MECHANICAL CHARACTERIZATION OF TRADITIONAL MASONRY IN AN HOMOGENEOUS TERRITORY: VALTELLINA

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Abstract. *The current Italian Building Code provides tables with standard values of the mechanical characteristics of existing masonry. These tables refer to specific typologies, as described, according to masonry texture. As experience suggests, the way in which the masonry is built up could really affect its structural behaviour, both in terms of mechanical properties and failure mechanisms. Furthermore, the code entrusts each Region to improve and better define these mechanical characteristics, specifically in areas where they could be regarded as homogeneous, in order to improve definitions of the quality, the behaviour and the mechanical properties with a higher degree of precision and knowledge.*

Valtellina, located in the north of the Lombardy region and in the middle of the Alps, can be regarded as a homogeneous area because of its specific masonry, built up with hard rock stones and weak lime mortar. The available in–situ experimental data about this masonry typology, achieved through MDTs and NDTs, was collected, implemented and improved with additional tests to identify the relevant mechanical properties. This was aimed to classify and structurally identify this specific regional masonry typology, never analysed before.

1 INTRODUCTION

The assessment of historic building vulnerability is a big issue in Italy, mainly due to the fragility of the area which is often subject to devastating events, such as floods and landslides, but above all earthquakes that, in recent years, have severely affected the national territory. Natural events, although not always of high intensity, often have a devastating impact on the historical buildings, in particular from the cultural point of view, since the repairs of the damages, whenever possible, always result in an effective loss of the cultural value of the artefacts.

In Italy the attention to the structural vulnerability under the effects of natural events was drawn from the earthquake that affected the Friuli region in 1976 and further increased with the subsequent seismic events (Irpinia 1980, Umbria-Marche 1997, L'Aquila 2009, Emilia 2012 up to the last Amatrice-Norcia 2016 earthquake and aftershocks). These experiences highlighted two crucial area of lacking knowledge that need to be improved:

- the damage and vulnerability of masonry and buildings subjected to seismic action;
- the predictive models, mechanical interpretations and effectiveness of the interventions.

The failure of a structural system focuses on the weakest link of the structural chain: while on the one hand the design of new buildings makes this evaluation simple, on the other hand for existing structures it is difficult to properly identify the relevant mechanism.

The current Italian Building Code [1] defines the properties of the masonry through numeric tables, which classify the stone and mortar masonries on the basis of six typologies, identified by the observation of the elevation texture, and the solid brick masonries on a single category. The mechanical characteristics of the walls can also be identified on a case-by-case base by carrying out MDTs (Minor Destructive Tests) and NDTs (Non-Destructive Tests). Furthermore, the code entrusts each region to improve and better define the mechanical characteristics of the masonries, specifically in areas that can be regarded as homogeneous in order to define their quality, behaviour and mechanical properties with a higher degree of precision and knowledge.

The aim of this research is a first collection of the available in–situ experimental data referred to the area of the Valtellina region, gained through MDTs (e.g. flat-jack tests, both single and parallel) and NDTs (e.g. sonic tests). Moreover, the analyses were implemented with other methods: further sonic tests to define the masonry quality and penetrometric tests to define the mortar properties. Data were finally processed in order to classify and mathematically determine the masonry typology and its relevant mechanical characteristics.

2 CONSTRUCTION MATERIALS

Valtellina, the study area, is a valley located in Lombardy, in the North of Italy, in the middle of the Alpine arc, close to the border with Switzerland. The geographical location of the valley has strongly influenced its historical and civil events: due to its key position between the South and the North of the Alps, the lordship of the valley has long been disputed between Milan in Italy and Chur in Switzerland, with alternate upheavals that have moved northward and southward the administrative and economic axis. For this reasons, this territory is a significant object of study, as it is peculiar and at the same time exemplary of the development of an area placed in "*the Alps, a unique region in the centre of Europe*"[2].

