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Local impact strength of various boat-building materials

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Abstract

An impact test series is performed using an instrumented impact test method according to the standard ISO 6603.

The materials tested were those most frequently used in boat-building, such as plywood, fibre-reinforced plastic, ABS (acrylonitrile/butadiene/styrene), PE (polyethylene), PC (polycarbonate) and aluminium.

The impact strength of the materials is compared taking into account thickness and weight of the specimens.

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List of symbols

t	thickness	[mm]
q	square weight	[kg/m^2]

FRP	fibre-reinforced plastic
ABS	acrylonitrile/butadiene/styrene
PE	polyethylene
PC	polycarbonate

1. Introduction

Local impact strength is one of the various properties that should be considered in the design and dimensioning of boat structures.

It is however rare that explicit requirements for impact strength are seen in, for instance, classification rules. On the other hand, indirect requirements, which may be expressed in terms of minimum panel thickness, are more common.

There are many understandable reasons why direct requirements are not used, one of them being the lack of adequate test standards. Also, the phenomena associated with impact strength are complicated and, to a great extent, unexplored. A further difficulty is the complexity of the accurate determination of impact loads.

In this publication, the term ‘impact’ refers to the case of local impact between a solid object and the structure, resulting in a point-loading with a high loading rate. Wave slamming, of which the high loading rate also is typical, does not fall in this category, since the loading is usually spread over a larger area or a line and water cannot be considered a solid object.

Some of the impact loads to be expected in boats can be predicted, such as items falling on the deck or collisions with floating objects of certain shape, size and mass. However, it is clear that accidental overloads can not be excluded, especially with boats attaining high speeds.

This report compares the local impact strength of various materials which are used in boat building. It is important to note that material strength is only one parameter determining the impact strength of the boat hull. Structural details, such as the amount and size of internal stiffeners can play an important role when impact energy has to be absorbed. Especially in the case of sandwich structures, the core significantly contributes to the impact strength, depending on its thickness and material properties [1].

Generally speaking, the impact energy can be absorbed in various ways. The elastic energy may be significant, if the panels can absorb energy by deflecting and introducing vibration into the whole structure. Wheter the impact energy can be absorbed by elastic response, and to what extent, depends on various factors, such as impactor speed, dynamic response of the structure and local stiffness and strength of the impact location. Typically, boat hulls have various points with very high local stiffness (for instance, near a bulkhead). Therefore, the possibility that most of the impact energy has to be absorbed locally by the material should be regarded as the worst case, yet a possible one.

2. Tested materials

The most commonly used materials in boat hulls are fibre-reinforced plastics (mostly glass-polyester), aluminium, thermoplastics (mostly ABS and PE) and wood. Table 1 shows the distribution of hull materials among the recreational and work boats manufactured in Finland between 1994 and 1996 and approved under the Nordic Boat Standard [2, 3].

Table 1. Distribution of hull materials among type approved recreational and work boats (Nordic Boat standard) built in Finland during 1994-1996. The total number of type approved boats built in this period is 22 038.

Hull material	Percentage
FRP (glass-polyester)	41
Aluminium	36
ABS	22
PE	1

It can be assumed that the majority of boats built in Finland without type approval are made of FRP.

This distribution is reflected in the choice of tested materials, which included various FRP laminates, ABS, aluminium and PE in different thicknesses. Additional materials being tested included polycarbonate (PC), which is used in windows and hatches, and different types of plywood, mostly used by amateur boat builders.

Table 2 shows the tested materials, including their measured thickness and square weight values.

Table 2. Material, thickness t and square weight q of the tested specimens.

	t [mm]	q [kg/m^2]		
Plywood				
Ply1	2.3	1.65	Aircraft (birch, 5 plies) (*)	
Ply2	3.0	2.34	Aircraft (birch, 6 plies) (*)	
Ply3	3.8	2.11	Asp-plywood (populus tremula, 3 plies)	
Ply4	6.4	4.13	Combi (birch / softwood, 5 plies)	
Plywood / FRP				
Ply5	4.0	3.26	Aircraft (6 plies) (*) + FRP (**) on outer face	
Ply6	7.0	4.99	Combi (5 plies) + FRP (**) on outer face	
FRP / Plywood / FRP				
Ply7	7.8	5.92	Combi (5 plies), + FRP (**) on both faces	
FRP			*fibre content / amount of continuous fibres (by weight)*	
FRP1	2.6	3.61	Glass mat-polyester	*22 vol.% / 0%*
FRP2	3.5	5.58	Glass/aramid (93%/7%)-polyester	*28 vol.% /54%*
FRP3	3.8	6.37	Glass-polyester	*41 vol.% / 88%*
FRP4	6.9	9.08	Spray-up laminate	*20 vol.% / 0%*
FRP5	7.1	11.3	Glass-polyester	*32 vol.% / 52%*
FRP6	7.7	11.0	Glass/aramid (90/10%)-polyester	*23 vol.% / 62%*
FRP7	11.5	16.9	Glass-polyester	*24 vol.% / 43%*
ABS				
ABS1	5.3	5.47		
ABS2	6.6	6.64		
ABS3	7.0	7.11		
PE			Simona PE-HWU	
PE1	6.0	5.67		
PE2	10.0	9.45		
PC				
PC	5.0	5.81		
Aluminium				
Al1	2.0	5.40	AlMg3 H32	
Al2	4.0	10.8	AlMg3 H32	
Al3	4.0	10.8	AlMg4.5 H32	

(*) grade III

(**) 1 ply stitched E-glass, ±45°, 318 g/m^2, epoxy matrix

3. Test method

A standardised impact test method which would be suitable for a wide variety of materials does not exist. However, it is necessary to choose one method in order to get comparable results between the different materials.

Among the standardised methods, the puncture test (falling dart) method according to ISO 6603 is widely used. This method includes procedures for performing both non-instrumented (Part 1) and instrumented (Part 2) tests [4, 5].

The ISO 6603 method was chosen also because of its suitable specimen dimensions providing relevant results for all the specimens tested in this series.

According to the standard, the ISO 6603 test method is applicable to rigid plastic specimens of thickness between 1 and 4 mm. However, it is stated that it can be used for specimens thicker than 4 mm, ‘if the equipment is suitable, but the test then falls outside the scope of this part of ISO 6603’.

