

Article

Ancient Ship Structures: Ultimate Strength Analysis of Wooden Joints

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Abstract

This paper presents an analysis of the ultimate strength of wooden joints of the structures of ancient wooden ships. The aim is to contribute to the discussion about how joining technology and types of joints contributed to the transition from ‘shell-first’ to ‘frame-first’ construction, of which the latter is still traditional Mediterranean wooden shipbuilding technology. Historically, ship construction has consisted of two main structural types of elements: planking and stiffening. Therefore, two characteristic carvel planking joints and two longitudinal keel joints were selected for analysis. For planking, the joint details of the ship *Uluburun* (14th c. BC) and the ship *Kyrenia* (4th c. BC) were chosen, while two different types of scarf joints belonging to the ship *Jules-Verne 9* (6th c. BC) and the ship *Toulon 2* (1st c. AD) were selected. The capacity, i.e., the ultimate strength of the joint, is compared to the strength of the structure as if there was no joint. The analysis simulates the independent joint loading of each of the six numerical models in bending, tension, and compression until collapse. The results are presented as load-end-shortening curves, and the calculation was performed as a nonlinear FE analysis on solid elements using the LSDYNA explicit solver. Since wood is an anisotropic material, a large number of parameters are needed to describe the wood’s behaviour as realistically as possible. To determine all the necessary mechanical properties of two types of wood structural material, pine and oak, a physical experiment was used where results were compared with numerical calculations. This way, the material models were calibrated and used on the presented joints’ ultimate strength analysis.

Keywords: hull planking; keel; wooden joints; ultimate strength; nonlinear FEA



Academic Editor: Simone Mancini

Received: 19 June 2025

Revised: 15 July 2025

Accepted: 19 July 2025

Published: 22 July 2025

Citation: Zamarin, A.; Rudan, S.; Bolf, D.; Lucchini, A.; Rossi, I.R. Ancient Ship Structures: Ultimate Strength Analysis of Wooden Joints. *J. Mar. Sci. Eng.* **2025**, *13*, 1392. <https://doi.org/10.3390/jmse13081392>

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1. Introduction

Throughout history, maritime civilisations have relied on wooden shipbuilding techniques to construct vessels capable of enduring the harsh conditions of the open sea. The structural integrity of these ships was largely dependent on the strength and durability of their wooden joints, which played a crucial role in maintaining stability and seaworthiness. This vast body of empirical knowledge accumulated by shipbuilders over centuries—transmitted to us today in the form of fragmented archaeological remains or, in later periods, written sources—often resists interpretation through abstract principles alone, as we lack the specific knowledge once held by ancient shipbuilders. Contemporary

engineering methods now allow for a more precise analysis and quantification of the performance of these traditional construction techniques, shedding light on their mechanical properties and ultimate strength [1,2].

Wooden joints in ancient ship structures were designed to withstand various forces, including bending, shear, and compression. Techniques such as mortise-and-tenon joints, scarf joints, and wedged, doweled, or pegged connections were commonly employed to enhance the resilience of wooden hulls [3]. However, the absence of standardised principles in historical shipbuilding has led to significant variations in joint performance. That said, despite the lack of standardisation, the transmission of know-how—presumably occurring within workshop environments such as shipyards—and the adaptability of these techniques allowed for the consistent development of shipbuilding across antiquity. This required shipbuilders to possess not only a deep practical understanding of timber behaviour but also considerable empirical knowledge of hull shaping and woodworking techniques. Since analytical solutions are generally unavailable for most problems in structural mechanics with realistic geometry and loadings, recent studies utilising finite element analysis (FEA) have provided valuable insights into the stress distribution and failure mechanisms of these joints [4]. Although FEA is suitable for different levels of structural analysis, whether global or detailed [5], the complex shape of the joints and scarfs, material nonlinearity, geometrical uncertainty, and contact mechanisms make FEA too computationally expensive for the analysis of full-scale models. Also, from an historical and underwater archaeology point of view, the remnants of wooden ship structures cannot confirm with certainty that the remaining imagined part of the ship's structure is exactly as it was constructed long time ago. Therefore, it is reasonable to carry out experimental testing as well as numerical analysis on a local part of the structure. Today's structural design of large steel merchant and passenger ships is greatly concerned in the ultimate strength of the ship's hull. Moreover, this is prescribed by the rules of classification societies as standard calculation procedure. This calculation pertains to determining the maximum vertical bending moment due to still water and waves that the structure can withstand before failure. The designer thus gains insight into the hull's strength reserve from the moment the allowable stresses are exceeded to the point of failure. Additionally, this allows for the simulation of the collapse mode and provides insight into which structural element is the most critical. Therefore, the concept of ultimate strength is also interesting for wooden ships, and since the joints of a wooden structure have always been a weak point in the strength and rigidity of the structure, the aim of this paper was to compare the ultimate strength of several different joints from different historical periods. This could then further clarify the continuous dilemma of the transition of wooden ship building technology from shell-first to frame-first construction. Historically, ship construction has consisted of two main structural types of elements: planking and stiffening. Therefore, two characteristic types of carvel planking joints and two types of longitudinal keel joints were selected for analysis. For the outer planking joints, the locked mortise-and-tenon joints of the *Ulu burun* (14th c. BC) and the *Kyrenia* (4th c. BC) were selected. It is worth noting that, due to the few remaining fragments, it is impossible to make a complete reconstruction or replica of the ships, especially the *Ulu burun*. As for the keel joints, two keyed hook scarf joints were chosen for examination: the first from the vessel *Jules-Verne 9*, dated to the late 6th century BC; the second from the ship *Toulon 2*, a first-century AD vessel.

The mortise-and-tenon technique is a woodworking method used to join outer planks by carving two opposing recesses—mortises—into the thickness of the wood along the same edge seam. A wooden tenon is then inserted into both mortises to create the connection. For this study, the authors chose to analyse the change in a more advanced version of this joint: the locked mortise-and-tenon joints.

In the *Uluburun* shipwreck, a 15 m long Syro-Palestinian trading vessel dated to the late 14th century BC, one can find the earliest known archaeological example of mortise-and-tenon joints in Mediterranean ship construction locked with pegs. According to [6], this refinement of the basic technique may have originated in the Levantine region, from which the ship is believed to have come. The tenons from *Uluburun* are notably long when compared to those from other known wrecks. The mortises are densely arranged along the planks, with cuts extending nearly the full width of each board, leaving only 1.5 to 2 cm from the plank edge. The dimensions have been reconstructed based on a broken tenon found in the wreck, suggesting lengths of approximately 30 cm, widths of 6.2 cm, and a thickness close to 2 cm. The wooden pegs used to lock the joints in place have an average diameter of 2.2 cm [7] (Figure 1 top-right and bottom-right).

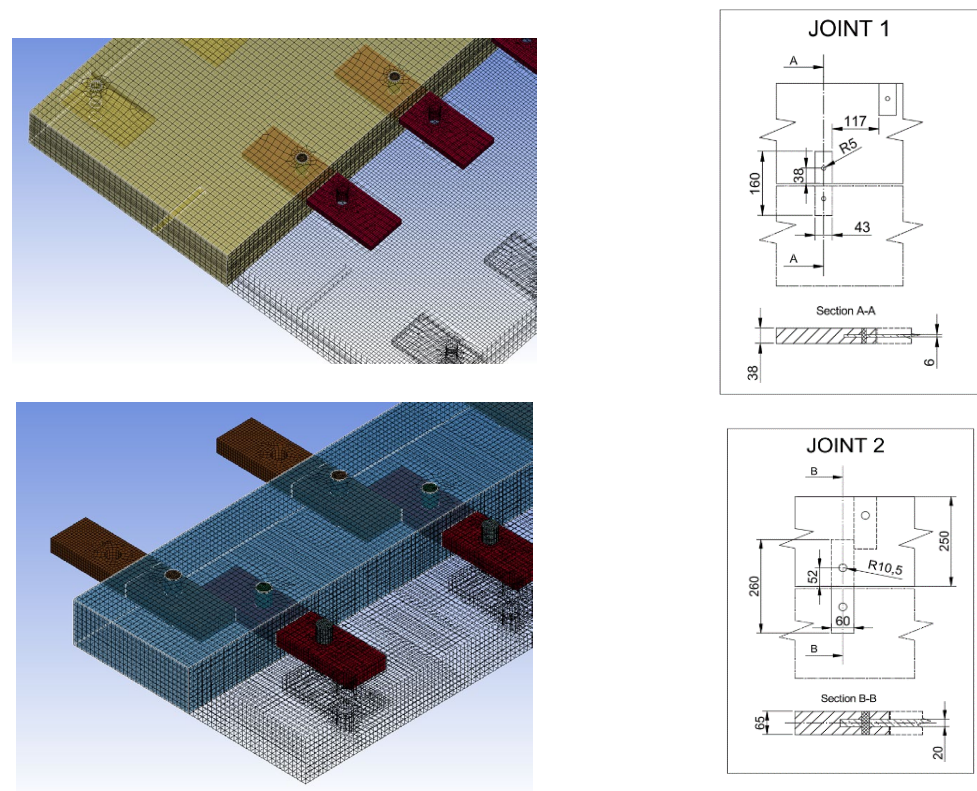


Figure 1. Plank joints: geometry models of *Kyrenia*—Joint 1 (top-left) and *Uluburun*—Joint 2 (bottom-left) and CAD topology drawings: *Kyrenia*—Joint 1 (top-right) and *Uluburun*—Joint 2 (bottom-right).

The *Kyrenia* shipwreck is one of the most important and noteworthy archaeological artefacts in Cyprus, a 14 m long merchant ship with 20 tons of deadweight. The construction of the ship has been attributed to the second half of the fourth century BC, while its sinking is estimated to have occurred in the first decades of the third century BC [8]. In the *Kyrenia* shipwreck, which is separated from *Uluburun* by a significant chronological gap, the mortises are 4.3 cm wide, cut to an average depth of 8 cm from the seam, and 0.6 cm thick. The tenons correspond to these dimensions in both width and thickness, with lengths ranging from 15 to 20 cm. Approximately 2 cm from the plank seams, the tenons feature symmetrical holes with a diameter of 0.6 cm, into which locking pegs were inserted. The average distance between the centres of successive joints is 11.7 cm, and the outer planking has an approximate thickness of 3.5 cm (Figure 1 top-left and bottom-left). As observed in the *Uluburun* wreck, the arrangement of joints likely followed an alternating pattern across adjacent seams; however, in the *Kyrenia*, the overall dimensions of both mortises and tenons appear significantly smaller [7].

