Energy absorption in sandwich laminate structures

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Abstract:

The significant result of this thesis is that the energy absorption of a sandwich laminate can be estimated using a simple spring force model. This means for a maritime vessel that the maximum survivable impact speed of the vessel can be estimated using nothing more than the speed of the craft and the mass ratio of the craft and the impactor. The calculation requires one to know the sandwich equivalent spring constant which is shown to be closely related to foam core shear and compressive modulus.

This thesis contains the development of a simplified model and an experimental test with data analysis of a slow non cutting impact. The test was performed on Divinycell foams of various grades and glass fibre laminates prepared with ATLAC AC300 vinyl ester. The experiments confirm with the data for compressive modulus at a rate of 90,5% statistical probability and shear modulus data at a rate of 88,34% that the simplified model is valid for the laminates tested.

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Tiivistelmä:

Tämän opinnäytetyön ratkaiseva tulos on, että sandwich laminaatin kyky sitoa energiaa voidaan ennakoida käyttämällä yksinkertaistettua jousivoiman matemaattista mallia. Tämä tarkoittaa vesiajoneuvon kannalta sitä, että sen suurin sallittu törmäysnopeus voidaan arvoida käyttämällä ainoastaan sen nopeutta ja ajoneuvon, sekä törmättävän esineen massakerrointa. Laskutoimitusta varten on tiedettävä laminaatin vastaava jousivakio, jonka osoitetaan tässä lopputyössä olevan läheisessä yhteydessä vaahtosydämen leikkaus- ja puristuskimmokertoimen kanssa. Tässä lopputyössä on esitelty yksinkertainen malli- ja koeosuus leikkaamattomasti läpäisevästä törmäyksestä data-analyysillä. Kokeet tehtiin erilaatuisilla Divinycell vaahdoilla ja lasikuitu laminaateilla, sekä ATLAC AC300 vinyyliesterillä. Kokeet vahvistavat yhteyden 90,5% varmuudella puristuskimmokertoimen kanssa, sekä 88,34% varmuudella leikkauskimmokertoimen kanssa.

Avainsanat:	Sandwich laminaatti, komposiitti, energian imeytyminen
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FOREWORD

The practical lamination and testing work for this thesis was conducted at ARCADA laboratory in the spring of 2010 by the author and thesis supervisor Rene Herrman.

The author wishes to thank Mr Herrman for his support during the thesis writing process.

1 INTRODUCTION AND OBJECTIVES

The focus of this thesis is the energy absorption of a slow, non cutting impact that simulates a collision at sea. With the results of the tests and application of a simplified momentum model it is possible to predict the necessary sandwich laminate energy absorption for the hull of a watercraft of a certain intended mass and speed.

This thesis applies the equations for kinetic energy and Hooke's law to determine the necessary thickness of the sandwich laminate needed for the hull to survive impact. The assumption being that the laminate behaves like a spring up until the point of skin rupture.

The objectives of this thesis are

1) Develop a mathematical model that would predict the behaviour of the sandwich laminates and to prove the model works to a reasonable degree.
2) Show that the results from the energy absorption abilities of the foams correlate with the stated compressive modulus and shear modulus values for each foam core.

2 LITERATURE SURVEY

2.1 COMPOSITES AND THEIR BEHAVIOUR

Due to the nature of composite structures defining energy absorption abilities for composites is different from structures made from traditional homogenous materials. (Saarela, O. Airasmaa, I. Kokko, J. Skrifvars, M. Komppa, V. 2003)

Although the principle behind composite structures is to combine the benefits from two distinct materials they also suffer from weaknesses related to both or all the materials included in the composite structure. Defects and flaws may originate in any of the individual components of the composite, in their interface or in the way the matrix and reinforcement components are distributed in the structure by producing areas with either too much resin or not enough resin. In addition, manufacturing conditions play a role in the integrity of the final composite structure. Moisture, various chemicals etc. can affect the coupling of the fibres and resin. Scratching the fibres may lead to unexpected failure. It is also important to understand that design features such as joints, holes, ply drops in laminates etc. can contribute to failure. When a failure occurs it is always due to an accumulation or combination of various sorts of damage such as instantaneous, impact type to creep or slow crack propagation and fatigue. (Ezrin, Myer, 1996).

2.2 MATHEMATICAL MODEL

Since the parameters in focus in this thesis work are the relation of the boats speed and mass to the amount of energy its hull needs to absorb without penetration during a collision it is necessary to start from the equation of kinetic energy of a moving body (I.S. Grant, W.R. Phillips 2001).

$$E_k = \frac{1}{2} m v_o^2 = E_0$$

Equation 1: Kinetic energy of a moving body

When the boat collides with the object, momentum is converted to velocity v_1 through the following function (I.S. Grant, W.R. Phillips 2001):

$$v_1 = \frac{m_0}{m_0 + m_1} * v_0$$

Equation 2: Conversion of momentum during collision

By inserting the v_1 value into the kinetic energy equation with the new mass of both the boat and the collided object it is possible to determine the kinetic energy after collision.

$$E_1 = \frac{1}{2}\, m_0\, v_1^2$$

Equation 3: Kinetic energy after collision

The change in energy ($\Delta E = E_0 - E_1$) can be found to be:

$$\Delta E = \frac{1}{2}\, m_0 \left(v_0^2 - \left(\frac{m_0}{m_0 +\ m_1}\right)^2 v_0^2 \right) = \frac{1}{2} m_0 v_0^2 (1 - \left(\frac{m_0}{m_0 +\ m_1}\right)^2)$$

Equation 4: Change in energy

The amount of energy absorbed by the composite can be found by integrating the force over distance. Here k is the equivalent spring constant describing the elastic part of the energy absorption before the fibres start to absorb the energy by rupturing. It can be seen as the slope of force over distance needed to penetrate the sandwich. Small x is used to denote the total displacement of the collision into the sandwich laminate (I.S. Grant, W.R. Phillips 2001).

$$\Delta E = W = \int F\, ds = \frac{1}{2} k x^2$$

Equation 5: Integrating force over distance

Since the change in energy is known the equation can be seen as:

$$k = \left(\frac{\Delta E}{x^2}\right) * 2$$

Equation 6: solving for constant

Or when solving for the displacement of the collision into the foam:

$$x = \sqrt{\frac{(\Delta E * 2)}{k}}$$

Equation 7: Solving for displacement

In the above equation x max is the full thickness of the laminate, k a constant, ΔE is dependent on m_1, m_o and v_0. Equation 8 is relevant when determining the maximum allowable speed of the watercraft since v_o is the only variable that can be affected when the boat is at sea.

$$v_o = \sqrt{\frac{2 * \Delta E}{m_o * \left(1 - \left(\frac{1}{1+z}\right)^2\right)}}$$

Equation 8: Solving for maximum allowable speed

2.3 Three-point-bending

In order to produce a total penetration the sandwich laminates were place on top of a cylindrical object as can be seen in Figure 5 with a of 76,5mm diameter hole that would allow for the steel balls to be pushed through the laminate. This method attempts to avoid three-point-bending. Figure 1 shows how forces act on a test piece in three point bending.

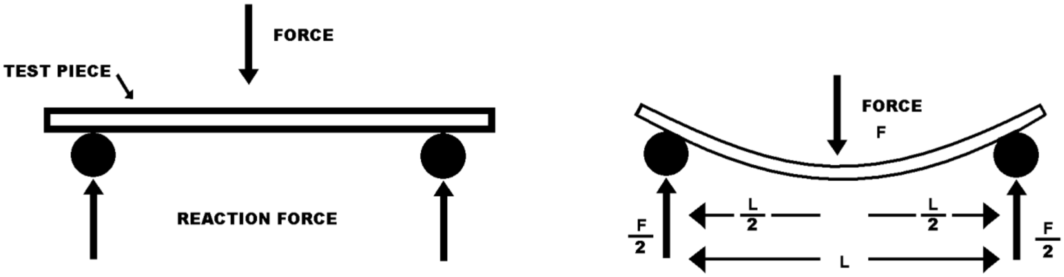


Figure 1: Sketch of three point bending

When three point bending is introduced into the test process it allows the structure to flex over an area that is larger than the ball used for testing (Deflection of beams 2010) and would affect the results obtained. Figure 5 shows the test setup at ARCADA lab.

