SECTION 2   RAW MATERIALS

1 General

1.1 Application

1.1.1 The mechanical characteristics of composite materials depend on raw materials' characteristics.

1.1.2 The present section gives general "state of the art" information about raw materials.

1.2 Definitions

1.2.1 The present chapter describes the main raw materials used in composite boat building.

The raw materials, used in boat building, are of four main types: resin systems, reinforcements, core materials, adhesives.

1.2.2 Resin systems

Also named matrix, resin systems are thermoset resins (initial liquid, hard and stiff cross linked material that does not return liquid when cured). Resin is used to:

- link reinforcements together
- protect them from impact, moisture and abrasion
- spread loads through reinforcements' layers.

Resin systems dealt with in this Chapter are polyester, vinylester and epoxy systems.

1.2.3 Reinforcements

Reinforcement fabrics are used to improve mechanical characteristics of composite materials.

Reinforcement fabrics may be constructed with interlaced yarns or without interlacing, named respectively woven rovings and stitched rovings.

Reinforcement fabrics dealt in this chapter are made of continuous yarns, manufactured with glass, carbon or para-aramid fibres.

1.2.4 Core materials

Core materials are used in composite sandwich structures to improve global moment of inertia of the whole laminate. Sandwich structures are made of two reinforced faces also named skins, separated by and jointed to a core.

Core materials dealt with in this chapter are synthetic foams, natural cores and honeycombs.

1.2.5 Adhesives

Adhesive materials are generally considered as resin systems, and are used to bond together different composite structures or to bond skins to core in sandwich structures.

2 Resin systems

2.1 General

2.1.1 Manufacturing and curing process

As a general rule, thermoset resin systems used in ship-building are obtained from a synthetic resin, also named polymer, made of long unsaturated chains of molecules.

The process, which allows to modify the arrangement of molecular chains from free independent chains to a three dimensional linked chains network, is called polymerisation or curing process.

This chemical reaction is observed where resin goes from its liquid state to its solid state. This reaction is accompanied by a heat discharge and is irreversible for thermoset resins.

The three dimensional network is obtained by different curing processes, according to the type of synthetic resin:

- for polyester and vinylester: by mixing synthetic resin with an unsaturated monomer (e.g. styrene) which creates the chemical links. In this case, the chemical reaction needs a catalyst to start the polymerisation process

- for epoxy: by adding a hardener which promotes the polymerisation process. In this case, macromolecular chains are directly linked to each other.

These two different chemical processes have an important effect on mechanical characteristics of the final resin system and particularly on the volumetric shrinkage during the polymerisation (source of stress concentration in the final composite between resin and fibre).

2.1.2 Glass Transition Temperature (Tg)

Glass Transition Temperature (Tg): the state of polymerisation may be appraised by measuring the Tg. This is the approximate temperature at which number of chemical links between molecular chains is significant to change mechanical properties of a cured resin.

The more polymerized is the resin, which means the greater is the number of chemical links between macromolecular chains, higher is the value of Tg.

Where Tg is measured, it is necessary to indicate the reference of the test method, taking into account that the measured value of Tg may vary from one method to another.

For epoxy resin systems in particular, Tg may be increased after the resin polymerisation by a post cure with an additional rise of temperature.

2.1.3 Speed of polymerisation

The speed of polymerisation process may be controlled:

• either by the amount of accelerators for polyester and vinylester resin systems

• or by the amount of a hardener for epoxy resin systems

• or by a controlled rise of temperature speed.

2.1.4 Resin system reference

The resin systems may be affected by:

• the chemical formulation of polymers used (basic resins, unsaturated monomers, catalysts or hardeners)

• the polymerisation process and the additive products used such as thixotropic or coloured agents.

Due to the above, resins are to be used within the limits fixed by the manufacturer. In this respect, the Surveyor may ask any useful justification to be submitted, such as:

• technical data sheet of resin system in a determined cured condition

• manufacturer guarantee for resin used in naval construction (stability regarding ageing in marine environment, resistance to hydrolysis...)

• type and proportion of catalyst, hardener and accelerator recommended by the manufacturer to be adjusted in the different circumstances of conditions of work (ambient atmosphere, i.e. temperature, relative humidity, dust)

• Type approval certificate for resin system granted by a recognized Society.

Note 1: As a general rule, mechanical tests are to be carried out on a panel laminate representative of the hull structure and polymerisation process as defined in Ch 12, Sec 5, [4].

These mechanical tests aim at examining the final performance of the resin system among others.

2.2 Resin systems type

2.2.1 Polyester system

Polyester resin systems are the result of mixing unsaturated polyester resin with an unsaturated monomer, also called co-polymer, and a catalyst. This reaction is named co-polymerisation.

• Monomer: the unsaturated monomer, generally styrene, is used to reduce the initial viscosity of the resin before polymerisation and to create the chemical links between chains of polyester macromolecules. The chemical reactive sites and so the chemical links are located all along the macromolecular chains of polyester.

This chemical reaction between polyester and styrene leads to the emission of styrene over, not used in the polymerisation. The global chemical polymerisation is stopped where all the styrene over emission is fully completed or where reactive sites of polyester are fully linked.

• Catalyst: generally of organic peroxyde chemical family, catalyst is used to initiate the reaction between polyester and monomer. It does not take part in the chemical reaction.

The catalyst proportion and its homogeneous mixing with the polyester/styrene resin before moulding are main parameters.

Too low proportion of catalyst may result in an incomplete polymerisation reaction, which may affect the mechanical properties of the final laminate. The catalyst proportion is to be defined by the resin manufacturer.