The majority of the specimens are thicker than 4 mm, but the equipment is in principle suitable for the tests as long as the amount of impact energy is high enough to penetrate also the thicker specimens.

The configuration of a test according to ISO 6603 is shown in Figure 1.

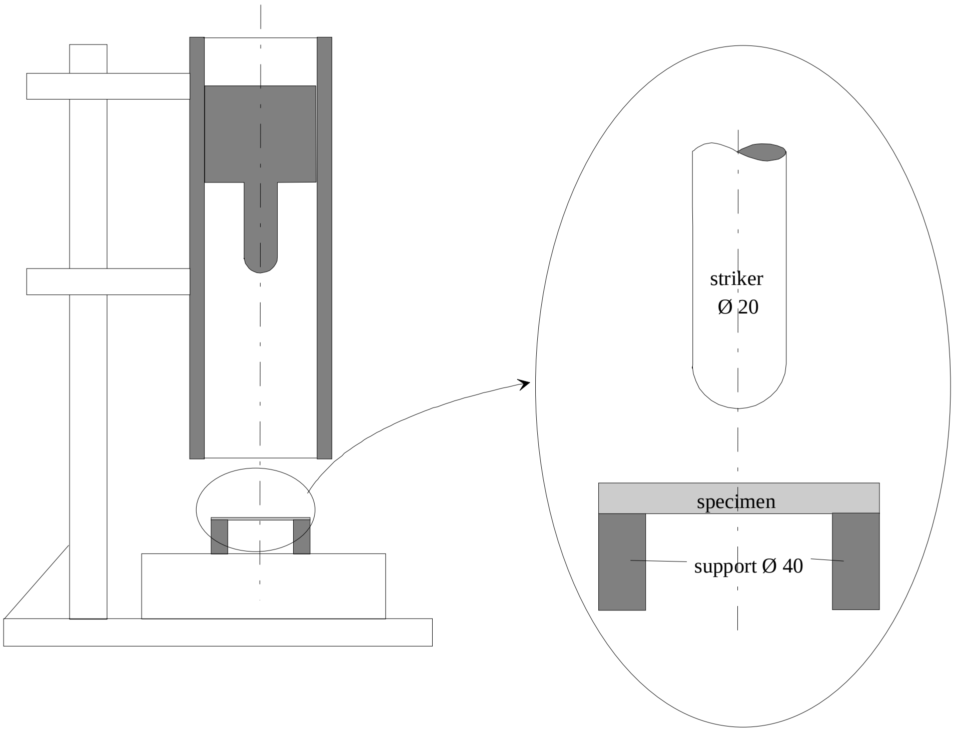

Figure 1. Test configuration presented in the ISO 6603 standard.

The shape of the impactor is a cylinder with a hemispherical tip. The diameter of the cylinder is 20 mm. The specimen support is a hollow cylinder with a 40-mm internal diameter.

The test specimen can be clamped onto the support, though the clamping device is optional. In the present test series, clamping was not used.

Figure 2. Instrumented falling weight impact tester.

The apparatus used for the tests is an instrumented falling weight impact tester shown in Figure 2.

The maximum falling height is 4 m, the falling mass being at present up to 80 kg. The resulting maximum impact speed is 8.7 m/s and the maximum available energy 2.8 kJ.

The total energy used in the present test series was below 600 J.

The apparatus is instrumented for measuring the acceleration during the impact. The measured acceleration data is transferred through a charge amplifier to a PC where it is directly post-processed. A low pass filter at 1000 Hz has been applied in the post processing.

With the instrumented method, the total absorbed energy is calculated from the measured force-time history. An example of the force and energy vs. displacement curve is shown in Figure 3.

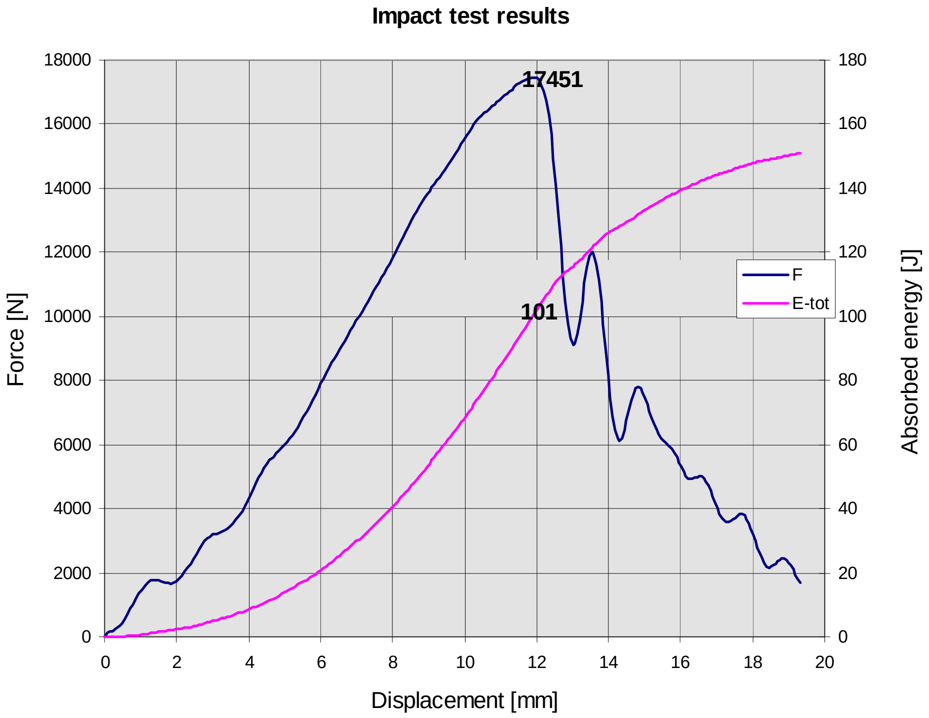

Figure 3. Example of a force-displacement curve and a corresponding absorbed energy-displacement curve.

The impact strength is defined as the total absorbed energy to the point of maximum force. This force and the corresponding energy value are shown in Figure 3.

The specimens were dry and tested at room temperature.