3 METHOD

In the practical experiment done for this thesis the materials used have been: bi-axial -45/45 E-glass 300 fibre 430g/m^3, Atlac 580 AC 300 vinyl ester (tensile strength 78MPa) and 7 different types of 10 mm thick Divinycell foam (DIAB). Figure 2 shows a schematic of a foam core sandwich laminate. On top and bottom are the fibre and resin skins and in between them is the foam core.

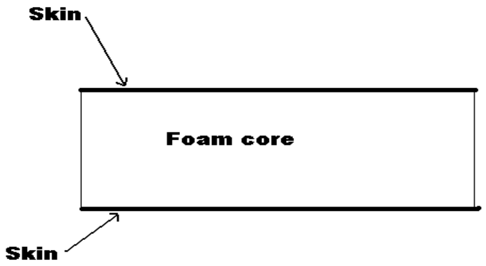


Figure 2: Schematic of a foam core sandwich laminate

3.1 Foam cores

Seven different foam cores were used in the laminates. The foam cores differed in material composition with the cores denoted by P being recyclable. Cores denoted by H have a high strength to density ratio and are widely used in various applications including marine applications (APPENDIX 1).

Table 1: Foam core properties

Material	**Tensile strength MPa**	**Compressive strength MPa**
H250	9,2	6,2
H100	3,5	2,0
H80GS (grid-scored)	2,5	1,4
P150	2,45	2,30
H60	1,8	0,9
H45GS (grid-scored)	1,4	0,6
P60	1,10	0,55

The actual laminates were formed by applying four layers of glass on top of the foam core and four layers on the bottom. Figure 3 shows H45GS foam core with grooves to assist resin flow. These grooves will affect the compressive strength of the foam due to added resin columns. Some foam cores used in this test had grooves cut right through the foam. When laminated, the resin will form a column between the top and bottom skin affecting compressive strength of the structure. All the laminates were laminated with bi-axial -45/45 E-glass fibre 430g/, Atlac 580 AC 300 vinyl ester.

Figure 3: Divinycell H45GS foam core before lamination

Vacuum infusion was used as the construction method of the sandwich laminates. A vacuum of -0.8 Bar was used during the one shot infusion of all of the foam cores simultaneously resulting in a uniform laminate. In Figure 4 the vacuum line can be seen at the top left of the image.

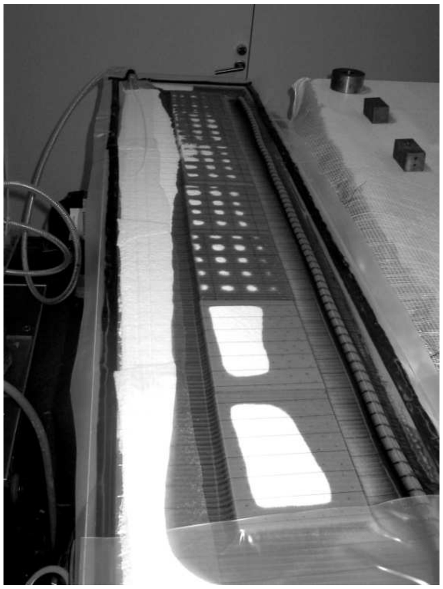


Figure 4: Vacuum infusion of cores

The foam cores are lined up on top of a glass plate with the glass fibres wrapped around. Resin injection line can be seen to the right of the glass plate. After infusion the laminates were cut to size so that they can be subjected to force tests on the Testometric machine at the ARCADA lab.

Figure 5: Test setup at ARCADA lab

Figure 5 shows the testometric machine with the metal sphere at the end of a conical die that was pushed into the sandwich laminates. The cylindrical holder for the sandwich laminates can be seen at the base of the machine

Figure 6 shows the edge of one of the laminates that were cut to size. It was decided that it was unlikely that the peel ply affected the results significantly and so it was left on the laminates.

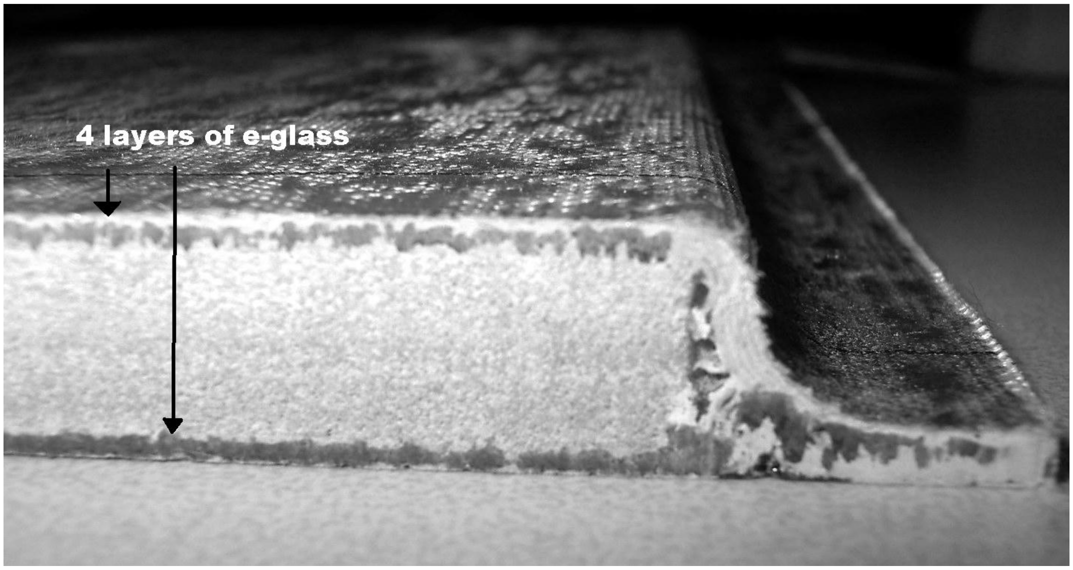


Figure 6: Edge detail of H100 foam core sandwich laminate

3.2 Energy absorption in recreational water craft

Buster X and Nautor Swan 60 models were chosen as representatives of totally different types of recreational boat.

The Buster X is made from aluminium and is a planning hull motorboat with a maximum weight with a Honda 75 Hp outboard engine of 1168kg. (APPENDIX 2), (Honda BF75 Outboard Engine – 75 hp boat motor specs and features 2010). Both boats are manufactured in Finland.

Nautor Swan 60 is a sailing yacht with a mass of almost 20 000 kg (Technical Details Swan 60 2010).

Figure 7 shows the respective kinetic energies of both boats at various speeds in knots on a logarithmic scale. It is notable that for the Swan sailboat speeds beyond 25 knots will not be achieved under normal operation due to the fact that it is a semi displacement hull and has a maximum speed relating to the hull length.

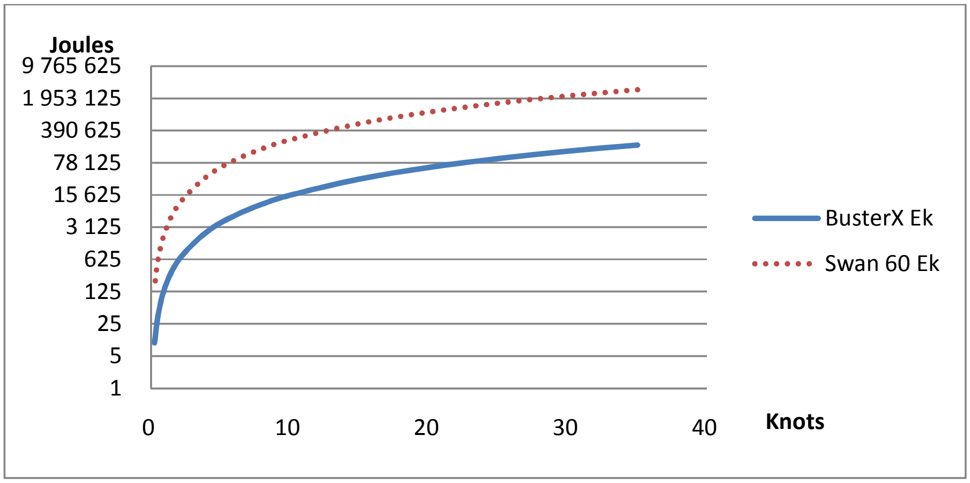


Figure 7: Kinetic energies (Ek) of Swan and BusterX

3.3 Sea Containers as colliding objects

Sea containers were chosen as the colliding object. These range from less than 20 000 kg to around 40 000 kg masses when fully laden. (Dimensions Of Sea Containers 2010)

Figure 8 uses Equation 7: Solving for displacement to determine the effective deflection a roughly 24000 kg sea container would cause in theory to P60 foam core if it were used as the hull material of either a Swan or a Buster boat. The graph implies at the necessary thickness required to survive the collision.