• Accelerator: an accelerator may also be added to control the chemical speed of reaction, according to the workshop environment (temperature for example).

Because the accelerator has no influence to initiate the polymerisation reaction, as long as there is no catalyst, it may be directly added by the manufacturer in the polyester resin system. This type resin is called pre-accelerated.

The polymerisation is carried out at room temperature and goes with an exothermic heat temperature.

The chemical network after polymerisation may be represented by Fig 1.
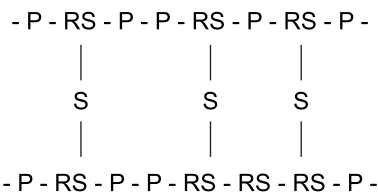
Two types of polyester resins are used in boat building: orthophtalic and isophtalic.

The mechanical characteristics and the water absorption resistance of isophtalic are higher than of orthophtalic polyester resin. Isophtalic polyester resin is then generally used for gelcoats and in the first layers located after the gelcoat.

The main physical characteristics of polyester resin systems are:

• a high volumetric shrinkage during polymerisation due to the great number of chemical links along polyester macromolecules and to styrene emission

• a moderate breaking strain due to the location of chemical links along polyester macromolecules

• a water absorption sensitivity due to ester functions in polyester macromolecules.

Figure 1 : Polyester

```
- P - RS - P - P - RS - P - RS - P -
       |           |         |
       S           S         S
       |           |         |
- P - RS - P - P - RS - RS - RS - P -
```

RS= Reactive Sites; P= Polyester; S= Styrene

2.2.2 Vinylester resin systems

Vinylester resin systems have the same polymerisation process than polyester systems.

Unsaturated vinylester resins differ from polyesters primary in their chemical structure by:

• the location of ester groups and reactive sites at ends of vinylester macromolecular chains

• the lower number of ester groups along chains

• the presence of epoxy groups along the chemical structure.

The chemical network after polymerisation may be represented by Fig 2.

The main physical characteristics of the vinylester resin systems are:

- Lower volumetric shrinkage during polymerisation than polyester, due to the lower number of chemical links between macromolecules

- a higher resistance to the water absorption due to the fewer ester functions along macromolecules of vinylester

- a higher breaking strain and ductility than polyester systems due to the location at ends and fewer number of reactive sites along the macromolecule

- high adhesive characteristics due to the presence, in macromolecules, of polarized molecules able to create non-chemical links (hydrogen type) between macromolecules.

Figure 2 : Vinylester

- RS - Vi - .... - Vi - RS -
| |
S   S
| |
- RS - Vi - .... - Vi - RS -
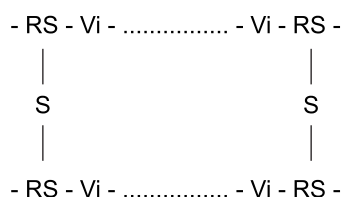
RS: Reactive site; Vi: Vinylester; S: Styrene.

2.2.3 Epoxy systems

Epoxy resins are made of long macromolecular chains of polymer with epoxy reactive sites located at ends of these chains. Epoxy resin systems polymerisation may be obtained by:

- mixing epoxy molecular chains with a hardener, generally polyamine or acid anhydride

- and/or rising curing temperature. In this case, epoxy sites may directly react during the polymerisation between each other, without need to add a hardener.

One of the two cases here above is necessary to initiate the reaction; and, in both cases, this chemical reaction is called polyaddition.

Taking into account that epoxy reactive sites do not need a co-polymer to create chemical links between themselves, the quality of a polymerisation may be increased by a second rise of temperature. This process is named post-cure.

The chemical network after polymerisation of polyepoxyde may be represented as shown in the Fig 3.

The main characteristics of epoxy resins are:
- a low volumetric shrinkage during polymerisation

- a higher breaking strain than polyester and vinylester ones due to the location of the chemical links at macromolecules ends and to the strong resistance of these links

- a high water absorption resistance due to the absence of ester group in the macromolecule

- very high adhesive properties.

Figure 3 : Epoxy

Epoxy

Hardener
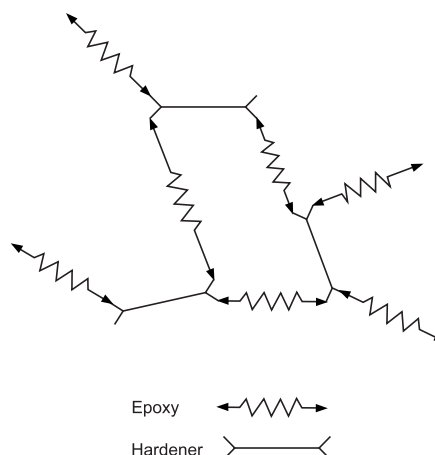
2.3 Homologation of resin systems

2.3.1 General

As a general rule, the resins used in the construction of a yacht are to be certified within the scope of Classification and in particular to assign the construction marks ✠ or •.

This resin system homologation process is described in [6].

2.4 Resins mechanical characteristics

2.4.1 General

As a general rule, the mechanical characteristics of the resin to take into account for laminate calculation are to be given by manufacturer and/or by mechanical test.

2.4.2 The minimum mechanical characteristics are given for information in Tab 1.

3 Reinforcements

3.1 General

3.1.1 As a general rule, the reinforcement fibres need to be arranged into fabric products to make handling possible.

These fabrics are textile structures made from continuous yarns, themselves made from an assembly of monofilaments.

In boat building, continuous yarns and monofilaments are generally named "fibres" and fabrics may also be named "rovings".

The main mechanical characteristics of reinforcement fabrics taken into account in the present chapter depend on:

- fibre type

- yarns' nature

- fabrics' nature.

