Reconstruction of the Hjortspring Boat- Theoretical Performance and Initial Test Results.

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Introduction.

In 1991 a group of people on the island of Als, Denmark, where the Hjortspringboat was excavated in 1921/1922, decided to build a replica of the boat. As the job was considered to be immense, a legal organisation , Hjortspringbådens Laug (The guild of the Hjortspring-boat) was formed in order to establish a platform, from where the work could be co-ordinated, funds could be raised and long range connection and co-ordination with the universities and museums could be established and maintained. Within two years the number of members reached 100 , and it has been constant ever since. The guild attracts people with a wide variety of backgrounds, that are relevant for the work, although no historians, archaeologists nor ship builders became members. Backgrounds of the members are skills and professions in wood carving, hydrodynamics, computerised geometry, stress analysis, sailing, metallurgy and very important a keen sense of quality.

The philosophy of the work was to build, test and display a full scale of the boat as accurate as the newest interpretation of the find. Furthermore we wanted to produce as much knowledge as possible and document all observations.
An initial analysis convinced us, that our predecessors were professional ship builders, that have made a line of still more refined boats. Not having this background, we had to use modern, theoretical tools in order to achieve our goals.
The results from the theoretical analysis will illustrate the quality of the Celtic Iron Age ship building and it will **give an input to the plan for testing the boat.**

The Basis.

The data used in the theoretical model was taken from Johannessens line drawing of the boat, as shown in Rosenberg (1937). Further data were produced through different tests of parts of the boat, produced by the building group for training purposes.
Valbjørn,K.V(1997).

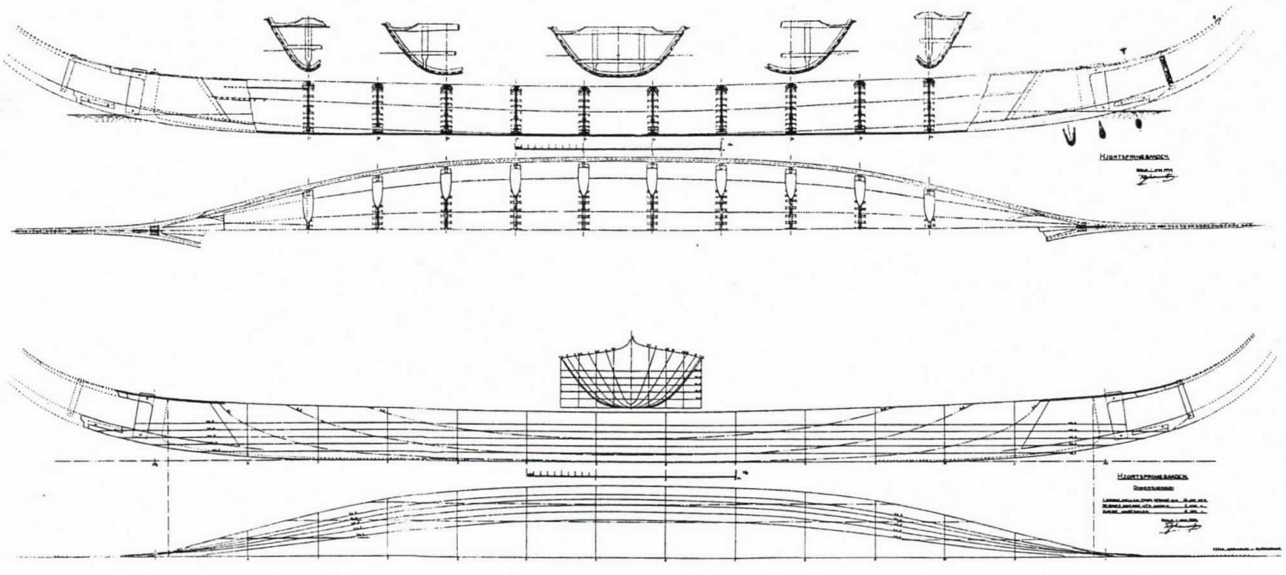

Figure 1. Johannessens Drawings (Rosenberg 1937).

The Hydrostatic Analysis.

Displacement.

