IL LATERIZIO NELLA COSTRUZIONE DELLA CUPOLA DI SANTA MARIA DEL FIORE A FIRENZE
BRICK IN BUILDING OF THE DOME OF SANTA MARIA DEL FIORE IN FLORENCE

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ABSTRACT This paper is part of the research which has being going on for some time now in the Dipartimento di Costruzioni of Florence University into the building of the dome of the cathedral of Santa Maria del Fio= re and in particular the materials used in it. Historical research was conducted mainly using documents from the Archivio dell'Opera. Research into the materials - this paper is concerned with the bricks and mortar used - was conducted through tests on core samples of appropriate dimensions. At the same time tests were carried out on samples of the existing single components and of modern masonry to compare the "old" with thz "new", so as to be able to use samples of modern materials and thus avoid the necessity of taking further specimens from the original.

1. INTRODUCTION

The two areas of research conducted on the materials of the dome of Santa Maria del Fiore are:

i) historical research concerning Brunelleschi and the material, involving study of material design and control of results, origins and suppliers: for this it is necessary to have maps, documents, details and evaluations of masonry of that time;

ii) development of materials with the same characteristics for the purpose of testing resistence: due to the difficulty of carrying out non-destructive tests "in situ" and the limited number and size of possible samples to be taken, an "equivalent" material is produced on the basis of historical data and chemical-physical analysis of the available materials with the emphasis on mechanical equivalence.

In this way it is possible to program for any series of tests and experiments on specimens created today with modern materials but the results of which are reasonably transferrable to Brunelleschi's masonry.

2. MATERIALS: HISTORICAL DATA

The first reference to materials used in the dome of Santa Maria del Fiore can be found in Brunelleschi's instruction for the construction of the dome according to his project, which he gave in 1420 and "ammended" in 1421.
There are reference to "forti macigni" (hard sandstones), "ferro stagnato" (tinned iron), "catene di ferro e di quercia" (iron and oak ties), "pietraforte" and in particular with reference to our topic "mattoni" (brick) and "spugna" (tuff): "...e da indi in su si muri di mattoni o di spugna, secondo che si deli= bererà per chi allora li avrà a fare, più leggeri che pietra".
There is also a reference after this to marble.
Not only did Brunelleschi describe the materials to be used, but he personally controlled the selection.

2.1. Brick

The dome of Santa Maria del Fiore was constructed without reinforcement and is thus a self-supporting structure, with eight sections resting on an octagonal drum. The stupendous brickwork is laid in a sophisticated "spina pesce" and "cor= da blanda" pattern. Brunelleschi himself directed day by day the eight teams of ten men, working contemporarily on each ring of brickwork, constructing vertical link elements for each successive ring and personally checking the laying of the bricks which he himself had "conceived" and had made in special shapes in order to obtain the greatest possible compactness and a perfect fit in terms of circumference and radius.
Before the building of the dome, split stone and rubble had been the materials mainly used in the construction of church walls and vaults, even though brick had been used in the Middle Age in Florence for the construction of the main walls. In fact the use of fair-faced brickwork was common in houses and palaces as was the use of brick in street paving.
The expert brick and tile manufacturers of the Arno Valley, south of Florence, and of Impruneta were the suppliers for the work. The most important was Pardo d'Antonio da Volterra, with his kilns at the Badia di San Salvatore at Settimo sull'Arno. He was supplier to the Opera from 1407 onwards.
The project for the dome was accepted in July 1420 and probably only drawn up in the autumn of 1418. Although it did not specify the construction materials, in order to be sure of obtaining the necessary bricks, the Opera drew up a contract with Pardo in 1418 for 200000 "quadroni angolij di mattoni". In 1421 the names of Bartolo di Marco, Nello di Andrea and Cambio di Antonio Maffei, called Ferro, all three from Campi Bisenzio, and Giovanni Nutini of Lastra a Si= gna were added to the list, together with orders for from 240000 to 1 million bricks. In September 1419 Pardo had prepared 400-600000 bricks, some fired (cottos) and some not yet fired (nudis), and the order from the workers to increase the order by 200000 pieces shows that the balance was leaning in favour of bricks rather than the volcanic "spugna" (tuff), which had been considered for reasons of economy but which nevertheless would have had to be imported from the volcanic regions around Monte Amiata. Anyway, the control of both the quality and form would have been easier in the case of bricks.
Even without wanting to believe literally every word of Manetti and later Baldi= nucci, it is certain that Brunelleschi parsonally paid particular attention to the materials used: "...e acciocché ogni piccol lavoro fosse fatto con quella esattezza, misura e qualità, ch'esso stimava necessario, non fidandosi d'alcuno, visitava ogni mattone, e ogni pietra, che fosse messa in opera, la quale voleva, che sempre fosse a canto vivo secondo l'opportunità del lavoro, portandosi anche sovente a visitare le fornaci stesse per assicurarsi della bontà e della buona cottura del materiale" (...so that every little job was done with the care and precision that he deemed necessary, not trusting others, he looked at every brick and every stone that was laid, to see that it was well squared, work permitting, and he often visited the kilns themselves to ensure that the bricks were of good quality and that they were well fired).
In December 1420 Pardo delivered 20950 bricks of which 250, "1/4 miglaio", were rejected as "farignij", and in July 1421 many more were not accepted because they were not of the necessary quality (Fig. 1).
Further problems with faulty bricks caused Pardo to lose the contract to Antonio Vannozzi who lost it in turn in 1423 to the rival, probably because he could not