Regarding the investigation of keyed hook scarf joints, the first vessel, *Jules-Verne 9*, is an Archaic Greek boat uncovered in 1993 during excavations at Place Jules-Verne in Marseille. Dated to the late 6th century BC, only a 5 m section of the hull, including one extremity, has been preserved. Reconstruction indicates a symmetrical design, suggesting that an identical keyed hook scarf with a vertical wedge was used at both the stem and sternpost (Figure 2 left). The presence of coral fragments embedded in the hull bottom supports the hypothesis that the boat was employed in coral fishing. Its estimated original dimensions are approximately 9.50 m in length and 1.88 m in beam [9].

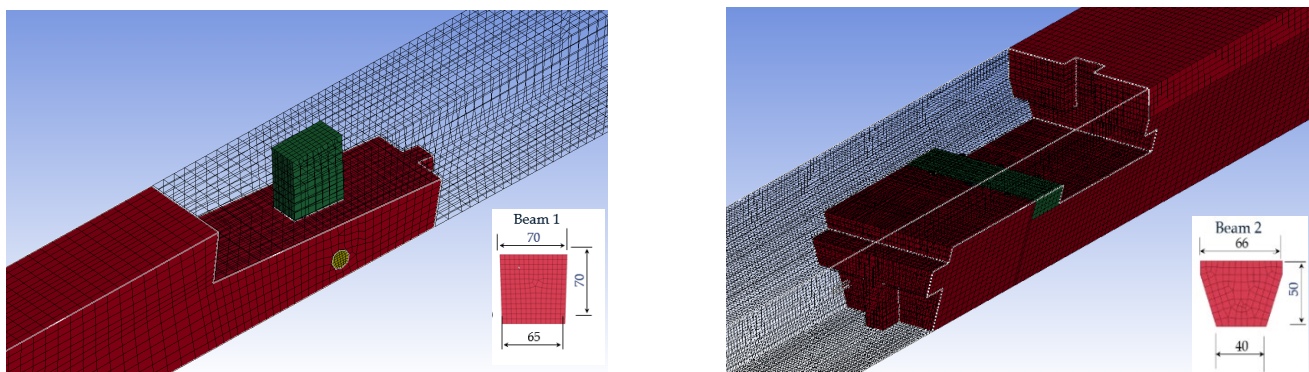


Figure 2. Keel joints: *Jules-Verne 9*—Scarf 1 (left) and *Toulon 2*—Scarf 2 (right).

The second vessel, *Toulon 2*, is a small Roman craft dated to the 1st century AD. Discovered during emergency excavations in Toulon in 1987, it is represented by a 6.3 m long preserved structure, which includes a keyed hook scarf joint connecting the keel to the stern, and has a reconstructed length of 6.41 m [10,11] (Figure 2 right).

Despite the chronological distance between them, both boats were selected for this research due to their comparable size and presumed use in coastal navigation within the same Mediterranean region. Moreover, the availability of high-quality documentation together with published analyses, makes these examples particularly well-suited for comparative evaluation under similar mechanical stress conditions.

The transition from shell-first to frame-based construction could be characterised as an evolutionary and experimental compromise between strength and stiffness. Both strength and stiffness could be achieved by closely spaced mortise-and-tenon joints. In the *Uluburun* shipwreck, a high degree of lateral and longitudinal stiffening was transferred to the hull planking by employing extraordinarily deep mortise-and-tenon joints, which resisted shear stresses exerted on the joints. The *Uluburun*'s widely spaced stiffening end joints acted as an internal additional stiffening system. Viking ships, at the other end of the strength–stiffness spectrum, were constructed to avoid stiffness. This allowed controlled hull displacements, especially twisting in response to torsional external loads.

Therefore, it would be challenging to explore the role of frames in other ships built by the shell-first technique, such as *Kyrenia*, whose frames are much more densely spaced compared to similar cross-sectional ship dimensions of its time. One of the conclusions from the literature [12,13] is that one ship construction method's inherent technological advantage over another was manifested purely based on strength levels. Due to a high level of structural flexibility in displacements achieved by the frame-based technique, it could be argued that this reduction in rigidity was an intentional technological decision intended to achieve a specific technological goal. So, strength was compromised in favour of flexibility, which could be interpreted as an inherent engineering advantage of the frame-based technique. Withstanding plastic deformation and failure is also an evident advantage of the shell-first method over the frame-first method. Regarding frame-first models, adding

frames consistently decreases von Mises stress levels while increasing rigidity. Therefore, the present paper aims to provide additional data on the ultimate strength of the joints themselves, including those of the planking and keel, as fundamental elements of the longitudinal strength of the ship, which could contribute to the argumentation of this discussion. Two distinct types of hull plank joints were selected for analysis. Although both employ similar assembly methodologies, they differ notably in the spatial arrangement of their mortise, wedge, and pegs. In Joint 1, the upper and lower mortise are vertically offset, separating the corresponding wedges (Figure 1 left). In contrast, Joint 2 features an adjacent mortise, enabling direct contact between the wedges of opposing planks. This configuration permits the wedges to engage across a narrow central segment of the peg body (Figure 1 right). Two keel scarf joint configurations were selected for comparative analysis in parallel with the plank joint investigation. Scarf 1 employs a simplified mortise–tenon joining approach, wherein the joint is secured solely by a locking peg engaged with the vertical wedge (Figure 2 left). In contrast, Scarf 2 incorporates a more structurally robust assembly mortise–tenon technique, utilising both wedge and pegs in conjunction with a specifically designed mortise–tenon geometry (Figure 2 right). This enhanced configuration is intended to improve joint strength and overall structural integrity by providing additional mechanical interlocking and load distribution capabilities. A summarised overview of the types and names of joints and the corresponding ‘shipwrecks’ is shown in Figure 3.

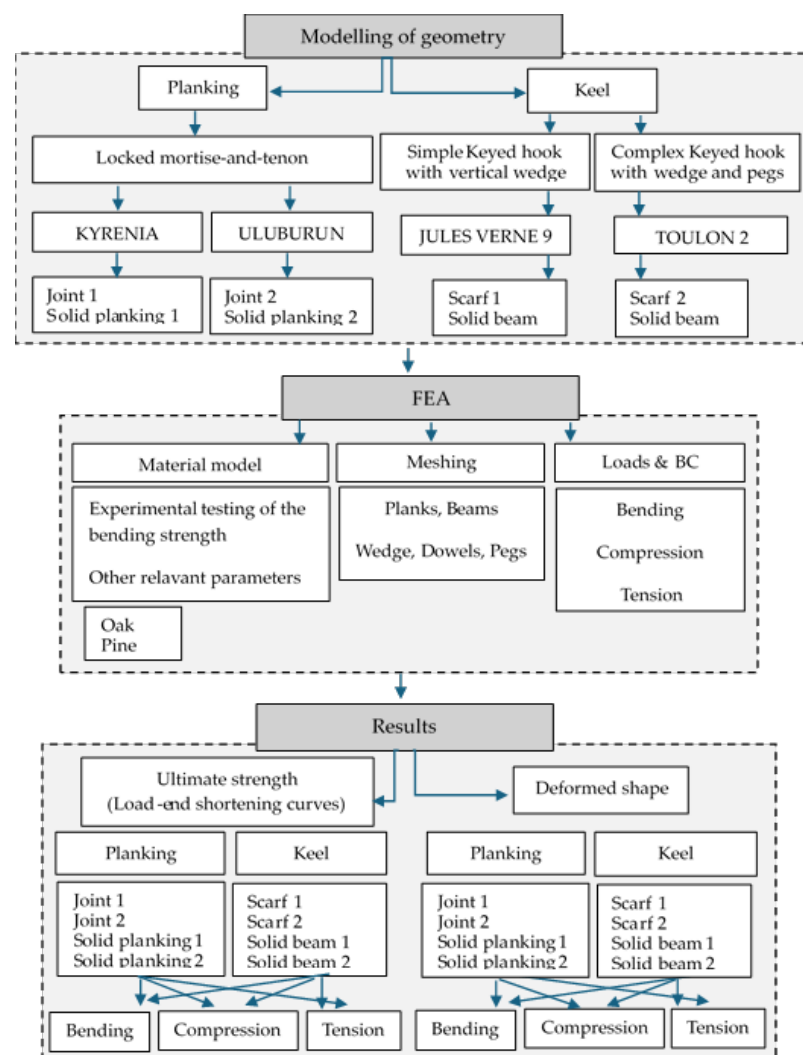


Figure 3. Methodology overview.

Although experimental tests along with numerical analyses of joints related to ship structures are almost nonexistent in the literature, the use of nonlinear FEA to determine the mechanical behaviour of joints with similar technology is common. The mechanical behaviour of the lapped scarf joint with oblique contact faces and wooden dowels is presented in [14]. Experimental tests and numerical models helped understand the load distribution in the joint and recognise the key parameters influencing the beam's performance. A comprehensive study [15] presented the behaviour of timber dovetail joints utilising both experimental and numerical investigations. A theoretical model for the dovetail joints was also developed with support from experimental and numerical results. Finally, a simplified calculation procedure was proposed to determine characteristic points of the moment–rotation relationship, from which a piecewise linear moment–rotation curve can be established for the design analysis of timber structures involving dovetail joints. The stiffness of scarf joints with dowels is presented by Fajman and Mica [16], and numerical studies on the tapered tenon joint were conducted by Koch et al. [17]. Nonlinear FEA of the mechanical performance of timber joint systems for the beam elements used in the construction of roofs, whenever they are bent at the same plane, was presented by del Coz Diaz et al. [18]. A complete three-dimensional numerical analysis was carried out assuming an orthotropic behaviour model of the material with a failure criterion based on the requirements of the Eurocode 5 rule. The nonlinearity is due to the contact between the joint's bolts and the wood's elements, as well as the large displacements in the system. Akbar and Aksa [19] have demonstrated the effectiveness of bolted connections in improving the structural integrity of traditional wooden ship joints.