Table 1 : Resins' mechanical characteristics

	Polyester	Vinylester	Epoxy
Density ρ_m	1,2	1,1	1,25
Poisson coefficient v_m	0,38	0,26	0,39
Tg (°C)	around 60°	around 100°	between 80° and 150° **(1)**
Tensile Young modulus (MPa) E_m	3550	3350	3100
Tensile or compressive breaking stress (MPa)	55	75	75
Tensile or compressive breaking strain (%)	1,8	2,2	2,5
Shear modulus (MPa) G_m	1350	1400	1500
Shear breaking stress (MPa)	around 50	around 65	around 80
Shear breaking strain (%)	3,8	3,7	5
(1) The actual value of Tg is depending on the polymerisation process used and in particular the temperature used in post-cure			

3.1.2 After fabrication of monofilaments and/or yarns, a surface treatment, named size, is carried on yarns in order to:

- create a cohesion between yarns

- improve the quality of the reinforcement/resin interface

- protect the yarns from manufacturing process.

This size plays a very important part to promote fibre/resin interfacial bond strength. In some cases (carbon and para-aramid fibres), size remains on yarns throughout the fabrics' manufacturing process. In other cases (glass fibre), a first size is applied during yarns' manufacturing to protect monofilaments and a second one is applied during fabric fabrication to improve fibre/resin interface bonding characteristics.

3.1.3 The linear density of a yarn, expressed in tex (g/km), has a direct influence on the strength of a yarn and then on final fabric.

3.1.4 Taking into account that a reinforcement may be affected by the nature of fibre, of yarn, of size or of fabric the Surveyor may ask any useful justification such as technical data sheets of used yarns and/or fabrics to be submitted.

3.1.5 As a general rule, mechanical tests are to be carry out on samples representative of hull laminate structure and polymerisation process as defined in Ch 12, Sec 5, [4].

At this stage, these tests aim at examining performance of yarns and fabrics as well as the fibre/resin interface bond strength.

3.2 Fibre type

3.2.1 Glass

Glass monofilaments are obtained by heating a mixture of silica and alumina up to approximately 1600 °C then by stretching the liquid through a die, made up of holes generally of 5 to 25 μm.

They have the same molecular arrangement than glass plates and then are considered as isotropic materials. It means that the mechanical properties are the same in lengthwise and crosswise directions.

The two main types of glass used in composite shipbuilding are the E and the R types. E-glass is the reference glass, generally used. R-glass has an higher mechanical resistance due to greater percentages of silica and alumina in its chemical composition.

Glass yarns have a standardized designation (ISO 2078), giving following information:
- type of glass
- type monofilament: C for Continuous and D for Discontinuous, commonly and respectively named strand and staple
- diameter of monofilaments in micrometer
- linear density in Tex.

For example, "EC15 800" means E-Glass made from Continuous monofilaments of 15 μm diameter and 800 Tex.

The main physical characteristics of the E-Glass are:
- a good tensile and compressive strength and stiffness
- a relatively poor impact resistance.

The main physical characteristics of R-Glass are the same than E-Glass with an improvement of roughly 20% as well as good interlaminar shear strength properties.

3.2.2 Carbon

Carbon monofilaments are mainly made from Poly-Acrylonitril) (PAN) precursor fibres.

PAN-precursor fibres are first oxidized (between 200°C and 300°C) and then carbonized under inert atmosphere (between 700°C and 1500°C). These steps rearrange the molecular structure into a network of aromatic carbon layers, which are all chemically linked. This chemical process makes the structure different in the lengthwise direction and in the crosswise direction, which explains the orthotropy of carbon monofilaments.

This first stage of fabrication gives the HS Carbon.

This Carbon may undergo an additional stage: a graphitization between 2000°C and 3000°C under inert gaz. This final stage increases the number of aromatic carbon layers and chemical links, which give the monofilaments a higher density and a higher Young modulus. Those types of Carbon are named IM and HM Carbon (respectively Intermediate Modulus and High Modulus).

Another type of Carbon, called Pitch Carbon, is also used in shipbuilding. Pitch-precursor carbon monofilaments are obtained by pitch fusion (between 350°C and 450°C), dying and high stretching. Stretching, which is in addition with the chemical process, gives monofilaments a higher anisotropic molecular arrangement than the HM carbon monofilaments then an even higher Young modulus.

Generally, one has to apply a size to carbon monofilaments in order to improve the quality of reinforcement/resin interface and to protect them from the different steps of reinforcements' fabrication.

The industrial designation of carbon multifilament is as follow. First one gives the type of carbon, then the number of monofilaments into the multifilament, expressed in thousands of monofilaments (e.g. HR-12k Carbon).

The main characteristics of carbon fibres are:

• very high tensile and compressive strength and stiffness

• a very low strength in the normal direction to the fibres' direction

• a relatively poor interlaminar shear strength and impact resistance.

3.2.3 Para-aramid

Aramid (Aromatic ether amid) fibres are organic man-made fibres. Para-aramid is the result of a polycondensation of a polyamine and an aromatic acid around 300°C.

Para-aramid monofilaments are obtained successively by hot-dying, cold-water solidification and "high-speed, high-temperature, dry-air" stretching. Stretching, which is a mechanical process, gives to para-aramid monofilaments a very high-oriented molecular organization in the "fibre" direction. Their behaviour and mechanical properties in transverse and "fibre" directions are then very different.

The main characteristics of the para-aramid fibres are:

• a very high impact resistance

• high tensile strength and stiffness and a poor compressive strength

• a very poor tensile and compressive resistance in transverse direction.

As a general rule, para-aramid are hard to wet by resin systems.

