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Understanding the Char-Bending Technique in Shipwreck Planks

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Abstract: Char-bending is a term used in marine archaeology literature to describe the process of shaping long hull components (planks, wales, stringers) by bending them over open fire, from Antiquity, up to modern times. Experiments were done on planks of two wood species with different cross-sections. The planks were heated over open fire while monitoring the internal temperature and charred layer thickness on the side of the plank facing the heat source. The results show that in order to reach the temperature inside the wood required for it to become pliable, the formation of a charred layer, an undesirable by-product, is unavoidable. It is explained why char-bending, in almost all cases, occurs on the concave side of the plank.

Keywords: char-bending; singe; scorch

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1. Introduction

Wood-bending techniques have been known and practiced for at least 4600 years in the production of components of ships, furniture, casks, chariots, and various tools [1]. The idea behind bending wood components to a specific curve is based on several arguments: to keep the grain aligned with the shape of the timber to maintain its strength as much as possible, to reduce the force needed to bend the wood, to prevent fracture of the wood when the curvature of the bend is too sharp, and to prevent spring-back of the timber after bending. Thermo-hydro-mechanical (THM) treatment for preparing a timber, such as a plank, for bending involves heating it in the presence of water for the time needed to allow the heat and moisture to penetrate throughout to make it pliable enough to achieve the correct shape. This process is still used in industry in the production of boats, furniture, and casks [1].

Among the methods of preparing wood for bending are: heating over open fire, steaming, soaking in water, and boiling in water. This work concentrates on heating over open fire. A feature of this process is charring of the face exposed to heat. Aspects of this method that were checked are: whether the charring is on the convex or concave side of the plank; the temperature gradient within the wood as a function of time, and the thickness of the charred layer as a function of time. Evidence of charred wood found in shipwrecks was examined and analyzed to discount other possible reasons for the charring.

1.1. Ancient Written Evidence

The earliest known written evidence is believed to be a contemporary description of char-bending from the 1st century BCE by Valerius Flaccus [2]. Claesson Rålamb described the process used by Vikings in the 11th century as heating planks over a bonfire while applying a downward bending moment (Figure 1).

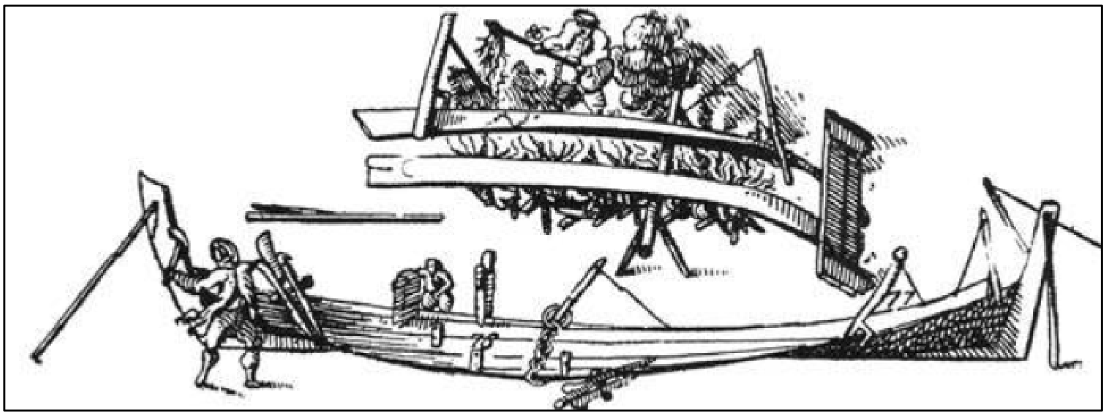

Figure 1. Heating of ships' planks over open fire by Vikings, ca 1600 [3].

1.2. Shipwreck Evidence

Many observations of charring in shipwrecks are related to a bending process. The earliest is from the 4th century BCE—in the Kyrenia shipwreck [4]. Most of the evidence is dated to the medieval era, and was found on the eastern shores of the Mediterranean and in the Yenikapı site, Istanbul (Table 1).

Table 1. Charred planks interpreted as evidence for preparing for bending over open fire.