4. Results

The results can be assessed in many ways depending on the purpose. It is relevant to compare the results both in terms of absolute values (absorbed energy values) and in relation to the specimen weight (specific absorbed energy values) and specimen thickness.

Figure 4 shows the absorbed energy values of the tested materials as a function of specimen thickness.

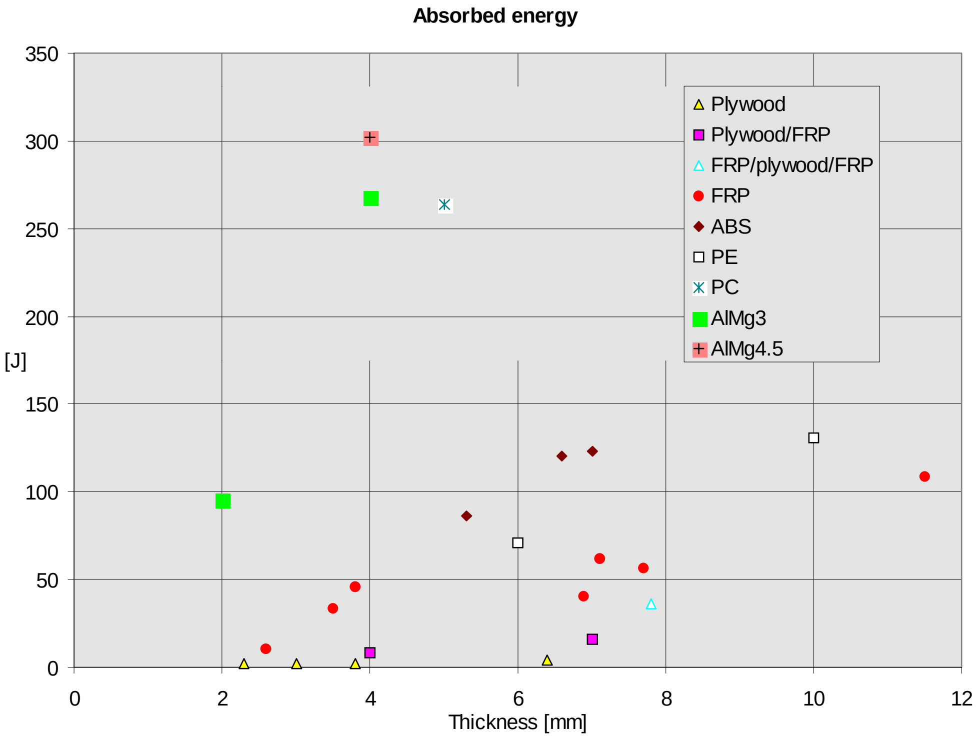

Figure 4. Absorbed energy as a function of specimen thickness.

Looking at Figure 4, we see that the differences in impact strength between the various materials are large, up to two decades for equal thickness.

Many structural items in boats are, at least to a certain extent, weight critical. Therefore, it is of more general value to compare the specific energy values which take into account the mass of the structure. The comparison of specific impact strength of the tested materials is presented in Figure 5.

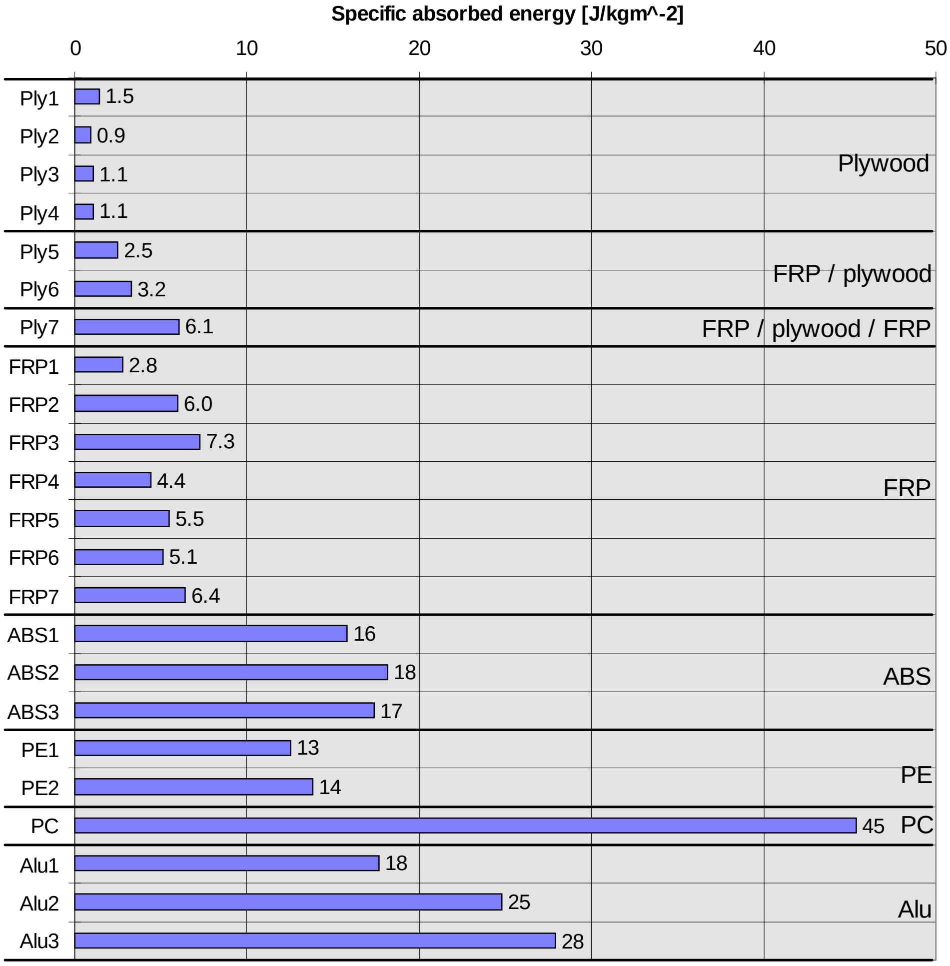

Figure 5. Comparison of specific impact strength (absorbed energy per square weight) of tested materials.

As is clearly shown in Figure 5, polycarbonate exceeds all other materials by far in terms of specific impact strength.