From a geological point of view, Valtellina is located in the western area of the Alps, characterized by silicate rocks, rather than the dolomitic and limestone ones which are present in the eastern area. The valley is located exactly along the Tonale fault, an imposing tectonic dislocation that runs from East to West in the central part of the Italian Alps, which means that most of the rocks placed along the territory are of metamorphic origin. The intrinsic characteristics of the metamorphic rocks (first of all their stratification) strongly influence the masonry construction techniques in the area. On the other hand, the relative difficulty in finding limestone rocks affects (in a negative way) the availability of lime mortars.

The historical buildings are usually made with the rock materials that were easily available (close to the construction site), which required minimal processing and allowed a fast use. Only for the buildings with iconic importance, as churches or noble palaces, the stones were sometimes taken at a greater distance and often selected and processed with a greater care in order to underline the prominence of these building. Anyway, in the Valtellina context this was mainly limited to the production of decorative elements such as mouldings, columns and pilasters. As for the type of stones used, Valtellina masonries can be classified according to three types:

› Rough-stone masonries *(Fig. 1)*: shapeless pieces of stone material, obtained exclusively by splitting the rock mass or collecting the rock pieces lying on the ground; their shape, often multifaceted irregular with sharp edges, allows for stable positioning of the components to be obtained even without the use of mortar to build drystone walls;
› Rough-hewn stone masonries *(Fig. 1)*: also called *"drafts"*, they have dimensions which are generally similar to the rough ones; they have a defined shape with a tolerance due to the surfaces processing;
› Cut-stone masonries *(Fig.1):* generally coming from compact rocks characterized by a good processing capability to be regularized with the squaring and finishing processes.

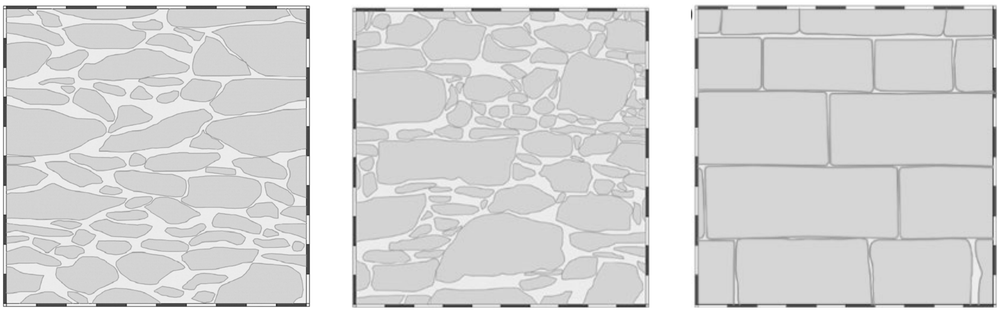


Figure 1: Rough stone masonry – *"Piatti-Reghenzani" Manor,* Teglio (TC1); Rough-hewn masonry – City hall, Ponte in Valtellina (PM1); Cut stone masonry - *Ganda Bridge,* Morbegno

The masonry walls built with rough stones represent the most common case in Valtellina. On the one side, as already stated, the scarce availability of easily workable stones limited the use of cut or carved stones to elements of particular value. The already mentioned predominant presence of metamorphic rocks naturally provided stones suitable for the construction. Indeed, because of their elongated shape and easiness of splitting according to the stratification plans, the lithic elements taken from metamorphic rocks are definitely suitable for the construction of the traditional wall texture.

The production of mortar is conditioned by the availability of suitable binders, to be used individually or in a mixture with each other. For this purpose, in the Valtellina area there are only very localized limestone outcrops. Extensive limestone outcrops, belonging to the group of the main Dolomia, can be found only in upper Valtellina, around Bormio.

The prevalent use of rough stones would lead to suppose the need of high mortar quantities inside the walls; however, the elongated conformation of the metamorphic stones implies that the rocks can be laid in rather horizontal courses, thus obtaining internal contact points and limiting the use of binding: this construction technique also derives from the tradition of the Valtellina walling method. To evaluate this circumstance, the front elevation of the walls was scanned in order to define the mortar quantity, which average percentage, referred to the whole masonry, was found to be around 25%. It should be noted that this is only a qualitative estimation: due to wall texture the actual mortar quantity in the section can be different from the quantity calculated on the basis of the front elevation.