3.2.4 Mechanical characteristics

As a general rule, the mechanical characteristics of fibres to take into account for laminates calculations are to be submitted by manufacturer and/or are given by mechanical tests.

The minimum mechanical characteristics are given in Tab 2 for information.

Table 2 : fibres mechanical properties

		Glass		Carbon			Para-aramid
		E	R	HS	IM **(1)**	HM **(1)**	
Density ρ_f		2,57	2,52	1,79	1,75	1,88	1,45
Tensile in fibre direction	Poisson coefficient ν_f	0,238	0,2	0,3	0,32	0,35	0,38
	Young modulus $E_{f0°}$ (MPa)	73100	86000	238000	350000	410000	129000
	Breaking strain (%)	3,8	4	1,5	1,3	0,6	2,2
	Breaking stress (MPa)	2750	3450	3600	4500	4700	2850
Tensile normal to fibre direction	Poisson coefficient	0,238	0,2	0,02	0,01	0,01	0,015
	Young modulus $E_{f90°}$ (MPa)	73100	86000	15000	10000	13800	5400
	Breaking strain (%)	2,4	2,4	0,9	0,7	0,45	0,7
	Breaking stress (MPa)	1750	2000	135	70	60	40
Compressive in fibre direction	Breaking strain (%)	2,4	2,4	0,9	0,6	0,45	0,4
	Breaking stress (MPa)	1750	2000	2140	2100	1850	500
Shear	Modulus G_f (MPa)	30000	34600	50000	35000	27000	12000
	Breaking strain (%)	5,6	5,6	2,4	3	3,8	4
	Breaking stress (MPa)	1700	1950	1200	1100	1000	500
(1) Taking into account the large diversity of IM and HM carbon, the values presented in this table are given for general guidance only.							

3.3 Reinforcement fabrics

3.3.1 General

Usually, reinforcing fibres are arranged into fabric products.

These fabrics may be made by:

- mechanical stitching of fibres (unidirectional fabrics)

- mechanical weaving of fibres (woven fabrics)

- chopped fibre chemically gathered into sheet

- combined fabrics mixing one or other previous described fabric product

- pre-preg fabrics.

Fabrics may be made of different types of fibre, one type of fibre per main fabric direction.

3.3.2 Mechanical characteristics

The mechanical characteristics will be influenced by the fibre type used for fabric products, by the direction and positioning of the fibre in the fabric products, but also by the various distortion of the fibre induced by weaving process, called waviness.

3.3.3 Unidirectionals (UD)

Unidirectionals are fabrics with fibres in one main direction, gathered by mechanical or chemical stitching, respectively with another fibre or a specific adhesive.

The main characteristics of unidirectionals are:

- high tensile and compressive strengths in the fibre direction, due to the high percentage of fibres in fibre direction and also to lack of waviness

- low tensile and compressive strengths in the crosswise fibre direction.

From a theoretical point of view, UD are used as reference for the calculations of elastic coefficients of the other fabric types.

3.3.4 Woven rovings

Woven rovings are made from two sets of fibres criss-crossing, which form a right angle. The one in the weaving direction is named warp, the other one weft. Weaving consists in repeating a basic interlace sequence between warp and weft rovings. This sequence is named basic weave.

The four main weave families used in composite shipbuilding are:

Plains : Each weft fibre passes alternatively under and over each warp fibre. This type of fabric is relatively difficult to drape due to its high stability. The fibres are strongly crisscrossed (high waviness)

Baskets : Similar to plains with an alternative pattern made up of 2 or more weft fibres alternatively interlaced with 2 or more warp fibres (high aviness)

Twills : One or more weft fibres pass alternatively under two or more warp fibres. The main interests of this fabric type are to make easier the drape process and to limit the bend fibre in the weaving process as well as to increase the wet operation, named wetting. This is a moderate waviness fabric

Satins : The weaving pattern is obtained by one or more weft fibres cross several warp fibres and then pass under only one warp fibre. Satins have the same interest than twills with a lower waviness and a higher wetting ability.

As a general rule, the weaving angle between weft and warp is equal to 90°.

The coefficient "woven balance" C_{eq}, indicates for each woven roving the amount of fibre laid in weft and warp direction.

3.3.5 Chopped Strand Mats (CSM)

Chopped strands mats (CSM) are made of fibres chemically gathered to form a web. As fibres are random assembled in the web, there is no main direction. That explains why CSM are considered as isotropic reinforcements.

Mats may be made of fibres shorter than 50mm (Chopped Strand Mats) or longer than 50mm (Continuous Strand Mats).

Chopped Strand Mats mechanical characteristics are low due to the short length of fibres and their non-alignment.

As a general rule, only continuous strands mats (with fibres longer than 50mm) are to be used.

The main characteristics of mats are the nature of fibre, the length of fibres and the area weight.

3.3.6 Combined fabrics

Combined fabrics mainly consist in the assembly by stitching together several reinforcement fabrics as for example:

- woven roving and CSM

- two woven rovings with different orientation (0° for one and 45° for the other) to make a combined fabric with main fibre orientation from -45°, 90°, 0° and 45°

- two UD with orientation equal to -45° and 45° to make a fabric named "bi-bias" or "biax"

- three UD with orientation equal to -45°, 0° and 45° to make a "three directional fabric".

3.3.7 Pre-pregs

The pre-pregs consist in reinforcement fabrics (usually UD, woven roving or combined fabrics) pre-impregnated with a resin system (itself pre-catalysed).

The main advantage of pre-preg fabrics is their accurate resin contents in the reinforcement fabrics.

As a general rule, it is necessary to initiate the polymerisation to activate the chemical reaction by rise in temperature.