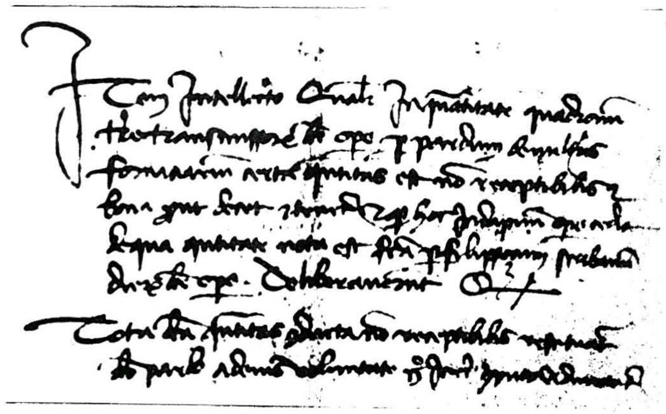

Fig. 1 - From "Bastardello Deliberazioni e Stanziamenti" - Serie II-1-79, anno 1421, a carta 9r.
"dicto die XXIIII mensis Julij"
"Item intellecto qualiter in quantitate quadronum terre transmissorum dicte opere pro Pardum de Vulterris fornaciarum certa quantitas est non receptibilis et bona..."

keep up with commitments.

A word in conclusion about the best clay which comes from the Pliocene deposits particularly found in the comune of Signa. The sedimentary complex ("Caotico"), as we know, appears disorganised with the complicated folding together of lithic blocks (even of different formations) embedded in a schistose clay matrix. This, like the quarries of Impruneta, provides excellent clay for brick-making.

2.2. Mortar

The documents and registers of the Opera reveal almost daily records of the enormous quantity of lime mortar which was delivered and used, but not the origin of the material, the whereabouts of the kilns, etc.

We know from Manetti that Brunelleschi paid much attention to the choosing of the limestone and to the heating process used to produce lime mortar: "La diligenza che metteva nella calcina era meravigliosa, ed andava alle fornaci in persona, rispetto alle pietre d'esse, e rispetto al cuocere, che pareva d'ogni cosa maestro, così de' mescugli delle rene con la calcina, e di quello che bisognava ..." (He followed the lime-making process with amazing diligence, going personally to the kilns, inspecting the stone and the heating process: he seemed to know about everything, the mixing of the sand with the lime and everything else).

The raw material used was probably a kind of limestone, "alberese" - a fine-ground white or yellowish-grey calcareous marlstone - and clay schist, marl schist, calcareous sandstone, rarely "breccia". "Alberese" was plentiful around Florence and was used mainly for the making of the lime mortar: the "Statuto dell'Università de' Fabricanti" (1542) records the "cavatori di pietre alberesi per far calcina".

A document of February 1421 refers to "fornaciai" beyond Porta Romana: "Giuliano di Paolo di Benedetto p.p. S.Frediano e Guido da Gangalandi...Fornacai prope Januam sancti petri gattolini de florentia mille trecenta quinquigenta modia Calcine lapidum Alberesium sine aliquo ciottolo..." (Fig. 2).

