Ship structures under sail and under gunfire

By Prof. Francisco Fernández-González

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Abstract

The ships of the three nations that fought at Trafalgar were serving in their navies for years before the battle. Their ages ranged from few months to over forty years. Their hulls and masts suffered from high seas and from ferocious combats as most of those ships sailed across the Atlantic and the Mediterranean.

Many of these ships were both old comrades and well-fought adversaries that joined in ports and met at sea in other encounters before Trafalgar. They were engineering masterpieces that sailed swiftly before and against the wind, with powerful wooden walls meant to give protection against the heaviest cannon balls. Their designers and builders include the top creators of wooden ships of 18th century: Slade and Henslow designed 16 of the British ships; Sané and Rolland built 11 of the best French ships; and Gautier, Romero Landa and Retamosa constructed the best 12 Spanish ships.

The structures of those hulls are here studied as living creatures that suffered scratches, illnesses and even gaping wounds, to find treatment and healing at the arsenals. The actual structures of significant ships of the three nations are analyzed and compared throughout their life cycles, with respect to their response to sea loads; and representative hull details are studied with analytical and experimental tools to show the response of the wooden walls to waves and gunfire. The role of time and sea loads is analyzed and a mechanical model is proposed to study the effect that treenails and bolts had on the strength of those hulls.

… Los nauios que son de madera, e han los vientos por freno, de que no han poder de se defender, cada que quisieren, nin dexarse caer de aquellas caualgaduras, en que van, nin desuiar se, nin fuyr, para guarescer, maguer sean en peligro de muerte …

(Título xxxiii, ley i: que cosa es la guerra de la mar …)

… Nauios para andar sobre la mar, son de muchas guisas. E porende pusieron a cada vno de aquellos su nome segund la facion, en que es fecho … E porende, estos nauios, quien los qsiere auer, para fazer con ellos guerra, deue catar tres cosas. La primera, que quândo los mandare fazer que sea la madera cogida para ellos, en sazon, que deue, e non se dañe ayna. La segunda, q sean fechos de buena forma, e fuertes, e ligeros, segû côuiene , a lo que han de fazer. La tercera que ayan sus aperejos, aque llaman xarcia, e son estos arboles, e antenas, e velas, e tymones, e espadas, e ancoras, e cuerdas, de muchas maneras. E todas, e cada vna dellas, ha su nome, segund el oficio que fazen …

(Titulo xxiii, ley vii: quales son mejores nauios …)

(Alfonso X, Partidas, II. A.D.1270)

Memories

He is pointing his glass towards the west. Dark clouds blind the Sun and run eastwards competing with foam caps coming from the far sea. A *light air from the north-west with a heavy swell* hides the northern horizon where Cádiz must be guessed. It is October 21, 1805. He is standing on a cliff, at Cape Trafalgar.

In the distance, five dozen ships of the line appear like floating logs topped with large white wings. They look like sea gulls. No sound. No men. Just wings, wind, waves.

Under the press of sail the logs reveal complex structures masterly worked and put together, complex riggings entangled with blocks, ensigns and colors hoisted and black ominous ports open.

Some structures look old and show signs of many battles won to seas and ships. All look like living creatures that the wind throws against the waves. To the observer, these structures are the romance of engineering. They show the genius of man as a builder of machines that defy time and nature, and last longer than many men.

But the observer sees back in time. He knows some histories behind some of the ships, for he is a student in the new school of Navy Engineers.

High noon. There is sound of drums, gunfire and shrieks. A fierce battle against guns and the sea. At dusk, all the ships are gone. Some are *mere hulks covered in wreck and rolling in the swell*. (HARR)

The loss of so many men and engineering masterpieces moves the observer to meditate on those wooden structures. He wants to remember who designed them and how they were built and looked after, but also which hazards they had to fight throughout their lifetime and how they had responded to waves, wind, guns. Here are his reflections.

Ships, Men, Yards

The following tables present for each ship of the three fleets the acknowledged number of guns, name of the designer or shipwright, where she was built and the year she was launched.

Spanish Ships-of-the-Line

Designed number of guns

Argonauta	80	J. Martín de Retamosa	Ferrol	1798
Bahama	64	Ignacio Mullan	La Habana	1784
Monarca	74	J. Fdz. Romero de Landa	Ferrol	1794
Montañés	74	J. Martín de Retamosa	Ferrol	1794
Neptuno	80	J. Martín de Retamosa	Ferrol	1795
Príncipe de Asturias	110	J. Martín de Retamosa	La Habana	1794
Rayo	80	Pedro Torres	La Habana	1748
San Agustín	70	François Gautier	Guarnizo	1768
San Francisco Ssís	70	François Gautier	Guarnizo	1767
San Ildefonso	74	J. Fdz. Romero de Landa	Cartagena	1785
San Juan Nepomuceno	70	François Gautier	Guarnizo	1766
San Justo	70	François Gautier	Cartagena	1779
San Leandro	74	J. Fdz. Romero de Landa	Ferrol	1787
Santa Ana	110	J. Fdz. Romero de Landa	Ferrol	1784
Santísima Trinidad	112	Mateo Mullan	La Habana	1769

French Ships-of-the-Line

Achille	74	Jacques-Noël Sané	Rochefort	1803
Aigle	74	Rolland	Rochefort	1800
Algéciras	74	Caro	Lorient	1804
Argonaute	74	Rolland	Lorient	1798
Berwick	74	Thomas Slade	Portsmouth	1775
Bucentaure	80	Jacques-Noël Sané	Toulon	1804
Duguay-Trouin	74	Rolland	Rochefort	1800
Formidable	80	Jacques-Noël Sané	Toulon	1795
Fougueux	74	J.M. Segondat	Lorient	1785
Héros	74	Rolland	Rochefort	1801
Indomptable	80	Jacques-Noël Sané	Brest	1790
*Intrépide**	74	J-Martín Retamosa	Ferrol	1799
*Mont-Blanc***	74	Jacques-Noël Sané	Rochefort	1791
Neptune	80	Jacques-Noël Sané	Toulon	1803
Pluton	74	Maillet	Toulon	1805
*Redoutable****	74	Jacques-Noël Sané	Lorient	1791
Scipion	74	Caro	Lorient	1801
Swiftsure	74	Wells	Deptford	1787

* Ex *Intrépido*

** Ex *Pyrrhus*

*** Ex *Suffren*

British Ships-of-the Line (WATT, LAV1)

Achilles	74	* Pompée	Cleverly	1798
Africa	64	Thomas Slade	Barnard	1781
Agamemnon	64	Thomas Slade	Adams	1781
Ajax	74	* Invincible	Randall	1798
Belle-Isle	74	Jacques-Noël Sané	Rochefort	1793
Bellerophon	74	Thomas Slade	Graves	1786
Britannia	100	1745 Establishment	Portsmouth	1762
Colossus	74	John Henslow	Deptford	1803
Conqueror	74	John Henslow	Graham	1801
Defence	74	Thomas Slade	Plymouth	1763
Defiance	74	Thomas Slade	Randall	1783
Dreadnought	98	John Henslow	Portsmouth	1801
Leviathan	74	* Courageux	Chatham	1790
Mars	74	Hohn Henslow	Deptford	1794
Minotaur	74	* Courageux	Woolwich	1793
Neptune	98	John Henslow	Deptford	1797
Orion	74	William Bateley	Barnard	1787
Polyphemus	64	John Williams	Sheerness	1782
Prince	98	Thomas Slade	Woolwich	1788
Revenge	74	John Henslow	Chatham	1805
Royal Sovereign	100	Edward Hunt	Plymouth	1786
Spartiate	74	Jacques-Noël Sané	Toulon	1785
Swiftsure	74	John Henslow	Adams	1804
Temeraire	98	John Henslow	Chatham	1798
Thunderer	74	Thomas Slade	Wells	1783
Tonnant	80	Jacques-Noël Sané	Toulon	1789
Victory	100	Thomas Slade	Chatham	1765

French types copied by the British

* *Courageux*	74	J. Geoffroy	Brest	1751
* *Invincible*	74	Pierre Morineau	Rochefort	1741
* *Pompée*	74	Jacques-Noël Sané	Toulon	1791

On British Ships at Trafalgar (WATT)

In October, 1805, the Royal Navy listed 912 ships of which 584 were in commission for sea service and 40 in ordinary but available for sea service and 131 were building or ordered to be built (WATT):

22 three-deckers, the largest 2500 tons burthen and about 4600 tons displacement,

96 two-deckers, the average 1690 tons burthen and about 3000 tons displacement,

133 frigate class, the average 910 tons burthen and about 1500 tons displacement,

average ratio of displacement to burthen tonnage was 1.84, 1.77 and 1.65 respectively.

The principal dimensions of ships of the line had been established in 1719 and revised in 1733, 1741 and 1745. Since then there was no very material changes in ship building or ordnance.

The authorities recognized the advantages of concentrating a heavier armament in a single ship and it was necessary in fleet actions to modify the order of line of battle that the 74 gun ship should not be crushed by a superior antagonist.

The metacentric height was about 12 ft to ensure a moderate angle of heel under sail and thus enable the lower lee guns to be used as long as possible.

Average cruising speed was about 4 knots for larger ships-of-the-line and 10 knots maximum for frigates.

The large tumble-home given to the ships was adopted mainly with the object of obtaining greater strength against transverse racking strains and facilitating the obtaining of suitable timber for the upper beams. But most important, it helped in reducing the wave action on the upper works; it also brought the upper deck guns closer to the centerline so as to keep them “within” the hull at large angles of heel.

At Trafalgar, the average age of the British line-of-battle ships was 17 years, with the *Britannia* launched in 1762 and the *Victory* in 1769. Of the 27 ships, 4 had been in Howe’s fleet the 1st of June, 1794; 3 were at St.Vincent; 5 had fought for UK and 1 against UK at the Nile in 1798; 3 were in Copenhagen; 6 made the journey from the Mediterranean to the West Indies and back in 1804. They were weather-beaten craft, often in poor repair.

A 32 or a 24 pounder with muzzle velocity of some 1500 ft/sec had a range of from 2000 to 2500 yards with 8 degrees elevation and about 1500 yards with 40 degrees elevation; at close quarters a 24 pounder was said to be able to penetrate 5 ft of solid oak, and an 18 pounder half that thickness.

Weight breakdown of a 74

Hull	55	%
Fitting	20	masts excluded
Propulsion	3.5	masts, sails, rig
Armament	10	ballast 6.5%

Timelines

British, French and Spanish ships had shared many days at sea, some as allied fleets and some as contenders in sea battles. They also had to fight strong winds and gales that battered their hulls.

Stresses and damages suffered by hulls structures represent a certain loss of reserve lifetime that can only be restored by adequate repair at a dockyard. In wooden hulls, stresses and damages accumulate in proportion to the severity of their loadings and the length of time at sea.

Wiener approach to accumulated damage by fatigue is now a common design tool for ships (IACS). In this section, we try to apply a similar approach to the ships of Trafalgar by analyzing their timelines and counting their days spent at sea and those spent in dock and disarmed condition.

For this exercise, we will use the data available for the *Santísima Trinidad* and the *Victory*, which besides sharing the role of flagships were of a similar age in 1805. They can be found in (MNM1) and (MKAY).

We will also use here Brian Lavery's (LAV2) detailed account of the life of the *Bellona* together with the detailed description and dimensions of her structure to carry out this analysis.

Detailed timelines of several British and Spanish ships are included in the Appendix.

Summaries are reproduced here below for *HMS Victory*, *HMS Bellona*, *San Juan Nepomuceno*, *Santísima Trinidad*, *Príncipe de Asturias*, *Santa Ana*, *Rayo* and *San Ildefonso*, the Spanish ones taken from González-Aller (GALL).

HMS Victory

Lifetime until Trafalgar = 35.5 years

Commissioned 12.83 years after launching

Disarmed during 4 periods, totalling 7 years

Struck from Navy List, hospital ship for 1.25 years

Drydocked for refitting (8 times), careened (2), reconstructed (1), totalling 6 years.

Service and campaigns added to 13.5 years operating at sea = 38.6 % of her life.

The *Bellona* Class of 74-gun ships

Six of the British 74's that fought at Trafalgar were similar to the *Bellona* and, although this ship missed the action, she was sailing Spanish waters right after the battle.

The *Bellona* was ordered in Dec.1757, begun in May1758 and launched in Feb.1760. Her design by T. Slade was the final step in the British response to the French and the Spanish two-deckers that had shown to be superior in the battles off Finisterre in 1747. With a 168 ft gundeck she was the elder sister of over forty ships built until 1787. The *Defence* (1763) and the *Bellerophon* (1786) of the *Arrogant* class, the *Berwick* (1775), the *Defiance* (1783) and the *Swiftsure* (1787) of the *Elizabeth* class and the *Thunderer* (1783) of the *Culloden* class were all at Trafalgar, two of them under French flag since they had been captured by the French.

The length of these 74's was kept below 170 ft which made their hulls better resistant to hogging deflection that was endemic to the ships of 80, 90 and 120 guns before the introduction of the diagonal bracing by R. Seppings in 1811.

The timeline of the *Bellona* can be considered representative of the timelines of other British ships in the second half of the 18th century.

Copper sheathing was regularly taken off, renewed or repaired, 16 times in the months-years: 9-64, 5-67, 3-80, 6-81, 1-82, 6-83, 10-85, 10-90, 12-97, 5-98, 11-99, 1-01, 6-05, 1-10, 1-11, 12-11. The longest intervals of 4.5 years occur after Trafalgar. They coincide with a decay of naval operations which is reflected in a similar decay of maintenance costs, but they also coincide with the stiffening of the hull that was achieved by doubling the shell and installing diagonal bracing of the Snodgrass system.

Number of Maintenance periods = 25

Number of years spent at dockyards = 530 d + 126 m + 3 y = 15 years approx.

4 periods decommissioned, totalling 17.7 years included 27 months at dockyards

Total lifetime in years = 54.6

Percentage of total maintenance time in total lifetime = 27.7 %

Percent lifetime decommissioned = 32.7 %

Total lifetime armed = 24 years = 44.4 %.

Total lifetime until Trafalgar = 45.7 years.

The *San Juan Nepomuceno*

Lifetime until Trafalgar = 39 years

Experienced 9 careens, one afloat in La Habana

Blocked in Brest for 2.5 years = 6.5 %

Disarmed during 5 periods, totalling about 10 years = 25 %

No significant damages reported in battle.

The *Santísima Trinidad*

Experienced 3 careens, totalling 19 months in 36.58 years lifetime.

Disarmed during 3 periods totalling 19.83 years = 54.20 %

Suffered 4 repairs, totalling over 12 months.

Percent lifetime inactive = 61.5 %.

Four times she suffered important damages, but only once in combat before Trafalgar.

Except for her maiden voyage and a short cruise to Newfoundland, most of her service life was in the Cádiz area, where she was stationed.

The *Príncipe de Asturias*

Total lifetime to Trafalgar = 11.75 years

Careens = 1

Percent lifetime commissioned = 85.1 %

The *Santa Ana*

Lifetime until Trafalgar = 21 years

Regularly careened every three years

Disarmed most of her lifetime: 8 years plus 6 drydocking periods

Short periods of activity, totalling little over 5 years.

Not involved in battles.

The *Rayo*

Total lifetime = 56 years

Disarmed during 7 periods, totalling over 24 years = 42.9 %

Drydocked and careened on 6 occasions totalling over 3 years = 5.4 %

Serviced in 11 campaigns and missions, totalling almost 5 years = 9 %

Stationed in Cádiz on 8 periods, totalling 15 years = 26.8 %

Other repairs, fitting and refitting, and unspecified works totalling 9 years

The *San Ildefonso*

Total lifetime until Trafalgar = 20.75 years

Disarmed during 3 periods, totalling 9.25 years = 44.6 %

Suffered 3 careens, with two copper sheathings.

She was not engaged in battles prior to Trafalgar.

Structures

In the following sections, the evolution of hull structures is analyzed taking the Spanish ships as an example to show how the ships of 1805 related to their predecessors.

From the West Indies to Europe

Ships of the line that fought at Trafalgar were the essence distilled from over a century of rational approach to ship design and shipbuilding in the major maritime nations of Europe.

Although by 1805 Naval Architecture was already a well established discipline based on scientific principles, the solutions for hull structures were still following in the wake of the big body of experience that had been accumulated by warships of the nations that had been fighting at sea for over one century.

Spain had to learn before other European nations that regular, safe navigation of the oceans required different structural solutions for the ships in her "flotas". Spanish naos and galleons that ran the *Carrera de Indias* represent a clear example of that learning that was reflected in the Spanish *Ordenanzas* of 1607, 1613 and 1618. These constitute the first "rules" for ship design and construction, a few decades before equivalent texts were adopted in France or in England.

We have documental proof that these rules were applied until 1720, when don Antonio de Gaztañeta Iturribalzaga proposed new rules based on new proportions that used, for the first time in Spain, full drawings of the ship hulls before construction.

However, structural design was not significantly changed in Spain until the second half of the 18th century, when first British and then French fabrication methods were incorporated in the Spanish hulls, mostly affecting wood treatment, construction details and techniques. So, we can trace the solutions used in the *Princesa* of 1741 and the *Santísima Trinidad* of 1769 to the *Ordenanzas* of 1618 that were followed by the proposals of Garrote in 1691 and later by Gaztañeta and Autran.

Wooden hull structures grew in size, complexity and technology from 1492 to 1805. The evolution from the medieval Castilian "nao" to the last line-of-battle ship is the history of learning to survive on the seas and against the guns. While the need for safe sailing in rougher waters for longer periods of time called for better solutions of intricate floating buildings, the need to protect precious cargoes, men and coasts required the use of floating fortresses that could sustain increasingly effective gunfire in all seas.

Spanish and Portuguese sailors had built knowledge on navigation and seakeeping several decades before other European nations, forced by the need to maintain the runs to the West and the East Indies, and the route Acapulco-Manila (*Carrera de Indias*, *Carrera de la India* and *Galeón de Manila*, *Navío de Acapulco* or *Nao de China*) (CANO, f5v).

The hull is the only foundation of the ship that provides buoyancy, cargo capacity, speed of motion and defense platform, for the ship is considered a house, a tower, castle or fortress, a knight's horse and a trench that needs adding the requirements of motion to the strength to oppose the enemy (CANO, f22r).

This provision requires a complex building made of members and parts that work together as a structure with strength, volume and form not devoid of beauty (CANO, f10r).

A research project carried out by a team directed by the author (GAZ1) proved that there is a line of continuity that relates the Cantabrian “naos” to the Spanish ships-of-the-line of 1805 in terms of structural solutions that constitute what may be called the “old Spanish tradition” (JUAN, t2, 17). In his *Examen Marítimo* of 1771, Jorge Juan criticizes the scantlings of the wood used in frigates and large ships based on the dimensional analysis of weights, forces and strength. His conclusion is that larger ships are proportionally weaker than smaller ones (JUAN, t2, 67-79), and frigates would be more rigid than first rate ships-of-the-line.

Structural solutions of wooden hulls show a solid, step by step evolution throughout history. The first Spanish ships that sailed the Caribbean tropical waters fought the “broma” or teredo worm (*teredus navalis*) by sheathing their bottoms with lead, a solution used in the Mediterranean twenty centuries before to protect keel and bottom planking joints.

The design of the ship was the design of the hull and it was made by experienced men who had crossed the Atlantic many times in their lives (CANO, 14r).

The structure of the hull is subjected to sea loads when the ship is in motion. In a sailing ship with low speed in waves, the form of the hull determines the response of the ship to waves. Rolling in waves is increased by fine bows and fine quarters and will cause higher dynamic sea loads on the hull. Therefore, the more “molded” timbers in the hull the stronger the hull under stern seas (CANO, 18r). This means that the the fullness of the middle body reduced heaving and pitching in those conditions.

As it happens today with many established engineering solutions, they were better explained when they first occurred. It is illustrative to read the rationale behind the hull members in one of the first texts that explained Spanish shipbuilding in 1611.

Hold stringers were hooked onto the heads of floor timbers and futtocks to hold them solidly together when the ship was thrown on her side ashore or at sea by the waves, and were not meant to provide longitudinal strength to the hull, *but when rolling, the hull should work all timbers together from the fashion pieces to the stem* (CANO, 32r). Beam clamps and side stringers had the same function.

Transverse strength was increased by coupling each standard knee (*curva llave*) on the beam head with one hanging knee under the gundeck.

Beams were joined to the head of frame timbers and dovetailed to the clamp that was bolted with forelocks to the timber under the beam head and fastened with harpoon nails to frames between beams.

One counter-clamp or waterway was hooked to the top of the beam and one stringer (spirketting or *draga*) was added between the waterway on the lower beam and the clamp under the gundeck.

Beam knees were hooked to these three pieces so that when the knees pushed or pulled on the side the longitudinal members made the whole side respond together.

Deck girders hooked on top of the beams were fastened with one knee at the forward and after ends. Other girders were hooked under the ledges and fastened to the girders on the beams.

Clamps, waterways, spirketting, side stringers and deck girders strengthened the hull against arching in hogging or sagging. (CANO, f35r)

Waterways on the upper deck were criticized for merchant ships carrying wine in hot climates, arguing that they retained the water on the deck and it would rot the beams, ledges and top timbers aided by the vapour of the wine in the hold. Conversely, waterway was a good solution for ships sailing in cold waters and carrying salt. The strength of the waterway could be substituted by dovetails, double knees and bolts with forelock. Besides that, it was easier to repair the upper works of a hull without upper deck waterway. (CANO, f36r)

The effect of double knees, standard and hanging, was better shown in hard rolling, as they held the weather side of the hull up so that it didn't push down on the lee side which would bend the weather side outwards and open the plank seams. (CANO, f36v)

When Thomé Cano wrote his work the first Spanish Establishments of 1607 were in force for all ships to be built for Spanish owners, both merchant and military. (ORD7)

A galleon of the highest rate had a breadth of 22 cubits (12.643 m) and 1351 tons burthen, with a gundeck length of 75 cubits (43.1 m) and a keel of 53 cubits (30.458 m).

Some structural requirements were:

- Frames composed of floor-and-futtocks bolted to each other with no space between.
- Iron bolts and nails were prescribed throughout the hull, riveted, clenched or harpooned. Hold beams were spaced the width of a barrel, the standard unit for tonnage equivalent to eight cubic shipbuilders' cubits (1.518 m3), and had three knees at each end.
- One rider was fitted under each hold beam, running from keel to clamp.
- Deck ledges were spaced one-third of a cubit. Dovetail was used to join ledges to clamps and waterways, and also to join floor timbers to first futtocks.
- Futtocks composing one half transverse section should leave less than 3/4 of a cubit space between head and foot.
- Side shell planks were 1/5 of a cubit (115 mm) from keel to the wales that were two fingers (35 mm) thicker.
- Waterways were especially strong and bolted to the side structure and to the beam heads, and a spirketting plank was fixed on top of it closing all spaces between top timbers.
- They had no standard knees on artillery decks.
- Hanging and lodging knees were fastened with five iron bolts and dented to the beams.
- Three double wales 1/3 cubit wide and the rest single wales.

Similar structural solutions for hull strength had been proposed thirty years before for the new Spanish galleons by the best ship designers and constructors who assembled in the Juntas called by Philip II in 1581 in Santander, Rentería and Seville (CASA). Solid timber extended from keel to wales and a profusion of knees, stringers and girders clamped the frames longitudinally. The structures of the best Spanish ships, the King's galleons were defined and constructed using a well established system that would prevail until 1750.

The specifications of Diego Brochero for four galleons to be built at Pasajes by Juan de Amassa in 1616 had the following dimensions in shipbuilders' cubits of 0.57468 m:

Tonnage: 500; Breadth: 17.5; Keel: 46; Length: 58.75;
Number of frames: 37 or 228.3 mm avg. per timber;
Clamps: 0.50×0.25; Beams: 0.33×0.25; Ledges: 0.33×0.25, with 0.25 space. (BROC)

Frame timbers and keel were fastened with bolts and treenails.

Since ledges were fastened to the clamps by dovetails and bolts, knees were deemed unnecessary.

Deck girders were double, hooked to the ledges and bolted to each other, one on the top and one underneath.

It was repeatedly stressed that the timbers were well joined together by means of stringers and other longitudinal timbers so that the heads would not move, *"for that was the key of the building"*. (BROC,1)

It was a constant practice to protect the heads of the futtocks in the hold from water by adjusting on them a plank (*escoperada*) hooked to the timbers (BROC,2)

They had three wales, one below gundeck, 0.33×0.50 cu; one double 0.33×0.67 in way of the ledges and one double 0.33×0.67 cu above gun ports.

These specifications are contemporary of the second Establishments of 1613 (ORD3) and the modifications that led to the final Establishments of 1618 that were in force until 1720.

A galleon of 1613 with 22 cubits breadth measured 1073 tons burthen for merchant and 1105 tons for Armada service. They had less tonnage, shorter length, 72.5 cubits, and longer keel, 54 cubits, than a 22-cubit breadth of 1607. The result was a structure with higher rigidity in bending.

They should have 43 floors and 42 first futtocks that filled 35 cubits of keel between the quarters of the length, which required timbers of 236.7 mm width.

Deck girders were laid in pairs one under the ledges, and one on top of them, joined together.

Space between ledges was augmented to 1/3 cubit.

An important change was the introduction of a number (as many as required) of pairs of diagonal pillars crossed as scissors between the heads of the hold beams and the deck girders above.

All important joints of deck members in the horizontal plane were dovetailed and bolted. (ORD3)

The 1618 Establishments reproduced the rules of 1613 except for the length and keel dimensions. (ORD8)

With respect to 1613, a first rate galleon of 22-cubits in breadth was shortened 4.5 cubits in length and 1 cubit in the keel, in an effort to reduce the hogging strain and maintain the shell planking seams watertight.

Almost the only addition was to specify the number of X pillars as 4 abaft the main mast and 2 forward.

The number of floors was reduced to 41 with 40 futtocks joined side by side along 33 cubits keel. Thus, the average width of one timber would be 234 mm, as in 1613.

The dimensional error admitted in construction could be important as the hulls were built on sandy beaches and it was quantified up to half a cubit in breadth, or about 2.3% for the highest rate and 3.0% for a medium size vessel. (ORD8,18)

The same rules were maintained in Spain for merchant and war ships until Gaztañeta's first proposals of 1712 where a complete lines plan was presented for the first time in Spain. (GAZ2)

Gaztañeta considered a warship a different type of vessel for which he lengthened the keel to 3.0 times the breadth and the length to 3.6 times for a 20-cubit vessel. That was a breaking proposal if one considers that in 1618 these ratios were 2.4 and 3.1 respectively.

At the same time, he reduced the scantlings of wood in the hull and designed the midships section so that ballast was eliminated or reduced to a minimum.

Gaztañeta's proposals were in line with those of Garrote's twenty years before. In 1691 Captain Francisco Antonio Garrote had denounced the excessive weight of wood and iron of Spanish hulls that suffered more damages at sea than other European vessels with lighter hulls and using treenails. In the introduction to his *Compilation for the New Construction of Spanish Vessels…* presented to the King in 1691, Garrote defined a basic problem of Naval Architecture when he defended that what caused Spanish hulls to *"yield their masts and open their seams"* in a storm were the bad proportions and forms of the hulls. (GARR)

Although Garrote's proposals were never enforced nor published they represent a pioneer step towards standardization of ship design and were known by Navy officials. Garrote discusses all aspects of the design based on his long experience at sea and justifies the dimension of up to 272 items covering all hull members, masts, rigging, sails and anchors for six ship rates, from 14 to 24 cubits of beam equivalent to 272 to 1371 tons of burthen.

The ratio L/B was 3.0 for all the classes, which was already advocated more than sixty years before, in opposition to the *Ordenanzas* of 1618, in order to reduce pitching and preserve the masts in rough seas, which resulted in longer service life. (DIAL)

A full form of the run of the hull abaft the quarter length was preferred so that strong enough framing could be fitted within the hull and the shell planking could stay watertight when the hull was taken out of the water. The same goal had the risers, "as many as possible" that were recommended. (DIAL)

The sheer of the wales was believed to be a good help against hogging, and was aesthetic too, but excessive sheer could not be followed by the gundeck; thus, the wales had to be cut at gunports and couldn't be aligned with clamps and beams. (DIAL)

A sixth-class vessel of the new type would have thirty moulded frames in half the length of 82-cubit-14-inch (47.459 m), which required average timbers 402 mm wide.

Scantlings were proportional to the beam. Thus, the keel height was 1/24 of the beam and the width 1/4 more to facilitate bolting to the floor timbers.

The scarphs of the keel should be horizontal to stop the water but the end scarph joining the foot of the stem should be hewn vertically and bolted horizontally for higher strength.

The conception of the hull structure maintained the Spanish system, with special attention to the careful arrangement and joining of knees and timbers using dovetails and hooks that fastened wide pieces of wood to each other.

The discussion of the structure was a continuation of the shipbuilders' debate during the 17th century and translated the preoccupation for attaining the necessary rigidity of the hull under shear. Diagonal bracing that was common in land buildings was not used in the hulls and oblique loads on the joints were only resisted by the transverse dimensions of the members.

The Proposals of 1720 (GAZ3) reflected what Gaztañeta himself had experienced as Superintendent of Forests and Shipbuilding when he followed the construction of the last galleon of the 17th century, the *N.S. de la Concepción y Las Animas*, a 90-gun captain ship of the Ocean Armada, launched at Colindres beach (Asturias) in 1688. (GAZ1)

The structure of her hull shows the use of numerous strong longitudinal members that provided longitudinal strength to the hull girder: stringers, clamps, waterways and 'tween deck stringers had heavy scantlings and were scarphed to provide structural continuity, and there were seven wales that added a significant cross section area in tension. (Table.1 in the Appendix)

An 80-gun ship of 1720 would have a gundeck length of 78 cubits, 65cu keel and 21cu breadth, with lighter scantlings than the classes of 1691.

