



Noah's Ark Design: Factoring Partial Composite Action

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Abstract

Ark-sized wooden ships are not only possible, but were actively contemplated in the early 20th century. Incomplete composite action, historically a weakness in wooden ships, can be greatly mitigated through the use of a sufficient number of low-tech high-stiffness dowel connectors. The deflection of the ark could have been held down to no more than 1.75–2.0 times that of a completely-composite ark that experienced no shear lag. In addition, the effects of limited lengths of timber, relative to the length of the ark, are not significant when such dowels are used.

Keywords

Engineering, Genesis 6–8, Wooden shipbuilding, Flood, Deluge

Introduction

Ships, regardless of their composition, have traditionally been modeled as box beams subject to wave-induced bending stresses. By far the greatest stresses on a ship's hull are imposed by those waves whose wavelengths approximate the lengths of the hull itself. These bending stresses reverse every few seconds, causing hogging (upward) deflection followed by sagging (downward) deflection, hogging deflection again, etc. (Lovett & King, 2004).

Previous engineering studies of Noah's Ark have neglected shear lag effects and the consequences of limited timber lengths. They have also tacitly assumed the existence of complete composite action. Let us consider each factor in turn. The total deflection of a box beam structure is a combination of that caused by flexure and by shear. The relative amount of shear deflection in a box beam is usually greater than that of a comparably-sized solid beam. In iron or steel hulls, the amount of shear deflection is still relatively small. In contrast, with wood, even under the condition of complete composite action (as in modern epoxy-glued cold-molded construction) the contribution of shear deflection to total deflection is significant.

Owing to the fact that individual timbers are shorter than the length of the hull, stresses have to be routed around the butt joints. This causes a loss of effective cross-section available to withstand tensile stresses, with a concomitant change in the location of the effective neutral axis during hull flexure (Milner & Peczkis, 2007). It is assumed, in contrast, that butt joints have negligible effects on the transfer of shear and compressive forces.

Wooden ships constructed with mechanical fasteners (treenails, nails, bolts, spikes, etc.) invariably experience partial composite action. This means that the extra deflection caused by the shear deformation (slippage) of the connectors must be added to that caused by the shear and flexure acting on the timber material itself. The slip of each connector can be approximated by the tangent to the curve that defines the amount of slip as a function of the amount of applied shear force. This, called the slip modulus, approximates the amount of force per unit slip, and is analogous to the spring constant in the tensile stretching of springs. As a first approximation, one can assume that all of the fasteners have an equal slip modulus, and that all connectors share the load equally.

A recently-published engineering study (Milner & Peczkis, 2007) explicitly factors shear lag effects, butt joints, and interlayer slip in the flexure of wooden ships. The purpose of this work is to apply the Milner and Peczkis analysis to the flexure of Noah's Ark. There is limited space for explaining things in this paper, and the reader is strongly urged to read Milner and Peczkis as a necessary companion to it. A glossary is provided for some of the engineering terms used in this paper. Note that the box beam is a satisfactory approximation to actual hull shape (see Future Research).

Some Material Parameters

An intuitively-appealing solution to the potential problems of mechanical fasteners is their complete replacement with glulam, or monocoque construction.

Among low-tech glues, blood albumin has proven to be sufficiently water-resistant to withstand continuous soaking for well over a year (Brouse, 1938). Arched structures built by the Aztecs have stood for centuries (Lambuth, 1977). Modern monocoque-constructed boats and small ships are a reality. However, it is unclear if the same would hold for giant wooden structures, notably ships. For this reason, use of non-mechanical connecting of timber pieces is not considered further.

The 100-meter long American schooners, from whom the “100-meter wooden-ship size limit” had been supposed, suffered from inadequate fastenings and construction from only short available timbers (mostly $<1/5$ ship length; Milner & Peczkis, 2007). We cannot, of course, know the sizes of timbers available to the antediluvians, but can consider some potential analogues. In nineteenth-century Australia, there commonly were groves of hundreds of giant eucalypt trees within a few km of each other. Many of these had trunk circumferences of 40 feet (12 m), which implies potential balk widths approaching 13 feet (4 m). Some of these trees had trunks 220 feet long (67 m) before even the first branch (Anonymous, 1850). Among American redwoods, a theoretical maximum height of 426 feet (130 m) is considered possible (Koch, Sillett, Jennings, & Davis, 2004).