The drawing data in figure 1, Rosenberg/Johannessen , (1937), are arranged in a way, that in total 12 sections are drawn with a mutual distance of one meter, starting one meter before frame 10 until one meter after frame 1. The distance between each frame is 1 meter. Five water-lines are drawn with the draught of 0.1, 0.2, 0.3, 0.4 and 0.5 meters.

For each water line the area of the submerged part of each profile is calculated.

In figure 2 these areas are plotted versus a lengthwise coordinate representing their position in the boat. The area under each curve is the volume of displacement.As the number of the frames is an equal number, one cannot use Simpsons formula for numerical integration. Instead the trapezoidal rule is used. Rawson, K.J. (1976) p. 23. The length of the 5 water lines are regarded as being equal, which is not the case, but the error is neglectable.

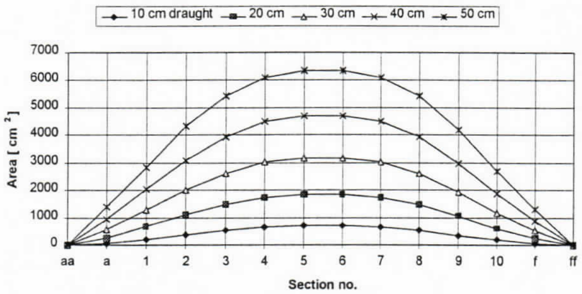

Figure 2. Immersed Areas of Sections for Draughts 10-50 cm.

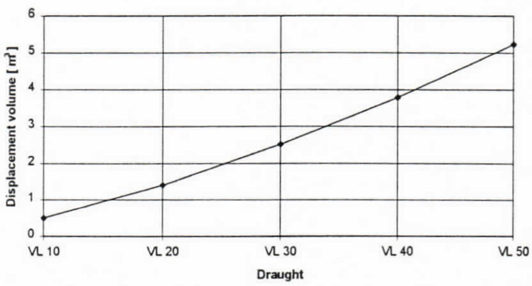

Figure 3. Displacements at Different Draughts.

Johannessen (Rosenberg, 1937) claims that the boat has a weight of about 550 kg. Accordingly, the empty boat will have a draught of o.1 m. With a nominal load of 2000kg, the draught will be 0.3 m.

Wetted Surface.

The wetted surface is determined in basically the same manner. Instead of calculating the submerged areas of the sections, the curve length of the submerged part of section is calculated. This curve lengths are integrated with respect to the lengthwise coordinate, again using the trapezoidal rule.

The result is shown below.

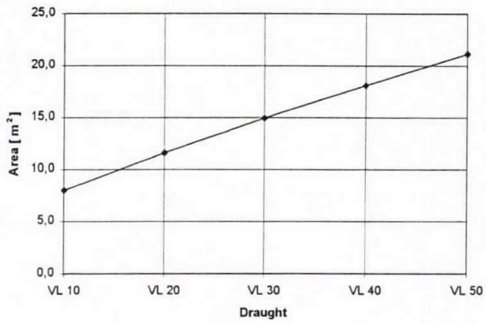

Figure 4. Wetted Surfaces.

The Metacenter at no Heeling.

The position of the metacenter depends on displacement and heeling angle. Initially the position of the metacenter at no heeling is calculated. This is used in order to evaluate the so-called initial stability. For each of the above sections and for each of the water lines , the gravity centre of the displaced water is calculated. The planar second moment of area of the water plane is calculated and then divided with the displacement.

The result gives the position of the metacentre in relation to the gravity centre, mentioned above, Rawson, K.J.(1976) p. 20.

The initial metacentre positions above the boat bottom at different displacements are documented in the Membership Ledger, section 2.5.1,p. 5 ..

Figure 6 in the next section shows the initial metacentre together with metacenters at different heeling angles at nominal load (2000 kg).

The Metacenters when Heeling.

When heeling the metacentre positions must be determined differently. Figure 5 explains the approach.

