# NATURALEZA Y CONSTRUCCION DE BARCOS.

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# Nature and shipbuilding

## Abstract

Wood has been over centuries of mankind's history the main material for shipbuilding. This activity has a close relationship with the history of the environmental impact of human development. Nowadays, the structural use of wood in the shipyards is reduced to a minimum. Nevertheless, the history of wood technology related to this activity, hides a treasure of useful information for the field of current timber structural design. Wood itself is currently being more and more deeply known, and this knowledge led to a higher comprehension of such information. Besides, new wood-based materials and components help to overcome some disadvantages of wood, hence giving to the material a new position in the ships of the future.

*Figure 1: Planks joining method in the ships of the Classical Antiquity. An example of quincunx pattern.*

## "The jungle of the sea"

This was the way a Spanish poet gave an artist impression of the "Invincible Army" built at the end of XVIth century to fight against the English: about one million cubic meters of round wood processed, roughly speaking, the average yield of some 1.4 million forest hectares in one year, or the result of clear cutting, say, 30.000 forest hectares. Starting at that point, with the defeat of the Army, the Spanish maritime power in the Modern Era began its decline, while the English one began its rise, with some parenthesis of Portuguese, French or Dutch domination during the XVIIth and part of the XVIIIth centuries. Before all of them, the different seas belonged to several Mediterranean, Nordic, Polynesian, Asiatic or other cultures. A manifold history with a common point: the pressure (and the technical development) over the natural resource wood.

The initial structural shape in man's architecture could be related to the dome formed by joining trees at their crown. The initial structural shape in human naval architecture probably could be these two options: joining papyrus sheaves, or keeping oneself over a raft. These types of "tied laminated" wood-based (or reed-based) composites are examples of the so-called wash-through vessels. The best rafts were those made with balsa wood, without drying (as the sap in the green timber helps to keep seawater out), lashed with ropes, in a way that it can be slightly deformed and adapted according to the loads. The start point for the good buoyancy properties of a papyrus ship is that the reeds of this plant have a watertight skin, and by pressing but ends, we can have a kind of elemental floater.

*Figure 2: Keel scarf (arrow shaped and dowelled). A great variety of scarf joints were used in traditional wood-based shipbuilding. This variety has to do with several parameters (number of steps, wedges, dowelled or not and dowel types, securing or not the tops by arrow shape or by tenons, different slopes…). When properly crafted, this joint can reach around 30 to 40 % efficiency in bending strength related to the material jointed, a little bit less in tension, and much more in compression. The distribution of the scarf joints used to be carefully chosen, according such limited efficiency. It must be noted that it is still in use in most current solid-wood based shipyards.*

Joining sheaves of these elements, it is possible to create a composite structural element of high performance, suitable to make from small canoes to big ships, fully rigged and prepared for deep-sea navigation. These type of reed ships sailed the seas of South Europe and Middle East since, at least, 3 000 B.C.

Through carving the trunk (from 8-9 000 years ago) and making log-boats man could reach the concept of "shell-first" (clinker-built boats). Gradually, the carvel construction (that is to say, a "skeleton-first" method) was broadly adopted during the Middle Ages, and gradually improved during the Modern Era. The Enlightenment Era brought the first "naval architects" as we know them now, and a scientific approach to the three main knowledge areas involved: wood technology, structural design and, hydrostatic analysis. This is a crude resumé of human technology history, where we could speak about extremely sophisticated structural devices. We'll briefly cite some examples.

The Egyptians. The basic boat made with papyrus sheaves, led with time to the Egyptian wood-based ships, with their shape closely based on their papyrus made ancestors. After some centuries, they developed different sophisticated building methods, like a complex system to make dismountable hulls. As an example of deep structural knowledge, some of their ships were based on the idea of the stressed hull: a controlled tension rope fastening the bow and the stern, hence providing a stress state through the entire hull. It was, probably, an evolution of a similar device of papyrus ships to prevent the overlapping reeds form being pulled apart, when the ship were subjected to heavy loads in deep-sea sailing; the device consisted in two stays running over the deck, and supported on a bipod mast. In some occasions, the hull itself was made without a keel or frames: a premonition of the present "surface resistant" structural systems. Their network through the ancient world provided them with the best materials, mostly Lebanon cedar and sycamore imported from abroad, or home grown locust, with minor quantities of some other species. The Phoenicians exported to Egypt enormous amounts of cedars (some of them being up to 60 m long) during centuries. The forest reserves in the present Lebanon were scarce by the IVth - IIIrd centuries B.C. In the IIIrd century B.C., it became more and more difficult to find proper timber in Egypt itself, and more and more expensive to find it abroad.