3 CONSTRUCTION TECHNIQUES

The construction techniques used in Valtellina are of course conditioned by the type and quality of the rocks and by the poorness of mortar used. Techniques that use rough or rough-hewn stones are defined "complex", as the arrangement has to follow precise rules and a careful selection of the stones to be used [3]. Techniques that use cut stones, called "ashlars", are defined "simple", as the parallelepiped shape deriving from shaping processes allows a simpler placement, with a lower quantity of mortar. Following the scarce use of cut-stones elements, the masonries detected on the territory of study are mainly made with “complex” techniques. It is worth noting that cut stones are often used only in the external fronts, giving a good look but no warranty that in the interior of the wall stones are laid in a correct way.

3.1 Drystone walls

Valtellina has a very peculiar “cultural” landscape, the most evident expression of which is the extensive terracing that characterizes the Rhaetian slope at the lowest altitudes, approximately up to 1000 m above sea level. The available information reports an historical overall terraced surface of around 60 km^2; the part currently cultivated (with vineyards) is less than 1/6 of its maximum historical extension. This landscape is mainly characterized by the use of retaining walls made with drystone technique [4].

Figure 2: Typical facing of a drystone wall of the Valtellina terraces

In the territorial context of this study the characteristics of drystone masonry (*Fig. 2*) have strongly permeated even the techniques of stone and mortar ones: that’s why useful information for the ordinary buildings can also came from the study of the construction techniques of the drystone masonry. On the basis of the technical literature the stability of a drystone wall is strongly related to the experience and to the skill of the mason, who has to respect six specific “rules of art” [5]: proper setting of the foundation (generally with low depth), vertical offset of the joints to obtain the optimal distribution of the weights; horizontality of the stone courses;

balancing of the stones; transversal connections to ensure a correct interlocking of the wall-layers and finally particular attention to the connection of the orthogonal walls (cornerstones).

3.2 Masonry walls

The main part of Valtellina buildings, even those that can be classified as cultural heritage (churches, palaces and rural nuclei) are characterized by a lithological variety and by the use of construction techniques almost indistinguishable from the drystone walls, although generally encompassing the use of mortar (*Fig. 3*).

Figure 3: Similarities among the drystone rural construction (left), stone and mortar rural construction (middle) and stone and mortar wall of the church of S. Ignazio in Ponte in Valtellina (right)

This results in a complication of the construction phases due to the need of lime and mortar production, but at the same time it simplifies the placement of the stones as it allows masons to pay less attention to the selection of the lithic elements, as mortar regularizes the areas of non-contact between the stones. However, the "rules of art" mentioned above for drystone masonry are systematically respected nonetheless.

Due to the scarcity of documentary and bibliographic sources, it was not possible to trace back a proper description of construction techniques in Valtellina: for this reason, a detailed analysis of the characteristic of two buildings historically representative of the local context was carried out: S. Ignazio Church at Ponte in Valtellina and Masegra Castle at Sondrio.

For the castle, the lithological variety of the stones shows a close relevance to the territorial context of the nearby Valmalenco, upstream of the Mallero river that flows in the nearby of the building; some blocks are also presumably attributable to the glacial deposits present on the Rhaetian slope. For this reason, the materials are of a crystalline nature, metamorphic or intrusive. The foundation masonry walls are laid out with sub-horizontal courses consisting in stone of various lithology and size (mainly gneiss and serpentine) and lime mortar of varying colour and grain size. The elevation walls are also characterized by sub-horizontal layers in stone blocks and mortar courses with large thickness.

The systematic observation of the wall facing masonries of the castle and of the other cases of study highlights that, regardless of the building periods, the masonries can be sorted into two types (*Fig. 4*):

- masonries made with stones laid with disordered texture,
- masonries made with stones laid with rather horizontal courses (good-texture).

These masonries can be built both with rough or rough – hewn stones, with the latter being predominant in the second type.