The ranking of the materials (from high to low specific impact strength) is PC, aluminium, ABS, PE, FRP and plywood.

Figure 6 compares the absolute values of absorbed energy of the tested materials.

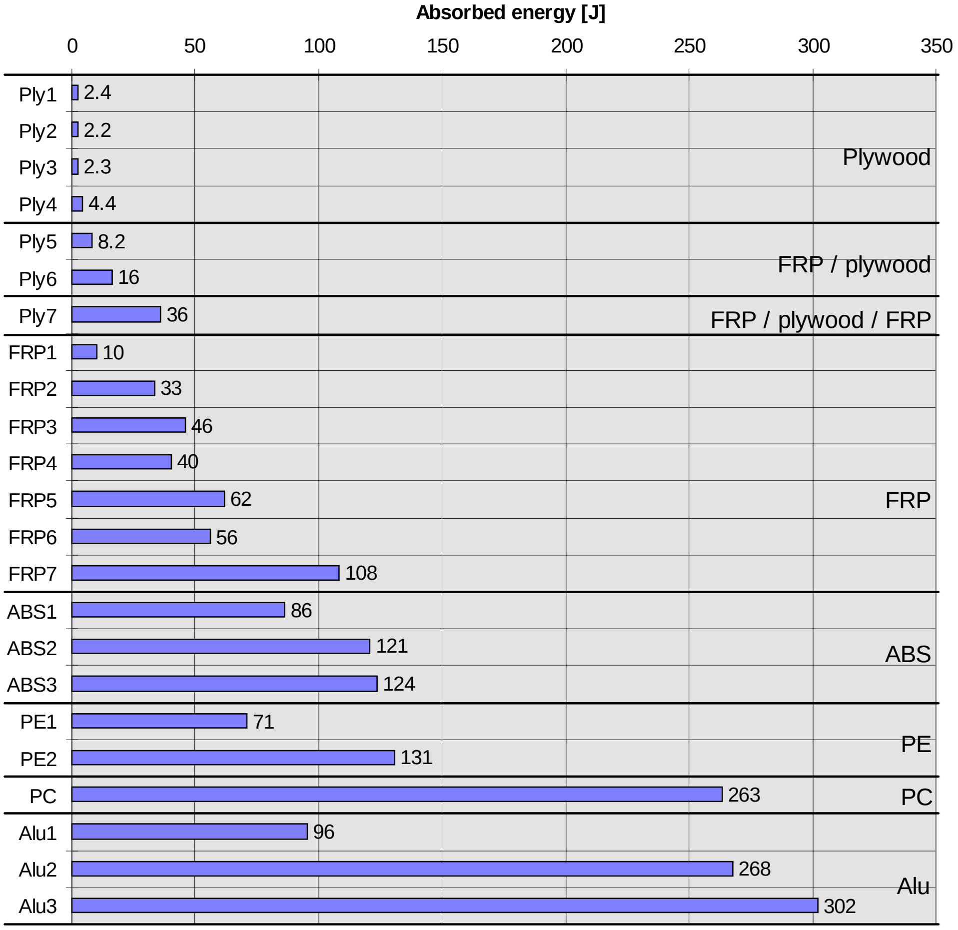

Figure 6. Comparison of impact strength (absorbed energy) of tested materials.

In order to illustrate the differences in impact behaviour between the materials tested, the force-displacement curves are shown on the same scale (Figure 7).

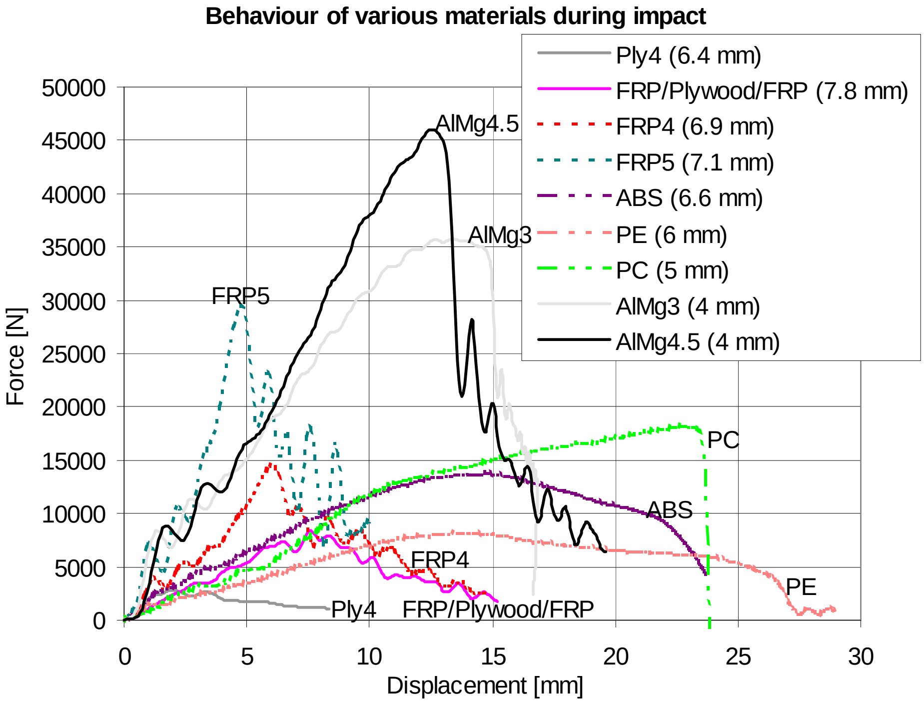

Figure 7. Force-displacement behaviour of tested materials during the impact. Note the differences in specimen thickness (between 4 and 7.8 mm).

Figure 7 clearly shows that the reason for the high energy absorption of both aluminium and thermoplastic materials (PC, ABS and PE) is their plastic behaviour. Their maximum force values are achieved at a displacement which is 2.5 to 5 times higher than their thickness. Plywood and FRP, on the other hand, are relatively brittle materials and their maximum force values are achieved at displacement values close to their thickness.

In the following chapters, the results within the different material groups are discussed in more detail.

4.1 Plywood

The specific absorbed energy of the plywood specimens is compared in Figure.