Greeks and Romans. The structural joining techniques of their ships preceded, by several centuries, nearly all the techniques we can trace in the "timber engineering" (applied both to ship and land structures) of the Middle Ages and the Modern Era. Some specific types of high structural responsibility joints were solved with geometric arrangements not far from the complex joinery that appeared in Asia some 1000 years afterwards. Construction of different ships (triremes, galleys...) involved complex exercises of stereotomy, with a mechanical problem added: joints shouldn't bee completely rigid, just rigid enough. An interesting detail, from a structural design point of view, is the ram: the element protruded at the lower part of the bow in the Greek war ships. As these were to be thrown one against other, the brutal impact forces of the attacker were transmitted back through its ram to its own hull. This had two pre-stressing devices, which endow it with a spring like behaviour. One was the external stem knee, with fastening arrangements mainly in compression and shear. The other were the high curling sternpost, which curve was quite similar to that obtained by soak-bending the top end of a tree. Besides, all these rigidity control devices must be adapted to the mechanical properties of the wood specimen used. The ram seems to have been thought also as an element to increase the efficiency of the forward oarsmen, working in a similar manner to modern bulbous bow. It provides an additional bow steering surface that help the hull to respond properly to the loads induced by the side rudders.
The hull, relatively thin, was made in such a way that it behaves much like a beam of open transversal section and thin wall. Light ribs provided transverse rigidity. Longitudinally, under the gangway, were placed a kind of lattice framework, creating a longitudinal girder (completed with the hypozoma, a tensioned rope fastening the bow and the stern) that provides significant strength and stiffness in the worst load case. This case used to be in hogging (see below, "...the basic problem"), or in oblique sheer. In recent replica studies (Coates, J.F. 1984), it was found that the bending moment, in hogging, could reach about 90 tonne metres, with a tensile stress in the gunwale (which had enough section to pull the flexural neutral axis of the hull up to its middepth) of about 6 MPa. The hypozoma could work in a similar way of a tendon in prestressed concrete, as it introduces an axial force in both ends of the ship, hence reducing (depending on its distance from the flexural neutral axis of the hull) the stresses induced by the bending load. In the cited case study, this device reduced the maximum stress by 1/3, and the shear stress in the shell planking was found to rise about 0.75 MPa. The planking of ancient Mediterranean ships was made by edge joining adjacent planks with tongues (harmoniai, in Greek language), set into individual mortices and dowelled (see figure 1). The precise proportion between the distance from the dowel to the edges of both the plank and the tongue, the relationship between the tongue width and the plank width, and the species to be used for tongue and dowel, were the main parameters taken into account in order to avoid a disproportionate sliding. What the studies show, in any case, is that the elements of ships like the Greek triremes were loaded to their limit.


*Figure 3: Detail of jointing technique between two a layered shell, a transversal rib, and a keelson, as can be found in Ancient Mediterranean wrecks, or in some current shipbuilding techniques.*

These developments were the result of intense shipbuilding activity related both to commerce and naval war. While the Mediterranean cultures were growing, their forest reserves were continuously decreasing (reaching dramatic situations in Athens in VIth B.C. or Rome in Ist B.C). Hence, learning to build boats with smaller timbers or different species, became a matter of technological survival, as important as the military control of highly-forested countries. Such a process (constant mechanical improvements adapting shipbuilding technology to a increasingly scarce resource of wood) can be traced, in one or another way, until the end of


*Figure 4: Typical transverse section of a Viking ship. Adjacent strakes were joined by nailing the overlapping area with treenails of top quality wood (when available). Knees were made with special parts of stems and/or branches.*

XIXth century.

The Arabs. During the first centuries of Islamic power, they based their maritime power on the same importation policy of ancient Egypt, from different countries, mostly the Middle East. Afterwards (VIIIth-IXth) they established their main shipyards in Al-Andalus (most of current Spain and Portugal). There, shipbuilding activity was based in the, by that time immense, forest reserves of different coniferous and oak varieties in the Iberian Peninsula. Their shipbuilding technology was very similar to the wooden ships one can currently see in, say, Oman. The shape and inner structure of its hulls has proved to be very complete and efficient already: recent replica studies, carried out under the perspective of current boat design knowledge, haven't suggested any relevant improvement.

By the XIIIth century, the scarcity of wood forced the inhabitants of Islam to negotiate the material supply with their natural enemies, the Christians. Wood technology and availability means a powerful navy, and this means a military powerful nation. If in pre-industrial times we can speak about a strategic raw material (with a parallel meaning to that of petroleum in present times), that is wood.