Below, in brief, the results of the tests performed by Bernard Erlin Ass., Northbrook, Illinois, on specimens of mortar taken from various parts of the dome and as a control, from other places: "All of the specimens were composed of a lime-natural sand mortar having similar materials. Sodium carbonate occurred in small voids in the mortar and on the surface. Sodium carbonate in even extremely small amounts should reduce the setting time of lime mortars...Thus the possibility exists that the mortar, advertently or inadvertently, was rapid stiffening".

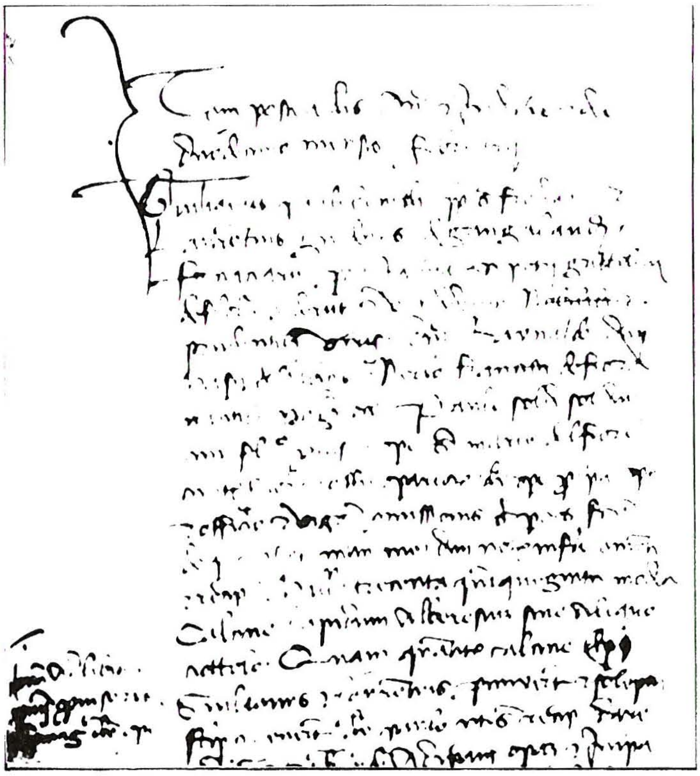

Fig. 2 - From "Bastardello Delibera=
zioni e Stanziamenti" - Serie II-
1-78, anno 1420-21, a carte 58r.
"Item postea dictis anno et indic=
tione et die duodecimo mensis fe=
bruarij"
"Giulianus Pauli Benedicti popoli
Sancti Frediani et Laurentius Gui=
donis de Gangalandi fornaciarj
prope ianuam Sancti Petri Gattoli=
ni de Florentia, dederunt et ven=
diderunt domino Paulo Soldi Soldi=
ni civi florentino provisori Ope=
re S.Marie del Fiore civitatis
florentine et officj operariorum
dicte Opere pro ipsa Opera et of=
ficio et vigore commissionis su=
pradicti per eos facte et..."

It may be said that no difference was noted in the composition of the mortar used in the dome and that used in the lower parts of the cathedral.

3. MATERIALS: MECHANICAL PROPERTIES

This part of the study is concerned with the analysis of the component materials of the dome of Santa Maria del Fiore. In dealing with an historical structure the problem arises of analysing in as much detail as possible the chemical-physical-mechanical characteristics by means of non-destructive tests "in situ" and, if this proves impossible, by means of taking specimens which are as small as possible.
Non-destructive tests may be carried out "in situ" using modern instruments and technology (ultrasound, induced currents, x-rays, etc.) to determine physical and chemical characteristics such as porosity, cohesion, permeability to water, etc. and also to determine the compressive strength using "flat jacks".
The tests, which are still going on, are outlined in the following paragraphs. Certainmore significant tests and their results are given in more detail, others are summarized.

3.1. Test on original material

Core samples of original masonry were subject to cataloguing, photographing and visual examination. A prototype program was drawn up in order to carry out as many tests as possible on a single specimen.
A general classification and description of the various components was made to work out the feasibility of performing tests both on the component materials (brick, mortar) and on their product (masonry).
The volume of every specimen was calculated.