Shipwreck	Date	Component	Side Charred	Location on Component	Component Thickness [cm]	Interpretation	Reference
Kyrenia	4th c. BCE	Wales	Concave inner face	Few 30-cm-long sections. All other places trimmed off	6.1, 8	Char-bending	[4]
Expanded log boat	1st c. BCE	–	Concave inner face	–	–	–	[5]
Grado	2nd c. CE	Garboard	Concave inner face	Extremities	5	Char-bending	[6]
Dramont E	5th c. CE	Garboard	Concave inner face	Extremities	4.8–5	Char-bending	[7]
Dor D	6th c. CE	Strake	Concave inner face	Extremities	3	Char-bending	[8]
Dor 2001/1	6th c. CE	Strake	Concave inner face	Extremities	2.3	Char-bending	[9]
Dor 2006	7th c. CE	Strake, wale	Concave inner face	Extremities	3.2, 16.1	Char-bending	[10]
Tantura A	6th c. CE	Strakes	Concave inner face	Extremities	2.5	Char-bending	[11]
Tantura E	7th–9th c. CE	Strakes	Concave inner face	Extremities	1.9–2.9	Char-bending, killing *T. navalis*	[12]
Tantura E	7th–9th c. CE	Stringers	Concave inner face	Extremities	4–7.6	Char-bending, Killing *T. navalis*	[12]
Tantura F	7th–8th c. CE	Strakes	Concave inner face	Extremities	2.7	Char-bending	[13]
MMB	7th–8th c. CE	Stringer	Convex outer face	Extremities	10	Char-bending	[14]
MMB	7th–8th c. CE	Strakes	Concave inner face	Extremities	3.1–4.2	Char-bending	[14]
YK 11	7th c. CE	Strakes	Concave inner face	Extremities	1.8–2.5	Char-bending	[15]
YK 14	9th c. CE	Strakes	Concave inner face	Extremities	0.8–3.6	Char-bending	[16]
YK 14	9th c. CE	Garboard	Concave inner face	Extremities	1.1–4.4	Char-bending	[16]
YK 14	9th c. CE	Wale	Concave inner face	Extremities	3.6–7.2	Char-bending	[16]
YK 17	8th c. CE	Wale	Concave inner face	Whole length	14	Char-bending	[17]
YK 3	10th–11th c. CE	Wale	Concave inner face	–	10	Char-bending	[18]
Drogheda Boat	16th c. CE	Strakes	Concave inner face	All over	2.2	Char-bending, killing *T. navalis*	[19]
B&W I	16th–17th c. CE	Strakes	Concave inner face	Extremities	4.5	Char-bending	[20]
Akko 1	19th c. CE	Garboard	Concave inner face	Extremities	4.5	–	[21]

1.3. Modern Evidence (20th–21st Centuries)

Preparing vessel components for bending is practiced nowadays in small shipyards in Japan, Bangladesh, South China, East Africa shores, Greece, and many other places (Figure 2). It was recorded by scholars during the 20th and 21st centuries. Greenhill mentioned using the char-bending technique in fishing boat building in Japan in the 20th century, but gave no details [22]. In Bangladesh, char-bending was practised in building fishing boats [23]. In the same area, char-bending is practiced in the production of dug-out canoes to push out the sides of the boat [24]. Richards describes the process of bending planks over open fire in Western Sarawak, Malaysia, and South China, where heating is done over open fire while applying a bending moment to the plank [25]. A similar process in a small shipbuilding yard in the Swahili Coast, East Africa is described by De Leeuwe [26].

Figure 2. Heating of planks over open fire in small boatyard in Vietnam (Photo: M. Yarkowich).

2. Materials and Methods

The THM process of preparing planks for bending is based on the influence of heat and moisture on the wood to make it pliable [1], and for it to be applicable it is required that the temperature and moisture content are uniform throughout the plank.

We know that the mechanical properties of wood change with temperature and with moisture. The temperature should be above a certain value throughout the volume of the plank under consideration. We carried out experiments to better understand the dependency of the temperature inside the wood on the time of exposure to the heat, the wood condition (green, seasoned or wet-seasoned) and the thickness of the charred layer; several series of experiments were carried out.

It may be noted that there is some confusion in the definition of 'seasoned wood': in some places it is defined as drying in a kiln at 100 °C [1]; in others it is described as 'air-dried wood' [27]. In this work, 'seasoned wood' means 'air-dried wood', and 'wet-seasoned wood' means 'air-dried wood' soaked in water until saturated.

The method of heating over open fire in Antiquity was based on a bonfire over which the wood was heated (Figures 1 and 2). Since a bonfire is not a reliable heat source and its distance from the heated object is difficult to control, it was replaced in our experiments by a commercial barbeque device, operated by LPG (liquefied petroleum gas)—a mixture of propane and butane. The timbers were laid on it, and the distance from the heat source and the flame height were kept constant (Figure 3). After several trial experiments, including direct fire (Figure 3(1)), a perforated plate between the flame and the wood (Figure 3(2)), and a solid plate between the flame and the wood, it was decided that the optimal set-up to minimize charring was to lay the wood flat on a 3 mm thick steel plate placed over the flames to spread the heat evenly (Figure 3(4)).

Figure 3. Commercial grill system used for heating the planks. (**1**) Burners are exposed. (**2**) Perforated sheet metal covers the flames. (**3**) Solid 3 mm sheet metal covers the flames. (**4**) Wooden plank is laid on the solid sheet metal (photo: M. Bram).

3. Methodology

Two series of experiments were carried out: one on timbers of Turkish pine (*Pinus brutia*), of 5 × 5 cm cross-section, and the other on cypress (*Cupressus sempervirens* L.) of 14 × 14 cm cross-section.

1. Three sets of timbers were cut from *P. brutia*. The first set was of green wood, the second of seasoned wood, and the third of wet-seasoned wood. The temperature in the wood was measured with thermocouples located inside holes positioned 0.5 and 3 cm from the side facing the heat source.
2. Two sets of timbers were cut from a trunk of *C. sempervirens*. One was seasoned and the other was wet-seasoned. The temperature in the wood was measured with

thermocouples located inside holes positioned 0.5, 3.5, 6.5 and 9.5 cm inside the wood on the side facing the heat source.

The thermocouples, Type K, gauge 20, were connected to a model EXRTECH 42150 recorder and the temperatures were recorded every 5 to 10 min.

The thickness of the charred layer created on the side facing the heat source was recorded in parallel as a function of time.