The Vikings. They were masters of the flexible hull, in a technological process that can be traced with evidence from the Bronze Age to the VIIIth or IXth centuries. It is still not clear if such flexibility was a result of other requirements (like lightness), or an intentionally given property, since flexibility is a characteristic associated with low weight, speed potential, strength or even seaworthiness. Lightness is important to navigate in all kind of waters and weathers, and for making it easy to drag the ships. A flexible wooden ship under some loading conditions can present a better behaviour compared to a stiff one. How flexible the structure must be, or can be, is always a key point related both to the joints and frames configuration. Flexibility is still used, in parts of Norway, to check the quality of a clinker built wooden boat, by shaking it in land and observing the shaking pattern. Anyhow, the spreading of the stress over a large area is an interesting property of a flexible boat, as it avoids stress concentration and takes advantage of wood toughness. Besides, such boat construction allows quick navigation regardless of water or weather types, and makes it easy to run the ships ashore (an important advantage from two points of view: proper maintenance and military flexibility).

Regarding material selection, oak and ash were the preferred species, but depending on the situation, any available species was used (birch, alder, elm, beech, lime, maple, pine...). Strakes were obtained by means of a splitting technique, using rather straight logs with a low content of reaction wood, knots, spiral grain or twisting. This technique results in mainly radial boards, sometimes 35 m long, with an optimum mechanical behaviour and stability. For making the knees, naturally shaped woods were chosen, by selecting the proper branches, hence avoiding parasite stresses. It's interesting to note that one of the potential reasons why the technically successful Viking ships disappeared from Southern Scandinavia was the progressive shortage of proper quality timber (while in Northern Norway, as was told, it is still possible to find relatives of such clinker-construction type).

The Chinese. Bamboo is an amazing structural element, with an extremely efficient material organization. It has been used until recently as suspension bars for heavy-duty vibrating machines, where it proved to be more cost effective than steel, and still is used for complex multi-storey scaffolding and buildings. Probably inspired by the inner structural configuration of bamboo, the Chinese developed, some twenty centuries before Europe, the bulkhead method. It consists in substituting the ribs and frames by diaphragms, frequently made with top quality woods (like sain), which keep the transverse rigidity of the hull within proper limits, and divide its interior space to tight areas.

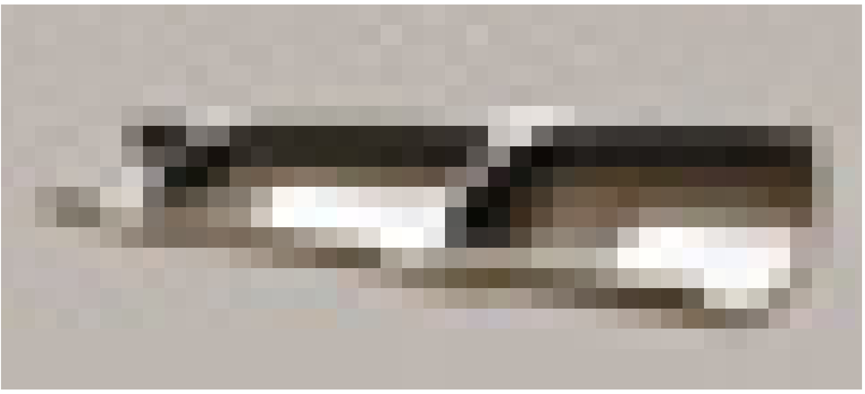
Figure 5: Model of the inner structural arrangement of bamboo

Modern Europeans. It is possible to trace the technological improvements which, starting form the different previous experiences led to the North European cogs in the XII and XIIIth centuries, the Portuguese and Spanish caravels and naos or the West European carrack in the XIV-XVIth centuries, and finally to the galleons of XVII-XVIIIth centuries, and the schooners, brigs and clippers of the XIX-XXth centuries. Until the XVIth century, it was not uncommon for the main European states to obtain the raw material for their navies in their own territory. But, by the XVIIth century, the requirements of the navy of any powerful nation were too much for their own forests.

Hulls were provided with more width planking (even doubled), and the structural importance of the frame become higher (the space between two consecutive frames, could be as narrow as the width of the frame itself). The new technical approach to naval architecture can be clearly shown in the words of F. Oliveira, a Portuguese Renaissance personality, in 1570: "[...] Nature teaches this in the bodies of sentient animals, in which there are also two parts that seem to respond to what I say and give an obvious example of these two necessities of the ships: one is the bones, that represent the strengthening pieces, because they support, straighten and form the body of the animal, such as the support does in the hull of the ship: the other is the skin that covers the bones, as the planking covers the support [...]". Skeleton-first approach, hence, was developed during a period between, roughly speaking, the XIth and XVIth centuries, with some early examples from the Low Middle Ages. In this structural configuration, the active role is conferred to the framework. Several improvements were made with time. One example is the use of scientific methods like hydrostatic analysis, by the Swedish F.H. af Chapman at the end of XVIIIth century. Other can be the introduction of iron bracing (hence coming back, in some sense, to a shell conception) by the English R. Seppings, in the first part of the XIXth century, bringing to the practise of naval architecture the modern approaches in structural design. Anyhow, the system was thought to be rather mature by the XVIIth century, as we can see in different attempts to standardise the material and components supply chain (like the establishment of strict contracting rules of the British Navy Board at the beginning of the century, or the extensive and precise catalogues of shapes and dimensions of timbers published by French and Spanish engineers at the end and the following

