Green design of strip-planked Iroko wood for boatbuilding

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ABSTRACT: Increasing attention for green design is promoting the need of innovation both in processes and in products used in boatbuilding. Wood is undoubtedly the most ancient and natural material used for boatbuilding and it is particularly suitable within the strip-planking technique. However, the use of conventional epoxy resins in wooden boats reduces the eco-friendly capability of the entire construction. A valuable solution to this problem may be represented by resins derived by natural and renewable resources, commonly addressed as bio-based resins. In the present research activity, two bio-based resins used as adhesives in the strip-planking technique based on Iroko wood were investigated. Experimental tests for the mechanical characterization according to the UNI EN 302-1 standard were performed. The mechanical properties of the two bio-based adhesives were compared to the mechanical properties of a conventional epoxy adhesive providing similar results. Furthermore, a new methodology to evaluate the shear modulus and strength was applied. The systematic analysis carried out gave interesting results on the possibility of coupling Iroko wood and bio-based adhesives within the strip-planking technology, in order to enhance the eco-friendly capability of wooden boats.

1 INTRODUCTION

Nowadays, the ninety percent of the small-size operating boats are made of FRP (Rubino et al., 2020). One of the main problems is their end-of-life management that, as described in (Nasso et al., 2018), represents a great concern for the environment. Even though some recycling and reusing strategies have been studied and developed (López et al., 2012; Nahil and Williams, 2011; Palmer et al., 2010; Pannkoke et al., 2000), the mixed presence of matrices and reinforcements makes such processes difficult and costly (Pickering, 2006), in addition to lowering the quality of the obtained products after recycling (Vo Dong et al., 2018). Furthermore, the FRP production involves a high quantitative of energy (Bose and Vijith, 2012) that is negative for the environment. Basically, raw material production processes and end-of-life solutions (such as re-use, recycling, or disposal) must be considered within the Life Cycle Assessment (LCA) of a boat (Önal and Neşer, 2018).

Thus, it seems clear the need of minimising the environmental impact and supporting a green development in the boatbuilding industry (Nasso et al., 2019) by introducing green materials and construction technologies. Within this framework, wood is reacquiring attractiveness for pleasure crafts and small-size passenger crafts since it offers various advantages: it is a natural and recyclable material, it entails low amounts of energy for growth and production, and it allows obtaining a highly refined final product. Indeed, applications of wooden boats were examined (Castegnaro et al., 2017; Kolat et al., 2007; Praharsi et al., 2019).

In addition, specific studies regarding mechanical properties of Iroko wood (Bucci et al., 2017) and Iroko laminates (Corigliano et al., 2017), used in boatbuilding, were already performed and presented by some of the authors.

Figure 1 shows the construction of the 141m four-masted staysail schooner Dream Symphony, the world's largest private sailing yacht constructed almost entirely of Iroko glued laminated timber. Material testing of Iroko laminated wood samples was carried out by some of the authors (Spurr, 2013).

One of the most advantageous processes for vessel construction based on wood is the strip planking technique. Indeed, this technology implies the possibility of both exploiting material properties at their best (by orienting the wood natural grains in the most proper direction) and of building a strong and rigid wooden structure through a relatively easy process.

Figure 1. The construction of the Dream Symphony hull made of Iroko glued laminated timber [from www.dsv-projects.com].

Strip-planked final products have a remarkable. strength-to-weight ratio, high fatigue resistance and resilience (Nasso et al., 2018; Nicolson, 1991).

In the strip planking technique, wood strips and veneers with different thicknesses are stratified (Figure 2). Strips and veneers are kept together through a proper adhesive.

Even though such a technique is based on wood, that is the most "green" material ever used in boat construction, it still includes the use of conventional resins as adhesives.