Table.2 in the Appendix compares some of the scantlings proposed about one hundred years before Gaztañeta.

British versus French construction in Spain in the 1760s

A technical debate was open in Spain by F. Gautier's criticism of the ships built in Ferrol with British methods introduced by Jorge Juan fifteen years before. The discussion questioned all aspects of hull design and construction, from scantlings to arrangement of wooden members, including the use of waterways, knees and riders. The aim was to reduce the hogging that was suffered by most of the new constructions. However, the remedy was not definitive since the bending strength of the hull could not be increased unless the tension members were reinforced. (MNM, Ms.1249)

Gautier attributed the hogging of ships in harbour and the leaks in their shell to the wide separation of beams and low sheer of the deck. Spanish officials defended that where wide timber was needed was underwater, that the hulls suffered more in a storm than in combat, that hogging was mostly an effect of wide floors and careening afloat, and it was more visible when decks had less sheer. Waterways were of little effect against hogging since they were not hooked due to the interference with lodging knees, although standard knees could help to compensate for it. However, the absence of a shear surface between the frame timbers could not be compensated.

The British constructors argued that oblique pillars were more effective against rolling strains than hanging knees and rider futtocks. The conclusion of the Spanish shipwrights was a tacit definition of the hull girder concept: *"Strengthening the upperworks and joining the frame timbers side by side, and the waterway which is the fastening of the ship, especially in pitching as it links the whole length of the vessel, are the best we can desire for the moment"*. (MNM, Ms.1249)

Traditional Spanish shipwrightry relied much in the solidity of the hull and hook-tied the members to one another (*trabazón*). The impossible goal of eliminating the hogging of the hull was always sought by means of continuous, intact wales and waterways. There was an extended concern whether concave wales helped maintain the hull ends up or sagged with time (LAV3, 99), which was a correct interpretation of the longitudinal strength of the hull in terms of vertical shear deflection, the same problem as solved by Robert Seppings' diagonals after Trafalgar.

However, by the end of the century, the concept of a ship had evolved from a building strong enough to float in all seas and seasons to a moving fortress that required a flotation caisson below and a propulsion system above.

The design of the *San Ildefonso*, 1782

The concept design of the *San Ildefonso* can be considered another technical milestone in Spanish shipbuilding of the 18th century. The technical analysis of the 74-gun ship design was a consequence of recent defeats of Spanish ships that confronted the British. The ideas that Julián Martín de Retamosa, the designer of the *Montañés*, presented to the King on Nov.16, 1782 constitute a discourse parallel to the debate held fifteen years before comparing French and British constructions. (AMN, ms203, d4)

The principal ideas in that document were aimed at increasing the speed of the ships that less then one month earlier had allowed the British to escape their chase (Oct.20, 1782), and suggested:

- To reduce the weight of the hull by using treenails instead of iron bolts
- Reduce the scantlings of timber members while keeping enough width to allow the use of treenails.
- To reduce the length since the British had shown a higher speed being shorter.
- To reduce the weight of the upper works by using pine and cedar instead of oak, thus gaining a margin for more ballast to lower the center of gravity.
- To use standards and lodging knees instead of inner-waterways. This was a recurrent matter of concern in Spain that revealed the poor resistance of the hulls to torsion.

Specialists that gathered at the three Departments of the Navy attributed the slowness of Spanish ships to different causes, among which:

- Excessive heaviness of the hulls.
- Lack of copper sheathing.
- Bad stowage.
- The use of circular arcs instead of ribbands to define the form.
- Excessive length and scarce breadth.

The order of the King was to design a ship that was faster under sail at the cost of duration. It was desired that the timbers were joined filling the space solidly from the bottom to the gundeck port sills *“so that a ball will encounter 14 more inches of wood between the frames”*. (GALL, Anexo 1).

The hull was to be reinforced with lodging knees and standards instead of the costly inner-waterways; to use deadwoods fore and aft instead of fork timbers; to reduce the number of hold riders from 13 to 6; and to arrange the riders obliquely since vertical riders were of little use. This latter provision pointed directly to the need for shear strength at the sides.

Scarphs, Joints, Dowels

Hull complexity

The hull of a ship-of-the-line was a complex puzzle of wooden members joined together with scarphs and fastened with treenails, bolts and nails.

Looking at it from the other side of the looking glass, the hull of those ships was a succession of discontinuities between wooden parts, facing one another through plane interfaces and loosely pinned at scattered points.

The proper use of treenails, bolts and nails had been a redundant matter of study and discussion by European shipbuilders since the 16th century. A Spanish manuscript of mid-17th century (GALA) showed that round nails were lighter and held tighter than square (*esquinados*) ones. The length of the shaft should be three times the thickness of the plank nailed to the timber. Each end of a shell plank should be nailed and riveted, with two nails if its width was one-third of a cubit and four if one-half cubit wide.

Scarphs were intended to make two parts respond to loads like one single piece. Therefore, each scarph was designed to resist a predominant type of directional loading. The more complex the loading the more complex the scarph would be. Thus, there were simple scarphs for axial loads and scarphs for transverse loads in one or two directions, scarphs for shear and scarphs for bending. The technique of keel scarphing was already practiced by the builders of the Greek trireme who sculptured artful joints using tables and coaks arranged in 3D, and the Egyptians planked the bottom of their boats with hook scarphs, sewn lashings (LIPK) and dovetail fastenings (HALD) for shear strength.

A recent research by F.Cabrera De Aizpuru (CABR) has studied the structural response of the joints used in traditional Spanish shipbuilding before 1750 and compared them with those used by British shipbuilders in those years. Detailed drawings from the unique *Diccionario Demostrativo* of 1756 by J. José Navarro, Marqués de la Victoria (MARQ) were analyzed using a mechanical model that took into account the orientation of the joints and the grain of the wood under different loadings. The results were not conclusive with respect to which details, the Spanish or the British were better under load.

Keel scarphs of the Spanish and French ships of Trafalgar were horizontal and were fastened with 8 vertical bolts driven through floors and the keelson. British ships used vertical scarphs with tables and coaks that were fastened with 8 horizontal bolts.

Doweling

Rigid fastening of two or three components of the wooden hull was commonly achieved using dowels that joined and reinforced the scarphs of different wooden members. Dowels were made of wood (treenails) and iron, copper or bronze (bolts, nails).

The rigidity of a joint depended on several characteristics that determined its engineering value, such as:

- The assembly process.
- The accuracy of relative positioning of the parts being joined.
- The ability to hold the parts rigidly together against all loads acting on the joint.
- The need to separate the parts for maintenance or replacement.
- The capacity to retain the fastening over a period of time.

Loads acting on a dowel can be decomposed in three different types:

- Tension, along the length of the dowel or shank
- Shear, across its transverse section, generally circular but also square
- Combined shear and tension, due to bending of the dowel induced by relative angular movement of the parts.

Shear

Joints designed for shear are less rigid than under tension (clenched bolts) since significant relative sideways displacement must take place between the parts before the dowel can take any shear load, which depends on the hole clearance. Clenched bolts add compression stress to the faces of every two parts so that transverse loads are resisted across the joint by friction between the two parts before the bolt shank takes any shear.

In the ships of Trafalgar treenails and bolts were used in joints where shear strength was the design requirement.

Friction forces were present between the parts when clamped by bolts but not when treenails were used, as was the case with the shell planking.

A simple model for doweled joints loaded in shear can be used to calculate several types of stresses that can limit the joint capacity:

(a) Transverse shear stress develops in the dowel's cross section in way of the interface between every two pieces.

Shear stress = Force / cross section area of the dowel (πr^2)

(b) Simultaneously, the dowel interface with the hole acts as a bearing for the dowel and is crushed by compression.

Compressive (crushing) stress = Force / bearing area (piece thickness $\times$ diameter)

(c) Where the hole is close to the edge of a piece in the direction of the load, the piece is subjected to shear stress along two shear planes connecting the hole to the edge.

Piece shear stress = Force / 2 planes (2 × distance to the edge × piece thickness)

Where there is more than one dowel in the joint an optimist model considers that all dowels resist the force at the same time whilst a conservative model considers one single dowel taking the whole load before the others.

(d) Where the dowel is loaded in bending, a combined stress state must be considered that takes into account normal bending stress (σ) and direct shear stress (τ) in the dowel.

Maximum principal stress = $\frac{1}{2}\,\sigma \pm \frac{1}{2}\,\sqrt{\sigma^2 + 4\,\tau^2}$

Tensile stress in the dowel should be kept below about 60% of the yield strength.

Lateral design load of bolted joints (RAWI)

For a two-member bolted joint, the lateral design load of a single bolt is determined by the minimum of the following yield expressions given by the National Design Specifications of the AF&PA (NDSW):

Mode I .... $Z = \frac{D\ t\ F}{4\ K}$ (Newtons)

Mode III .... $Z = \frac{k\ D\ ts\ Fm}{3.2\ (2+R)\ K}$

Mode IV .... $Z = \frac{D^2}{3.2\ K}\sqrt{\frac{2\ Fm\ Fb}{3\ (1+R)}}$

where

$$k = -1 + \sqrt{\frac{2\ (1+R)}{R} + \frac{2\ Fb\ (2+R)\ D^2}{3\ F\ ts\ ts}}$$

R = Fm/Fs

F ..... Fm or Fs for Mode I

t ...... tm or ts for Mode I

Fm .. dowel-bearing strength of main member (MPa)

Fs .... dowel-bearing strength of side member (Mpa)

tm ... thickness of main member (mm)

ts ..... thickness of side member (mm)

Fb ... nail-bending yield stress (Pa)

D ..... nominal bolt diameter (mm)

K = 1+ (θ/90)

θ ...... max. angle of load to grain.

Design dowel-bearing strength of wood members in dry condition (12-19% MC)

Bolt parallel to grain .... $F = 77.25\ G$ (Mpa)

Bolt perpendicular to grain .... $F = 212\ G^{1.45}\ D^{0.5}$ (Mpa)

G = specific gravity

D = bolt diameter (mm)

Effect of moisture content (MC)

A study of bearing strength in Germany in 1949 (FAHL) proposed:

$F(m) = 26\ F(12) / (m+14)$, ($N/mm^2$) for m% moisture related to F at 12% MC.

For Finnish spruce (g=0.48) and 20 mm bolts (KAPO):

$F = 46.7 – 1.35\ m$, (N/mm^2) when $m < 22.5$ %

F = 16.5 limit for spruce saturated at $m > 22.5$%
similar for southern pine

Another regression for three species (WILK) gives:

$F(m) = 49.95 – 1.186\ m$ (N/mm^2)

Ultimate compressive strength

Relation between the crushing strength at the face of a fastener hole (i.e. dowel-bearing strength) and the compression strength (KUVE) for 6.7 mm diameter bolt:

Dowel-bearing Strength (Fe) = 0.6 Fc + 6 (N/mm^2)

where Fc = compression strength.

For diameters more than 6.1 mm (LASO):

Dowel-bearing Strength (Fe) = 0.7 Fc (N/mm^2)

Another equation proposed (RAWI) taking into account spruce, fir and southern pine testing:

Dowel-bearing strength parallel to grain (Fe) = 0.438 Fc + 11.897 (N/mm^2)

Modes of Failure of Doweled Joints (AFPA)

- Mode I .... Only one (main or side) member bearing
- Mode II ...... Both (main and side) member bearing
- Mode III ..... One member bearing and dowel yielding in the other
- Mode IV .... Dowel yielding in both members

- Mode I

$$P = (q)\ (l)$$

P .... Nominal Lateral Connection Value .... (lbs)
(l) ...... dowel-bearing length in member(s) .... (in)
(lm) if main member; (ls) if side member, double for double shear
(q) ..... member(s) dowel-bearing resistance = F. D .... (lbs/in)
(qm) if main member; (qs) is side member
F .... member dowel-bearing strength .... (psi)
D .... dowel diameter .... (in)

- Modes II-III-IV

$$P = \frac{-B + \sqrt{B^2 - 4\ A\ C}}{2\ A}$$

– Mode II
A = 1/(4qs) + 1/(4qm)
B = ls/2 + g + lm/2 — g = gap between members (in)
C = –(qs) (ls^2)/4 – (qm) (lm^2)/4

– Mode III

A = 1/(2qs) + 1/(4qm)	if main member bearing
A = 1/(4qs) + 1/(2qm)	if side member bearing
B = g + (lm/2)	if main member bearing
B = g + (ls/2)	if side member bearing
C = –Ms – (qm) (lm^2)/4	if main member bearing
C = –(qs) (ls^2)/4 – Mm	if side member bearing
Mm = Fb (Dm^3/6)	main member dowel moment resistance (in-lbs)
Ms = Fb (Ds^3/6)	side member dowel moment resistance (in-lbs)

Fb = dowel bending strength (psi)
Dm, Ds = diameter of dowel at yielding location (in)

– Mode IV
A = 1/(2qs) + 1/(2qm)
B = g
C = – Ms – Mm

Dowel Bearing Strength Estimates, F (psi)

Wood-based products

Parallel-to-grain	F proportional = $0.67 \times$ F ultimate
Perpendicular-to-grain	F proportional = $0.5 \times$ F ultimate

Lumber (bolt, drift pin, lag screw)

Parallel-to-grain	F proportional = 7862·G1.07 / D0.17
Perpendicular-to-grain	F proportional = 3178·G1.15 / D0.51
Parallel-to-grain	F at 0.5 % = 11200 G
Perpendicular-to-grain	F at 0.5 % = 06100 G
Parallel-to-grain	F ultimate = 11735 $G^{1.07}$ / $D^{0.17}$
Perpendicular-to-grain	F ultimate = 6355 $G^{1.15}$ / $D^{0.51}$

Lumber (nail, wood screw)

F proportional = 0.8 of same for bolts

F at 0.5 % = 16600 $G^{1.84}$

F ultimate = 0.8 of same for bolts

G = specific gravity, oven dry

D = fastener shank diameter (in).

Dowel Bending Strength Estimates, Fb (psi)

Bolts, lag screws, drift pins

F proportional = Fy (yield)

F at 0.5 % = Fy/2 + Fu/2

F ultimate = Fu

Common nails, spikes, wood screws

F proportional = 0.6 Fu (ultimate)

Calculated Nominal Lateral Connection Values must be reduced to Design Values by factors given by NCS for different Fastener types and Modes of yielding:

Bolts, drift pins	mode I	4	Ko
	II	3.6	Ko
	III, IV	3.2	Ko
Lag screws	mode I	4	Ko
	II, III	2.8	Ko
	IV	3	Ko
Nails, spikes, wood screws	all modes		Kd

Ko = 1 + 0.25 (θ /90), with θ = angle of load to grain

Kd = 2.2 for d < 1/6 in

Kd = 10 d+0.5 for d < 1/4 in

Kd = 3 for d > 1/4 in

Application to Ships of the Line of 1805

Dowel-Bearing Strength of Lumber Members for different G and D values

Parallel-to-grain .... F proportional = 7862 $G^{1.07}$ / $D^{0.17}$

Perpendicular-to-grain .... F proportional = 3178 $G^{1.15}$ / $D^{0.51}$

G	0.4	0.5	0.6	0.7	0.8
D	Proportional F parallel / F perpendicular to grain (psi)				
0.4	5601 / 1768	7112 / 2285	8464 / 2818	10194 / 3364	11760 / 3923
0.6	4217 / 1438	5355 / 1858	6508 / 2292	7675 / 2736	8854 / 3190
0.8	3448 / 1242	4378 / 1605	5321 / 1979	6275 / 2363	7239 / 2755
1.0	2949 / 1108	3745 / 1432	4552 / 1766	5368 / 2109	6192 / 2459
1.2	2959 / 1010	3296 / 1305	4006 / 1609	4724 / 1921	5450 / 2240
1.4	2330 / 933	2959 / 1206	3596 / 1488	4241 / 1776	4893 / 2071
1.6	2123 / 872	2695 / 1127	3275 / 1390	3863 / 1659	4456 / 1935
1.8	1955 / 821	2482 / 1061	3016 / 1309	3557 / 1563	4103 / 1822
2.0	1816 / 778	2305 / 1006	2802 / 1240	3304 / 1481	3812 / 1727

In the following applications, some typical joints used in wooden hulls of 1805 are evaluated using (NDSW) formulations in inches of 25.4 mm.

Symbols used are:

Gm .... specific gravity of main member

Gs .... specific gravity of side member

Lm .... length of dowel hole in main member, in

Ls .... length of dowel hole in side member, in

D .... dowel diameter, in

Gap .... separation between main and side members, in

Fb .... bending strength of dowel

Sp/u .... proportional or ultimate limit.

Results are joint capacity forces for each mode of failure of the joint, in pounds.

P1m .... dowel bearing (crushing) in main member

P1s .... dowel bearing in side member

P2 .... dowel bearing in the two members

P3m .... dowel bending in main member, crushing in side member

P3s .... dowel bending in side member, crushing in main member

P4 .... dowel bending in the two members.

For main (m) and side (s) members, the orientation of the bearing to grain is specified by the values of bearing pressures in lb/in, as F1 for parallel and F2 for perpendicular loadings.

Joint	#1	#2	#3	#4	#5	#6	#7
Gm	0.75	0.75	0.75	0.75	0.60	0.70	0.70
Gs	0.75	0.75	0.75	0.50	0.60	0.70	0.70
Lm	14	14	13	12	12	15	15
Ls	9	9	5	4	5	15	15
D	1.0	1.0	1.0	0.70	1	1.0	1.25
gap	0	0	0	0	0	0	0
Fb	10130	15200	20000	20000	10130	20000	10130
Sp/u	p	u	p	p	p	p	p
F1m	—	—	—	—	—	—	—
F2m	2283	2283	1625	1917	1766	2109	2352
F1s	5779	5779	4694	2785	4552	—	—
F2s	—	—	—	—	—	2352	2352
P1m	52011	52011	28895	11140	22760	31635	35280
P1s	20547	20547	11415	7668	8830	31635	35280
P2	16352	16352	12203	8178	8968	13104	14613
P3m	12054	12185	11294	8167	8049	10676	11889
P3s	12303	14430	8192	3615	6340	10676	11889
P4	2551	4072	3385	1749	2250	2878	3022

Joint #5 simulating a deck beam and planking with oak treenail that shows better balance of joint strengths than Joint #4 with iron bolt and harder main member.

Joint #6 and Joint #7 simulat an oak frame composed of two twin timbers. Joint #7 with 1.25in treenail has higher joint strength in all modes of failure than Joint #6 with an 1in iron bolt.

Loadings on Hull at Sea

To study the response of a ship hull to the sea we must separate static from dynamic loads. Static loads can be modeled using hydrostatic characteristics of the ship and inert masses on board. Dynamic loads depend on the accelerations acting on each mass on board. Some dynamic loads are cyclic and their magnitude and direction change with the frequency of the ship motions involved. The effects of cyclic loads are cumulative along the ship lifetime causing the structure to deteriorate. Other dynamic loads belong to the category of impacts, which cause sudden and localized damages to some hull elements. Direct wave impacts only affect the shell but slamming impacts require the masts and rigging to respond to acceleration forces, which are the cause of dismasting in severe storms.

Static loads

Flotation of the hull in calm water or in waves imposes pressure forces on the underwater body. Wave profiles produce a shift of buoyancy along the waterline thus generating shear forces and bending moments that are the basis for longitudinal strength calculations used in ship structural design. In modern, welded hulls, bending stresses can be neglected when the ratio L/D is smaller than 10, while shear forces take a greater significance. In the ships of Trafalgar, L/D was lower than 10, so negligible bending stresses should be expected if they had strength moduli in accordance with their depth. However, carvel shell construction used in those ships resulted in longitudinal strength moduli much lower than welded construction and, therefore longitudinal bending had to be taken into account. The resistance to longitudinal slippage cannot be measured by the section modulus, but rather by the effective inertia of the section.

Hogging of the hull was induced by the weights located close to the hull ends acting on long hulls. However since the 1740s, French and Spanish ships were much appreciated by Britain for their longer hulls. Still in the early 1790s Snodgrass recommended giving the ships ten to thirty feet more length in order to separate the gun ports from each other and from the ends to increase their strength and to reduce the hogging. (LAV1,v1,123)

Careening, launching and drydocking for repair, fitting or refitting and arming or disarming a ship afloat were operations that subjected the hull to high strains. An analysis of some of these loadings is included in another chapter.

Dynamic loads

The response of the ships in motion at sea can be studied using dynamic models that consider the ship as a rigid body with natural periods of linear and angular motions about three orthogonal axes fixed to the hull. However, the local response of a member of the hull has to take into account the structural flexibility that allows structurally important local distortions in the form of vibration.

An approximate estimation of the heave, pitch, roll, sway and yaw motions of a rigid ship, considering surge to be a second order quantity, requires the use of hydrodynamic coefficients that are highly dependent on added mass and frequency of encounter. These coefficients can be derived using simulation techniques like the Five Degree of Freedom Sea-keeping Program (MITL). Storms should be modelled using their intensity and duration, what can be done using the Bretschneider Spectrum.

Rolling, pitching and heaving imposed the heaviest loads on a sailing ship. Opening of shell planking seams and dismasting was a common result of a heavy storm.

Current formulas accepted for predicting ship motions in ship design can be used to estimate amplitudes and accelerations of the ships of Trafalgar. The formulas included in the new Common Structural Rules for Tankers and Bulkcarriers (IACS) do not differ from other formulas used for other ship types. Their application is based on simple design parameters such as block coefficient, length and metacentric height.

We have estimated these values for five significant ships of 1805, using their approximate molded dimensions, in meters:

	Trinidad	*Victory*	*Vaisseau-74*	*Montañés*	*Bellona*
Length	55.80	56.20	55.20	52.90	51.20
Breadth	16.16	15.80	14.30	14.20	14.25
Mean draft	7.50	6.17	6.50	6.80	6.20
Volume	4647	3350	3000	2860	2600
Block c.	0.687	0.611	0.585	0.525	0.575
KMt	9.3	7.7	7.1	7.5	7.3
KMl	49.8	45.1	47.8	45.0	42.2

Meters, seconds and degrees are used in the following formulae where:

L, length (m)

B, breadth (m)

GM, metacentric height (m)

Cb, block coefficient

A common acceleration parameter a0 is used as a basis for calculation of linear accelerations due to heave, sway and surge:

$a0 = (1.5) \times (1.58 - 0.47 \times Cb) \times (2.4/ \sqrt{(L)} + 34/L - 600/L2)$ (non-dimensional)

Heave acceleration = a0·g (m/s^2)

Sway acceleration = 0.3 a0.g (m/s^2)

Surge acceleration = 0.2 a0.g (m/s^2)

Roll period: Troll = 2.3 Kr / $\sqrt{(GM)}$ (seconds)

Kr = .40 B (approx.)

Roll angle = 9000 (1.25 – 0.025 Troll) Fp · Kb / [(B+75) π] (degrees)

Fp = 0.5 for 1.E-4 probability level

Kb = 1.0 for ships with bilge keel

Pitch period: Tpitch = $\sqrt{(2 \pi \lambda / g)}$ (seconds)

Where λ = 0.6 (1 + Tc / T) L, with Tc = loading condition draft

Pitch angle = Fp (960 / L) $(V/Cb)^{0.25}$ (degrees)

These formulas give for our ships, in seconds and degrees of single amplitude:

	Trinidad	*Victory*	*Vaisseau-74*	*Montañés*	*Bellona*
Troll					
GM=1.0	14.9	14.5	13.1	13.1	13.1
GM=1.5	12.1	11.9	10.7	10.7	10.7
GM=2.0	10.5	10.3	9.3	9.3	9.3
Roll angle					
GM=1.0	13.8	13.9	14.8	14.8	14.8
GM=1.5	14.9	15.0	15.8	15.8	15.8
GM=2.0	15.5	15.7	16.3	16.3	16.3
Tpitch	6.5	6.6	6.5	6.4	6.3
Pitch angle					
V= 3 kt	12.4	12.7	13.1	14.0	14.2
V= 6 kt	14.8	15.1	15.6	16.7	16.8
V= 9 kt	16.4	16.7	17.2	18.5	18.6

The fact that roll and pitch amplitudes are almost equal but pith period is about half the roll results in pitch accelerations almost four times the roll acceleration and explains the constant worry expressed by ship constructors and ship operators during the XVII century that the ships broke their masts in stormy seas. (GARR)

Uncoupled, tangential accelerations due to roll and pitch can be estimated for any point at a distance R from each center of rotation.

$$A \text{ tangent} = (\text{Angle in radians})\ R\ (2\ \pi\ /\ \text{Period})^2,\ m/s^2$$

The lower main mast of these ships reached about twice the breadth above the center of rotation. With these figures, the accelerations at the lower mast head for average values of GM =1.5 m and V = 6 knots would be, in m/s^2:

	Trinidad	*Victory*	*Vaisseau-74*	*Montañés*	*Bellona*
Acc. Roll	2.27	2.31	2.72	2.70	2.71
Acc. Pitch	7.80	7.55	7.28	7.98	8.31

Roll accelerations are higher in 74-gun ships than in the First Rate vessels.

Maximum accelerations at the topmast head would double these figures, and the effective spring effect of the stays can be understood.

Hull structures of Romero Landa's Ships

Five of the ships in the Spanish squadron at Trafalgar were Romero Landa's designs.

- *Santa Ana*, 112 .... Ferrol, 1784-1816
- *Príncipe de Asturias*, 112 .... La Habana, 1794-1812
- *San Ildefonso*, 74 .... Cartagena, 1784-1805-1816
- *Monarca*, 74 .... Ferrol, 1794-1805
- *San Leandro*, 64 .... Ferrol, 1787-1812

Calculation of hydrostatics was done using trapezoidal integration which resulted in significant errors. Actual displacement was over 11 percent heavier than calculated and metacentric radius was overestimated by about 20%. However, since the preparation of a ship for navigation was done afloat and using a practical approach, the importance of these errors was more academic than practical for the final condition of the ships going to sea, especially in relation to the ballast that amounted to some 13.5% of the displacement. (JMJG, 2-43)

Sea water density as measured by Jorge Juan was taken as 779 ounces (460/16 gr each) per cubic foot of Burgos (278.63 mm cubed), which equals 1.035.

The *Reglamento de Maderas Necesarias para la Fábrica de los Baxeles del Rey*, published by Romero Landa in Madrid, 1784, (ROME) specified the number and dimensions of the members of the hull, equipment, masts and rigging for ships of 100, 74, 64 and 34 guns.(JMJG)

For 100-gun and 74-gun ships that fought at Trafalgar, the number of pieces and their scantlings given in Spanish inches of 23.2 mm were:

Number of guns	**100**	**74**
Keel, pieces	5	5
Transoms	2+9	2+8
Counters	12	12
Breasthooks	7	5
Floors	63	63
Rider floors	15	13
Beams, hold	43	43
Beams, gundeck	31	31
Beams, 2nd deck	36	36
Beams, 3rd deck	36	—
Hanging knees, hold	38	32
Hanging knees gundeck	64	64
Hanging knees 2nd deck	70	70
Hanging knees 3rd deck	60	—

Number of guns	**100**	**74**
Lodging knees, 2nd deck	24	24
Lodging knees, 3rd deck	16	—
Scantlings	100	74
Keel	24×22	21×18.5
Stem	24×22	21×18.5
Breasthooks	17.5/16	16.5/15
Sternpost	30/22×22	29/20×22
Main transom	23	20
Fashion pieces	16	15
Floors, futtocks	16.75	15
Riders	16.75	15
Beams, hold	16.26	15
Beams, gundeck	18.5×17.3	18.5×17.3
Beams, 2nd deck	17.5×16.25	15
Hanging knees, hold	14	12.5
Hanging knees, gundeck	14	14
Hanging knees, 2nd deck	11	11
Lodging knees, 2nd deck	10	10

Actual scantlings of the ships were different, as given below in Spanish inches (JMJG).

– *Santa Ana* (112 guns)

	Width	Mold	
Timbers, gundeck	15	16	
Section spacing	12-6		frame stations
Frame (room)	30		2 timbers
Space (gap)	7.5		
Beam gundeck	18.5	17.5	
Knees	14	14	
Beam middle	17.5	16.5	
Knees do.	11	11	
Beam high	15.25	15.25	
Knees do.	11	11	
Beam quarter	12.5	9.5	
Knees do.	11	11	

7 anchors: 82 + 78 + 77 + 76 + 68 + 38 + 32 qt = 451 qts = 45100 lbs.

(1 qt = 100 lbs = 46 kg; 1 ft = 278,63 mm; 1 in = 1/12 ft = 23.2 mm)

The *Santa Ana* was launched with drafts 20ft aft and 14ft-5in fore.

The *Conde de Regla* (112, La Habana, 1786) had 11in hogging when launched.

The *San Hermenegildo* (112, La Habana, 1789) had 11in hogging when launched.

The *Real Carlos* (112, La Habana, 1787) was launched with drafts 19-6 aft, 12-6 fore

The *Reina Luisa* (112, Ferrol, 1791) was launched with drafts 21-7 aft and 13-6 fore.

The *Príncipe de Asturias* (112, La Habana, 1794) was launched with 11-4 fore.

Al these ships sailed at full displacement with drafts of 28ft aft and 26ft fore.

– *San Ildefonso* (74 guns)

(pie-pulgada of Burgos, ton-quintal-libra of Castilla)

(1 pie = 278.63 mm = 12 pulgadas; 1 ton = 20 quintales = 2000 libras = 920 kg).

Length	190
Breadth	52-0
Depth	25-0
Draft aft	24-4
Draft fore	22-10
LCB	2-11.25 forward of midship
Displacement	2933-1190

The *San Telmo* (Ferrol, 1788) was launched with drafts 19-2 aft and 13-5 fore.

The best waterline for the *San Telmo* was found in her sea trials with drafts 24-4 aft and 22-10 fore, using 6000 qq stone ballast and 6300 qq iron ballast.

Heel with hard winds caused the gundeck freeboard to drop from 6-9 to 3-6 on the leeward side.