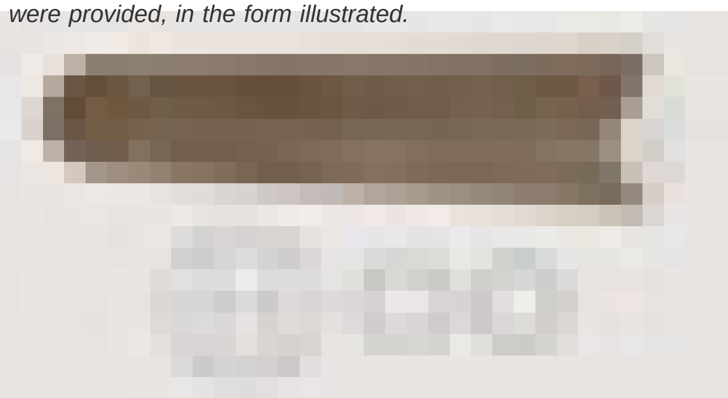

*Figure 6: Typical composed masts configuration. A composed mast not only solves the problem of searching too big trees, but it is a mechanically efficient solution, because of the lamination effect. In simple arrangements, the different timbers could be simply superposed and bounded with bolted iron rings. When the structural requirements were higher, specific shear connectors were provided, in the form illustrated.*

century).

This system of construction required vast amounts of wood, and the problem was not only the volume of wood, but also the proper quality. One example of this is the adequate piece for the sternpost and its related structural bars: for it, solid oak members of 8 or 9 meters long and 60 centimetre wide were requested. An oak tree can need 100 to 200 years (even more), depending on the species and climatic area, to be able to produce such timbers. For the external planking, solid boards ranging from 15 to 30 centimetres were used. To shape the boards, they were exposed to steam, and bolted or nailed directly to the frame while they were still warm, or previously fixed to proper formworks or burdens.
Frames were made with paired elements, with an overlapping method providing a lamination effect that reduces the effects of timber-growth characteristics.
Some other examples can be related to the searching of specific trunk shapes, with extreme cases like the lower stern, which required old trees with big branches approximately 90 degrees bifurcated. Green oak was normally preferred for such elements (and still is in the Mediterranean wood based shipyards), and this specie grows even slower than common oak.

A new forest management philosophy arose then. French forests then started being managed by strict laws (around 1669), oriented to provide the navy with the best material possible, then and in the future. The present state of their forests owes much to such policy. The idea was to make France self-sufficient; nevertheless they still needed to buy some special materials, like logs for masts, or even oak in some periods.
Due to different socio-economic factors, like the early industrialization (and its energy requirements) or the uncontrolled private or public forest owners, English forests were not able at all to supply the quantities and qualities of wood that their enormous navy requested. The English developed a precise strategy in order to guarantee the different channels of timber importation, mainly from the Baltic states, from Ireland or the American Colonies. Shipbuilding technology was in continuous adaptation to the market situation. A typical example of this was the structural configuration of the masts, made from entire logs when the American timber was available, and by composed sections of smaller Nordic timbers, when the Colonies became independent. The Baltic timber trade was by that time (towards the end of XVIIIth century) rather efficient, even using a modern quality control system, partially oriented to naval architecture.

Spain put every forest in a determined distance from seashore and navigable rivers under naval officers control. Hence, the first modern forestry administration appeared in Spain by the middle of XVIIIth century, directly linked to the development of wooden shipbuilding activity, just like it happened in France some one hundred years before.

In the present, wooden boat building has only a limited (but rather increasing in some areas) use. We can identify three main lines, from a technological point of view:
(1). Traditional fishermen boats and ships. They are built in a tradition maintained without mayor evolution since the last, say, two hundred years; with basic elements that can be traced back more than one thousand years. Form lines, structure configuration and joints design are traditional, regardless of the modern wood-processing techniques used, or the punctual use of modern metals or synthetic materials. We must note that a careful study of these boat-building technologies shows that they are rather efficient, when all parameters are considered.
It is possible to find all over the world specific areas (small, but rather stable, on the whole) where such tradition is alive.
(2). A few particular wood-based shipyards can be found concerned with heritage recovery: the building of ancient replicas is becoming a mater of increasing interest. From a scholarship point of view there exists still much to learn from ancient shipbuilding and the best manner is build and navigate in the old way. Analysing related information, useful learning on timber structural behaviour is being gained.
(3). Glued-laminated based boats. In their design, current knowledge on hydrodynamics and structural analysis is, to one or another level, applied. At a basic level, traditional form lines are built with plywood; at the top, complex wood composites-based yacht designs are made using computer tools. Hence, form lines and structural arrangements can be subjected to verification by a scientific method (although the basic inspiration use to be based on craft traditions). Mixed approach (solid wood and laminates) is not also uncommon, be it for aesthetic, economical or technical performance reasons.