Selecting the most adequate adhesive is fundamental for many marine sectors ("Adhesives in Marine Engineering - 1st Edition," n.d.; Corigliano et al., 2019; Grabovac, 2003; Sapronov et al., 2020) because the adhesive joints are generally the weakest spots of the structures (Kolat et al., 2007). On the other hand, the epoxy resins commonly used contribute negatively to the eco-friendly feature of the final products. As a result, searching for alternative adhesives less environmentally detrimental is crucial. A valuable and interesting solution could be represented by bio-based epoxy resins, which are an absolute innovation in the nautical field. Due to this reason, feasibility studies regarding the properties of bio-based adhesives coupled with wood must be performed, in order to assess their suitability for application in boatbuilding. Such properties will be necessary to perform vessel structural sizing, in accordance with the requisites provided by Classification Societies and International Standards. In particular, the Germanischer Lloyd gives criteria based on the comparison of the stress of each individual layer and the average breaking stress (tension/compression) of the material (Germanischer Lloyd, 2011).

Therefore, through a focused research activity, the mechanical properties of two different bio-based adhesives were assessed by means of experimental tests and compared with the ones of a conventional epoxy resin. The Iroko wood essence, particularly used in wooden boatbuilding, was chosen. Among the mechanical properties, a particular attention was given to the shear elastic modulus and the shear strength. Experimental tests for the mechanical characterization according to the UNI EN 302-1 standard were performed. The mechanical properties of the two bio-based adhesives were compared to the mechanical properties of a conventional epoxy adhesive. Furthermore, a new proposed methodology (Corigliano et al., 2021), that can be applied in an easier way with respect to standard lap-joint testing, to evaluate the shear modulus and strength was applied.

Figure 2. Strip-planked boat construction.

2 MATERIALS AND METHODS

2.1 *Materials*

Iroko is one of the most used wood types in boatbuilding technologies and is the essence chosen for the manufacturing of specimens.

Iroko is a large hardwood tree known to be a very durable wood. Within the strip-planking technique, Iroko can be used in multiple ways such as for transversal frames and longitudinal girders. Its main properties are reported in Table 1.

Table 1. Iroko properties.

Property	
Origin	West coast of tropical Africa
Grain	Interlocked
Log diameter [cm]	From 80 to 100
Specific gravity*	0.64 ± 0.06
Fibre saturation point [%]	23
Crushing strength* [MPa]	54 ± 6
Static bending strength * [MPa]	87 ± 15
Modulus of elasticity* [MPa]	12,840 ± 2496

* at 12% moisture content.

The conventional adhesive, commonly used in strip-planking technology, is the following bi-component system:

– Epoxy resin:
  - Bisphenol A Diglycidyl ether;
  - Epoxide derivatives mw < 100.

- Curing agent:
  - Alkyl ether polyamine;
  - M-Xylene diamine;
  - Isophorone diamine.

Two bio-based epoxy adhesives having similar mechanical properties to the ones provided by the conventional adhesive were chosen. These bio-based adhesives are produced by Cardolite Corporation (Antwerp, Belgium) and have both resin matrix and amine hardener made from high amount of renewable resources (cashew nutshell). Cardanol is the main resin component and is obtained from cashew nutshell liquid (CNSL): it is characterized by a long aliphatic side chain that provides excellent water, salt-water, and moisture resistance. In particular, the bio-based epoxy adhesives selected are the following bi-component systems:

- FormuLITE 2501LCA + UltraLITE 2009HSF (herein referred as “A”);
- FormuLITE 2501A + FormuLITE 2002B (herein referred as “B”).

Their natural-origin content is equal to 34.8% and 45.4%, respectively.

The properties of the compared adhesives are reported in Table 2.

Table 2. Properties of the investigated adhesives.

	Conventional Epoxy Adhesive	Bio-Based Adhesives	
Property	C	A	B
Pot life [min]			
at 20 °C	37	-	-
at 25 °C	-	18	58
Viscosity [mPa s]			
at 20 °C	800	-	-
at 25 °C	-	1300	1100
at 40 °C	240	600	377
Ultimate Tg [°C]	62	75	73
Tensile strength [MPa]	64	64	52
Tensile modulus [MPa]	2850	2886	2599
Tensile elongation at F_{max}/at break [%]	3.6/6.9	4.51/6.27	4.3/ 11.3
Flexural strength [MPa]	102	(117) *	73
Flexural modulus [MPa]	3070	(2921) *	2104
Natural-origin content [% wt]	-	34.8	45.4

* the values refer to a similar adhesive produced by Cardolite Corporation.