4. Results

Series 1:

In the green *P. brutia* wood charring began when the average temperature reached 35 °C (Figure 4).

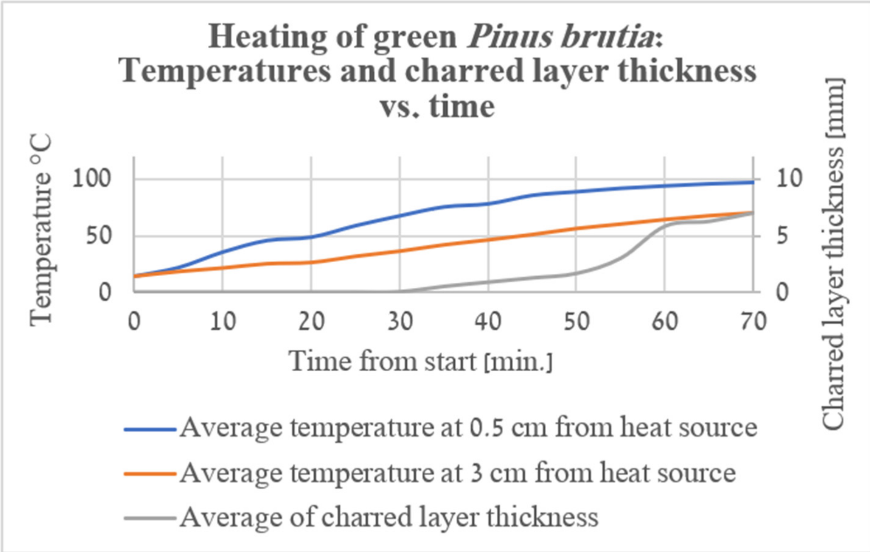

Figure 4. Heating of green *P. brutia*; temperature rise and thickness of charred layer as functions of time. The experiment was stopped due to ignition of the wood.

In the seasoned *P. brutia* wood charring began when the average temperature reached 60 °C (Figure 5).

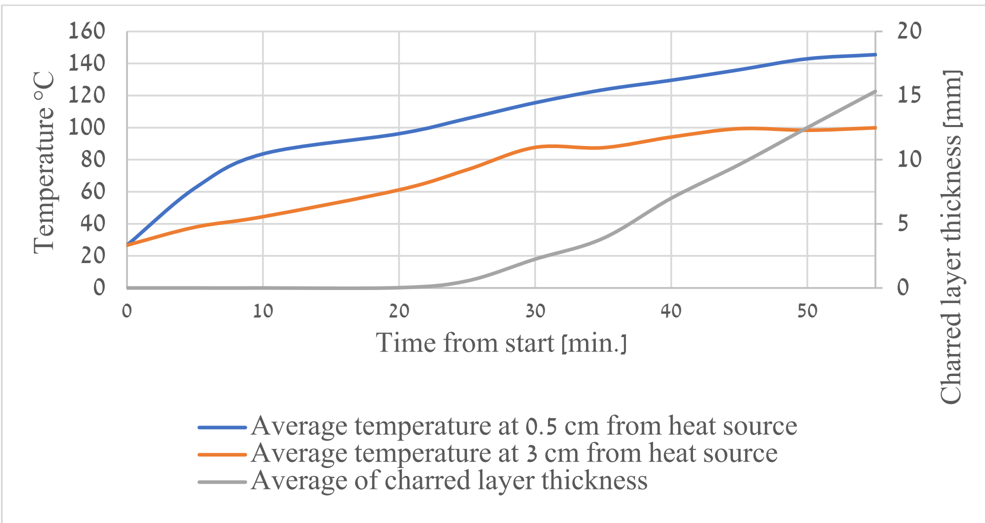

Figure 5. Heating of seasoned *P. brutia*; temperature rise and thickness of charred layer as functions of time.

In the wet-seasoned *P. brutia* wood charring began when the average temperature reached 45 °C (Figure 6).

