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Photogrammetry and reconstruction of a Roman cargo vessel

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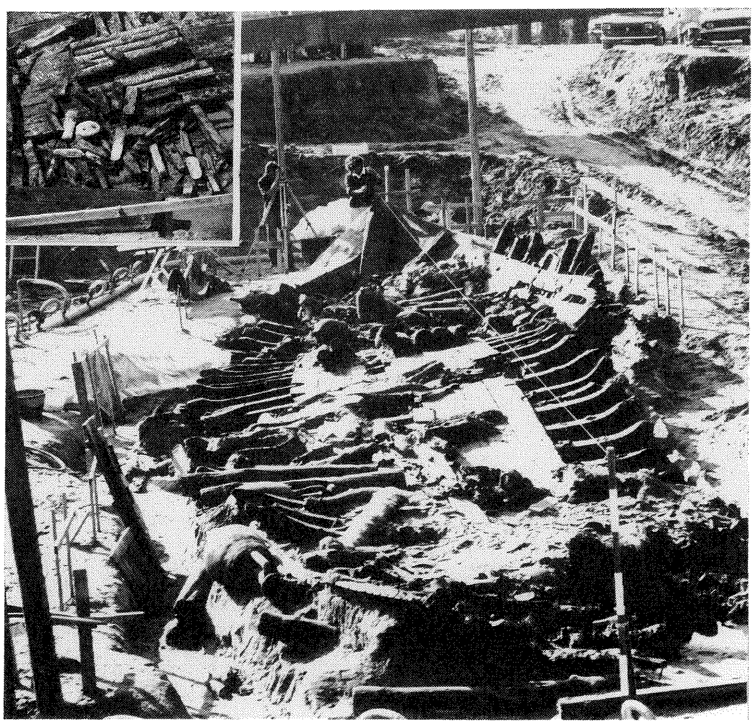
ABSTRACT The remains of a Roman river cargo boat that sank around 10 B.C. - 20 A.D. have been discovered in the Ferrara area (Italy). The finds were plotted during excavation to permit their reconstruction when conservation work has been completed. Calculations based on the plottings carried out and historical-critical considerations have enabled a hypothetical reconstruction of the boat in its original form.