2.2 *Methods*

Two different Standards that specifically address mechanical tests on wood adhesives were selected.

The Standard UNI EN 302-1 “Adhesives for load-bearing timber structures Part 1–Determination of longitudinal tensile shear strength” (UNI, 2013) was used for tensile-shear tests on lap-jointed strips. The specimens were made of two rectangular-shaped strips, glued together by means of a lap joint (Figure 3). The experimental tests were performed at a constant crosshead speed not exceeding 5 mm/min, such that the time required to reach failure was in the range from 30 s to 90 s.

The Standard ASTM D905-03 “Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading” was used to implement an ad hoc shear test by compression loading (shortly, compression-shear) that could be performed with common laboratory machinery (Corigliano et al., 2021). Specifically, the specimens are made of three square-shaped panels, glued together in order to form a parallelepiped as shown in Figure 4. During the test a compression load was applied both on the upper surface of the central panel and on the lower surfaces of the two lateral panels, using three equal steel bars. The crosshead motion is set at a rate of 5 mm/min until failure.

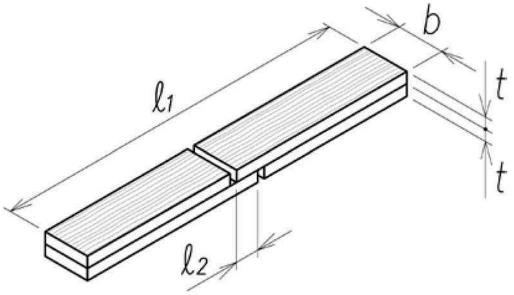
A servo-hydraulic Instron testing device with a load-cell of 250 kN and a resolution of 1% on the recorded load value was used to perform the tests.

Wood panels for the manufacture of the specimens were properly prepared by sanding rough surfaces with a sandpaper having a grit size equal to 60. Then, the adhesive was applied as a uniform layer. The test pieces were manufactured using the three adhesives.

In order to properly identify each specimen and collect the results in an orderly manner, all the test pieces were indexed with a code that gives information regarding the wood essence, the adhesive used and the test type. Each specimen reports an alphabetic code (letter meanings are in Table 3) followed by a number that identifies a specific specimen.

Table 3. Letter meanings of the specimens’ code.

Test code	Wood code	Adhesive code
TS Tensile Shear **CS** Compression Shear	**I** Iroko	**A** Bio-based epoxy resin A **B** Bio-based epoxy resin B **C** Conventional epoxy resin B



Symbol	Quantity
b	Width of test pieces, (20.0 ± 0.1) mm
l_1	Length of test pieces, (150 ± 5) mm
l_2	Length of overlap (length of tested surface), (10.0 ± 0.1) mm
t	Thickness of panel for close contact glue line, (5.0 ± 0.1) mm

Figure 3. Geometry and dimensions of the UNI EN 302-1 specimens.

Mean values ($\overline{x}$) and root mean square (RMS) values were calculated for each evaluated mechanical property.

The 5-percentile value (i.e., the value with 5% probability of occurrence), assumed as the threshold characteristic value, for data normally distributed is so determined:

$$X_k = \overline{X} - 1.645 \text{ RMS} \tag{1}$$

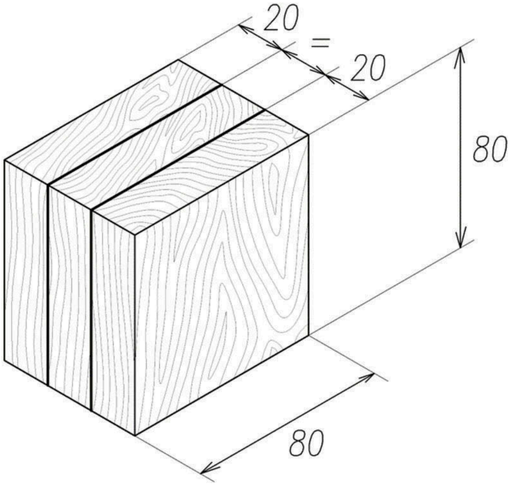


Figure 4. Geometry and dimensions of the ASTM derived *ad hoc* specimens.