## Wooden shipbuilding: the basic problem.

"...we haven't yet any Technique worthy of such name. What we call Technique is the use of the force without leniency...". These words of Albert Einstein preceded his idea of an example of authentic technique: navigate against the wind using its own force.
The reference bring to this article the idea that wooden sailing ships have been at the top of mankind's technological skills: deep

*Figure 7: Typical stress distribution pattern (shear stresses on the left, normal stresses on the right) in the transverse section of a boat, when sailing. Of course, the signs can vary with the supporting conditions (hogging, sheer, oblique sheer). That way, main structural members will be subjected to reverse loading (or two-sided cyclic loading), with short time periods. This can provoke creep in the member, hence reaching its rupture far below its strength limit if continually loaded with the same stress sign. Besides, the efficiency of joints can be affected to a major extent. Wood rheological characteristics are another key to understand its behaviour as structural component of a ship.*

comprehension of material behaviour, precise feeling of loads and stresses. The development of this authentic technique, has required a continuous process of learning about the inner mechanical aetiology of the material wood, from the tree to the shaped plank or veneer.

The main supporting conditions to analyse ships structurally are the hydrostatic forces in different hypothesis: hogging (with the whole ship only supported longitudinally in its middle section), sheer (with the ship supported over two waves, each curl at each end of the gangboard) and oblique sheer (when sailing obliquely to the waves), and when launching. Loading conditions are given by the impulse mechanism (sails, oars, engines) and the kinetic friction effects (both with air and water). The effect of prestressing devices (like those cited above, or simply, the prestressed rigging), must also be taken into account. Usually, the ship is assumed to act as a beam, and the cross-section is not deformed significantly. The worst hypothesis tends to be the torsional loads (mainly in oblique sheer), under which the deformation of the hull will be a rotation around its longitudinal axis (that is, the St. Venant torsion), and an axial deformation (caused by the warping moments). The more open the section of a hull (like in ancient flexible ships) is, the more dominant is the effect of the warping torsion. Figures 7 and 8 gives an idea of the stresses and deformation patterns.

The proper control of these forces is one of the key issues in the design of wooden ships. The traditional (and current) wooden ship construction is based on the idea of making a hull of controlled rigidity. Quoting J.E. Gordon (1968): "The orthodox ship construction was like a five bar gate without the diagonal member". The goal is to reach very high deformation levels without rupture, and here, the toughness properties of wood (already exposed), play a major role. The idea is, plainly speaking, to scale this material property up to the entire structure. More or less intuitive methods of focusing the problem have been revealed in the historical notes. Nowadays, computer techniques allow us an analytical comprehension of the topic, but still a trained intuition helps.

The final goal is that our structure (hull, masts and ropes) should be reliable: with a specified probability, it must carry the loads while keeping the deformation within prefixed limits, in a defined life span. The probability level can be suggested by standards or recommendations (or even by insurance companies). The deformation limits, being usually much higher than with land structures, are normally determined by the user, or by common experience.

This relative rigidity allows the wood to shrink and swell without leaking too much (or not at all, if high quality craftsmanship or proper wood based composites are used), and maintaining the mechanical integrity of the entire ship. The possibility of differential shrinking and swelling is very important, as the equilibrium moisture content can be very different from one part to another part of the entire structure when it's sailing. It's also important to avoid compression set effects by proper detailing.

The final shape of a hull is the expression of, on one side, the pure hydrostatic analysis, and on the other, the mechanism it uses to carry the shear load without local or global sagging. Sagging, furthermore, can happen not only with the initial loading, but also due to the gradual deformation that a wooden boat hull will acquire during its life. From a purely theoretical point of view, we can think about infinite different shapes of a wooden hull, and only a more or less algorithmic optimisation process can lead to the definitive shape of a design. This optimisation has much to do with the way chosen to arrange the inner ribs of the shell, as it has major constructive implications.

A more or less standardised method of bidimensional expression has been developed and experimented through the last four hundred years in order to bridge the gap between the definition of the hull shape and the processing requirements of the different wood members, no matter you use scantlings of CAM methods. The different types of joints used, are organized in a way that a more ductile behaviour can be attained. Besides, the transverse structural frames are made through beam brackets and hanging knee joints, which provide a semi-rigid fixing effect between all the curved elements. These elements, depending on the boat size, are made of single or laminated members. Such lamination used to be (see below) achieved by nailing, bolting or gluing. Longitudinal structural members are normally joined, when they are not laminated, with different variations of scarf or lapped joints.