The *San Francisco de Paula* (Cartagena, 1788) sailed on her best waterline with drafts 24-8.5 aft and 22-9.5 fore, using 6800 qq of stone ballast and 5691 qq of iron ballast with 1003 qq of mortar.

The *Europa* (Ferrol, 1789) was launched with drafts 18-10 aft and 14-3 fore.

Three sister ships *Intrépido* (Ferrol, 1790), *Infante D.Pelayo* (La Habana, 1791) and *Conquistador* (Cartagena, 1789) were given to the French in 1801.

Station frames were centered on molded sections, or design stations, that were spaced 11ft-8in (3251 mm) and ran uninterrupted from the keel to the upper rail.

Three filling frames were laid between two station frames, each built up of two timbers with 30 in siding that left 5in (116 mm) space between frames.

Space between frames was filled with pine, cedar or other soft wood pieces from 3 ft below the waterline to 2 ft above it.

Ballast in iron was placed in approximately 20% of the length amidships, surrounded by stone ballast to form a ballast coffer held with chip wood.

From the head of 1st futtock to the keelson the space between floor timbers was widened by 1.5 inches (35 mm) at the inner face of the floors and futtocks so that the iron ballast would be born by the sides of the timbers and not by the outer shell.

The procedure to lay the ballast was as follows. Tar (*brea*) was applied to the timbers that were to receive the ballast. A layer of lute (*zulaque*) 4in thick was the applied up to the floor heads. Then ground brick was added in alternate layers with iron and fine mix to fill up the space up to 1ft above the floor heads. Above this point, only the mix of gravel and brick was laid up to the heads of 1st futtocks. This system was applied from station 16 aft to station 13 forward. The length of the ballast at the ends of the hold diminished to station 24 aft, where length of iron was 5ft and the length of mix 9.5ft, and to station 21 forward where the length of iron was 4ft and the length of mixture 7.17ft. The very ends of the hull were filled with hardwood to support the bolts.

The total weight of ballast applied by this system to the *San Ildefonso* was 82.65 tons, composed of:

Lime, brick and stone walls	89250 lb
Tallow and tar	3000
Lime for the lute	7500
Tallow for ditto..............................	1066
Small ball shots and iron	64500 lb

Scantlings in *pulgadas* (23.2 mm)

	Width	Mold	
Timber	14		
Frame = 2 timbers	28		
Space (gap)	12		filled in way of the waterline
Keel	18	20	
Keelson	18	14	
Stem	18	20	
Stern post	18	30/19	
Floor	14	15	
Floor rider	14	14	
2nd futtock	14	14.5	
2nd rider	14	13.5	

	Width	Mold	
4th futtock	14	14	
4th rider	14	13.5	
Breasthooks	14		
Hold beam	13	13	
Hold standard	11		
Gundeck beam	16	17	
Hanging knee	12		
6th futtock	14	13	
Upper timber	14	11.5-7.75	
Upper beam	12	13	
Hanging knee	10		
Gundeck girders	9	10	3 on each side
Upper deck girders	8	8	3 on each side
Planking			
Outer bottom		4.75	
Growing to		8	to join the main wale
Main wale		8-9.5-8.5	8 strakes from hold beams to upper port sills
Waterway gundeck	15	15	shaped as a knee
Waterway upper	13	13	ditto.
Waterway qrterdk	9	9	ditto.
Inner ceiling hold		4.75	interrupted by “thick stuff”
Thick stuff		7	3 strakes
Inner shell hold		5-9	at gundeck beam shelf (clamp)
Inner shell gundeck		7.5-4.5	spirketting and planks
Upper deck clamps		7	
Inner shell upper		5-3	spirketting and planks
Quarterdeck clamp		5	
Lower deck		2	on hold beams
Gundeck		4	
Upper deck		3.25	

To allow for ventilation of the beam heads and the space between the outer shell and the inner planking a 1 in to 2 in gap was left at the inner strakes at the side between the filling pieces or the lodging knees and the waterways.

The structure of the *San Ildefonso* differs from British 74s like the *Bellona* (LAV2) and the *Thunderer* (DOMO), and also from French *74s* (BOUD). It has much wider spaces between frames (12 in vs 3 to 5) and the planks, outer and inner are smoothly tapered from the garboard strake to the wales and to the rails, thus reducing the frictional resistance of the hull.

José de Mazarredo reported on the *San Ildefonso*, after the sea trials run with the *San Juan Nepomuceno* in the summer of 1785 (JMJG,2-211):

> "The poop is too simple. Ledges 8in wide and 5in with planking 2in thick were warped by sun heating, which opened the seams and rotted the deck structures. When pitching in medium wind the mizzen topsail sheets pulled the poop deck upwards dismantling the supports of the wheel like I had never seen in any other ship before".

The design of the *Monarca* (R.Landa, Ferrol, 1794) was followed by the *Montañés* (Ferrol, 1794) a design of Julián Martín de Retamosa who narrowed the lines of Romero de Landa. With 180 tons less displacement the *Montañés* had 5in more draft forward and 3in more draft aft than the *San Ildefonso*. An immediate result of this was to reduce the hogging of the hull as underwater volume was shifted from midships to the ends and therefore it was more evenly distributed along the keel.

The Spanish Navy was eagerly pursuing the best design of their 74s. Thorough sea trials were conducted to compare the *Monarca* and the *Montañés* in order to select the best solution. Although the *Montañés* sailed better than the *Monarca* except with following or head winds, the results of the trials were not conclusive and the Junta held in Cádiz on 12 Dec.1794 on board the *Conde de Regla* decided that *"it is not convenient to select one construction system so that the progression leading to the perfection of the Naval Architecture is not obstructed"* (MNM,Ms.2322).

<u>Effect of arming/disarming afloat on hull structures</u>

The *San Ildefonso* (74, Cartagena, 1784) was launched with drafts 19 aft and 13-3 forward.

The hull was hogged by 11in in lightship condition.

Arming of the ship consisted in embarking masts, sails, guns and other weights that represented some 25% to 30% of the standard displacement of the ship.

Since this weight can be assumed uniformly distributed along the length of the hull, longitudinal bending stresses produce normal and shear deformations that add to the ones generated at launching.

A simple model of the ship can help understanding this situation.

San Ildefonso (74)

Section spacing			=	11ft-8 in	=	3251 mm
Frame room, 2 timbers	=	2×15	=	30 inches	=	697 mm
Space between filling frames (gap)			=	5 inches	=	116 mm

Cruising and Launching Drafts (JMJG)

- Drafts: coded as “FFII” = Feet-Inch (Burgos), to base of keel.

  Thus, a draft of 1909 menas 19 ft 09 in of Burgos.

  1 ft of Burgos = 12 in = 278.63 mm

- Displacement, Ballast: in Toneladas of 2000 libras = 920 kg

- Tonnage: (L+K) (3B+D) D/144, with Length, Beam, Draft in Sb-cubits

  Sb-cubit = shipbuilder’s cubit = Burgos Foot × 33/16 = 574.68 mm

Hogging measured after launching

	Cruise Draft		Tonn	Displ.	Ball.	Launch Draft		Hog at launch
	Aft	Fore				Aft	Fore	
S. Trinidad	2907	2700		4903	1000	2005	2004	
Santa Ana	2801	2601	2308	4342		2000	1405	109
San Josef	2908	2708		5167				
S. Hermeneg.	2802	2602	2308					11
Reina Luisa						2107	1306	
Conde Regla	2802	2602	2148	4342		1909	1300	11
Príncipe Ast.	2800	2600				1900?	1104	
San Ildefonso	2404	2210	1620	2934		1900	1303	11
Monarca	2404	2210	1640			1901	1400	
Montañés	2603	2404						8
San Telmo	2404	2210			615	1902	1305	
San Leandro	2305	2201	1466			1806	1300	

The *SantísimaTrinidad* data are after rebuilding and careening in 1795.

Some of the ships that survived Trafalgar were lost due to lack of maintenance and careening. Such were the fates of the *Conde de Regla*, sunk in La Carraca in 1811 and the *Príncipe de Asturias* and the *San Leandro* that sank in La Habana in 1812.

The base line of the molded lines plan is located at the upper edge of the keel rabbet, therefore to obtain molded drafts the drafts given in the references must be reduced on the average by:

Vessels above 90 guns .... 350 mm

74-gun vessels .... 250 mm (300 mm the *Bellona*)

Launching and Floating Out

From land to water

Keel blocks in a slipway of an 18th century dockyard had a slope that varied from 1/12 (or one inch per foot) to as much as 1/8. This slope was close to the trim of the light hull when it was launched by the stern, and justified launching this way since the reactions under the pivot point at the stem were small and sagging could be avoided. Stern launching had substituted stem launching used in the 17th century, when warships were built on temporary slopes and beaches. Then, the hull was laid with her bows towards the sea and the launching required that a considerable force be applied to the stern post using complex manoeuvring gear and tackling that involved many people and oxen. Then the hull had to descend a longer way down until enough draft of water was found at the stern, and the hull was subjected to sagging during the long pivoting phase of the launching. However, this sag would compensate the "natural hog" due to the full midship sections.

Floating a hull in a drydock, either after construction, careening or repair could impose similar stresses on the structure. An important difference was that the drafts could be changed more slowly and the trim could be controlled better, since the hull could be floated with zero trim if so desired.

Nevertheless, being borne to the sea by stern launching at a slipway or by floating out in a drydock, the hull was subjected to hogging stresses produced by the unbalanced distribution of weights and buoyancy along the ship length.

Lightship condition

Light ship condition in launching would include the lower masts but not the ballast or other hull outfitting and the keel was bent upwards in hogging as much as one foot in a 74-gun ship. This distortion was greater when the hull structure was still loose or some upper longitudinal members were still missing. However, when the ship was floated in a repair drydock the ballast was kept within the hull and both trim and hogging were reduced.

The *San Ildefonso* (74) was launched with 19ft-0in draft aft and 13ft-3in draft fore, and her sister ship *Europa* floated with 18ft-10in draft aft and 14ft-3in draft fore.

The trial condition of these ships was with 24ft-4in aft and 22ft-10in forward, and their arming and fitting, including ballast would reduce the hog to 8 to 4 inches amidships.

At her launching, the *Montañés* (74) floated with molded drafts of 5800 mm aft and 4100 mm forward (MEJI) that gave her a molded displacement of 1704 m^3 with 17.6 m^2 submerged midship section area. In trials she sailed with molded drafts of 7064 mm aft and 6530 forward and underwater volume of 2858 m^3, with 21.43 m^2 submerged midship section area.

This differential sectional area curve was to be balanced by the difference between full load or trial displacement and lightship condition, which was made up of outfitting, arming, men and consumables plus the ballast. It can be seen that the effect of these weights would be to add a sagging moment thus reducing the hog at launching. The sagging effect would be somehow reduced by the hogging effect of the movable ballast that was located at the ends of the hold.

The molded draft of the *Santísima Trinidad* in full load condition was 7893 mm aft and 7173 mm fore, which gave her a molded displacement of 4682 m³. In 1795 she left drydock number 2 in Carraca with her keel almost levelled at 5328 mm molded draft, which gave 2807 m³ displacement.

The section area curve at launching shows a steep increase of areas from 4.9 m² aft to 68.9 m² amidships that would have caused a high hogging moment unless ballast was added along the center half length.

Hull structure weight

The weight of the hull can be estimated as a function of the length of the timbers and their scantlings. The distribution of wood along the ship length will follow a curve that is proportional to the distribution of the length of timber in each cross section of the hull.

For a given scantling, the length can be taken as proportional to the length of the frame contour up to the gundeck. Transverse elements not belonging to the contour, such as beams, knees and other transverse members within a cross section can be assumed proportional to an equivalent length that is a function of the cross section area. These weights represent about 50% of the weight. Therefore, curves for hull weight can be estimated for some representative ships of Trafalgar, as shown in the following table that presents frame length and area of the two sides, calculated at quarter points of the length for each ship.

Figures assigned to the perpendiculars actually belong to the last sections, next to the ends and are essential to draw the weight distribution curve at the ends.

Cross section areas are molded, to the level of the lower gun sills, assumed at 1.8 m (or 6 ft) above the molded draft at midlength for all ships.

	Trinidad	*Victory*	*Vaisseau-74*	*Montañés*	*Bellona*
– T sills, (m)	9.30	8.00	8.30	8.60	8.00
– Frame Length (m)					
AP	23.13	24.55	19.70	20.65	20.54
0.25 L	26.50	23.60	22.60	23.22	22.38
0.50 L	24.66	21.95	24.09	24.97	22.88
0.75 L	27.84	24.80	23.40	24.06	23.68
FP	18.63	15.42	17.30	14.83	15.18
– Section area (m^2)					
AP	34.16	16.04	20.41	20.99	18.87
0.25 L	110.00	92.00	79.08	81.71	77.73
0.50 L	131.40	112.42	102.92	99.28	96.86
0.75 L	122.46	104.5	87.40	91.61	92.49
FP	42.95	36.30	33.38	23.83	28.54

Taking the maximum values equal to 100 we obtain the following normalized hull weight curves for the five ships:

	AP	0.25 L	0.50 L	0.75 L	FP
Length	83.1	95.2	88.6	100	66.9
SQR(area)	51.0	91.5	100	96.5	57.2
Total *Trinidad*	68.2	94.9	95.9	100	63.1
Length	99.0	95.2	88.5	100	62.2
SQR(area)	37.8	90.5	100	96.4	56.8
Total *Victory*	69.6	94.6	96.0	100	61.6
Length	81.8	93.8	100	97.1	71.8
SQR(area)	44.5	87.7	100	92.2	56.9
Total *Vaisseau-74*	63.2	90.8	100	94.7	64.4
Length	82.7	93.0	100	96.4	59.4
SQR(area)	46.0	90.7	100	96.1	49.0
Total *Montañés*	64.4	91.9	100	96.3	54.2
Length	86.7	94.5	96.6	100	64.1
SQR(area)	44.1	89.6	100	97.7	54.3
Total *Bellona*	66.1	93.1	99.3	100	59.8

These curves show that the newer constructions had their maximum weight section abaft the older ones, and the latter are fuller in shape. They can be used for analyzing the hull bending in launching, floating out or careening afloat.

<u>Disarming and Careening</u>

– Disarming

  After a campaign at sea, a ship was disarmed and handed in to the dockyard master (port captain) for conservation.

  Essentially, disarming consisted in dismounting and disembarking from the ship everything but the hull structure, the ballast, the lower masts and the bowsprit. Thus, the following parts and elements were normally taken away and stored at the dockyard:

  - Guns, carriages and shots, hand arms and weapons
  - Anchors and cables
  - Barrels, all tools and implements
  - Spares and repair parts
  - The rudder
  - Upper masts, yards and sails
  - The rigging and blocks
  - The hearth
  - All consumables, movable elements and furniture.

In the disarmed condition a 74-gun ship would float with 2.6 m above the water at midships, i.e. 1.0 m higher above the water than in full load condition, where the gundeck sills were 1.62 m above the waterline. (BOUD)

In order to reduce hogging deformation of the hull, the two ends could be supported by floating box-like devices that supplied the needed buoyancy.

Disarming a warship was justified by the increase of useful lifetime that many elements composing the ship would gain when disarmed. The table below (BOU,vIII, 246) gives the expected lifetime with annual maintenance of 1/100 the value of the ship in armed and disarmed conditions:

	Armed	Disarmed
Hull	10	15
Copper sheathing	5	10
Masts and yards	8	20
Sails	3	12
Rigging	3	12
Blocks	6	15
Cables	4	12
Barrels	8	12
Pumps	20	24
Boats, launch	4	12
Gun carriages	16	24
Guns	40	50
Anchors, ballast	40	50

These figures show that the maximum service lifetime of the hull was reduced by 1/3 by staying at sea, or in other words, 2 months at sea would reduce by 1 month the predicted life of the hull. Sails, rigging and cables were more perishable at sea but had no direct influence in the duration of the hull itself, although they could have an effect in the response of the hull to sea loads, and hence in the lifetime of the ship.

– Careening

Careening of the hull was normally done afloat. After taking away some guns, shifting others to the lower side and securing other moving parts on board, the hull was inclined until the keel was exposed above the water. This operation was done hauling down the masts from other ships, from flat floating pontoons or from the shore. Previously, the hull was reinforced internally with false gun ports and cross struts that joined the beams, the bilges and the keelson. Special attention was given to providing lateral support to the masts so that the decks were not strained.

The ballast and other heavy items onboard were shifted to the lower side and ballast was laid forward in order to get a horizontal keel above the water without the need to use an excessive pull on the fore mast.

The result was bending of the inclined hull that was stressed in hogging more than in the upright condition. It was common practice to mend the caulking of the upper plank seams after careening. (GARR, c.19)

This hogging stress was significantly higher when the ship “gave her side” (*dar lado*) over a floating pontoon or was “put up hill” (*dar monte*) by inclining her on a sandy beach or slope. (GALA)

In 1767 the straining and hogging of the hulls during careening afloat over a pontoon was still a matter of concern during the discussion that compared English and French constructions in Spain. (MNM, Ms.1249)

The most complete careening consisted in replacing the shell planks and exposing the frame timbers or “firm” hull (*carena de firme*). Partial careening was done when quick repair of a leaking hull was necessary; then caulking was renewed and only the planks found rotten or damaged were replaced.

Hull Materials

The Appendix to this chapter includes tables with the mechanical properties of several wood types showing the effect of Moisture Content, duration and orientation of load to grain (WOOD, 2-6).

It is noteworthy that Mahogany can accept higher shear loads and greater bending energy when wet than dried. Virginia Pine has slightly better tearing resistance wet than dried.

Properties of elm used for keels were comparable to those of oak.

Most woods have a shear capacity perpendicular to grain much higher than parallel to grain and they fail by crushing under the shear force before. Besides, radial and tangential shear parallel to grain may differ much for some tree species. Tests of western juniper have shown tangential shear strength 1.3 to 1.45 times its radial shear strength. (BURK)

Since wood is an orthotropic material with 3 different strength axes, Young modulus will be different in each direction, and three values of Poisson modulus have to be considered that will give three different values for the shear modulus G.

For longitudinal (L), radial (R) and circumferential or tangential (T) directions, the values of E for spruce and beach are given in 1E8 Mpa in the Appendix (BUC1).

Stress waves in Wood

The response of wooden members of the hull to dynamic loads is dependent on the speed with which stress propagate across the material.

Non-destructive evaluation techniques are commonly used to inspect large timber members of all kinds of structures, including historical buildings and ships. In 1997, historical *USS Constitution*, launched on 21st Oct.1797, was restored using a methodology developed by the USDA Forest Product Laboratory based in the known fact that stress waves travel at speeds that are much slower in deteriorated wood than in sound wood (ROSS).

The success of this technique for locating deteriorated zones in timbers confirms that damaged wood is lazy to propagate stresses through it. This is coherent with the fact that the capacity of wooden hulls to resist loads is significantly reduced after the wood has been subjected to stresses that have damaged some regions.

The result of partial damage is then a reduction of the hull strength that can be related to the service life of the ship expressed in terms of cumulative damage.

The speed of stress wave propagation in wood varies with angle to grain for different types of wood and moisture content (MC):

	Speed of stress wave, microsec/ft		
	Perpendicular		Parallel
	Sound /	Severe decay	Sound
Douglas Fir, creosoted	260	1300	
Birch, 6%MC	212		58
Red oak, 6%MC	185		60

These figures relate to the speed of sound in wood. For solids, the speed of sound can be formulated as:

$$V = \sqrt{(\text{Young modulus, N/m}^2 / \text{density, kg/m}^3)} \quad \text{(m/s)}$$

This expression gives average values in m/s for some hull materials:

Iron	5950		
Wood	Along fiber	Across ring	Along ring
Pine	3320	1400	790
Oak	3860	1540	1290
Elm	4460	1500	1140

Moisture content is the amount of water absorbed by the wood related to its dry weight. The fibers reach their saturation point at around 25 to 30 percent MC.

The value of MC can be related to relative humidity after a long exposure by a curve giving:

5% MC	for	20% RH
10		55
15		75
20		85
25		92
30		100

When wood dries from fiber saturation of MC=30% to MC=0, shrinkage occurs mainly in the tangential and radial directions of the timber. Circumferential shrinkage can reach 9% in larch while radial shrinkage is only 4.5%. Pine and spruce are more stable.

Dynamic Loading

Under dynamic 3-point bending loading, crushing strength of wooden plates depends on the strain rate, as shown in (BUC2) by the linear function:

$$\sigma = \sigma\_static + \alpha \times \text{Unit strain velocity}$$

Static σ was found equal to 78 MPa for oak and pine, but coefficient α was 0.0657 for oak and 0.406 for pine for strain rates from 500/s to 1200/s.

Although it is generally accepted that the strength of wood under impact is about 20% higher than under static loading, tests run at Mendel University in 2000 have given values that vary from 100% to 200% increase for spruce and beech in compression with strain rates from 1E3/s to 1E4/s, results that invalidate previous design values. (BUC1)

Impact Loads

When a ball impacts a wooden beam it takes some time for the stress wave to travel to the end support of the beam and back to the impact point. Therefore, the effect of the boundary condition of the beam at the support can be neglected when the contact of the impacting ball ends before the return wave reaches the impact point. (RUSS)

In ship hulls the velocity of the shot ball takes longer to pierce the wooden walls than the stress wave to rebound on the supporting timbers and the way the planking is supported plays some role in the response of the sides to impacts.

The speed of the ball during penetration was about 300 to 200 m/s while the velocity of the stress wave would be about 3000 m/s. Therefore, the stress wave rebounds and reaches the ball when the span between supports is ten to fifteen time the penetration of a zero-width projectile. For a space between frames of 20 inches the stress wave would reach back the projectile when it has pierced 2 to 1.33 inches into the wood and the supports would influence the response of the wood during the rest of the penetration. Actual frame spaces were smaller and real size balls would cause the supports to have a certain influence on the process.

High speed impact response of composite materials such as wood presents three major failure modes: punching shear, tensile fiber breakage and delamination. They occur in successive stages across the thickness of the material. The relative thickness of material responding to each mode depends on the impact velocity and determines the share of energy that is absorbed in the penetration process and the deceleration of the ball as a consequence (LANG). These three failure modes were observed in the series of tests carried out at ETSIN-UPM in 2005 and are reported in this paper.

Load Duration Factor

Wood can accept different load levels depending on the duration of its application.

Higher stress can be resisted for a shorter period of time.

The duration of the load is defined as the total accumulated length of time that the full design load is applied.

Appendix B of the US National Design Specification for Wood Construction (NDS) gives the curve for the Load Duration factors based on Cd=1.0 for 10 years "normal" duration.

$$\mathrm{Cd} = 2.0 - \frac{\log(\mathrm{T})}{8.5} \text{ for T in seconds}$$

The design values given by NDS apply to a standard cumulative load duration of 10 years. For other cumulative load durations, the designer should apply other appropriate Cd factors.

The NDS curve gives Cd=2.0 for instant, impact loads, Cd=1.6 for 10 minutes loading, 1.25 for 7 days, 1.15 for 2 months, 1.1 for 1 year and 0.9 for permanent loads..

As an example based on this criterion, if a structure is designed for 1 year of normal cumulative load of a certain value equivalent to Cd=1.1, that "cumulative" load level should be reduced by 10% for the structure to last 10 years, but that level could be increased by some 10% if the structure was designed for only 10 days of cumulative load application.

Partial loads and partial durations

If a load combination that is applied for a shorter period of time is lower than the allowed product of (Cd for that duration) × (design for 10 years), that leaves the material with extra duration that can be used by other loads.

Let us assume a case where a load with duration factor C1 is applied for a period of time T when it could be accumulated to a total length of time T1.

The material has used a fraction T/T1 of its allowed life. All that rests is a fraction of its service life under load = 1 – T/T1.

If the remaining fraction of life is to be spent under one only load, the allowed intensity of that load will be given by the duration factor C2 with a limit time T2 and could be applied for a cumulative length of time X such that X/T2 = 1 – T/T1.

In general, each load (i) with a duration factor C(i) can be applied for a accumulated length of time T(i) equal or less than their limit length of time T_limit(i), with this limiting condition:

$$\text{Sum of all} \left[\frac{\mathrm{T}(\mathrm{i})}{\mathrm{T\,lim}(\mathrm{i})} \right] = 1$$

For the ships of Trafalgar, the cumulative effect of all loads taken by the hull during its service life could be estimated based on the values of the design loads and the loads imposed by the sea and the battles during the life of each ship.

Design loads can be estimated with relation to "design sea conditions" acting on a structural model of the ship. Then, extreme loads could be estimated so that the equation above is satisfied.

Mechanical Model

A Mechanical Model for the analysis of the effect of bolts and treenails in the structural response of wooden hulls.

Side shell

A wooden hull subjected to longitudinal bending does not behave like a beam built of continuous parts of isotropic homogeneous material such as steel, aluminum or even multilayered FRP. A wooden hull is split into layers and pieces that are loosely joined together at a finite number of sparsely distributed locations.

Shell planking of wooden ships is connected to frame timbers, floors and futtocks by treenails and bolts driven on transverse planes. Timbers are joined in pairs to form rigid transverse frames using bolts driven along a longitudinal axis.

The joint between each pair of timbers in a transverse frame is rigid as long as the bolts joining them resist tension and shear, up to a value of normal and shear stresses below the yield strength of the bolts, and as long as the timbers resist the clamping stress and the bearing stress imposed by the shear and bending of the bolts. Only to those limits can a pair of timbers be considered one single frame with regard to the structural rigidity of the hull.

One shell strake can be assumed rigidly joined to a frame while the dowels joining them resist the shear load imposed by the bending of the hull in hogging or sagging. Since shear is applied to frames perpendicular to the grain it causes no damage. But the shell receives longitudinal shear parallel to the grain where the resistance is lowest. However, crushing forces on the treenails and bolts were applied parallel to the grain in the shell and perpendicular to the grain in the frames.

Ships of the line of the 18th century had their hull normally deflected by hogging due to the usual distribution of weights and buoyancy along the length. Thus, the shell plating above the neutral axis was subject to tension and the lower hull to compression.

Since butts of shell strakes were fitted very tightly they were good for resisting compression forces while their dowels did not have to resist much shear. Therefore, lower side and bottom planking could be considered fully effective in compression.

But things were different with the shell strakes in tension. There, the dowels had to resist the forces that tried to open the space between frames and separate the top timbers. Therefore, the effectiveness of these strakes was limited to the strength of the dowels subjected to tension by or against the frame timbers.

The result of this behavior is that the transverse area of planking in tension has to be substituted by the effective area that resists one of two main failure modes:

(1) Bearing the dowel shank under crushing while the dowel resists transverse shear.

(2) Bending of the dowel in the timber while crushing the shell plank

A more complete treatment of dowel joint failures is included in the Appendix with application to different types of joint following a methodology recommended by the US National Design Standards (NDS).

Crushing and Shear

For this mode of failure, we can write:

Bearing strength = (crushing stress) × (bearing area) = Compression allowed

Shear strength of dowel = (shear stress) × (cross section area) = Shear allowed

Bearing area in the frame timber was larger than in the shell plank and so the compression allowed was limited by the shell.

For equal limit value of the forces allowed we get:

$$\text{Bearing area} = (\text{cross section of dowel}) \times \frac{(\text{shear stress of dowel})}{(\text{crushing stress of plank})}$$

In other words, in way of each dowel hole, treenail or bolt, the shell plank area that can resist tension is limited to this bearing area.

Therefore, the effective area in tension of the shell can be calculated by substituting the actual cross section area of the plank by:

$$(\text{Cross section of dowel}) \times \frac{(\text{Shear stress of dowel, perpendicular to grain})}{(\text{Crushing stress of plank, parallel to grain})}$$

Where shear and crushing stresses are the limiting values accepted for the dowel and the shell materials, not greater than their proportional limits.

Typical values for treenails give a value close to 1.0 times the cross section of the dowel.

For iron bolts, the factor multiplying the cross section of the dowel would be about 3.8 times greater.

The effective transverse section of the hull can be calculated using this factor and an effective neutral axis can be found that will be much closer to the keel than to the upper part of the hull, and tension in the upper planking would be proportionally increased.

Bending and Crushing

This failure mode involves bending of the dowel in the frame timber and crushing the bearing surface of the shell plank by the unbent shank of the dowel.

The dowel is assumed to bend close to the interface between the two parts.

The crushing pressure can be assumed to vary linearly from zero at the outer face of the plank to a maximum allowable value at interface plane of the joint. For an average distribution with constant value across the thickness of the shell we can write:

Moment of crushing force = (crushing force) × (plank thickness) / 2

Crushing force = (crushing stress) × (bearing area)

Acceptable bending moment on dowel = (bending stress) × (section modulus)

$$\text{Bearing area} = \frac{\text{Bending stress}}{\text{Crushing stress}} \times \frac{\text{Section modulus}}{\dfrac{\text{Plank thickness}}{2}}$$

For a circular section, the section modulus is = (cross area) × (diameter / 16)

Therefore, the cross section of the plank should be substituted by:

$$\frac{\text{Bending stress of dowel}}{\text{Crushing stress of shell parallel}} \times \frac{(\text{cross section}) \times (\text{diameter of dowel})}{8\ (\text{plank thichness})}$$

For typical 2 in treenails and 8 in shells, this value becomes:

1/16 times the cross section of the treenail.

For one 1 in iron bolt, the value of the effective section would be:

1/8 times the cross section of the bolt.

The equivalent section of a bolt results twice the value of the equivalent section of a treenail.

The effective transverse section of the hull and its effective neutral axis can be calculated using these effective areas for the planking.

Shear strength of shell

Each shell plank could resist transverse vertical shear forces with its cross section area if the planking were solidly joined to the frames that carry the shear.

Since planks are joined to each timber by just two dowels (bolts or treenails) the shear force can only be resisted by the cross section of these dowels or the crushing strength of the bearing surface in the plank, whichever fails first.

