Comparison of non-destructive *in situ* techniques for vertical load strength assessment in masonry walls.

N. Gucci - M. Sassu (1)
Istituto di Scienza delle Costruzioni, Università di Pisa
Via Diotisalvi 2, 56126 Pisa, Italy.
P.P. Rossi - A. Pulcini (2)
Istituto ISMES - Via G. Cesare 29, 24124 Bergamo, Italy

Abstract.

Comparisons are made between the well-known non-destructive technique of flat-jack tests used in masonry, and the recently introduced PNT-G penetrometer, best suited to *in situ* measurements of mortar strength. A method is proposed for determining the stress-strain response law of masonry walls subjected to vertical loads, by means of PNT-G measurements and monoaxial tests on the blocks making up the masonry structure. The technique is checked on a trial sample of already existing buildings and found to be particularly effective in the case of masonry faces made up of mortar whose resistance is low comparing to that of blocks.

1 Introduction.

Determining the values for strength in the presence of monoaxial compressive stresses of masonry faces is a matter of extreme significance in quantifying their degree of safety in relation to loads acting upon them.

Often experimental strength determinations are performed through non-destructive methods [1] [2] [3] of the direct or indirect type, depending upon whether the mechanical properties of the masonry themselves are being measured or some other related parameters are instead determined. A typical example of the former type of measurement technique is the use of flat-jacks [4] [5]: from the pressures exerted upon the masonry by the jacks, both the load and the monoaxial deformation law can be determined. The second, instead, is exemplified by the dynamic penetrometer [6] [7]: from the energy necessary to bore a hole of given dimensions in the concrete mortar, one can arrive at the characteristic compressive strength, not only of the mortar, but of the masonry itself, through opportune analyses once the mechanical strength of the stone blocks is known [8] [9] [10].

The current study deals with comparisons of the two above-mentioned experimental methods, namely the flat-jack and dynamic penetrometer, as applied in two specific trails, both on mixed stone and brick masonry structures. The trials considered here regard, on the one hand, an historically important building, the *Teatro Goldoni* in Livorno, a theater whose construction dates back to the mid-nineteenth Century, and on the other, a low-cost housing block built in the same city during the 1930s and whose decay has caused some static structural instability. By comparing the two methods, it has been possible, aside from checking the reliability of each, to predict, by means of a simple modeling procedure [11] [12], the flexural limit value for the masonry compressive strength revealed through the flat-jack tests, as well as an estimate of the apparent elastic modulus by exploiting the results of the penetrometer tests.

2 Description of the trials.

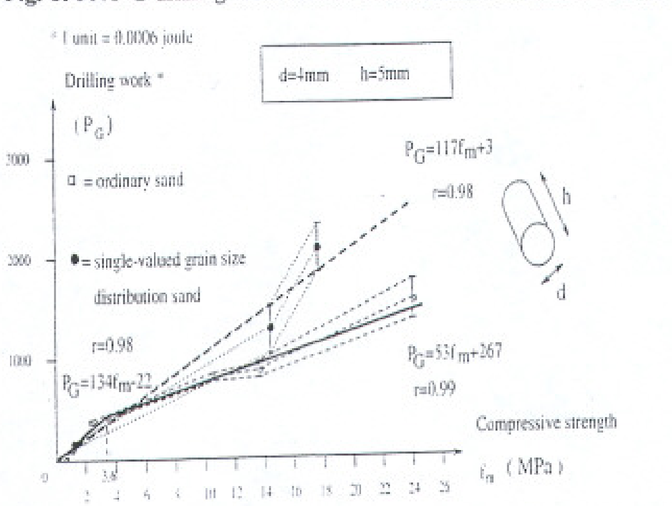
The flat-jack test allows measurement of monoaxial stress states within building walls. After first surveying the area involved geometrically, insertion of the flat-jack (a chamber formed by two thin metal disks of reduced thickness and varying shape within an oil circuit) is performed by means of a plane cut with a circular saw. The oil pressure necessary to reposition the measurement points, displaced by the cut, back to their original positions is then releated to the value of the normal compressive force acting within the wall. Insertion of a second jack parallel to the first allows for the application of successive monoaxial stresses on the intervening part of the wall, with repeated cycles of varying load levels up to rupture of the sample. Thus, aside from investigating the dissipative capacity of the studied wall, cyclic-type deformation curves can be obtained, together with the relative elastic moduli and flexural or collapse stress values.

The penetrometer tests were performed by means of a rotating bit driven by a small electric motor (a drill powered by a battery). The characteristic resistance of the masonry's concrete mortar is calculated from the value of the energy expended in order to bore a hole of given dimensions, subtracting the energy dissipated by the motor's ac-celeration and idling. This value can be related to the adhesive strength among the sand grains of the mortar, particularly if, as often occurs, the mechanical properties of the binding agent are lower to those of the sand. In fact, as seen elsewhere [7], when dealing with high-strength binders, a portion of the work expended in boring the hole is consumed not only in breaking the bonds among the sand, but also in pulverizing a part of these latter.

