NDT ON ANCIENT TIMBER BEAMS: ASSESSMENT OF STRENGTH/STIFFNESS PROPERTIES COMBINING VISUAL AND INSTRUMENTAL METHODS

Ario Ceccotti [1], **Marco Togni** [2]

Abstract

Twelve ancient beams of Fir wood (Abies alba Mill.), were extracted from a XV century building under reconstruction. The large timber elements (average section 34.5 x 30.5) were studied in order to assess stiffness and strength properties. Visual inspection was performed both for the in situ assessment and for the correct interpretation of the subsequent non-destructive (NDT) instrumental tests. The NDT techniques used were stress waves propagation, vibration and hardness. All tests were performed in the laboratory, bearing in mind the practical constraints of in situ operations (time of realisation, easiness of use, etc.). Results show that a thorough visual inspection can provide a reliable chart of the effective residual sections of the beam. Non-destructive parameters (E-moduli or strength indexes) resulted as being closely related to stiffness and ultimate bending strength of the beams (correlation coefficients R~0,8), even though the sample's numerosity do not authorise any generalisation. Further improvements in those relationships were achieved through the combination of non-destructive and visual methods into multi-parameter regressions.

1. INTRODUCTION

The repairing and re-using of ancient buildings, containing large timber structural elements, are very common in all Europe. Frequently old existing structures, with a historical and artistic value too, require a correct assessment of the actual load bearing capacity of each component as **individual**, for performing the correct restoring and/or strengthening operations only when required.

Basic grading is already possible, just using the characteristic values statistically determined through sampling, grading (visually or with NDT) and testing of freshly sawn lumber, but these procedures are not adequate for large and ancient timber beams which have to be graded on site.

In order to estimate timber structural quality, several instrumental methods have been developed and new progress is needed [1] [2].

This *technological age* pushes us to look for the "Method", as single and optimum, suitable for assessing strength/stiffness properties of fresh lumber, and ancient timber beams, too. But, when timber beam size is large, the heterogeneity and variability inside a single element increase, making tests less and less reliable. As well, NDTs are usually calibrated on lumber of a standard dimension and in only

[1] Department of Civil Engineering, Florence University
[2] Institute for Forest Management and Technology, Florence University
The results of this research shall be equally credited to the two authors.

few cases, through failure tests, quantitative data can be related to the actual strength values of full-dimension ancient beams.

Furthermore, even though age does not appear to affect strength and stiffness properties on beams loaded to a limited load level [3], a cumulative damage, due to accidental events (wet conditions, momentary overloads, fire, *restorations*, etc.), is directly related to age and can increase the heterogeneity of the material.

In this study full-dimension ancient timber beams were subjected to visual surveying, non-destructive and bending tests, in order to obtain non-destructive parameters and strength/stiffness values, practical indication about best procedures and achievable results.

2. THE MATERIAL

Twelve ancient timber beams were extracted from a XV century Florentine building, during restoration and reconstruction works. No test on dendrochronology was executed, but the timber probably had the same age and origin of the structure, since documents did not reveal that the floor containing the beams had been subjected to interventions [4].

The timber was Fir (*Abies alba* Mill.), traditionally used for structures in many old buildings, particularly in central Italy, due to the availability of large trees purposely cultivated for this utilization.

The average transverse size was 34.5x30.5 cm, the range of height was 32-38 cm and the length was less than 500 cm. The original length was about 900 cm, but during work on the building, all beams were truncated for better handling. So, while the initial length/depth ratio was equal to 25-29, the beams used had a ratio of 13-15.

Annual rings of wood were very thin (less than 1.2 mm per ring); decay and anomalies were largely present; on the length studied no evident residual deformations (creep) were found; few insects holes (*Anobium sp.*) were visible.

3. VISUAL INSPECTION, THE FIRST NDT

Usually the first step for the *in situ* assessment of old timber beams is the visual inspection. It can be done more or less thoroughly, but generally the main information on the history and actual conditions of the material is achievable through this kind of approach [5].

The selected timber beams have been deeply evaluated with these purposes:

- visual strength grading according to different standards;
- supplying a chart representing all the faces of the beams, a kind of ”map” of decay and defects distribution;
- estimating the internal and invisible anomalies;
- evaluating the critical section and the residual portion still functioning.