The Effective Shear Area of the plank can be defined by the ratio:

$$\frac{\text{Maximum Shear Force at a cross section}}{\text{Allowable Shear Stress in the plank}}$$

In ships-of-the-line of the 18th century, frame timbers had larger moulded dimension (height) than the shell planking and therefore the crushing strength of the frame timbers was greater than the planking's.

Therefore, the maximum shear force at a section was the greater of these two forces:

Shear force resisted by the dowel at the interface of the joint.

Crushing force resisted by the shell at the bearing area of the dowel.

Shear Force = (limit shear stress of the dowel) × (section area of the dowel)

$= Sd\ \pi\ d^2/4$

Crushing Force = (limit compressive stress of plank) × (bearing area of dowel)

$= Sc\ b\ d$

- For treenails, Sc = Sd/2, and for b = 4 d (with 2 in treenails) the ratio of these two forces would be 0.40.

  This means that a treenailed joint can accept a crushing force on the plank that is 2.5 times the shear accepted by one 2in treenail.
- For iron bolts, Sc = Sd/4, and for b= 8 d (with 1 in bolts) the ratio of the two forces would be 0.40.

  This means that an iron bolted joint could accept a crushing force on the plank that is 2.5 times the shear accepted by one 1in iron bolt.

Effective shear area of the plank can be estimated now, with the shear of the dowel as the limiting force:

Effective shear area = (Sd/Sp) (section area of dowel)

- For treenails, Sd = 4·Sp, and Effective Shear Area of the plank is 4 times the shear area of the dowel.
- For iron bolts, Sd = 8·Sp and the Effective Shear Area of the plank is 8 times the cross section of the bolt.

Deck planking

The decks of the ship-of-the-line were built with strakes of butted planks nailed to the beams.

As in the shell, accurate butting of the ends would provide enough mechanical continuity of the material to take in-plane compression loads when the ship was sagging. However, in hogging the planks are loaded in tension when the beams pull apart from one another.

Fore and aft deflection of the beams was restricted by the lodging knees. Carlines or carlings added to this restriction in tension only when their ends were dovetailed or bolted to the beams.

In all cases, as in the side shell, in-plane tension on the planks was only applied through the nails, and the effective cross section of the plank in tension can be calculated with the same model derived for the outer shell.

Keel scarphs

Keel pieces of a ship of the line were joined with special bolted scarphs.

Vertical scarphs used by the British and horizontal ones used by the French and the Spanish relied on the same mechanical principle. They combined the effect of butts, hooks, tongue-and-groove and table-and-coak and were rigidly fastened by bolts that joined the two pieces one to another and to the floors and keelson.

Keel scarphs in a hogged ship would be subjected to compression, which would make the joint more secure against water leaking into the hold. However, as the ship was subjected to alternate hogging and sagging there would be tension on the joint. Under tension, the butts would separate, the two pieces would resist mutual compression and shear and the bolts would be loaded by shear while crushing the wood at their bearings.

The effect of the bolts in tension follows the model derived for the shell, but the mechanical model for the scarph in tension should include the compression and shear capacity of the wood.

The total capacity of the scarph would be the sum of the bolt and the wood strengths.

Typical keel scarphs of 74-gun ships would be 4ft-6in long and would have the table-and-coak or the tongue-and-groove cut to 1/3 of the width and the height of the keel that offered 3 internal butts in the joint. Therefore, the effective area of wood compressed in sagging would be 1/3 of the keel section. At the same time, the tables or tongues would have to resist the shear stress imposed by the tension on about 1/3 of the longitudinal section of the scarph.

The scarph would be fastened with 8 clenched iron bolts 1-1/4in diameter (LAV3, 80) and (DOMO, 70). They would add shear and bearing strength to the joint that can be estimated using the same mechanical model derived for the side shell.

Frame timbers

Two timbers were bolted in pairs to form one frame. A 74-gun ship was bolted with 1.5 in iron rods that bore on the timbers in two orthogonal directions. Compression was parallel to grain when shear forces were applied along the timbers, as the hull would experience in torsion at sea. But the bolts would compress the bearing in the timber perpendicular to grain when shear was applied perpendicular to the frame contour, what could be the effect of large impacts produced by waves, gun shot or grounding on the shell.

Bolts were separated about the room of the two timbers and clenching increased the shear strength of the frame considerably through friction between the two timbers.

Effect of chocks between frame timbers

The *Bellona* had 32.5 inches room and space. For 14 in timbers and 2.5 in chock, a joint using 1.5 in white oak dowel would have a nominal connecting value of 2039 pounds for failure mode IV and 10338 pounds for mode III. The use of 1.25 in iron bolts would reduce the joint capacity by 10% for mode III but would increase the value for mode IV by another 10%.

The connecting value of the joint would be increased by 20% for failure mode III and by 100% for mode IV if there were no gap between the timbers.

Cross chocks for frames

Pentagonal wooden chocks were used to connect the head of one futtock to the foot of the next and so obtain a longer timber. The joint was a double plain scarph. Length of one chock was about 2 times its width, which provided room for two 2in treenails, one fastening each “wing” of the chock to one futtock. (DOMO, 71-73)

Although the treenails could resist shear and crushing along the scarph, there were only two of them and that type of shear could only be produced by axial tension or compression of the timbers, which was prevented by the other half frame bolted alongside.

The main purpose of the treenails was not structural but continuity of the timber and a better quality of the joint compared to a plain butt. They connected more easily the ends of the timbers and protected them. These treenails were not meant to confer bending strength to the joint since the ends of the two futtocks were rigidly fastened with 4 clenched 1.5 in iron bolts to the middle of the futtock laid alongside.

Hanging knees

These pieces were essential to the transverse rigidity of the frames. Fixity of the beam ends was only possible through these members that connected the beam to the side structures.

Although small hanging knees could be fastened under the beam the ships-of-the-line had larger knees with the horizontal arm bolted alongside the beam. This arrangement placed the foot of the knee higher above the deck and helped support the deck plating under the guns.

Each arm or leg of the knee was bolted with four or five 1in iron bolts staggered and clenched. Bolts were spaced from 12in to 15in

The main purpose of the hanging knees was to confer transverse strength to the frame to resist transverse loads on the sides, vertical loads on the beams and raking loads from waves and wind. Their effect was restricted to the transverse plane.

The degree of fixity that a knee would provide was directly dependent on the length of the arms and the rigidity supplied by the bolts.

Assuming perfectly rigid frames, the end moment capacity of a knee is the product of the forces resisted by the bolt multiplied by the distance of the bolts to the corner.

Each bolt could resist a force that was the lowest of three possible modes of failure:

- Shear of the bolt at the interface with the beam.
- Crushing of the bearing in the beam or the knee.
- Bending of the bolt and crushing of the bearings in the beam or the knee.

The mechanical model for these types of failure is similar to the model proposed for the side shell and the limit force for each bolt can be formulated as follows if friction forces at the interface are ignored:

- Maximum shear force = (bolt section) × (limit shear stress)
- Maximum bearing force = (bearing surface) × (limit crushing stress)
- Maximum force for bending and crushing = the greater of the two values:
- For bending: (bolt strength modulus) × (limit bending stress)
- For crushing: (bearing area) × (limit crushing stress)

The vertical leg of the knee would respond to similar loads and stresses and its vertical shear capacity can be calculated using the same formulas.

Lodging knees

Since the 17th century, horizontal knees were fastened to the ends of the beams and to the frames. They were bolted to the side structure through shelves, clamps, frame timbers and shell planking and wales. The fore and aft leg could fill the space between one beam and the next or its hanging knee, but it could also leave a space if the beam spacing was too wide. The transverse arm about 5ft long was bolted alongside the beam and to the hanging knee if there was one on the opposite side.

Lodging knees served a dual structural purpose. The first one was to form a rigid connection of the beam heads with strong longitudinal members of the hull at sides that provided bending strength in the horizontal plane. The second purpose, as important as the first, was to clamp several frames together in a bundle adding lateral rigidity to the effect of wales, waterways and clamps. Thus, frame timbers were held together against longitudinal tension produced by hogging and the effectiveness of the shell planking as part of the hull girder was locally increased.

Hooked Wales and Planking

The design of hooked joints in side planks and wales must take into account the ratio of compressive strength and shear parallel to grain. Thus, the dimensions of a tooth of a dented joint should comply with the equation:

$$\text{Height} \times \text{compressive strength} = \text{Length} \times \text{shear strength}$$

For oak and pine the ratio compressive / shear strength is approximately 3.0.

Therefore, teeth designed for tension should be at least three times longer than high.

Similarly, the oblique seams of hooked joints used in wales and other longitudinal thick stuff should have in general a slope less than 1/3.

Treenails, bolts and nails of a 74-gun ship

French 74's hulls generally used the following solutions (BOUD, vIII, 140):

- Iron nails for planking with square heads.
- Total length = 9/4 plank thickness
- Length through plank = 4/9; length into timber (frame or beam) = 5/9
- Shank diameter = length / 20
- Shell planks of 4in (108 mm) used 9in (243 mm) with 12 mm diameter.
- Longer nails of 7in (189 mm) to 30in (810 mm)
- Medium nails of 4in (108 mm) to 7in (189 mm)
- One iron nail of 15in (405 mm) weighed 1.050 grams.
- Iron bolts (*goujons*) were used to join every pair of frame timbers together.
- They were round or square with 27 to 30 mm side or diameter.

- Clenched long iron bolts (*chevilles*) joined pieces forming the stem, sternpost and deadwoods.
- They were square or round and were fastened with 2in forelock.
- Maximum length was 12 ft (3900 mm) with 40 to 50 mm diameter.
- Shorter ones were 27 mm diameter
- Treenails (*gournables*) joined each pair of frame timbers together.
- Their diameter was the width of the timber/12.

<u>Application to the *San Ildefonso* (74)</u>

The scantlings and arrangement of material in the midship section of the *San Ildefonso* (JMJG, 2-178-179) have been used for these calculations.

The application of this mechanical model to the scantlings of the *San Ildefonso* using the diameters of bolts and treenails used in her hull gives the effective scantlings in longitudinal bending, and the resultant effective neutral axis and section modulus of the hull.

Calculations have been carried out in four cases with different participation of the wooden members in the longitudinal strength of the hull in hogging:

Case 1.- All longitudinal wood is 100% effective. Gun ports and hatch openings are excluded. Gundeck and upper deck are included.

Case 2.- Same material as Case 1. The neutral axis has been adjusted so that all items above it are 50% effective.

Case 3.- Same as Case 2, but the neutral axis has been adjusted so that all material in tension is 25% effective.

Case 4.- Same as Case 3, but with the two decks excluded.

The results are compared in the following table:

	Case 1	Case 2	Case 3	Case 4
Effective area in tension	100%	50%	25%	25%
Effective section area (cm^2)	29206	17074	10838	4474
Neutral axis to BaseLine (mm)	6729	5869	4840	1875
Inertia for bending ($m^2 \cdot cm^2$)	198100	158164	121474	33758
Strength modulus at Keel ($m \cdot cm^2$)	27114	24290	21936	13192
Idem at Upper Deck ($m \cdot cm^2$)	96384	55498	31768	8562

The reduction of area from Case 2 to Case 3 due to lower dowel joint efficiency produces a significant increase of 203% in tension stress at upper deck level, while flexibility of the hull is increased by 63% and the compressive stress at keel by 23%.

Application to the *USS Constitution*

It is interesting to compare these figures with those calculated for the hull of the 44-gun frigate *USS Constitution* of 1797 (MAGO) using the same mechanical model. Since her nickname “Old Ironsides” reflected the condition of a hull that could resist gunfire it will be interesting to know how her hull responded to sea loads:

	Case 1	Case 2	Case 3	Case 4
Effective area in tension	100%	50%	25%	25%
Effective section area (cm^2)	30830	18198	11460	4208
Neutral axis to Base Line (mm)	5392	4853	4129	1687
Inertia for bending ($m^2 \cdot cm^2$)	122000	96828	73720	16014
Strength modulus at Keel ($m \cdot cm^2$)	20308	17704	15538	6956
Idem at Upper Deck ($m \cdot cm^2$)	68646	41814	24250	2922

The loss of rigidity and strength from Case #1 to Case #4 results significantly higher in the *USS Constitution* than in the *San Ildefonso*. However, this frigate was built with no space between frame timbers, which would increase the efficiency of the hull in bending to a percentage closer to 100%.

Scantling to Rules after 1870

The objective of this study is to compare the hull members and their scantling in three ships of Trafalgar with those that they would have if they were designed to comply with merchant ships Rules from 1871 to 1931. The purpose is to analyze the changes in wooden hulls that would collect the lessons learned at sea through more than one century after the battle.

The Rules chosen are those of Bureau Veritas International, founded in Brussels in 1828, that reflect a worldwide experience with wooden sailing ships and steamers alike.

They also reflect the experience acquired by the Génie Maritime during the period when the ships of Trafalgar were operating.

Similar scantlings, joints and structural arrangement required by the Rules for 1871 (BV71) were also required for 1912 (BU12) and for 1931 (BV31), which shows that the structural solution of wooden hulls was a well established practice accepted by the international maritime community.

We use data from three significant ships at Trafalgar from the three countries: the *Santísima Trinidad*, the *HMS Victory* and the French *Vaisseau de 74*.

Included in the Appendix are the rules applicable to these ships translated by the author, together with comments and calculations.

Here we present only the conclusions of this exercise.

<u>Application of the Rules for 1912</u>

	S. Trinidad	*Victory*	*Vaisseau-74*
Tonnage dimensions (mm)			
Length	61578	56693	55210
Breadth	16254	15880	14300
Depth	8034	6584	6988
Scantling dimensions (mm)			
Length	62000	57000	55760
Breadth.	16254	15880	14300
Depth	8034	7104	7420
Scantling Numerals	8096	6430	5916
Displacement, t	4683	3934	2934
Block coefficient	0.578	0.560	0.558

Application of the Rules for 1871

The *International Rules for Wooden Vessels* of 1871 measured the hulls with different criteria than the Rules for 1912. Scantlings were based on a Numeral that was the product of:

Length × Breadth × Depth × 0.7 measured in foot-inch.

	S. Trinidad	*Victory*	*Vaisseau-74*
Scantling dimensions (mm)			
Length	61250	56700	54920
Breadth	15650	15260	13650
Depth	7600	7100	7000
Scantling dimensions (feet)			
Length	200.95	186.0	180.18
Breadth	51.34	50.06	44.78
Depth	24.93	23.29	22.96
Scantling Numerals	179187	151799	129676

With these Numerals, the scantlings by 1871 Rules are shown in inches and eighths of a British inch for mould and siding. They are presented for each element together with the 1912 requirements and the actual height and width of the three ships in mm for comparison.

	S .Trinidad	*Victory*	*Vaisseau-74*	
Keel	500-420	500-410	490-400	1912
	19.7-16.7	19.7-16.4	19.2-15.7	1871
	567-464	534-534	517-407	actual
Stem, Stern post	510-420	500-410	500-400	1912
Frame spacing	770	740	740	1912
	696*	455*	819*	actual
Floors	430-310	410-300	410-300	1912
	16.7-12.2	16.5-12.1	16.0-12.6	1871
	348-302	330-312	339-325	actual
Timbers down	270-270	270-270	270-260	1912
	10.6-10.6	10.6-10.6	10.6-10.4	1871
Timbers up	230-220	230-220	220-210	1912
	8.7-8.7	8.7-8.7	8.4-8.7	1871
Keelson	560-550	540-530	530-520	1912
	22.1-22.1	21.7-21.7	21.0-21.0	1871
	464-418	508-508	434-298	actual
Main transom	450-450	440-430	430-430	1912
	17.7-17.7	17.5-17.5	17.0-17.0	1871
	604-488	384-710	461-434	actual

* Single timbers in the *Victory*, double in the *Trinidad* and the *Vaisseau-74*

	S. Trinidad	*Victory*	*Vaisseau-74*	
Deck shelves	240-300	230-300	220-300	1912
	9.3-12.0	9.1-12.0	8.6-12.0	1871
	250-	190-380	204-407	actual
Deck clamps	150-300	150-300	140-300	1912
(Thick strakes)	6.0-12.0	6.0-12.0	5.3-12.0	1871
Beams	260-300	250-300	250-300	1912
	10.3-11.7	10.3-11.7	10.1-11.6	1871
	395-418	360-360	379-434	actual
Waterway	240-300	220-300	200-300	1912
	15.2-15.2	14.7-14.7	13.7-13.7	1871
	313-372	190-430	407-407	actual
Inner Strakes	110	100	100	1912
(Ceiling)	174	102	108	actual
Stringers	180	170	160	1912
Garboard strake	210	210	210	1912
	8.3	8.3	8.1	1871
Bilge strakes	180	170	160	1912
	7.1	7	6.3	1871
(Lower side)	104	134	122	actual
Wales	180	170	160	1912
	7.0	6.6	6.3	1871
	221	203	217	actual
Underwater planking	120	110	110	1912
	104	134	122	actual
Deck planking (pine)	110	100	100	1912
	4.1	4.1	4	1871
	104	102	198	actual
Gunwale	140	140	140	1912
(Covering board)	5.4	5.4	5.3	1871
Rudder stock	450-450	450-450	440-440	1912
	17.7-17-7	17.7-17.7	17.4-17.4	1871
	n.a.	n.a.	n.a.	actual

The comparison of these scantlings shows that the scantlings required in 1871 were still accepted forty and sixty years later. The only differences are found in beams and waterways or stringers. While beams were strengthened waterways were lightened.

Actual scantlings of the three ships were significantly stronger than those required by B.V. Rules for merchant vessels one century later, except the keelson, floor timbers and bilge strakes. Being ships of war could explain the stronger scantlings, and the type of construction based on frames composed by double timbers could explain the reductions.

Comparison of iron and wooden knees for equivalent strength and rigidity

Wooden knees as iron knees act as rotational restrictions of the joints.

Their effect can be modelled by the rotation that can be resisted at the bend while not surpassing an allowable working stress level.

Length of legs and mode of fixing them to the members they join serves to make the two members collaborate in the transmission of the loadings to the knee.

(a) Knee under Bending Moment

We can propose two cases, each governed by one condition, for a given value of the moment applied to the joint:

Case-a: Moment = Section modulus × Allowable stress

Case-b: Moment = Unit rotation × Young Modulus × Inertia

For Case-a:

Section modulus = (Cross sectional area) × (Height) = (d) cubed,

where (d) is a nominal dimension.

We can find the value of (d-wood) that makes a wooden knee as effective as one made of iron by equating the moments they accept at the bend while keeping the geometry of their cross sections:

(d-wood) = (d-iron) × Cubic root of (iron-stress / wood-stress)

assuming:

Iron-stress = 1000 kg/cm^2

Wood-stress = 60 kg/cm^2

We get (d-wood) = 2.55 times (d-iron), which would give for the three ships a requirement of knees with the following cross sections:

For Case-b:

For the same rotational rigidity, we have

E-iron / E-wood = I-wood / I-iron = (d-wood / d-iron) to the 4^{th}.

assuming E-iron / E-wood = 15

Therefore, here we get (d-wood) = 1.97 × (d-iron)

This shows that wooden knees required for rigidity are lighter that those required for strength in bending.

(b) Knee under Shear Force

Shear rigidity and strength can be used as measuring values to compare the response of the horizontal leg of hanging or standard knees.

For a given load, angular deflection caused by shear is inversely proportional to

$$(\text{G-module}) \times (\text{Section area})$$

Shear stress is inversely proportional to

$$(\text{Section area})$$

Assuming a relation of allowable shear stress of iron to wood = 10, we get

$$(\text{Section of wood}) = 10 \times (\text{Section of iron})$$

which gives (d-wood) = 3.16 $\times$ (d-iron)

For the same angular deflection, with G-iron = 15 $\times$ (G-wood), we get

$$(\text{Section of wood})\ 15 \times (\text{Section of iron})$$

hence, (d-wood) = 3.87 $\times$ (d-iron)

Here, we get that wooden knees required for rigidity are heavier than those required for stress under shear.

Wooden Walls under Gunfire

The term “wooden walls” has been coined to refer to the sides of the ships of the line of the 18th century (HOWA, cV), (LAV3). It is a lucky name as those ships were meant not as much to endure the seas as to survive in combat.

A straight approach for analyzing a hull structure under gunfire is to justify its construction as a solid armor that can resist the heaviest shots expected in combat.

Following this approach we should prove that the ship structure was reinforced when the gun power was increased, and that the arrangement of the hull elements was adequate to the geometry and energy of the shots, not considering the evolution of fighting tactics at sea.

A different approach could be based on the analysis of the extra strength that those hulls had above what was strictly required for ocean navigation at all times and in all seas, as discussed in a previous chapter.

Most hulls were solid up to the first futtock head and ship designers at the end of the century tried to keep the space between frames up to the main wales below a certain distance *to stop the balls* (GALL, Anexo 1). Frame space ranged from 3 in (76.2 mm) in British hulls to 7.5 pulgadas (174 mm), the diameter of a 36 lb ball, in the Spanish vessels.

The overall strength of a wooden wall to stop gunfire can be represented by two terms: the space between frames and the average thickness of timber in way of the frames.

Penetration in wood

A table included in (BOUD, v4, 137) gives average ideal penetration in oak in centimeters, obtained in tests with land guns, perfect balls and 1/3 charge dry powder, with the ball hitting perpendicular to the wood surface (*tir en belle*). Although penetration of balls fired by ship guns in battle must have been significantly less, these values can be used for our analysis.

Lb	0 m*	100 m	200 m	400 m	600 m	1000 m
36	140	130	120	100	90	65
18	120	110	100	80	60	40
8	100	90	80	65	49	27

* Penetration for 0 m has been extrapolated by the author.

Using these values for interpolation, we have estimated the figures for 30-livre and 24-livre balls in the same conditions.

30	135	125	115	94	80	57
24	128	118	108	87	70	40

It was common practice to shoot a broadside at about 200 meters range.

Diameters given by (BOUD, vII-L.xxxx) for French guns are:

174 mm for 36-livre; 138 mm for 18-livre and 106 mm for 8-livre balls;

Interpolation gives 165 mm for 30-livre and 154 mm for 24-livre balls.

Energy spent in penetration is consumed by the resistance of the wood, which is proportional to the ball diameter times the thickness of the plank, working along its path through the thickness of the plank.

$$\text{Penetration work} = C \times (\text{diameter}) \times (\text{penetration squared})$$

Equating penetration work and kinetic energy of the impact, we can define a relation for each gun:

$$\text{Diameter} \times \text{Velocity} = K \times \text{Penetration}$$

where K takes care of wood strength and ball material.

For a 24-livre gun with 413 m/s muzzle velocity and penetration of 1.28 m at 0 m with a ball of 0.154 m diameter, K = 49.69 m/s

Impact velocity can now be estimated by the relation:

$$\text{Impact Velocity (m/s)} = K \times \text{Penetration} / \text{Diameter}$$

This formula coincides with the one proposed in (OKUN) for metal armor.

For any two ranges L1 and L2:

$$\frac{\text{Velocity at range L1}}{\text{Velocity at range L2}} = \frac{\text{Penetration at L1}}{\text{Penetration at L2}}$$

Application to a 24-livre gun gives:

$$\text{Velocity of impact at 100 m} = 413 \times (118/128) = 380 \text{ m/s}$$

and 348 m/s at 200m; 280 m/s at 400m; 226 m/s at 600 m; 129 m/s at 1000 m.

The same formula can be used to estimate the muzzle velocity of any calibre based on the muzzle velocity of the 24-livre gun and the penetration at L = 0 and the shot diameter of both guns.

Muzzle velocity of 30-livre = 413 × (135 / 165) / (128 / 154) = 406 m/s

Muzzle velocity of 36-livre = 413 × (140 / 174) / (128 / 154) = 400 m/s

Muzzle velocity of 18-livre = 413 × (120 / 138) / (128 / 154) = 432 m/s

This analysis shows that the strength of a solid wooden wall, or the energy that it opposes to penetration by a given round shot is proportional to the product of the diameter of the shot ball times the square of the thickness of the wall.

Alternative model

A different model for the penetration of a wooden hull by a ball shot would be to consider the energy spent in penetration as proportional to the volume of wood that is destroyed by crushing, splitting and tearing. In this model:

$$\text{Penetration work} = C \times (\text{wood thickness}) \times (\text{diameter squared})$$

where C includes all material characteristics related to the fracture of the fibers.

In this case the energy equation will give:

$$(\text{Diameter cubed}) \times (\text{Impact velocity squared}) = K \times (\text{thickness}) \times (\text{diameter squared})$$

and therefore,

$$\text{Impact velocity squared} = K \text{ Thickness} / \text{diameter}$$

with this model, for any two ranges L1 and L2 and a given gun,

$$\frac{\text{Velocity at L1}}{\text{Velocity at L2}} = \sqrt{\frac{\text{Penetration at L1}}{\text{Penetration at L2}}}$$

Now, for the same 24-livre gun with 413 m/s muzzle velocity and penetration of 1.28 m at 0 m with a ball of 0.154 m diameter, K = 20521 m^2/s^2

And the muzzle velocities would be:

$$\text{Muzzle velocity of 30-livre} = 413 \times \sqrt{(135/165)/(128/154)} = 410 \text{ m/s}$$

$$\text{Muzzle velocity of 36-livre} = 413 \times \sqrt{(140/174)/(128/154)} = 406 \text{ m/s}$$

$$\text{Muzzle velocity of 18-livre} = 413 \times \sqrt{(120/138)/(128/154)} = 422 \text{ m/s}$$

The velocities predicted by the two models are very similar and also close enough to the given velocity for a 24-pounder, which could also be used for approximate calculations.

Damage in Combat

Two Spanish ships that suffered severe flooding after combat are brought here for discussion. The *Santísima Trinidad*, representing the old construction, and the *Monarca* as an example of the latest designs.

– *Santísima Trinidad* at *St. Vincent*

During five hours, on 14 February 1797 the Trinidad sustained the close gunfire from one 98-gun ship, the *Blenheim* (98), and three 74's, the *Orion*, *Irresistible* and *Excellent* after having sustained the attack of two more 74's, the *Captain* and *Culloden*.

She was completely dismasted, her starboard side and quarter taken to pieces, with sixty hits at waterline level, several guns dismounted and flooding at 37 inches of water per hour. (GALL)

– *Monarca* at Trafalgar

The Monarca was taking on 36 inches of water per hour, a rate similar to that reported by the Santísima Trinidad. After blocking the breaches at waterline level, she was still taking 24 inches of water per hour through breaches underwater and in the waterways. (FERR).

Since the permeability of the hold was very low the area of water surface in the hold was small and the level of water in the hold would increase rapidly.

A general formula for estimating the total equivalent breach area in the hull would be:

$$\text{Area of Breach} \times \text{Inflow Velocity} = \text{Hold Water Area} \times \text{Rate of Level Increase}$$

where the area of the breach is reduced by a shape factor and the hold waterplane area is reduced by the surface permeability of the hold at each level. In ships where the hold was full with ballast and other objects, the two factors would have a similar value and the total area of breach in the hull could be estimated as:

$$\text{Ideal Inflow Velocity} = \sqrt{2 \times \text{Gravity} \times \text{Head of Water}} = \sqrt{64.4\ \text{H} - \text{ft}}\ \ (\text{ft/s})$$

where H is the head of water above the center of the breach.

$$\text{Area of Breach} = \text{Hold Waterplane Area} \times (\text{Inches/hour}) \times 2.88\text{E} - 6 \big/ \sqrt{\text{H-ft}}$$

For a 74-gun the hold waterplane at the upper side of the riders would be about 238 m^2. Thus, if the centroid of the breach was located at 3 ft below the waterline, the Area of Breach that caused 24 in/hour flooding would be:

Total Area of Breach = 0.0285 m^2, or a circular hole of about 190 mm diameter.

This opening is equivalent to the breach that would be caused by a 32-pound ball of 155 mm diameter. Even when multiplied by a value of 5 for the ratio of Permeability to the Shape Factor of the opening, this figure tells how solid the hull was underwater.

For a breach at 1 ft below waterline, the equivalent area would be 9 times larger.

The Appendix to this chapter includes relevant data of the frigates HMS Shannon, USS Chesapeake and USS Constitution, besides references and the author's comments to British, French and Spanish Naval Ordnance, with a discussion on gunfire range and penetration.

Impact Model Tests

Several series of tests were carried out at the Welding Lab of the Escuela Técnica Superior de Ingenieros Navales (ETSIN), UPM, from May to September 2005, by a team integrated by Prof. F. Molleda, Asst. Prof. J. Mora and the author.

The object of these tests was to analyze the response of oak and pine wood to impacts similar to those produced by a naval gun round shot. The objectives were to learn the failure modes, the effect of doweling and doubling, with a focus on the morphological effect of impacts rather than to obtain quantitative measurements of the wood strength under gunfire.

A 300-J Charpy pendulum with 185 cm maximum elevation was used to hit the wooden pieces, fitted with a standard wedge and with a 30 mm diameter steel ball to simulate a 24-pound ball scaled to 1/5. Impact velocity was 6.0 m/s in all cases.

In order to cover a range of shell-and-timber arrangements, wooden pieces were cut to lengths of 100, 130, 160, 190 and 220 mm, with 20 mm thickness and widths of 20, 30 and 50 mm. Opening of the support piece was varied from 40 to 60 and 80 mm, to model different frame spaces.

The effect of treenails and bolts was simulated using bamboo pegs of 3 mm diameter and iron nails of 2 and 2.5 mm diameter, varying in number, spacing and arrangement. The holding effect of dowels on the shear separation of wood layers was studied on single pieces of wood. Double pieces were joined with nails to analyze the stiffening effect of the back piece and the nails.

The effect of water content was simulated by soaking some pieces in water from Trafalgar and Alicante during 72 to 96 hours to reach saturation. Average specific gravity of dry wood used was 0.814 for oak and 0.529 for pine. Specific gravity of treenails was 0.822. Oak pieces immersed 92 hours in Trafalgar water with density 1.022 reached 0.985 density and pine 0.710 representing a water absorption ratio of 0.33 in pine and 0.20 in oak, with respect to dry weight.