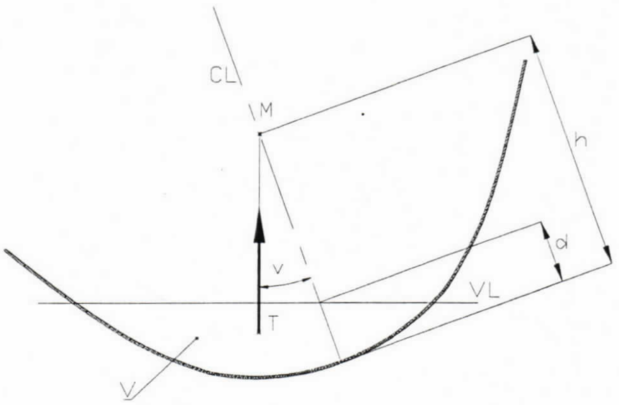

Figure 5. Metacentre at Heeling.

Firstly, one has to calculate the gravity centre of the displaced water at all sections and all heeling angles. The metacentre is found as the intersection of the centre line and a vertical line through the gravity centre. The detailed calculation is shown in the Membership Ledger, section 2.5.1. p.5.
Below is shown the position of the metacentre at different heeling angles at nominal load (2000 kg /0.3 m draught /2.5 m^3 displacement).

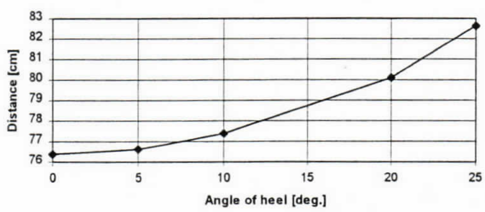

Figure 6. Positions of Metacentres above Bottom at Displacement 2.5 m^3.

It is significant, that the metacentre position is fairly constant regardless of the heeling angle. It means, that the boat has very little form stability (due to the nearly circle sector shaped bottom profile).

Gravity Centre of the Boat with Load.

A theoretical determinination of the gravity centre of the boat and the crew is very inaccurate. We have made some measurements using the middle section of the boat, that was produced by the building group for training purposes. Valbjørn, K.V. (1997). Using this results together with the calculated metacentre, one can illustrate the rightning moment when the boat is heeled, as shown below. (The initial, static stability).

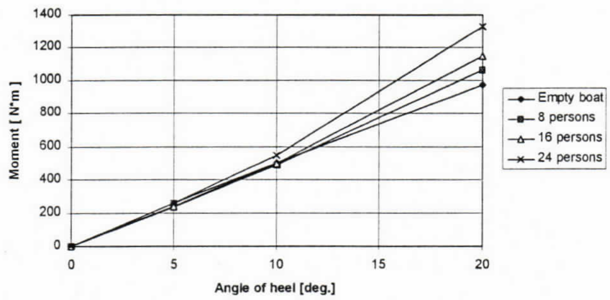

Figure 7. Rightning Moment.

The calculations show, that when 22 men are placed in a symmetrical position onboard the boat and an additional man steps on the gunwale midships, the boat will heel 12 degrees, just about letting in water.
More accurate results will be produced at the sailing test. It will be an interesting experience.

Hydrodynamic Analysis.

Shape and other Characteristic Coefficients.

In order to compare different types of ships and boats, it is customary to calculate various coefficients, that express hydrodynamic characteristics of the boat types. Some coefficients are dependent of the draught.
Below are shown different coefficients at both 0.3 and 0.2 m draught. In themselves they are not descriptive and should only be considered being data for readers, that would want to compare the Hjortspringboat with other boat designs. (We refrain from giving the definitions,

which can be found in Rawson,, K.J.(1976) ,vol 1,p.12 and vol.2 p.383 and McGrail, S. (1978), p.136).
Three of the coefficients are, however, used when calculating the residual resistance. These are **marked.**.
Beam refers to width at the water line.

Coefficient	**Draft 0.30 m**	**Draft 0.20**
Length-Beam Ratio	10.0	10.8
Length- Draught -	47	66
Beam -Draught -	**4.7**	**6.1**
Fineness water plane coeff.	0.6	0.61
Mid ship section coeff.	0.75	0.75
Block coeff.	0.41	0.43
Prismatic coeff.	**0.55**	**0.58**
Vertical prismatic coeff.	0.69	0.70
Manpower coeff.	14.7	
Active padlers coeff.	13.3	

Constants:

Length const.	**10.5**	**11.8**
Breath const.	1.05	1.10
Draught const.	0.22	0.18
Wetted surface const.	8.1	9.3
Section area const.	0.172	0.147

Table 1. Coefficients and Constants.