Visual evaluation of original wood defects, estimation of decay (evaluated by using simple tools: awl, gimlet, drill...), identification of previous interventions or accidental events and visual grading were performed on the 12 specimens.

Data were recorded as follows:

- dimension and distribution of knots;

- average and maximum slope of the grain;
- dimension and distribution of checks and ring shakes (estimated);
- location, extension and depth of decay (estimated);
- average width of growth rings and possible changes in the rates of growth.

Like instrumental tests supply data which have to be compared to relationships related in literature, the visual inspection as well provides a number of values comparable firstly with operator's experience.

3.1 Visual strength grading

Data were then used for the visual strength grading according to three rules: DIN 4074-1989 1st part, "*Sortierung von Nadelholz nach der Tragfähigkeit-Nadelschnittholz",* UNI 8198-1981 *"Segati di conifere - Classificazione in base alla resistenza meccanica"* and the rule proposed by GIORDANO (1947) [6].

These grading rules, in their original form, apply to medium-size, freshly sawn and sound structural timber. Hence *ad-hoc* adjustments were necessary to account for the large size and decay of the beams: the shrinkage fissures (not going through) were excluded from the grading criteria; the admissible values for decay were adjusted to accept also large beams with an external decay, not deeper than 5% of the thickness, in the second and third grades. On ancient timber beams some surface decay can be frequently present, due to momentary wet conditions, but it is not enough to prevent the structural use of this kind of material.

adapted grades			graded beams and		strength classes	revised strength
DIN 4074	UNI 8198	Giordano		grade determining defect	EN 338	N/mm^2
S13	S10	I	T12	-	C30	25.4
S10	S8	II	T3, T10	decay, decay and knots	C24	20.3
S7	S6	III	T9	decay and knots	C16	13.5
	rejected		T2 T4 T5 T8	ring shake,		
			T1	grain dev. and ring shake,	-	-
			T6 T7 T11	decay		

Table 1 List of grades with adapted limitations for decay and checks; corresponding strength classes as indicated in EN 338 and characteristic strength values hypothesising that k_h factor (EN 384) depending on the average height of beams, has been applied to the f_{m05} of a sample statistically significant

4. INSTRUMENTAL TESTS

In the field of repairing and strengthening structures, many kinds of NDTs have been developed. The non-destructive tests used in this study were *stress wave propagation*, *free vibration* and a property related to *hardness*. This selection was made bearing in mind the practical constraint of *in situ* execution of the tests and the reliability of these methods compared to other techniques [1] [2].

4.1 Stress wave velocity in longitudinal direction

Stress wave velocity can be directly related to the elastic properties of timber. Interesting relationships have been obtained with strength and stiffness properties, on freshly sawn little beams [7].

The SYLVATEST ultrasonic device was used for measuring the stress wave propagation time in the longitudinal direction of the beam. The thin extremities (Ø 5 mm) of two piezoelectric transducers, especially conceived for testing timber, were gently but firmly pressed into small holes punched in the wood: both on *a)* the ends of the beam to perform the *end-to-end* test, and *b)* the faces (close to the end) at a 45 degree inclination, in order to simulate the *in situ* test, where the ends of beams and the extrados are usually not accessible.

The adequate connection of the wood-to-metal interface, without couplant, and the high power of the instrument provided a readable signal, though decay and anomalies, high energy absorbers, were present along the beams.

<u>Stress wave decay</u>

The loss of energy of the first stress wave has also been measured along the surface of the beam, by means of an accelerometer and memory oscilloscope. An exponential decrease was found related only with wood damping. A more comprehensive approach on stress waves spectral analysis is necessary.

4.2 Stress wave velocity in transversal direction

Anomalies and decay, present in the inner part of large beam, and the local elastic properties can be surveyed and estimated by the measurement of stress wave propagation time in transversal direction, perpendicular to the longitudinal axis of the beam. In this condition, "transversal" direction, varying from the radial to the tangential one, is due to the dimension of the beam and the unknown way of stress waves.

The PUNDIT, an ultrasonic device conceived for testing concrete, was used for this test. The cylinder-shaped transducers allowed the measurements to be performed also on rough surfaces, using vaseline grease as couplant. The propagation time was measured from one lateral face to the other, each 25 cm along the whole beam.