The principal outcome of these tests is summarized here:

- Oak wood splits in longer needles and layers than pine.
- Wider openings make the pieces bend before breaking, which increases the energy absorbed in the impact dramatically.
- Saturated wood becomes more flexible and breaks less and with less separation.
- Holes drilled for treenails function as crack stoppers, whereas hammered nails act as crack directors.
- In double samples, the back piece is little affected by the impact.
- The ball, being wider and smoother than the wedge, involves a larger volume of wood to absorb the impact energy.

- Under impact by a wedge, only the very front layer is deformed by the impact while the back layers are first split by shear and then torn by tension produced by bending.
- Under impact by a ball, the front layers are crushed to a depth before bending and breaking by shear and tear. Back layers are deformed by bending and not always break.
- The back supports don't crush the back layers locally.

Note of caution

Scale models of structures for modelling blast and impact effects follow the laws of dynamic similitude (SABN, 492). For a model built of the same material as the prototype, with geometrical scale 5 and with gravity forces neglected, velocities and pressures are not scaled but the scale for time is 5 and the scale for forces 25. Therefore, these tests were modelling impact velocities of 6 m/s and not the actual ball impact at over 300 m/s, in both cases much lower than the velocity of sound in wood.

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Appendices

Appendix to Timelines

❖ Timeline of the *HMS Victory* until Trafalgar

Events	*Dates*	*Service/Maintenance*
Ordered	13.12.58	
Sheer draught by T.Slade	6.6.59	
Keel laid at Chatham	23.6.59	
Launched (floated)	7.5.65	
Completed	x.69	
Trials	x.69	
Careen in Chatham	x.71	CR
Careen in Chatham	x.75	CR
Fit out for service	-4.78	FT 2 m
Commissioned	12.3.78	
Engagement off Ushant	23.7.78	
Refit, Plymouth	31.7.78	RF 20 d
Channel service	-3.79	7 m
Refit, Portsmouth	4.79	RF
Refit, copper sheathed	3.80	RF
Channel, Cape Spartel	-11.82	2 y 8 m
Paid off, Portsmouth	11.82	DA
Middling repair	-3.83	RP 5 m
In reserve	-11.87	DA 4 y 8 m
Large repair	-4.88	RP 5 m
In reserve	-x.89	DA 1 y
Fit out	-x.89	FT
Channel service	-8.91	2 y
Repair at Portsmouth	2.91	RP
Channel service	-12.92	1 y 9 m
Refit for Mediterranean	-2.93	RF 3 m
Campaign to Toulon, Italy	-11.94	1 y 9 m
Repairs at Portsmouth	-2.95	RP 3 m
Mediterranean service	-11.96	1 y 8 m
Gibraltar, St.Vincent	-10.97	10 m
Paid off at Chatham	10.97	DA found defective

Events	*Dates*	*Service/Maintenance*
Hospital ship	-1.99	1 y 1 m
Large reconstruction, Chatham	-4.03	RC 3 y 2 m
Mediterranean service	-4.05	1 y 11 m
Campaign in West Indies	-8.05	3 m
Refit, Portsmouth	-9.05	RF 2 m
Cádiz blockade	-10.05	2 m

- Maintenance operations are abbreviated as:
  FT = fitted out;
  RF = refitting;
  DA = disarmed, paid off, in reserve;
  RC = reconstructed;
  RP = repairs.

- Summary
  Lifetime until Trafalgar = 35.5 years
  Commissioned 12.83 years after launching
  Disarmed during 4 periods, totalling 7 years
  Struck from Navy List, hospital ship for 1.25 years
  Drydocked for refitting (8 times), careened (2), reconstructed (1), totalling 6 years
  Service and campaigns added to 13.5 years operating at sea = 38.6 % of her life.

❖ Timeline of the *HMS Bellona*

Events	*Dates*	*Service/Maintenance*
Ordered	28.12.1757	
Begun	10.5.58	
Launched	19.2.60	
Commissioned	22.2.60	
Sailing with the Western Squadron	8.4.60	
		RF 38 d Ago.60
		RF 79 d Mar 61
Fierce action with the *Couraguex*	14.8.61	
Repaired at Lisbon	Sept.61	
		CS 81 d Dec 61
Sail from Portsmouth after copper sheathed	1.2.62	
		FT 15 m Apr.64
Fitted as guard ship at Portsmouth	4.4.64	
		RF 53 d Sep.64
		RF 43 d May.67 *
		RF 14 d Apr.70
Sailed from Portsmouth	1.10.70	
Entered Chatham and laid up in ordinary	14.5.71	
		RF 3 y Apr.74
		RF 17 m Apr.80 **
Refitted for Channel Service	18.4.80	
Captured Dutch *Princess Caroline*, 44g	30.12.80	
Helped relief of Gibraltar	Apr.1781	
Reported in bad condition	Apr-May.81	
Refitted at Portsmouth	May-Jul.81	RF 2 m Jul.81*
Returned to Portsmouth	Dec.1781	
		RD 2 m Mar.82
Sailed from Spithead with fleet and convoy	11.9.82	
Helped relief of Gibraltar; go to West Indies	Oct.82	
At Leeward Islands	Jan.83	
Returned to Portsmouth	25.5.83	
		RP 20 d Jun.83
Paid off at Portsmouth and laid up in ordinary	7.6.83	

Events	*Dates*	*Service/Maintenance*
		RP 7 m Apr.86 **
Decommissioned	3.10.87	
Paid off	7.12.87	
Decommissioned as guardship at Portsmouth	11.2.89	
Review of the fleet and mock battle	18.8.89	
		FT 7 m May.90
Sailed with the Grand Fleet	Sept.90	
Returned to Portsmouth	Oct.90	
Guardship at Portsmouth	Jan.91	
Mobilised for a threat of war with Russia	Jun.91	
Paid off at Chatham	12.9.91	
		RP 22 m Sep.93 **
Launched after middling repair	9.7.93	
Decommissioned	18.7.93	
Joined Howe's fleet in the Channel	2.9.93	
Unsuccessful chase of the French fleet	7.11.93	
		RF 25 d Jan94
Chased part of French squadron	5.6.94	
Sailed to West Indies	13.10.94	
Arrived at Martinique	14.11.94	
Led attack on French squad. Near Guadeloupe	5.1.95	
Action with Spanish squad. At Caspagarde Is.	2.2.97	
Attack on Puerto Rico	Apr.97	
Return to Portsmouth and begun refit	Oct.97	
		RF 4 m Feb.98 *
		RD 50 d Jun.98 **
		RP 3 m May.99 *
At Gibraltar	May.99	
Joined St.Vincent's fleet off S.Sebastian	May.99	
Leading capture of three frigates	19.6.99	
In Torbay with St.Vincent's fleet	Sept.99	
		RF 2 m Feb.01
Sailed to the Baltic with Sir Hyde Parker sq.	12.3.01	
Grounded on a shoal off Copenhagen, no fight	3.4.01	
Sailed from the Baltic		7.7.01

Events	*Dates*	*Service/Maintenance*
With blockading squad off Cádiz	Oct.01	
At Jamaica, reported to be "an old crazy ship"	16.3.02	
Paid off at Portsmouth and laid up in ordinary	6.7.02	
Docked at Portsmouth	11.4.05	
Launched after doubled and braced (Snodgrass)	28.6.05	
		FT 37 m Ago.05 **
With Strachan's squadron, no action		Oct.05
		RP 1 m Dec.05
Sailed from Plymouth for Barbados	19.5.06	
Chased *Foudroyant*, destroyed the *Impetueux*	14.9.06	
In Hampton Roads, US	Jul.07	
With the fleet at Basque Roads; failed attack	7.3.08	
Took part in Walcheren expedition	Jul.09	
Took part in Santo Domingo expedition	Sep-Nov.09	
		RF 7 m Mar.10 *
On patrol off Flushing	Sep.10	
		RP 70 d Mar.11
Blockading the Dutch coast	1811-12	
		RP 50 d Jan.12
Return from St. Helena	May.13	
Off Flushing	Jul.13	
Joined squadron off Basque Roads	Sep.13	
With the Channel fleet off Cherbourg	Oct.13	
Arrived at Chatham	4.2.14	
Docked	19.7.14	
Broken up at Chatham	Sep.14	

Marks * and ** distinguish two increasing levels of cost of the maintenance carried out on the hull only: ** for over 10,000 pounds and * for over 2000 pounds.

- Maintenance operations are abbreviated as:

  FT = fitted;

  RF = refitted;

  CS = copper sheathing;

  RP = repair;

  RD = repair damages.

Total number of days, months or years spent at the dockyard is marked with d, m and y respectively in front of the sailing date.

Copper sheathing was regularly taken off, renewed or repaired, 16 times in the months-years: 9-64, 5-67, 3-80, 6-81, 1-82, 6-83, 10-85, 10-90, 12-97, 5-98, 11-99, 1-01, 6-05, 1-10, 1-11, 12-11. The longest intervals of 4.5 years occur after Trafalgar. They coincide with a decay of naval operations which is reflected in a similar decay of maintenance costs, but they also coincide with the stiffening of the hull that was achieved by doubling the shell and installing diagonal bracing of the Snodgrass system.

- Summary

  Number of Maintenance periods = 25

  Number of years spent at dockyards = 530 d + 126 m + 3 y = 15 years approx.

  4 periods decommissioned, totalling 17.7 years included 27 months at dockyards

  Total lifetime in years = 54.6

  Percentage of total maintenance time in total lifetime = 27.7 %

  Percent lifetime decommissioned = 32.7 %

  Total lifetime armed = 24 years = 44.4 %.

  Total lifetime until Trafalgar = 45.7 years

- Timeline of the *San Juan Nepomuceno*

Events	*Dates*	*Service/Maintenance*
Ordered	15.6.1763	
Keel laid	19.6.65	
Launched	18.10.66	10 m
Commissioned	5.4.67	5 m 15 d
Trials in Ferrol and Cartagena		
Careen in Ferrol	-2.2.68	CR
Disarmed in Ferrol		DA 2 y 8 m
Careen in Ferrol	x.10.70	CR
Disarmed afloat	-x.11.76	DA 6 y deteriorated
Careen in Ferrol	-29.12.76	CR
Rearmed		
Transferred to La Habana	x.1.77	
Refitted in La Habana	-15.5.79	RF
Refitted afloat in La Habana	9.11.81	RF
Cruising Caribean Sea		
Campaigns in Cuba and Puerto Rico	-17.7.83	6 y 6 m
Enters Cádiz		9.9.93
Careen in Ferrol	28.9.84	CR
Trials in Cartagena		
Transferred to Ferrol	2.2.86	
Careen, copper in Ferrol	-x.4.90	CR
Cruising in Atlantic		
Disarmed in Ferrol	x.10.90	DA
Rearmed		9.2.93
War with French Convention	-31.12.93	hull damages
Transferred to Cartagena	9.10.94	
Collisions in storms	x.2.95	hull damages
Missions in Mediterranean		
Battle of Cape S. Vicente	14.2.97	little action
Disarmed in Cádiz	x.10.97	DA 4 m
Refitted in Carraca	x.1.98	RF
Rearmed		
Enters Cartagena after storm	21.5.99	hull damages

Events	*Dates*	*Service/Maintenance*
Campaign to England, enters Brest	-9.8.99	
Cruising Bretagne	-x.8.01	3 m
Blocked in Brest	-29.4.02	2 y 5 m
Disarmed in Ferrol		DA needs careening
Careen in Ferrol	x.10.02	CR
Careen in Ferrol	x.10.04	CR
Rearmed in Ferrol	13.11.04	
Flagship of C. D. Churruca	10.3.05	

- Summary

  Lifetime until Trafalgar = 39 years

  Suffered 9 careens, one afloat in La Habana

  Blocked in Brest for 2.5 years = 6.5 %

  Disarmed during 5 periods, totalling about 10 years = 25 %

  No significant damages reported in battle.

❖ Timeline of the *Santísima Trinidad*

Events	*Dates*	*Service/Maintenance*
Ordered	14.8.1767	
Begun	30.9.67	
Launched	2.3.69	17 m
Commissioned	19.2.70	1 y
Enters Vigo with damages	12.4.70	
Repaired afloat in Ferrol	-21.7.70	RP 65 d
Total ballast = 1974 tons		
Disarmed afloat in Ferrol	-6.76	DA 5 y 10 m
Drydocked in Ferrol	-28.3.78	RF 14 d Mar.78
Full careen in Carraca	-7.8.78	CR 4 m
Service in Cádiz	-23.6.79	10 m 15 d
Campaign to England	-13.9.79	80 d
Storm damages and sickness		
In Brest	-9.11.79	RP 56 d
Campaign in Cádiz-Gibraltar	-31.12.79	40 d
Storm damages in N. Africa		
Repaired in Cádiz	Jan.80	RP ?
Service in Cádiz	Jul.80	10 d
Campaign in S.Vicente	-1.11.80	90 d
Severe SSW storm 30 10.80		
Service in Cádiz	-6.2.81	90 d
Cruising S. Vicente	-28.3.81	50 d
Cruising S. Vicente	-19.6.81	50 d
In Cádiz	-23-7.81	35 d
Campaign with France	-23.9.81	60 d
Mahon, Channel, Gibraltar, Menorca, Brest		
Careen, mast, copper in Carraca	-15.4.82	CR 7 m 10 d
Campaign in Channel, Ferrol, Spartel	-5.9.82	90 d
Campaign to Algeciras	-13.9.82	5 d
Combat at Cape Spartel	-28.10.82	25 d
Service in Cádiz	-23.4.83	6 m
Disarmed	-x.95	DA 12 y
Careen, upgraded, caulked in Carraca	-x.95	CR 6 m

Events	Dates	Service/Maintenance
Rearmed in Cádiz	-4.8.96	9 m
Campaign with France	-20.12.96	135 d
Newfoundland, Toulon, Brest, Cartagena		
With J. Cordoba squadron	-3.3.97	30 d
Combat of cape S. Vicente	-14.2.97	very severe damages (1)
Repaired, rised to 4 decks in Carraca	-x.11.97	RP 8 m
Service in Cádiz	-2.11.02	5 y
Careen, bulged 6 in, copper	-24.12.02	CR 50 d (2)
Disarmed	-12.12.04	DA 2 y
Caulked the upperworks, armed, ready	-18.6.05	FT 6 m

- Summary

  Suffered 3 careens, totalling 19 months in 36.58 years lifetime.

  Disarmed during 3 periods totalling 19.83 years = 54.20 %

  Suffered 4 repairs, totalling over 12 months.

  Percent lifetime inactive = 61.5 %.

  Four times she suffered important damages, but only once in combat

  Except for her maiden voyage and a short cruise to Newfoundland, most of her service life was in the Cádiz area, where she was stationed.

(1) Damages suffered at Cape S. Vicente, 14.Feb.1797

During five hours the S. Trinidad received close gunfire from one 94-gun, the Blenheim, and three 74's, Orion, Irresistible and Excellent, after having fought two more 74's, Captain and Culloden. She was completely dismasted, her starboard side and quarter breached, taking 37 inches of water per hour, with 69 dead and 407 wounded. She struck the flag but four Spanish ships, the *Conde de Regla*, *Príncipe de Asturias*, *San Pablo* and *Infante Don Pelayo* rescued her and put the British ships to escape.

(2) Major works done in Carraca, Nov-Dec.1802

Solid bulging was fitted, 6 in thick on each side, from stem to stern. Caulked to the timbers, sheathed with 3/4 in pine planking and lute ("zulaque"), all nail and bolts heads covered with mastic and a canvas on top, and then copper planks of 1/12 in over construction frames and 1/24 in elsewhere from keel to the bulging.

- Timeline of the *Príncipe de Asturias* until Trafalgar

Events	*Dates*	*Service/Maintenance*
Launched in La Habana	28.1.1794	
Enters Cádiz	17.5.95	
Service in Cádiz		
Campaign with France	-5.10.96	
Newfoundland, Cádiz, Mediterranean		
Battle of Cape St. Vincent	14.2.97	hull damages
Enters Cádiz	3.3.97	
Blocked in Cádiz	10.4.97	RD
Chase of the British to *S. Vicente*	6.2.98	
Blocked in Cádiz		17.2.98
Careen in Carraca, copper sheathed	-x.9.98	CR 2? m
Campaign to Menorca	12.5.98	
Enters Cartagena	20.5.98	Heavy storm
Campaign with France	29.6.99	
Blocked in Brest	-29.4.02	
Enters Cádiz	13.5.02	
Collision with the *Bahama*	x.6.02	bow damaged
Enters Cartagena	26.6.02	
Squadron to Napoles	22.7.02	RP 1m
Enters Cartagena	4.12.02	
Enters Ferrol	26.2.03	
Disarmed	-13.11.04	DA 1 y 9 m
Leaves Ferrol	10.8.05	

- Summary

Total lifetime to Trafalgar = 11.75 years

Careens = 1

Percent lifetime commissioned = 85.1 %

❖ Timeline of the *Santa Ana* until Trafalgar

Events	*Dates*	*Service/Maintenance*
Ordered	22.3.1783	
Drawings approved	18.6.83	
Launched in Ferrol	29.9.84	
Put to sea	24.11.84	
Drydocked in Carraca	16.1.87	CR
Service in Cádiz	3 y 6 m	
Careen in Carraca	15.6.91	CR timbers rotten
Disarmed in Cádiz		
Full careen	x.x.94	CR
Rearmed	18.2.96	DA 4 y 6 m
Disarmed	x.7.96	6 m
Rearmed	x.1.97	DA 6 m
Service in Cádiz		1 y
Chase of the British to S.Vicente	6.2.98	
Blocked in Cádiz	17.2.98	
Careen in Carraca, copper sheathed	-x.9.98	CR 2? m
Campaign to Menorca	12.5.98	
Enters Cartagena	20.5.98	Heavy storm
Campaign with France	29.6.99	
Grounded in Rota	21.7.99	
Careened, new keel, coppered	-10.1.00	RF 5 m
Disarmed in Cádiz	-x.02	DA 3 y
Deck fitting afloat	x.1.05	
Careened in Carraca	-9.9.05	CR 3 m
Rearmed	30.9.05	

- Summary

Lifetime until Trafalgar = 21 years

Regularly careened every three years

Disarmed most of her lifetime: 8 years plus 6 drydocking periods

Short periods of activity, totalling little over 5 years.

Not involved in battles prior to Trafalgar.

- Timeline of the *Rayo* until Trafalgar

Events	*Dates*	*Service/Maintenance*
Ordered	x.x.1748	
Launched in La Habana	28.6.49	
Sailed to Cádiz	1.3.52	2 y 8 m
On station in Cádiz		5 y 7 m
Remasted in Cádiz	x.10.57	RF
Careen, keel, shell in Carraca	27.4.58	
Put to sea	x.5.59	CR 1 y
Refitted	-2.1.60	RF
On station in Cádiz		2 y
Careen in Carraca	-x.1.62	CR 7 m
Caulked	x.2.65	FT masts rotten
Mission to Genova	x.3.65	2 m
Return to Cartagena	11.8.65	
On station in Cádiz		3 y
Needing drydocking in Carraca	x.8.68	DA 6 m
Careen in Carraca	-x.4.69	CR 3 m
Rearmed		2 y
Disarmed	x.4.71	DA 8 y
Needing careening in Ferrol	x.x.74	
Careen in Carraca	x.7.76	CR
Rearmed in Cádiz		
Armed	23.6.79	
Campaign with France to England	23.7.79	2 m
Enters Brest	13.9.79	
Enters Cádiz	8.2.80	7 m
Campaign in S. Vicente	-29.8.80	7 m
Campaign with France	30.10.80	2 m heavy storm
Cruising S. Vicente	x.4.81	6 m new bowsprit
Campaign with France		
Menorca, Channel, Brest, Cádiz	-23.8.81	1 y
On station in Cádiz	-4.1.82	4 m
Cruising S. Vicente	-12.2.82	storm damages
On station in Cádiz	-5.6.82	4 m

Events	*Dates*	*Service/Maintenance*
Campaign in S. Vicente, Ouessant		
Newfoundland, Algeciras	-13.9.82	3 m
Combat of Cape Spartel	20.10.82	no damages
On station in Cádiz	-23.4.83	6 m
Disarmed in Cádiz	23.4.83	DA 8 m
Careen, copper	x.8.83	CR 4 m
Rearmed	x.12.83	
On station in Cádiz	-25.4.84	4 m
Missions in Cádiz and Cartagena	-16.11.84	7 m
Disarmed in Cádiz		DA 3 m
Rearmed	3.2.85	
Missions to Mahon and Cartagena	-6.4.85	2 m
Disarmed in Cádiz		DA 3 y 10 m
Rearmed	x.2.90	
Disarmed in Cádiz	30.12.90	DA 1 y 2 m
Rearmed	16.2.92	
Disarmed in Carraca	x.x.98	DA 9 y
Full careen, copper, upgraded to 100 g.	x.x.00	CR
Rearmed in Cádiz	1.10.05	

- Summary

Total lifetime = 56 years

Disarmed during 7 periods, totalling over 24 years = 42.9 %

Drydocked and careened in 6 occasions totalling over 3 years = 5.4 %

Serviced in 11 campaigns and missions, totalling almost 5 years = 9 %

Stationed in Cádiz on 8 periods, totalling 15 years = 26.8 %

Other repairs, fitting and refitting, and unspecified works totalling 9 years

- Timeline of the *San Ildefonso* until Trafalgar

Events	*Dates*	*Service/Maintenance*
Ordered	23.2.1784	
Keel laid	26.3.84	
Launched	22.1.85	
Trials	-19.8.85	40 d
Disarmed in Cartagena	9.1.86	DA 2 y 9 m
Trials	10.4.88	
Careen, masting, copper in Carraca	-15.7.88	CR
Trials in Cartagena	-5.10.88	10 d
Disarmed in Cartagena	9.10.88	DA 6 m
Rearmed	13.4.89	
Cruising to Cádiz	-8.8.89	4 m, damaged
Return to Cartagena	-27.12.89	
Disarmed in Cartagena	28.12.89	DA 3 y
Modified interior arrangement	1792	
Rearmed		
Campaigns and missions with Britain to France	20.4.93	4 y
Enters Cádiz	-3..3.97	
Careen in Carraca	x.12.97	CR
Blocked in Cádiz		
Chase Bristish squad.	-13.2.98	
Blocked in Cádiz		
Two Missions to America	20.12.98	3 y 6 m
Disarmed in Ferrol	x.6.02	DA 3 y
Needing full careen in Ferrol	x.6.02	
Careen, copper in Ferrol	-21.7.05	CR x? m
Sailed	27.6.05	
Rearmed and fitted	13.8.05	

- Summary

Total lifetime until Trafalgar = 20.75 years

Disarmed during 3 periods, totalling 9.25 years = 44.6 %

Suffered 3 careens, with two copper sheathings.

She was not engaged in battles prior to Trafalgar.

Appendix to Structures

Excerpts from references used in this chapter are transcribed in Spanish for further quotation. Tables 1 and 2 presenting details of scantlings by the author are also included.

CANO, f5v: "Aunque más se tengan y cuenten los Italianos por marineros sónlo tan solamente para su mar de Italia… que por ser sus navegaciones cortas no tienen necesidad de sciencia… de que usan y están muy diestros los marineros Españoles, Portugueses y Andaluzes con particular primor y excelencia sobre todas las naciones del mundo: las de los Franceses, Ingleses y Olandeses."

CANO, f22r: "La misma cuenta y aún mucha más (que un Edificio de la Tierra) es justo lleve y tenga la Nao, que juntamente es Casa, Torre, Castillo, Fortaleza, Baluarte, Pavés, Caballero, Plataforma, Trinchera… y más siendo esta (Fábrica) de la Nao la de un Edificio movible y que ha de contrastar con tantos y tan fuertes contrarios..."

CANO, f10r: "Viniendo a ser una Nao, cuando bien y del todo acabada y cargada y artillada, navegable y puesta a la vela, con ellas tendidas y estiradas al viento fresco y Galerno, en tranquilo y magnífico mar, una de las admirables y particulares cosas que hay que ver en el Mundo, o muchas juntas en una. No habiendo otra más semejante y parecida a una Dama…"

CANO, f14r: "… enseñarnos lo que tan bien teneis comprehendido en cinquenta y tres años que habeis Navegado, haciendo veinte y nueve Viajes a Indias…"

CANO, f18r: "… Que es ser malas de Mar al Anca… Cuando las olas le dan por la cuadra arrójanla sobre la amura por hallarla allí vacía y sin lleno… y después que la ola ha pasado cae sobre la cuadra que también la tiene vacía por lo pocos maderos que tiene de cuenta… por no hallar donde escorar cae con mucha fuerza…"

CANO, f32r: "… Conviene que desde el principio de la Fábrica los Planes crucen con las Estamenaras, u Orengas, que todoe s uno, mientras más mejor, y que en estas junturas lleven sus dos Machos, uno en revés de otro y por encima sus dos Palmejares, que coja el uno las cabezas de los Planes con el cuerpo de las Estamenaras y el otro las cabezas de las Estamenaras con el cuerpo de los Planes endentados, y Empernados, porque si la Nao pusiere a monte, o quedare en seco, no descalime, que echará luego la Estopa fuera, y se anegará si no llevare esta fortaleza."

CANO, f33r: "Los Palmejares irán corriendo por las junturas de los henchimientos de Cabezas con los Virotes hasta llegar a Proa y Popa, bien endentados y clavados, porque en los Balances haga la Nao la fuerza por junto en todos los maderos, llegando desde las Aletas al Branque."

BROC,1: "… por que no jueguen las cabezas, que es la llave de las fabricas."

BROC,2: "… y encima de una singla ha de yr una tabla bien ajustada, que servirá de aldaola y con ella la escoperada del granel."

ORD8,18: "… Si se ofreciere en todo género de Navíos, que por el peso de las maderas, y los terrenos de los astilleros ser blandos, abriere algo mas la manga de las medidas que les pertenece hasta cantidad de medio codo, no por eso se entienda haber excedido, ni alterado la buena fábrica, sino cumplido con las ordenanzas, como no sea en ninguna de las medidas de suso referidas, excepto en la manga, que esto suele suceder por el peso de las maderas, y los terrenos de los astilleros blandos, donde es fuerza consentir las escoras aunque mas cuidado se ponga con ellas".

Table 1 SCANTLINGS PROPOSED BY GARROTE (1691), ORDENANZAS (1618), DIALOGOS (1633) AND GAZTAÑETA(1720)

1 shipbuilder's cubit = 574.68 mm = 24 shipbuilder's inches or "ounzes"

	1691	*1618*	*1633*	*1720*
	—	shipbuilder's cubits		—
Beam	22	22	22	21
Keel	66	53	60	65
Length	75-13	68	80-16	78
Tonnage	1057	1075	1200	
Guns	78			80
Pounds	24,16,10			
	—	shipbuilder's inches		—
Keel	27.5×22			22×20
Keelson				14×10
Frames 1	14		12	12×11
Frames 2	9.33		8	12×10
Top timbers				9
Clamps 1	11	6×12		6×12
Clamps 2	7.33			
Beams 1	22			16×16
Beams 2	14.67			12×12
Ledges 1	11	5×8		
Ledges 2	7			3×9
Knees				12
Girders 1	9	5×8		6×12
Wale 1	11×15	8×16	8×16	8×16
Riders, floors				16×16
Riders, futtocks				14×16
Hold riders				15×20
Waterways				6×12
Spirketting				5×16
Shell planking		5	5	5×10-12
Num. deck beams	14		26	26-28
Num. hold beams	7		5.5 cu space	6
Num. hold knees	94			
Num. riders			2.67cu space	12

NOTE.- Table composed by the author.
Blank values were missing in the references available.

Table 2 SCANTLINGS OF THE "CAPITANA" OF 1688 AS BUILT

1 shipbuilder's cubit = 574.68 mm = 24 ounces or shipbuilder's inches

	1688
	cubits
Beam	22.5
Keel	69.39
Length	81.23
Tonnage	
Guns	90
	ounces
Keel	24 × 24
Keelson	
Floors (3)	13 × 18 to 14
Futtocks	12 × 16 to 12
Top timbers	12 × 12 to 10
Hold stringers (3)	8.5 ×16
Clamps 1	8.5 × 16
Clamps 2	7 × 20
Clamps 3	5 × 21
Beams hold	12 × 13
Beams 1	12 × 12
Beams 2	12 × 10
Beams 3	12 × 8
Knees 1	13 × 13
Knees 2	12 × 12
Knees 3	9.5 × 10
Wale 1	9 × 23
Wale 2	8 × 15
Wale 3	8 × 15
Wale 4	7 × 14
Wale 5	7 × 12
Wale 6	7 × 11
Wale 7	7 × 10
Waterways 1	16 × 16
Waterways 2	15 × 15
Waterways 3	12 × 12

- (ORD7). Excerpts

MNM, Colección Fdez. de Navarrete, F.23, D.47.

Ordenanzas expedidas por el Rey a 21 de diciembre de 1607 para la fabrica de los navios de guerra y mercante, y para la orden que se habra de observar en el arqueamiento de los que se tomasen a particulares para servicio en las armadas reales.

…

Todos los Navíos que fabricaren para el comercio los naturales de estos Reynos conviene que los hagan por las susodichas medidas, y traza, y con las mismas fortificaciones sin discrepar en nada, y para los que huvieren de navegar de merchante a las Yndias, se advierte lo siguiente.

Desde principios del año de mil y seiscientos y diez en adelante todos los Navíos que se recibieren para navegar en las Flotas de las Yndias han de ser fabricados con las dichas medidas, traza y fortificación, y de hasta quinientas y sesenta y siete toneladas, y de ay abaxo, y no mayores, porque desta manera podrán entrar, y salir por las barras de San Lúcar de Barrameda, y San Juan de Lua cargados sin alijar nada, y harán la Navegación más breve, y serán los Navíos más duraderos, y toda la carga y Navegación de las Flotas más igual, y con menos riesgo de mar, y enemigos, y más comodidad de los dueños de las mercaderías para la carga, y descarga, y se aprestarán las Flotas con más brevedad y menos costa, y si desde aquí adelante acudieren a Sevilla para las dichas Flotas Navíos de estas medidas y traza, prefieran en la carga a todos los otros tanto en España como en las Yndias.