2. Methodology

The scope of the work, presented as the methodology, consists of three parts: geometry modelling, creation of the numerical model and FEA, and finally, the presentation of results. For a clearer understanding, it is illustrated in Figure 3.

2.1. Structural Modelling and Geometry of Joints

The geometrical models of the plank joints and keel assemblies were developed using 3DEXPERIENCE R2024x CAD software, with necessary simplifications applied to facilitate efficient and accurate meshing. Special attention was given to modelling features requiring inter-plank and inter-joint gaps, which were explicitly incorporated into the geometry to reflect the intended physical assembly conditions.

To prepare the models for finite element analysis, the geometries were adapted for meshing in LS-DYNA PrePost v4.10.5, employing 8-node solid elements. In accordance with the best practices for solid meshing, certain geometric features, such as wedge-like structures, small radii, and acute angles, were simplified or modified to ensure mesh quality and stability. Complex regions that could not be adequately simplified through CAD adjustments were instead meshed manually within LS-DYNA using the software's mesh generation tools. These regions were not explicitly modelled but rather constructed directly within the meshing environment.

In addition to the joints themselves, boundary elements such as indenters/punchers and supports were meshed directly in LS-DYNA, taking into consideration mesh size regarding master–slave contact-type requirements. The finalised mesh configurations for planking Joint 1, prepared for four-point bending and tension–compression analysis, are illustrated in Figure 4.

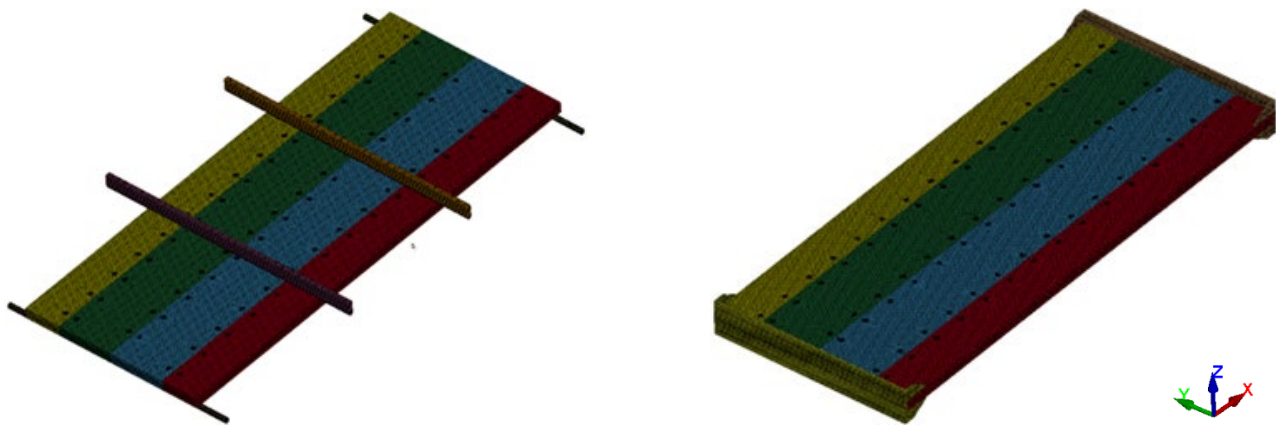


Figure 4. Joint 1—configuration/meshing for 4 pt bending (left) and tension–compression analysis (right).

2.2. Experimental Testing of Bending Strength

Since a full-scale experiment or one conducted on a replica, or even on a part of the structure, is highly challenging both in terms of time and financial resources, this research utilises experimental data [20] to determine the mechanical properties of wood—oak and pine—as the primary materials of the structure. The obtained results have been validated through numerical simulation and serve as fundamental input parameters in creating a material model for all numerical analyses of the planking and keel joints. In both cases, the planking of Joint 1 and Joint 2 are made of pine, while the wedges end pegs are made of oak. In the keel scarf joints, all parts of both scarf joints are made of oak. It is important to note that there may be slight variations in the mechanical properties of the oak and pine used in the experiment compared to those of the original structure due to different oak and pine species. Although specific studies on wood were conducted for both vessels, revealing the use of deciduous oak (*Quercus* sp., sect. *Quercus*) for the keel of *Jules-Verne* 9 [21], *Toulon* 2 exhibited a greater variety of wood types. In *Toulon* 2, the keel was made of *Quercus ilex* L., the stern transitional timber of *Ulmus* sp. and the sternpost of *Alnus* sp. [22]. However, since the paper aimed to assess the structural performance related to the shape of the joint alone—without introducing variables associated with the mechanical properties of different wood types—all elements were assigned the material properties of deciduous oak and general pine. This standardised approach made it possible to isolate and analyse the mechanical behaviour of the joint configuration itself, rather than the influence of varying wood densities. This research has disregarded these differences since no experiment was found or conducted on a replica of the actual joints, implying that the differences are not significant.

The bending strength test was conducted following the ISO 13061-3 [23] standard. The specimen dimensions were $b = 20$ mm, $h = 20$ mm. The support span was fixed at $L = 300$ mm. The specimens were cut to the specified dimensions with a tolerance of ± 1 mm. The moisture content of the specimens was measured at 12%. A minimum of 5 specimens was required for each type of wood. The three-point bending test method was selected. As output data, the dependence of the force applied to the specimen on the displacement of the loaded part of the specimen was recorded. The testing speed was 7 mm/min. The device used for testing was a Zwick model 22973, with a measuring range of 0 to 10 kN, as shown in Figure 5. The results of the calculated mechanical properties for pine and oak according to ISO standards and based on experimental data are presented in Table 1.

The verification of the obtained values of the mechanical properties for pine and oak was conducted through calibration of the numerical model by comparing the obtained deflections, as shown in Table 2. The numerical simulation was conducted using the LS-

DYNA software package, followed by mesh sensitivity analysis which was performed during the execution of the three-point bending test simulation, where coarse mesh consisted of 31,504 finite elements while fine mesh consisted of 69,632 finite elements, yielding somewhat higher maximum deflection in the case of fine mesh, although not in every case. The simulations continued, and validation refers to the results obtained with fine mesh models.

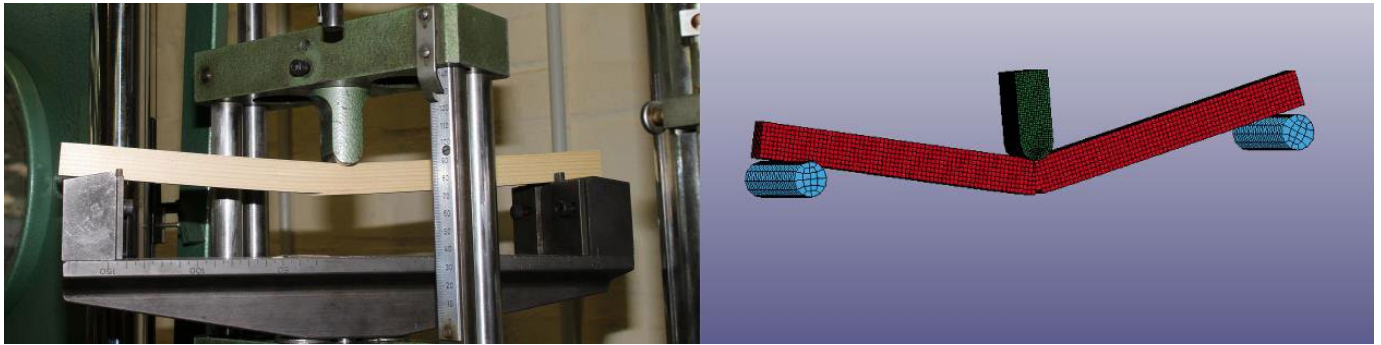


Figure 5. Deflection on the test device and in the numerical simulation [20].

Table 1. Results of the calculated mechanical properties for pine and oak based on experimental data.

Item	Title	Variable	Type of Wood		Units
			Pine	Oak	
	Density	ρ	673	770	kg/m ³
Moduli	Parallel Normal Modulus	E_L	11.35	11.138	GPa
	Perpendicular Normal Modulus	E_T	246.8	801.9	GPa
	Parallel Shear Modulus	G_{LT}	715.2	902.2	GPa
	Perpendicular Shear Modulus	G_{TR}	87.5	211.6	GPa
	Parallel Major Poisson's Ratio	ν_{LT}	0.157	0.448	
Strengths	Parallel Tensile Strength	X_T	68.3	118.4	MPa
	Parallel Compressive Strength	X_C	19.67	59.3	MPa
	Parallel Shear Strength	$S_{ }$	7.27	13.8	MPa
	Perpendicular Compressive Strength	Y_C	3.80	8.2	MPa
	Perpendicular Tensile Strength	Y_T	1.64	5.7	MPa
	Perpendicular Shear Strength	$S_{\perp}$	10.20	12.3	MPa

Table 2. Comparison of displacements obtained from the experiment and by numerical calculation.