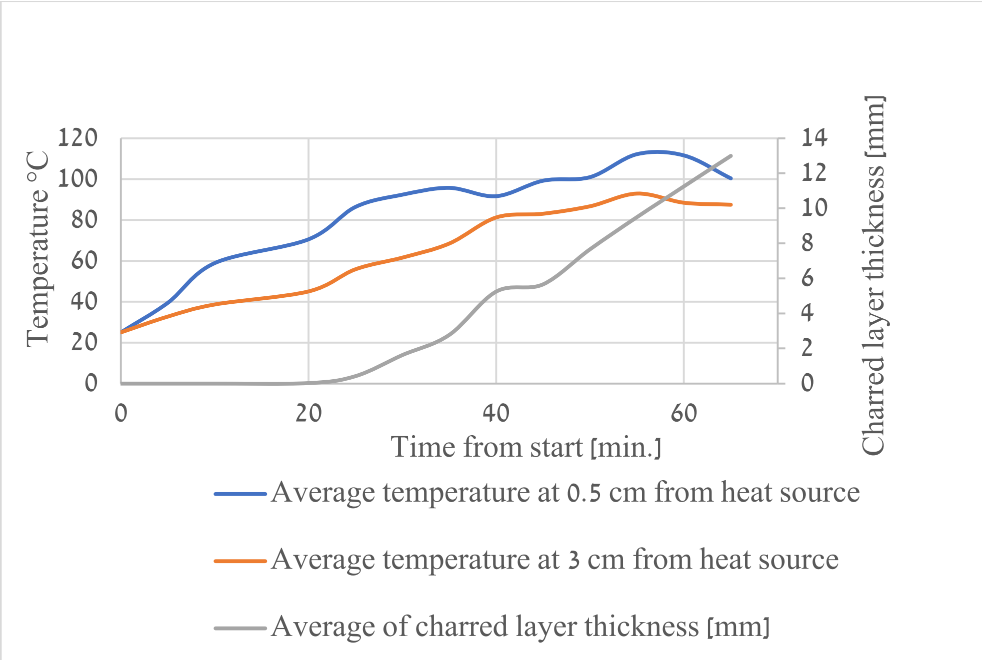

Figure 6. Heating of wet-seasoned *P. brutia* (fully saturated); temperature rise and thickness of charred layer as functions of time.

Series 2:

In the seasoned *C. sempervirens* wood charring began when the average temperature reached 40 °C (Figure 7).

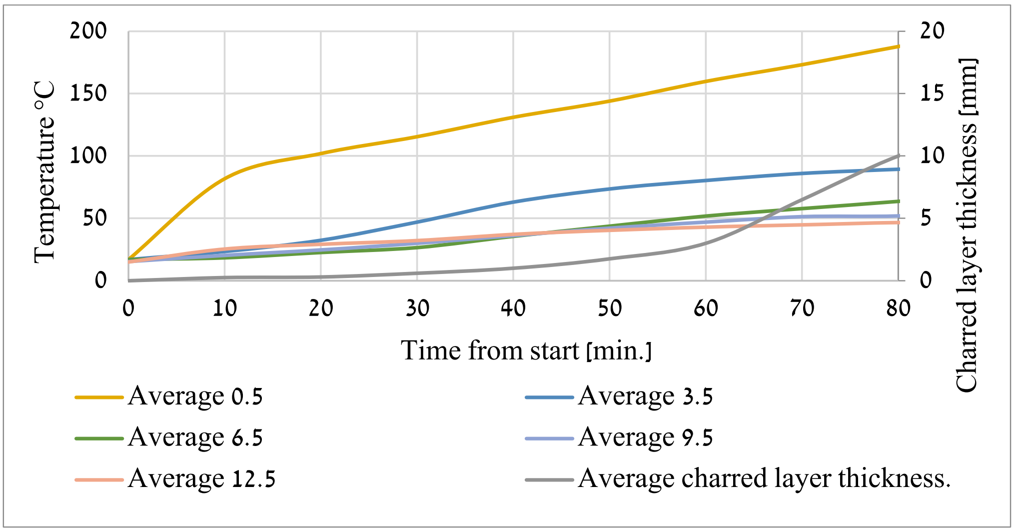

Figure 7. Heating of seasoned *C. sempervirens*; temperature rise and thickness of charred layer as functions of time.

In the wet-seasoned *C. sempervirens* wood charring began when the average temperature reached 23 °C (Figure 8).

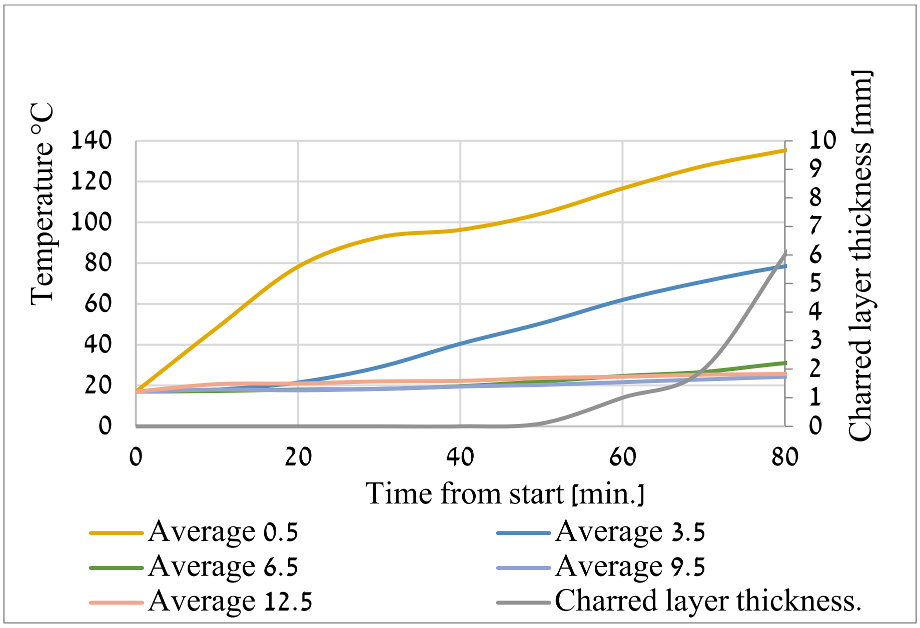

Figure 8. Heating of wet-seasoned *C. sempervirens*; temperature rise and thickness of charred layer as functions of time.

In all the experiments it was shown that charring began long before the temperature inside the wood reached the desired temperature, about 100 °C.

Note: The uneven increases in temperature and charred layer thickness in Figures 4–8 are due to averaging of the measured data.