1 AIM OF THE SURVEY

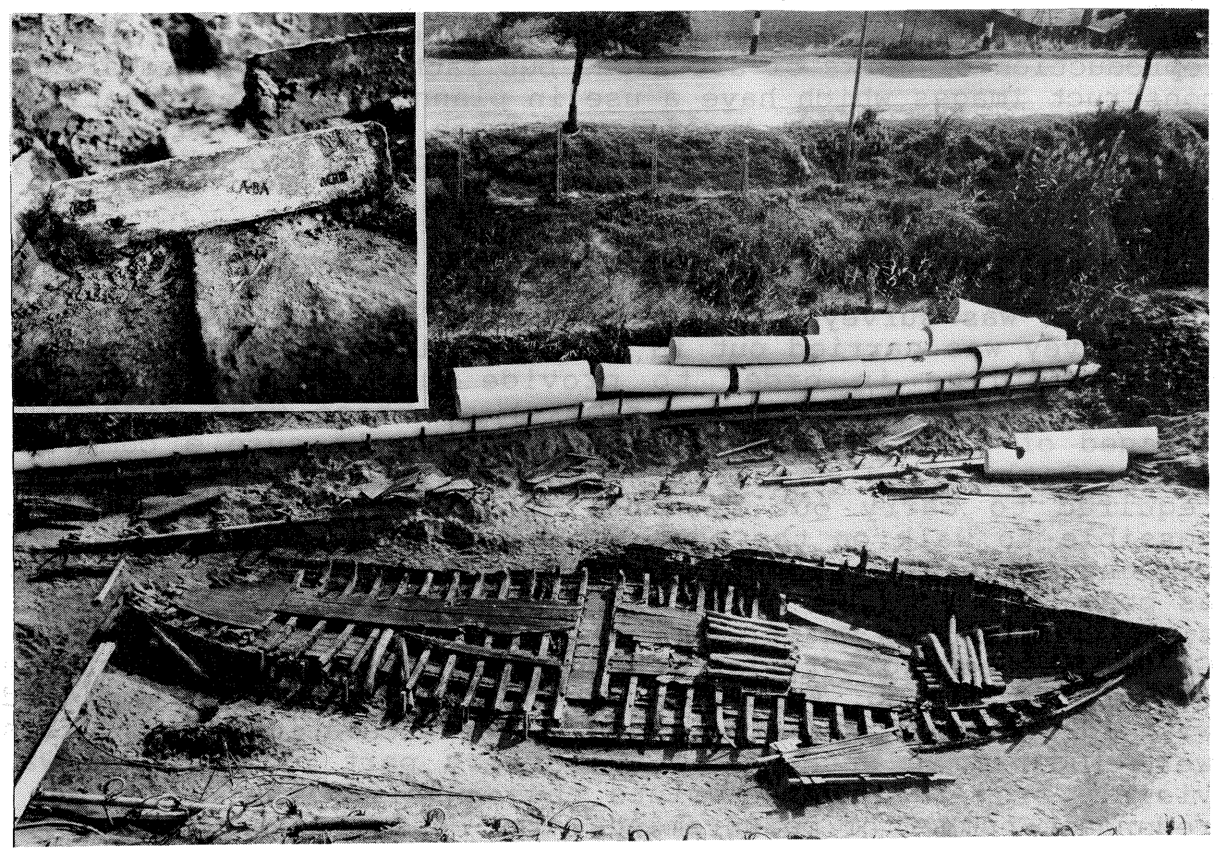
Following the discovery of the wreck of an ancient boat buried in the silt of a canal in the Comacchio (Ferrara) hinterland (Fig. 1),

Fig. 1



the Archaeological Service of the Region Emilia-Romagna organised the recovery of the remains. The canal waters were diverted and the area around the wreck was drained and pumped dry to reveal the find. The boat was a Roman decked cargo vessel of considerable size; the find was approximately 21 metres long and well preserved thanks to the silt covering. There had probably been a further three or four metres of vessel which had been destroyed. Closer observation of the wreck suggested that it was the remains of a cargo boat for river navigation, about 25 metres long. The silt was gradually removed to reveal a cargo of lead ingots bearing the mark of Agrippa which made it possible to date the find to between 10 A.D. and 20 B.C. (Fig. 2.).

Fig. 2



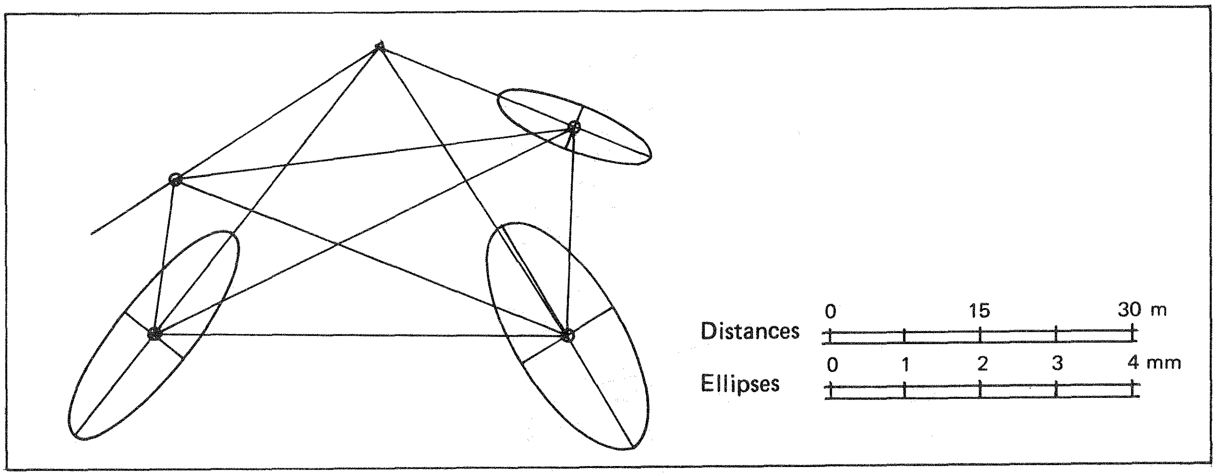
To recover the wreck, once the cargo had been removed, it was necessary to remove the components of the vessel (decking, timbers and planking) and then subject these one by one to a preservation treatment. Once restored, the parts were to be put back together again to reconstruct the boat in a museum. It was clear that the first thing to do was to survey the wreck as accurately as possible in order to catalogue the various components qualitatively and quantitively so that once preservation work had been completed it would be possible to rebuild the vessel as close to its original form as possible. The various components had to be treated individually. The treatment entails immersing components in tanks containing resins diluted in solvents, a type of osmosis then takes places with the resins replacing the water impregnating the wood thus preventing further deterioration of the components. All wooden archaeological finds undergo this treatment, the length of