A preparatory study, for performing the same test, was executed with the SYLVATEST. It showed that the measurements were not repeatable without holes for transducers, because every little displacement of their thin extremities produced different results due to the heterogeneity of the rough surfaces; furthermore, the preparation of many holes took a long time and it was rather destructive.

On the contrary, the large surface (~20 cm^2) of the PUNDIT transducers assured a good repeatability and the independence from the accuracy of the position.

4.3 Hardness

Wood hardness is a parameter closely related to density, and density shows fairly good relationships with all the wood properties.

Two PILODYN devices, Pilodyn 6J single shot and Pilodyn 4JR repeating shot, were used to measure a parameter closely related to density [8] [9]. PILODYNs are dynamic instruments based on the action of a calibrated spring, able to drive a flat-head steel pin into the wood. This dynamic test for hardness was performed on three faces of the beam, the visible ones referring to the original *in situ* condition, taking care that the direction of the pin was perpendicular to the growth rings, to avoid the application of an adjustment factor [9].

The measurements were repeated every 25 cm, along the whole beam.

Decay, but especially surface decay, very likely affects the test results to a significant degree.

4.4 Free longitudinal vibration

The frequency of natural free flexural and longitudinal vibration are tightly related to stiffness. Free longitudinal vibration was chosen, since the flexural one is better related with E (modulus of elasticity), but also more difficult to be measured due to the uncertainty about the constraints of the beam in service (unknown supports and load conditions). The preferable free-free ends arrangement, using ”knife” supports and beams disassembled from structures, is hard to be reproduced outside the laboratory and requires the correct assessment of the nodal points position. In addition, the frequency of the specimens tested could be affected by shear modulus due to the low length/depth ratio [10].

The vibration of timber beams was measured with an accelerometer fixed along the beam, and the first frequency was determined with a portable signal analyser (RION) by means of the FFT analysis.

4.5 Remarks on non-destructive tests

Non-destructive tests showed their precious qualities and limits when applied on large and ancient timber beams.

Stress wave test in longitudinal direction provided a realistic mean value closely related to the stiffness property of the beams, but, when ring shakes, hard and localized decay, different moisture contents, etc. were present, stress waves detected their way through sound wood, unaffected by these anomalies, and only the fastest wave component could be measured.

Stress wave test in transversal direction provided a good qualitative representation of the decay distribution and anomalies, but:

- invisible seasoning checks (on beam extrados, *in situ*) could be mistaken for decay and hard decay (fig. 1-a);
- ring shakes could be crossed by stress waves without slowing down when two split margins of beam had a good connection (fig. 1-b);
- moisture gradient, commonly present in a large timber element, as in our sample, could not be measured with accuracy on site but it had an influence on the propagation time [7] (fig. 1-c);
- knots close to transducers, with their longitudinal axis in the same direction of the stress waves, could wrongly increase the velocities.

Free vibration in longitudinal direction did not seem responsive enough to the lowering of E due to ring shakes.

Hardness has usually good relationship with density, which has a high variability inside a large beam. That means the hardness properties measured are closely related to the surface density, explored by the PILODYNs’ pins; consequently, an overestimation of the surface properties, where a higher concentration of decay is present, was provided.

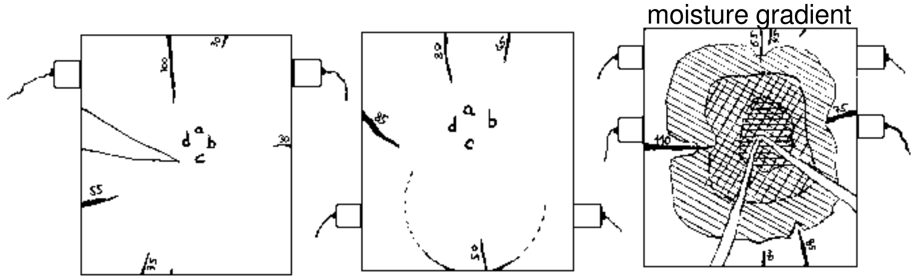

Fig. 1 Some limits of stress waves on large beams (sect.4.5): *a)* checks, *b)* ring shake, *c)* moisture

5. Mechanical tests

Laboratory tests were performed on the beams in order to determine moduli of elasticity (E_0, E_{app}), bending strength (f_m, on the beam cross-section as a whole), strength determining defects and failure mode. The span of the four point loading test was 4.2 m.