The Special and Unique Case (So Far) of the Charred Stringer from the Ma'agan Mikhael B Wreck

The Ma'agan Mikhael B (MMB) wreck is a merchant ship about 20 m long, dated to the 7–9th century CE, found off the shore of Kibbutz Ma'agan Michael, some 35 km south of Haifa in Israel [28]. This ship has about 10 stringers that run along the ship, from stern to bow. One of them, HL-12, had a cross-section of a half log, and was originally 5 m long. It was bent along its length with its flat face of the cross-section facing the convex side of the bent beam and nailed to the frames of the ship (Cohen and Cvikel) [14]. A piece 2 m long was retrieved and examined in the laboratory. The unique feature of this stringer was the charring. In all cases of charred wood found in wrecks (Table 1), as well as evidence recorded in small shipyards in the Levant and the Far East from the 20th and 21st centuries, the charring appears on the concave side of the wood. In this stringer, the charring appears on the convex side (Figure 9).

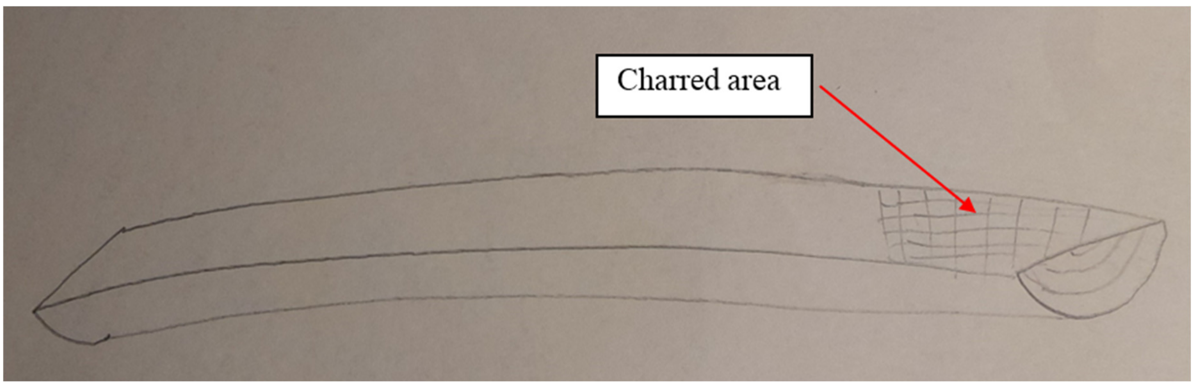

Figure 9. Sketch of stringer HL-12 indicating the location of the charring on the flat side.

This blackened area of the stringer was believed to be charring, but was also suspected to be a fungus culture grown on the wood due to its stay of about 14 centuries under water. Six samples were prepared and checked under a scanning electron microscope (Jeol EDS system), and the relative amount of carbon (C), expressed as percentage of the total (Atom count) elements in the sample. This procedure was based on the understanding that the relative amount of carbon in charred wood would be higher than that in the same non-charred wood, due to burning and evaporation of other elements by heat. Black samples taken from the wreck were also checked for the existence of fungus.

Samples:

Sample no. 1: Black piece 1 cm thick.

Sample no. 2: Black piece 0.1 cm thick.

Sample no. 3: Non-black piece 0.1 cm thick.

Sample no. 4: Charred piece 1 cm thick of *C. sempervirens*—positive control group.

Sample no. 5: Non-charred piece 0.1 cm thick of *C. sempervirens*—negative control group.

Sample no. 6: Non-charred piece 1 cm thick of *C. sempervirens*—negative control group.

The results showed that the concentration of carbon in the black material taken from the MMB wreck was similar to the charred positive control group (Figure 10). There was no evidence of fungus in the samples.

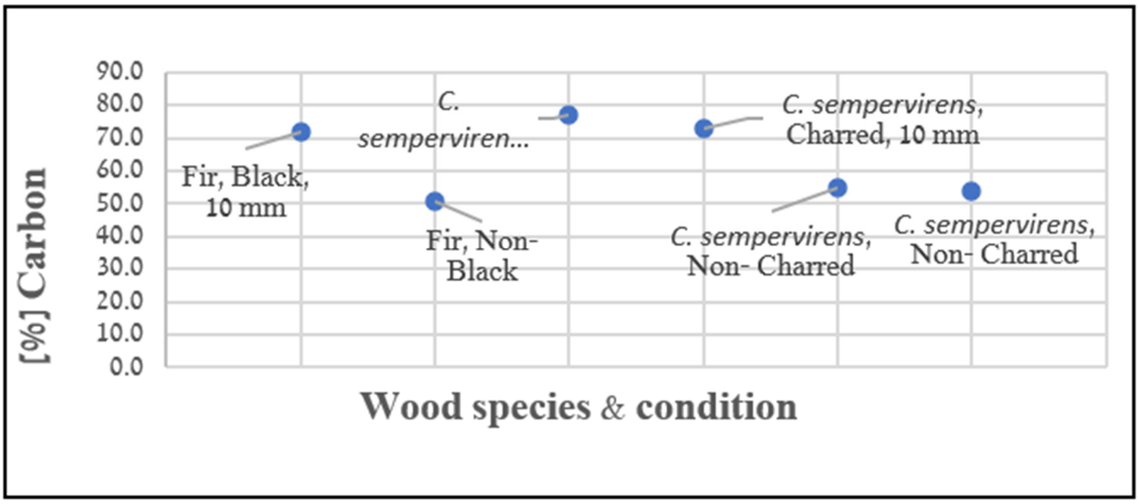

Figure 10. Carbon concentration in samples from the MMB stringer and reference groups, showing thickness of the samples.