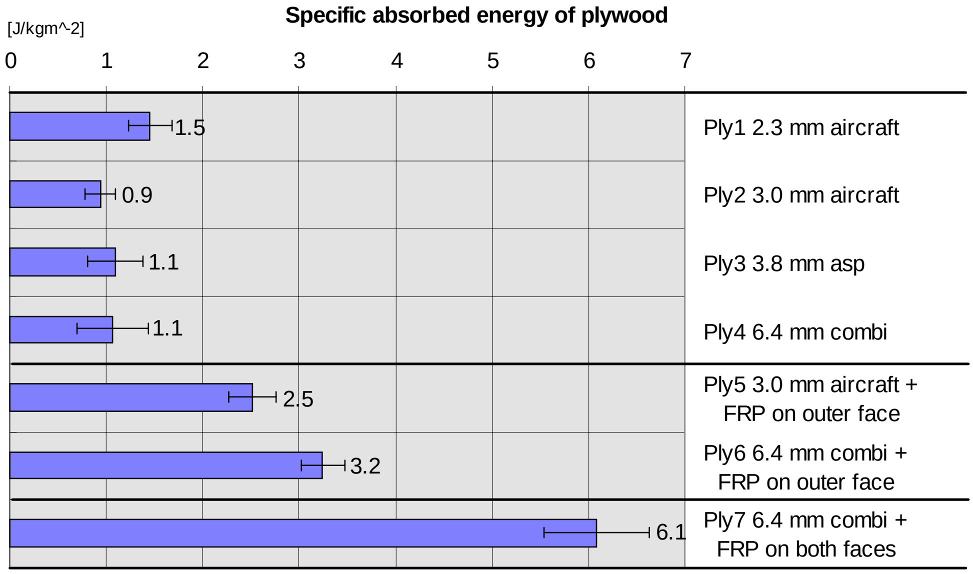

Figure 8. Mean values and standard deviation (error bars) of the specific absorbed energy of plywood specimens. Note that the last three specimens (Ply5-7) are reinforced with FRP.

An interesting observation is that asp (populus tremula) and combi (birch-softwood) plywood have the same specific impact strength. The difference between the 2.3-mm (5 plies) and the 3.0-mm (6 plies) aircraft plywood is remarkable. One possible reason for the relative weakness of the 3.0-mm type is that it has two plies with the same orientation on top of each other in the middle, whereas the ply orientation changes between each ply in the 2.3-mm type.

Coating the outer face with a thin FRP laminate (one layer of glass-epoxy) increases the specific impact strength by a factor of 2.7 and 2.9 for aircraft and combi plywood respectively, whereas coating both faces of the combi plywood with FRP increases the specific impact strength by a factor of 5.5.

4.2 FRP laminates

Figure 9 compares the specific absorbed energy of the FRP specimens.

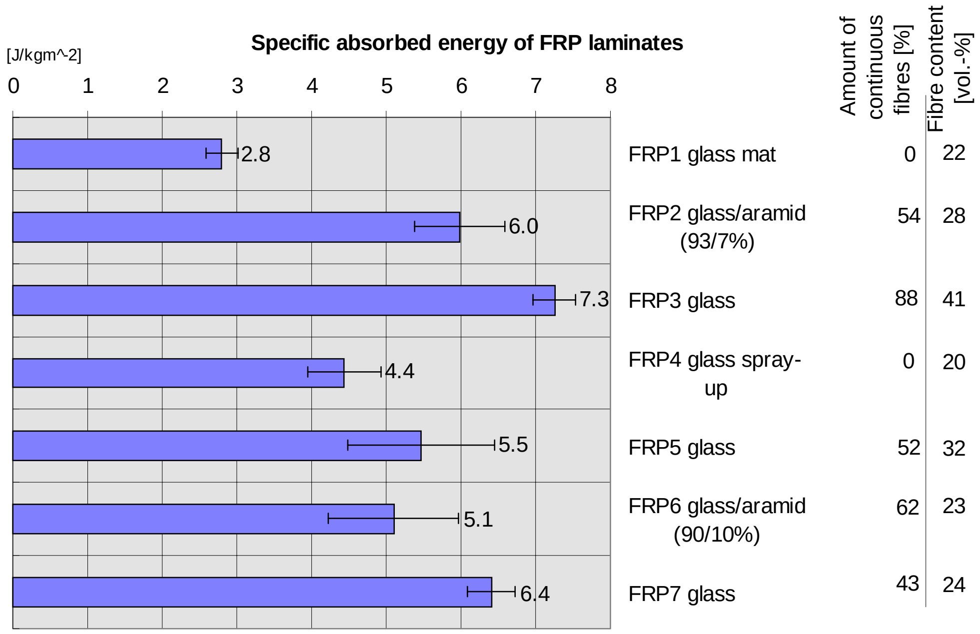

Figure 9. Mean values and standard deviation (error bars) of the specific absorbed energy of the FRP specimens. Note the considerable differences in fibre content and in amount of continuous fibres.

The large differences in specific impact strength shown in Figure 9 are partly due to differences in fibre content and amount of continuous fibres. All laminates are made of polyester resin.

It is not surprising that both a high fibre content and a high amount of continuous fibres produce higher specific impact strength values. This is illustrated in Figures 10 and 11.

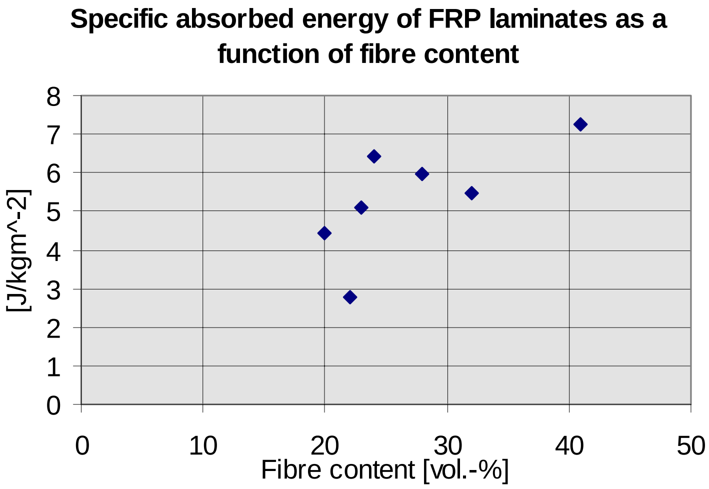

Figure 10. Specific absorbed energy as a function of fibre content.