## Shipbuilding-related wood properties.

## Purpose-grown wood, purpose-made structural material.

The variability of wood as a mechanical design material (within species, within bio-geographical areas, and within the tree itself) can be seen as a problem. Nevertheless, if we take a closer look at our topic, with a technologically open mind, we can see it as an opportunity. In the following table we can see the range of mechanical characteristic values, taken over a sample of 160 different commercial species:

| *Property:* | *Min. value* |
|---|---|
| Bending strength (MPa) $^{\text{parallel}}$ | 14 |
| Tension strength (MPa) $^{\text{parallel}}$ | 8 |
| Compression strength (MPa) $^{\text{parallel}}$ | 16 |
| Shear strength (MPa) $^{\text{parallel}}$ | 1,7 |
| Mean modulus of elasticity (GPa) $^{\text{parallel}}$ | 7 |
| Mean shear modulus (GPa) | 0,44 |
| Toughness (Nm) | 6,6 |
| Density (Kg/m$^3$) | 140 |

A similar figure (in terms of the range of values) can be obtained with other mechanical profile parameters. We must add the different behaviours regarding natural durability or ability to impregnate, and the different behaviours in processing. Besides, of course, we must add the extreme price variability, and (see below), the different environmental impact associated with the use of one or another wood, or even simply, its commercial availability.

If we manage to orientate ourselves in this jungle of data, the result is a kind of "purpose made" natural material. It is always possible to find the proper wood for the proper use in any mechanical construction. The ideal material profile for different parts of a wooden ship or boat depends on which structural element it is intended for. To have a rough idea, check the table in final page.

Taking into account different factors, environmental issues included, we can think of some 30- 60 different commercial species (that's, 30-60 different material profiles) with proper potential use in shipbuilding, depending on the market area where we are.

## Wooden composites and some complementary materials.

Wooden composites are one of the keys to increasing the performance of wood as a naval architecture material. But, before speaking about its use, we should be aware that making wood based composites is a traditional way of using wood material in shipbuilding. Skins were nailed laminated surface structural members, and long masts were iron-binded laminated lineal structural members. In these and other cases, the so-called lamination effect was used (intuitively) to deal with the intrinsic variability of wood and give finally more homogeneous composite elements. The statistical meaning of this effect, when it comes to analyse the reliability of a component, is behind the conception of most wooden composites.

There are two main composites used in shipbuilding, based on the use of top-quality adhesives: bonded veneers, or bonded timbers with small thickness (see Mr. Hunt's chapter). These materials are rather common in furniture making or building. The special difference in shipbuilding is that, in many cases, the laminate must be made ad hoc on a rather big scale.
When the hull shape is complex (with high degree of double curvature), it is made beforehand, setting several layers of veneers over a formwork.

One thing must be kept in mind: the difference between wood and laminates is not a matter of different materials, but of different degrees of the incidence of natural variability. We are making wood in a manner not so different (from a engineering point or view) from the way that Nature does if. One important advantage of laminates comes from the already mentioned variability: the proper selection of the raw material for the wooden sheets, from the inner skin to the exterior one, gives an extreme example of a purpose made natural engineering material. Regarding shapes, the traditional way to manage the problem of extremely curved members (typically, angle ribs or knee brackets) was to look in the forests for trees with specific shapes... or even cultivate it in the required way. It is not uncommon, in some coasts where a small tradition is still alive, to find this way of work still in use. Nevertheless, in modern design the more or less standard procedure is to make laminate frames (see Mr. Hunt's article). We can divide the method in two main groups, the surface of lamination being transverse to the hull, or curved (parallel to the hull). The last one gives more mechanically efficient solutions, but it requires much more craftsmanship.

Another topic might be not the shape itself, but the size, particularly with the design of masts. The current answer to the traditional methods noted above has to do with the use of different types of solid composite sections, or the hollow section approach.

With the accelerate development of new adhesives since the last World War, composites became more and more reliable. By the sixties, the successive generations of synthetic structural materials added another improving possibilities. Epoxi formulations are now a common way to make local reinforcements (frequently to shear or tension) or repairs. New wood-based composites are continually arising. A basic example can be the insertion of synthetic sheets in multi-laminar composites, in the simplest case, gluing metallic or plastic sheets to wooden members. This idea has its antecedent in the composite hull made with an iron framework planked with wood, or with wood covered with metal planks, used by half the XIXth century; such composite construction probed to be very efficient (but expensive) when a proper metallic alloy was used.

## Durability.

The structural use of wood in an adverse environment like a marine one is quite a specific topic. But first, we must be aware that nearly every environment is adverse in some way or another for any structural material, each one with its own problems. The average service life of a wooden ship (provided it survives storms and wars, and it's properly maintained) used to range between 20 and 50 years. Strictly speaking, it is not so different from the service life of current metals or resin-based ships; of course, the maintenance requirements are different too.