Resistance and Effective Power of Propulsion.

The resistance by the boat against its movement through the water at different velocities (or the force needed to propel the boat) may be calculated from the line drawing and the derived characteristics. It is normal practice to divide the total resistance into two elements.
The frictional resistance is the force which would be experienced when moving a flat plate of equal surface area as the boats wetted area through the water at the same speed. **The residual resistance** stems from the wave making of the boat and the separation of the boundary layer.
The two resistance components are here calculated for the nominal load of 2000 kg giving a displacement of 2.5 m^3 and a draught of 0.3 m. The calculations are based on Gertler, M. (1954).
In figure 8, below the friction and the total resistance is shown as function of speed.

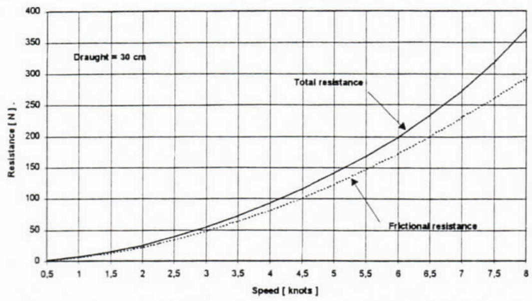

Figure 8. Resistance of Propulsion

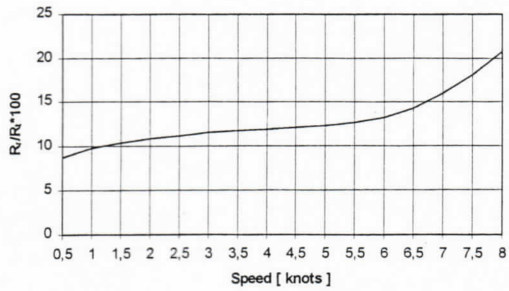

Figure 9. Residual Resistance i % of Total Resistan

This figure illustrates the main characteristic of the Hjortspringboat, i.e. an extremely slim boat with a lon water line. At 8 knots only 20 % of the power is used f overcoming wave resistance and separation from the boundary layer. Thus the importance of keeping the friction low to achieve high speed is evident. The estal lished traces of linseed oil and animal fat might explai this.
The power of propulsion is determined by multiplyin the resistance with the speed. It is shown below, also function of speed.

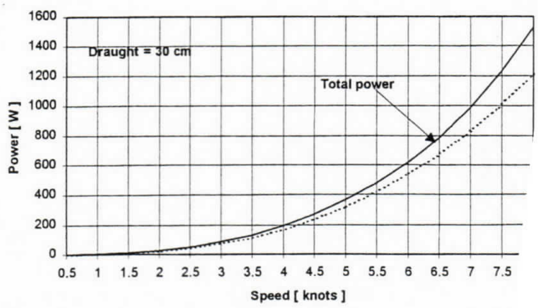

Figure 10. Effective Power of Propulsion (at ment 2.5 m^3)

A differentiation of power with regards to load (at nominal load) shows, that an extra 4 % displacement (f.inst. 100kg ballast) will only raise the power requirement 1.8 %(at 8 knots). The captain could, consequently, ballast the boat with some hundred kg´s midships, when crossing open water in order to enhance the stability without reducing speed significantly.

Performance of the Paddles.

The find contained 15 paddles, all different but with the common characteristics of being very light and slim. The latter characteristic is significant, as one would expect much broader paddles as is found in the many log boat finds in Denmark, and spontaneoúsly evaluated being more powerful. As slim paddles or oars only are advantageous in high seas ,Coates, John (1991), and as the boat is not suitable for high seas,(see later) , we wanted to investigate the paddle design.
An analysis of the padling function shows, that broader paddles have a higher hydraulic efficiency.
The paddling process is an intermittent one. The paddlers have to perform a work in each stroke, lifting the paddles out of the water against gravity, a work that is not regained when lowering the paddles again .This leads to the conclusion, that there is an optimum of wideness of the paddles, an optimum that is physiologically determined and dependent of the boat velocity.