Figure 10 shows that increasing the fibre content leads to an increase in specific impact strength. Note that there are substantial differences in the amount of continuous fibres (chopped strand mat vs. woven or stitched roving) within the laminates. The effect of the amount of continuous fibres on the specific impact strength is shown in Figure 11.

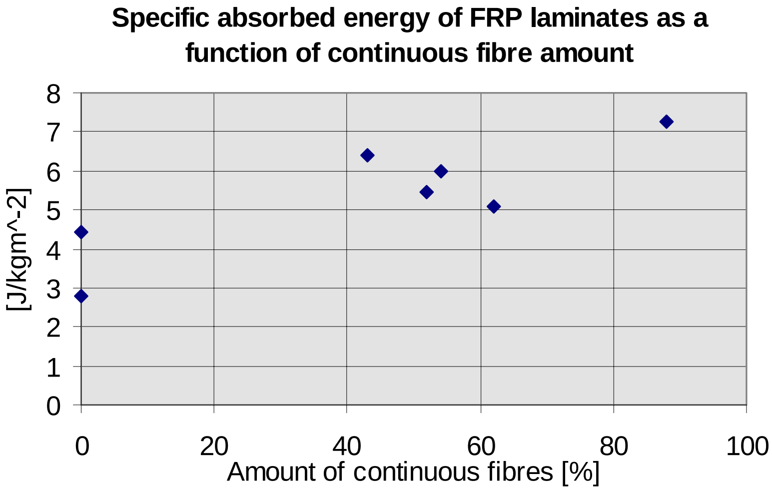

Figure 11. Specific absorbed energy as a function of continuous fibre amount.

The two parameters shown in Figures 10 and 11 explain partly the differences in specific impact strength between the laminates. There are, however, also other parameters to be considered, such as the reinforcement lay-up. It is interesting to compare laminates 5 and 7 which contain the same reinforcements, except that laminate 7 has more chopped strand mat layers in the middle, which creates a ‘mini-sandwich’ lay-up. Due to this configuration, the specific impact strength is increased by 16%.

4.3 Thermoplastics

Figure 12 compares the specific absorbed energy of the thermoplastic materials ABS, PE and PC.

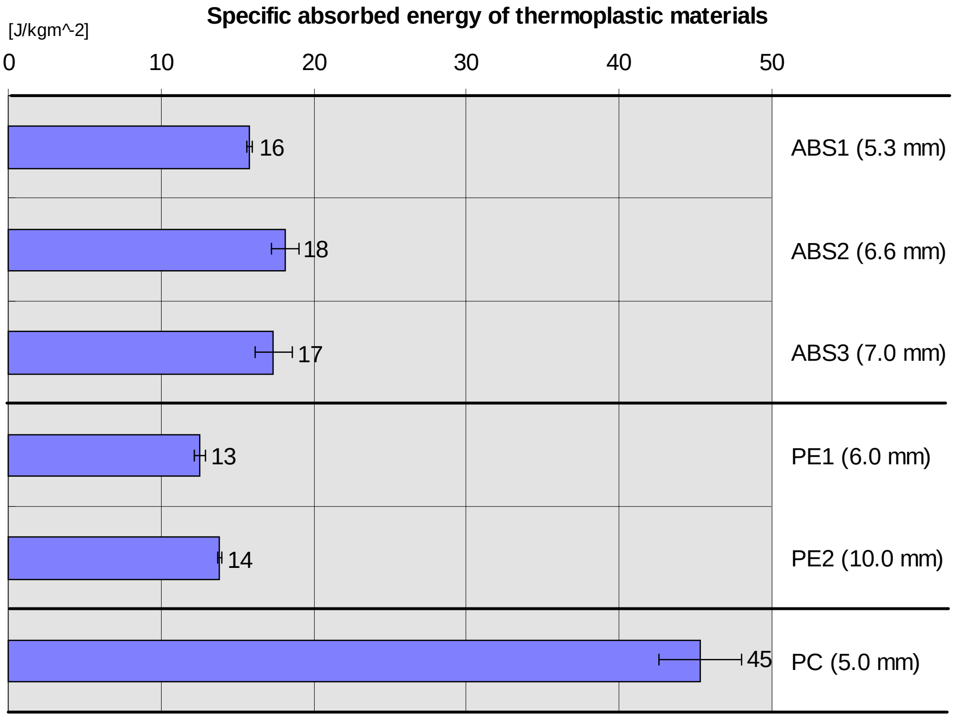

Figure 12. Mean values and standard deviation (error bars) of the specific absorbed energy values of the thermoplastic materials ABS, PE and PC.

The far higher specific impact strength of PC compared to ABS and PE is clearly shown in Figure 12. The specific impact strength of ABS is approximately 25% higher than that of PE and approximately 60% lower than that of PC.

The effect of the thickness on the specific impact strength of the ABS and PE specimens is negligible.

4.4 Aluminium

Figure 13 compares the specific absorbed energy of the aluminium specimens.

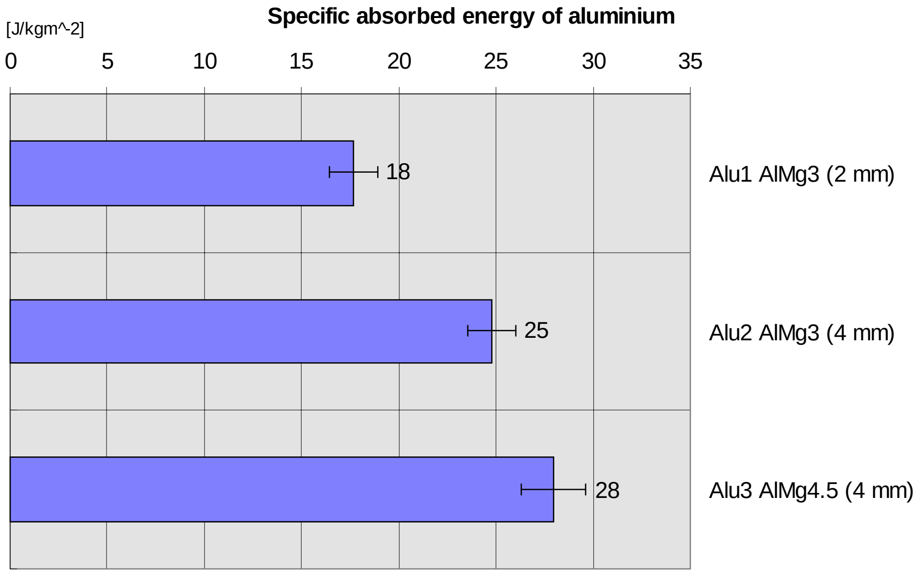

Figure 13. Mean values and standard deviation (error bars) of the specific absorbed energy values of the aluminium specimens.