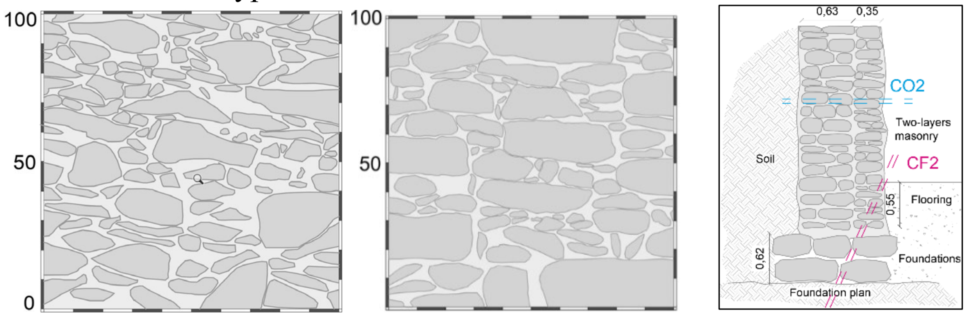


Figure 4: Masonry wall facing and section of the Masegra Castle masonries

4 DATA COLLECTION

The analysis of the masonry mechanical characteristics is a fundamental basis for the correct modelling of the structural behaviour of the building. Both for existing buildings [1] and for cultural heritage ones [7] Non-Destructive (NDTs) and Minor Destructive (MDTs) tests allow the quantitative determination of these characteristics. It is important to underline, how the Guidelines [7] explicitly state, that "*Non Destructive diagnostic Techniques of indirect type, such as sonic and ultrasonic tests, assess the homogeneity of the mechanical parameters ... but they do not provide a reliable quantitative estimation of their values ... Therefore, the direct measurement of the mechanical parameters ... in particular those relating to resistance, can be performed only through Minor Destructive or Destructive Tests, even if applied to limited portions. Calibrations of Non Destructive Tests with (Minor) Destructive Tests can be used to reduce the invasiveness of the investigation campaign.*"

The numerical analysis performed in the present research was developed from the wide database made available by the company Foppoli Moretta & Associati consulting engineers and coming from their professional activity. Both NDTs and MDTs were performed in compliance with the standards listed in Table 1.

Table 1: Reference standards for the tests performed

TEST		CODE
FJs	Single flat jack	*ASTM C 1196-14 (2014). Standard test method for in situ compressive stress within solid unit masonry estimated using the flatjack method.*
FJp	Parallel flat jacks	*ASTM C 1197-14 (2014). Standard test method for in situ measurement of masonry deformability properties using the flatjack method.*
SO	Sonic test	*UNI EN 12504-4 (2005), Prove sul calcestruzzo nelle strutture - Parte 4: Determinazione della velocità di propagazione degli impulsi ultrasonici.*
PT	Penetrometric test	Jurina, L. (2007), *La caratterizzazione meccanica delle murature parte prima: prove penetrometriche*. Politecnico di Milano – DIS
CO	Corings	*UNI EN 12504-2 (2019), Prove sul calcestruzzo nelle strutture - Parte 1: Carote - Prelievo, esame e prova di compressione.*

The available dataset has been integrated with experimental tests, specifically carried out for this work, which have been marked in bold in the following Table 2.

Table 2: Tests performed

Nr.	Location	Code	Construct. Year	FJs	FJd	SO	PT	CO
1	Vervio	SA1	1664	3	3	-	-	2
2	Sondrio	SS1	1885	4	4	-	-	4
3	Teglio	BT1	1433	-	-	**5**	**8**	-
4	Bianzone	BB1	1600	2	1	**5**	**2**	2
5	Ponte in Valtellina	SI1	1640	-	-	**3**	**10**	3
6	Sondrio	ST1	1826	6	6	-	-	-
7	Gravedona	GS1	-	3	3	-	-	-
8	Ponte in Valtellina	PM1	1942	3	3	-	-	-
9	Teglio	TC1	1700	3	3	-	-	3
10	Livigno	LS1	1954	3	3	-	-	-
11	Sondrio	CM1	1041	9	9	6	**10**	10
12	Bormio	BS1	1965	-	3	-	-	-
13	Tirano	TB1	-	2	3	9	-	2
14	Villa di Chiavenna	VC1	1800	**2**	**2**	**3**	**2**	-
15	Madesimo	MC1	-	-	-	**4**	-	-
16	Livigno	FC1	1912	-	-	**8**	**4**	-
17	Germasino	GM1	-	-	3	-	-	-
	TOTAL nr.			40	46	43	36	26