The studies under consideration were conducted utilizing semicircular flat-jacks of dimensions 340x225x4 *mm* with a pressure chamber 2.4 *mm* in width. The fissure was made with a circular diamond saw and the geometrical measurements were made with a removable mechanical comparator, using a series of steel repers 5 *mm* in diameter bridging the fissure. The flat-jack measurements were executed on samples of approximate dimensions 40x50x20 *cm*, and the deformation curves resolved in the direction of the load by means of three 400 *mm*-long measuring bases, while a fourth base furnished the corresponding curve in the transverse direction.

The instrument utilized for the penetrometer tests is the recently developed PNT-G penetrometer [6] [7] [8], consisting of a drill with 4 *mm* bit calibrated for a bore depth of 5 *mm*. During each test the instrument is connected to a self-calibrating energy counter with an acoustic signaling apparatus which emits a tone at both the start (completed calibration) and end of each trial (reached depth of 5 *mm*). The overall number of flat-jack tests is 7 on the Teatro Goldoni and 13 on the housing block, called the Filzi building. Table 1 provides a summary of the key values obtained through the flat-jack trials (stress, tangent elastic modulus, flexural and rupture limit stresses); Table 2 presents the data relative to the full set of penetrometer measurements, indicating, aside from the instrument readings, the mean rupture strengths of the mortar calculated from the calibration curves of the PNT-G (see fig. 1).

Fig. 1: PNT-G drilling work-mortar flexural limit correlation curve.



3 Data processing and results.

The masonry tested during these trials demonstrated generalized properties of modest mortar strength in comparison to that of the stone blocks (roughly corresponding to a italic classification of mortar type M4). Such a situation renders more pronounced the "confinement effect" of the blocks to the mortar, increasing the weight-bearing capacity of the mortar, whose simple compressive strength can be assessed by means of the penetrometer calibration curves.

Seeking a first approximation towards quantifying this effect, recourse can be had to the simple model proposed by Atkinson and Noland

[11]. In this model the masonry is made up of regular stacks of bricks with coursing joints both of which are elastic and have respective thicknesses of s_b and s_m. The relative Young e Poisson's moduli are designated by E_b, ν_b, and E_m, ν_m; the former being constant while the second varies depending on the principal stresses acting on each of the mortar beds. Moreover, the trials revealed that in the absence of elevated vertical loads and low transverse confinement stresses such as in these buildings tested, E_m and ν_m can be assumed to be nearly constant up to the flexural limit. Although more thorough treatments (which for example account for the strong dishomogeneity of the transverse stresses in the mortar joints both within their thickness and along their depth) do arrive at greater accuracy of assessment, they also require a good deal more analytical rigor, an effort which is unfortunately often made futile by the large number of unknowns in the problem [14].

According to the model adopted here, the mean load state on the masonry structure induced by a vertical pressure σ is governed by:

$$\sigma_{ym} = \sigma_{yb} = \sigma \,, \tag{1}$$

$$\sigma_{xm}\, s_m + \sigma_{xb}\, s_b = 0 \,, \tag{2}$$

with the congruence condition between mortar and brick

$$\varepsilon_{xm} = \varepsilon_{xb} \,. \tag{3}$$

An increase in vertical load brings about a corresponding increase in the bounding pressures on the mortar and brick, whose values are given by:

$$\Delta\sigma_{xm} = \Delta\sigma \frac{n\nu_m - \nu_b}{1+nr} r \,, \tag{4}$$

$$\Delta\sigma_{xb} = \Delta\sigma \frac{\nu_b - n\nu_m}{1+nr} \,, \tag{5}$$

in which $r = s_b/s_m$ and $n = E_b/E_m$. On the other hand the tests carried out have shown that the resistance domain of the mortar relative to the vertical loads is furnished by

$$f_k = f_{ko} + \mathrm{K}\,\sigma_{xm} \tag{6}$$

where f_{ko} is the resistance to simple compression and K is an experimental coefficient with values ranging from 2 to 5 which accounts for the degree of bounding; the lowest values corresponding to mortars either of mediocre mechanical properties, such as those in question, or of non small thickness relative to that of the brick.