Until now, we have had no knowledge whether the other stringers from the MMB wreck were charred, and if they were, on which face of the cross-section the charring appears. We offer two explanations of the 'wrong' location of charring on the HL-12 stringer from MMB wreck: The first is that it was a mistake of the shipwright. The second is based on the heat transfer in a beam with the same half-log cross-section as the HL-12 stringer. A typical cross-section of a half-log shows that the distance of the mass centre from the flat face is less than that from the round face (Figure 11) [29]. Understanding that the heat from the fire had to reach the mass centre of the half-log, the shipwright chose by intuition to locate the fire facing the flat side of the half-log cross-section.

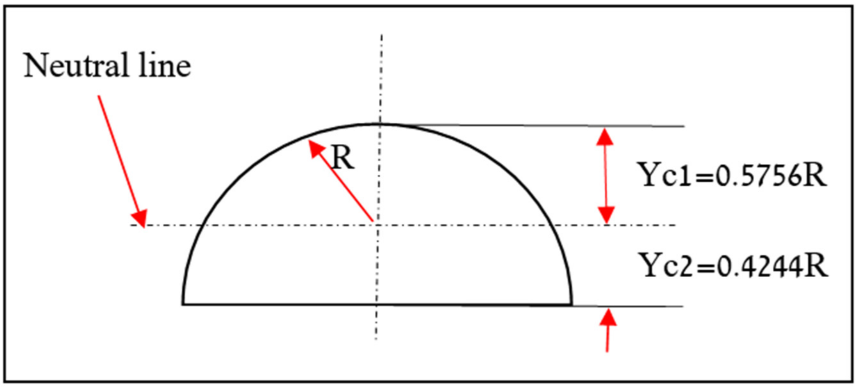

Figure 11. Distances of the concave and convex faces of a half-log to the neutral line [29].

5. Discussion

We are not sure that there was always charring when a timber was heated over open fire, especially in thin planks, where heat can penetrate the wood before it is charred. It might happen that the wood was charred during the heating, but the charred layer was cut away. We argue that the expression 'char-bending' is wrong, a more accurate term would be: 'preparing for bending by heating over open fire'.

A charred layer in a shipwreck can be interpreted in several ways:

- Char-bending
- Prevention or extermination of *T. navalis* infestation
- Accidental fire in the ship
- Thickness reduction.
- Proximity to heat source in the ship—the galley stove.

In this work we examined only the planks, wales or stringers from shipwrecks that have charred layers in the bent areas of the ship (Table 1). The location of the charring, only on the bent area, disproves the explanation of preventing or exterminating shipworm (*Teredo navalis*), which would be expected to be over the whole length of the plank, especially those immersed in bilge water, or on the outer side of the ship below the waterline. Actually, there is no evidence for charring of the planks on the side facing the water, where *T. navalis* attacks. The argument of the existence of *T. navalis* in the bilge water can be refuted by the fact that in most of the cases charring is close to the bow or stern, which are not the lowest parts of the ship, and where no bilge water is expected. These are also the areas in which the planks and stringers require sharper curvature. The argument which refutes the option of fire in the ship is based on the fact that the charring is only on the planks, not on nearby components, such as frames, futtocks, ceiling planks, stanchions, etc. The argument of thickness reduction (as in the technique practised in dug-out canoes) is refuted by the fact that it would have left no traces of charring, since the charred layer would be removed in the process. The galley fire should not have left any traces on the ships' wooden components, since the stove was usually surrounded by bricks.

The relation between the effects of heat and moisture content on the mechanical properties of wood was researched by [1,30], and can be summarized as follows. Three components of the wood were considered: cellulose, hemi-cellulose and lignin, and the dependence of each component on moisture was established [31]. The glass transition temperature (Tg) is defined as the temperature at which the wood components become pliable; i.e., below Tg the material is mostly brittle, and above it the material behaves mostly elasto-plastically. The relation between the Tg and the moisture content of the wood shows that the Tg goes down as the moisture content rises. In the lignin the Tg is a clear-cut point (Figure 12), while in the hemi-cellulose and the cellulose it is within a range of moisture content (Figures 13 and 14).