…

La Casa de la Contratación de las Yndias que reside en Sevilla ha de nombrar persona de sciencia y conciencia que reconozca, mire y considere lo que podrá cargar cada Navío destas medidas, de manera que pueda salir, y entrar para las dichas barras sin alijar de la carga que huviere embarcado, y hazer seguramente su Navegación; y porque los dueños de Naos, y cargadores dellas no puedan con su descadenada codicia usar de engaño, cerca desto porná (pondrá ?) la dicha persona dos señales de fierro en el codaste, y branque de cada Navío, de manera que aquel fierro, o señal quede sobre el agua, y esta persona tenga un libro en que asiente la parte donde fixare en el Navío las dichas señales declarando en quantos codos de agua está aquella señal, y los que huviere della a la lemera.

- (DIAL). Excerpts

  Dialogo entre un Vizcaino y un Montañes sobre construcción de naves, su arboladura, aparejo, etc. (Anonimous, ca.1632)

  Transcribed from “Arca de Noé”, Disq.Náu. Vol.V, C. Fdez. Duro, pp. 106+
  y en Col.Navarrete, tomo I, doc.11, pp.227-290.

Vizcayno.- La primera duda que se me ofrece es la de la Quilla pues dice Vm que el Galeon que fuere 22 codos de manga haya de tener 66 codos de quilla, que es tres veces la manga, no le dando las ordenes de S.M. mas de 55, que es dos mangas y media.

Montañes.- Es asi que las ordenes de S.M. no dan de quilla mas que dos mangas y media, pero la experiencia nos ha mostrado que todo navio largo de quilla es mas descansado que el corto porque cabecea menos contra la mar, y corre mas a la vela, y por esta causa dura mas, y los Arboles estan mas seguros y los aparejos trabajan menos.

…

Montañés.- … en España no saben hacer los raseles como debian, pues los asientan angostos y entablados que no se pueden fortificar por dentro, y asi en quedando en seco se descaliman por alli conviene que este rasel sea ancho, y abierto al modo del que tienen las Carabelas, y Navios flamencos, que los tales dan lugar á que se fortifiquen con bularcamas por dentro, empernandolas con las tablas, maderos, y palmejares con que fortifican las Juntas de las Maderas.

…

Montañes.- Todas las bularcamas que he dicho ha de llebar, y mas si fuere posible, porque es la mayor fortaleza que se le puede echar para las ocasiones que se pueden ofrecer de quedar en seco teniendo esta parte, que es sobre que carga este peso bien fortificada no se descalimará, como lo hacen de ordinario los navios que son floxos por abajo.

...

Montañes.- Muy necesario es que las cintas, y cubiertas de los Galeones tengan sus arrufaduras, asi por la hermosura de ellos, como para la fortificacion que ayuda á sustentar que no se quebrantara con tanta facilidad, y en ellas y en los durmientes y trancaniles de las cubiertas se claban las cavillas ó pernos de fierro con que se fortifica lo necesario.

- (MNM, Ms.1249)

  Comparación de la fábrica Inglesa y la Francesa

  El 18.Abr.1767 Arriaga envía una carta al Cde.de Vegaflorida en la que le pide su opinión sobre la que le dirigiera Gautier desde Ferrol diez días antes, en la que afirma que: " son muy urgente reparar y fortalecer cuantos navíos existen ahí, así en Grada y Diques como desarmados, por parecerle no haber uno solo capaz de aguantar un tiempo ni sostener largo combate".

  Varios son los defectos que apunta Gautier en su informe sobre los navíos que se construyen “a la inglesa” en Ferrol:

  - necesitan reparos frecuentes y costosos
  - por la debilidad de su fábrica
  - son endebles de espesor, los miembros son como fragatas ligeras
  - las cavillas los sujetan muy débilmente unos a otros y la fábrica se separa
  - los tablones son delgados y de pino para la artillería de 24
  - los trancaniles y contras-, que son las únicas sujeciones, están muy mal puestos
  - los baos están muy distantes entre sí
  - las cubiertas están sin curvidad
  - todos los navíos están quebrantados en el puerto
  - están expuestos a hacer agua, como el nuevo *S.Genaro*, con las cubiertas entreabiertas, los baos dislocados y los víveres averiados por haber tenido algunos golpes de viento fuerte desde Cádiz
  - “no atino por qué se despuebla a los Montes de España de sus mayores Arboles para sacar sólo muy pequeñas Maderas”

  Admite Vegaflorida algunos de los reparos de Gautier y propone que se pongan 16 curvas llaves, 4 en cada costado en las cubiertas de la 1ra y 2da baterías, alternando entre sí; y que se aumente el vuelo de los baos en 2 pulgadas. Pero aduce que:

  - la experiencia de los navíos de guerra ingleses ha sido muy buena navegando en todos los mares, y ellos reconocen que no son tan fuertes como éstos
  - los navíos trabajan más en un temporal que en un combate
  - el espesor que importa en combate es debajo del agua
  - la flaqueza del S.Genaro se debe a su construcción y no a su diseño, y que por la urgencia sus materiales no todos se cortaron en sazón y muchos se pudrieron
  - el quebranto se nota más que en nuestra antigua fábrica porque los navíos no tienen arrufo en sus cubiertas ni baterías, que lo disimulaban
  - al tener más plan padecen más quebranto al carenarlos sobre chatas para descubrir sus quillas, pero no en los diques, y
  - fortificándolos con trancaniles a la española y pernería de hierro se elimina el quebranto

- la duración de los navíos no depende sólo de su fortaleza sino principalmente de la bondad de sus materiales, porque,
- de los navíos de la antigua fábrica, construídos del 14 al 22 sólo quedaba en el 49 el S.Fernando, convertido en chata en La Carraca, y algunos de La Habana, por sus buenas maderas.

En su informe como Junta de Constructores expertos, D.Howel, T.Williams, J.Loughman y J.Hughes se definen como

- "profesores de la Construcción, de que hacen particular efectiva profesión", pero que han construído, "no por sus ideas, como habrían hecho si los hubieran dejado a su arbitrio, sino según las reglas que se les han predefinido";
- y que "los navíos Ingleses no sólo han resistido y resisten Combates y temporales inseparables de las Navegaciones sino que son más fuertes y mejores que los Franceses".

y argumentan:

- Que los miembros de todos los navíos estaban juntos menos en el "*San Genaro*", que por R. Orden de 28.Mar.1764 distaban tres pulgadas.
- Que los navíos ingleses se reforzaron para los balances quitando las curvas y sobreplanes y poniéndoles unos puntales oblicuos.
- Que las cabillas bien puestas son mejores que los clavos de hierro y no se pudren, pero dejaron el uso de la cabillería en obediencia a la R. Orden de 6.Dic.1763.
- Que sólo se quebrantaron los navíos que se carenaron en chatas.
- Que el "*San Juan Nepomuceno*", construído a la francesa, muestra grandes defectos en su estructura a pesar de ser más gruesa.

Sobre las mismas críticas de Gautier, la Junta de Contra Maestres de Construcción de Ferrol que convocó el Capitán J. Salomón, expresaba en 24.Abr.1767 que:

- parece innegable la mayor fortificación de los navíos de fábrica Española sobre la Inglesa, especialmente si se atiende a su principio en 1750, de que dista mucho la actual, mediante las correciones de los mismos profesores y las que ha establecido S.M.;
- la Construcción Española usaba más espesor en sus ligazones, e iban éstas encoramentadas, y no con la poca firmeza de la cabillería de madera como sucede a la Inglesa, propensa a pudrirse fuera del agua;
- no quita fortificación al buque el que en la medianía de la batería se coloquen tablones de pino, especialmente si fuesen del que llaman de la tierra que, sobre sólido y consistente es fuerte y no raja como nuestro roble;
- aunque se ha vuelto a los trancaniles a la española, no van endentados por causa de las curvas valonas;
- las curvas llave suplen la falta de endentado, pero en modo alguno la de encoramento de armazones;

- no parece dudable que cuanto más se ligue un Navío será menos velero, mas la experiencia enseña que no sólo en el ligado de sus miembros pero en el accidental de tener más o menos tesas las jarcias y Arboladuras se nota visible diferencia en el andar.

y terminan los Maestres asegurando:

- “que las proporciones de los Navíos Ingleses son excelentes y, a muy poca diferencia, las mismas que aquella Nación tomó de nuestra fábrica antigua de Vizcaya y Montaña;
- que los fondos son buenos;
- y que fortificando las obras muertas, y poniendo encoramento, y trancanil que es la sujeción de un Navío con especialidad en las cabezadas como que liga todo el largo de los Vageles, serán los más perfectos que por ahora podemos desear ...”

Esta discusión técnica sobre los sistemas de construcción naval es muy importante, y guarda relación con la investigación que 35 y 30 años antes – tenía Gautier 4 años – hicieran B. Geslain y B. Ollivier en los Arsenales ingleses por encargo de Luis XV.

Otras misiones similares fueron frecuentes a lo largo del siglo.

- Excerpted from Jorge Juan's Examen Marítimo (JUAN, t2, 68-69)

"113… La resistencia de los maderos es como los cubos de sus diámetros, y los momentos que sobre ellas se exercitan, por ser los pesos como los cubos de las mangas, son como los quadrados-quadrados, o los momentos de inercia como las quintas potestades, por cuyo motivo a dimensiones proporcionales, menos resiste el Navío grande que el chico, y por consiguiente mayores gruesos necesitaba en su maderas: todo lo contrario de lo que practican los tales Constructores.

Si representa (g) el grueso de las Quadernas, (a) su ancho, (n) el número de ellas y (m) la manga del Navío, habría de ser generalmenteen todos constante la expresión ($n.g^2.a/m^5$) para que sean igualmente fuertes: y así se ve, que aunque los gruesos (g), los anchos (a) y el número de Quadernas (n) fueran como las dimensiones lineales o mangas (m) siempre quedaría la expresión (1/m): lo que manifiesta que aun en este caso quedarían las Fragatas más fuertes: y esto, con todo que llevaran mucha menos madera, en razón inversa de las mismas mangas: añadiéndose, que por lo ordinario no hacen los Constructores (n) sino como ($m^{2/3}$), lo que reduce la expresión a ($1/m^{4/3}$).

Esta theórica la comprueba diariamente la experiencia: no se de continuo sino Navíos grandes desbaratados, descoyuntados y rotos, quando las Fragatas se mantienen firmes y sin el menor quebranto."

… … …

"114. En nuestros Navíos españoles, construidos por Gastañeta, las quadernas iban tan unidas como a la Inglesa, pero las uniones o empalmes de unas piezas con otras eran menores, lo que disminuía cada pieza de pie y medio o dos pies en su largo, que importaba en todo alrededor de 1000 quintales de peso que se le quitaban al Navío; siempre era alivio, pero por obra falsa, como saben los buenos Constructores.

"115. Los Franceses dan mayor distancia entre las Quadernas, no ponen tanta curvería, de suerte que un Navío de 70 cañones con 46 pies Ingleses de manga sólo ocupó 90260, que equivalen a 57522 quintales de peso. Este Navío tenía la misma Eslora y Puntal que el otro que citamos construido a la Inglesa, con que los pesos de sus buques han de ser como las mangas, esto es como 48 a 46; si el buque de aquel es de 37100 quintales, el de este debía ser de solos 1546 quintales menos, en lugar de 3977 que se halló en el todo de sus pesos; luego la diferencia 2431 procede de la menos cantidad de maderas y herrages que llevó el Navío Francés; añadiendo a esto algo más por la cantidad de lastre que estos Navíos necesitan. La distancia entre Quadernas era mayor de 4 pulgadas, lo que hacía que cupiesen en todo el Navío 8 Quadernas menos, cuyo peso es con corta diferencia, de 1030 quintales, que rebaxados de los 2431 ya no quedan sino 1041, que procederán de la menos curvería, y otras piezas menos que se ponen a la Francesa."

- (GALL, Anexo 1)

ANEXO 1. DEL CORPUS DOCUMENTAL DE LA CAMPAÑA DE TRAFALGAR

J. IGNACIO GONZÁLEZ-ALLER HIERRO. PAGS. 1363-1375.
PAPEL SOBRE CONSTRUCCIÓN HECHO POR EL OFICIAL DE LA SECRETARÍA DE MARINA DON JULIÁN DE RETAMOSA Y PRESENTADO A S.M. EN 16 NOVIEMBRE DE 1782.
1807-febrero-23, Madríd
SIGNATURA: AMN, ms. 203, doc. 4e (copia)

… … …

La Real Orden de 20 de octubre de 1780 dispuso la introducción del forro de cobre en los buques de la Armada con papel de estraza entre la plancha y el vivo de la madera del casco. Otra orden del mismo rango de fecba 31 de mayo de 1782 determinó cambiar el papel por zulaque (pasta de betún) (AMN, Col Vargas Ponce, ms. 69, doc. 1l). No obstante, estas medídas aún no se habían puesto en vigor en la mayoría de los buques cuando Julián de Retamosa presentó este documento a la consideración de S.M. Después de hacer varias reflexiones sobre la pesadez de nuestros navíos, para éste y otros defectos, se propone reducir sus tres principales medidas de eslora, manga y puntal con proporción a sus clases.

Considera conveniente que las cuadernas se unan entre sí con cabillería y no con clavazón de hierro, especialmente en el cuerpo sumergido de la nave, de que resultará al navío un aligeramiento de 1.600 quintales equivalentes a 2.666 pies cúbicos y a tres pulgadas menos de calado. Que se reduzcan a 5 en lugar de 13 el número de bulárcamas, se aligeren los navíos en los gruesos de sus maderas, especialmente en las cuadernas, y se omita el contratrancanil, volviendo al uso de las curvas de alto abajo y valonas.

Explicadas las mejoras que resultarán de estas enmiendas y no pendiendo sólo de ellas la buena marcha del buque sino de la perfecta disposición de su cuerpo inferior, de la más corta altura de sus obras muertas, ligereza de sus maderas y de la rectitud de sus secciones horizontales, huyendo en la parte de proa de inflexiones o violentas curvas como más arreglado a las leyes del choque de los fluidos contra las superficies para que no tengan oposición recta al fluido que resbala, parece que un navío de 74 construido de pino o cedro en todas sus partes podría completar sus principales dimensiones en esta forma.

… … …

Convendría a este navío darle 15 pulgadas de grueso en la cabeza de sus planes, y a línea 16 con reflexión a la cabillería de madera; 3 pulgadas de claro entre cuadernas, macizándose éstas hasta cabezas de genoles, en inteligencia de que desde la línea de flotación arriba es indispensable usar del pino o cedro, o en caso de ser de roble disminuirlo en razón de la gravedad específica de las dos primeras clases de madera.

… … …

1º Considerar el excesivo largo que se ha ido dando a los buques de guerra, y si conviene disminuirlo, de que resultarán las demás proporciones, pues se ha notado que los buques enemigos y los nuestros más cortos andan más que los actuales más largos.

2º Si conviene o no ligarlos tanto, sujetándolos a un extremo, que puede ser parte de la causa de su menos vela.

3º Si se les podrá o no disminuir de madera, ya en piezas superfluas o ya en sus gruesos, especialmente en sus obras muertas, pues es visible la diferencia de los que usan nuestros enemigos en ellas.

4º Que propusiesen las juntas y facultativos la variación que debiera hacerse en las arboladuras.

Enterado el Rey de estas reflexiones en 16 de noviembre de 1782, mandó se remitiesen a las juntas de los departamentos y de facultativos para que informasen sin reparo el modo de remediar el enorme defecto de la poca velocidad o andar de nuestros navíos, por cuya causa no se pudo atacar a los enemigos en la guerra anterior, como se muestra en el diario del último encuentro y caza dada a la escuadra inglesa los días 19 y 20 de octubre del mismo año por la española y francesa, muy superior en fuerza, y en el impreso dado al público en Cádiz por la misma Marina.

Resumen de los dictámenes de las juntas de los tres departamentos y oficiales facultativos, sobre un papel de enmiendas en varios puntos de construcción de buques, trabajado de orden del Sr. Marqués González de Castejón, ministro de Marina, y presentado a S.M. por el mismo marqués en 16 de noviembre de 1782, a resultas del combate naval de octubre anterior

Entre los 25 oficiales generales y particulares que componen las 3 juntas de los departamentos, inclusos otros a quienes el Director General pidió dictamen sobre tan importante punto, cuya ventilación y enmiendas causaron los continuos oficios del Director General cuando mandó la escuadra combinada, atribuyendo su poco favorable caza a los buques enemigos a la pesadez de los navíos que mandaba, de modo que ningún buque francés o español podía alcanzar a otro enemigo que huyera a popa o a un largo, aunque estuviera desarbolado de su palo mayor o trinquete; hay tal diversidad en los dictámenes que no se pueden reasumir más las resultas.

El director general don Luis de Córdova atribuye el poco andar de nuestros navíos a la suciedad de sus fondos por falta del forro de cobre, pues en una y otra construcción había navíos excelentes, que aunque advirtió menos bolineros los de construcción inglesa, podía errarse o acertarse en el establecimiento de una nueva construcción.

… … …

Don José Mazarredo conviene en que se siga la construcción francesa, atribuyendo el poco andar a la suciedad de fondos faltos de forros de cobre y malas estibas, añadiendo son nuestros navíos muy ronceros por sus enormes capacidades, para lo cual propone muchas enmiendas, como son aumentar a unos zapatas, hacer iguales el palo mayor y el trinquete, añadir embonos y otras.

… … …

El ingeniero director don José Romero no aprobaba el método de arcos de círculo, que dice es impracticable, y sólo conveniente multiplicar vagaras o maestras para asegurarse con esta multitud de tentativas, de la exacta descripción del bajel, y le parecía lo más conveniente sobre el navío *San Juan Nepomuceno* hacer las siguientes enmiendas: aumentarle un pie de manga, disminuirle 8 pies de eslora, algunas pulgadas al puntal y darle segunda línea de fuerte.

… … …

Don Manuel Travieso, tratando sobre la fortificación de los navíos en que advertía muchas piezas inútiles, dice que es obra precisa macizar desde el sollado hasta el batiporte de la 1ª batería, con que en las claras entre cuadernas hallará una bala 14 pulgadas más de espesor que le estorbe su paso a todo el costado; que son superfluos los contratrancaniles por ser obra costosa, y que los navíos sin ellos sufrían muy bien grandes temporales; que con 4 bulárcamas o sobreplanes tiene un navío lo suficiente para su fortaleza, y debían suprimirse hasta el número de 13 que está en práctica, conceptuando muy preciso no usar de piques u horquillas, sustituyendo los dormidos y astas reviradas con lo que se economiza y aprovecha mucha madera, sin dejar de ser las obras fuertes y seguras, de cuyo dictamen fue también don José Romero, a quien se le pasó a informe.

… … …

En punto a fortificación parece del dictamen de las curvas valonas y de peralto y no al de contratrancaniles; que son utilísimos los dormidos y macizos de planes en lugar de horquillas; que no pasen de 6 las bulárcamas que se pongan, las cuales no deben cortar los trancaniles; que no era de mucha entidad la bulárcama puesta verticalmente, siendo mejor ponerlas diagonales, y que la prueba se hiciese con el navío de Romero y otros dos de construcción francesa en lugar de los dos de Bryant y Retamosa.

… … …

❖ *Santísima Trinidad*

La distribución de los pesos por conceptos:

Casco	61,5 %
Arboladura	3,0 %
Artillería	8,9 %
Respetos, botes	3,6 %
Víveres (3 meses)	10,0 %
Tripulación	1,8 %
Lastre	11,2 %

El lastre era muy variable, dependiendo de la campaña y de las condiciones, llegando en algún caso al 6%

...

En la construcción a la inglesa los dos planos estaban separados una pulgada, unidos entre sí por dados atravesados por pernos, con lo que resultaba el casco algo más ligero y débil.

Los pernos de unión o encoramentado eran de hierro, fabricados en Vizcaya o en Jubia (Ferrol).

Cuando vinieron los técnicos ingleses, introdujeron la novedad de emplear cabillas de madera para disminuir peso, pero se abandonó pronto porque en climas tropicales se aflojaban desbaratándose los buques.

Appendix to Loadings on Hulls at Sea

(LAV2,v1,123)

“I am of the opinion that all the ships of the present are too short, from ten to thirty feet according to their rates. If ships in future were to be built so much longer as to admit of an additional timber between every port, and if the foremost and aftermost gunports were placed a greater distance from the extremities, they would be stronger and safer, and have more room for fighting their guns”.

Appendix to Hull Materials

- Mechanical Properties of Hull Materials

E = Young's Modulus; G = Transverse Modulus; R = Tension Strength; Y = Yield.
Units: kg/cm^2

	E	G	R	Y
Iron	2.0E6	8E5	3400	1300
Steel	2.1E6	8.3E5	4500	2400
Copper	1.15E6	4.2E5	2200	500
Brass	0.8E6	3.2E5	1600	650
Oak	0.1E6		600/1200	
Teak	0.16E6		300/1100	
Red pine	0.11		300/900	
White pine	0.11		200/300	

- Properties of some woods used in shipbuilding (WOOD, 2-6)

	RedOak	WhiteOak	Mahogany	VPine
Moisture content green, %	80	70	58	88
Static bending, psi				
Fiber stress at proportional limit	4400	4700	—	4000
Modulus rupture	8500	8100	9200	7300
Modulus elasticity 1000	1360	1200	1290	1220
Work to, in-lb/cu.in				
Proportional limit	0.85	1.08	—	0.75
Maximum load	12.6	11.3	10.2	10.9
Impact bending height, in				
To failure with 50 lb	43	42	—	34
Compression parallel, psi				
Fiber stress at proportional limit	2590	2940	—	2500
Max. crushing strength	3520	3520	4540	3420
Compression perpendicular, psi				
Proportional limit	800	850	710	390
Shear parallel, psi				
Max. shearing strength	1220	1270	1310	890
Tension perpendicular, psi				
Max. tensile strength	740	760	—	400
Hardness, .444 in ball, lb				
Load to embed 1 radius, side	1030	1070	650	540

	RedOak	WhiteOak	Mahogany	V.Pine
Moisture content dried, %	12	12	12	12
Static bending, psi				
Fiber stress at proportional limit	8400	7900	—	7100
Modulus rupture	14400	13900	11100	13000
Modulus elasticity 1000	1810	1620	1430	1520
Work to, in-lb/cu.in				
Proportional limit	2.30	2.31	—	1.86
Maximum load	15.0	13.3	6.8	13.7
Impact bending height, in				
To failure with 50 lb	43	39	—	32
Compression parallel, psi				
Fiber stress at proportional limit	4610	4350	—	3820
Max. crushing strength	6920	7040	6430	6710
Compression perpendicular, psi				
Proportional limit	1260	1410	1210	910
Shear parallel, psi				
Max. shearing strength	1830	1890	1050	1350
Tension perpendicular, psi				
Max. tensile strength	820	770	—	380
Hardness, .444 in ball, lb				
Load to embed 1 radius, side	1300	1330	760	740

Ratio of “wet” to “dry” properties of each wood

	RedOak	WhiteOak	Mahogany	VPine
Ratio of moistures	80/12	70/12	58/12	88/12
Static bending, psi				
Fiber stress at proportional limit	0.52	0.59	—	0.56
Modulus rupture	0.59	0.58	0.83	0.56
Modulus elasticity 1000	0.75	0.74	0.90	0.80
Work to, in-lb/cu.in				
Proportional limit	0.37	0.47	—	0.40
Maximum load	0.84	0.85	1.50*	0.80
Impact bending height, in				
To failure with 50 lb	1.00	1.08	—	1.00
Compression parallel, psi				
Fiber stress at proportional limit	0.56	0.68	—	0.65
Max. crushing strength	0.51	0.50	0.71	0.51
Compression perpendicular, psi				
Proportional limit	0.63	0.60	0.59	0.43
Shear parallel, psi				
Max. shearing strength	0.67	0.67	1.25*	0.66
Tension perpendicular, psi				
Max. tensile strength	0.90	0.99	—	1.05*
Hardness, .444 in ball, lb				
Load to embed 1 radius, side	0.79	0.80	0.86	0.73

- Orthotropic 3-D values of Young Modulus E

For longitdinal (L), radial (R) and circumferential or tangential (T) directions, the values of E for spruce and beach are given in 1E8 Mpa (BUC1):

	Spruce	Beech
E(L)	95.6	137.0
E(R)	10.37	22.40
E(T)	4.87	11.40
G(LR)	7.5	16.10
G(RT)	0.39	4.90
G(TL)	7.2	10.6
V(RL)	0.029	0.073
V(TL)	0.020	0.044
V(TR)	0.25	0.36
sp.gravity	0.429	0.75

Appendix to Scantlings to Rules

Excerps selected, adapted and translated by the author from (BV71), (BV12) and (BV31)

Rules for 1912 and 1931 are practically identical.

Different requirements found for 1871 are highlighted in italics

(3.1) Bottom and side shell of ships for unrestricted navigation should be sheathed with copper or metal, but not with zinc, up to a height 2/3 of the depth at midship.

When wales are fitted the shell should be copper-sheathed up to 1/2 of the depth at the midship.

(1871: For trade round the Horn and Cape of Good Hope, up to one foot under the load draught)

Ships constructed under special survey may be granted Class 3/3 for the number of years given in Table A below for each type of wood and each structural element.

(7.2) The duration of the Class given in Table A can be extended in the following cases:

+ 2 years when all wood in the hull is for at least 8 years; +1 year if less than 8 years.

Or +1 year when wood is for less than 12 years and the hull has been salted during construction or within 6 months after launching.

+ 1 year when all nails in the shell and deck are of galvanized iron, copper or metal.

Or + 2 years when all nails, bolts and fittings of the hull are of galvanized iron, metal or copper.

+ 1 year when wood used in principal elements is for 10 or 11 years and treenails are of (acacia) or wood of equivalent quality from the gunwale (regala) to the bilge (vuelta del pantoque). These principal elements are: keelsons (carlingas), deck beams (baos) and hold beams (falsos baos), gunwale (regala), waterways (trancaniles), inner waterways (contratrancaniles), (cosederos), beam shelves (durmientes), clamps (contradurmientes) and shroud chains (cadenates de obenques)

TABLE A

Elements

Quilla	1	
keel		quille
Roda y codaste	2	
stem, stern post		étrave, étambot
Apóstoles y macizos	3	
knightheads, deadwood		apôtres, massifs
Varengas	4	
floors		varangues
Genoles y barraganetes	5	
futtocks, top timbers		genoux, allonges
Yugos y gambotas	6	
transoms, cant timbers		lise d´hourdy, barre d'arcasse jambettes
Carlinga	7	
keelson, mast step		carlingue
Baos y buzardas	8	
beams, breasthooks		barrotes, guirlandes
Curvas	9	
knees		courbes
Madre de molinete y timón	10	
Rudder stock		mèches de guindeau et de gouvernail
Forro hasta flotación	11	
shell below waterline		bordé jusqu'a la flottaison
Forro de flotación a regala	12	
shell above waterline		bordé jusqu'au plat-bord
Regala, trancaniles, guirnalda	13	
gunwale, waterways, stringer		plat-bord, fourrure de goutière, serre-goutière, bretonne
Hiladas e hiladas de refuerzo	14	
strakes, reinforced strakes		vaigres, vaigres de renfort
Palmejares	15	
side stringers		serres d'empatture
Durmientes, contras	16	
shelves, clamps		bauquières de pont et d'entrepont

Wood types

Teca, acacia, roble verde, id. Africa, id. meridional, greenheart .... A

Teck, acacia, chêne vert, d'Afrique, meridional, greenhart

Teak, locust, Africa, live and southern oak, greenhart

Roble blanco de Europa y de América .... B

Chêne blanc

White oak 1st quality

Pino-tea, alerce y pino meridional C

Pitch-pine, méléze et pin meridional

Pitch-pine and southern larch

Pino de Oregón .... D

Pin d'Oregon

Red cedar

Hackmatack, enebro y alerce ordinario .... E

Hackmatack, génevrier et méléze ordinaire

Hacmetack, tamarac, juniper and larch

Pino rojo .... F

Pin rouge

Red pine 1st quality

Roble ordinario de buena calidad .... G

Chêne ordinaire de bonne qualité

Common white oak

Pino amarillo y olmo de América .... H

Yellow birch et orme de l'Amerique

Yellow pine

Pino negro superior de bahía Fundy y de costas del Océano I

Spruce superieur de la baie de Fundy et des côtes de l'Océan

Bayshore spruce

Pino negro, pino y abeto ordinario .... J

Spruce, pin et sapin ordinaires

Common spruce and ordinary red pine

Olmo, arce y haya .... K

Orme, érable et hêtre

Elm, maple, beech and birch

Alamo blanco L

Bouleau

Poplar

Cicuta .... M

Hemlock

Hemlock

Elem.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Wood																
A	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
B	12	12	11	11	11	11	11	11	11	11	11	11	11	11	11	11
C	10	9	9	9	10	10*	11	11	–	8	12	11	11	11	11	11
D	8	8	9	9	9	9	10	10	9	8	11	10	9	9	9	9
E	8	8	9	9	10	10*	9	9	11	7	10	9	9	9	9	9
F	8	8	9	9	9	9	8	9	9	7	10	9	9	9	9	9
G	10	9	8	9	8	8	8	8	8	8	10	8	8	9	8	8
H	12	9	8	9	8	8	8	–	–	8	12	8	8	9	8	–
I	5	5	8	9	9	8	8	8	9	–	9	9	8	9	8	8
J	5	5	5	6	6	6	5	5	6	–	6	6	5	6	6	5
K	12	4	4	4	4	4	4	4	–	4	12	4	–	4	4	4
L	9	5	4	4	4	4	4	4	–	4	10	4	–	4	4	4
M	–	–	–	3	3	–	–	–	–	–	–	–	–	–	–	–

* this duration can be extended to 11 years when these elements are salted

1871: Duration assigned to wood types A, C and D was 10 years.

