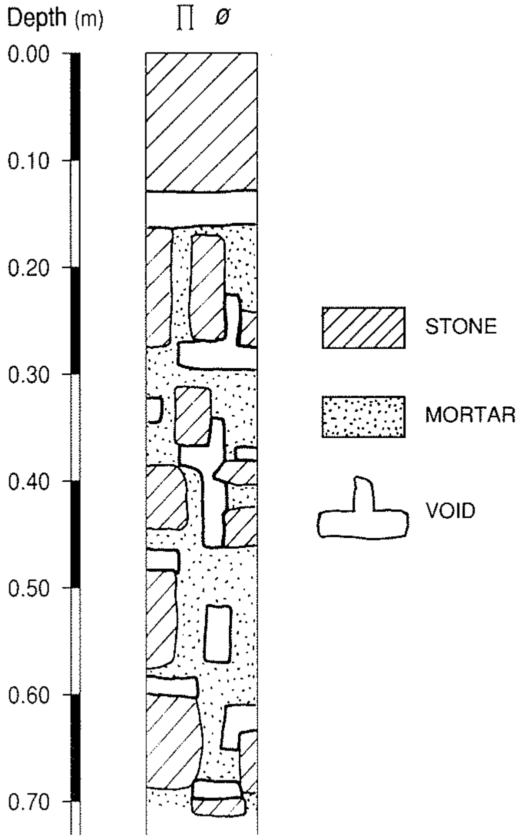

Figure 5 - Video-camera survey

The effects under vertical and horizontal actions on the mechanical characteristics and on the structural behaviour of such typical constructions are very important. They can be generally connected to the out-of-plane behaviour of the multiple withe walls, i.e. instability of the single withe under compression and the flexural failure under horizontal forces. This effect can be greatly influenced by the local conditions in the middle of the wall, where the two withes come into contact and eventually interact, so that the bigger stones and filling materials (smaller stones and mortar) can protrude. For this reason, the actual bonding characteristics of walls must be carefully investigated, and if possible categorized.

For this purpose the investigated walls were carefully surveyed, documenting the type and dimensions of the stones. The comparison with the thickness of the wall can in fact give some information on the internal bonding conditions. The internal characteristics are inspected by drilling cores (Fig. 3) and then the holes are surveyed utilizing a micro-camera. Both techniques are neccessary; the first is important for extracting materials for visual inspection, and in some cases for chemical analyses, the second for detecting internal voids (Fig. 5), which cannot be recognized from the core material (Fig. 4). This last one is always very incoherent in the studied masonry due to the effects of coring operations on weak mortars.

MECHANICAL CHARACTERIZATION OF MASONRY

Non destructive tests

The flat-jack testing techniques has been used for the analysis of the mechanical characteristics of the stone masonry structures. This technique is used to determine the state of stress and the deformability characteristics of the masonry. As clearly known, the state of stress is determined by releasing the masonry with a cut and reloading it with a flat-jack. The deformability characteristics are determined by inserting two flat-jacks at a distance of 50 cm apart.

The great extent of heterogeneity in this type of masonry, has made it necessary a complete redesign of the testing equipment, in order to solve the problem of the different deformabilities of the materials cut in order to insert the flat jack. A new type of steel disc with diamond tools was used, which allows the cut in the wall to be large and deep enough, and therefore sufficiently representative of the average characteristics of the whole masonry.

The calibration of this new testing technique was performed directly at the site through a comparison with a conventional compression test. In fact, it is practically impossible to recreate in the laboratory a masonry specimen of the examined type. The testing phase for the measure of the state of stress in shown in Fig. 6, and the second phase for the determination of deformability characteristics is presented in Fig. 7. It is clearly seen that the cut surface consists of stones and mortars with very different mechanical characteristics.

The stress-strain diagrams obtained by flat-jack tests on two different types of masonry are shown in Fig. 8. The values of the state of stress are also indicated in the diagrams. Diagram (a) represents a masonry with fairly good mechanical characteristics, where the state of stress is very close to the estimated compressive strength value. Diagram (b) represents a very poor masonry type which, in spite of being subjected to a much lower state of stress, is not in better conditions, because the sudden decreasing stiffness is a clear sign of the starting of a failure process.