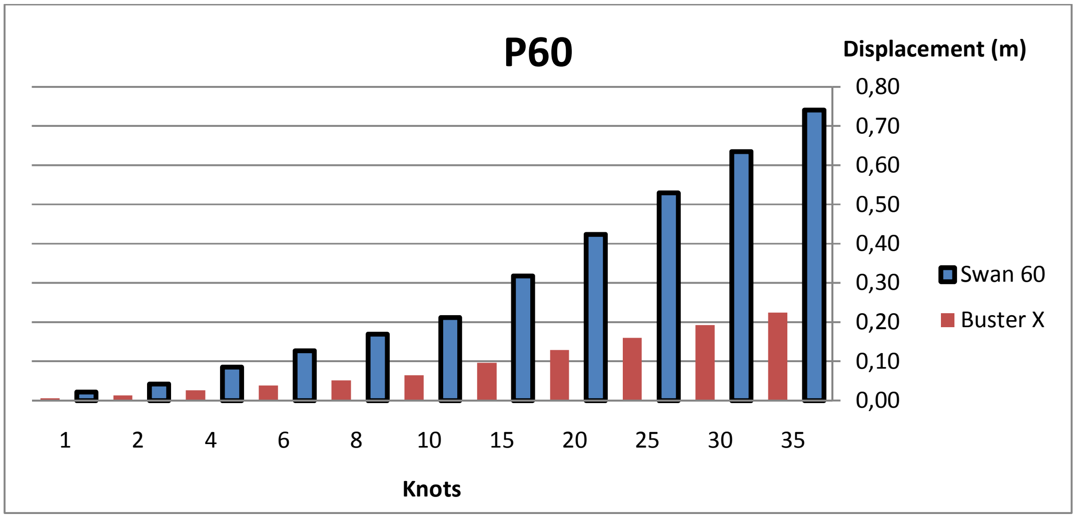


Figure 8: Displacement of collision in P60 foam core

4 RESULTS

Each foam core laminate was cut out with a band saw from the one shot laminate structure. They were then subjected to a destructive force test on the Testometric machine at ARCADA engineering lab. The range of the machine is from 4,00N to 5000N with a load Cell / Amplification of 500kgf. (Calibration Certificate 2007, Testometric materials testing machines)

The 21mm diameter sphere did not manage to penetrate any of the laminates so the results are included only for the 13,5mm sphere penetration tests. In this case penetration was achieved in all laminates except with H250 foam core.

4.1 Equivalent model

It is necessary to understand what is happening to the sandwich laminate during the application of force. Figure 9 shows the force distribution in P60 foam sandwich laminate as the sphere penetrates through the laminate. The model graphed in Figure 9 can be applied to all laminates with the exception of H60 where it was not possible to determine the force redistribution point without reasonable doubt.

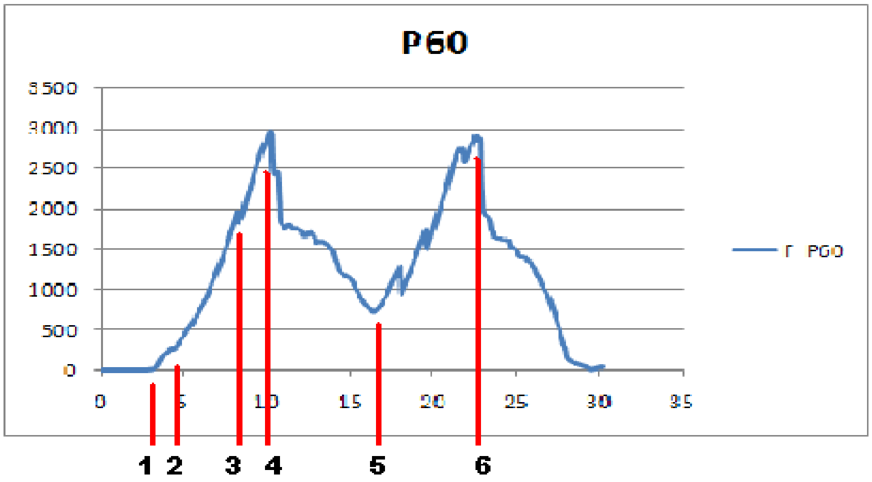
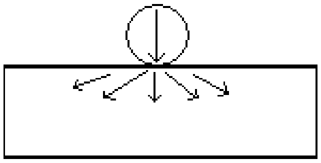


Figure 9: Critical points during testing of P60 foam core sandwich laminate

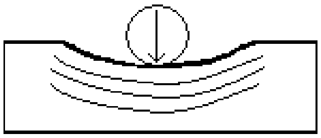
The stages in Figure 9 are:

1.



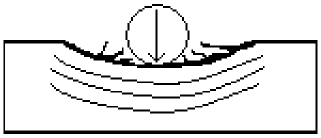
In the first stage the force is taken up by the whole laminate structure which goes into compression as the top skin stiffness distributes the force.

2.



The second point is the end of the saddle, where the top skin no longer absorbs the force but is now beginning to bend and the force is distributed into the foam core, which is in compression during stages 2 and 3.

3.



Force redistribution point. Small notches in the graph indicate fibre delamination in the top skin and foam interface.

4.

End of elastic deformation means that the foam core is no longer elastically absorbing the force. From this point on the core is plastically damaged. The surface skin has suffered delamination and the core will suffer water damage from this point onwards.

5.

At this point the load is now absorbed by the bottom skin. As the graph progresses, notches denote fibre delamination in the same way as after point 3. The hull can no longer be considered watertight.

6.

The end of the lower surface deformation. The die used for the test has now fully penetrated the sandwich laminate.

The notable portion of Figure 9 is between stages 2 and 4 where a relatively straight line can be seen. This is the portion that indicates that the behaviour of the sandwich laminate follows the behaviour of a simplified spring constant.

The following figures (Figure 10 to Figure 16) illustrate portions between point 2 and point 4 of the same graph as in Figure 9.

A trend line has been calculated with the r^2 value displayed. The r^2 value describes how closely the trend line follows the chart data. A value of 1 would mean a perfect relationship. Visible in the charts is also the y value or slope of the line. This slope can be related to the modulus of the foam core as the k value. The unit of this value is N/mm due to data scale. It is notable that this is the same data as used in Figure 9 and Figure 17 but with fewer data points. The graphs have been corrected to start from the end of the saddle point at the x-axis.