Both bending and shear failures occurred. The main reasons for bending failures were knots, grain deviation and decay while for shear failures were seasoning checks, ring shakes and particularly the low length/depth ratio (sect. 2). After the shear breakage, bending tests were carried on in order to obtain, at any rate, a bending failure of two disjoined parts of beams. The strength of split beams ($f_{m\ mean}$) was estimated by averaging the bending strength of the two parts; the calculation was made considering the two beams, with different sizes, simply one upon the other. This estimation, disregarding the problem of friction between the split parts, partially overrated the strength properties of the beams; but $f_{m\ mean}$ was equally considered a good approximation of the actual strength properties. Here, it is necessary to recall that our purpose was not the production of ready-to-use relationships or strength values but the study of the best approach to the on site evaluation, also supported by tested mechanical properties.

beam	density	E_0	f_m	failure determining defect(s) and main failure mode		$f_{m\ mean}$
	kg/m³	N/mm²	N/mm²			N/mm²
T 1	480	8689	25.0	ring shake, checks	- shear	41.2
T 2	483	8273	28.0	ring shake, checks	- shear	38.3
T 3	516	18266	39.6	fissures - shear and bending at once		80.6
T 4	464	13048	25.8	ring shake, checks	- shear	45.5
T 5	487	12906	44.8	slope of grain, knot	- bending	*44.8*
T 6	505	10355	33.9	localised decay	- bending	*33.9*
T 7	464	8102	30.9	knots, diffuse decay	- bending	*30.9*
T 8	513	14013	47.0	checks	- shear	69.1
T 9	498	11747	38.5	knots	- bending	*38.5*
T 10	478	12243	29.4	checks	- shear	56.6
T 11	469	7104	15.3	diffuse decay	- bending	*15.3*
T 12	449	11630	30.1	checks	- shear	58.3

Table 2 The main mechanical values, the strength determining defects and failure mode (E_0: modulus of elasticity, f_m: bending strength, $f_{m\ mean}$: average bending strength for split beam)

The whole sample revealed an interesting strength behaviour because the final load was always preceded by a long sequence of cracks coupled with high acoustic emissions. The corresponding load/deflection diagram of all timber beams tested was characterised by a large non-proportional share over the limit of elasticity (fig. 2). Consequently, in a load-sharing structural system, this semi-ductile behaviour is a further assurance that a critically loaded wooden element would not lead the structure to collapse, but, during its plastic phase, it would be supported by the co-operating timbers, helping the safety.

The moisture content, measured at three different depths of beams, showed a gradient ranging from 11 to 16%. No adjustment was proposed either for stiffness value or for density, due to the uncertainty about the real average of moisture along the whole beam.

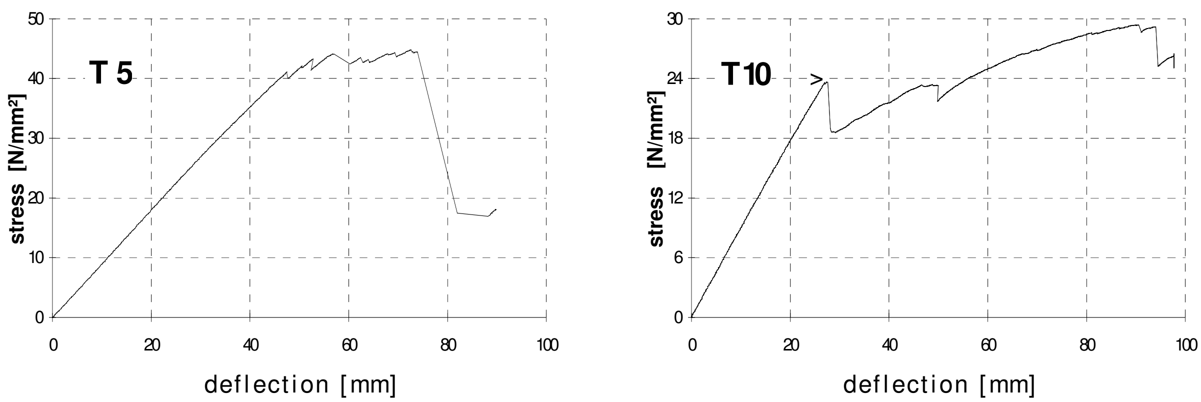

Fig. 2 Stress/deflection diagrams: a) beam T 5, bending failed; b) beam T10, shear failed in >