After availability by size, the next limiting factor is the usability of timbers, especially thick and wide ones, after seasoning. Different kinds of trees vary widely in their ability to withstand seasoning without essentially self-destructing. The pyinkado, a tree native to India, is an example of a tree that can be cut into large balks (406 mm square in this instance; Pearson & Brown, 1932, p. 430) without encountering intolerable problems from distortion, splitting, or checking during seasoning.

In all probability, no kind of tree existed whose balks were long enough to span the entire length of the Ark. For this reason, the potential effects of timbers shorter than hull length must be addressed. In this study, two extremes of available timber lengths were considered: short (75 feet—23 m) and long (200 feet—61 m).

Methodology

Throughout this work, it is assumed that planar sections of the hull remain planar during the flexure of the Ark. Milner and Peczkis (2007) have shown that this assumption is most closely realized through the use of transverse bulkheads, as had long been employed in Chinese junks. In contrast, the use of many-piece frames (ribs) consisting of short pieces of wood bolted together, and characteristic of wooden shipbuilding in the west, has long been

recognized as a major structural liability. Moreover, transverse bulkheads, even when themselves composite in nature, and containing modest-sized passageway holes, are stiffer than even one-piece ribs. (The latter is achievable through the steambending of long timbers or the modern use of glulam).

Figure 1 shows the deflection magnification factor as a function of the ability of connectors to resist shear forces. Figure 2 tabulates the results of computations relative to a small Ark. Figure 3 illustrates the direct plank-to-plank fastening methods that are central to the success of an adequately-stiff Ark. (For further explanation, see the captions).

In order to use the formulae used by engineers to model the behavior of box beam structures in flexure, the amount of slip in the connectors needs to be combined with the deflection caused by shear in the material. This combination, called the effective shear modulus, is always smaller than the shear modulus of the material itself. The effective shear modulus (G' , as used in Figure 2) is computed by treating the collective connector slippage and the shear modulus of the material as two springs in a series. The customary E/G of about 15 for wood itself, or fully-composite wooden assemblies, thereby gives way to a larger ratio (E/G' , Figure 2). The less the degree of composite action, the greater the value of E/G' .

To minimize the total number of possible variables in the calculations performed here, some of which are shown in Figure 2, those variables applicable to poorly-understood factors were left constant throughout this analysis. Thus, owing to the apparent absence of information on the allowable deflection limits of large wooden vessels, the range of allowable deflection magnification factors (relevant to that of

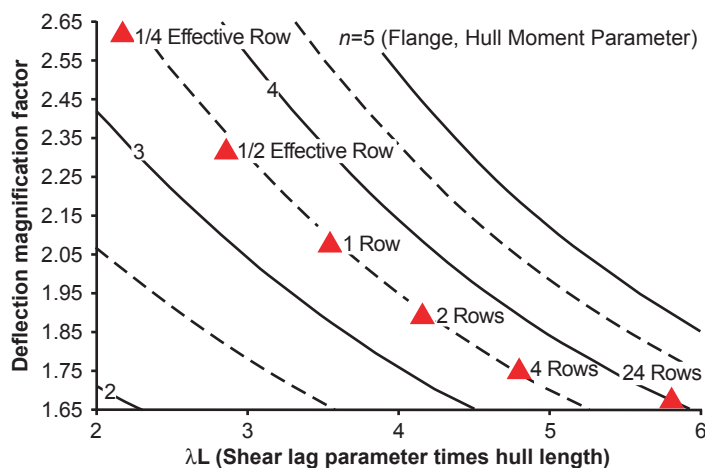


Figure 1. This figure is a modification of Figure 5 of Milner and Peczkis (2007). The deflection magnification factor is shown as a function of the number of rows of fasteners, each of which has a slip modulus of 57,000 N/mm. (The first two entries are one row of connectors at $1/4$ th and $1/2$ of the quoted value for slip modulus). All this is applicable to a small ark (whose n -parameter is 3.4).