Type of Wood	Deflection, mm	
	Experiment	Numerical Simulation
Pine	6.78	7.0
Oak	9.2	9.0

2.3. Numerical Model

2.3.1. Loads and Boundary Condition

When selecting loads and boundary conditions, the requirements of the standard tests for experimental determination of the mechanical properties of wood panels in bending, ASTM [24], and solid wood girders, ASTM [25], were taken into account. The load was defined by the speed and direction of the indenter/puncher displacement, with the minimum test time being 5 min for compression and tension and 6 min for bending. The specified parameters directly affected the calculation time. The boundary conditions for both types

of joints and scarfs were as follows: a free end on the side of the displacement/load application for compression and tension and a clamped support on the opposite side. In the case of bending, the supports were freely supported at the span ends, and the displacement/load was applied in the vertical direction downwards over two connected punchers. The complexity of the model arises from the need of the fine-tuning of the contact definition, use of nontrivial material model (wood), and a large number of finite elements. As a result, the calculations had to be performed on a supercomputer. The time step in an LS-Dyna explicit calculation is a function of the speed of sound in the selected material and the size of the finite elements. To make the analysis efficient, finite elements were sized as small as required to correctly model the smallest structural details, and the time step was not altered, i.e., the LS-Dyna default time step was used to secure the stability of the calculation. The authors believe that the model was too complex (and expensive for calculations) to be used also for the mesh size sensitivity study, and it was built on the basis of the authors' significant experience in performing complex NFEM analyses. See Table 3 for planking joint simulations and Table 4 for keel joints for all necessary numerical analysis data.

Table 3. Numerical analysis data for planking joints.

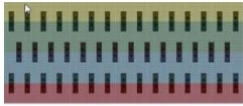
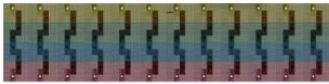
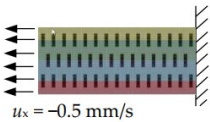
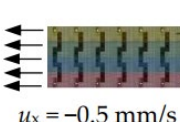
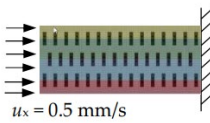
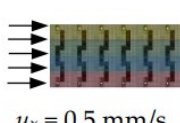
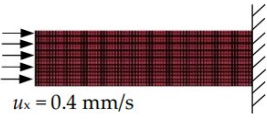
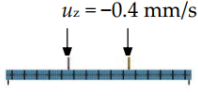
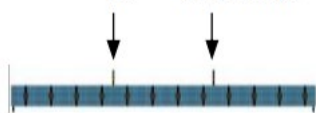
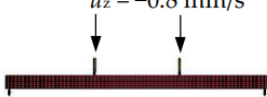
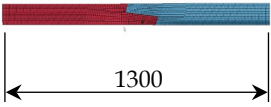
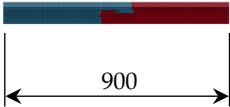
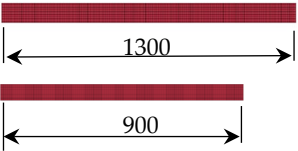
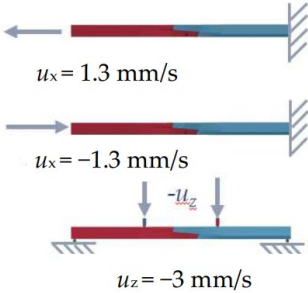
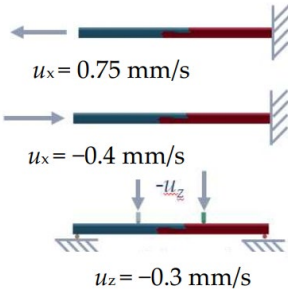
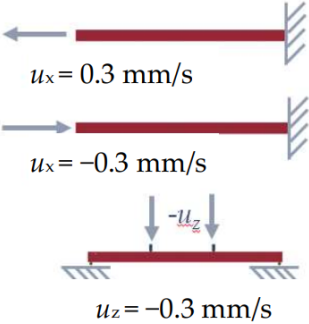
Structural Element	Planking		
Type of planking joint/ Planking thickness, mm	Joint 1— <i>Kyrenia</i> 38 mm	Joint 2— <i>Uluburun</i> 65 mm	Solid planking (no joint) Planking 1—38 mm; Planking 2—65 mm
Model length and breadth, mm	 1825 × 640	 3120 × 800	 Planking 1—1825 × 640  Planking 2—3120 × 800
Loads and boundary conditions: tension	  $u_x = -0.5 \text{ mm/s}$	 $u_x = -0.5 \text{ mm/s}$	 $u_x = -0.4 \text{ mm/s}$
compression	  $u_x = 0.5 \text{ mm/s}$	 $u_x = 0.5 \text{ mm/s}$	 $u_x = 0.4 \text{ mm/s}$
bending	  $u_z = -0.4 \text{ mm/s}$	 $u_z = -0.4 \text{ mm/s}$	 $u_z = -0.8 \text{ mm/s}$
Material/ Material model	PINE: planking OAK: wedges, dowels, pegs LS-Dyna Mat-143, transversally isotropic with erosion		
Mesh size, mm	$5 \times 5 \times 5$		
Beams	$2 \times 2 \times 2$		
Wedges, Dowels and Pegs			
Finite element type	Solid, 8-point hexahedron intended for elements with poor aspect ratios, efficient formulation		
Solver	Dynamic, explicit, nonlinear		

Table 4. Numerical analysis data for keel scarfs.

Structural Element	Keel		
Type of scarf joint/ Beam cross-section	Scarf 1—Keyed hook with vertical wedge Beam 1	Scarf 2—Keyed hook Beam 2	Solid beam (no joint) Beam 1 and Beam 2
Model length, mm			
Loads and boundary conditions (top to bottom: tension, compression, and bending)			
Material/ Material model	OAK LS-Dyna Mat-143, transversally isotropic with erosion		
Mesh size, mm Beams Wedges, Dowels, and Pegs	$5 \times 5 \times 5$ $2 \times 2 \times 2$		
Finite element type	Solid, 8-point hexahedron intended for elements with poor aspect ratios, efficient formulation		
Solver	Dynamic, explicit, nonlinear		

2.3.2. Material Model

The wood model consists of several formulations merged to form a comprehensive model: elastic constitutive equations, failure criteria, plastic flow, hardening, post-peak softening, and strain-rate enhancement. Therefore, numerous parameters are necessary for the realistic application of material model 143 within the LS-DYNA [26] software package. The part concerning the basic mechanical properties is presented in Table 1, while the remaining parameters related to failure criteria, hardening, and post-peak softening are shown in Table 5. The influence of wood grade is significant, as it is well-known that the characteristics of clear wood (without knots) differ from those of actual wood. Therefore, high-grade DS-65 wood was used in the analysis, with reduction factors ranging from 0.80 to 0.93 between clear wood and low-grade wood. The DS-65 wood grade, also known as Select Structural, is one of the highest grades of timber. It is characterised by its high quality and limited characteristics that affect strength or stiffness—FHA Report (USA Federal Highway Administration Report) [27]. This grade is typically used in applications where high strength, stiffness, and good appearance are desired. The effects of moisture, temperature, and strain rate were disregarded, meaning that the default values of the material model were applied. The parameter selection was carried out carefully, starting with the parameters already existing in the literature for similar materials. Three-point bending tests were performed for two reasons: to determine the modulus of elasticity in bending and to validate the numerical simulation of the three-point bending test. The combination of the evaluated parameters (density, modulus of elasticity in bending) and

existing parameters determined a final set of parameters. Then the numerical experiments were performed and validated by comparing the maximum deflection before the failure for different types of wood, as presented in Table 2. It should be noted that the material model is nonlinear, includes the contact algorithm, and the simulation ends with failure. As the validation was successful, see Table 2, it may be concluded that the complexity inherent in such a type of simulation supports the choice of the material model and its parameters, particularly since two rather different types of wood were considered and analysed, using two different sets of material model parameters. The material model for wood used within these analyses was developed in the frame of the USA FHA Report [27] and represents transversally isotropic wood material with erosion. Transversely isotropic means that the properties in the tangential and radial directions are modelled the same, i.e., $E_{22} = E_{33}$, $G_{12} = G_{13}$, and $\nu_{12} = \nu_{13}$. This reduces the number of independent elastic constants to five, E_{11} , E_{22} , ν_{12} , G_{12} , and G_{23} . The Poisson's ratio in the isotropic plane, ν_{23} , is not an independent quantity. It is calculated from the isotropic relation: $\nu = (E - 2G)/2G$ where $E = E_{22} = E_{33}$ and $G = G_{23}$.

Table 5. Wood material model parameters for pine and oak.

Item	Title	Variable	Type of Wood		Units
			Oak	Pine	
Hardening	Parallel Hardening Initiation	$N_{ }$	0.2	0.2	
	Parallel Hardening Rate	$c_{ }$	600	600	ms
	Perpendicular Hardening Initiation	$N_{\perp}$	0.2	0.2	
	Perpendicular Hardening Rate	$c_{\perp}$	300	200	ms
Softening	Parallel Mode I Fracture Energy	$GfI_{ }$	0.0225	0.03413	MPa m
	Parallel Mode II Fracture Energy	$GfII_{ }$	0.0440	0.07061	MPa m
	Parallel Softening	B	20	20	
	Parallel Maximum Damage	$dmax_{ }$	0.99	0.99	
	Perpendicular Mode I Fracture Energy	$GfI_{\perp}$	0.000441	0.000401	MPa m
	Perpendicular Mode II Fracture Energy	$GfII_{\perp}$	0.000880	0.000830	MPa m
	Perpendicular Softening	D	20	20	
	Perpendicular Maximum Damage	$dmax_{\perp}$	0.99	0.999	

The wood model failure criterion is formulated from six ultimate strength measurements obtained from uniaxial and pure-shear tests on wood specimens:

- X_T - Tensile strength parallel to the grain
- X_C - Compressive strength parallel to the grain
- Y_T - Tensile strength perpendicular to the grain
- Y_C - Compressive strength perpendicular to the grain
- $S_{||}$ - Shear strength parallel to the grain
- $S_{\perp}$ - Shear strength perpendicular to the grain

For the parallel modes, the yield criterion comprises two terms involving two of the five stress invariants of a transversely isotropic material. These invariants are $I_1 = \sigma_{11}$ and $I_4 = \sigma_{12}^2 + \sigma_{13}^2$. This criterion predicts that the normal and shear stresses are mutually weakening, i.e., the presence of shear stress reduces the strength below that measured in uniaxial stress tests. Yielding occurs when $f_{||} \geq 0$, where

$$f_{||} = \frac{\sigma_{11}^2}{X^2} + \frac{(\sigma_{12}^2 + \sigma_{13}^2)}{S_{||}^2} - 1, \quad X = \begin{cases} X_t & \text{for } \sigma_{11} > 0 \\ X_c & \text{for } \sigma_{11} < 0 \end{cases} \quad (1)$$