The impact strength values of AlMg3 and AlMg4.5 provide interesting material for comparison. AlMg4.5 has a 12% higher impact strength. This difference is half of the difference in the respective breaking strength values (250 MPa vs. 310 MPa).

The effect of specimen thickness is considerable, as is evident when comparing the 2- and 4-mm thick AlMg3 specimens. The specific impact strength value of the 4-mm specimen is 39% higher than that of the 2-mm specimen.

5. Discussion

It has to be kept in mind that sufficient impact strength is not the only requirement governing the dimensioning of a boat hull. Other parameters, such as the flexural stiffness and strength of the hull panels, are usually in the foreground. These parameters depend on the panel thickness, the stiffener spacing and, naturally, the stiffness and strength values of the material.

Therefore, it is interesting to compare the impact strength results of the tested materials also with typical panel thickness values used in boat hulls. Table 3 shows a comparison of approximate hull bottom thickness values typically used in 4.5 m long motor boats with a maximum speed of 30 knots. The thickness values in Table 3 assume a dimensioning method corresponding to the Nordic Boat Standard [2].

Table 3. Corresponding hull bottom thickness values for different materials.

	Typical bottom panel thickness for a 4.5 m motor boat with a maximum speed of 30 knots [mm]
Plywood	9.0
FRP	4.7 - 5.9 (*)
ABS	5.3
PE	6.0
AlMg3	2.5

(*) 4.7 mm for a laminate containing chopped strand mat and woven roving, 5.9 mm for a spray-up laminate

6. Conclusions

Based on the present impact test series of 23 different specimens containing plywood, FRP, ABS, PE, PC and aluminium, the following conclusions can be drawn:

- The differences in impact strength between different materials are large, up to two decades for equal thickness.

- Because most boat structures are at least to some extent weight critical, it is more relevant to compare the specific impact strength values than the impact strength values in absolute terms.

- In terms of specific impact strength, the ranking of the different materials is as follows (as percentage of the strongest material):

    1. Polycarbonate (100%)
    2. Aluminium (40 - 62%)
    3. ABS (36 - 40%)
    4. PE (29 - 31%)
    5. FRP (6 - 16%)
    6. Plywood with FRP reinforcement (6 - 14%)
    7. Plywood (2 - 3%)

- The reason for the higher specific impact strength values of aluminium and the thermoplastic materials (PC, ABS and PE) is their high degree of plastic deformation: the maximum force values occur at displacement values between 2.5 and 5 times the thickness. Plywood and FRP are more brittle, achieving the maximum force levels at displacement values close to those of their thickness.

References

1 Hildebrand, M. 1996. Improving the impact strength of FRP-sandwich panels for ship applications. Espoo, Technical Research Centre of Finland, VTT Technical Report VAL B 138. 42 p.

2 Nordic Boat Standard. 1990. Recreational boats less than 15 metres. Helsinki, Merenkulkulaitos.

3 Nordic Boat Standard. 1990. Work boats less than 15 metres. Helsinki, Merenkulkulaitos.

4 ISO 6603/1-1985. Plastics - Determination of multiaxial impact behaviour of rigid plastics - Part 1: Falling dart method. 14 p.

5 ISO 6603/2-1989. Plastics - Determination of multiaxial impact behaviour of rigid plastics - Part 2: Instrumented puncture test. 12 p.

Appendix A: Tested materials

Specimen	Thickness [mm]	Remarks	
Plywood			
Ply1	2.3	Aircraft (birch, 5 plies) (*)	
Ply2	3.0	Aircraft (birch, 6 plies) (*)	
Ply3	3.8	Asp-plywood (populus tremula, 3 plies)	
Ply4	6.4	Combi (birch / softwood 3/2 plies à 1.4 mm)	
Ply5	4.0	Aircraft (6 plies) (*) + FRP (**) on outer face	
Ply6	7.0	Combi (5 plies as above) + FRP (**) on outer face	
Ply7	7.8	Combi (5 plies as above), + FRP (**) on both faces	
(*) grade III	(**) Reinforcement: 1 ply stitched E-glass, 318 g/m^2, ±45° to the plywood fibres, resin: West Systems epoxy 105/205		
FRP			*fibre content*
FRP1	2.6	Glass mat-polyester Lay-up: M300 / JM300 / M300 / JM300 / M225 /H30 Resin: Neste G300, hand lay-up	*22 vol.%*
FRP2	3.5	Glass/aramid (93%/7%)-polyester Lay-up: M450 / 9811/M300 / ±45(200+200) / 9811/M300 / 9811/M300 Resin: Neste F207TPE, hand lay-up	*28 vol.%*
FRP3	3.8	Glass-polyester Lay-up: M300 / DB400/100-E01 / DBLT1150-E01 / DBLT1150-E01 / DB800/M100-E01 Resin: Neste F207TPE, hand lay-up	*41 vol.%*
FRP4	6.9	Sprayed glass-polyester laminate Resin: Neste M105TB	*20 vol.%*
FRP5	7.1	Glass-polyester 2×CSM300 / 2×DBL800 / 8×CSM300 / 2×DBL800 Resin: Norpol 720-800, hand lay-up	*32 vol.%*
FRP6	7.7	Glass/aramid (90/10%)-polyester CSM225 / CSM450 / CSM450 / CSM300 / 900-0/90 / 900A-±45 / CSM225 / 900-0/90 Resin: Norpol 720-800 , hand lay-up	*23 vol.%*
FRP7	11.5	Glass-polyester 2×CSM300 - 2×DBL800 - 12×CSM300 -2×DBL800 Resin: Norpol 720-800, hand lay-up	*24 vol.%*

Specimen	Thickness [mm]	Remarks
ABS		
ABS1	5.3	
ABS2	6.6	
ABS3	7.0	
PE		
PE1	6.0	Simona PE-HWU
PE2	10.0	Simona PE-HWU
PC		
PC	5.0	
Aluminium		
Al1	2.0	AlMg3 H32
Al2	4.0	AlMg3 H32
Al3	4.0	AlMg4.5 H32

Appendix B: Test results

The test results are documented below. The maximum force (F) and absorbed energy (E) values are shown in the first two columns and the respective mean values (x), standard deviation (s), relative standard deviation (v) in the last columns.