Some biological agents causing deterioration are characteristic of the use of wood in marine environments. The most important one are marine borers (shipworms and gribbles). There exists a rather small amount of published research with clear and useful information relating the degree of infestation (which itself is difficult to be measured) to the associated lack of strength, and little of it is useful from the engineer's point of view. The mechanical strength loss is mainly caused by the effects of tunnelling, ranging between 3 and 10 mm in diameter, linked to the feeding habits of the animal (it can eat wood, or, more seldom, it simply uses the tunnel to help it filter plankton).
To have a rough idea, a severe gribbles infestation can completely destroy a one-inch board of a strake in one year, or even less. Wood decaying fungi must also be considered. So, another factor in the design of wooden boats is whether marine borers or decaying fungi are active in the area, and which types of them we must face.

Normally, different types of chemical treatments are available, apart from or connected with finishing coatings. They really have a long history: the Vikings used a kind of wood-tar to protect the hulls of their ships (the process was used to impregnate the exterior wooden surfaces of their main buildings). In Asia, highly valuable ships mast were made with teak buried several for several years in humid earth. In some parts of the Persian Gulf, a mixture of animal fat and hydrated lime is used to coat the hulls; in India, they still use a varnish from plant resin, animal fats, fish oils, lime-plaster and vegetable oils. More recent coating materials are an elastomeric polyurethane based varnish, which prevents the marine borers from fixing on to, or entering into the wood. The use, at the end of XVIIIth century of copper covering over the wood planking, was an efficient strategy (that leads to the composite construction above cited).

Some modern impregnation processes were used in the beginning of the XIXth century, applying wood-tar creosote, especially when the ships where expected to remain in warm-water harbours for prolonged periods. Creosote and copper-

| *Use* | *Some requested characteristics* | *Some species used* |
|---|---|---|
| Decks | Small shrinkage coefficient, saline environment resistance, low humidity absorption, high surface hardness | Larch, pitch pine, oak, cypress, afrormosia, mayflower, lauan, white peroba, peterebi, tatajuba, teak, iroko… |
| Deck girders | High static bending resistance, hardness and durability, low shrinkage coefficient | Aleppo pine, white pine, red pine, larch, ash, Columbian pine, Sitka spruce, sapele, padouk, kauri, jatoba… |
| Ribs and frames | Very high static and dynamic bending resistance, toughness, nails and screw extraction good qualities | Cypress, oak, green oak, olive tree, cordia wood, red louro, elm… |
| Keels, plating and strakes | High toughness, marine borers resistance | Green oak, balau, southern cypress, larch, Aleppo pine, oak, greenheart, cumaru, angelin, lapacho, alep, mancone, red river gum, Australian cypress pine, billian, jarrah, camphor… |
| Masts | Low density, high resistance to bending and compression | European spruce, longleaf pine, larch, Weymouth pine, kauri, Columbian pine… |
| Oars | High resiliency | Lawson cypress, ash, alder, elm, afina, western spruce, huckberry… |

chromium-arsenic compounds, applied singly or in combination are commonly used. From a mechanical point of view, some inconvenience must be regarded. Salt impregnation, particularly when full-cell pressure treatment is given, tends to make wood brittle. And, as can be imagined from the rest of this article, brittleness is one of the main mechanical characteristic that a material for our purpose should never have to a high level. Coal-tar derivatives are inert substances, therefore they do not have an intrinsic negative effect. However, if we want the treatment to be really effective, we must use high temperatures besides high pressure, hence causing some degradation degree in the wood.

Furthermore, because of its environmental impact (see next point), there is a global tendency to avoid impregnation with biocides, as far as possible. Anyway, the allowed impregnation products in the near future will have less biocide potential than current ones. The alternative strategy is to use naturally durable timbers, especially in areas with higher risk (some 20-40 cm below and above the water line). Another important point is detailing towards durability, mainly with solutions oriented to facilitate quick water drainage. In the best traditions of ancient shipbuilding, even the spatial organization of complex scarf joints where thought in that way.

Durability is always a relative concept, as no biological material is an everlasting one. We must look at wood natural durability as one more parameter in the material profile, and analyse the reliability of the solution with a fixed life-span approach.

Several studies are advancing in the knowledge of the natural durability mechanisms of wood, usually based on the presence of extractives materials within the wood structure. For instance, silica content, within the wood structure provides significant resistance, if the material is in an aggregated form, not diffuse or disorganized. Some other toxic substances can also play a role. Frequently, durable woods are also dense and hard, but hardness and density by themselves doesn't provide significant resistance to marine borers.

A periodic maintenance program must be always established, in order to review the coatings. In this sense, is important that the structural design itself allows the substitution of entire structural elements, or the repair by prosthesis (normally made with wood based materials and/or reinforced epoxy formulations), without dismantling the entire hull. This can determine some constructive dispositions. In some coastal areas of Asia the strategy is, simply, to add new side shell plating without removing the older one.