For the perpendicular modes, the yield criterion comprises two terms involving two of the five stress invariants of a transversely isotropic material. These invariants are $I_2 = \sigma_{22} + \sigma_{33}$ and $I_3 = \sigma_{32}^2 - \sigma_{22}\sigma_{33}$. Yielding occurs when $f_{\perp} \geq 0$, where

$$f_{\perp} = \frac{(\sigma_{22} + \sigma_{33})^2}{Y^2} + \frac{(\sigma_{23}^2 + \sigma_{22}\sigma_{33})}{S_{\perp}^2} - 1, \quad Y = \begin{cases} Y_t & \text{for } \sigma_{22} + \sigma_{33} > 0 \\ Y_c & \text{for } \sigma_{22} + \sigma_{33} < 0 \end{cases} \quad (2)$$

Element erosion occurs when an element fails in the parallel mode, and the parallel damage parameter exceeds $d_{\parallel} = 0.99$. Elements do not automatically erode when an element fails in the perpendicular mode. Separate damage formulations are modelled for the parallel and perpendicular modes. If failure occurs in the parallel modes, all six stress components are degraded uniformly. This is because parallel failure is catastrophic and will render wood useless. If failure occurs in the perpendicular modes, then only the perpendicular stress components are degraded. This is because perpendicular failure is not catastrophic: the wood is expected to continue to carry the load in a parallel direction. Based on these assumptions, the following degradation model was implemented:

$$\begin{aligned} d_m &= \max(d(\tau_{\parallel}), d(\tau_{\perp})) \\ d_{\parallel} &= d(\tau_{\parallel}) \\ \sigma_{11} &= (1 - d_{\parallel})\bar{\sigma}_{11} \\ \sigma_{22} &= (1 - d_m)\bar{\sigma}_{22} \\ \sigma_{33} &= (1 - d_m)\bar{\sigma}_{33} \\ \sigma_{12} &= (1 - d_{\parallel})\bar{\sigma}_{12} \\ \sigma_{13} &= (1 - d_{\parallel})\bar{\sigma}_{13} \\ \sigma_{23} &= (1 - d_m)\bar{\sigma}_{23} \end{aligned} \quad (3)$$

Here, each scalar damage parameter, d , transforms the stress tensor associated with the undamaged state, $\bar{\sigma}_{ij}$, into the stress tensor associated with the damaged state, σ_{ij} . The stress tensor $\bar{\sigma}_{ij}$ is calculated by the plasticity algorithm prior to the application of the damage model. Each damage parameter ranges from zero for no damage and approaches unity for maximum damage. Thus, $1 - d$ is a reduction factor associated with the amount of damage. Each damage parameter evolves as a function of a strain energy-type term. Mesh size dependency is regulated via a length scale based on the element size (cube root of volume). Damage-based softening is brittle in tension, less brittle in shear, and ductile (no softening) in compression.

Wood exhibits pre-peak nonlinearity in compression parallel and perpendicular to the grain. Separate translating yield surface formulations are modelled for the parallel and perpendicular modes, which simulate gradual changes in moduli. Each initial yield surface hardens until it coincides with the ultimate yield surface. The initial location of the yield surface determines the onset of plasticity. The rate of translation determines the extent of the nonlinearity. For each mode (parallel and perpendicular), two parameters are needed: the initial yield surface location in uniaxial compression, N , and the rate of translation, c . For pre-peak nonlinearity to initiate at 80% of the peak strength, input will be $N = 0.2$ so that $1 - N = 0.8$. If material hardens rapidly, a large value of c is input, like $c = 1$ msec. Otherwise, when the material hardens gradually, a small value of c is input, like $c = 0.2$ msec. Detailed elaboration on additional parameters and integrated procedures such as plasticity consistency condition, elastoplastic stress updates, post-peak hardening G_{hard} , regulating mesh-size dependency, and default damage parameters (four for the parallel modes (B , G_{fI} , G_{fII} , and d_{max}) and four for the perpendicular modes (D , $G_{\text{fI}\perp}$, $G_{\text{fII}\perp}$, and $d_{\text{max}\perp}$)) can be found in the USA Federal Highway Administration Report [27]. The authors made a systematic effort not to perform a number of complex and expensive

experiments for the exact material model parameter determination but instead focused on obtaining a usable set of parameters, enabling successful validation of the numerical simulation. Therefore, even if the material model properties are not exact for the type of wood tested, validation of the numerical analysis assured the authors that they are good enough for performing the comparative analysis of a complex study of ancient joints. While obtaining parameters that are close to the ideal ones would certainly be beneficial, the results of a complex comparative study of the two joint types clearly show the differences between the two, with the identical sets of parameters used, which is a scope of the paper.

3. Results and Discussion

The analysis results are presented as two sets of load-end shortening curves: one set for two types of planking joints and the other for two types of keel scarf joints. A comparison is made for solid planking against Joints 1 and 2 as well as the joints themselves, while for keel joints, a comparison is made for solid beams against Scarf joints 1 and 2 and between the scarfs themselves. These curves illustrate the relationship between applied force and deformation throughout the entire deformation range, from initial elasticity to ultimate failure. This way, the analysis is presented as global, which means that a detailed inspection/analysis of the parts of joints such as wedges, pegs, and pins is left out for additional local analysis with eventual geometry topology optimisation. After completing the numerical analysis, each model was checked for the accuracy of deformations in shape and intensity throughout the load duration. Also, results in the form of ultimate strength as load-end shortening curves are separated for tension–compression and bending conditions. The first step within the result control process, prior to the construction of load-end shortening curves, was a visual check and numerical check of deformation shape as well as numerical stress limits. LS-DYNA's explicit simulation allows for precise deformation and stress control. It can record the results in each user-defined time instance for each joint type, location, and type of analysis shown in Table 1. Due to the large number of combinations (two times two joints, two solid planking types, and three stress states), only the deformation shape on bending (Figure 6 top) and compression (Figure 6 bottom) and tension stresses in the x-direction for Joint 1 (*Kyrenia*) (Figure 7) are presented.

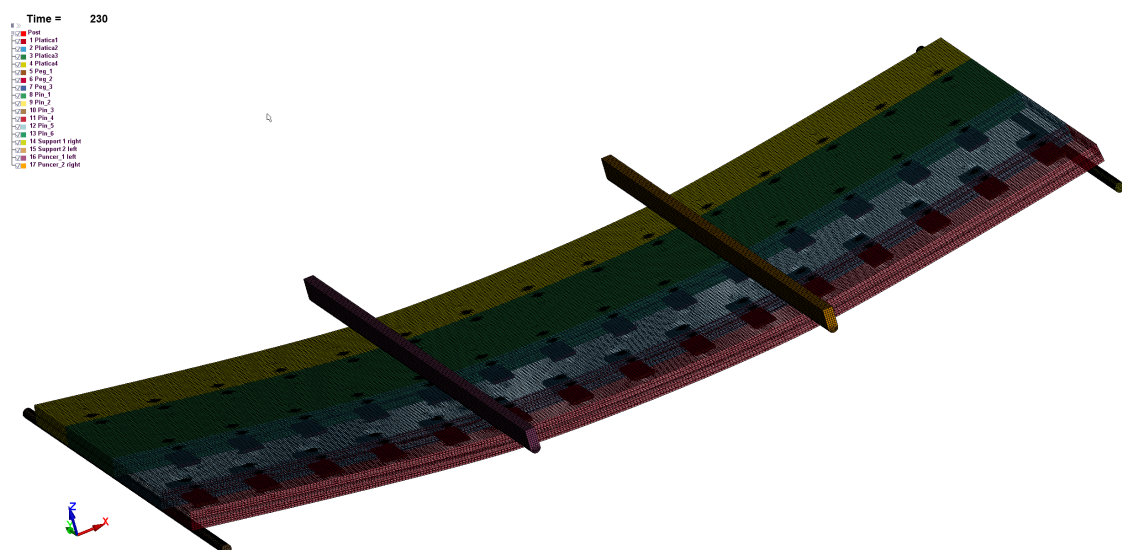




Figure 6. Deformed models at the time instance of maximal load for bending (top) and compression (bottom)—Joint 1 (Kyrenia).

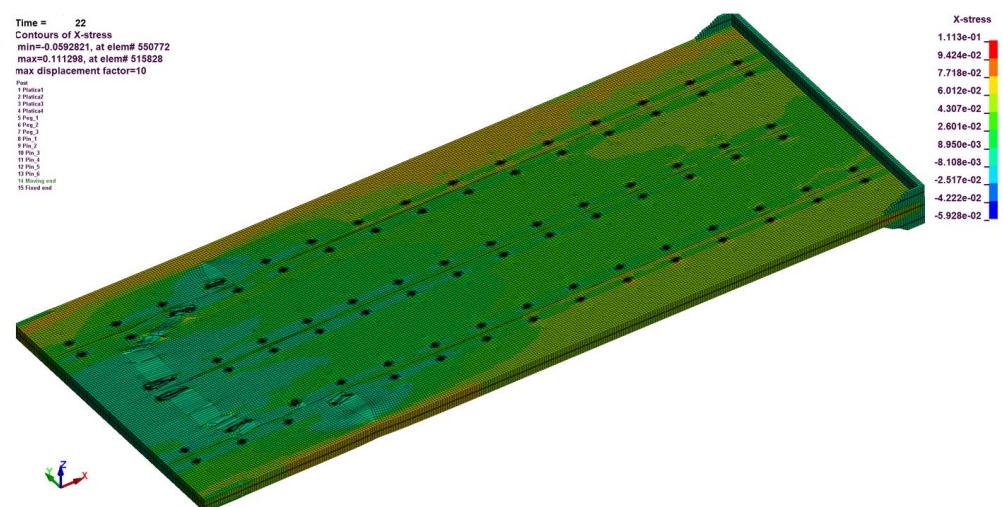


Figure 7. X—stress distribution in tension—Joint 1 (Kyrenia).