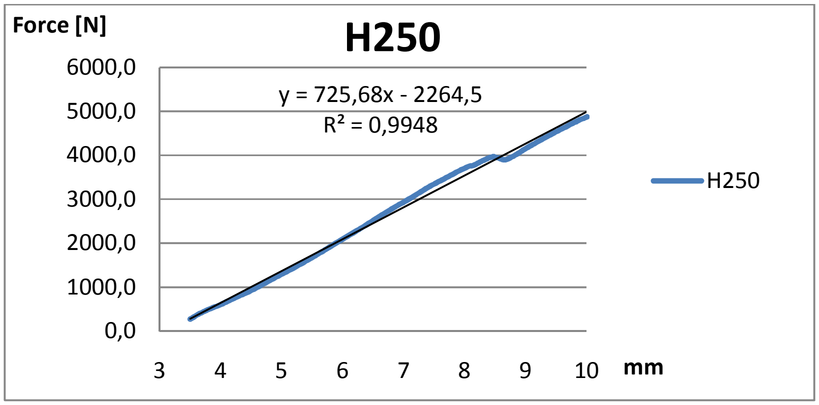


Figure 10: H250 laminate with y = 725,68 at an occurrence rate of 99,48%

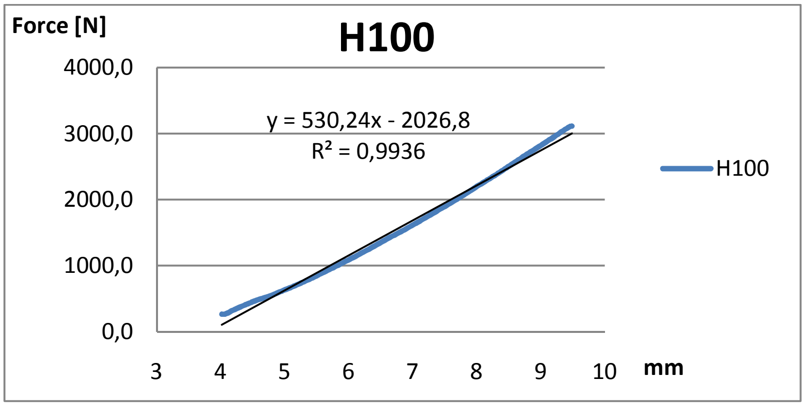


Figure 11: H100 laminate with y = 530,24 at an occurrence rate of 99,36%.

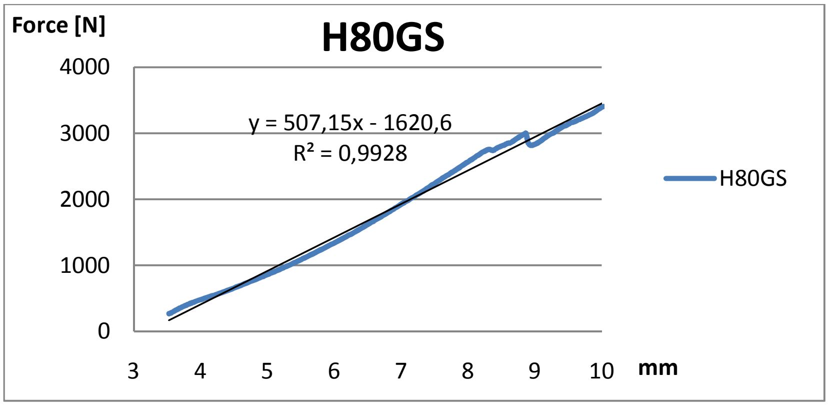


Figure 12: H80GS laminate with y = 507,15 at an occurrence rate of 99,28%

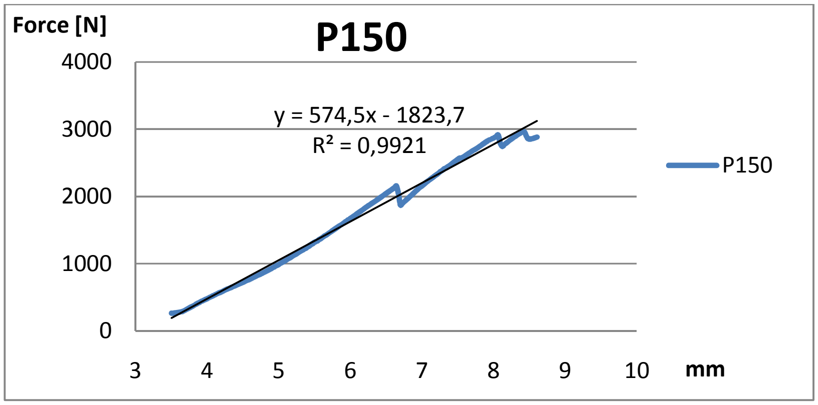


Figure 13: P150 laminate with y = 574,5 at an occurrence rate of 99,21%

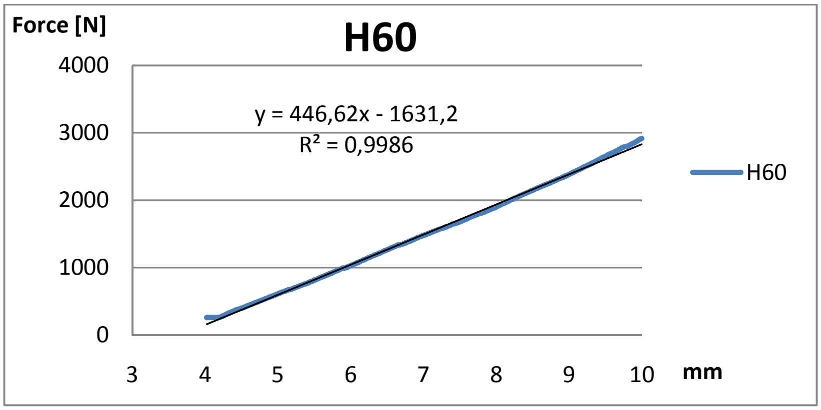


Figure 14: H60 laminate with y = 446,62 at an occurrence rate of 99,86%

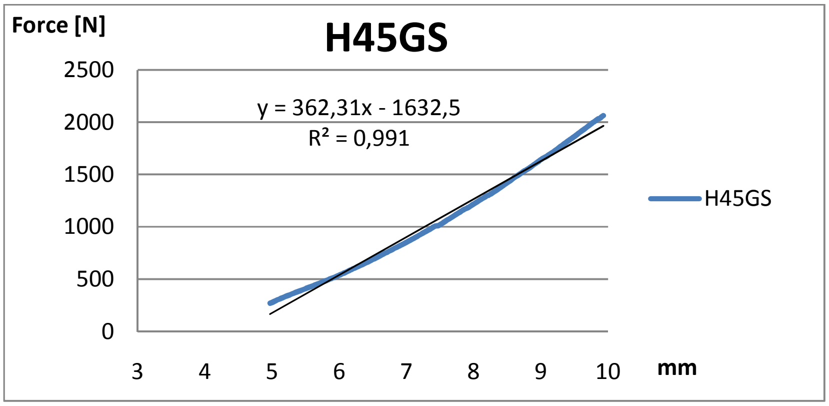


Figure 15: H45GS laminate with y = 362,31 at an occurrence rate of 99,1%

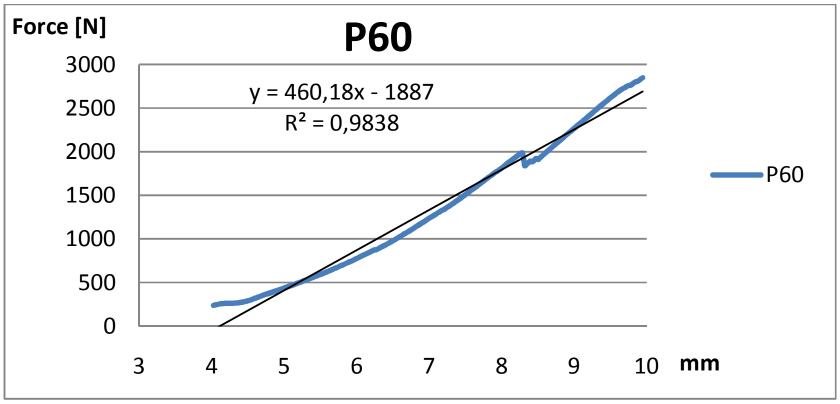


Figure 16: P60 laminate with y = 460,18 at an occurrence rate of 98,38%

Figures 10 to 16 show that between the saddle point and the end of elastic deformation point the force distribution over distance forms in almost 99% of the cases a straight line. The exception is P60 laminate, with 98% rate. This makes it reasonable to assume that a simple spring model can be used in determining the performance of these foam cores in a collision situation.