6. Results

<u>Relationships</u>

Fairly good relationships between different non-destructive parameters (E-moduli or strength indexes) and strength/stiffness properties are shown in tables 3 and 4.

	stress wave velocity				free vibration	
	v_0	**v_{45}**	**$E_{us\,45}$**	**$E_{us\,0}$**	**frequency**	**E_{fr}**
E_0	0.85	0.85	0.93	0.92 (1)	0.68	0.91
E_{app}	0.80	0.84	0.89	0.86	0.78	0.93

E_0, E_{app}: static moduli of elasticity, four point and three point loading test; v: stress wave (s.w.) velocity; E_{us}: s.w. modulus of elasticity; 0, 45: degree of inclination of the s.w. transducers; E_{fr}: free long.vibration modulus of elsticity

Table 3 Correlation coefficients between stiffness and non-destructive tests ((1) chart in fig. 3-a)

Correlation coefficients testify that a realistic prevision of stiffness properties is possible also on large and old beams. Obviously, good relationships with E_0 were expected since the main part of NDTs has been based on it.

The correlation coefficient between f_m and E_0 was the highest; this result confirms the data that was shown as closely related in the literature. In fact, the best results on timber grading can usually be achieved by means of strength grading machines, based at least on one static modulus of elasticity [11].

	E_0	E_{app}	$E_{us\,45}$	$E_{us\,0}$	v_{45}^2	v_0^2	frequency	E_{fr}
$f_{m\,mean}$	0.89	0.84	0.87	0.79	0.84	0.75	0.84	0.82

Table 4 Correlation coefficients of non-destructive data *vs* average bending strength of split beams

Notable relationships were not found between data acquired with visual inspection (knots, slope of grain etc.) and strength/stiffness properties. Gross density was relatively correlated to hardness, gained through the two PILODYN devices (P.6J r=-0.86; P.4JR r=-0.83), but the results did not allow us to estimate density, applied also for dynamic moduli, through this NDT parameter.

Simple regressions

R squared in simple regressions suggested that an appropriate indication on strength property is achievable using these kinds of NDT. Reliability depends on the statistical parameters, particularly on the numerosity of the sample.

model	charts	y	x	A	B	n	R^2 [%]
y=Ax + B	*fig. 3-b*	$f_{m\,mean}$	E_0	$5.132 \cdot 10^{-3}$	12.6	12	76.7
	fig. 3-c		$E_{us\,45}$	$5.603 \cdot 10^{-3}$	33.5	12	75.8
			$E_{us\,0}$	$7.296 \cdot 10^{-3}$	67.7	12	62.2
			V_{45}	$2.948 \cdot 10^{-2}$	113.1	12	69.0
			V_{45}^2	$2.831 \cdot 10^{-6}$	37.0	12	69.7
			V_0	$4.288 \cdot 10^{-2}$	193.8	12	55.6
			V_0^2	$3.912 \cdot 10^{-6}$	76.7	12	56.0
			E_{fr}	$7.228 \cdot 10^{-3}$	42.2	12	67.5
	fig. 3-d		frequency	$4.806 \cdot 10^{-1}$	218.1	12	70.4
			E_{app}	$6.121 \cdot 10^{-3}$	9.5	12	70.6

Table 5 The most meaningful simple regressions, linear model

Multiple regressions

An attempt to improve the prediction of the strength of the sample was performed coupling a non-destructive parameter, able to supply a global evaluation of the timber, with a local parameter resulting from the visual inspection and related to strength properties [12]. Among different local parameters, the knot ratio A, according to DIN 4074, was chosen. The correlation coefficient of this parameter with $f_{m\,mean}$ is very low ($f_{m\,mean}$ *vs* A: r = -0.46) but the highest among the other data (slope of grain, K.A.R., ring width, etc.).