3.4 Homologation of reinforcement fabrics

3.4.1 The reinforcements fabrics are to be used within limits fixed by the manufacturer, taking into account the resin systems and laminating process used by the yard.

In this respect, the Surveyor may ask any useful justification to be submitted, such as:

- technical data sheet of reinforcement fabrics, specifying the fibre nature and characteristics

- manufacturer guarantee for the use in shipbuilding.

As a general rule, the reinforcement fabrics in the construction of a yacht are to be certified within the scope of Classification and in particular to assign the construction marks ✠ or •.

The reinforcement fabrics homologation process is described in [6].

4 Core materials

4.1 General

4.1.1 Core materials are used in sandwich composite structures.

The aim of a core material in a composite is to increase the laminate stiffness by increasing its thickness. The core material acts similar to the web of a beam, and so is basically subject to shear forces.

The main characteristics of a core material are low density, shear strength and also capacity to take compressive and shear loading without buckling failure.

Three main families are used as core material:

- foam cores obtained from expanded synthetic resins

- natural material, mainly balsa wood

- manufactured material such as honeycombs.

4.2 Foam cores

4.2.1 General

Foam cores may be manufactured from a large variety of synthetic resins and in a large range of densities and thicknesses.

All the foam cores are to have closed cells to avoid water migration.

The foam cores are to be compatible with resin systems and adhesives used and must withstand to temperature when they are used for pre-pregs process or post-cure process.

Some foam cores need to be heat treated before use to reduce the amount of gassing given when they are submitted to temperature rising during laminating process such as post-cure or pre-preg work.

It is to the manufacturer responsibility to define the process of this operation.

The foam materials are to be used within the limits fixed by the manufacturer and in particular for their compatibility with resin and adhesive systems used and working process when rising temperature is provided.

The purpose of the present subarticle is to describe the main mechanical characteristics of the most used foam cores in shipbuilding.

4.2.2 PVC foam (PolyVinyl Chloride)

The main characteristics of PVC foams are highly resistant to water absorption, to many chemical products and in particular styrene used in polyester and vinylester resin systems.

There are two different types of PVC foams: cross linked PVC and uncross linked PVC (also named linear PVC). The linear PVC foam is more flexible and their mechanical properties are lower than cross linked ones. Cross linked PVC are however more brittle than uncrossed PVC.

4.2.3 PU foam (Polyurethan)

As a general rule, PU foams are only used for lightly loaded structures and as frame or girder formers.

Their mechanical characteristics are relatively low, and the interface between foam and skins may be subject to brittleness with ageing.

4.2.4 PMI foam (Polymethacrylimide)

The PMI foams are used for their high strength and stiffness. They are also used in construction process requiring temperature rising (pre-pregs for example) due to high dimensional stability.

4.2.5 SAN foam (Styrene Acrylo Nitrile)

The main SAN foam characteristic is highly resistant to impact loads.

Their mechanical characteristics are similar to cross linked PVC with higher elongation and toughness.

4.3 Homologation of foam cores

4.3.1 The foam cores are to be used within the limits fixed by the manufacturer.

In this respect, the Surveyor may ask any useful justification to be submitted, such as:

- technical data sheet of foam

- manufacturer guarantee regarding work process.

As a general rule, the foam cores used in the construction of a yacht are to be certified within the scope of Classification and in particular to assign the construction mark ✠ or •.

The foam cores homologation process is described in [6].

4.3.2 As a general rule, mechanical characteristics of the foam cores to take into account for sandwich calculations are to be given by manufacturer and/or are given by mechanical tests.

For information only, the standard mechanical characterisitcs of different types of foam cores in relation to their density are given in Tab 3.

Table 3 : Foams

	Voluminal mass (kg/m³)	Modulus			Breaking Stresses			Poisson coefficient v_{12}, v_{21}
		Tensile E_1, E_2 (MPa)	Compressive E_3 (MPa)	Shear G_{12}, G_{13}, G_{23} (MPa)	Tensile σ_1, σ_2 (MPa)	Compressive σ_1, σ_2 (MPa)	Shear τ_{12}, τ_{13}, τ_{23} (MPa)	
PVC Linear	50	21	18	8	0,7	0,3	0,3	0,36
	60	29	28	11	0,9	0,4	0,5	0,31
	70	37	38	14	1,1	0,6	0,7	0,27
	80	44	49	18	1,3	0,7	0,8	0,25
	90	52	59	21	1,4	0,9	1,0	0,24
	100	59	69	24	1,6	1,0	1,2	0,23
	110	67	79	27	1,8	1,2	1,3	0,22
	130	82	99	34	2,2	1,5	1,7	0,21
	140	89	109	37	2,4	1,6	1,9	0,21
PVC cross linked	50	37	40	18	1,0	0,6	0,6	0,02
	60	47	51	22	1,4	0,8	0,8	0,05
	70	57	63	27	1,8	1,1	1,0	0,07
	80	67	75	31	2,2	1,4	1,1	0,08
	90	78	88	36	2,5	1,7	1,3	0,09
	100	88	102	40	2,9	1,9	1,5	0,10
	110	98	116	44	3,3	2,2	1,6	0,11
	130	118	145	53	3,9	2,8	2,0	0,12
	140	129	161	57	4,3	3,0	2,2	0,12
	170	159	209	71	5,2	3,8	2,7	0,13
	190	180	243	79	5,8	4,4	3,0	0,13
	200	190	260	84	6,1	4,7	3,2	0,13
	250	241	352	105	7,4	6,0	4,1	0,14
SAN	50	52	29	13	0,9	0,4	0,7	0,11
	60	65	37	16	1,2	0,5	0,8	0,18
	70	78	44	18	1,5	0,6	0,9	0,20
	80	92	50	21	1,7	0,8	1,0	0,19
	90	107	55	23	1,9	0,9	1,1	0,17
	100	122	60	26	2,0	1,1	1,2	0,15
	110	137	64	29	2,2	1,2	1,3	0,12
	130	168	71	34	2,5	1,6	1,5	0,06
	140	184	74	36	2,6	1,8	1,6	0,03
	170	234	83	43	2,9	2,4	1,9	0,03
	190	268	88	48	3,1	2,8	2,1	0,03
	200	285	90	51	3,1	3,0	2,1	0,03
PMI	50	54	59	21	1.9	0.8	0.8	0.4
	60	69	76	24	2.1	1.1	1.0	0.6
	70	84	94	28	2.3	1.5	1.2	0.6
	80	101	112	33	2.6	1.9	1.5	0.7
	90	119	132	39	2.9	2.3	1.8	0.7
	100	137	152	45	3.2	2.7	2.1	0.7
	110	155	173	52	3.6	3.2	2.4	0.6
	130	195	217	71	4.5	4.2	3.1	0.5
	140	215	239	83	5.0	4.8	3.5	0.4
	170	280	311	131	6.8	6.7	4.7	0.2