4.2 Comparison of laminates

Below is a graph of the force over distance distribution of all the laminates. It is notable that the data for H250 is not complete due to the inability to fully penetrate the laminate. What is visible, however, is that the force distribution curves are similar between all the laminates with the aforementioned H250 as an exception

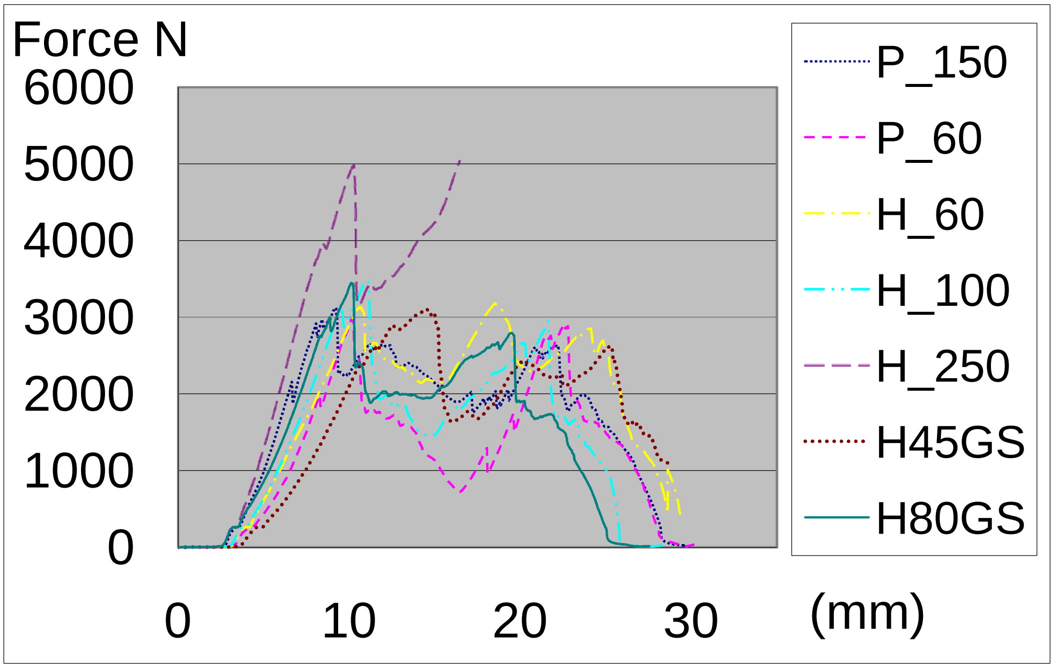


Figure 17: Force distribution of sandwich laminates

This can be seen as confirmation that the laminates behave in a similar way regardless of the type of foam core used in them. Importantly, it is visible that the graphs of all laminates contain a straight line from the end of the saddle until the force redistribution point. Confirmation that it is reasonable to use a simplified model for a spring constant to describe the behaviour of a sandwich laminate can be seen from Figure 10 to Figure 16.

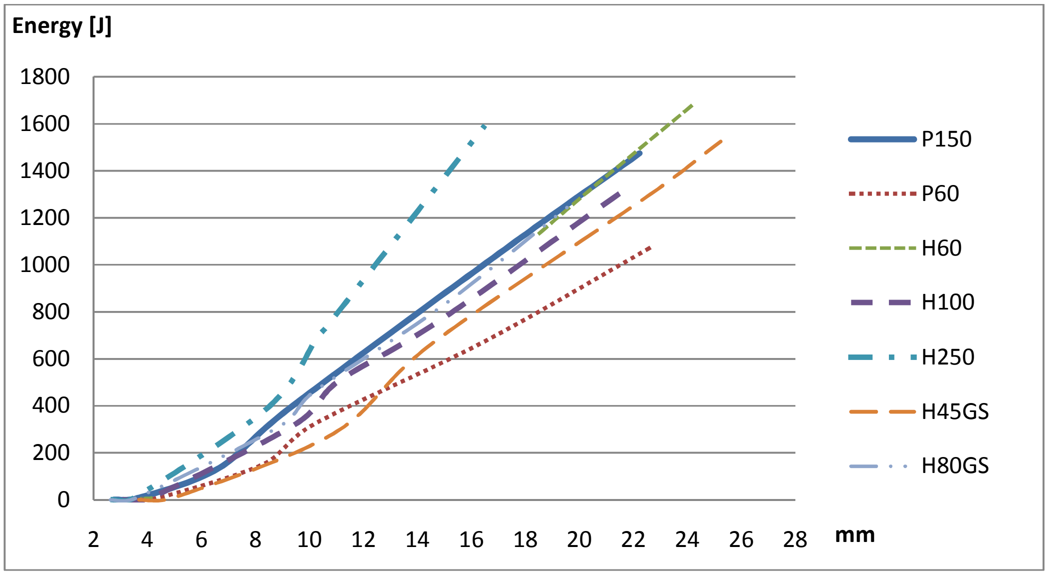


Figure 18: Energy absorption of laminates

Figure 18 displays the amount of energy absorbed by each laminate as the ball is pushed through during the testing. In this graph it is notable that the values for y-axis are in thousandth of Joule. It is also notable that the distance exceeds well beyond the 10 mm average thickness of the laminates. This is due to the fact that the ball was allowed to go through the laminate instead of the laminate being held on a solid surface. Thus the laminate has the ability to keep absorbing energy until the ball has penetrated right through the laminate (see Figure 5 for the test setup).

Table 2: Energy absorbed by laminates during penetration test

		Start	**1st. Saddle**	**Force redist. point**	**end of elastic def.**	**Inner surf. start**	**Inner surf. end**
P150	s (mm)	2,76	3,64	6,65	9,23	17,23	22,22
	E (J)	559	6 945	134 228	387 031	1 065 868	1 473 994
P60	s (mm)	3,23	4,40	8,29	10,16	16,46	22,57
	E (J)	502	8 097	151 797	321 746	672 591	1 070 065
H60	s (mm)	3,19	4,16		18,52	20,67	24,13
	E (J)	533	7 113		1 134 867	1 345 917	1 674 897
H100	s (mm)	3,08	4,07	9,49	11,02	14,85	21,64
	E (J)	494	7 110	323 377	500 977	765 856	1 317 281
H250	s (mm)	2,72	3,47	8,48	10,28	10,62	16,44
	E (J)	518	6 005	395 008	692 730	735 117	1 584 810
H45GS	s (mm)	3,69	4,97	10,87	14,54	22,66	25,23
	E (J)	646	9 525	281 484	664 938	1 302 623	1 524 865
H80GS	s (mm)	2,62	3,56	8,87	10,16	14,88	19,54
	E (J)	518	7 268	311 852	459 571	821 548	1 244 002

Table 2 displays the data used for drawing the graphs shown from Figure 10 to Figure 16. It is notable that E stands for energy and the values are in thousandth of a Joule. The values for inner surface start and end for H250 laminate are in yellow due to the inability to fully penetrate the laminate.

5 ANALYSIS

As shown in Figure 17, the force distribution in the laminates is rather straight until the end of the elastic deformation stage (stage 4). This would imply that these laminates behave in a spring like fashion to a certain measureable point.

Although Figure 8 would imply that a thickness of over 40 cm of P60 foam core is needed for a Swan 60 to survive a collision with a 24000 kg container at 20 knots speed it is not necessarily the case in practice due to the actual amount of reinforcement material used. The graph in Figure 8 is based on the P60 foam compression strength value from DIAB datasheet (APPENDIX 1)

Figure 19 shows the relationship between the manufacturers stated compression and shear modulus values and the k –value derived from the actual tensile test of the laminates (Figure 10 to Figure 16). The graph for compressive modulus occurs at a rate of 90,5%. In the case of shear modulus the rate of occurrence is 88,34%.

It is evident that most of the datasheet values correlate with the y-slope (k-value) from the actual tests. There are a few exceptions however: H45GS, P60 and H80GS respectively.

It would be reasonable to expect better performance from foams that have grooves in them or even cuts through them due to their ability to hold more resin and especially when the resin connects both top and bottom skins. The data would imply such performance for H80GS and P60 but not so for H45GS. It is notable that the die used for the penetration is smaller than the individual foam squares formed by the cuts and grooves so the full benefit of the interconnection of the laminates might not be reached in this test.