Anyway its introduction allows a noticeable improvement of determination coefficients. Of course, once again, results, shown in table 6, have to be considered only as a promising trace for further investigations.

model	charts	y	x	z	A	B	C	R^2 [%]
y=Ax+Bz+C		$f_{m\,mean}$	A	$E_{us\,0}$	-89.7	6.92 10-3	-50.8	71.3
	fig. 3-e			$E_{us\,45}$	-93.4	5.41 10-3	-22.2	89.5
				v_{45}^2	-96.5	2.74 10-6	-25.6	83.4
				v_0^2	-93.4	3.71 10-6	-62.4	65.2
	fig. 3-f			E_{fr}	-75.9	6.71 10-3	-29.0	72.5

Table 6 Multiple regression combining visual and instrumental methods

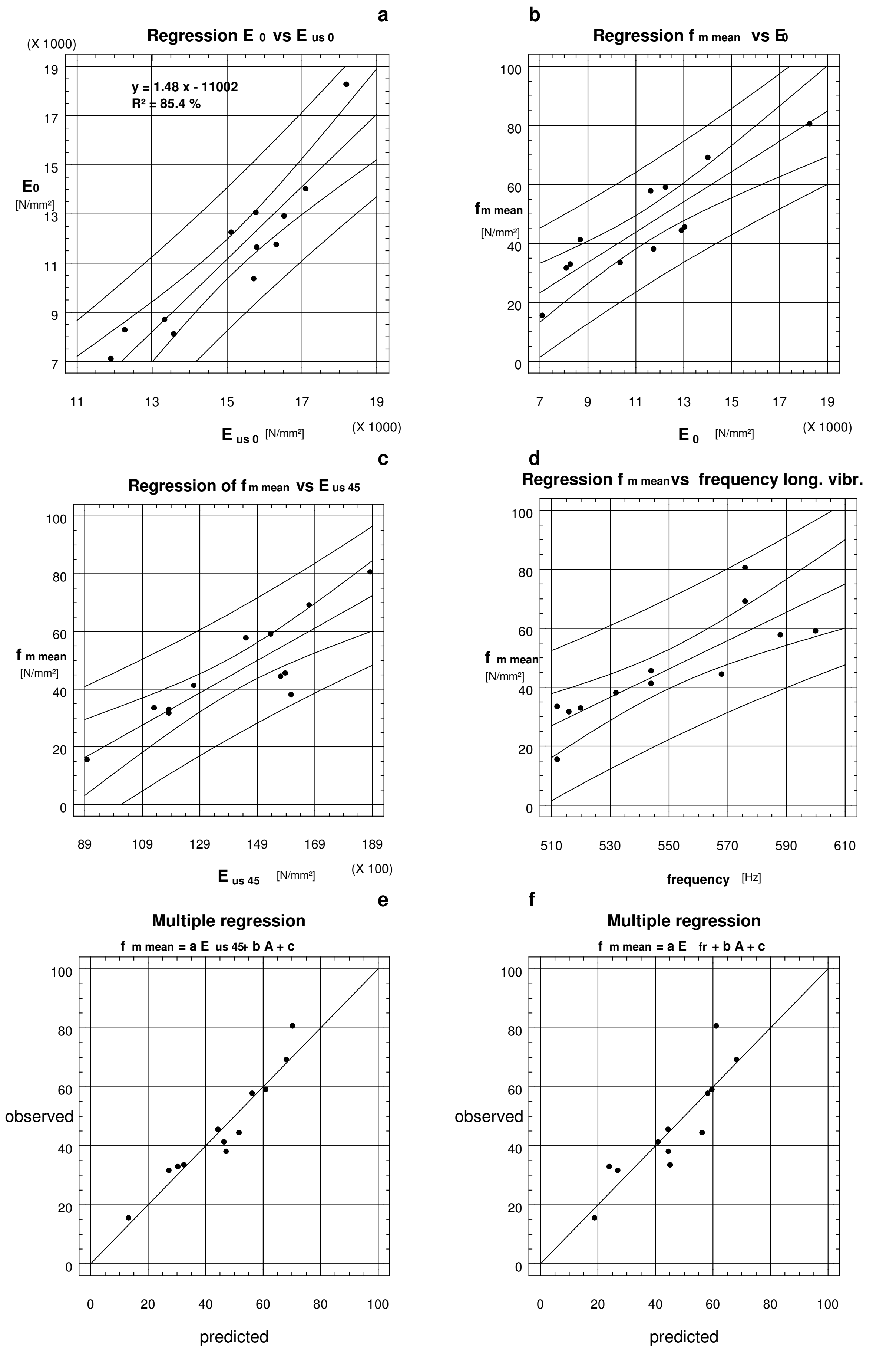

Fig. 3 Simple regressions: *a*: 'r' in table 3; *b*, *c* and *d* in table 5; multiple regressions: *e* and *f* in table 6

7. Conclusions

The mechanical tests showed very high values of strength/stiffness properties, though defects and decay were present. Disregarding $f_{m\ mean}$, due to the split beams, excellent results were also achieved with f_m, which was the highest strength datum before early shear failure. They encourage investigating large section timber, to increase the knowledge about properties and strength resources of such material.

The adjustment of the rules, conceived for new structural timber, is a requirement for grading old, full section beams. Otherwise, no ancient beam, partially decayed and with checks, could be accepted by the existing visual strength grading rules.

Single-parameter linear regressions showed an interesting correlation between non-destructive values and strength; results can be improved by joining NDT methods in multi-parameter regressions, and particularly by combining global and local properties measured on the beams.

The purpose should be the development of an optimal grading for on-site large timber beams. The way could be to combine an a*d-hoc* strength grading rule with one or more machine based parameters, calibrated on the species.

The improvements envisaged require an increased number of investigated samples, hence, the grading and testing of a greater number of timber members, extracted from old buildings, and the implementation of a dedicated data base, possibly at a trans-national level.

References