Table 3: Resume of the (average) results

Building	$E_{d\,(0.4\text{-}0.8)}$ [N/mm^2]	$G_{(0.4\text{-}0.8)}$ [N/mm^2]	ν	$E_{e\,(0.4\text{-}0..8)}$ [N/mm^2]	σ_v [N/mm^2]	σ_{max} [N/mm^2]	v_p [m/s]	f_m [N/mm^2]
SA1	3030	2702	0.10	3967	1.20	2.10	-	-
SS1	5314	-	-	4973	0.50	2.80	-	-
BT1	-	-	-	-	-	-	1590	1.80
BB1	5263	-	-	7562	0.60	2.40	1534	1.80
SI1	-	-	-	-	-	-	1603	1.70
ST1	4076	1069	0.10	5262	0.40	2.50	-	-
GS1	3724	710	0.20	5433	0.50	2.90	-	-
PM1	2119	963	0.10	3095	0.50	2.30	-	-
TC1	1095	415	0.50	2564	0.50	1.50	-	-
LS1	1340	629	0.10	2698	0.40	2.00	-	-
CM1	2744	1059	0.30	5582	0.60	3.10	2277	1.70
BS1	11142	-	-	14213	-	4.00	-	-
TB1	2256	1064	0.10	3651	0.30	2.70	1655	-
VC1	4444	1893	0.20	4829	0.60	4.00	2786	1.10
MC1	-	-	-	-	-	-	1917	1.50
FC1	-	-	-	-	-	-	2493	1.60
GM1	721	313	0.20	1802	-	1.40	-	-

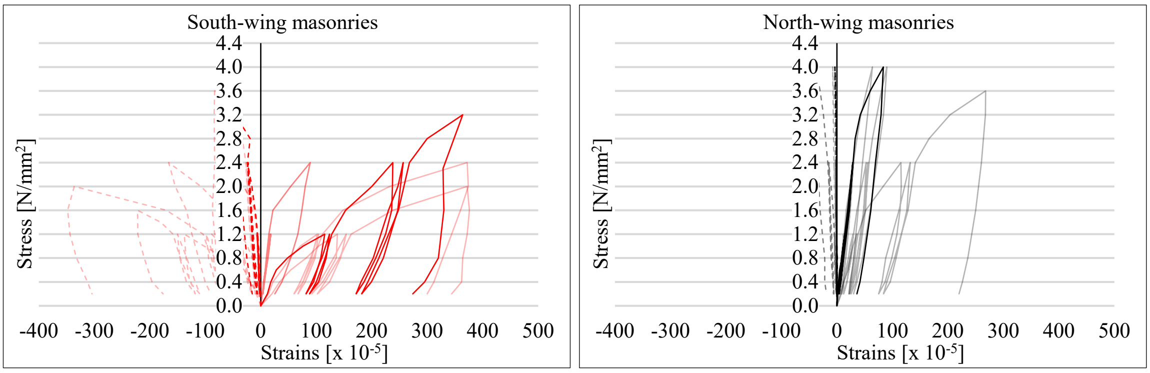
Numerical data taken from these tests have been processed to obtain the most significant mechanical characteristics of the masonries, as follow:

- Single flat jack [9], [10]: masonry compressive stress state (σ_v);
- Double flat jack [9], [10]:
  - deformability module (E_d), calculated at the first loading stage;
  - tangential deformability module (G), calculated at the first loading stage;
  - Poisson coefficient (ν), calculated at the first loading stage;
  - elastic module (E_e), calculated at the first unloading stage;
  - maximum compression strength reached for the masonry (σ_{max});
- Sonic test [10], [11]: elastic sonic wave propagation velocity (v_p) inside the masonry;
- Penetrometric test on mortar [12]: compression strength of the mortar (f_m).

The values of the average mechanical properties, determined for each of the buildings analysed, are summarized in the previous Table 3.