3.1. Planking Joints

Initial numerical analysis was performed over solid wooden planking with no joints and a thickness corresponding to the thickness of *Kyrenia* and *Ulluburum* planking, 38 mm and 65 mm, respectively. The deformation of the models with joints is shown in Figure 6, while stresses are monitored according to the data specified within the material model. Deformation shapes at the time instance of maximum load for Joint 1 and Joint 2 are depicted for all three stress states: bending (top), compression (middle), and tension (bottom). Results for bending currently have the highest reliability, as the numerical model's geometry aligns with the standards for experimental determination of the mechanical properties of a wooden plate on bending, ASTM D304-17 method B [24]. The same geometry and mesh are retained for tension and compression. The ultimate strength capacity for bending is presented in Figure 8, and tension–compression is presented in Figure 9 for both

types of joints. Numerical values for the maximal load and related displacement for both solid planking types and both types of joint and all stress states, bending, compression, and tension, are shown in Table 1.

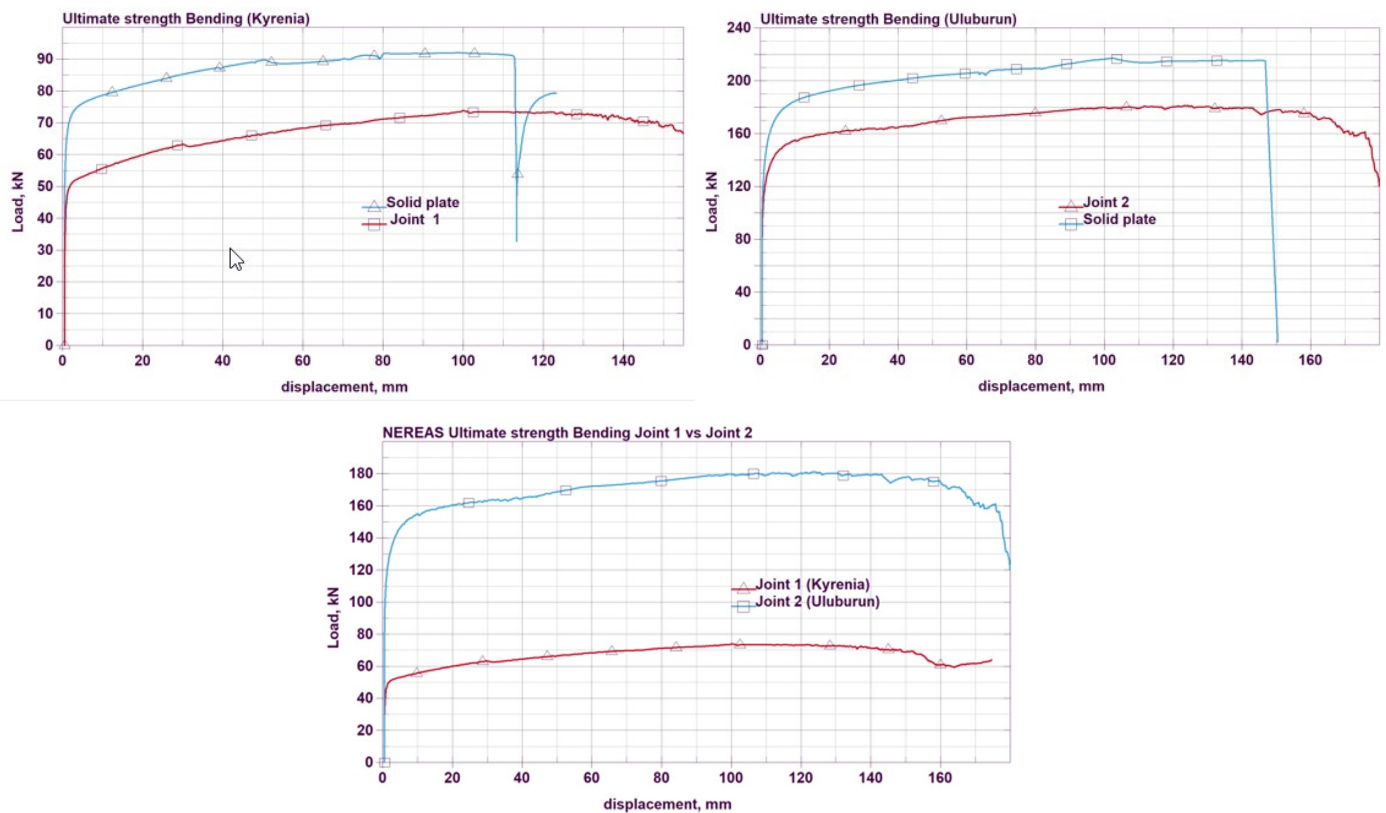


Figure 8. Load-end shortening curves for bending: Solid planking 1 vs. Joint 1 (*Kyrenia*), Solid planking 2 vs. Joint 2 (*Uluburun*), and Joint 1 vs. Joint 2.

Numerical values for maximal load and related displacement for both solid plankings and both types of joints and for all stress states: bending, compression, and tension, are shown in Table 6.

Table 6. Maximal load and related displacement for both solid planking types and types of joints.

Model	Max. Load, [kN]			Displacement, [mm] at Max. Load		
	Bending	Compression	Tension	Bending	Compression	Tension
Solid planking 1 (<i>Kyrenia</i>)	92	490	1820	90.0	11.0	12.5
Solid planking 2 (<i>Uluburun</i>)	216	1010	3300	102.0	11.2	17.5
Joint 1 (<i>Kyrenia</i>)	73	590	1100	99.0	6.6	10.8
Joint 2 (<i>Uluburun</i>)	180	790	2650	105.0	10.0	14.0

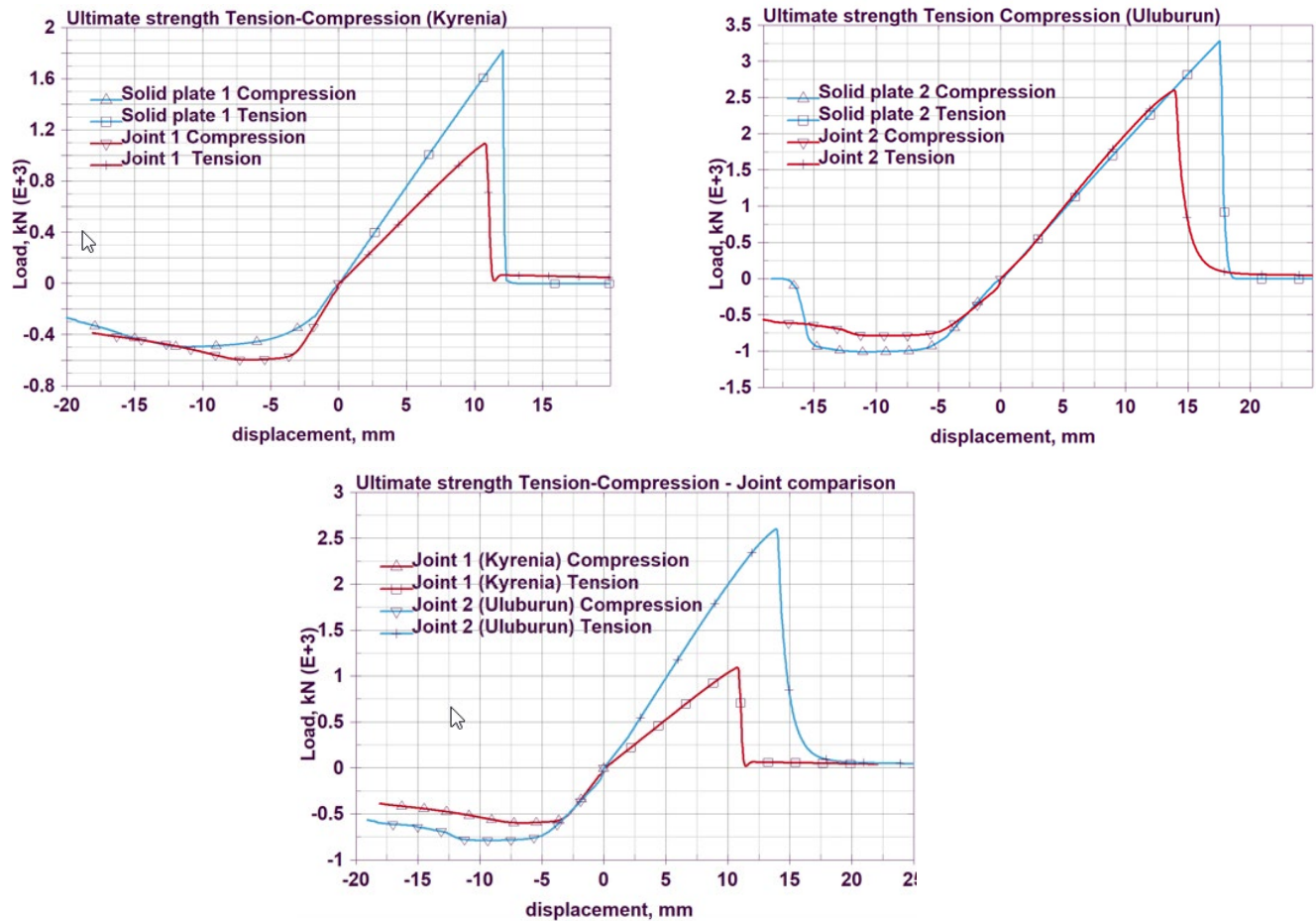


Figure 9. Load-end shortening curves for tension–compression: Solid planking 1 vs. Joint 1 (*Kyrenia*), Solid planking 2 vs. Joint 2 (*Uluburun*), and Joint 1 vs. Joint 2.