treatment varying according to the thickness of the wood. In our case the thickest remains required a treatment of at least 4 or 5 years. Since the wreck could therefore not be measured directly, photography was therefore the only feasible method for analysing the shape of the boat.
The aim of the survey was therefore to precisely define the shape and size of the individual parts of the find and to establish their position in relation to the wreck itself. Another aim of this study was to establish the original shape of the boat, identifying and quantifying the deformation of the hull caused by both the cargo (lead ingots) and the water; the decaying effect of the water was, fortunately, minimised by the silt sand which protected the wood against attack from the principal types of micro-organisms. We have thought it important to emphasise these aims since it is no longer possible to limit the possibilities offered by photogrammetry to the faithful reproduction of works of art alone but rather it is necessary to construct images which have a use in planning the interventions necessary on the work itself and which can also be used in conjunction with other forms of research to improve the quality of our knowledge.

2 SURVEY

The wreck was surveyed from the edges of the excavation area. The survey was carried out in stages during the various phases of dismantling in order to provide full documentation of components (decking, beams, planks) as these were gradually cleaned of sand and made visible and also because a complete view of the find was often obstructed by the scaffolding required to carry out dismantling. It was for example not possible to walk on the boat without damaging it and as each component was brought to light it had to be treated as quickly as possible; climatic conditions were such that the boat was at times covered with water.
Given the need to correlate the various surveys, a time stable network was set up. The network consisted of 5 pillars equipped with forced centring on the edges of the excavation. The pillars were located in such a way that every part of the boat was visible from at least 4 points thus enabling the taking of a redundant number of measurements. The control points consisted of numbered white disks fixed to the boat with small nails; these nails also acted as target points for collimation
The reference network was surveyed using all the angles and all the distances; the angle measurements, both horizontal and vertical, were carried out using Wild T2 theodolites; distance measurements were taken twice with Wild DI 20 and AGA 12 geodimeters; as already mentioned, instruments and targets were equipped with forced centring. The horizontal network was calculated separately from the vertical network and in both cases blunders were studied using the well-known Data Snooping method. Before compensating the vertical network, the differences in height measured from the two ends were averaged. Figure 3 shows the reference network and the standard ellipses obtained with a minimum constraint adjustment; the m.s.e. of the heights were always less than 2mm.