This Table shows which wood types are preferred for each element and which types are not used for others. It also confirms that teak, oak and greenhart were considered the best woods for hulls.

Classed ships should be surveyed periodically to keep their class. These surveys were scheduled for mid term and end of every type period. The total time within the class 3/3 could be extended for a length of time that ran from 6 years for a 9-year class hull to 11 years for a 16-year class hull, making a maximum total class time of 15 and 27 years respectively.

After the total length of time was elapsed the ship would enter a lower class 5/6.1 for another maximum length of time of 12 years for a 9-year and 18 years for a 16-year hull. After this, a third class 5/6.2 would be given for an unlimited number of 3-year extensions, after passing yearly surveys.

Since Class reflected the state of the hull in terms of fitness for mission, its philosophy can be applied to judge the state of warships and analyze their maintenance as it was carried out at dockyards.

All elements had to be replaced when their thickness or section was significantly reduced or damaged. As an example, deck planking would be replaced when its thickness was reduced by 18% for 75 mm planks and by 23% for planks over 90 mm.

Scantlings given in Table B are for oak. They can be reduced by 1/8 to 1/10 for teak and southern oak.

Scantling Numeral = L·B·D

L = length on deck to external faces of stem and stern post

B = breadth outside framing

D = depth from lower edge of keel rabbet to upper face of main beam

1871: Main dimensions used to calculate the Scantling Numeral were:
Length between inner sides of stem and stern posts.
Breadth measured on the ceiling.
Depth measured from the ceiling to the upper side of upper-deck beam at midlength)
Scantling Numeral was the Gross Register Tonnage = L·B·D (7/10).

KEEL, STEM, STERN POST, KEELSON (Art.17)
(Quille, Étrave, Étambot, Carlingue)
(Quilla, Roda, Codaste, Sobrequilla)

KEEL pieces to be more than 15 m long, except the fore end.

Scarphs length at least 5 times the keel height with ends to be at least ¼ the keel depth

1871: Keel to consist of two lengths only for vessels under 300 tons, of three lengths for vessels up to 600 tons and of four lengths above that tonnage.
When the keel is composed of more pieces, an outer or lower keel is required, with the main keel at least 1/2 and the upper or main keel 2/3 of the moulding in the table.

Scarphs: flat and as in 1912

When the keelson has more than 3 lengths a hog or rider keelson ¾ the section of the keelson should be added or 2 sister keelsons each 2/3 of the dimensions of the main keelson instead.

STEM scarphs to be at least 3.5 times the stem depth

Ships longer than 38 m shall have a second keelson 2/3 the section of the lower keelson.

MEMBERS (Art.18)

FLOORS are to be at least B/2 long in the midship sections

FUTTOCKS are to overlap at least 7 times their depth

MEMBERS can reduce their depth and width by 1/4 only when they run continuous up to the forecastle and poop decks.

1871: The shift of timbers to be B/7.

Spacing between the frames on the keel not to exceed ½ the siding of the floors. When there is space between the timbers of a frame, the spacing should be reduced.

BEAMS, HOLD BEAMS, PILLARS, SHELVES, WATERWAYS, INNER W. (Art.19)

(Barrots, Barres sèches, Épontilles, Bauquières, Fourrures et Serre-Goutière)

(Baos, Baos vacíos, Puntales, Durmientes, Trancaniles, Contratrancaniles)

Clearance between BEAMS of planked decks is not to exceed 1 meter.

When the hold depth is 5.80 m the hold beams will alternate with 1 and 2 deck beam spacings.

When the hold depth reaches 6.40 m hold beams are to be fitted under every deck beam.

Scarphs of SHELVES are to be cut in their width with a length 3.5 times their height.

1871: Ledges to be 1/3 the section of the beam and supported in the middle by Carlings that are 1/2 the sectional area of the beams.
Stanchions 1/3 the sectional area of the beam)

One WATERWAY is to be fitted on each head of every beam, with vertical scarphs of length 3.5 times the width of the waterway.

When ship length exceeds 28 m an INNER-WATERWAY is to be fitted inboard.

Beam heads are to be fixed together with waterways, shelves and clamps.

When a "breton wale" or spirketting is fitted, it should be as thick as the clamp and 5 to 10 cm higher than the waterway.

Wooden pillars are to be fitted under deck beams with a section 2/3 of the beams they support.

OUTER SHELL, PLANKING, STRINGERS, DECKS (Art.20)
(Bordé extérieur, Vaigres, Serres démpatture, Ponts)
(Forro exterior, Tablazón, Palmejares, Cubiertas)

For ships with L/D = 6 or less, the accumulated height of wales shall be D/3; when L/D=8 the accumulated height shall be 2 D/5.

Bilge strakes shall be paired to hold stringers, and their width is to be limited to 300°mm.

1871: Inside bilge strakes to extend from one strake below the floor heads to one strake above the heels of the third futtocks, but in no case their entire width to be below B/6.

Shell strakes are to maintain their thickness over central 3L/5 of the hull. Plank thickness above 8 cm can be tapered towards the ends up to 20%

All shell planking shall be at least 6 m long.

1871: Planks to be at least 22ft long

Shell strake butts in a frame shall be separated by at least 4 intermediate strakes.

1871: Butts on two adjoining planks not to be nearer to each other than 5 ft.

Plank scarphs in contiguous strakes shall be separated by at least 3 frame spaces.

Deck planking butts shall be separated by 2 beam spaces and 3 deck strakes at least.

Deck planking shall be at least 7 m long.

Hold stringers shall extend from one strake below the floor head to one strake above the second futtock foot.

Total width of hold stringers shall be at least B/6 on each side.

Where first futtocks don't reach the center of the keel they are to be fixed by a reinforced strake on each side of the keelson, with the scantling of a stringer and bolted to the floors.

KNEES, RIDERS, DIAGONALS, BREASTHOOKS (Art.21)
(Courbes, Porques, Diagonales, Guirlandes)
(Curvas, Bulárcamas, Diagonales, Buzardas)

1912 Rules do not give detail scantlings for wooden knees.

1871: Vessels of 400 tons and upward to have 2 vertical hanging knees to each deck beam.

All hold beams to have vertical hanging knees.

All beams, including hold and decks have to be fixed by horizontal knees (lodging) at each head.

All hold beams shall have hanging knees. Those in way of the masts and the hatchway shall be extended as riders and shall be fixed to the floors by 2 bolts.

When the hull members are made of spruce, hackmatack or equivalent woods, all knees under the hold beams shall be extended as riders on top of the floors, and the thickness of the vertical leg can be 12 mm less than the throat.

Width of wooden knees is to be not less than 4/5 the width of the members they are bolted to. Height of the throat is to be at least 1.5 times the width.

Lodging knees shall be bolted to every frame.

In vertical iron knees the length of the legs shall be enough to accommodate 3-4 bolts in the horizontal arm and 5-7 bolts in the vertical leg. Wooden knees shall have more bolts than iron ones.

All knees shall have one bolt at the center of the bend. Hanging knees shall have the first bolt in the vertical leg not more than 200 mm down from the center bolt.

Ships over L/D=10 as well as those built of pine, spruce, hackmatack or fir with a Scantling Numeral higher than 200 will be fitted with iron diagonals in their hold, separated from 1.85 to 2.45 m so that at least 4 diagonals cross at right angle at midship.

These diagonals shall be fixed by 2 bolts to every frame and will extend from the gunwale down to the heads of the first futtocks.

Ships over 4.85 m of depth shall be fitted with breasthooks separated not more than 1 m. Horizontal legs shall be B/4 long at least. Lower breasthooks will cross at 45º over the planking and will extend up to above the hold beams.

Their dimensions shall be 3/4 those of the deck beams.

1871: Mean spacing of breast hooks and crutches in the hold not to exceed 3 feet.
The length of hooks and crutches and their pointers to be equal on each side to B/4.
The knees to be sufficiently long to receive from five to seven bolts in the leg and from three to four bolts in the leg.

1871: Spacing of deck beams on which planks are fitted not to exceed 4 feet.
Five feet spacing is allowed when carlings are introduced.
Vessels of 18 ft depth of hold to have hold beams under every deck beam
Vessels of 20 ft depth of hold to add an orlop beam at the bow connected to the sides by two horizontal knees at each end.
Vessels over 24 feet depth of hold to have two decks and orlop beams under every second hold-beam.

BOLTS, NAILS, TREENAILS (Art.22)
(Chevillage, Clouage, Gournablage)
(Pernos, Clavazón, Encabillado)

Keel and keelson shall be bolted to every floor. At least half of the bolts shall be “riveted”.

Bolts in scarphs of the keel and other principal members not to be more than 12 in (300 mm) apart. Scarph ends to be fixed by 2 bolts.

Before erecting the frames, they should be assembled with 4 iron bolts at each futtock.

Partial floors or double floors shall be fixed with “riveted” bolts to the stringers or to the reinforced strakes.

1871: Frames to be connected with four square frame bolts in each futtock, and five in the first foothook, or naval timber.

The keelson to be bolted in every floor timber; half of the bolts may be dump bolts, and must in that case be driven at least through 4/5 of the thickness of the keel; the other half to be clinched under the keel or on the keelson.

Knightheads shall be bolted to the stemson and to the hawse pieces.

Bolting of apron and fore deadwood shall be with the same step as the keelson, and copper or brass bolts shall be used not to react with the copper sheathing.

Each beam head is to be fixed with one bolt to the waterway and to the shelf.

Shelves and clamps under the decks will be fixed with 2 bolts to each frame, driven from the outside through the shell and “riveted” on the inside.

When a shelf is 150 mm thick or more it shall be vertically bolted to the clamp every 2 frame spaces.

1871: Thick strake under clamps to receive 2 bolts in each frame.
When clamps are 6 in thick or more they must be tie-bolted to the thick-stuff under them, with one bolt in every second room.

The main transom will be fixed to the stern post with 2 bolts in X, "riveted" outside.

Waterways of the main deck shall be fixed to the shelf through the beam head. Besides, they shall be fixed to every frame with a bolt through the side shell, riveted inside the waterway.

Inner waterway will be bolted to every beam and riveted under it. Besides, a bolt will be driven through the waterway, frame and shell, and riveted outside or inside.

1871: Lock strakes to have a through-bolt clinched under each beam, and two horizontal bolts in each space between the beams driven from the outside, and clinched on the inside.

Stringers shall be fixed with treenails and bolts. Bolts shall be used in the central 3L/5, one every 3 frames, through the shell and riveted inside.

When these bolts don't run through the outer shell the time duration of Table A shall be reduced by 2 years time.

When stringers are 150 mm or wider they should be bolted to each other every 3 frames, apart from being bolted to the frames and outer shell.

Outer shell planks less than 120 mm wide shall be fixed with 2 treenails or 2 bolts to every frame.

Shell planks from 120 to 200 mm wide shall be fixed with 2 treenails and 2 nails, or 1 bolt plus 1 treenail and 2 nails, 4 joints in all, unless the ship has treenails in which case each crossing will have 3 joints, namely 1 bolt and 2 nails.

Shell planks from 200 to 250 mm wide will be fixed by 3 treenails or 3 bolts to every frame; when wider than 250 mm they will receive 4 treenails or 4 bolts on every frame.

1871: Outer planks to be further secured by a bolt driven through the timber next to the butt, and clinched inside, and a treenail in each timber receiving no through-bolt.

Planks 12 inches wide require two treenails in each timber.

Planks of inner lining will be fixed by 2 treenails or 2 bolts to every frame.

1871: Each inside bilge strake to be secured with a bolt at each butt, and at least one through-bolt in every second frame clinched inside on rings of the same metal. When bilge strakes are 6 in or upwards they must be tie-bolted in every third room, independently of the through-bolts and treenails.

Where outer shell is fixed with copper or metal bolts two thirds of them shall be riveted inside.

Plank ends shall be fixed with one bolt riveted on a washer on the inside end.

Garboard strakes thicker than 150 mm shall be bolted to the keel every two floors on the central 3 L/5 of the hull.

1871: Wales to have through preventer-bolts at each butt, a through-bolt clinched inside in every second frame in vessels under 500 tons and in every frame in vessels above that tonnage; when the wales are through-fastened with oak or locust treenails, a through-bolt in every third frame will be allowed.

Breasthooks shall be fixed to the stem and stern post compounds by one central bolt and their legs shall be fixed to every frame by two bolts riveted on washer outside and every three frames one shall go through the outer shell planking.

Spacing of bolts joining the riders shall not be larger than 450 mm above the hold stringers and 250 mm on the hold stringers.

Bolts joining each pair of frames shall be 1/12 the width of the frames in diameter.

Bolts shall be dimensioned in accordance with Table C for the principal elements of the hull.

Treenails made of oak or acacia shall have diameters depending on the Scantling Numeral L×B×D as follows:

22 mm for Scantling Numeral up to 900

35 mm for Scantling Numeral greater that 2260

Treenails of woods softer than oak shall be 3 mm more in diameter.

1871: Oak and locust treenails to be in proportion to the size of the wood through which they pass. Mean size for 200 ton vessels to be 7/8 in; for 300 tons, 1 in; for 400 tons, 1-1/8 in; for 500 tons, 1-1/4 in; for large tonnage, 1-3/8 in.

When hackmatack, pine or timber inferior to oak is used for treenails, diameter must be increased by one-eighth of an inch.

Treenail holes are not to be bored before the other fastenings are regulated.

When hull is made of oak treenails can be substituted by nails but then their shell planks shall be fixed by bolts riveted inside every two frames.

Nails shall have a length of twice the thickness of the planking plus 30 mm.

When the hull is to be salted, iron nails shall be galvanized.

SCANTLINGS IN ACCORDANCE WITH BUREAU VERITAS 1912 RULES

TABLE B – Height-Width in mm (tour-droit; grúa-línea)

	Trinidad	*Victory*	*V-74*
Numerals	8096	6430	5916
Keel	500-420	500-410	490-400
Stem, Stern post	510-420	500-410	500-400
Frame spacing	770	740	740
Floors	430-310	410-300	410-300
Timbers down	270-270	270-270	270-260
Timbers up	230-220	230-220	220-210
Keelson	560-550	540-530	530-520
Main transom	450-450	440-430	430-430
Deck shelves	240-300	230-300	220-300
Deck clamps	150-300	150-300	140-300
Beams	260-300	250-300	250-300
Waterway	240-300	220-300	200-300
Ceiling	110	100	100
Stringers	180	170	160
Garboard strake	210	210	210
Bilge strakes	180	170	160
Wales	180	170	160
Underwater planking	120	110	110
Deck planking	(pine)	110	100
Gunwale	140	140	140
Rudder stock	450-450	450-450	440-440

TABLE C – IRON BOLTS DIAMETER (mm)

Keel, keelson, stem .... Stern, breasthooks	40	37	35
Deadwoods, aprons	43	40	38
Scarphs, shelves, ... Beam heads, knees	30	29	27
Knee bends	33	32	30
Waterways, inner w. .... Bilges, stringers	29	25	25
Wales, knee legs .... Planking and ends	25	24	22

TABLE D – IRON KNEES, RIDERS, BREASTHOOKS

(Dimensions in mm)

– Vertical knees			
Width	127	115	115
Thickness at bend	115	108	108
Thk at horizontal end	13	13	13
Thk at vertical end	19	19	19
Horizontal leg, length	1220	1140	1140
Vertical leg, length	1830	1710	1710
– Lodging knees			
Section	80% of vertical knees sections		
– Riders			
Thickness....................................	77	70	70
– Breasthooks			
Width	139	127	127
Thickness at bend	139	127	127
Legs	B/4	B/4	B/4

- ❖ Equivalence of hull terms in Spanish, French and English

Alefriz	râblure	rabbet
Escarpe	écart	scarph
Barrotes	barrotins	—
Entremiche	entremise	filler
Cintas	préceintes	wales
Hilada de	virure de	bilge strake
Pantoque	bouchain	—
Puntal	creux	depth of hold
Vagra	vaigre	inner strake
Palmejar	serre d'empatture	stringer
Cinta bretona o cosedera (sobretrancanil)	virure bretonne	upper waterway spirketting
Durmiente	bauquière	beam shelf
Sotadurmiente	serre-bauquière	clamp
Contratrancanil	serre-goutière	inner waterway
Trancanil	fourrure de goutière	waterway
Regala	plate-goutière	gunwale

Appendix to Wooden Walls under Gunfire

- *HMS Shannon* and *USS Chesapeake*

  One of the best sources for studying round shot damage on late 18th century wooden hulls is the report on the fight between the British frigate *HMS Shannon* and the American frigate *Chesapeake* on June 1st, 1813. (SHAN)

  The report describes the damage caused to the *Shannon* by hits of 25 round-shot and to the *Chesapeake* by 56 round-shots apart from other types of projectile. Penetration of 32-pounder carronades and 18-pound round-shots was through several parts of the two ships and as deep as 10 to 14 inches in their masts.

  The battle was fought within pistol range and most of the round-shots caused full penetration through the wooden wall that would be composed of 10 to 8in futtocks and 6°in wales. (TAKA)

  On her main deck, the *Shannon* was armed the same as every other British frigate of her class, and her established guns on the quarter-deck and forecastle were 16 carronades, 32-pounders, and four long 9-pounders, total 48 guns.

  But Captain Broke had since mounted a 12-pounder boat-carronade through a port purposely made on the starboard side of the quarter-deck, and a brass long 6-pounder, used generally as an exercise gun, through a similar port on the larboard side; besides which there were two 12-pounder carronades, mounted as standing stern-chasers through the quarter-deck stern-ports.

  For these last four guns, one 32-pounder carronade would have been more than an equivalent. However, as a 6-pounder counts as well as a 32-pounder, the *Shannon* certainly mounted 53 carriage-guns. The ship had also, to be in that respect upon a par with the American frigates, one swivel in the fore, and another in the main top.

  The armament of the *Chesapeake*, the fourth frigate of the *Constitution*-class, was afterwards found on board of her, 28 long 18-pounders on the main deck, and 20 carronades, 32-pounders, and one long shifting 18-pounder, on the quarter-deck and forecastle, total 49 guns; exclusively of a 12-pounder boat-carronade, belonging to which there was a very simple and well-contrived elevating carriage for firing at the tops, but it is doubtful if the gun was used.

  Five guns, four 32-pounder carronades and one long 18-pounder, had it was understood, been landed at Boston. Some have alleged, that this was done by Captain Lawrence, that he might not have a numerical superiority over his antagonists of the British 38-gun class: others say, and we incline to be of that opinion, that the reduction was ordered by the American government, to ease the ship, whose hull had already begun to hog, or to arch in the centre.

On the 1st of June, early in the morning, having received no answer to several verbal messages sent in, and being doubtful if any of them had even been delivered, Captain Broke addressed to the commanding officer of the *Chesapeake* a letter of challenge, which, for candour, manly spirit, and gentlemanly style stands unparalleled. The letter begins:

> *“As the Chesapeake appears now ready for sea, I request you will do me the favour to meet the Shannon with her, ship to ship, to try the fortune of our respective flags”*. The *Shannon*'s force is thus described: *“The Shannon mounts 24 guns upon her broadside, and one light boat-gun, 18-pounders upon her main deck, and 32-pound carronades on her quarter-deck and forecastle, and is manned with a complement of 300 men and boys (a large proportion of the latter), besides 30 seamen, boys, and passengers, who were taken out of recaptured vessels lately”*.

Five shot passed through the *Shannon*; one only below the main deck. Of several round shot that struck her, the greater part lodged in the side, ranged in a line just above the copper.

The *Chesapeake* was severely battered in her hull, on the larboard quarter particularly. A shot passed through one of her transoms, equal in stoutness to a 64-gun ship's; and several shot entered the stern windows.

She had two main-deck guns and one carronade entirely disabled. One 32-pounder carronade was also dismounted, and several carriages and slides broken. her three lower masts, the main and mizzen masts especially, were badly wounded. The bowsprit received no injury; nor was a spar of any kind shot away. her lower rigging and stays were a good deal cut; but neither masts nor rigging were so damaged that they could not be repaired, if necessary, without the ships going into port.

- *USS Constitution* (Old Ironsides)

On October 21, 1805 the frigate *USS Constitution* celebrated her eight birthday. She was the first of Henry Knox's plan to build the first warships for the US Navy: four 44-gun frigates (*Constitution*, *President*, *United States* and *Chesapeake*) and two 36-gunners (*Constellation* and *Congress*), under the bill approved March 27, 1794 to defend US interests from barbarian piracy in the Mediterranean.

She was launched at Hartt's Naval Yard in Boston and designed by Joshua Humphreys, a well established Philadelphia shipbuilder, who wrote the essential requirements for these ships (MAGO, 64):

> *"… none ought to be built less than 150 feet keel, to carry twenty-eight 32-pounders or thirty 24-punders on the gun deck, and 12-pounders on the quarter-deck. These ships should have scantlings equal to 74's and I believe may be built of red cedar and live oak. … The beams for their decks should be of the best Carolina pine, and the lower futtocks and knees, if possible, of live oak.*
>
> *The greatest care should be taken in the construction of such ships, and particularly all her timbers should be framed and bolted together before they are rised."*

The British complained that she was not a frigate but a disguised line-of-battle ship, and after her success in the war of 1812, the British constructors cut down some of their old 74's to two decks to fight the *Constitution* and *President* with vessels of similar rating.

The *Constitution* did not want to go to sea. The declivity of the slipways had been reduced after the previous 10 of July the *United States* had been damaged in a premature launching caused by excessive declivity of the ways. The ship stopped after twenty-seven feet. The next attempt moved her thirty feet down, but her stern had settled on the ways below and her keel had acquired a permanent hog that was never removed. She was finally put to sea after increasing the declivity of the ways. (MAGO, 67). In the restoration of 1927 the hog measured was fourteen inches and the keel 157ft-10°in.

The framing of the *Constitution* was laid up with no space between the timbers. That made a very solid hull that demonstrated its strength under gunfire. In the engagement of August 19, 1812 with *HMS Guerrière*, her side was struck by enemy shot that was rebound and made a sailor shout "her sides are made of iron", which coined her current nickname "Old Ironsides".

The midship section shows the following dimensions:

Molded breadth	43 ft-6 in
Extreme breadth	44 ft-8 in
Oak keel.........................	18 in × 24 in
Oak shoe	6 in
Oak deadwood..............	9 in × 24 in
Oak keelson	18 in × 18 in
Oak upper keelson.........	15 in × 18 in

Live oak frames	15 in mold at keel to 9 in at gunport sills
Yellow pine beams.........	15 in × 18 in gundeck
Live oak knees	10 in thick 82 in throat
Oak side plank	7 in × 10 in, 6 planks at water-line
Oak spirketting...............	5 in gundeck, 6 in upper,2 planks each
Clamps	5 in, 2 planks
Waterways	15 in square beveled
Diagonal risers	6 pairs each side, tennoned to keelson
Garboard	6 in
Outer shell......................	5-1/2 to 4 in, up bilge
Main wales.....................	6 × 7 in × 10 in
Inner ceiling	6 in
Decks (2).........................	4 in white oak 6ft from side 4 in yellow pine rest 6 in white oak 2 strakes under pillars, 2 str. hatch edge

Upper and gundeck had thirty two beams and berth deck below thirty one. Orlop deck had only sixteen beams, nine centered at the mainmast and seven at the foremast.

(MAGO, 88) quotes that *“during the repair in 1833 a piece of timber 9ft long, 27in wide, 14in thick weighing 1460 pounds was removed from her. On breaking it up, in it were found 364 pounds of iron and 163 pounds of copper”*. These dimensions should belong to a piece of deadwood astern, fastened with many iron bolts and using copper nails for the shell planking and sheathing.

From these figures we obtain:

Total weight white oak	933 lb
Specific gravity ditto	0.633
Proportion of wood	63.9%
Proportion of iron	24.9%
Proportion of copper	11.2%

With specific gravity of 450 lb/cu-ft iron occupied 0.033 the volume of oak, which requires that 3.3% of the face surface of the timber be occupied by bolts providing a high density of reinforcement to the hull that would help stop gun shots.

- Data on British Naval Ordnance (LAV4, pV, c14, 80)

  Windage: in 1770, a 32-pounder had 0.233 in in 6.412 in diameter = 1/28 of the bore.

  - 32-pounder of 1782
    - Bore = 6.41 in
    - 10 ft = 58 cwt
    - 9 ft-6 in = 55 cwt
  - 24-pounder of 1780
    - Bore = 5.823 in
    - 10 ft = 52 cwt
    - 9 ft = 47 cwt
  - 18-pounder of 1780
    - Bore = 5.292 in
    - 9 ft-6 in = 41-43 cwt
    - 9 ft = 39-42 cwt
  - 68-pounder carronade of 1796
    - 5 ft-2 in = 36 cwt
  - 42-pounder carronade of 1790
    - 4 ft-3.5 in = 22 cwt
  - Powder charges used in 1800
    - 33 percent of the ball was the standard for guns
    - Carronades had only 8%
  - Breeching of guns in 1800
    - 7 in ropes for 32- and 42-pounders
    - 5.5 in ropes for 12- and 18-pounders
  - Gun tackle in 1800
    - 3 in ropes for guns above 24 pounds
    - 2 in ropes for 9- and 6-pounders

❖ From Royal Navy: The Official *HMS Victory* website. (VICT)

This website includes technical data of the 32-pounder smoothbore gun:

Shot weight	32 lbs (14.4 kg)
Range, point blank	400 yds (364 m)
Range, 1º elevation	820 yds (746 m)
Range, 2º elevation	1200 yds (1092 m)
Range, 3º elevation	1500 yds (1365 m)
Muzzle velocity	1600 fps (485 m/s)
Penetration 100yds	42 in (106 cm) solid oak
Penetration 400 yds	31.5 in (80 cm) solid oak

❖ Data on French Naval Ordnance

– Poids du navire (BOUD, v4, 266):

Chêne (brut)	80.500 pieds cubes (p.e.= 0.75)
Sapin du Nord (brut)	15.000 pieds cubes (p.e.= 0.50)
Fers, total	130.000 livres
Clous	62.500 livres
Cordage	200.000 livres
Poulis	9.659 livres
Voiles	18.500 aunes
Ancres	27.734 livres
Artillerie, affûts	
Poudre, balles	125.081 livres
Lest	9.600 livres
Foutailles	29.329 livres

1 livre = 489 g = 16 ounces × 30.5 g

– Mortier-éprouvette de la poudre (BOUD, v2, 170)

Incliné à une élévation de 45º

Chargé avec 3 onces (92 g) de poudre doit

lancer un globe de bronze de 60 livres

à une distance plus de 90 toises (174.5 m)

– Shooting range (BOUD, v4, 133)

Gravity pulls a round ball down from 3 to 4 feet at 100 toises (195 m) and from 20 to 23 feet at 200 toises (390 m). Therefore, guns in ships of the line were pointed at an angle of 1º40’ above the horizontal so that the ball would cut that plane at a distance that could be used for reference. The point blank distance (*but en blanc*) had the following values for French calibres in livres (489 grams):

- For a 36-livre, 650 meters
- For an 18-livre, 600 meters
- For an 8-livre, 500 meters.

The curve through these points interpolates 640 meters for a 30-livre and 625 meters for a 24-livre gun.

In ideal test conditions in land:

- A 36-livre gun with 16º elevation would reach 3300 meters when fired with 1/3 weight of powder *received at 100 toises*, and the flight would take 18 seconds.
- A 24-livre gun at 1º40’ elevation would reach 600 meters in 1.5 seconds with a muzzle velocity of 413 m/s.
- Shooting at an enemy ship could be done in different ways.
- Shooting to sink (*tir à couler bas*) would aim at 5 to 6 feet below the waterline. The effect on the hull would be reduced by the obliquity of the hit.
- Ricochet shooting was achieved with 5º to 10º elevation and a proper sea surface, on targets at 600 to 1000 meters.

- Comments on Spanish Naval Ordnance

Based on HISTORIA DEL EXPEDIENTE SOBRE AUMENTO DE FUERZA EN LOS BUQUES, ARTILLÁNDOLOS CON CAÑONES RECAMARADOS, included in (GALL, Annex.2)

1806-marzo-8, Madrid

SIGNATURA: AMN, ms. 203, doc. 3 (copia de época)

OBSERVACIONES: Sigue un capítulo titulado “Sobre los obuses”, que lleva fecha 8 de marzo de 1806, época en que se debió escribir la historia del expediente. El texto se refiere a la obra de Francisco Javier Rovira “Compendio de Matemáticas dispuesto para las Escuelas del Real Cuerpo de Artillería de Marina. Tomo IV De la Artillería de Mar y Tierra. Cádiz, Imprenta de la Academia de Caballeros Guardias Marinas. Año de MDCCLXXXVII

Establishes caliber 30 for the Navy as a substitute for 24, a heavier ball to be used against the British that used caliber 32 where we used 24. for Spanish 32 is like British 34, and since diameters of our balls of 36, 30 and 24 pounds differ by about half an inch its use will not be a problem in any ship and the result would be an increase in force since they would have 24-ponders instead of 18-pounders and in general they would have guns of one caliber higher.

Rovira includes a table with the range of each gun at 5º elevation and using 1/4 weight of powder, based on French units of toises (1.9488 m) and livres (489 grams):

Ball, livre	36	24	18
Range	766	858	842
ImpactVelocity	28	29.33	29

These velocities are just modules that Rovira used to compare shot energies and gun capacities. They are assumed proportional to the real velocities and are equal to the square root of the range in toises.

– Analysis of the table –

An ideal shot made with angle of elevation α above the horizontal and muzzle velocity V has a total range of 2 C and describes a parabola with height H at middle range C.