Figure 6 - Flat-jack test for the measuring of the state of stress

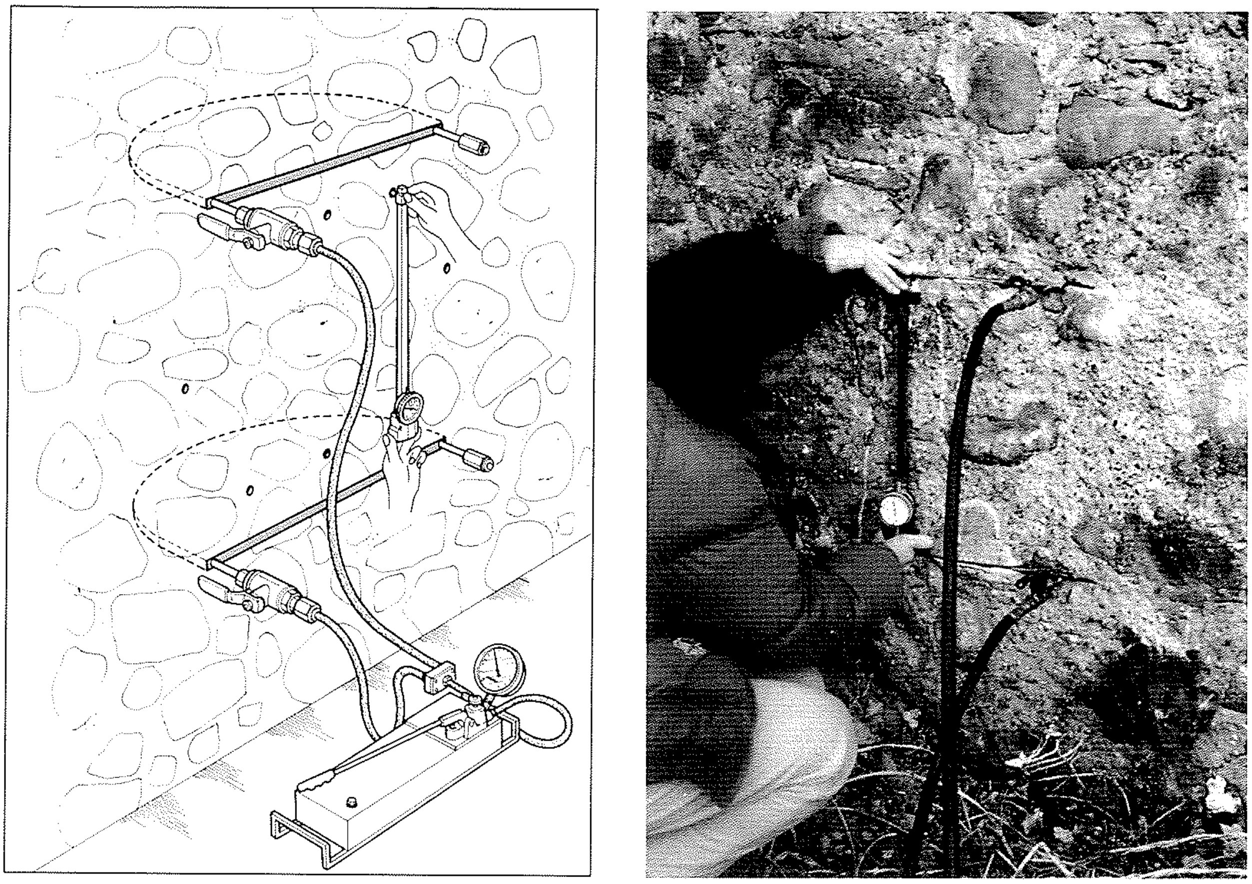

Figure 7 - Deformability test with two flat-jacks

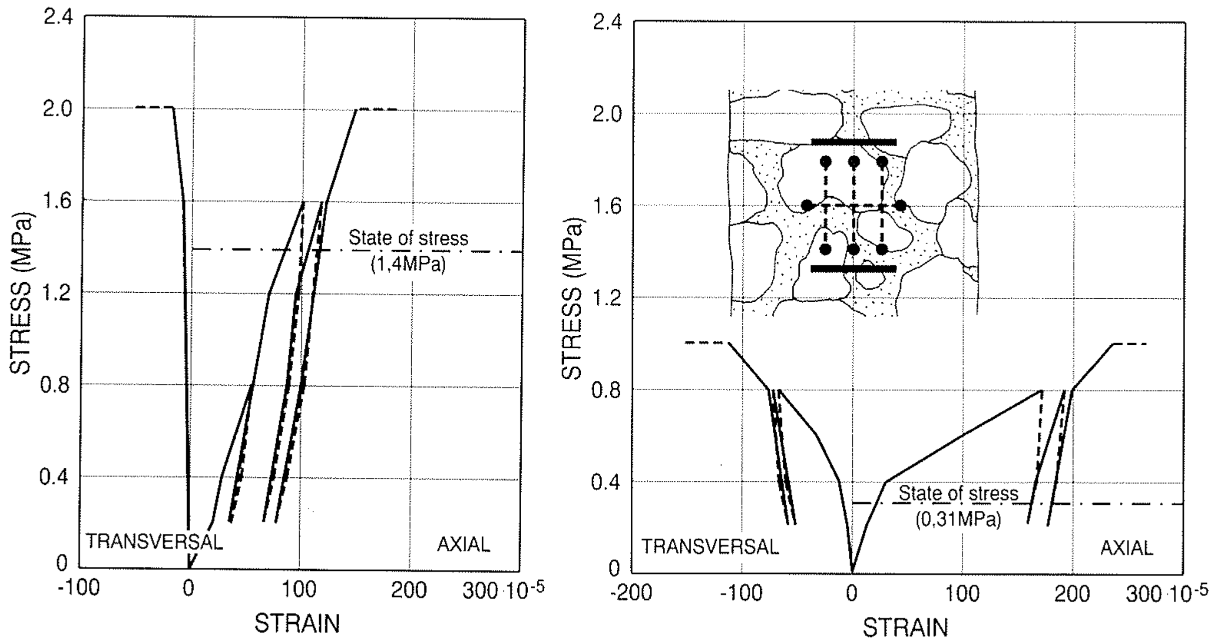

Figure 8 - Stress-strain diagrams obtained by flat-jack tests on two different types of masonry

LARGE SCALE IN-SITU TESTS

The large scale conventional compression tests, shown in Fig. 9, were conducted on masonry specimens prepared as schematically indicated in Fig. 10. The most important and delicate phase of the investigation was the preparation of the specimens: it is in fact essential to operate on a significant and undisturbed portion of masonry in order to obtain the prescribed uniform distribution of compressive stress during the test.

The first critical decision was on the dimensions of the specimen; this in fact must meet several requirements. First scale effects are to be avoided, for this reason the minimum dimension (the width) has been chosen of the order of at least three times the maximum dimension of the natural stone units. Second, the height to width and the height to thickness ratios must be such as to avoid edge effects, allowing the formation of uniformly distributed compressive stresses in the central portion of the specimen, and buckling failure. The measure of the strains indicated in Fig. 10 confirmed that this condition had been substantially achieved. Finally, the masonry must be kept un-disturbed during cutting and constructing the capping made with concrete blocks. This is necessary in order to make the loaded edges plane enough, to facilitate the distribution of the applied loads, and to keep the withes from interacting.