[1] Falk, R.H., Patton-Mallory, M., McDonald, K.A., «Nondestructive testing of wood products and structures: state-of-the-art and research needs» *Nondestructive testing and evaluation for manufacturing and construction: Proceedings of conference, 137-147, 9-12 August 1988;*

[2] Anthony, R.W., Bodig, J., «Nondestructive evaluation of timber structures for reliable performance», *Proceedings of the Second Pacific Timber Engineering Conference New Zealand, 1989*

[3] Kuipers, «Effect of age and/or load on timber strength» *CIB-W18,19th Meeting, Florence, 1986.*

[4] Bacciardi, Breschi, Clemente, Pecchioli, *Analisi di un contenitore e metaprogetto di una funzione urbana*, CLUSF, Firenze, 1978.

[5] Bonamini, G., «Restoring timber structures - Inspection and evaluation», *Timber Engineering STEP 2 (STEP/EUROFORTECH - EU Comet Programme), D3, Centrum Hout, 1995*

[6] Giordano, G., *La moderna Tecnica delle Costruzioni in Legno*, Hoepli, Milano, 1947

[7] Sandoz, J.L., «Grading of construction timber by ultrasound», *Wood Science and Technology, 23, 95-108, 1989*

[8] Hoffmeyer, P., «The Pilodyn instrument as a nondestructive tester of the shok resistance of wood» *4th Nondestructive Testing of Wood Symposium, Washington, august 1978*

[9] Görlacher, R., «Zerstörungsfreie Prüfung von Holz: Ein "in situ"-Verfahren zur Bestimmung der Rohdicte» *Holz als Roh- und Werkstoff, n. 45, 273-278, 1987*

[10] Chui, Y.H., «Vibration testing of wood and wooden structures - Practical difficulties and possible sources of error» *New Brunswick, Canada, 1989*

[11] Blass, H., Gard, W., «Machine strength grading of timber» *Proceedings of Pacific Timber Engineering Conference, Gold Coast, Australia, 11-15 July 1994*

[12] Ceccotti, Nakai, Togni,«Strength grading of structural timber by non-destructive methods: a case study in Italy» *1st European Symposium on Nondestructive Evaluation of Wood, Sopron, 1994*

Acknowledgements

The research was performed with the facilities of the Laboratory of the Department of Civil Engineering, Florence University. Authors wish to thank the whole personnel of the *Lab*, specially Mr. Saverio Giordano, for their fundamental support.