A simple mathematical model gives the hydraulic efficiency of the paddling process and the slip of the paddles relative to the surrounding water. Taking into account the hydraulic efficiency and estimating the the paddles to be dipped into the water during half of the stroke one can find the power which is equivalent to the so called shaft horse power of an engine driven ship. This quantity is shown in figure 11. This power is almost twice the effective power in figure 10.

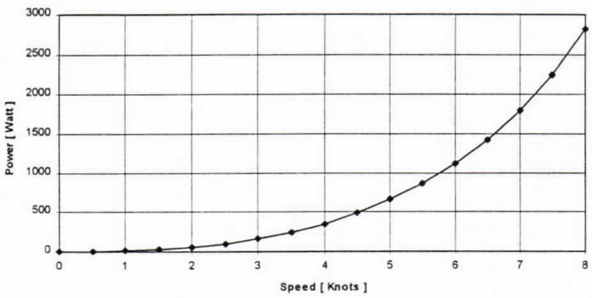

Figure 11. "Shaft Horse Power" vs. Speed.

The number of paddle strokes required for propulsion of the boat depends upon the area of the paddles for a given speed. The tendency is shown in figure 12 which indicate that the paddling frequency increases with decreasing area of the paddles. No figures are shown at the axes because some coefficients are still unknown.

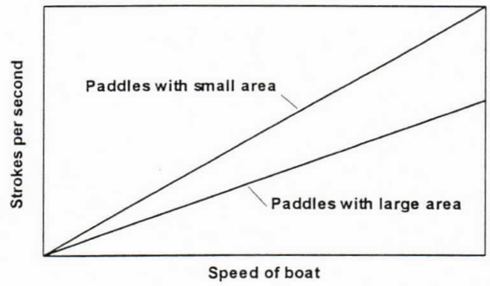

Figure 12. Paddling frequency vs. Boat speed

The paddle function will be investigated in the practical tests of the boat.

Stress Analysis.

Shear Strength of the Seams.

The performance of the boat depend to a large extend upon the strength of the seams. The mechanics of sewn joints were analysed by Coates (1985). The stitches are considered as springs, clamping the planks together. When subjected to a shear force the planks are prevented to slide relative to each other by friction. The friction coefficient for wood on wood is 0.68 when wet. (Coates 1985).
An experiment was made with two planks with the length of 600 mm joined by stitches as used in the Hjortspring boat with regards to tightening, knots, stopping material and geometry The seam was subjected to shear by a variable force acting in the direction of the seam and the relative movement of the two planks were recorded. The result is shown in figure 13.

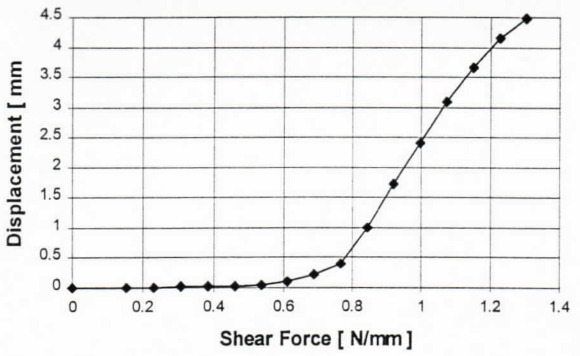

Figure 13. Displacement vs. Shear Force of a Seam.

It is seen that the planks do not move before the shear force exceeds 0.5 N/mm seam. Shear forces above this value cause the planks to move relative to each other with a rather low velocity. This movement stops after 2o-60 seconds, indicating a viscous friction mechanism. An important observation is that when the shear force is released, the planks do not move back towards their original position. This means that the seams can not tolerate alternating directions of shear forces, as this would lead to wear.

The Boat as a Beam.

Firstly, one has to calculate the forces, that strain the boat. Looking at the boat as a girder or a beam , there are three sets of forces, that attack the boat, the weight and the load , attacking downwards, and the buoyancy forces, attacking the boat upwards. These three sets of forces counter-balance each other.

As to the weight of the boat, a rough estimation of the distribution is sufficient, as the boat weight is only 20 % of the total weight. The pay load of the boat must be distributed in accordance with frame positions. The below figure shows the downward forces, all referred to frame positions and to transversal sections with a mutual distance of 1 m. Half a boat only.