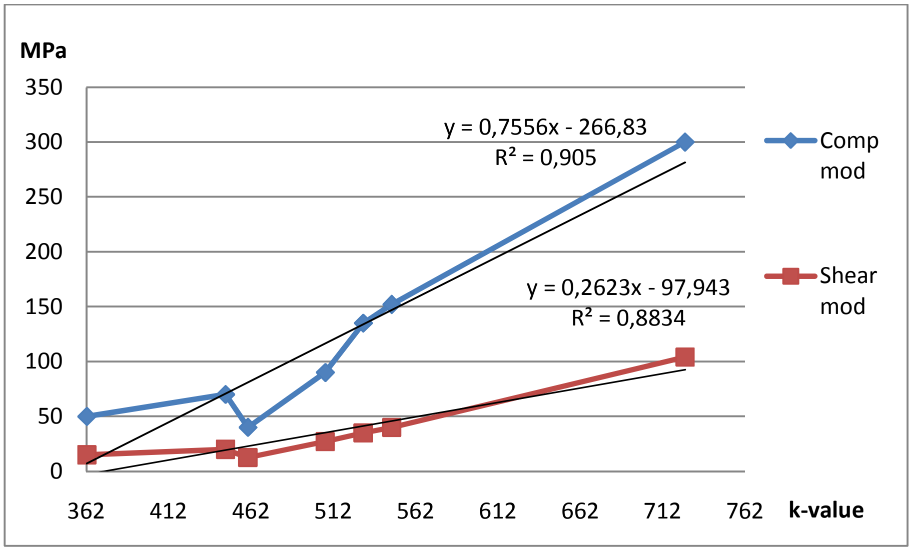


Figure 19: Compressive and Shear modulus of laminates

5.1 Practical application

In order for the work to have practical meaning it should be possible to determine the maximum allowable speed of the vessel.

$$v_o = \sqrt{\frac{2 * \Delta E}{m_o * \left(1 - \left(\frac{1}{1+z}\right)^2\right)}}$$

Equation 9: Solving for maximum allowable speed

In the above equation: v_o denotes the maximum allowable speed for the vessel in question, the z value is a mass ratio:

$$z = \frac{m_1}{m_o}$$

Equation 10: Mass ratio

5.1.1 Buster and Nautor Swan at sea

In a hypothetical situation where the captain of a Buster X would have reason to expect to encounter sea containers of 23956kg mass they would calculate according to Hooke's law for potential stored energy:

$$\Delta E = \frac{1}{2} * k * x^2$$

The data used in this thesis needs to be normalised for k in the following way:

$$k = y - value\ from\ tests\ * 1000 * (x * 100)$$

11: Normalising k-value

Here k is the y –value taken from the graphs of Figure 10 to Figure 16 and multiplied with 1000 to correct for scale. The thickness of the foam in metres is denoted by x times 100 to get a multiplier assuming the foams behave in the same way regardless of thickness.

This value is then used in the final formula to produce the maximum allowable speed for the water craft before the foam core reaches the end of elastic deformation (Equation 9), which in all practical sense means a breach of the hull.

Below are two tables that illustrate the calculation and result for maximum allowable speed for both Buster X and Nautor Swan boats when colliding with a sea container in the hypothetical case where the boats would be made of the same laminates as tested in this thesis.

Table 3: Maximum allowable speed for Buster X with tested laminates

	H250	**P150**	**H100**	**H80GS**	**P60**	**H60**	**H45GS**
k	725,68	547,50	530,24	507,15	460,18	446,62	362,31
k*(x*100)*1000	725 680,00	547 500,00	530 240,00	507 150,00	460 180,00	446 620,00	362 310,00
ΔE	36,28	27,38	26,51	25,36	23,01	22,33	18,12
m/s	**0,26**	**0,22**	**0,22**	**0,21**	**0,20**	**0,20**	**0,18**

Table 4: Maximum allowable speed for Nautor Swan with tested laminates

	H250	**P150**	**H100**	**H80GS**	**P60**	**H60**	**H45GS**
k	725,68	547,50	530,24	507,15	460,18	446,62	362,31
k*(x*100)*1000	725 680,00	547 500,00	530 240,00	507 150,00	460 180,00	446 620,00	362 310,00
ΔE	36,28	27,38	26,51	25,36	23,01	22,33	18,12
m/s	**0,08**	**0,07**	**0,07**	**0,07**	**0,07**	**0,07**	**0,06**

In Table 3 the values for Buster X are as follows:

$$m_o = 1168\ (kg)$$

$$m_1 = 23956\ (kg)$$

$$x = 0{,}01\ (m)$$

In Table 4 the values for Nautor Swan are as follows:

$$m_o = 18700\ (kg)$$

$$m_1 = 23956\ (kg)$$

$$x = 0{,}01\ (m)$$

The maximum allowable speed for the vessels differs rather due to the difference in masses. The Nautor Swan at almost 20 000 kg would impart a lot more energy for the laminate hull to absorb during a collision and has lower maximum allowable speeds as a result.

A secondary calculation was done to see what the figures would look like if the mass of the colliding object was lesser and the hull thicknesses larger.

A Buster X was chosen to be the colliding object (m_1) and the hull thickness (x) as 0,04 m (four times the thickness of the tested laminates).

Table 5: Buster X colliding with Buster X

	H250	P150	H100	H80GS	P60	H60	H45GS
k	725,68	547,50	530,24	507,15	460,18	446,62	362,31
k*(x*100)*1000	2 902 720,00	2 190 000,00	2 120 960,00	2 028 600,00	1 840 720,00	1 786 480,00	1 449 240,00
ΔE	2 322,18	1 752,00	1 696,77	1 622,88	1 472,58	1 429,18	1 159,39
m/s	**2,82**	**2,45**	**2,41**	**2,36**	**2,25**	**2,21**	**1,99**

Table 6: Nautor Swan colliding with Buster X

	H250	P150	H100	H80GS	P60	H60	H45GS
k	725,68	547,50	530,24	507,15	460,18	446,62	362,31
k*(x*100)*1000	2 902 720,00	2 190 000,00	2 120 960,00	2 028 600,00	1 840 720,00	1 786 480,00	1 449 240,00
ΔE	2 322,18	1 752,00	1 696,77	1 622,88	1 472,58	1 429,18	1 159,39
m/s	**2,06**	**1,79**	**1,76**	**1,72**	**1,64**	**1,61**	**1,45**

With a thicker hull and a lighter object to collide with both boats have higher allowable maximum speeds for all laminates.

In Table 3 the values for Buster X are as follows:

$$m_o = 1168\ (kg)$$

$$m_1 = 1168\ (kg)$$

$$x = 0{,}04\ (m)$$

In Table 4 the values for Nautor Swan are as follows:

$$m_o = 18700\ (kg)$$

$$m_1 = 1168\ (kg)$$

$$x = 0{,}04\ (m)$$

6 DISCUSSION

To relate the formulation and the results of the calculations to the actual tests made on the completed sandwich laminates it is important to realise the difference in the structural properties of a composite laminate and the foam. In the composite laminate the purpose of the fibre reinforcement is to distribute the force over a large area in order to create a strong structure. The matrix resin has a certain compression strength and the fibres will react differently once delamination occurs. What this means is that the performance of the laminate in a collision situation will change depending on the type of reinforcement, the resin and the way the laminate has been manufactured. This means that these results are not directly applicable as such on any given laminate. It is advisable to conduct a test run on a laminate made out of the intended materials for calibration purposes.

The laminates studied in this thesis had four layers of glass fibre on each side of the foam core. All tests were conducted in room temperature. A future study should determine how the sandwich laminates behave with different reinforcement and matrix materials and at different temperatures. This could be done either as a separate thesis work or as coursework by students.

Some of the foam cores had grooves and cuts in them e.g. to make it easier to wrap the foam onto a curved form and for the final structure to hold more resin. Especially when a cut or groove extends through the foam connecting the top and bottom skin the compression properties of the laminate change when compared to a smooth surfaced foam core of the same foam material. This increases the mass of the completed structure. How this affects performance is only inferred by some of the data collected by this thesis but not studied in depth.

For maritime application, tests that simulate a cutting, glancing collision as when the boat hits a submerged rock or an iceberg could be advisable to produce information on how the foam and fibre laminates behave.