Fig. 3



The control points were observed from the vertices of the network taking a redundant number of angle measurements. Error measurements were due not only to the size of the nail head being used as target points but also to the steep angle of the sightings and the variations in the shape of the find which underwent considerable distortion as it dried out in the sun. To keep humidity levels constant, the wreck was continually sprayed with water; the jets of water at times caused the loss of control points; the distortions caused by variations of temperature and humidity could have considerably modified the position of the points between the time of surveying and subsequent image acquisition. Analysis of the data made it possible to eliminate some of the blunders (probably those due to resetting of the control points washed away by the jets of water).
The coordinates of the control points were adjusted in two different ways: first, by holding all the vertices of the reference network fixed and secondly by adjusting all the observations together (even observations between the vertices of the network) with reference to minimum constraints. The results in both cases were equivalent taking into account the estimated uncertainty. The maximum m.s.e. measured on the control points was approx. 3 mm both horizontally and vertically.
Of the three control networks observed, i.e. decking, beams, planking, the latter proved to be the most accurate. The large number of measurements taken made it possible to obtain good results for the coordinates of the control points: redundancy for each control point was at least two horizontally and at least three vertically. It should be remembered however that a photograph is immediate while surveying requires considerably more time since the instrument has to be moved to enable the high number of measurements required. Given the rapid deformation of the wreck caused by changes in humidity, the position of the control points could have been different during photogrammetry in comparision with that during surveying.