3 RESULTS AND DISCUSSIONS

3.1 *Shear properties of lap joints by tensile loading*

Seven specimens for each adhesive (A/B/C) were tested. Figure 5 shows a specimen during the test.

Figure 5. Lap-jointed specimen during the test.

For each specimen, the test results are represented by a force-displacement graph (Figure 6).

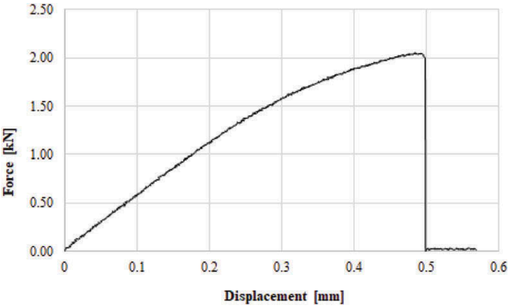


Figure 6. Typical force-displacement graph of a lap joint test (TSIB04).

For each specimen, the mean shear stress was calculated in accordance with UNI EN 302-1 Standard as, $\bar{\tau} F_{max/A}$, where F_{max} is the applied load at failure and A is the bonded surface area.

Furthermore, the shear modulus G for the adhesive layer was calculated as follows:

$$G = \frac{\bar{\tau}}{\gamma} = \frac{\Delta F/A}{\Delta w/c} = \frac{c(F_2 - F_1)}{A(w_2 - w_1)} \quad (2)$$

in which is the mean shear stress and γ is the shear strain; c is the mean adhesive layer thickness (measured from the specimens sample and equal to 0.199 mm); $(F_2 - F_1)$ is the load increase on the straight part of the force-displacement curve; A is the bonded surface area; $(W_2 - W_1)$ is the displacement increase corresponding to the range $(F_2 - F_1)$.

Due to the lack of a formula aimed at evaluating the shear modulus G within the UNI EN 302-1 Standard, the authors introduced equation (2) in their previous work (Corigliano et al., 2021).

For each test, the load increase was chosen in order to obtain a coefficient of determination R^2 of the load-displacement linear regression higher than 0.99.

Tables 4 shows the obtained results.

Table 4. Results for lap joints shear properties by tensile loading.

		G [MPa]	$\bar{\tau}$ [MPa]
TSIA	$\bar{X}$	3.944	8.068
Bio-adhesive A	RMS	0.777	1.704
	x_k	2.667	5.265
TSIB	$\bar{X}$	4.021	8.349
Bio-adhesive B	RMS	1.302	1.418
	x_k	1.879	6.017
TSIC	$\bar{X}$	3.675	8.921
Conventional adhesive C	RMS	0.811	1.692
	x_k	2.340	6.137

It is possible to assert that the bio-adhesive A provides the best result in terms of shear modulus but the worst result in terms of shear stress. As regards the bio-adhesive B, it provides a value for the shear stress nearly equal to the one provided by the conventional adhesive; however, the value of the shear modulus is the worst one due to the high value of dispersion.

3.2 *Shear properties of adhesives by compression loading*

Nine specimens for each adhesive (A/B/C) were tested. Figure 7 shows a specimen during the test.

For each specimen, the test results are represented by a force-displacement graph (Figure 8).

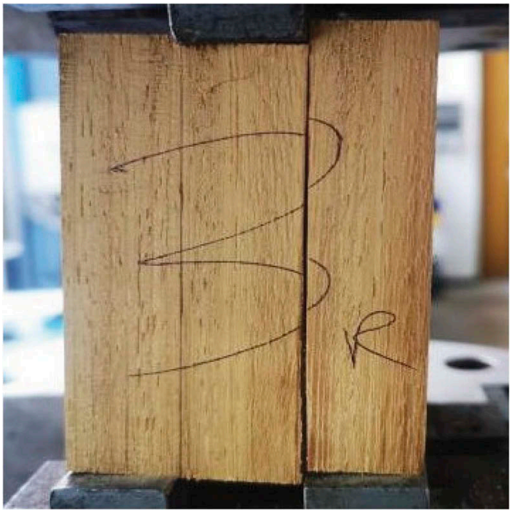


Figure 7. Compression shear test.