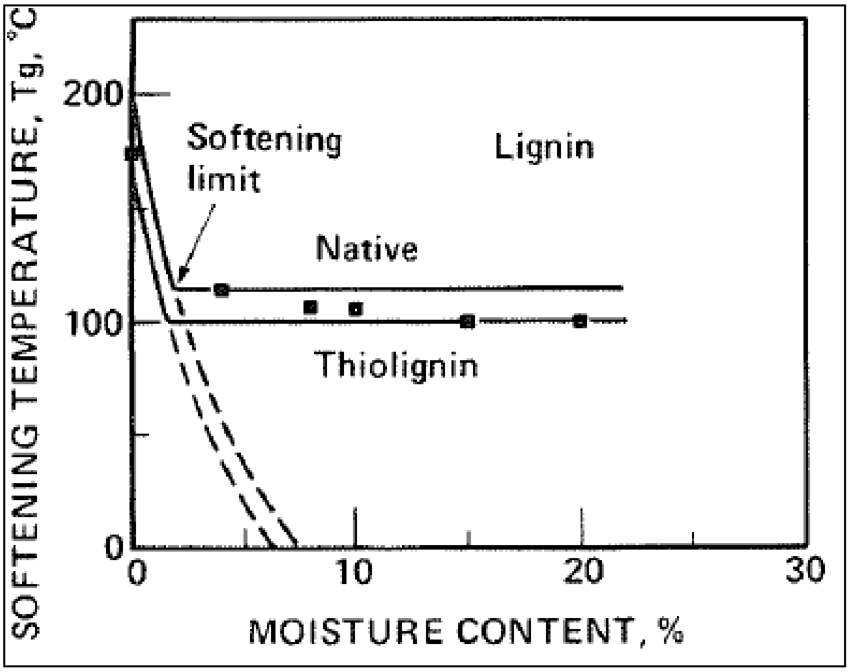

Figure 12. Tg as function of moisture content and temperature in lignin [32] (authors).

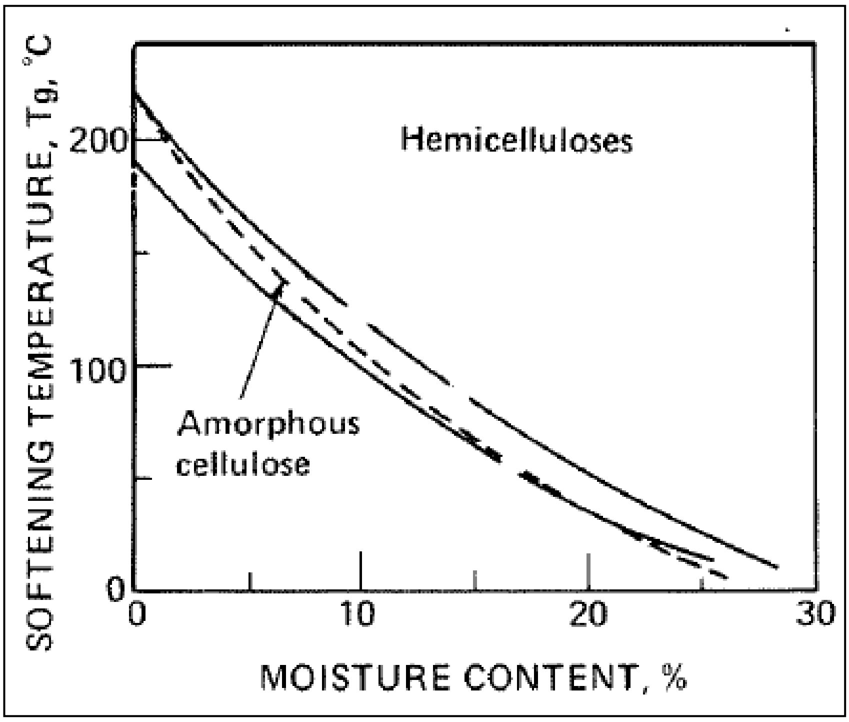

Figure 13. Tg as function of moisture content and temperature in hemi-cellulose [32] (authors).

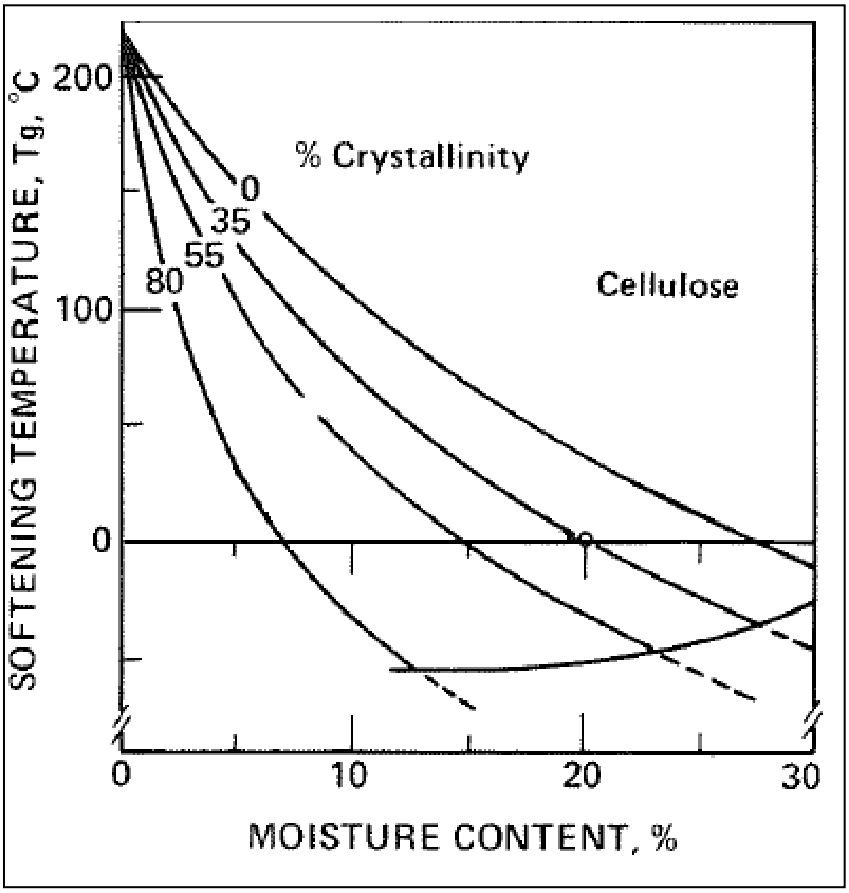

Figure 14. Tg as function of moisture content and temperature in cellulose [32] (authors).