The upward forces (the buoyancy forces) depend on the shape of the boat and the waves.

One can calculate the buoyancy of the boat at still water and subjected to waves.

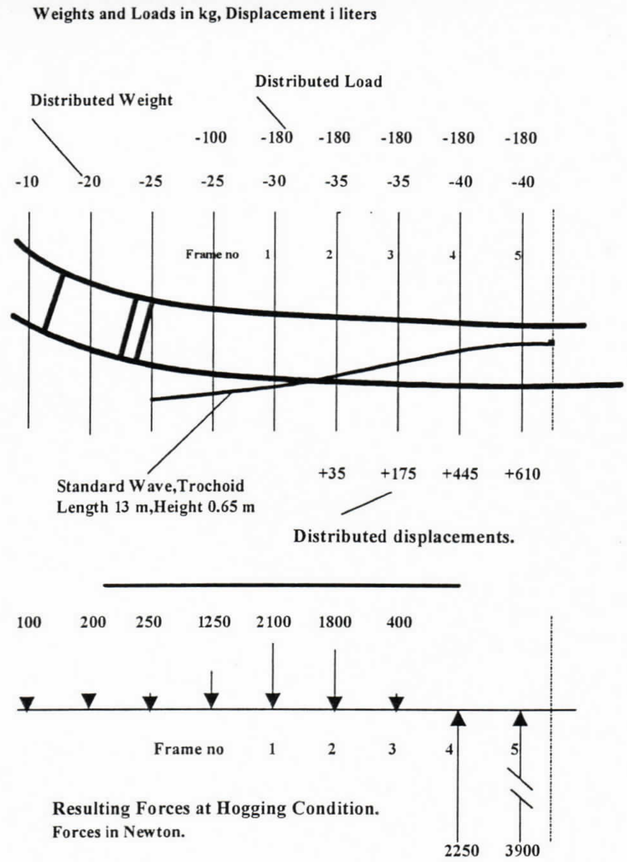

Figure 14. External Forces at Boat Hull.

It is costumary to calculate the buoyancy forces at a wave length equal to the water line length (here 13 m) and a wave heigth of 5 % of the length (Rawson,K.J, 1976, p.179). This relation can only exist, when the water depth exceeds half a wave length, (6.5 m).

The forces were calculated at wave conditions (both hogging and sagging) and also in still water. Above is shown the forces at hogging condition as an example.

Based on the above figure, the curves for the shearing force and for the bending moment can be drawn.

They are shown below for all three conditions. For sagging, the sign is reversed.

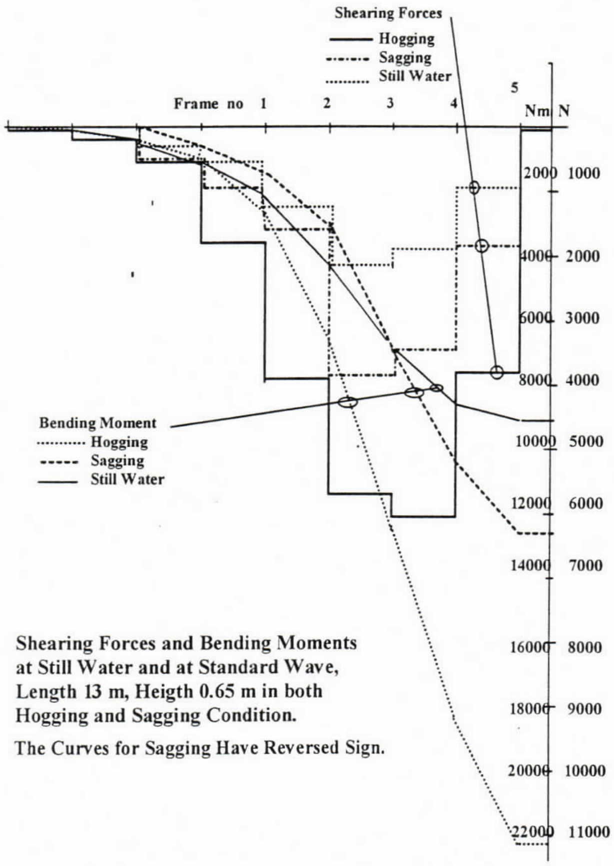

Figure 15. Internal Forces in Boat Hull.