3.2. Keel Joints

Like the planking joint analysis, the initial numerical analysis was performed over solid wooden beams with no scarf joints and cross-sectional shapes corresponding to *Jules-Verne 9* and *Toulon 2* keels (Figure 2). The deformation of the models with scarfs is shown in Figure 10, while stresses are monitored according to the data specified within the material model. Deformation shapes at the time instance of maximum load for Scarf 1 and Scarf 2 are depicted for all three stress states: tension (top), compression (middle), and bending (bottom). As in the case of planking joints, the results for bending currently offer the highest reliability, as the numerical model’s geometry aligns with the standards for the experimental determination of the mechanical properties of a wooden beam on bending, ISO 13061-4 [23] or ASTM D198-21 [25], with the same geometry retained for tension and compression. The ultimate strength capacity for bending is presented in Figure 11, and for tension–compression in Figure 12, for both scarf joints.

Table 7. Maximal load and related displacement for both solid beams and types of scarfs.

Model	Max. Load, [kN]			Displacement, [mm] at Max. Load		
	Bending	Compression	Tension	Bending	Compression	Tension
Solid beam 1 (<i>Jules-Verne 9</i>)	31.0	270	480	43	7.5	12.5
Solid beam 2 (<i>Toulon 2</i>)	18.1	110	180	38	3.7	5.6

Table 7. Cont.

Model	Max. Load, [kN]			Displacement, [mm] at Max. Load		
	Bending	Compression	Tension	Bending	Compression	Tension
Scarf 1 (Jules-Verne 9)	2.1	18	10	17	2.0	1.5
Scarf 2 (Toulon 2)	8.1	25	41	34	4.0	2.8

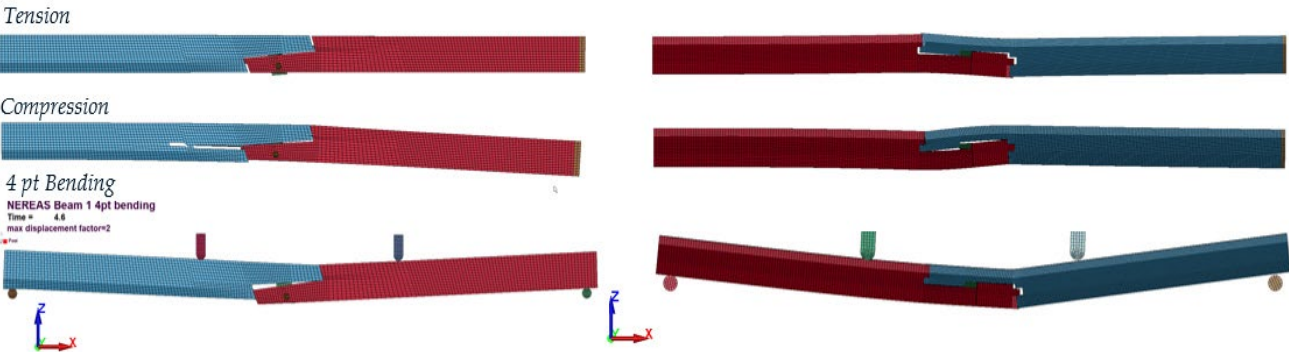


Figure 10. Deformed models at the time instance of maximal load for bending, compression, and tension: Scarf 1 (left) and Scarf 2 (right). Numerical values for maximal load and related displacement for both solid beams and both types of scarf joints and for all stress states, bending, compression, and tension, are shown in Table 7.

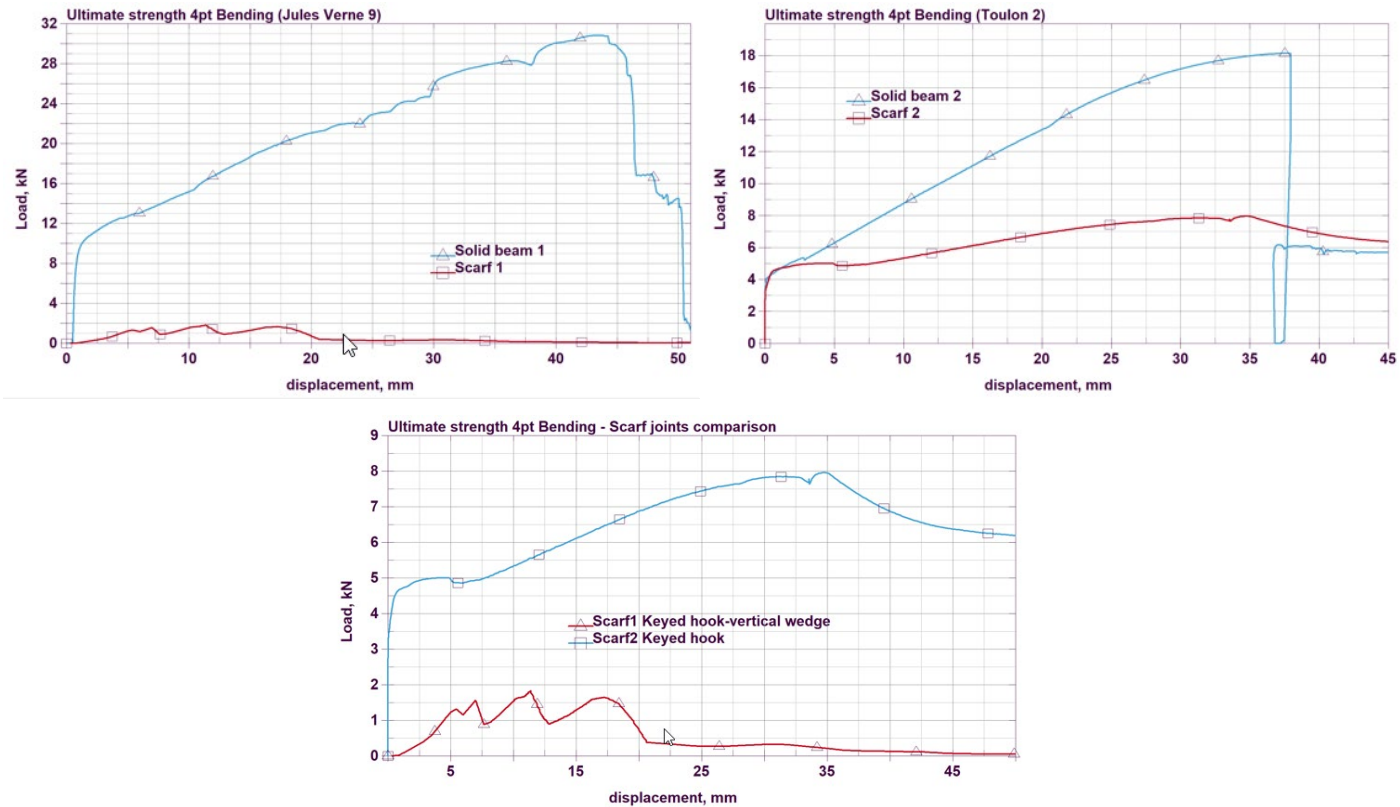


Figure 11. Load-end shortening curves for bending: Solid beam 1 vs. Joint 1 (Jules-Verne 9), Solid planking 2 vs. Joint 2 (Toulon 2), and Joint 1 vs. Joint 2.

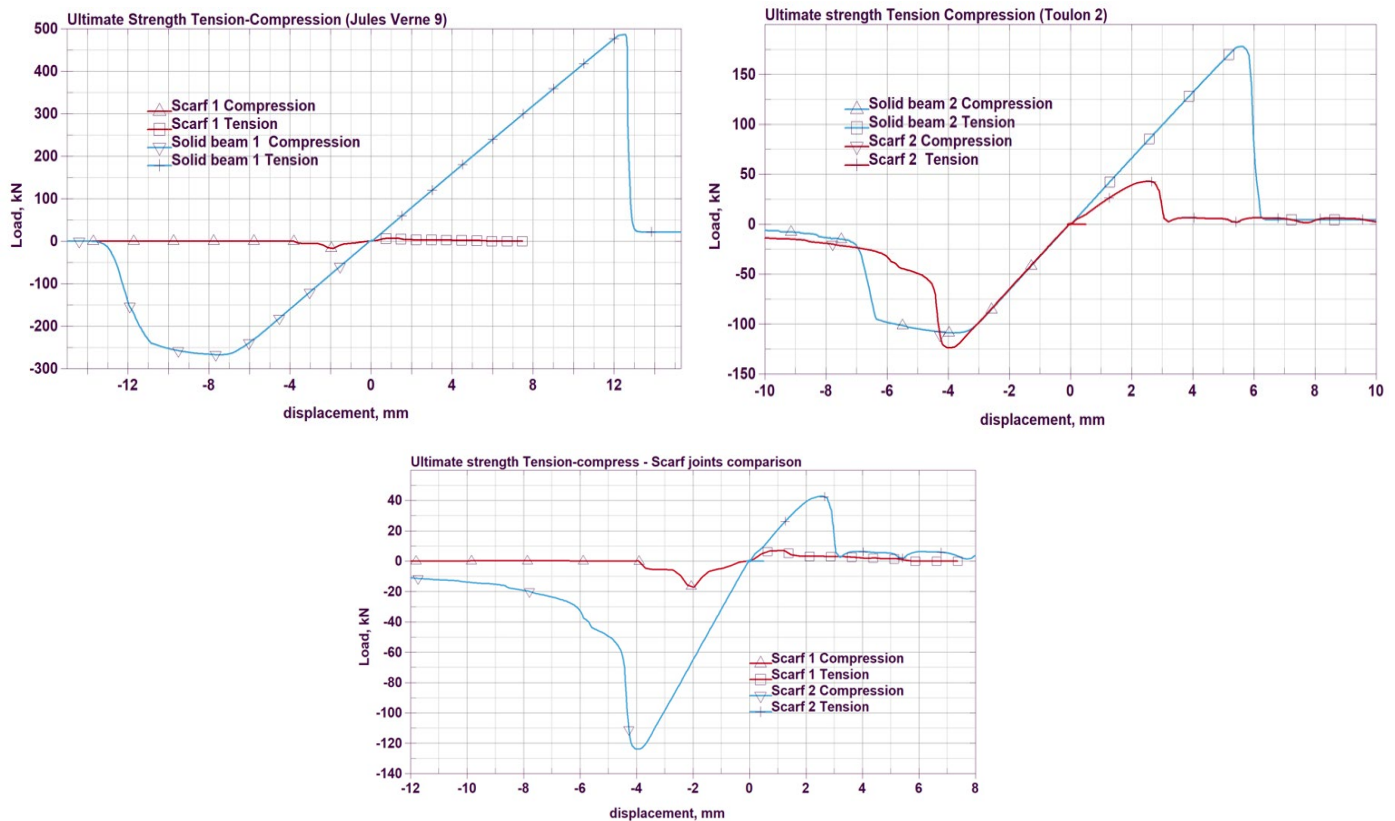


Figure 12. Load-end shortening curves for tension–compression: Solid beam 1 vs. Joint 1 (*Jules-Verne 9*), Solid planking 2 vs. Joint 2 (*Toulon 2*), and Joint 1 vs. Joint 2.