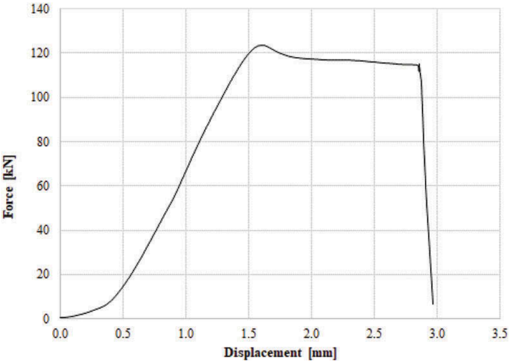


Figure 8. Typical force-displacement graph of a compression-shear test (CSIA08).

For each specimen, the mean shear stress $\bar{\tau}$ was calculated as $\bar{\tau} = F_{max}/A$, where F_{max} is the applied load at failure and A is the bonded surface area. The shear modulus G in compression test was calculated by means of eq. (2), considering the mean adhesive layer thickness c equal to 0.388 mm (as evaluated from specimens sample). Table 5 shows the results.

It is possible to assert that the bio-adhesive A provides a value for the shear stress nearly equal to the one provided by the conventional adhesive; however, the value for the shear modulus provided by the bio-adhesive A is lower than the one offered by the conventional adhesive. As regards the bio-adhesive B, its values for both shear modulus and stress are the worst among the three adhesives tested.

Table 5. Results for shear properties by compression loading.

		G [MPa]	$\bar{\tau}$ [MPa]
CSIA Bio-adhesive A	$\bar{X}$	3.561	9.643
	RMS	0.492	0.183
	x_k	2.752	9.342
CSIB Bio-adhesive B	$\bar{X}$	3.358	9.360
	RMS	0.415	0.238
	x_k	2.676	8.969
CSIC Conventional adhesive C	$\bar{X}$	3.798	9.600
	RMS	0.187	0.154
	x_k	3.491	9.347

4 CONCLUSIONS

The possibility of using bio-based adhesives in boatbuilding technologies represent a valuable solution to increase the eco-friendliness of wooden boats and to implement a development within the novel "green boatbuilding" concept. The strip-planking technology fits well in this framework due to its advantages in terms of implementation ease and exploitation of material properties. With reference to this technology, one wood essence typically used was coupled with two types of bio-based epoxy adhesives. The mechanical properties obtained through the tests were compared to the ones obtained for a conventional epoxy resin commonly used in boatbuilding. A general consideration is that the obtained properties for the three adhesives tested are comparable, and consequently the results are satisfying.

In details the following conclusions can be drawn.

As regards the tensile-shear tests:

The bio-adhesive A gives the best result in terms of shear modulus, while the bio-adhesive B gives a value of shear stress nearly equal to the one given by the conventional adhesive.

As regards the shear tests by compression loading:

- The bio-adhesive A gives a value of shear stress nearly equal to the one provided by the conventional adhesive. As for the shear modulus, the mean values provided by the bio-adhesive A and the conventional adhesive are nearly equal, but the first one is penalised by a higher dispersion that lowers the characteristic value. The situation is different for the bio-adhesive B, which gives the worst results for both shear modulus and stress.

It is worth doing some considerations also on the results obtained between the tensile-shear and the compression-shear tests. Indeed, the mean values for both shear modulus and shear stress evaluated with both test procedures are comparable. The main difference regards the values of dispersions, which are greater for the results coming from the tensile-shear test. As a consequence, the shear test by compression loading seems to give more precise values. Therefore, it is possible to assert that the testing procedure derived from the ASTM Standard by the authors is valid to assess shear properties under compression loading. Its main advantage, as well as the high precision of results, regards the possibility of using common testing devices in laboratories.

As a conclusion, the results obtained so far validate the application of bio-based adhesives in boatbuilding technologies and further studies aimed at increasing their mechanical characterisation and knowledge are currently in progress.

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