It is notable that so far there are few reliable ways to pre-determine the final strength of a composite laminate in a way that would allow for estimates between varying amounts of fibre layers. The manufacturing nature of composite structures is one major influence in this. However, future research into developing systems that could be fibre and resin specific in determining the resulting strength of the structure would be useful

7 CONCLUSIONS

This thesis has shown that

1) the foam core sandwich laminates do under a penetrative non-cutting and non-bending test, display a straight section, that can mathematically be predicted between 98, 38% and 99,86% rate of occurrence.
2) The tested energy absorption abilities of the foam cores do in correlate with the stated compressive modulus at a rate of 90,5% statistical probability and shear modulus values at a rate of 88,34%.

This means that not only is it reasonable to use the tested energy absorbing values for the foam cores but that for statistical probability of between 90,5 and 88,34% the values could be taken directly from the datasheet and used for predicting the behaviour of the foam.

REFERENCES

Buster X [Online] (Updated 18 May 2010) Available at http://o.buster.fi/X.1491.0.html [Accessed 18 May 2010]

Calibration Certificate 2007, Testometric materials testing machines, ARCADA lab

Deflection of beams [Online] (Updated 12 October 2010) Available at http://www.clag.org.uk/beam.html [Accessed 12 October 2010]

Dimensions Of Sea Containers [Online] (Updated 18 May 2010) Available at http://www.easy-moving.it/Container.htm [Accessed 18 May 2010]

Ezrin, Myer, 1996. *Plastics Failure Guide: cause and prevention*. Munich; Vienna; New York: Hanser; Cincinnati: Hanser/Gardner

Honda BF75 Outboard Engine – 75 hp boat motor specs and features. [Online] (Updated 18 May 2010) Available at http://marine.honda.com/Products/modeldetail/BF75EFI [Accessed 17 May 2010]

I.S. Grant, W.R. Phillips., 2001. *The Elements of Physics*; Oxford University Press,

Saarela, O. Airasmaa, I. Kokko, J. skrifvars, M. Komppa, V. 2003. *Komposiittirakenteet*. Muoviyhdistys, Helsinki

Technical Details Swan 60. [Online] (Updated 17 May 2010) Available at http://www.nautorswan.com/TechDetails_60/tabid/275/Default.aspx [Accessed 17 May 2010]

APPENDICES

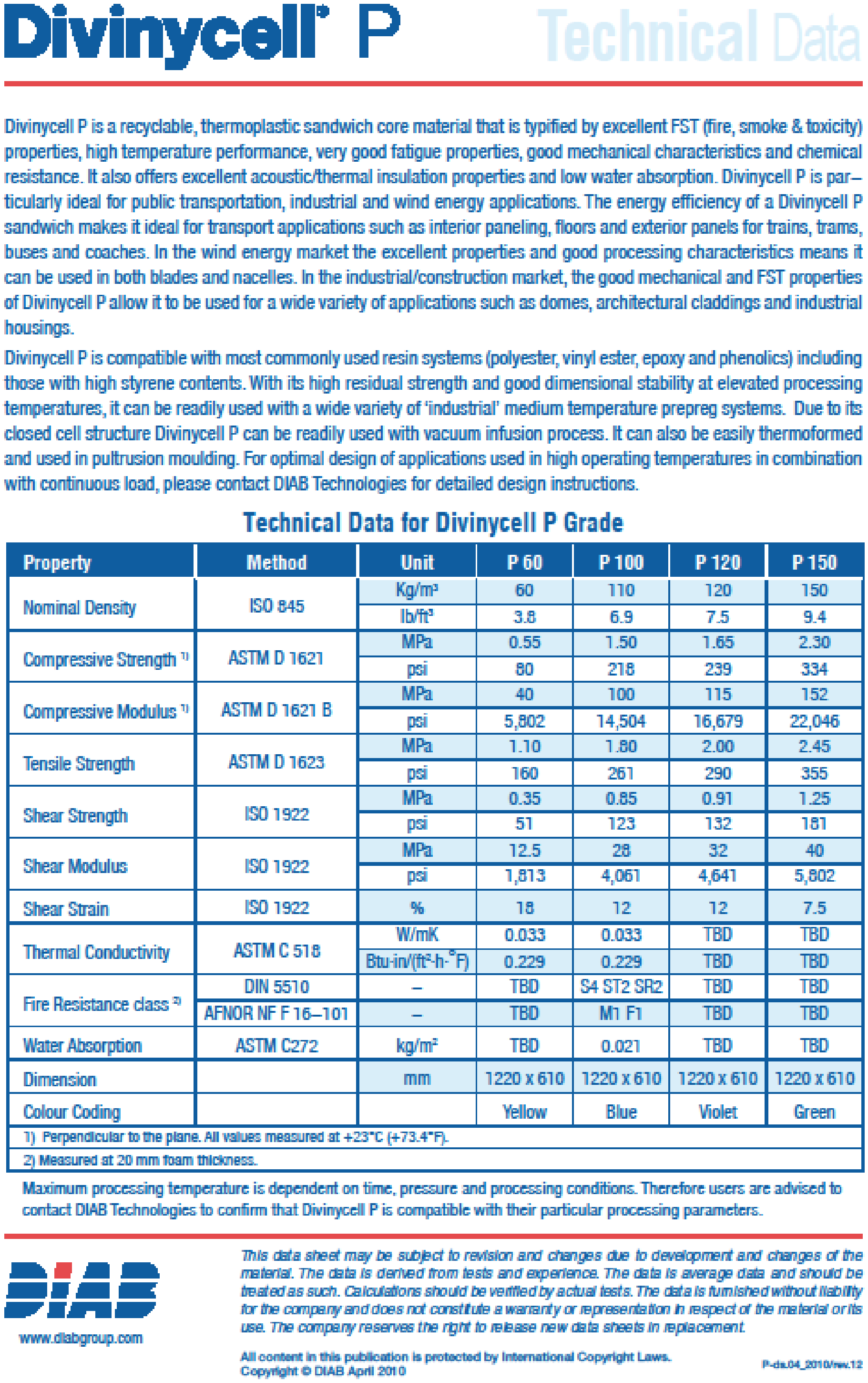
APPENDIX 1

DIAB datasheet for Divinycell P and Divinycell H foam cores

APPENDIX 2

Buster X technical specifications sheet

APPENDIX 1



Divinycell® P Technical Data

Divinycell P is a recyclable, thermoplastic sandwich core material that is typified by excellent FST (fire, smoke & toxicity) properties, high temperature performance, very good fatigue properties, good mechanical characteristics and chemical resistance. It also offers excellent acoustic/thermal insulation properties and low water absorption. Divinycell P is particularly ideal for public transportation, industrial and wind energy applications. The energy efficiency of a Divinycell P sandwich makes it ideal for transport applications such as interior paneling, floors and exterior panels for trains, trams, buses and coaches. In the wind energy market the excellent properties and good processing characteristics means it can be used in both blades and nacelles. In the industrial/construction market, the good mechanical and FST properties of Divinycell P allow it to be used for a wide variety of applications such as domes, architectural claddings and industrial housings.

Divinycell P is compatible with most commonly used resin systems (polyester, vinyl ester, epoxy and phenolics) including those with high styrene contents. With its high residual strength and good dimensional stability at elevated processing temperatures, it can be readily used with a wide variety of 'industrial' medium temperature prepreg systems. Due to its closed cell structure Divinycell P can be readily used with vacuum infusion process. It can also be easily thermoformed and used in pultrusion moulding. For optimal design of applications used in high operating temperatures in combination with continuous load, please contact DIAB Technologies for detailed design instructions.