Once the value of f_k is known one can definitively determine the limit state of the masonry structure beyond which inelastic strain assumes non-negligible values. Finally, estimate of the post-elastic behavior of the masonry structure can be evinced from the deformation curve proposed in [14] and corroborated by other experimental evidence. On this curve a point in the inelastic realm is identified by a load equal to about 4/3 its rated flexural limit stress, to which corresponds a strain twice as great as that at the elastic limit. This in turn is easily deduced from the simplified expression, valid within the framework adopted by Atkinson, for the masonry's apparent elastic modulus:

$$E = E_b \frac{1+r}{n+r}. \tag{7}$$

In summary, the procedure adopted with the aim of predicting several of the results obtained with flat-jack studies is the following:

- PNT-G measurement of f_{ko} and the consequent estimation of E_m e ν_m;
- determination of n and ν_b on sample bricks, as well as r;
- calculation of the confinement pressure σ_{xm} and evaluation of f_k;
- estimation of the apparent deformation curve of the masonry.

Table 3 presents the primary assessments performed with the above-outlined method and by comparing the results with those in Table 1, the effectiveness of the proposed technique can be appreciated. Finally, for the sake of comparison Table 4 presents the measurements of f' performed with the flat-jacks and those of f_k obtained with the PNT-G. Comparing the two sets, good agreement can be seen between f' and f_k in terms of both mean values and standard deviations, though this latter term is of course an index of the samples' variability rather than any parameter of precision. Furthermore, both the standard and maximum deviations calculated from the differences between the single measurements obtained with the two experimental methods are quite reassuring, in that they are restricted to a much narrower range than the mean values themselves.

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Tab. 1: Flat Jack meseaures and results.

Pos	1G	2G	3G	4G	5G	6G	7G	1F	2F	3F
σ	12.6	10.8	9.4	8.3	11.4	9.4	7.1	5.8	5.4	1.7
E	53300	38100	61500	80000	25000	66700	40000	32300	20000	1900
Ep	20000	28600	16300	35000	18000	31000	14500	13000	8000	600
f'	14.8	16.7	22.1	19.8	14.1	16.2	10.8	10.6	10.8	3.8

Pos	4F	5F	6F	7F	8F	9F	10F	11F	12F	13F
σ	3.8	3.6	5.8	1.7	1.1	2.2	2.7	2.2	4.8	3.6
E	31000	38500	25000	20000	1800	5700	14300	14700	34500	7000
Ep	17500	11600	9500	8500	**	2800	5200	5600	10500	2500
f'	10.8	13.1	9.8	10.7	**	8.3	8.7	9.7	15.1	8.9

Note: Terms meseaured with flat jack
σ: normal stress [daN/cm2]
E: tangent Young moduli [daN/cm2]
f': flexural stress limit [daN/cm2]
Ep: inelastic Young moduli [daN/cm2]
** : collapsed wall

Tab. 2: PNT-G meseaures.

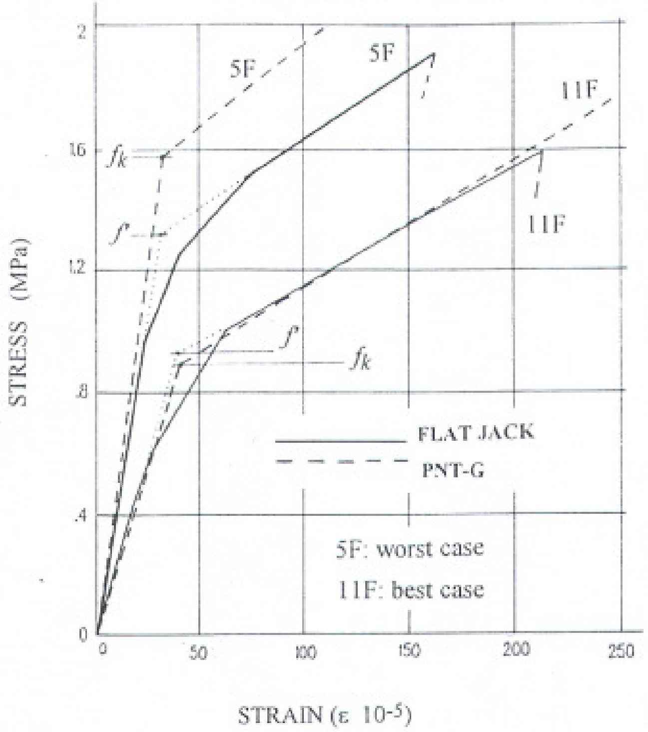
Pos.	1G		2G		3G		4G		5G		6G		7G	
	108	161	338	174	488	329	200	74	283	97	295	81	30	199
	135	231	291	138	264	239	150	132	272	156	88	452	86	187
	236	244	260	109	175	212	126	164	298	192	64	397	168	91
	104	196	276	200	246	129	67	280	265	127	236	361	47	166
PNTG	179	176	284	142	248	319	276	338	211	179	149	522	64	123
Val.	99	145	181	192	432	465	283	171	184	195	88	220	48	111
	196	107	163	156	267	223	99	164	179	238	95	71	183	51
	195	152	247	137	341	88	208	91	144	120	179	309	54	198
	147	130	263	160	452	383	150	110	153	136	143	370	64	82
	138	153	168	191	335	196	209	242	197	158	270	192	348	133
Mean	161.6		203.5		291.55		176.7		189.2		229.1		121.65	
fko	12.43		15.65		22.43		13.59		14.55		17.62		9.36	