3.2. Tests on the original brick

3.2.1. Compressive test

Cubes of material of 40 mm dimension were extracted using a special water saw. The cubes were left to dry out at a temperature of 20°C with 60% relative humidity for ten days and then tested for axial compression until fracture occurred, using an oil dynamic press of 3000 kN and a strain rate of 1 N/mm^2 per second.

Evaluation of results (Fig.3)

n	16
$\bar{x}$	24.475
s	3.173
$s_{\bar{x}}$	0.793
V	12.960
P%	0.032

3.2.2. Tensile test

Tensile tests were carried out on specimen cubes of the same dimension as those used inthe compressive test. The indirect tensile test "brasilian" was performed.

Evaluation of results (Fig. 4)

n	16
$\bar{x}$	2.309
s	0.295
$s_{\bar{x}}$	0.073
V	12.77
P%	0.031

3.2.3. Calculation of Young's modulus and Poisson's ratio

Calculation of Young's modulus was carried out on brick prisms taken from core samples. Strain gauges of the type LA 21 10/120, length 10 mm, were used. Maximum load was calculated on the basis of results of the compressive test. Three cycles were effectuated, the third to failure, with increases of 1 kN. A press of 3000 kN was used. The stress-strain diagrams were made according to the degree of strain registered by the vertical strain gauges on sides 1-3 of the prism and from this the Young's modulus E was calculated (ASTM-D3148-72). The Poisson's ratio ν was calculated as the ratio between the axial strain and the transversal strain registered by the horizontal strain gauges on sides 2-4 of the prism. Below are the stress-strain diagrams for two specimens having the dimension 33.35x38.80x120.00 mm (I) and 40.60x29.80x100.27 mm (II), respectively with slenderness ratio 3.09 and 2.47 (Figg. 5-6-7-8).

Values obtained for E and ν are:

$$E = 11085,30\ N/mm^2$$

$$\nu = 0,18$$

3.2.4. Calculation of unit density

For the calculation of ϱ_d, the ratio of dry weight and apparent volume, the cubes subsequently subjected to the compressive test were used.

Evaluation of results (Fig. 9)

n	16
$\bar{x}$	1550
s	87
$s_{\bar{x}}$	21.7
V	5.61
P%	0.0135

3.2.5. Calculation of density of solid particles

For the calculation of ϱ_s, tests were performed on the same cubes as in 3.2.4., pulverised.

Evaluation of results (Fig. 10)

n	16
$\bar{x}$	2.38
s	0.058
$s_{\bar{x}}$	0.0145
V	2.43
P%	0.0061

3.2.6. Calculation of porosity and compactness

Porosity was calculated by the expression:

$$n\% = 100\ (1 - \varrho_d / \varrho_s)$$

Compactness is expressed:

$$C\% = \varrho_d / \varrho_s \times 100$$

Evaluation of results (Figg. 11-12)

n	16	16
$\bar{x}$	34.30	65.70
s	4.50	4.50
$s_{\bar{x}}$	1.125	1.125
V	13.110	0.068
P%	0.032	0.017

3.2.7. Coefficient of imbibition and unit weight

Evaluation of results (Fig. 13)

n	16
$\bar{x}$	18.04
s	0.175
$s_{\bar{x}}$	0.0437
V	0.970
P%	0.0024

Values for dry and saturated unit weight are:

$$\gamma_d = 16.18\ kN/m^3$$
$$\gamma_s = 19.22\ kN/m^3$$

3.3. Tests on original mortar

3.3.1. Compressive test

Evaluation of results (Fig. 14)

n	16
$\bar{x}$	19.54
s	2.501
$s_{\bar{x}}$	0.625
V	12.79
P%	0.0319

3.3.2. Tensile test

Evaluation of results (Fig. 15)

n	16
$\bar{x}$	3.82
s	0.142
$s_{\bar{x}}$	0.035
V	3.71
P%	0.0092

3.3.3. Calculation of Young's modulus and Poisson's ratio

Values obtained are:

$$E = 7848.00 \text{ N/mm}^2$$
$$\nu = 0.27$$

3.3.4. Coefficient of imbibition and unit weights

$$C_i = 17.67$$
$$\gamma_d = 16.57 \text{ kN/m}^3$$
$$\gamma_s = 19.52 \text{ kN/m}^3$$

3.4. Tests on modern materials

Results of these tests are summarized in the following paragraphs.