The result of these dependencies shows that the wood's mechanical properties, MOE (Modulus of Elasticity) and MOR (Modulus of Rupture), decrease when the moisture content rises, i.e., the wood becomes softer and more elastic. Thus, the practice of preparing wood for bending would rely on having the moisture content as high as possible, which reduces the Tg, and the temperature as high as possible, to keep the wood temperature above the Tg. This principle is applied in steaming, boiling in water, and heating green or wet-seasoned wood over an open fire.

In a letter dated to 1663, the writer says that a quantity of wood, destined for shipbuilding, was actually seasoned (dried-out), since it was cut four years earlier. However, since wood for shipbuilding should be in the 'green' condition when heated over open fire for bending, this specific batch of wood was unacceptable [33].

The results of the experiments of heating wood over open fire showed that the side of the wood facing the heat source becomes charred long before the temperature inside the wood reaches the desired range of 80–100 °C, (Figures 4–8). Thus, it can be stated that charring is an undesired side effect of heating over open fire. This statement is backed by several sources, such as Richards' description of the process of bending planks over an open fire in Western Sarawak, Malaysia, where he emphasizes that the heating is done without charring the plank [25].

Desmond, in his description of various methods of preparing planks for bending, says that heating over open fire is good only for 'small scantling' timbers [34]. Our interpretation is that he meant that large beams would have been charred in the process.

Valerius Flaccus described the process of preparing wood for bending over open fire as: "being softened into pliancy over a slow flame. . . " [2] which can be interpreted as avoiding charring in the process of heating. Shipwrights would have preferred to avoid the charred layer, since charred wood loses its mechanical properties, and the wood that takes the load is thinner.

Why Does Charring Occur on the Concave Side of Planks, Wales, or Stringers?

In almost all cases of charred wood in shipwrecks which are related to bending, the charring is on the concave side of the wood. The following are possible explanations for this observation:

(a) Reducing the water content on this side, to prevent possible cracking during bending, due to excess water pressure [31].
(b) Charred layer on wood is cracked (Figure 15) and cannot carry any load. If the cracked area is subjected to tension, as on the convex side of a bent beam, such cracks could be sites of stress concentration, causing a crack that might extend into the wood under the charred layer
(c) The heat source evaporates the water on the side it faces, causing the plank to bend.

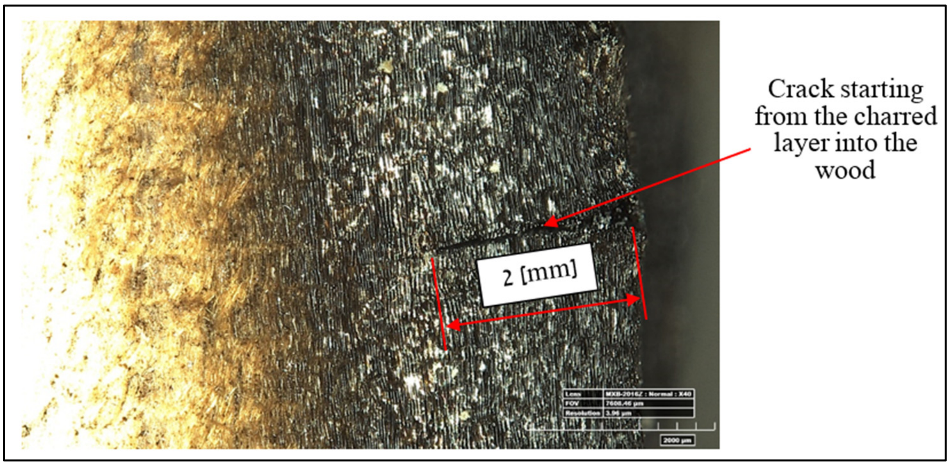

Figure 15. Charred *P. brutia* with crack (Photo: M. Cohen).

6. Conclusions

a. Of all the various methods for preparation of wooden planks for bending, the one involving soaking in water and heating over open fire was probably the most widely used by shipwrights. Wherever such a preparation was deemed necessary for ship building, the charring of the planks was an unwanted side effect only, because it almost always leads to a reduced thickness and thus reduced strength and also to the cracking of the planks and thus to damaging the ship. Ideally, the shipwrights would have preferred to avoid it altogether, although in some cases, such as bending relatively thick planks, charring is unavoidable. To prevent that from happening, another preparation method would have to be used.
b. When heating a plank over an open fire the side facing the heat source usually contracts (due to evaporation). Therefore, as a preparation for bending, it was almost always done by exposing to the fire the side that at the end of the process would be the concave face of the plank (generally—the inner side of the hull).

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Data Availability Statement: Data available on request due to restrictions e.g., privacy or ethical. The data presented in this study are available on request from the corresponding author.

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