As mathematical model the boat is considered being a I-beam, where the forces attack the beam in the central, longitudinal , vertical plane.

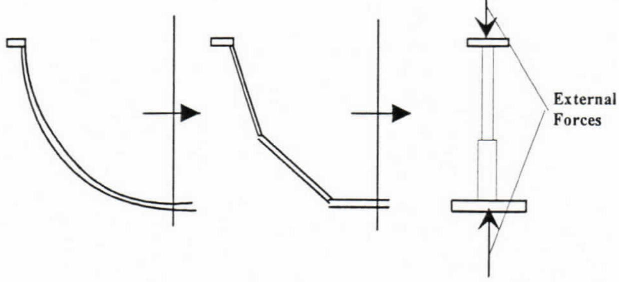

Figure 16. Structural Model.

Odd as the model seems, the results are considered quite representative, as the boat form over the middle 7 m, where the stresses are important, shows fairly parallel lines. The shell effect is insignificant.
The major inaccuracy lies in excluding the "elasticity" of the seams. The bending of the hull will thus be larger than calculated below.
Furthermore the simplification with regards to the points of attack of the outer forces will give inaccuracies. .

Finite element methods are for the time being outside our possibilities, we hope , however, at a later date to perform calculations based upon those.

	Hogg.	Sagg.	Hogg-Sagg.	Still W.
Max gunwale Stress	3.5	- 1.9	5.4	1.4
Max keel Stress	- 1.8	1.0	-2.8	-0.8
Max shear force	5.2	-3.4	8.6	1.9
Max deflection	-19	11	-30	- 9

Table 2. Stresses and Strains.

Stresses in N/ mm^2, shear force (at lower seam) in N/ mm seam length and deflection of stem relative to mid ships in mm. Negative signs means compression or downward deflection of the stem.

Interpretation of the Stress and Strain Analysis.

Tension and compression in the gunwale and the keel is acceptable as the bursting strength of lime wood along the fibres is stated as being 85 N/mm^2 (Member Ship Ledger, section 3).

The maximum shear forces at the lower seam are extremely high at hogging and sagging conditions and will probably lead to leaks as they would lead to alternating directions of the shear forces and thus to wear of the stopping. It is not advisable to cross open water , when fully developed waves with a height of 0.65 m are present. At this condition the stems will oscillate with a vertical amplitude of more than 30 mm. At shorter waves (near the coast), the figures related to still water may be used, showing that much more acceptable forces and deflections are present.

Conclusions.

The analysis shows that the boat is not an open water boat, it is a coastal and river boat. Avoid having crew members at the stems and at thwarts 1 and 10 will reduce the wave influence on stresses and strains considerably. Ballast between thwarts 4 and 7 will help, both for increasing stability and for reducing stresses.
The boat is indeed very well designed for fast sailing (we have still some doubts as to the slimness of the paddles) and for being carried over land or up onto the beach by the crew.

The many aspects that have been touched above, will be further analysed through sailing tests, thus they will form part of the plan for these tests.

References.

-Hjortspringbådens Laug, Medlemsmappen (The Member Ship Ledger).

Rawson, K.J. and Tupper, E.C. : (1976) Basic Ship Theory.,Volume 1 and 2 . Longman.

Gertler, Morton (1954),: A Reanalysis of the Original Test Data for the Taylor Standard Series. Navy Department, the David W.Taylor Model Basin, Report 806, Washington D.C.

McGrail, Sean (1978), Logboats og England and Wales, BAR, British Series 51 (i).

Rosenberg, G. , (1937) ,Hjortspringfundet, Det kongelige Nordiske Oldtidsskriftselskab, Gyldendal.

Valbjørn, Knud V. et al, (1997), Reconstruction of the Hjortspringboat - Philosophy, Execution and Initial Results, ISBSA 8 ,Gdansk 1997.

Coates, John (1991), Power and Speed of Oared Ships, Crossroads in Ancient Shipbuilding, ISBSA 6, Roskilde , p. 249.

Coates, John (1985), Sewn Plank Boats, BAR Int. Series 276.