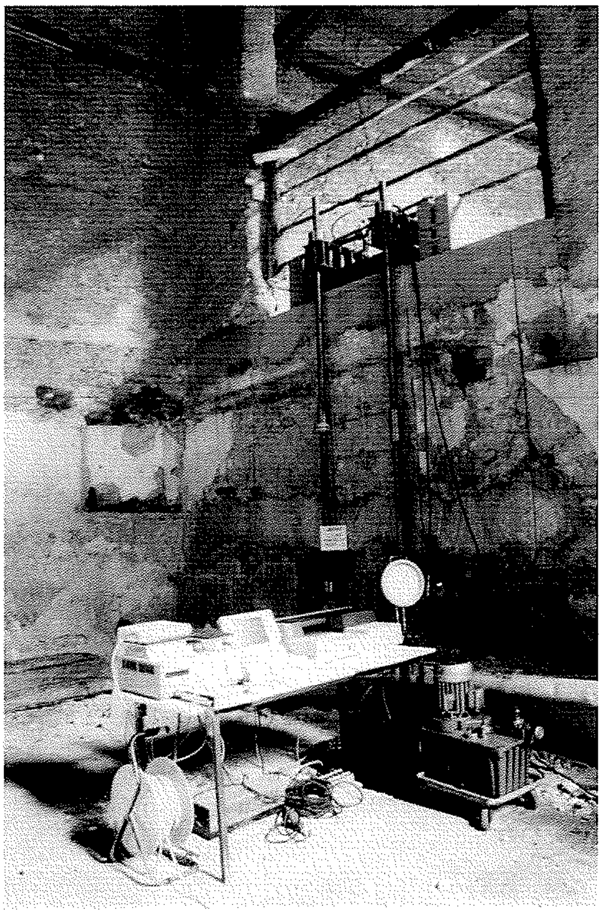

Figure 9 - Large scale in situ compression test

A special wire-saw was used for the vertical cuts . First, the top block was constructed in the wall and then the bottom one, this last one in two or three different phases.

The application of loads and the measurement of the deformations were very carefully performed. In fact, large flat-jacks were employed as a further measure to avoid load eccentricities and local stress concentrations.

The deformations were measured on both faces of the panel, in three positions in both vertical and horizontal directions, since local irregularities were expected to exist due to the previously described pronounced heterogeneity of the masonry. Furthermore, the deformations were measured in the middle of the specimen in a direction perpendicular to the plane of the wall in order to check the occurence of buckling effects.

ANALYSIS AND COMPARISON OF THE TESTS RESULTS

The major scope of this phase of the research was to verify the feasibility and the significance of test methods which were specifically adapted for the described type of masonry and to calibrate the flat-jack technique, which is intended to be the current approach to determine the mechanical characteristics of such masonry. In this light the results were very satisfactory, as can be seen by examining and comparing a typical example of the test results obtained so far and shown in Fig. 10. This figure displays the stress-strain curves corresponding to the flat-jack test and to the destructive compression test conducted in the same location.

An important first finding was the unexpected regularity of all the experimental diagrams, which demonstrates that specimen preparation and test equipments and techniques are able to substantially limit the unavoidable effects of the local heterogeneity of masonry, thus ensuring repeatibility, an essential feature of any test technique. The second important aspect regards the comparison between the results of the two types of tests, and in particular the calibration of the flat-jack technique. From a qualitative point of view the excellent agreement is self evident: this is very important as it demonstrates that the two tests indicate the same physical phenomenon and behaviour. The comparison however, is even more significant between the deformability and strength values measured in the two cases as shown for two of the tested specimens in Table 1, where E1 and E2 are the moduli of elasticity measured in the two ranges of stresses: 0.0-0.4 MPa and 0.4-0.8 MPa respectively.

	Specimen A		Specimen B	
	FJ	DT	FJ	DT
E1 (MPa)	490	490	290	240
E2 (MPa)	240	240	170	--
Strenght (MPa)	1.0	1.0	0.8	0.6

Table 1: comparison between strength and deformability parameters obtained by means of the flat-jack technique (FJ) and of the destructive test (DT) in two different masonry panels.

First of all, it can be observed that the restraining effect of the masonry surrounding the flat-jack test zone, on the measured deformability, is practically negligible. This behaviour can be connected to the poor quality of the masonry; this is confirmed by the very low strength and extremely large deformability of the E values given in the table. In the case of specimen B it was not really possible to measure the value of E2 since the instruments were taken out when the collapse of masonry was feared in the corresponding range of stresses.

It is worth noting however, that the test furnishes high strength values in spite of the confining effect being negligile during the flat-jack test. Such behaviour can be explained with out-of-plane second order effects on the two, practically separated withes composing the walls. They were actually detected measuring the displacements in the direction perpendicular to the wall plane at the centre of the panels.