3.4.1. Tests on bricks

Bricks were tested for compressive and tensile strength. Data of results are:

$$\sigma_c = 35.00 \text{ N/mm}^2$$
$$\sigma_t = 2.56 \text{ N/mm}^2$$

A test of initial absorption was performed. The initial absorption was calculated by the expression:

$$S = (p_w - p_d)/A$$

where:

p_w = wet weight

p_d = dry weight

A = surface of area immersed

The average value obtained is:

$$S = 9.45 \text{ g/dm}^2 \text{ per minute}$$

Results of tests of imbibition, unit density and density of solid particles, porosity and compactness are:

$$C_i = 18.63$$
$$\varrho_d = 1720 \text{ kg/m}^3$$
$$\varrho_s = 2.55$$
$$n\% = 32.54$$

$$C\% = 67.46$$

Compressive and tensile tests were carried out on cubes of brick 40 mm in dimension and the results compared with those obtained from tests on whole bricks, the object being to be able to use small-size specimens of original brick for testing (as was in fact done).
Average values obtained are:

$$\sigma_c = 36.84 \ N/mm^2$$
$$\sigma_t = 2.61 \ N/mm^2$$

with variations of 5% and 2% respectively compared to the preceding data.
Results of tests to calculate Young's modulus and Poisson's ratio are:

$$E = 9613.8 \ N/mm^2$$
$$\nu = 0.14$$

Walls of solid bricks of the form UNI 3622 were produced for sampling. Core samples of brick, 29.5 mm in diameter, taken parallel to the mortar bed provided slenderness ratios of h/d = 2.5 and h/d = 1.0 respectively.
Results of compressive and tensile tests are:

$$\sigma_c = 11.60 \ N/mm^2 \quad (h/d = 2.5)$$
$$\sigma_c = 15.15 \ N/mm^2 \quad (h/d = 1.0)$$
$$\sigma_t = 2.68 \ N/mm^2 \quad (h/d = 2.5)$$
$$\sigma_t = 1.10 \ N/mm^2 \quad (h/d = 1.0)$$

3.4.2. Tests on mortar
The composition and preparation of the mortar (also used in the construction of the walls mentioned above) is that of plastic mortar.
The results of compressive test and tensile test are:

$$\sigma_c = 21.18 \ N/mm^2$$
$$\sigma_t = 4.65 \ N/mm^2$$

Calculation of Young's modulus and Poisson's ratio gave:

$$E = 7946.10 \ N/mm^2$$
$$\nu = 0.22$$

3.4.3. Tests on masonry
The test of compressive strength was performed on walls 120 mm thick, 435 mm long and 425 mm high with seven layers of mortar.
Results are:

$$\sigma_c = 8.62 \ N/mm^2$$

Values of tangent and secant modulus of elasticity and of Poisson's ratio are:

$$E_t = 3420.00 \ N/mm^2$$
$$E_s = 5345.00 \ N/mm^2$$
$$\nu = 0.245$$

From one wall cubes with 100 mm sides and with an intermediary layer of mortar were taken. The cubes were subject to tests of tri-axial compression in the ENEL C.R.I.S. laboratories at Niguarda (Milan).
Values obtained for cohesion and angle of internal friction (ASTM-C.801-75) are:

$$c = 2.308 \ N/mm^2$$
$$\varphi = 47.98^0$$

Finally tests on core samples, taken from the walls, of brick with a mortar bed

in a central position, 29.5 mm diameter, slenderness ratio h/d = 2.5 and h/d = 1.0, provided the following results in tests of compressive strength and tensile tests:

$$\sigma_c = 18.40\ N/mm^2 \quad (h/d = 2.5)$$
$$\sigma_c = 17.13\ N/mm^2 \quad (h/d = 1.0)$$
$$\sigma_t = 1.46\ N/mm^2 \quad (h/d = 2.5)$$
$$\sigma_t = 1.52\ N/mm^2 \quad (h/d = 1.0)$$

4. CONCLUSION

As we said in paragraph 3., research is still going on and final results will be given in a later report.
Research is also being conducted by the "Centro di Studio sulle Cause di Depe= rimento e Metodi di Conservazione delle Opere d'Arte"-C.N.R., of Florence University, under the direction of Prof. F.Piacenti into the mineralogical-petrographic characteristics of core samples taken from the dome of Santa Maria del Fiore, using the following methods:

i) mineralogical-petrographic analysis using diffractometers by x-rays and thin section studies;
ii) physical analysis to determine parameters to correlate with other physical characteristics, such as those calculated in paragrapf 3.2.;
iii) tests using a scanning electron microscope to tackle the problem of surface of discontinuity with occurs at the holding of mortar and brick.