*l (mm)	60,960	*s (mm)	508	A (mm ²)	103,226
*r	3	*E (MPa)	10,000	√2C	1.14210E-03
l/√2C	69.6221523			C	6.52191E-07
α	0.945669	*L (mm)	156,900	*t _{lam} (mm)	254
2w (mm)	26,150	2h (mm)	15,690	*t _w , *t _f (mm)	406
l/L	0.38852772	β	0.5110704	2βh (mm)	8,018.695

	A	y	A _v	y _{av}	A(y-y _{av}) ²	I ₀
1	1.06E+07	15,487	1.65E+11	8,018.694	5.93E+14	1.46E+11
2	5.90E+06	11,651	6.88E+10	8,018.695	7.79E+13	2.60E+13
3	5.85E+06	4,213	2.46E+10	8,018.694	8.48E+13	2.83E+13
4	1.00E+07	203	2.04E+09	8,018.694	6.14E+14	1.38E+11
Row of SUMS	3.24E+07		2.60E+11		1.37E+15	5.45E+13
					I (mm ⁴)	1.42E+15
	E/G'	62.53		I _s (mm ⁴)	1.2066E+15	
0.972	Effective Section in Tension			n	3.40	

Figure 2. This figure is constructed from the same spreadsheet used to create Figure 6 of Milner and Peczkis (2007). Independent variables are marked with an asterisk. (L)—length of the Ark; (r)—number of rows of fasteners; (l)—length of plank or balk; (2w)—outside width of the hull; (E)—modulus of elasticity of the wood; (2h)—outside height of the hull; (A) cross-sectional area of the hull; t_w and t_f—thickness of the balk or plank as measured in the inside-outside direction relative to the hull; t_{lam}—thickness of the balk or plank as measured in the direction perpendicular to both hull length and to the inside-outside direction of the hull. Other parameters are more technical and are defined in Milner and Peczkis. As for the Hull Section Properties, the A-terms refer to cross-sectional areas of the major components of the hull, the y-terms refer to distances from a reference axis, and the the I-terms refer to moments of inertia (for illustration, see Milner & Peczkis).

complete composite action and absence of shear lag) was conservatively set at 1.75–2.0.

Although high-MOE (modulus of elasticity) wood is known to be stronger and stiffer than its low-MOE counterpart, the absence of information on large-connector slip modulus in high-MOE wood compels the use of 57,000N/mm as the slip modulus of a single dowel connector, as in Milner and Peczkis (2007). This value is based on connector embedment in low-MOE wood. It is still usually considerably greater than that of treenails used to fasten planks to frames, or bolts placed into oversized holes to do the same, as was customary in traditional wooden ship construction.

To minimize the danger of brittle connector-wood failure, the thinnest dimension of wood balks was

never set at less than 254mm (10 dowel diameters). (To minimize potential problems with hidden defects and the seasoning of the wood, it was never set greater). For similar reasons, and owing also to the staggered deployment of the fasteners from one level to the next, the horizontal collinear spacing of the fasteners was set at a constant value of 508mm (20 dowel diameters) (Figure 3).

Data on group reduction factors, applicable to the collective slippage of large connectors, is lacking. For this reason, it is neglected. However, the calculations, especially when based on multiple rows of connectors, are usually insensitive to the effective non-involvement of a sizeable fraction of connectors. For instance, the results for eight rows of connectors are little better than those using seven connectors; the latter can accommodate the effective non-involvement of one row of connectors.

In order to cover all relevant possibilities, Milner and Peczkis (2007) is applied to extremes of Ark length (Lovett, 2006), balk length, and numbers of rows of fasteners (with implied Ark-wall thickness). Only some of the results are mentioned here.