Pos.	1F		2F		3F		4F		5F		6F		7F	
	123	145	152	78	24	131	181	132	133	160	88	34	106	120
	106	132	84	102	55	112	162	149	323	89	61	85	138	157
	139	54	130	145	29	94	140	99	319	320	80	86	123	113
	171	109	106	176	96	33	55	87	147	66	34	171	130	237
PNTG	100	108	290	210	111	130	54	44	268	356	171	106	120	99
Val.	44	114	91	223	113	106	57	217	105	229	90	123	72	156
	132	110	207	101	42	16	310	179	59	214	83	184	34	86
	84	126	110	100	51	23	128	96	119	175	69	105	120	161
	92	98	122	167	66	59	93	51	221	103	139	118	108	49
	75	67	88	95	61	92	65	107	174	275	92	76	121	131
Mean	106.45		138.85		72.2		120.3		192.75		99.75		120.05	
fko	8.19		10.68		5.55		9.25		14.83		7.67		9.23	

Pos.	8F		9F		10F		11F		12F		13F	
	47	26	53	61	209	44	83	80	391	379	37	16
	31	69	48	77	133	41	104	63	61	210	63	276
	30	66	107	62	44	43	152	81	193	268	137	243
	44	14	164	156	79	67	91	133	178	222	83	109
PNTG	57	70	90	84	107	161	156	176	167	268	120	184
Val.	91	60	115	126	153	135	47	169	384	56	222	97
	183	37	91	27	70	43	123	140	283	134	147	79
	126	52	169	71	67	129	82	102	116	130	112	102
	22	34	98	110	149	74	108	190	179	111	145	83
	28	64	65	157	156	94	74	188	285	140	118	159
Mean	57.55		96.55		99.9		117.1		207.75		126.6	
fko	4.43		7.43		7.68		9.01		15.98		9.74	

[daN/cm2]

Fig. 2: Typical axial masonry stress-strain diagrams



Tab. 3: PNT-G results.

Pos	1G	2G	3G	4G	5G	6G	7G	1F	2F	3F
Eb	55000	40000	60000	80000	30000	70000	50000	40000	30000	20000
Em	12400	15600	22400	13600	14500	17600	9400	8200	10680	5500
n=Eb/Em	4.44	2.56	2.68	5.88	2.07	3.98	5.32	4.88	2.81	3.64
r=sb/sm	15	15	15	15	15	15	15	10	10	8
E	45278	36438	54303	61296	28121	59018	39372	29574	25763	15469
Ep	15093	12146	18101	20432	9374	19673	13124	9858	8588	5156
s	1.1	1.1	1.4	1.1	1.1	1.1	0.9	0.5	0.5	0
fk	14.6	17.8	24.5	15.8	16.7	19.7	11.3	9.2	11.7	5.5

Pos	4F	5F	6F	7F	8F	9F	10F	11F	12F	13F
Eb	40000	50000	30000	30000	**	20000	20000	20000	40000	20000
Em	9200	14800	7700	9200	**	7400	7700	9000	16000	9700
n=Eb/Em	4.35	3.38	3.90	3.26	**	2.70	2.60	2.22	2.50	2.06
r=sb/sm	10	8	12	8	8	8	10	8	10	8
E	30667	39549	24534	23977	**	16818	17464	17609	35200	17889
Ep	10222	13183	8178	7992	**	5606	5821	5870	11733	5963
s	1.1	1.1	1.4	1.1	0	1.1	0.9	0.5	0.5	0.5
fk	9.8	15.9	8.3	9.9	4.4	7.9	8.1	9.2	16.1	9.9

Note: terms deduced from PNT-G
Eb,Em: block and mortar Young moduli [daN/cm2]
E,Ep: tangent and inelastic wall Young moduli [daN/cm2]
s:mortar transverse pressure [daN/cm2]
fk: mortar flexural limit [daN/cm2]
** : collapsed wall

Tab. 4: Comparision between Flat Jack and PNT-G flexural limit.

	Flat jack: f'	PNT-G: fk	stand. dev.	max. dev.	
Goldoni	16.36 +/- 3.73	17.20+/- 4.16	2.49	3.5	[daN/cm2]
Filzi	9.25 +/- 3.82	9.68 +/- 3.38	1.76	2.8	