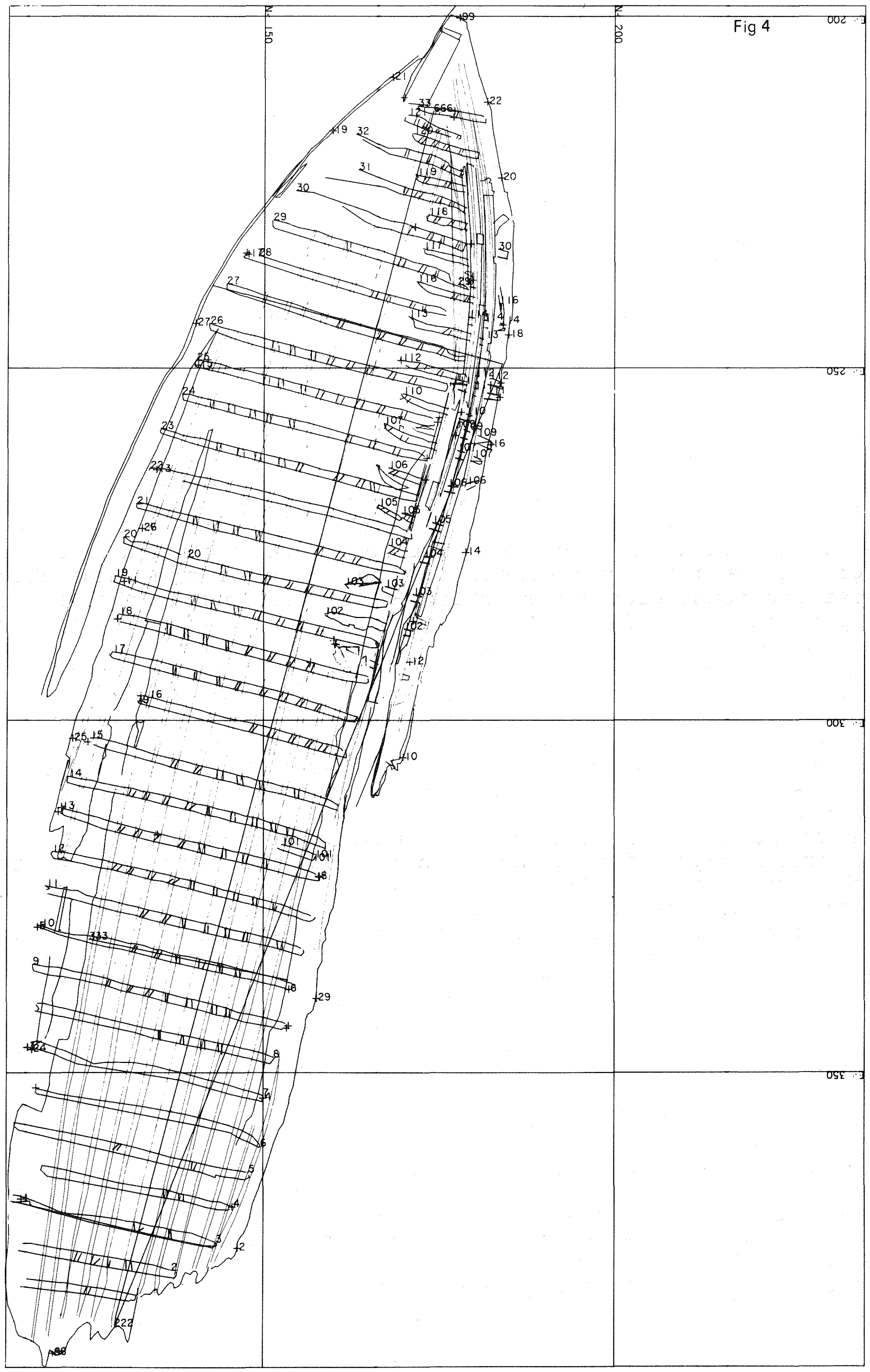


Fig 4

3 DATA ACQUISITION

A photogrammetric survey consists of three consecutive phases:

a) image acquisition with a metric camera
b) definition of the coordinates in a particular reference system of the orientation points of optic models
c) graphic plotting of the object photographed on carefully chosen projection planes at the selected scale ratio.

a) Image acquisition

For the photographic part of the study we wished to make a series of photographic surveys in layers. Initially the boat was fully decked and the survey could therefore only be made by projection on a horizontal plane. The control points (in the form of numbered disks) were positioned and three series of photographs were then taken: the first at the centre of the boat and the other two at the ends. Photos were taken from a distance of 20 m and from a height of 15 m; this made it possible to stereoscopically cover the complete boat at a scale of approx. 1:166 with three series of two stereogrammes each. With this phase completed, the planks making up the deck of the boat were then removed for preservation treatment and the basic framework of the vessel (consisting of beams and planking) was thus revealed. A new series of numbered discs were located and photographs were again taken using the method previously described but this time with the aid of a hydraulic lift and a bi-camera; each of the 33 beams was individually photographed from a near frontal position, from a distance of approx. 6 m to provide images at 1:40 scale. With this phase finished, all the beams were removed for treatment. Next, a new series of numbered disks were positioned and the planking was stereoscopically photographed using the same method as that used for the decking. All photographs were taken with metric cameras; at the same time each photograph was repeated using a non-calibrated Hasselblad camera.

b) Definition of the orientation points

In between each photographic session we determined the coordinates of the orientation points of optic models (the points being represented by the various series of numbered discs) of the reference system selected with the method already described.