Calculations have been performed for the deflection magnification factors resulting from one row of fasteners at one-quarter and one-half of the adopted slip modulus of 57,000N/mm (Milner & Peczkis, 2007), and then for 1, 2, and 4 rows of fasteners at this slip modulus. Then, as an extreme excursion, they have also been figured for a 2-meter thick Ark wall, which allows the accommodation of 24 rows of fasteners (Figure 1).

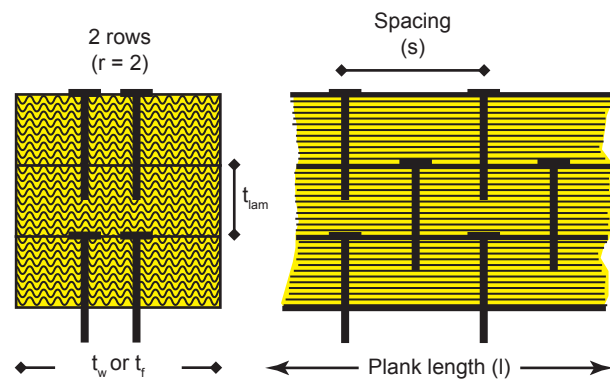


Figure 3. Method of direct plank fastening (not to scale): Hull cross section (left) and hull wall side view (right). Each plank or balk, and the one underneath it, is impaled through its midsection by one or more rows of dowels.

Results

Simple computations (not shown) indicate that western wooden ships in the past had generally experienced small degrees of composite action, commonly with deflection-magnification factors of 4.0 or more. This owed to the relatively weak and indirect fastening of planks to ribs (which themselves consisted of multiple pieces that could move past each other), and with only caulking (oakum) existing between one plank and the next. A more favorable situation arises from the one row of 1/4th stiff fasteners, but this hull still suffers from a deflection-magnification factor of nearly 2.65 (Figure 1). Another hull, using one row of half-rigid connectors, is not much better.

A much greater degree of composite action is clearly achieved by using a large shear area (thick walls) combined with *multiple* rows of fasteners that *directly* connect one plank or balk to the next one (Milner & Peczkis 2007: Figure 3 here). As shown in Figure 1, adequate results are obtained through the use of at least two rows of full-strength fasteners (each at a shear rigidity of 57,000 N/mm).

The total deflection of Noah's Ark need not have been greater than a factor of two over that of a theoretical comparably-sized vessel experiencing no shear lag effects and complete composite action of its structural components. Pointedly, it becomes asymptotically more difficult to achieve deflection-magnification factors below about 1.75. It can be seen from Figure 1 that, increasing four rows of fasteners to 24 effects only a modest further reduction in deflection-magnification factor.

In order to provide sufficient wood to support the staggered carvel fasteners, the Ark walls, deck, and bilge must have all been respectively 254, 330, 406, 483, or 2007 mm thick (in the inside-outside direction of the hull) for 1, 2, 3, 4, or 24 rows, respectively, of fasteners. This compares to the 2/3rds of a cubit (297 mm or 349 mm) needed to resist tensile, compressive, and shear strains at an intensity of about 6 MPa (Lovett, 2006, p. 76).

Effects of Limited Timber Lengths and Butt Joints

In conventional wooden ships, the short lengths of timbers (relative to total hull length), aggravated by the small slip moduli of the connectors, created serious problems. By contrast, the differing lengths of balks figured here (calculations not shown) do not themselves lead to noticeable differences in the deflection magnification factor provided that the slip modulus approaches as great a value as used here (57,000 N/mm for at least one row), and the balk length is at least about 1/5th of the total hull length. Under these conditions, there is only a modest loss of effective cross-section in tension (typically 3–9%:

Figure 2). And, in each case, the β value (height of neutral axis) has to be changed by only a few percentage points from the 0.5 expected from the butt-joint-free Ark section (Figure 2).