With vertical velocity V1 and horizontal velocity V2, assuming a perfect shot without loss of energy during the flight:

$V1 = V \cdot \sin \alpha$

$V2 = V \cdot \cos \alpha$

$V1\ V1 = 2\ g\ H$

$V1 = V2 \tan \alpha$

for a parabola, $\tan \alpha = 2\ H/C$

$V1 = V2\ 2\ H/C = 2\ g\ H/V1$

hence, $V1\ V2 = g\ C$

and we can write: $C = V1 \cdot V2/g = (V^2/g) \cdot (\sin 2\alpha)/2$

The total range will be: $2\ C = V^2 \sin(2\ \alpha)/g$

Now we can calculate the velocity as a function of α and $2\ C$.

The kinetic energy is: $Ec = M\ V^2/2 = M\ C\ g/(\sin(2\ \alpha)$

Although perpendicular impact causes the greatest damage, the velocity V can be used for estimates since the side of the hull is never vertical, either because of tumblehome or heel.

The angle of elevation α is limited by the height of the gun port to some 14 degrees, but it is also limited by the fact that for the same range 2 C, a higher elevation would produce a longer trajectory with longer flying time and higher angle of impact with smaller horizontal velocity V2.

For the tables given by Rovira, it results:

For $\alpha = 5$ degrees, $\sin(2\ \alpha) = 0.1736$

$g = 9{,}81\ m/s^2 = 5{,}046$ toises/second²

$V^2 = (2\ C)\ g \sin(10^o) = (2\ C)\ 29.0668$

and $V = \sqrt{}\ (\text{range}) \times 5.39$ toises/second.

This shows that Rovira used a module of velocity and not the actual velocity of impact, which was valid for comparison of guns.

When no energy is lost the velocities given in the original table must be multiplied by a factor of 5.39 to obtain the velocity of impact, which would give impact velocities of approximately 156 toises/sec or about 300 m/s. This figure compares fairly well with the velocities estimated by the author for French guns using (BOUD, IV, 137)

- Data from U.S. Army Ordnance of 1850

Diameter and weight of shots used in US Army guns given in (USAO, 27) and corresponding specific gravity are:

Pounds	42	32	24	18
Diameter	6.84	6.25	5.68	5.17
Weight	42.7	32.6	24.4	18.5
Sp. gravity	7.054	7.059	7.039	7.077

Ranges are given for siege and garrison guns on siege or sea-coast carriages for round shots with different powder charge:

SHOT, LB	POWDER, LB	ELEVATION	RANGE, YARDS
18	4.5	1º	641
		2º	950
		3º	1256
		4º	1450
		5º	1592
24	6	0º	412
		1º	842
		1º30’	963
		2º	1147
		3º	1417
		4º	1666
		5º	1901
	8	1º	883
		2º	1170
		3º	1454
		4º	1639
		5º	1834
32	6	1º45’	960
	8	1º	713
		1º30’	800
		1º45’	900
		2º	1100
		3º	1433
		4º	1684
		5º	1922
	10.67	1º	780
		2º	1155
		3º	1517

These figures show that increasing the charge of powder from 1/4 to 1/3 of the ball weight reduces the range of a 24-pounder for elevations higher than 3º but increases the range of a 32-pounder for all elevations. Since muzzle velocity should be expected to increase with the charge of powder, the reduction of range for 24-pounders can only be explained by a higher relative air resistance on the ball along longer trajectories resulting from higher elevations.

The actual trajectory of a ball shot has an angle of fire less than the angle of fall. But as the weight of the projectile increases and its velocity decreases, the resistance of the air decreases, the trajectory described becomes more like a parabola and the angle of fall becomes more nearly equal to the angle of fire (GIBB, Ch.V).

Excerpts of Gibbon’s work included in this Appendix give a clear explanation of the physics of gun firing.

- Excerpts from Chapter V. Projectiles (GIBB)

Solid Shots are divided into *balls*, or those used in heavy guns, and *bullets*, which are used with small ones. Solid shots being denser than shells, are much more accurate in their fire, especially at great distances. They have greater power of overcoming the resistance of the air, and consequently greater velocity and penetration when they strike. They are made of cast iron, and used principally in *guns*. Their fire increases in accuracy and range as the size or calibre increases.

The *resistance of the air* is the principal cause of the decreased velocity and accuracy of balls. This resistance is proportional to the surface. A ball twice the size of another, meets with much greater resistance; but its weight is 8 times as great, which enables it to overcome that resistance with greater ease.

Two projectiles moving with the same velocity, the retarding force will be proportional to their surfaces, or to the squares of their diameters. But the velocity which will produce this retarding force is equal to the force divided by the mass of the projectile (V= F/M, since F = MV), which is itself proportional to the cube of the diameter into the density. Hence the losses of velocity caused by the resistance of the air in the two projectiles, are proportional to the squares of the diameters, divided by the cubes of these diameters into the densities, or inversely proportional to the diameters into the densities.

With the same density, but different diameters, the loss is inversely proportional to the diameter; and the largest ball loses the least. Consequently, for great ranges, large balls must be used.

With the same diameter, but different densities, the most dense loses the least, so that dense projectiles have the greatest range.

And finally, in order that two balls, moving with the same velocity, shall be equally retarded, the respective products of their diameters by their densities, must be equal to each other. Thus, in order that a cast-iron ball shall be retarded the same as an ordinary musket-bullet of 0.65 inch in diameter, both having the same velocity, we must have the following relation:

$$D \times 7.207 = 0.65 \times 11.352,$$

in which, (D) is the diameter of the iron ball; 7.207 is the density of iron, and 11.352 is the density of lead. Thus, we have $D = 0.65 \times 11.352/7.207 = 1.02$ or a little over one inch. The weight of such a ball would be $= \pi/6\ (1.02)^3\ 0.2607 = 0.145$ lb or something over two ounces, instead of about one ounce, which is the weight of the musket -bullet. Hence, cast-iron bullets for muskets would be inferior to leaden ones, as their loss of velocity is greater and the deviations more considerable; wherever, therefore, balls are used approaching the size of the musket-bullet, lead is the best material.

Spherical projectiles, to be serviceable, should offer sufficient resistance to the action of the powder, in order that the initial velocity to be given them may be great enough to produce the necessary results, such as penetration, &c. They should be as near spherical as possible; homogeneous in their structure; have their centers of gravity and figure as near together as possible; be as dense as possible, present no roughness on the surface, which would be liable to injure the piece; and if hollow, should have capacity to hold sufficient powder to fulfill the object for which they are fired.

… … …

From what precedes it will be seen that lead, if hard enough, would be the best metal to use in projectiles, forged iron the next, and then cast iron, which is much cheaper than forged.

… … …

- Excerpts from Chapter VII. Theory of Fire (GIBB)

The initial velocity of the ball depends on the charge; the quality of the powder; the length of the gun; the size and density of the projectile; on the amount of windage, and on the size of the vent, especially in flint-lock guns.

With a given length of gun, and particular projectile, there is a maximum charge beyond which no increased velocity is obtained. This charge must be determined by experiment; though the charges used are generally less than the maximum, the rule generally laid down being, that as the velocity increases very slowly from a third of the weight of the shot up to the maximum, it is not advisable to use a greater charge than one-third, on account of the effect on the piece, the waste of powder, and the recoil.

… … …

Powder develops a greater force as it meets with more resistance to its expansion, so that the heavier a projectile, the greater becomes the quantity of motion it receives. Thus one projectile double the weight of another, receives of the same amount of powder a much greater velocity than one-half of that given to the lighter one.

… … …

With a given charge, projectiles with the least density, and smallest diameter, receive the greatest velocity; but out of the gun the advantage soon disappears, for such projectiles have the least power to overcome the resistance of the air. The charge necessary to produce a given velocity increases with the density of the projectile.

… … …

Experiment shows that for angles within 15º above or below the horizontal, the variations in the point-blank ranges may be neglected, and the trajectory considered as constant.

… … …

Mean Trajectory. A knowledge of the trajectory described by a ball is necessary in order to understand and apply the principles of fire. The curve may be calculated by means of an approximate equation; but it is better to employ this method in connection with the determination of points by practical experiments.

… … …

The effect of solid shot increases with the calibre and the velocity. As the shot acts simply by its force of striking, the quantity of motion imparted to it should be as great as possible.

For an ideal parabolic trajectory, the time of flight equals twice the time of free fall of the ball from its highest reach, H. For a value of gravity of 32.2 ft/s^2, the time of flight becomes one half the square root of H. For an angle of elevation θ, the height H equals the range times the tangent of θ divided by four and the time of flight would be equal to the square root of the range times the tangent of θ divided by four.

As long as the penetration process is slow compared to the speed of sound in the material of the hull and the iron ball (in the order of 3500 and 5000 m/s), the entire kinetic energy of the impact is involved in the penetration. (OKUN)

The kinetic energy is transformed into work absorbed by the resistance of the material of the hull over the thickness T meters causing the hitting mass M of the ball to decelerate by A m/s^2. The mass M can be assumed constant since iron balls would not break upon impact, but the resistance of the wood will change during the penetration process.

"Only the wood volume in front of the ball is informed by the impact shock wave that the projectile has hit the plank surface before it caves in and thus only this front volume gets involved in the surface penetration, where most of the energy is absorbed, with the rest of the projectile only involved in pushing through the back layers afterwards."

Using a dimensional analysis approach for a hard material of thickness T (ft) and an undeformed ball with diameter D (ft) and weight W (lb), (OKUN) gives:

$$T / D = V \sqrt{[(0.5 / K)(W / D^3)]}$$

where K can take extreme values of 0.5 to 1.0:

K = 1.0 models the case where the ball breaks one slice of the armor after another without the layer behind being affected by the response of the one in front of it.

K = 0.5 implies that the entire volume of plate material in front of the projectile is resisting the penetration from the first instant; the material at the back of the plate is involved in the plank's resistance to the penetration of the material at the front surface of the plank.

- Recoil Energy and Velocity

The recoil of a gun depends on three component reactions: the reaction to the acceleration of the ball along the barrel until it leaves with the muzzle velocity; the reaction to the acceleration of the expanding gas produced by burning the powder and the reaction to muzzle blast when the gas leaves the barrel and escapes.

The escaping gas velocity is about 1.5 times the muzzle velocity.

In terms of momentum of weight,

$$Wgun \times Vgun = Wball \times Vball + Wgas \times Vgas$$

The recoil impulse is then, in terms of mass,

$$Igun = Mball \times Vball + Mgas \times Vgas, \ (kg \cdot s)$$

The free recoil (initial) velocity of the gun will be,

$$Vgun = g \times Igun / Wgun$$

The recoil energy of the gun or its kinetic energy,

$$Egun = 0.5 \times Mgun \times Vgun^2$$

One part of this energy is absorbed by the side walls that hold the tackle, another part is spent in friction of the carriage with the deck and a third part is used to give the gun its kinetic energy during the recoil period.

For example, a 32-pounder gun weighing 3000 kg firing a 14.5 kg ball at 400 m/s muzzle velocity with 2.9 kg of powder (a charge of 1/5) will give:

Recoil impulse, ... $Igun = (14.5 \times 400 + 2.9 \times 600) / 9.81 = 768.6 \ (kg \cdot s)$

Free recoil velocity, ... $Vgun = 9.81 \times 768.6 / 3000 = 2.513 \ (m/s)$

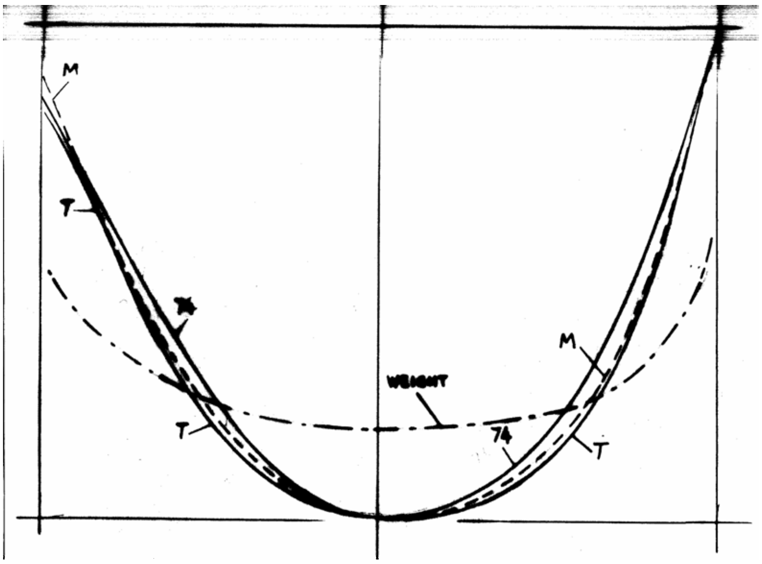
Energy of recoil, ... $Egun = 0.5 \times 2.513^2 \times 3000 / 9.81 = 965.8 \ (kg \cdot m)$

Using a charge of 1/3 the ball would increase Igun to 886.8, the free recoil velocity to 2.9 m/s and the recoil energy to 1286 kg·m.

FFG-Oct.2005

Appendix: Figures

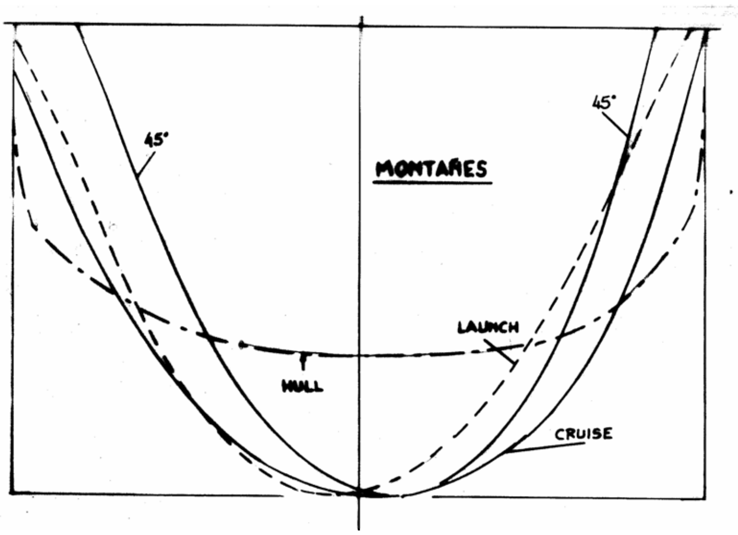
Hogging in Cruising



Cruising displacement section areas.

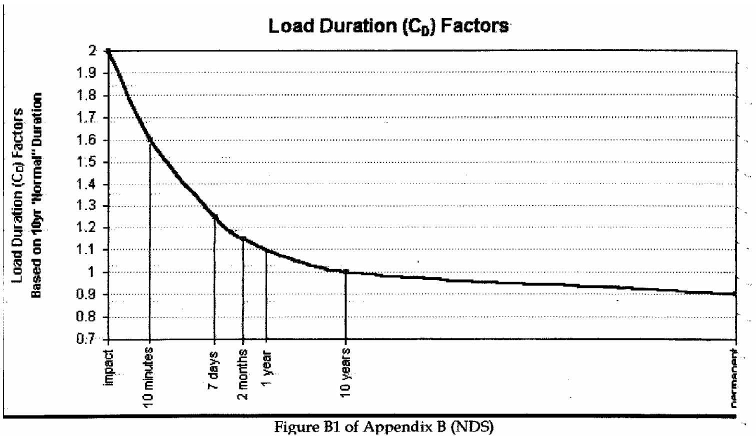
Lightship weight distribution *Santísima Trinidad, Vaisseau-74, Montañés*.

Launching, floating out, careening



Section areas in cruising, at launching and heeled 45º. *Montañés*

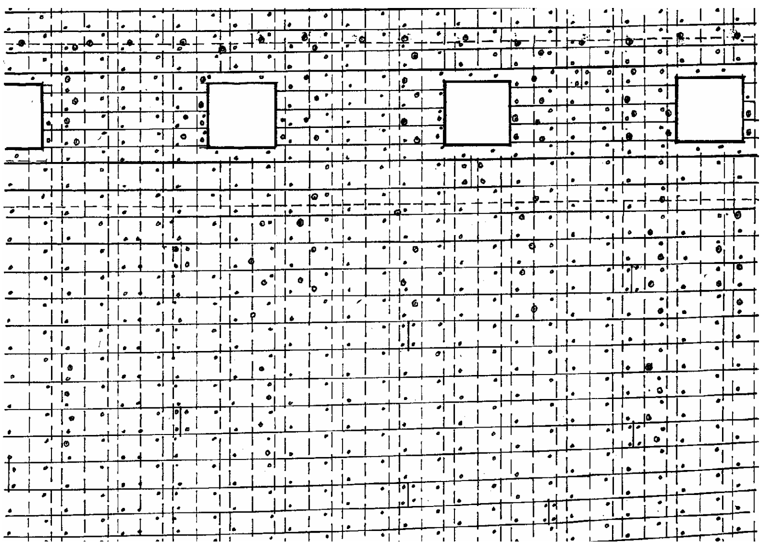
Cummulative Load Effects



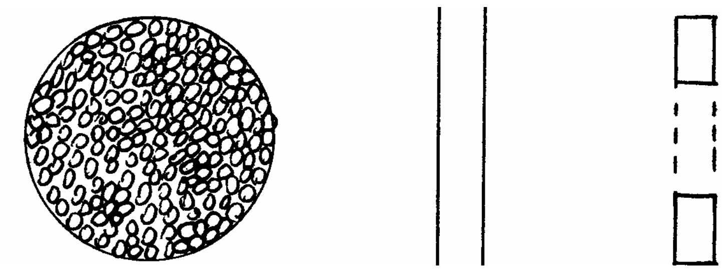
Allowable load (i) = Cd (i) × Design Load for 10 year life

Life loads = Σ (L_applied / L_allowed) < 1.0 (0.9 permanent)

Wood vs Joints

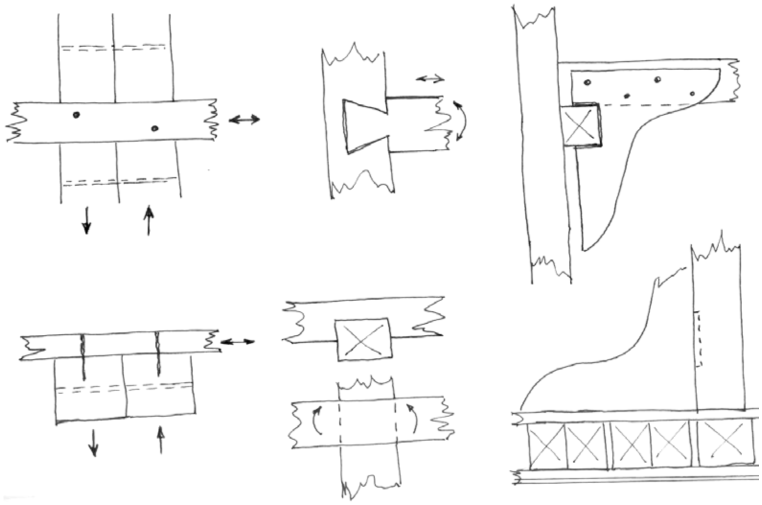


The role of Shear

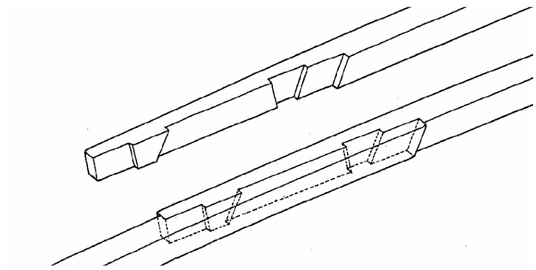


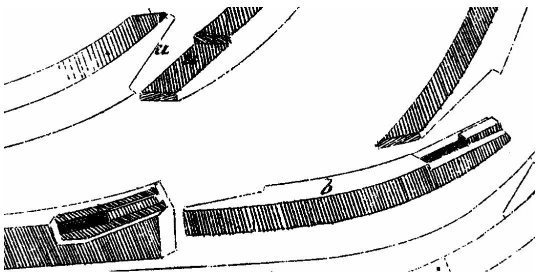
$I = n \cdot i$ I, Z I / n^2 Z / n

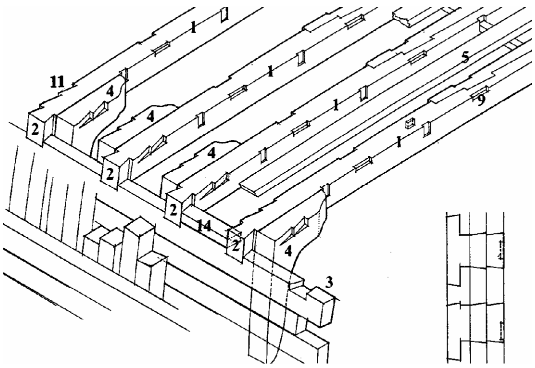
Shearing the sides

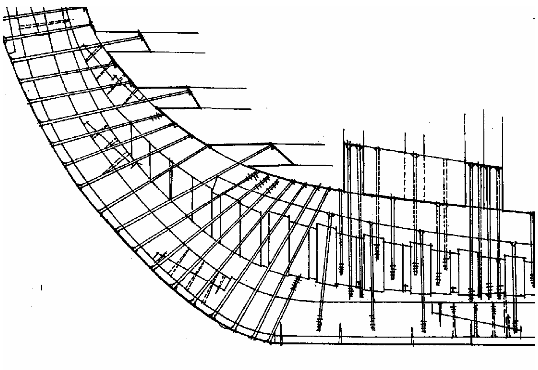


Scarphs, Joints, Dowels

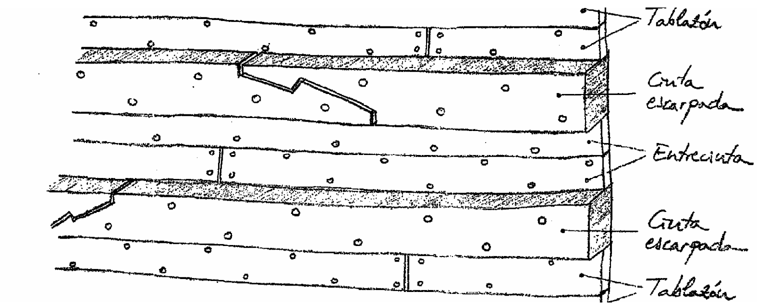


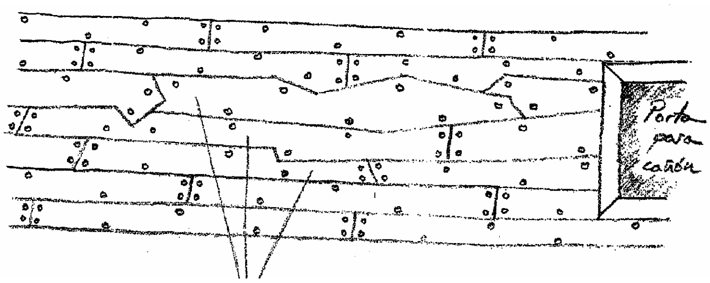




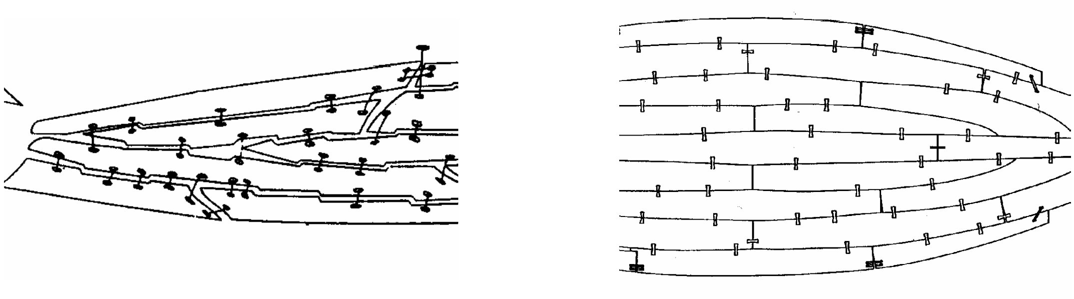


Wales and Planking



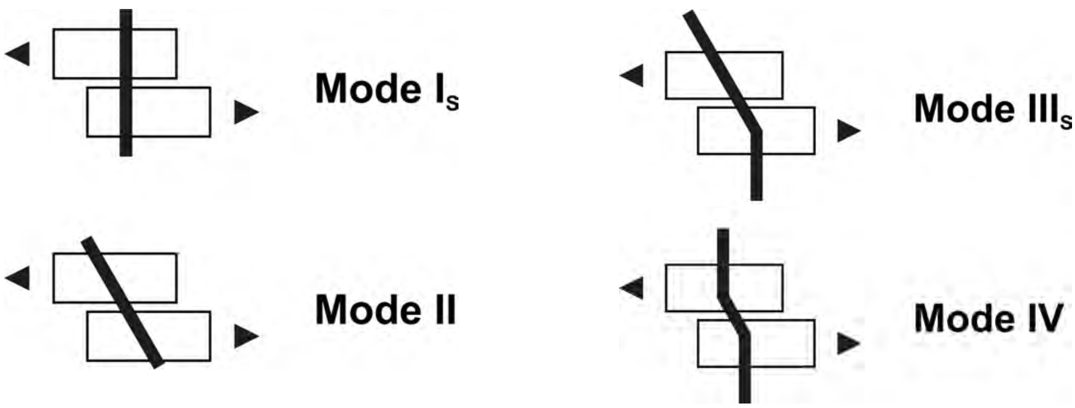


Antique Technology

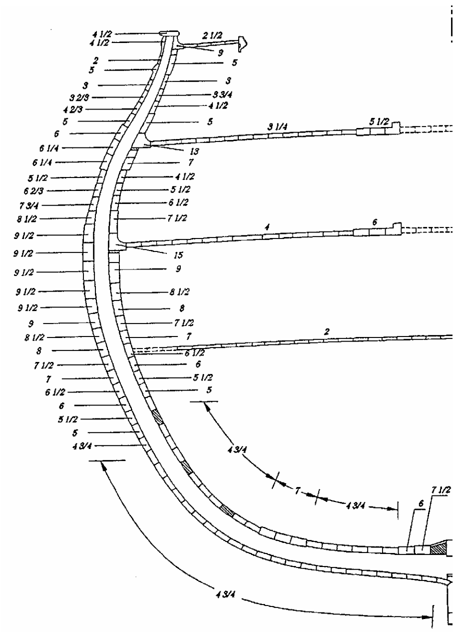


Cheops and Dashur boats

Dowel efficiency Modes of failure



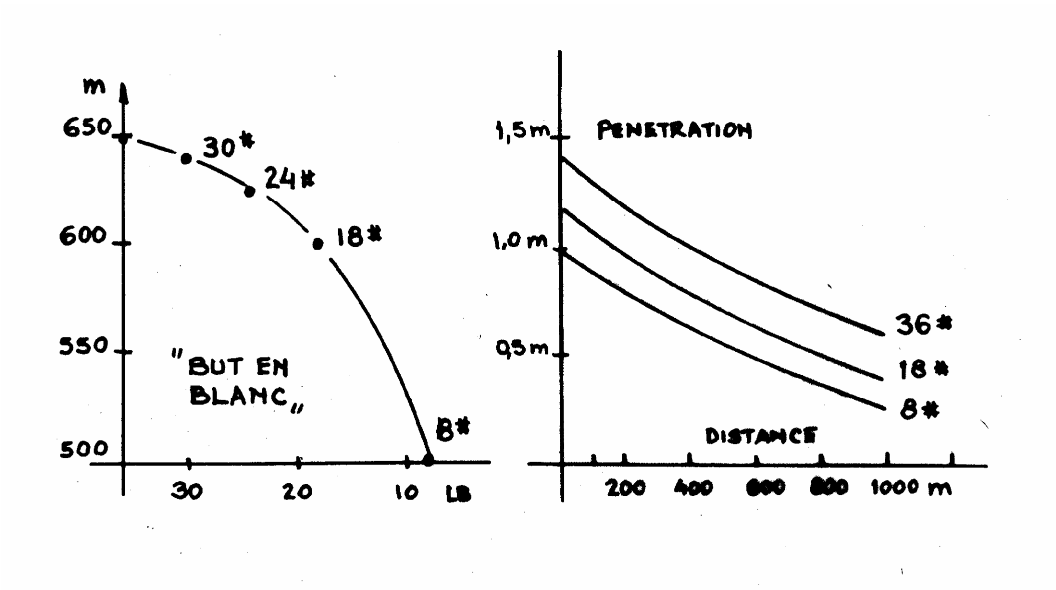
Equivalent Hull Girder



Navío San Idelfonso

Eff.	N.A.	I	
%		mm	m^4
100	6729	19.8	
50		4840	12.1
25		4840	12.1
25		1875	3.37

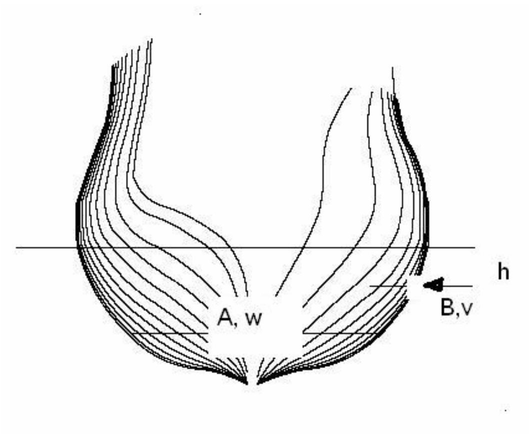
Gunfire



Impact Model Tests

Material Space Supports Doweling Moisture Backing

Damage by gunfire



Santísima Trinidad (1797)

Monarca at Trafalgar (1805)

$$Vol = B \cdot c \cdot \sqrt{2 \cdot g \cdot h}$$

$$v = 24 \text{ in/hr}$$

$$\mu = c$$

$$A = 238 \text{ m}^2$$

$$B = 285 \text{ cm}^2$$