5 DATA ANALYSIS

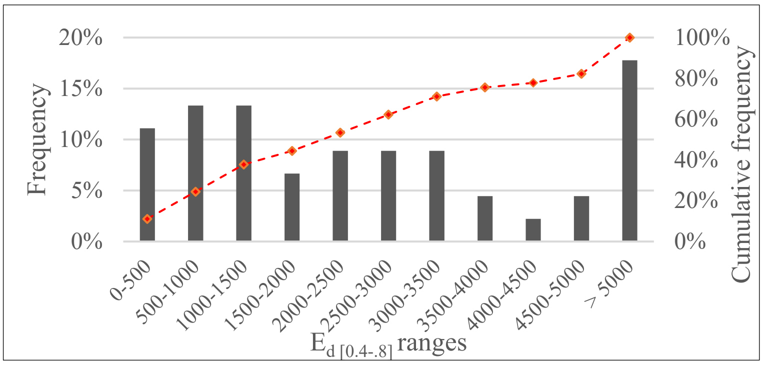
The collected data is a significant statistic base that allows a relevant analysis both with reference to the single test and by matching the results of different methods in order to identify the significant characteristics. By way of example, in Graph 1 the stress vs. strain curve obtained from the double flat jacks tests performed at Masegra Castle (CM1) are plotted: the mechanical characterization suggests grouping the samples into two typologies.



Graph 1: Stress-strain relationship of the castle masonries – South-wing (red) & North-wing (black)

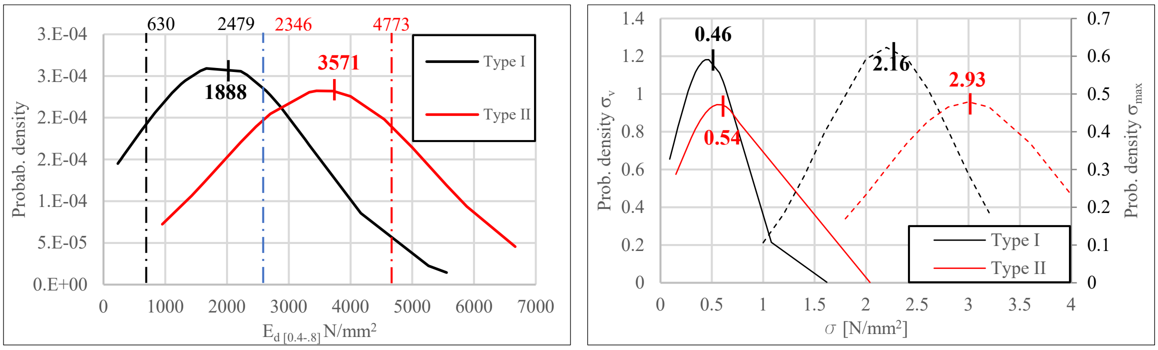
Further analyses highlighted a linear correlation between the deformability modules $E_{d[0.4\text{-}.8]}$ calculated at the first load stage and the elastic modulus E_e calculated at the first unloading stage. The draft data provides a correlation with $R^2 \cong 77\%$, by purging them from some values with little reliability allow to give up to $R^2 \cong 92\%$, indicating a very good correlation.

Based on the above considerations, the frequency of the deformability modules of the single tests were plotted in Graph 2. It is a matter of fact that the Valtellina masonries have a very high variance of modules, therefore it is difficult to make considerations on this draft data. Following the previous typological and mechanical observations, the walls were divided in compliance with the description of the elevation texture between “masonry with disordered texture” (type I, n. 25 reference tests) and “masonry with rather horizontal courses” (type II, n. 15 reference test). The higher module values $E_{d\,[0.4\text{-}0.8]} > 5000$ were identified as anomalous and excluded from the analysis.



Graph 2: Deformability module frequency distribution - percentage and cumulative frequency

This way it was possible (Graph 3 left) to draft two normal distribution curves referred to type I and type II and to calculate the respective 25% and 75% percentiles. It can be noted that the disordered masonries have an average value $E_{d\,[0.4\text{-}0.8]} = 1888$ N/mm^2, while the good-texture masonries have an average value $E_{d\,[0.4\text{-}0.8]} = 3571$ N/mm^2. The values calculated according to the different typology are summarized in Table 4. It has to be noted that the average $E_{d\,[0.4\text{-}0.8]}$ values found are not very different from the values that can be calculated for the two masonry typologies identified at Masegra Castle, as previously described.