The values presented in this table are given for general guidance only.

Note 1: τ_{13} and τ_{23} are identical to respectively τ_{IL2} and τ_{IL1}

Table 4 : Balsa

	Voluminal mass (kg/m^3)								
	80	96	112	128	144	160	176	192	240
Young modulus (MPa), parallel to sandwich in-plane E_1 , E_2	23	33	42	51	61	71	80	89	116
Young modulus (MPa), normal to sandwich in-plane E_3	1522	2145	2768	3460	4083	4706	5328	5882	7750
Shear modulus (MPa), normal to sandwich in-plane G_{13} , G_{23}	57	80	103	127	150	174	197	218	286
Shear modulus (MPa), parallel to sandwich in-plane G_{12}	40	55	70	90	105	120	140	150	200
Coefficient ν_{12} , ν_{21}	0,015	0,015	0,015	0,015	0,015	0,015	0,015	0,015	0,015
Breaking compressive (MPa), normal to sandwich in-plane σ_3	3,53	5,12	5,95	8,17	9,69	11,35	12,80	14,32	18,96
Breaking traction (MPa), parallel to sandwich in-plane σ_1 , σ_2	0,28	0,34	0,42	0,51	0,56	0,64	0,69	0,78	1
Breaking compressive (MPa), parallel to sandwich in-plane σ_1 , σ_2	0,48	0,58	0,71	0,87	0,95	1,1	1,17	1,33	1,7
Shear breaking (MPa), through sandwich thickness τ_{13} , τ_{23}	0,94	1,1	1,33	1,62	1,73	1,93	2,05	2,33	2,93
Shear breaking (MPa), parallel to sandwich in-plane τ_{12}	0,7	0,9	1,2	1,5	1,8	2	2,3	2,5	3,4
The values presented in this table are given for general guidance only. **Note 1:** τ_{13} and τ_{23} are identical to respectively τ_{IL2} and τ_{IL1}									

4.4 Natural materials

4.4.1 General

The natural material used is the wood, and so the mechanical characteristics of wood as core are intrinsically linked to the structure of wood used.

Two main technics are used to make sandwich with wood core which differ from the wood grain orientation in relation to the sandwich plane:

- wood grain running normal to the sandwich plane (balsa). In this case, the wood core behaviour is similar to foams or honeycombs.

- wood grain running parallel to the sandwich plane (cedar for example). In this case, in addition to ensuring stiffness and shear resistance of the sandwich, the wood core directly takes part to the global sandwich bending due to significant stiffness.

4.4.2 Balsa

The main mechanical characteristics of balsa are:

- high compressive and shear strength

- high stability where heated.

Balsa is available in a large range of density and thickness.

Where balsa is used with high density and thickness, the grain may be transversally solicited by the global sandwich bending.

For information, the standard mechanical characteristics of the balsa core material in relation to their density are given in Tab 4.

4.4.3 Red cedar

Red cedar is generally used in typical construction, named "strip planking". With its wood grain running parallel to the sandwich plane, the cedar is also participating to bending stress located perpendicular to the cedar grain where its resistance is weaker.

For information, the main mechanical characteristics of red cedar, for a voluminal mass equal to 350 kg/m^3, are in Tab 5.

Table 5 : Red cedar

|	
Young modulus (MPa), parallel to grain E_1	6000
Young modulus (MPa), perpendicular to grain E_2 , E_3	300
Shear modulus (MPa) G_{12}	350
Shear modulus (MPa) G_{23}	250
Shear modulus (MPa) G_{13}	350
Coefficient ν_{12}	0,47
Coefficient ν_{21}	0,02
Breaking traction (MPa), parallel to grain direction σ_1	40
Breaking traction (MPa), perpendicular to grain direction σ_2	1,5
Breaking compressive (MPa), parallel to grain direction σ_1	25
Breaking compressive (MPa), perpendicular to grain direction σ_2	2,5
Breaking, shear stress (MPa) τ_{12} , τ_{13} , τ_{IL2}	5
Breaking, shear stress (MPa) τ_{23} , τ_{IL1}	10
The values presented in this table are given for general guidance only.	

4.5 Honeycombs

4.5.1 General

Honeycombs are cores whose geometry is described as shown in Fig 4. Honeycomb cores are available in a large range of materials (meta-aramid, thermoplastic resins), cell shape and size thickness. The cells' shapes are closely linked to the manufacturing process of the honeycomb.