c) Graphic and numeric plotting of the stereoscopic models

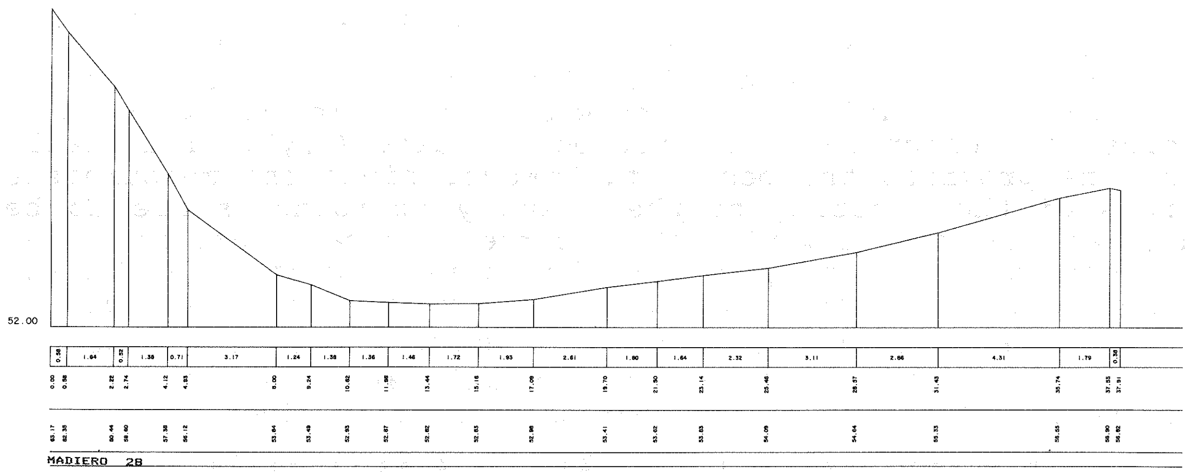
Having obtained the coordinates of the orientation points of the optic models in the manner described, we plotted the stereomodels using an analytic plotter. An analytical instrument was used because it made possible horizontal and vertical graphic representations of the optical models even though the photos used as a basis were not taken from truly horizontal or vertical positions (the photos of the beams, for example, were taken at an angle). Analytic plotting also guaranteed the highest degree of precision possible both graphically (since an automatic plotting table could be used) and in terms of memorising the numeric data.
To plot the first stereogramme of the deck (i.e. the photo of the bow section) we carried out the referencing of the optic model taking eight points of the stereogramme distributed

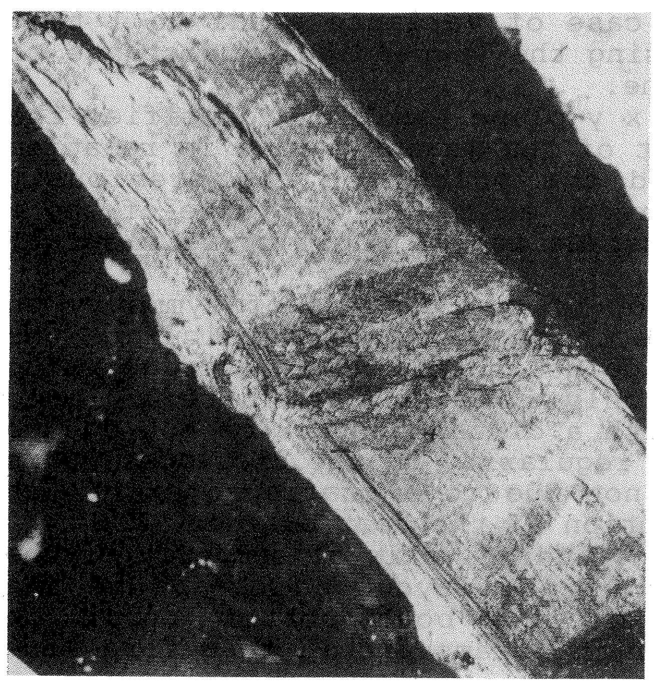
according to the classic layout. On completion of relative orientation the average parallax error residual in y was 1μm on the eight points: for the absolute orientation of the same model we took the control points surveyed from 13 to 22 and point 99, the residuals varied between -2 and +3 mm for the x coordinates, from -5 to +5 mm for the y coordinates and from +4 to -5 mm for the z coordinates. For the measurements on the other hand the remainders varied between +4 and -5 mm. For the second model the control points from 1 to 12 and point 88 were taken as referencing points, the residual parallaxes and the coordinate residuals were not different from the previous values. The same results were obtained plotting all the other models of: the deck and beam planimetry; the sections of the beams and the planking, and the cross and lengthways sections of the boat.
Plotting may be summarised as follows:
First phase: plotting at 1:10 scale of the three stereoscopic models of the deck.
Second phase: plotting at 1:10 scale of the three stereoscopic models after the decking had been dismantled (Fig. 4) In this phase the upper parts of the jute binding, a type of bracing, holding the planks to the beams, were surveyed.
Third phase: plotting at 1:10 scale of the 14 stereoscopic models of the front view of the 33 beams and the corresponding cross sections of the boat.
Fourth phase: plotting at 1:10 scale of the three stereoscopic models of the planking after the complete dismantling of the 33 full beams and of the 22 half beams and removal of the facing structures on the inside of the boat's sides. In this phase two cross sections and one lengthways section were carried out. During plotting we also collimated a series of points on the beams which corresponded roughly to what must have been the longitudinal axis of the vessel. Stereoscopic photos were taken using a Veroplast mono-camera produced by the Officine Galileo fitted with a TERGON lens with a calibrated focal length of f = 151.93 mm. The radial distortion of this lens, taken at the calibrated focal length, was measured previously and never exceeded more than 14 μm. Stereoscopic photos of the beams were taken using a bi-camera manufactured by Officine Galileo; this consisted of a 550 mm calibrated base with a Veroplast camera mounted on each end; the two cameras had two AERGON lens with calibrated focal lengths of f = 150.03 mm and f = 149.99 mm. The radial distortion of these lenses was measured prior to use and was never more than 14 μm for the right camera and 12 μm for the left camera. Ground glass AVIPHOT PAN - 100 photographic plates by AGFA-GEVAERT were used.
Plotting was carried out using a DIGICART stereo comparator produced by Officine Galileo linked to a MICRO PDP-11 computer and a Wild TA-10 automatic table. Subsequent processing of the plotting data to arrive at a reconstruction of the boat was carried out using a DIGITAL VAX 780 computer and Tectronix interactive videographics.