Graph 3: Normal distribution curve of deformability modulus and of σ_v and σ_{max}

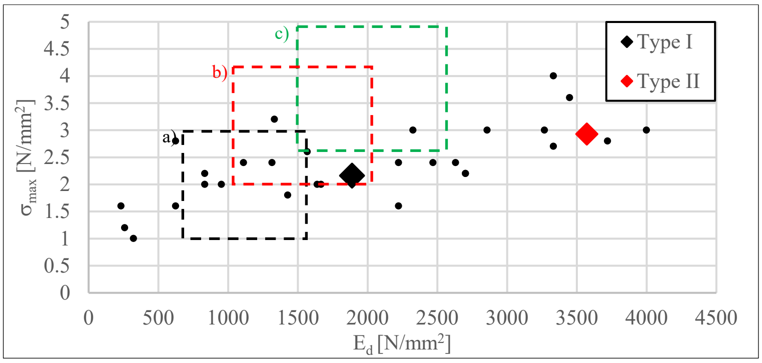
The two distribution curves (type I and type II) intersect for a good part of their development, focusing not only on the type of stone used, but also on the masonry construction technique: walls with good texture, which have a high contact among the stones (little mortar quantity) have a higher elastic modulus. Conversely the strength of the mortar is not a discriminating factor because it presents no relevant variations.

Analysing the overall masonry stress state it is possible also to note that in any case the current compression stress does not exceed the maximum detected one (Graph 3 right): thus, the average value of the safety coefficient $\gamma = \frac{\sigma_{max}}{\sigma_v}$ can be calculated, which turns out to be quite satisfactory in the test load conditions (means static with only own-weights).

Table 4: Resume of the mechanical characteristics of the masonry, according to the type

Masonry type	$E_{d\ (0.4\text{-}0.8)}$ [N/mm^2]	$G_{(0.4\text{-}0.8)}$ [N/mm^2]	ν [-]	$E_{e\ (0.4\text{-}0..8)}$ [N/mm^2]	σ_v [N/mm^2]	σ_{max} [N/mm^2]	v_p [m/s]	f_m [N/mm^2]
I	1888	750	0.18	3578	0.46	2.16	1332	1.45
II	3571	1344	0.09	5360	0.54	2.93	2443	1.41

A further attempt was made to divide the masonry characteristics by type of construction (civil, ecclesiastical and noble buildings), by location (higher, middle and lower Valtellina) and by construction period, but no significant result was obtained, proving that there was no real difference in the construction techniques among the mentioned classes. The only qualitative observation was that the noble buildings are mainly made with disordered stone masonry and that the buildings, from the 20th century onwards, are mainly built with rough-hewn ashlars.



Graph 4: $E_{d[0.4\text{-}0.8]}$ - σ_{max} correlation with the limits proposed by the Italian guidelines

Finally, the values of $E_{d[0.4\text{-}0.8]}$ were plotted versus the maximum detected compression stress σ_{max}. This graph doesn't have a very good correlation, but it allows an interesting graphic comparation with the ranges (dashed box) provided from the Italian Code [1] table C8.1.5. These ranges were be compared to the values provided from the current anaylsis (clash-dot lines): for the masonries classified as type II, the identified Valtellina masonry proved to be stiffer than the values provided by the code. The available data are of course limited to the walls that were brought to compression failure during the tests.

6 CONCLUSIONS

The masonry construction techniques in Valtellina are strictly connected to the historical, cultural and geological features of this territory. On the basis of more than 190 NDTs and MDTs, this paper proposes a preliminary classification of the typical local masonry walls (made with stone and mortar) into two typologies: "*masonry with disordered texture*", "*masonry with rather horizontal courses*". The data analysis allows the estimation of the typical mechanical characteristics and their variation. The type of construction, the location and the construction period do not seem to be influential parameters in this analysis. This work can be regarded as a first effort, as suggested the Italian Building Code, for the definition of the mechanical characteristics of the typical masonry that can be regarded as homogeneous in a specific area of Lombardy region.

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