All these parameters act upon the final mechanical characteristics of the honeycomb core.

Figure 4 : Honeycombs

Hexagonal cell

Rectangular cell
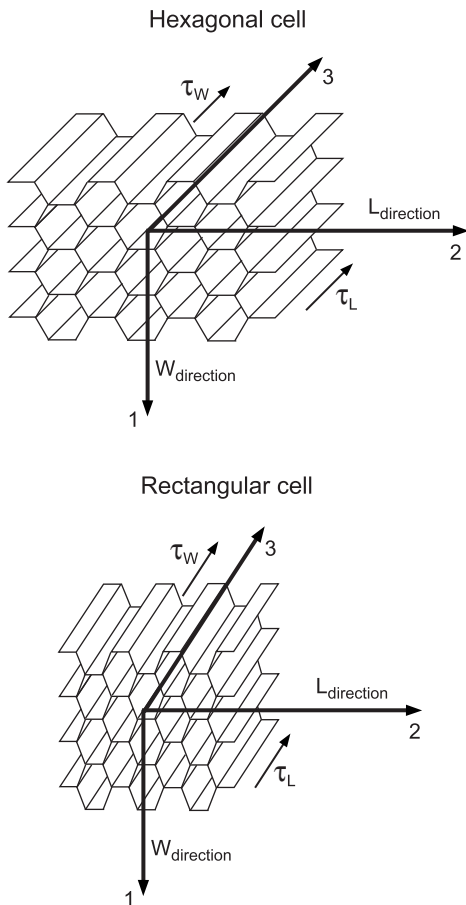
4.5.2 Thermoplastic honeycombs

The most common polymers used for thermoplastic honeycombs are polyethylen, polycarbonate and polypropylene.

As a general rule, these thermoplastic honeycomb cores have relatively low stiffness and mechanical characteristics and are difficult to bond with the sandwich skins.

The cell shape may be diverse due to the fact that these honeycomb cores are obtained by extrusion process.

The use of thermoplastic honeycombs is submitted to a special examination on a case by case basis due to the important diversity of these cores and their temperature sensitiveness.

Special examination is mainly carried out through mechanical tests to estimate the interface and shear resistance of the core in a sandwich construction.

4.5.3 Meta-aramid honeycombs

The meta-aramid honeycomb cores are obtained from an aramid paper, dipped in resin system.

The density of the aramid paper directly acts upon the shear characteristics while the dip operation in resin acts on the compressive characteristics of the honeycomb.

Note 1: Two honeycombs with same density may differ from a mechanical point of view (shear and compressive stresses) in relation to their respective paper thickness and number of dip operations in resin.

Two main cell shapes are available: hexagonal and rectangular. Second shape is being obtained from the hexagonal one with an over expand mechanical operation.

The main advantage of the rectangular cell shape is its curving ability.

From mechanical characteristics point of view, the two main particulars of honeycomb are:

- shear characteristics are different in the two directions of a honeycomb sheet

- for a given honeycomb, shear stress depends on its thickness.

Honeycomb cores are mainly used with pre-pregs process. Honeycomb sheets need to be heat-treated before use to reduce the amount of gassing where they are submitted to temperature rising during pre-preg process.

This material, relatively difficult to stick to sandwich skins must be dust-free and cleaned before use.

For information, the standard mechanical characteristics of meta-aramid honeycombs in relation to their density, cell size, and thickness are given in Tab 6.

Note 2: The failure mode under traction and compressive stresses along L and W directions as well as in plane shear stresses are not dependent on honeycomb characteristics only but also on the characteristics of the global sandwich laminates (core thickness and skins characteristics).

These failure modes are estimated on a case by case by mechanical tests as defined in Ch 12, Sec 5.

5 Structural adhesives

5.1 General

5.1.1 In the present article, the structural adhesive is used to create a structural connection between:

- two composite structures, already cured, as for example the deck/hull gluing

- one composite structure, already cured, with another element, not cured, as for example the stiffener matting-in with the hull

- two raw materials, as for example, the gluing of the foam core with a sandwich skin

- two elements of different kinds, as for example, the windows / hull assembly.

Table 6 : Meta-aramid honeycombs

Voluminal mass	Hexagonal								
	E_1 (in W direction)	E_2 (in L direction)	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{21}	τ_{13} (in L direction), τ_{IL2}	τ_{23} (in W direction), τ_{IL1}
48	13	16	3	37	25	0,82	0,82	1,2	0,7
50	13,6	17	3,3	39	26	0,82	0,82	1,3	0,75
56	14	18	4,1	46	30	0,82	0,82	1,5	0,85
64	17	20	5	59	38	0,82	0,82	1,8	1
96	21	27	6	87	57	0,82	0,82	3	1,7

Voluminal mass	Rectangular								
	E_1 (in W direction)	E_2 (in L direction)	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{21}	τ_{13} (in L direction), τ_{IL2}	τ_{23} (in W direction), τ_{IL1}
48	105	12,5	1,5	19	36	0,263	0,263	0,75	0,8
50	108	12,8	1,6	19,5	37	0,263	0,263	0,8	0,85
56	114	13	1,9	21	40	0,263	0,263	0,95	0,9
64	135	13,5	2,1	23,5	43,5	0,263	0,263	1,1	1
96	180	15,5	3,3	31	58	0,263	0,263	1,9	1,5

Note 1: The values presented in this table are given for general guidance only. The mechanical characteristics given by the supplier and taking into account the cell size and paper thickness of the honeyycombs are to be taken into account for rules calculations.