4 RECONSTRUCTION

To attempt a reconstruction of a boat's original shape one needs to know the layout of the wreck at the time of recovery. Here it is best to study beams since they maintain their original form better than the planking due to their greater stiffness. The beams were immersed in a resin bath immediately following dismantling and could therefore no longer be measured directly. Photogrammetry had to be used. On the stereo-plotter the upper points of the beams were surveyed (these are easier to collimate stereoscopically), the spatial coordinates were memorised and the profile was drawn; figure. 5 is a drawing of the most complete beam. In this phase it was more important to express the profile in a mathematical form rather than attempt a graphical reconstruction of the beams where the use of function splines to interpolate the measurement data is more appropriate. Unfortunately none of the beams were found whole. Only five of the beams had, in part, one of their two sides as well as the bottom. The reconstruction of the original shape of the boat is therefore very complex and requires detailed historical research in order to arrive at a "model" to which the data can be adapted.

Fig. 5 **Fig. 6**





At the moment we have carried out numerical processing of the coordinates measured on the beam points with the aim of identifying the boat's axis of symmetry and the present (deformed) layout of the bottom and to reconstruct the form of a typical beam. We chose to work on the beam points rather than on the planking points since the beams form the basic framework of the boat and make it easier to arrive at a reconstruction of the boat's original form; these points are also generally easier to collimate. In order to identify the longitudinal axis of symmetry of the boat we tried to establish the centre of the beams and then took the line of beam centres as the position of the axis of symmetry. Identifying the beam centre was facilitated by the presence on the beams of a bracing consisting of jute bindings holding the planking to the beams. The centre of a beam was taken as the half way point between these jute bracings (fig. 5). Where there were no braces present we used photographic interpretation but here the results were probably less reliable and data derived in this way has not for the moment been taken into consideration.
The centre coordinates were processed to obtain the position of the boat bottom which was practically horizontal. To simplify the procedure we first considered the horizontal coordinates. The orthogonal polynomial method was used to find the polynomial degree in x which best interpreted the data (x;y). Predictably the line provided the best fit. However since the measurement errors of the plotting of the x and y coordinates are to be taken as the same it would not be correct to carry out the usual regressions x on y and y on x. A functional regression model was therefore used assuming the variance in x and y to be equal, and hence their ratio to be known, $\lambda = \sigma^2 y/\sigma^2 x = 1$; the model is therefore "identifiable" (Kendall, page 379) and an estimate of the angle coefficient of the regression line is given by:

$$b = \{s^2_y - s^2_x + [(s^2_y - \lambda s^2_x) + 4\,\lambda s_{xy}]^{1/2}\}/2s_{xy}$$

where s^2_x, s^2_y, s_{xy} are the central second order moments computed by the data.
It will be noted that in the case of variance equal to 1 that the regression is made minimising the perpendicular distance of the point measured from the line.
Once the straight line on the x y plane had been identified the same regression was carried out of the measurement z in relation to a parameter which ordered the points on the previously estimated straight line; as already mentioned the value of the z coordinate was practically constant and an angle coefficient of nearly zero had been obtained.
Having established the position of the centres of symmetry on the estimated straight line we then proceeded to calculate the spatial distance between such points obtaining an average value of 54 ± 2 cm; in one case only however was there a large deviation from this average with a distance of 70 cm not due to a measurement error. Given the regularity of the distances, this exception was in our opinion not due to a craftsman error but was rather the deliberate intention of the boat builder.
Having thus established the longitudinal axis of symmetry of the boat we proceeded to a study of the layout and shape of the beams. The current layout of the boat bottom could be established from the layout of the beams and it therefore made

sense to study the shape of the beams. As far as can be established from photographs, the beams seem to be nearly parallel and lying at right angles to the axis; we have for the moment assumed such a hypothesis without having carried out any numerical analysis.

From the plotted beam profiles there appear to be three well defined shapes for the section from the boat side to the central point (one assumes that this shape is repeated for the other half of the beam which in most cases was partly missing): the boat side is initially slightly curved, the boat bottom is rectilinear and the join between the side and the bottom is clearly rounded.

Rather than looking for a function describing the whole beam we attempted to establish the polynomials which best interpolated the experimental data in each of the following three intervals: the points on the boat sides (to obtain the inclination of the boat sides in relation to the bottom), the points on the boat bottom (to obtain the general layout of the beams lying on the river bed) and the points of the rounded parts with partial superimposing with the others (to study the curvature of the side).

The polynomial degree which gave the best fit was found using the orthogonal polynomial technique which proved the most efficient way of providing the accurate statistical estimates on the goodness of fit carried out by increasing the interpolating polynomial degree.

We found that a straight line provided the best fit both for the bottom and for the upper part of the sides at least until close to the bow where the transverse dimensions of the beams decrease and the curvature of the sides increases; the join between side and bottom on the other hand was interpolated well with second and third degree polynomials. Table 1 shows the angle of the sides in relation to the bottom where such a calculation was possible.

Table 1

beam	25	26	27	28	29
angle (gon)	235.0	154.0	143.4	144.2	126.8

For the layout of the boat bottom, the beams appear to be on a plane perpendicular to the boat's axis; their inclination from the horizontal can be obtained with the angle coefficient of the straight line which interpolates the bottom of the beams. Table 2 shows the angles of inclination (in gon) for each beam position along the boat's axis; this made it possible to quantify the amount of distortion in time undergone by the wreck resting on the canal bed.

Table 2

beam	angle (gon)	beam	angle (gon)	beam	angle (gon)
18	-10.6	22	-5.4	26	2.6
19	-9.8	23	-4.0	27	6.4
20	-7.7	24	-1.5	28	8.0
21	-7.0	25	0.0	29	5.1

4 FURTHER DEVELOPMENTS

Figure 6 shows a reconstruction of the boat frame; this reconstruction is the most plausible given current knowledge and research. The study of the shape of the wreck has not yet been completed and will continue with analysis of other points. Although these points cannot be collimated well and are consequently less reliable for plotting coordinates they can however provide further information on the shape of the planking. Further study into the history of Roman boats is needed to find models which can be used as a guide for the reconstruction of the boat. Following this it will be interesting to analyse the loss of accuracy derived from the use of non-metric cameras through a study of the photos taken with a non-calibrated Hasselblad camera.

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