However the results at this stage of the research, which have been outlined in this paper, are sufficient to demonstrate the relevance of comparing the "old" with the "new". The correlation of data obtained has proved that it is possible to program and perform tests and experiments on specimens of modern materials and transfer the results to Brunelleschi's masonry in particular and thus historical masonry in general.

5. NOTATION

σ_c = ultimate compressive strength (N/mm^2)
σ_t = ultimate tensile strength (N/mm^2)
ε = linear strain
E = Young's modulus (N/mm^2)
ν = Poisson's ratio
ϱ_d = unit density (kg/m^3)
ϱ_s = relative density of solid particles
n = porosity
C = compactness
C_i = coefficient of imbibition
γ_d = dry unit weight (kN/m^3)
γ_s = saturated unit weight (kN/m^3)
n = numerousness of samples
$\bar{x}$ = arithmetical mean
s = standard deviation
$s_{\bar{x}}$ = standard error of mean
V = coefficient of variation per cent
$P\%$ = error per cent

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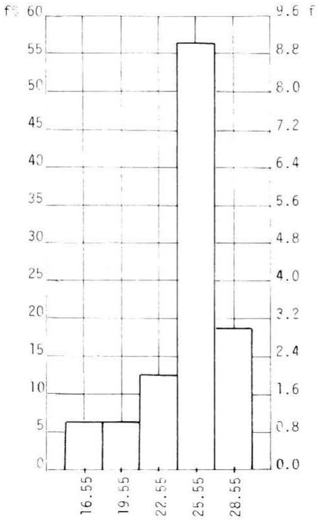