This general approach of gaining durability by design, which is an intrinsic part to the wood-based shipbuilding (and land-building) traditions, is being now increasingly accepted as a sound strategy in the conception of modern wood-based land structures.

Weathering, in structural parts not subjected to more or less continuous contact with water, can be also a special issue, but it is more an aesthetic one. The net thickness loss of an untreated exposed element ranges from 1 to 15 mm/century, depending on wood species and climate. Even when erosion increases the effect, this is not important in the life span of a boat. Besides, protective coatings in a marine environment tends to be more durable than in an inland one, because the equilibrium moisture content variation is lower. To give an idea, in an inland exterior exposition in the South of Europe, the moisture content can reach values from 8 to 18%, in the same place during one year. In the coastal areas, the variation can be as low as 10 to 11% (in some places of the Mediterranean), or 13 to 17% (in some parts of the Atlantic coasts). Obviously, if the wooden boat is intended to travel around different seas within a year, the total variation can be not so far from inland values (as the equilibrium moisture content in the sea can reach values near 20%, even a little bit more), resulting in a quickest coating deterioration.

## Environmental considerations

We have tried to highlight at the beginning of the article the close relationship between shipbuilding and environmental pressure (specially over the forests). Currently, the importance of wooden shipbuilding being statistically insignificant in total naval construction activity, it cannot have the same significance as it did in the past. However, each minor impact is becoming important, particularly if we note that some species frequently used in boat building are in severe danger of extinction. The selection of these species use to be related to the requirement of extremely high durability or good aesthetical properties. Some teak varieties or mahogany are common examples. Furthermore, the negative effect of the use of some species is multiplied: for each cubic meter of (for example) mahogany that reaches the market, dozens of cubic meters of commercially-unknown, but technologically-interesting species are cut down and simply left on the forest soil. Hence, the area of forest degraded is extremely disproportionate to the natural structural material obtained.

If we make a market survey, not much more than 150 species are in normal use, at a global scale. Studies from the XVIIIth and XIXth centuries presented technological properties of 200 to 300 (depending on the authors) different woods, and that means different mechanical profiles and aesthetic parameters. Recent studies raise that number to some one thousand of species with potential use in wood production. It is extremely difficult today to know precisely the real number, and it is near impossible to have, at a global scale, a clear enough picture of the environmental impact associated with the industrial use of each one. Anyhow, one thing is becoming clear: Nature produces hundred of different tree species suitable for sustainable exploitation. We can say that the forests around the entire planet are reservoirs of natural structural materials. The negative impact isn't generated by the use of wood itself, but by the uncontrolled market pressure. Some attempts are being made to avoid this situation, through environmental labelling or certification systems. There are now under discussion, or in practise, several proposed systems or protocols. One of these methods, by the way, has a extremely lucid name: Smart Wood. Our task now is to learn more about the mechanical properties of each wood, and the ecological limits of its use.

Another illustrative point is the potential of positive effect of solid-wood boat building shipyards on the proper management of the surrounding forests reserves, provided the ecological exploitation limits are respected. As pointed out before, building solid wood ships means using quite different tree shapes, hence naturally variable forests are, to some extent, required. In the Mediterranean coastal area, for example, where small wood-based shipyards are still active, is normal to find a higher care in the neighbouring woodlands, as it is a prerequisite to keeping the trade profitable.

Finally the different effects linked to the use of chemical preservatives must be taken into account. Such effects are related to several steps in the entire life cycle: production of the preservative, application methods and its by-products, the effect of leaking in use, and the end of life. Chemically-treated wood cannot (at least should not) be used for energy production, unless suitable but economically ineffective measures are taken. In any case, treated wood will be naturally degraded sooner or later, hence releasing the biocide product to the environment.

The limited life span, as was noted, must be considered as just one more parameter in the reliability equation to be solved, not as an intrinsic defect. When man creates a structure with a biological material, he is taking part in an everlasting existence and death cycle, and all of the game rules must be respected. Wooden ships are among the most complex artefacts that man has been able to make, so that they can be shown as a metaphor of human cultural development. Most big human cultures have been traditionally growing against

## Final excursus: aeronautics.

The mechanical problem to be solved in boat design is, to some extent, similar to that of monocoque planes: the skin takes the main forces. In fact, the making of the skin of wooden aircrafts is similar to the making of some wood based modern hulls. The shell of this kind of aircraft was (in some cases still is) frequently made with a light wood core and harder wood veneers in the inner and exterior faces. Various form of modern process technology can be used: some kinds of spruce or ash are mechanically moulded to the desired shape in making the frames, superpressed plywood is used for sticks or propellers...

In the beginning of this article, I suggested that most of the technology we can find in the traditions of framing of timber building, was experienced first in shipbuilding. To end, let me note another example of knowledge transfer within the world of wooden mechanical design: the experience gained in the making wooden propellers, has led now to the use of poplar veneer as base material for huge blades of modern wind generators.

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