Note 2: τ_{13} and τ_{23} are identical to respectively τ_{IL2} and τ_{IL1}

5.1.2 The main mechanical characteristics of a structural gluing joint mainly depends on the following parameters:

- resin systems and additives such as thixotropic agents
- type of the components to be bonded as well as their surface preparation (abrasing, cleaning,...)
- geometry and thickness of the bonded joint
- curing process of the bonded joint.

5.2 Structural adhesive characteristics

5.2.1 The large range of adhesive resin systems, curing adhesive process, type of components to be bonded and the large variety of joint geometry do not permit to define typical mechanical characteristics.

As a general use, the mechanical values to take into account are given by the manufacturer, paying attention to the mechanical type tests context from which the mechanical values are taken from.

5.2.2 As a general rule, a maximum breaking shear stress from 5 N/mm^2 to 10 N/mm^2 (for high performance bonding) is usually considered.

6 Raw materials certification

6.1 Construction marks

6.1.1 Definition

Construction mark refers to the mode of survey of raw materials used in construction of a yacht and is granted in scope of classification.

6.1.2 The possible construction marks are:

- Construction mark ⊞ where the principal raw materials are homologated or surveyed at works (or on reception at the yard) by the Society
- Construction mark • where the principal raw materials have not been surveyed by the Society under the terms of one of the previous schemes; in this case, the yard is responsible for ensuring that the raw materials comply with the Society's requirements.

6.1.3 Principle of assignment of construction marks

This article stipulates the arrangements to be adopted in assigning the construction marks ⊞ or •.

Materials concerned by certification are:

- gel-coats and laminating resins
- reinforcement fabrics
- core materials for sandwich laminates.

Other materials may occasionally be submitted for Society approval (e.g. adhesives or structural plywoods).

Note 1: The purpose of survey of raw materials by the Society is to ensure compliance with the requirements of the relevant Society's Rules (within the framework of theoretical calculation of the mechanical properties of the composite). However, the findings of such surveys are not to be used as the only basis for the order specification. The Yard must issue a proper specification to its Supplier.

6.2 Assignment of construction mark ⊞

6.2.1 General

The construction mark ⊞ is assigned when one of the following modes of survey of raw materials is used:

- Homologation of raw materials

- Acceptance of specific mechanical tests carried out on raw materials used for construction

- Homologation already granted by another Society, recognized by Bureau Veritas.

6.2.2 Homologation of successive stages

The homologation of raw materials requests two successive stages:

- Type approval

- Homologation itself.

6.2.3 Type Approval

The Society ensures that certain technical data in the Supplier data sheets comply with the relevant requirements of the Society's Rules.

A test programme, drawn up jointly by the Supplier and the Society, is performed, and the results are examined, so that the declared properties may be confirmed.

For information, the standards' test programme is generally as follows:

- Gel coats:

  - Tensile test (modulus, elongation): ISO 527 or equivalent

  - Moisture absorbency: Standard ISO 62 or equivalent

- Resin:

  - Density: ISO 1675 or equivalent

  - Tensile test (modulus and breaking strength): ISO 527 or equivalent

  - compressive test (modulus and breaking strength): ISO 604 or equivalent

  - Shear test (modulus and breaking strength): ISO 1922 or equivalent

  - Voluminal shrinkage: ISO 3521 or equivalent

  - Glass Transition Temperature: ISO 11357 or ISO 11359 or equivalent

- Reinforcements fabrics:

  - Surface weight: ISO 3374 or equivalent

  - Tensile test: ISO 4604 and ISO 4606 or equivalent

- Prepregs:

  - Glass content: ISO 9782 or equivalent

  - Surface weight: ISO 10352 or equivalent

- Core materials - foams:

  - Density: ISO 845 or equivalent

  - Tensile test (modulus and breaking strength): ISO 1926 or equivalent

  - compressive test (modulus and breaking strength): ISO 844 or equivalent

  - Shear test (modulus and breaking strength): ISO 1922 or equivalent

- Core materials - balsa:

  - Density: ISO 3131 or equivalent

  - Shear strength: ISO 8905 or equivalent

- Core materials honeycombs: Test program to be defined with the Society.

Certain tests may be dropped from this list, and other additional tests requested, depending on the particular use of materials, or experience acquired with such materials.

Reports, issued in the forms stipulated in standards, are submitted to the Society for examination.

Tests are generally done either in laboratories recognized by Bureau Veritas, or in presence of the Surveyor. In the former case, the laboratory reference is stated.

Samples may be taken from the production line or from stocks at the Supplier. Sampling conditions must also be stated by the Supplier.

A type approval certificate is issued for each type of raw material.

6.2.4 Homologation of raw materials

During homologation, the Society checks that the Supplier of mass-produced raw materials is capable of reproducing satisfactory the products examined during type approval. For this purpose, the Supplier must submit documents on the various phases described below, as a basis for survey of the production line by the Surveyor:

- Organisation and means of production of raw materials for homologation

- Procedures for purchase, acceptance testing and storage of various materials used in the manufacture of the products

- Procedures for manufacturing of the products

- Survey procedures used during production phases

- Tests and surveys performed on completion of production.

6.2.5 Acceptance of specific mechanical tests

On a case by case basis, where raw materials are not homologated as defined in [6.3], specific mechanical tests, based on these defined in Ch 12, Sec 5, [4], may be accepted by the Society.

The raw material samples are to be defined in accordance with the Society.

6.3 Assignment of construction mark •

6.3.1 The construction mark • is assigned where one of the forms of survey of raw materials, described in [6.2], is not applied.

In this case, the yard is responsible for ensuring that the materials used in the construction meet the relevant requirements of the Society's Rules.