Experimental results				Mean values	
F	E		**ABS1**	**F**	**E**
10151	86.0			**[N]**	**[J]**
10229	85.0		x	**10462**	**86.4**
10828	86.7		s	325	1.2
10641	87.8		v [%]	3	1
F	E		**ABS2**	**F**	**E**
13711	127.8			**[N]**	**[J]**
14272	118.3		x	**14087**	**120.7**
14277	115.9		s	325	6.3
			v [%]	2	5
F	E		**ABS3**	**F**	**E**
15311	128.8			**[N]**	**[J]**
15127	131.5		x	**14970**	**123.5**
14610	114.1		s	311	8.1
14831	119.5		v [%]	2	7
[N]	[J]		**Alu1**	**F**	**E**
F	E			**[N]**	**[J]**
17451	100.8		x	**17134**	**95.5**
17152	97.7		s	327	6.7
16798	88.0		v [%]	2	7
[N]	[J]		**Alu2**	**F**	**E**
F	E			**[N]**	**[J]**
36797	258.0		x	**36242**	**267.8**
36187	263.7		s	529	12.4
35743	281.7		v [%]	1	5
[N]	[J]		**Alu3**	**F**	**E**
F	E			**[N]**	**[J]**
46022	288.6		x	**46152**	**301.9**
46282	315.1		s	184	18.7
			v [%]	0	6

Experimental results				Mean values	
[N]	[J]		**FRP1**	**F**	**E**
F	E			**[N]**	**[J]**
4695	11.0		x	**4554**	**10.1**
4439	9.1		s	106	0.8
4537	10.3		v [%]	2	8
4544	10.0				
			FRP2	**F**	**E**
F	E			**[N]**	**[J]**
14652	30.4		x	**14568**	**33.4**
14968	33.6		s	362	3.4
14092	31.4		v [%]	2	10
14560	38.1				
			FRP3	**F**	**E**
F	E			**[N]**	**[J]**
21600	47.2		x	**21036**	**46.2**
21520	46.4		s	616	1.7
20645	47.5		v [%]	3	4
20377	43.7				
			FRP4	**F**	**E**
F	E			**[N]**	**[J]**
16137	45.1		x	**15332**	**40.3**
14875	38.7		s	1349	4.5
14472	39.0		v [%]	9	11
13921	34.3				
17253	44.3				
			FRP5	**F**	**E**
F	E			**[N]**	**[J]**
32243	54.7		x	**31215**	**61.8**
30856	58.1		s	1018	11.3
31746	81.9		v [%]	3	18
29626	57.5				
31604	57.0				
			FRP6	**F**	**E**
F	E			**[N]**	**[J]**
21305	46.1		x	**23210**	**56.1**
23283	52.3		s	2021	9.4
21498	58.4		v [%]	9	17
23661	52.8				
26304	71.1				
			FRP7	**F**	**E**
F	E			**[N]**	**[J]**
38139	108.2		x	**40539**	**108.3**
40386	105.3		s	2679	5.1
38855	102.8		v [%]	7	5
45015	116.2				
40300	109.2				

Experimental results				Mean values	
			PE1	**F**	**E**
F	E			**[N]**	**[J]**
8546	74.2		x	**8220**	**71.1**
8114	69.8		s	231	2.3
8207	71.4		v [%]	3	3
8014	68.9				
			PE2	**F**	**E**
F	E			**[N]**	**[J]**
13884	128.5		x	**14067**	**130.9**
14029	131.2		s	151	1.7
14244	132.5		v [%]	1	1
14111	131.4				
			PC	**F**	**E**
F	E			**[N]**	**[J]**
18123	251.6		x	**18517**	**263.4**
18910	275.2		s	556	16.7
			v [%]	3	6
			Ply1	**F**	**E**
F	E			**[N]**	**[J]**
828.7	2.7		x	**960**	**2.4**
843.3	2.9		s	114	0.4
1047	2.2		v [%]	12	16
1053	2.1				
1030	2.1				
			Ply2	**F**	**E**
F	E			**[N]**	**[J]**
1069	2.1		x	**1144**	**2.2**
1276	2.9		s	79	0.4
1126	1.9		v [%]	7	17
1148	2.0				
1102	2.2				
			Ply3	**F**	**E**
F	E			**[N]**	**[J]**
1252	2.4		x	**1211**	**2.3**
1187	2.26		s	235	0.6
1586	2.08		v [%]	19	27
985	1.6				
1047	3.3				

Experimental results				Mean values	
			Ply4	**F**	**E**
F	E			**[N]**	**[J]**
2859	3.5		x	**2605**	**4.4**
2257	2.9		s	236	1.5
2560	3.7		v [%]	9	35
2789	6.6				
2561	5.6				
			Ply5	**F**	**E**
F	E			**[N]**	**[J]**
3069	7.9		x	**3194**	**8.2**
3695	9.2		s	454	0.8
2622	7.5		v [%]	14	10
2967	8.9				
3616	7.4				
			Ply6	**F**	**E**
F	E			**[N]**	**[J]**
4690	16.8		x	**4627**	**16.2**
4371	14.4		s	271	1.2
4868	16.6		v [%]	6	7
4891	17.5				
4315	15.6				
			Ply7	**F**	**E**
F	E			**[N]**	**[J]**
9579	34.2		x	**8532**	**36.0**
8389	31.7		s	605	3.3
8382	37.0		v [%]	7	9
8302	40.4				
8010	36.6				