A Brief Historical Perspective

The construction of stiff wooden ships, through the use of planks or balks impaled to the ones below them (sometimes called carvel construction, but with some ambiguity in terminology), is hardly new. It goes back to antiquity. In the nineteenth century, the heyday of wooden shipbuilding, periodic efforts were made to revive such methods (for example, Deming, 1831), but this never became common. The relatively weak and flexible plank-on-frame construction methods that typified nineteenth century ships were motivated by *economics* (relatively low labor intensiveness of frame-based methods), not lack of know-how about the construction of much stiffer wooden ships!

It should be noted that, not only have giant wooden ships apparently existed in the past (Woodmorappe, 1996), but their construction had been a recognized possibility even in more recent times. For instance, during the revival of U.S. wooden shipbuilding around the time of WWI (caused by a shortage of steel), Bogert (1917) wrote the following in a nautical-engineering journal:

Wooden ships can be built to stand any strain that ordinary sea service may impose, and that, too, when of much larger size than any yet constructed ... A ship is a hollow girder and most wooden ships have suffered in the past from lack of longitudinal strength in their decks. A wooden ship 420 feet long [128 m] by 60 feet beam [18 m] by 42 feet beam [13 m] is a perfectly practical proposition. (Bogert, 1917, p. 247)

The foregoing-described ship is close to the dimensions of the Ark using the smaller cubit.

Future Research

Although ships are seldom exactly box-shaped, and there is uncertainty about the exact shape of the Ark (Lovett, 2007), this is of little relevance to the present study. Milner and Peczkis (2007) have noted that the equivalent box dimensions serve as a good approximation of even ship hulls whose cross sections depart significantly from rectangularity. Additionally, a pointed bow and stern can readily be "added on" to an otherwise eight-cornered box structure. They also point out that, provided that openings in the hull are small and few in number, these can be modeled as local stress concentrations superimposed upon an otherwise-homogenous box-girder structure. These factors should be addressed in detail in the future.

This study has factored the walls of the hull as the only "webs" in the Ark box beam. This should be expanded into a study that includes the shear transfer

caused by interior trusses, stanchions, longitudinal bulkheads, etc.

As the hull “skin” is immersed in water, the wet timbers begin to swell and to exert pressure on their neighboring timbers. This may lead to membrane stiffness, which could be of sufficient degree to add rigidity of the hull. This should be explored.

This study has been limited to hull flexure. Torsion can also be a significant factor, especially in hulls made of low shear modulus material, and should be examined. There is also need for a study of slamming and whipping effects on a giant wooden hull.

Conclusions

An apparently-seaworthy Noah's Ark could have been built to the size indicated in Scripture, even at the larger value of the cubit (52.6cm). The structural problems of large nineteenth-century U.S. ships (notably excessive flexibility and resulting leakage) need not have applied to the much-larger Noah's Ark. The deflection-magnification factor caused by incomplete composite action can be limited to manageable levels given a sufficient number of high-shear-stiffness direct timber-to-timber fastenings. Also, under such conditions, exceptionally-long pieces of timber are not necessary to achieve a large fraction of the available cross-section of the hull in tension.

Glossary

Composite action (partial)—The degree to which pieces of timber work together, when fastened by mechanical fasteners, as compared with the complete composite action of a hypothetical single-piece wooden structure.

Glulam—Abbreviation for glued laminations (wood layers).

Modulus of elasticity—A measure of the resistance of a material to tensile (stretching) and compressive (squeezing) forces.

Moment of inertia—A measure of the thickness of a material combined with its distance from a reference axis.

Oakum—Old hemp ropes to which oil is added. This combination is rammed between planks for caulking.

Shear—a force applied sideways against a material, tending to make its layers slide past each other.

Shear deformation—the distortion of a material caused as it passes the shear force from its neighbor to another neighbor.

Shear lag—the inability of shear forces to be adequately transferred across the top and bottom of a box beam as parts of the top and bottom are situated too far from its sides. The lower the shear modulus of the material and the slip modulus of the fasteners, the more severe the shear-lag effects.

Shear modulus—A measure of the resistance of a material to shear forces.

Slip modulus—A measure of the resistance of an embedded nail, spike, etc. to a shear force.

Treenails, or Trunnels—Wooden pegs.

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