3.3. Discussion

Ancient shipwrecks' wooden material varies both in species and preservation due to natural degradation processes. It may be speculated that different wood types might have been used in ancient ships for the same or similar types of joints and that wooden material degrades also during regular service. While this may lead to a number of different material combinations, the results indicated the importance of the topology of the shape, which accounts for the most significant difference between two types of joints. Therefore, the authors believe that the topology and structural assembly of the joints plays a crucial role in their strength and particularly when similar strength wood species are used. By analysing the deformation shape, it is observed that the deflection curves for all bending deformations, both the planking (Figure 6) and the keel (Figure 10), correspond to the expected physical behaviour given the boundary conditions (Tables 3 and 4). The same applies to tension–compression, although the numerical models for these load cases do not have tabs at the ends, meaning they do not have the specimen's shape as prescribed for compression/tension tests. Instead, the model ensures a fixed end through boundary conditions, extending 300 mm long and across the entire width. This means that failure due to tension and buckling under compression will not occur precisely in the model's centre. This applies only to the planking (Figure 6 bottom and Figure 7), whereas for the keel, due to the scarf joint positioned at the centre of the model, failure occurs precisely there.

By verifying the deflection values at maximum load (Tables 6 and 7) for planking, the deflections/deformations correspond to expectations—greater deflections in joints compared to solid planking and less shortening/elongation in joints compared to solid planking. For the keel, the deflections in scarf bending are smaller than those of the solid beam. The difference in planking behaviour can be explained by the solid planking being

made of pine. At the same time, the joints incorporate wedges and pegs made of oak, which are additionally positioned along the neutral axis of the cross-section, increasing the joint's stiffness. In contrast, all joint components of the keel are made of oak.

Looking at the maximum load, i.e., load-end shortening curves throughout the simulation and in light of the corresponding deflections, it is evident that the ultimate strength of the planking joints is comparable to that of solid planking of the same thickness throughout the simulation duration. For Joint 1 (*Kyrenia*), the strength is 80% of the solid planking's strength, while for Joint 2 (*Uluburun*), it is slightly higher at 84%. This can be partially explained by the stronger material (oak) used for wedges and pegs, whereas the full planks are made of pine in both cases. In tension, the strength of Joint 1 is 61%, while Joint 2 reaches 80% of the solid beam's strength. These results, compared to previous studies such as Helfman et al. [13], offer a more detailed understanding of the specific mechanical behaviours of individual joint configurations, rather than assessing the overall performance of early shipbuilding technologies in contrast to later construction methods.

The deformation patterns and intensity of scarfs observed were consistent with realistic scenarios, as described by Baumann et al. [28]. From the results illustrated in Figures 11 and 12, it can be generally concluded that the ultimate strength of scarfs is significantly lower compared to a solid beam of the same cross-section, especially in the case of the keyed hook scarf with a vertical wedge, which retains only about 10% of the strength of a solid beam across all stress states.

On the contrary, the keyed hook scarf exhibited a smaller difference, with its ultimate strength in tension reaching 25% of the solid beam's strength. Under compression, while the ultimate strength remained comparable in intensity, the energy absorbed was notably lower, as reported in [29]. Bending results provide more reliable insight since the numerical model is based on standardised sample dimensions and shapes, ISO [23]. In this case, the ultimate strength of the keyed hook scarf with a vertical wedge joint was around 10% of that of a solid beam, while the keyed hook scarf joint retained nearly 40% of the solid beam's strength. The purpose of this paper is to demonstrate the methodology for the evaluation of the strength of different wooden structural joints using a nonlinear finite element method and perform a comparative structural analysis. Only bending results were quantitatively validated, and for the other types of loads (compression, tension), further validation is needed. Regarding shear strength, it was neglected, although it can be significant in the analysis of planking, especially in mortise–tenon joints [30,31]. The focus was on bending and compression as the two primary states that stress the keel and planking joints.

It is indeed impossible to perform a significant numerical analysis of the strength and/or stiffness of wooden ship joints, especially historical ones, without including marine archaeology and materials science, especially relating to wood [32].

4. Conclusions

The interdisciplinary approach to studying ancient ship structures combines historical documentation, experimental testing, and computational modelling. By applying state-of-the-art engineering methods, researchers can reconstruct and evaluate the performance of wooden joints used in historical shipbuilding. This paper aims to contribute to the growing body of knowledge by analysing the ultimate strength of wooden joints in ancient ship structures, employing advanced simulation techniques and empirical testing. The findings will enhance understanding of historical shipbuilding practices and provide valuable insights for modern applications in sustainable maritime construction. The results also will serve as a foundation for further investigations into the mechanical behaviour of wooden joints, ensuring that the legacy of historical shipbuilding continues to inform and inspire future advancements in naval architecture and maritime engineering.

The research presents the results of the ultimate strength analysis for a set of joints and a set of scarfs, with each set consisting of two joints, two solid plankings, two keels, and two solid beams, all numerically simulated for bending, tension, and compression. In total, 24 quasi-static simulations were conducted. The simulations were performed using solid elements, a fine mesh, and a complex nonlinear material model with failure mechanisms and element erosion, as well as contact algorithms. This required significant computational resources and, consequently, long computation time. Some specific conclusions are as follows:

- Based on load-end shortening curves, it cannot be concluded that Joint 1 (*Kyrenia*) is stronger than Joint 2 (*Uluburun*) compared to the solid plankings. In fact, the relative difference for Joint 2 is smaller (16% compared to the planking versus 20% for Joint 1), despite Joint 2 belonging to a much earlier historical period of shipbuilding. A similar conclusion can be drawn for tension, again favouring Joint 2. In compression, Joint 1 exhibits a higher maximum load in the 2–8 mm shortening range than the solid planking.
- When comparing the two scarfs, it is evident that the keyed hook scarf (Scarf 2—*Toulon* 2) performs significantly better, showing four to six times greater strength than the keyed hook scarf with a vertical wedge (Scarf 1—*Jules-Verne* 9) across all three stress states. The differences observed in joint performance between the *Jules-Verne* 9 and *Toulon* 2 vessels may also be linked to the evolving need to manage longitudinal stress in a boat that is no longer constructed using the sewn-plank technique.
- However, when looking at the presented analysis of mortise-and-tenon joints, it becomes evident that ‘more recent’ does not necessarily imply ‘more efficient’. This opens the possibility that the transition towards different joint configurations over time was not driven solely by structural performance. Other factors, such as construction efficiency, material availability, or ease of replacement, may also have played a significant role.

To enhance the accuracy of these findings, experimental validation for all stress states would be necessary, allowing the calibration of the numerical model accordingly. Based on these initial results, future research should focus on a detailed analysis of joint parameter variations. However, only further research and experimental validation of these results on different kinds of joints and boatbuilding techniques would provide a deeper insight into how ancient shipwrights adapted their techniques to different maritime needs and construction methods. Due to the complexity of the model and the analysis itself, the load cases applied (bending, tension, and compression) were selected not only since these are elementary load cases but also because comparison between the structure with joints and the ideal structure becomes more complex. While shear or torsional loads are indeed representative for wooden ships, especially slender ones, the comparison of the results might be challenging, since the ideal structure is expected to have a very high torsional stiffness when compared to the structure with joints. The analysis of the structure with the joints would be very sensitive to the contact algorithm. In addition, although the ship may be subjected to torsion, it remains to be seen in future research whether locally this torsion affects the critical structural details.

Another important aspect is the problem of material ageing, which should be taken into account when utilising an advanced numerical material model. Still, the study of wood archaeology in archaeological contexts remains complex. Ancient timbers often show overlapping traces of both mechanical wear from past use and biological or chemical degradation due to long-term burial conditions, making it extremely difficult to isolate and quantify the original archaeological behaviour. Further interdisciplinary research will be

essential to better characterise these variables and refine the mechanical models applied to ancient wooden structures.

Author Contributions: Conceptualisation, A.Z., S.R. and I.R.R.; methodology, A.Z. and S.R.; software, A.Z. and D.B.; validation, A.Z., D.B. and S.R.; formal analysis, A.Z.; investigation, A.Z., S.R. and A.L.; resources, A.Z. and D.B.; data curation, D.B. and S.R.; writing—original draft preparation, A.Z.; writing—review and editing, A.Z., S.R., D.B., A.L. and I.R.R.; visualisation, D.B.; supervision, A.Z.; project administration, S.R. and I.R.R.; funding acquisition, S.R. and I.R.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Croatian Science Foundation, in the framework of the NEREAS Project Numerical Reconstruction in the Archaeology of Seafaring, IP-2020-02-3420.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The presented research has been supported by the Croatian Science Foundation, in the framework of the NEREAS Project Numerical Reconstruction in the Archaeology of Seafaring, IP-2020-02-3420 and by the University of Rijeka, Croatia, under the project No. UNIRI-ISKUSNI-TEHCNIC 23-194 Fluid-structure Interaction in the Analysis of Marine Composite Sandwich Structures with Advanced Materials Application. Sincere thanks to Pierre Poveda for generously providing the original 3D shapes of the *Toulon 2* and *Jules-Verne 9* keel geometries. His contribution is greatly appreciated.

Conflicts of Interest: The authors declare no conflicts of interest.

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