Fig. 3 - Histogram of σ_c values

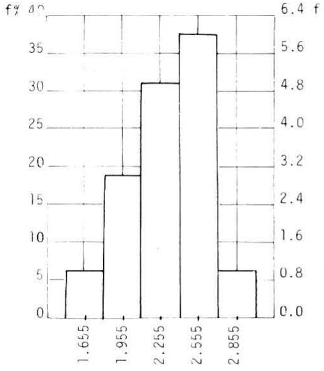

Fig. 4 - Histogram of σ_t values

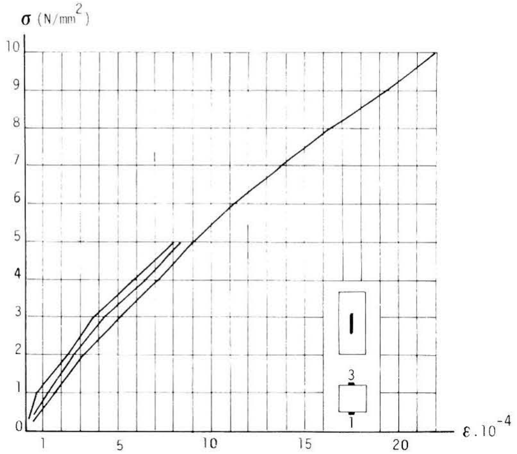

Fig. 5 - Sample "I" - Strain gauges 1-3

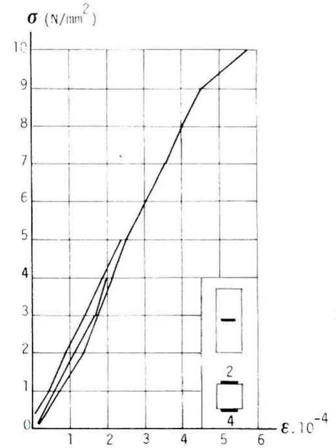

Fig. 6 - Sample "I" - Strain gauges 2-4

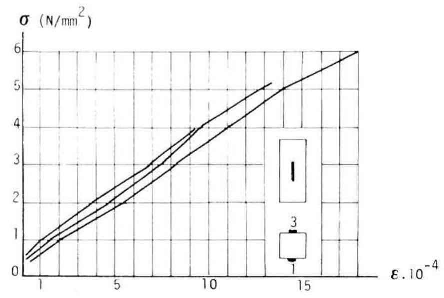

Fig. 7 - Sample "II" - Strain gauges 1-3

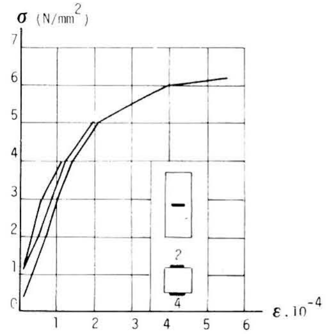

Fig. 8 - Sample "II" - Strain gauges 2-4

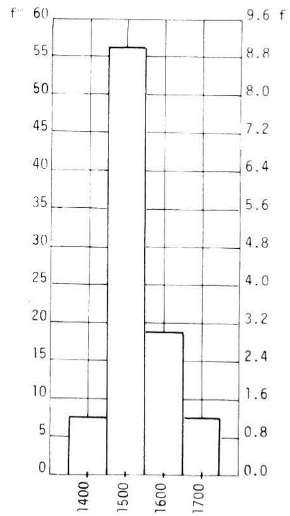

Fig. 9 - Histogram of ϱ_d values

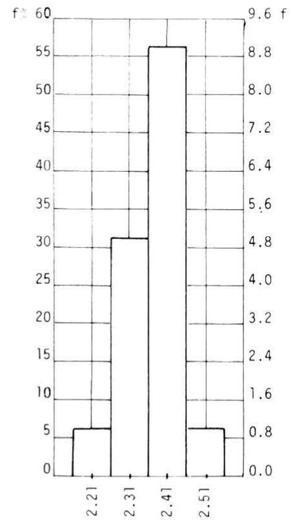

Fig. 10 - Histogram of ϱ_s values

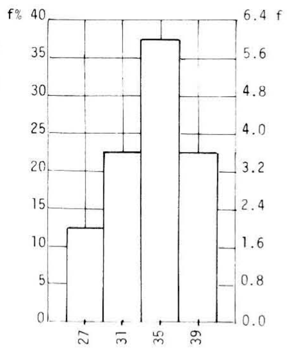

Fig. 11 - Histogram of n values

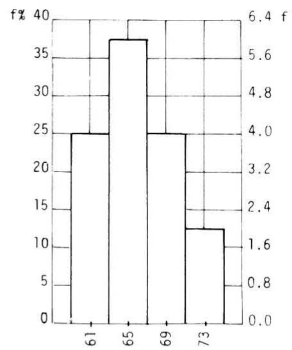

Fig. 12 - Histogram of C values

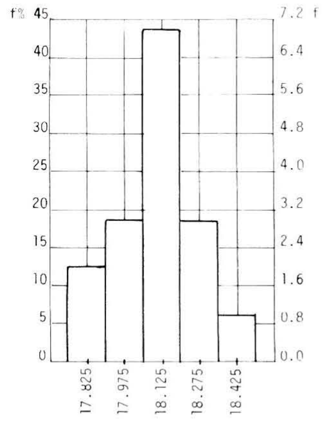

Fig. 13 - Histogram of C_i values

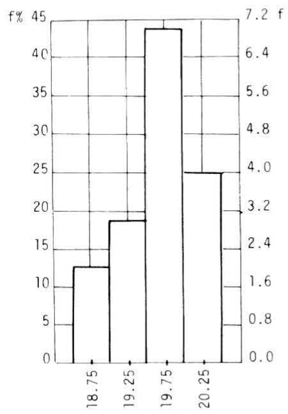

Fig. 14 - Histogram of σ_c values

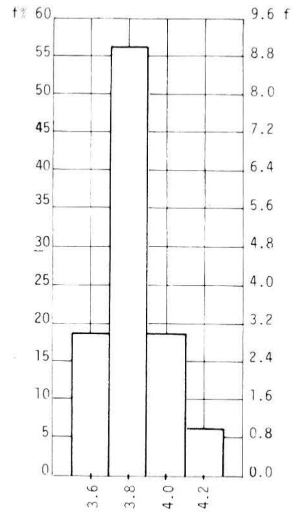

Fig. 15 - Histogram of σ_t values