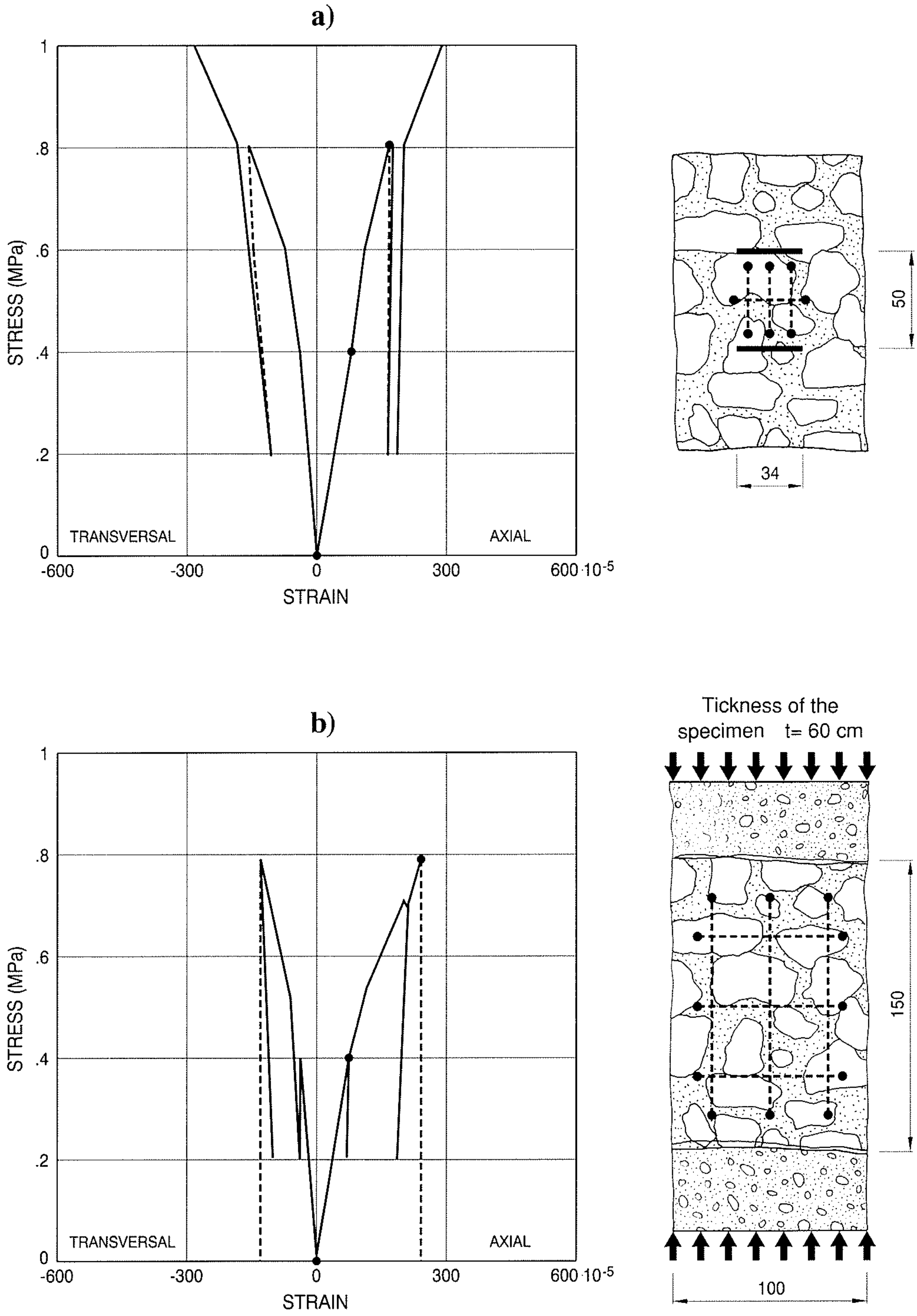

Figure 10 - Comparison between stress-strain diagrams obtained by a flat-jack test (a) and a conventional compression test - (b) on the same masonry.

CONCLUSIONS

This paper presents the results of the first phase of a comprehensive research project which has being carried out to evaluate the mechanical characteristics and the structural behaviour of both virgin and repaired and strengthened stone masonry buildings.

The scope of this research phase was the validation and calibration of test methods to determine the basic mechanical properties of virgin masonry, taking into account the specific characteristics of the most populare types of masonry in the studied region (generally of poor quality and extremely hetergeneous).

The tests confirmed the reliability of the two employed test techniques: a precisely adapted version of the flat-jack technique and an in-situ destructive compressive test on masonry panels. The second type of test is in this phase used for calibrating the first one, but its set-up has an even greater interest as it will be applied in the next research phases to strengthened masonry walls, where in some cases (e.g. when the jacketing technique is used) flack-jacks cannot be employed.

Very interesting information was obtained in terms of the mechanical characterization of the investigated structures. It was in fact possible to estimate the deformability and strength parameters of truly undisturbed specimens. The existence of local structural weaknesses, which can be only qualitatively foreseen theoretically, have been also demonstrated and their effects quantified.

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