Technical Data for Divinycell P Grade

Property	Method	Unit	P 60	P 100	P 120	P 150
Nominal Density	ISO 845	Kg/m³	60	110	120	150
		lb/ft³	3.8	6.9	7.5	9.4
Compressive Strength [1]	ASTM D 1621	MPa	0.55	1.50	1.65	2.30
		psi	80	218	239	334
Compressive Modulus [1]	ASTM D 1621 B	MPa	40	100	115	152
		psi	5,802	14,504	16,679	22,046
Tensile Strength	ASTM D 1623	MPa	1.10	1.80	2.00	2.45
		psi	160	261	290	355
Shear Strength	ISO 1922	MPa	0.35	0.85	0.91	1.25
		psi	51	123	132	181
Shear Modulus	ISO 1922	MPa	12.5	28	32	40
		psi	1,813	4,061	4,641	5,802
Shear Strain	ISO 1922	%	18	12	12	7.5
Thermal Conductivity	ASTM C 518	W/mK	0.033	0.033	TBD	TBD
		Btu-in/(ft²-h-°F)	0.229	0.229	TBD	TBD
Fire Resistance class [2]	DIN 5510	–	TBD	S4 ST2 SR2	TBD	TBD
	AFNOR NF F 16–101	–	TBD	M1 F1	TBD	TBD
Water Absorption	ASTM C272	kg/m²	TBD	0.021	TBD	TBD
Dimension		mm	1220 x 610	1220 x 610	1220 x 610	1220 x 610
Colour Coding			Yellow	Blue	Violet	Green

1) Perpendicular to the plane. All values measured at +23°C (+73.4°F).

2) Measured at 20 mm foam thickness.

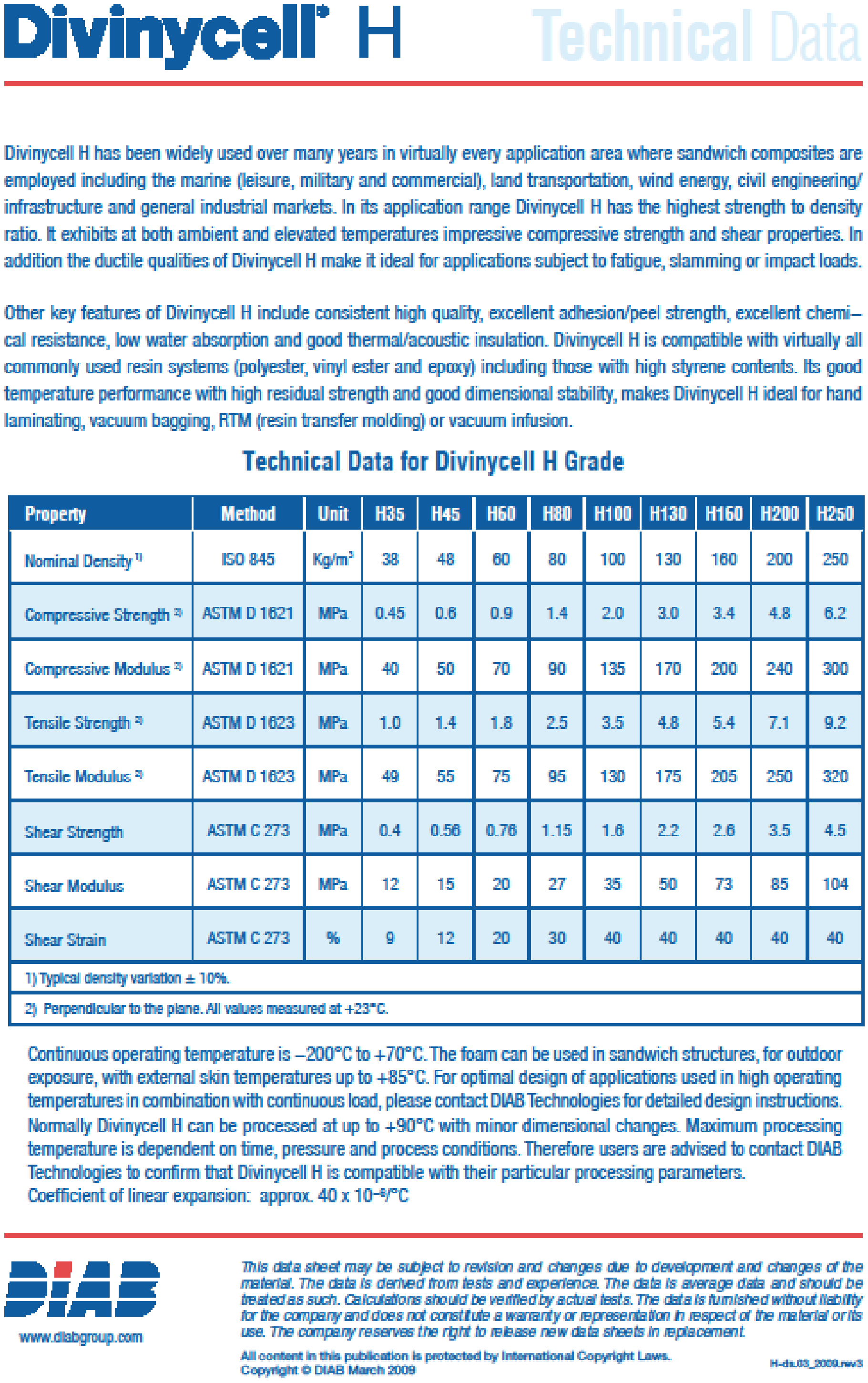
Maximum processing temperature is dependent on time, pressure and processing conditions. Therefore users are advised to contact DIAB Technologies to confirm that Divinycell P is compatible with their particular processing parameters.

DIAB

www.diabgroup.com

This data sheet may be subject to revision and changes due to development and changes of the material. The data is derived from tests and experience. The data is average data and should be treated as such. Calculations should be verified by actual tests. The data is furnished without liability for the company and does not constitute a warranty or representation in respect of the material or its use. The company reserves the right to release new data sheets in replacement.

APPENDIX 1



Divinycell® H Technical Data

Divinycell H has been widely used over many years in virtually every application area where sandwich composites are employed including the marine (leisure, military and commercial), land transportation, wind energy, civil engineering/ infrastructure and general industrial markets. In its application range Divinycell H has the highest strength to density ratio. It exhibits at both ambient and elevated temperatures impressive compressive strength and shear properties. In addition the ductile qualities of Divinycell H make it ideal for applications subject to fatigue, slamming or impact loads.

Other key features of Divinycell H include consistent high quality, excellent adhesion/peel strength, excellent chemical resistance, low water absorption and good thermal/acoustic insulation. Divinycell H is compatible with virtually all commonly used resin systems (polyester, vinyl ester and epoxy) including those with high styrene contents. Its good temperature performance with high residual strength and good dimensional stability, makes Divinycell H ideal for hand laminating, vacuum bagging, RTM (resin transfer molding) or vacuum infusion.

Technical Data for Divinycell H Grade

Property	Method	Unit	H35	H45	H60	H80	H100	H130	H160	H200	H250
Nominal Density 1)	ISO 845	Kg/m^3	38	48	60	80	100	130	160	200	250
Compressive Strength 2)	ASTM D 1621	MPa	0.45	0.6	0.9	1.4	2.0	3.0	3.4	4.8	6.2
Compressive Modulus 2)	ASTM D 1621	MPa	40	50	70	90	135	170	200	240	300
Tensile Strength 2)	ASTM D 1623	MPa	1.0	1.4	1.8	2.5	3.5	4.8	5.4	7.1	9.2
Tensile Modulus 2)	ASTM D 1623	MPa	49	55	75	95	130	175	205	250	320
Shear Strength	ASTM C 273	MPa	0.4	0.56	0.76	1.15	1.6	2.2	2.6	3.5	4.5
Shear Modulus	ASTM C 273	MPa	12	15	20	27	35	50	73	85	104
Shear Strain	ASTM C 273	%	9	12	20	30	40	40	40	40	40

1) Typical density variation ± 10%.

2) Perpendicular to the plane. All values measured at +23°C.

Continuous operating temperature is −200°C to +70°C. The foam can be used in sandwich structures, for outdoor exposure, with external skin temperatures up to +85°C. For optimal design of applications used in high operating temperatures in combination with continuous load, please contact DIAB Technologies for detailed design instructions. Normally Divinycell H can be processed at up to +90°C with minor dimensional changes. Maximum processing temperature is dependent on time, pressure and process conditions. Therefore users are advised to contact DIAB Technologies to confirm that Divinycell H is compatible with their particular processing parameters.
Coefficient of linear expansion: approx. 40 x 10^{-6}/°C

DIAB
www.diabgroup.com

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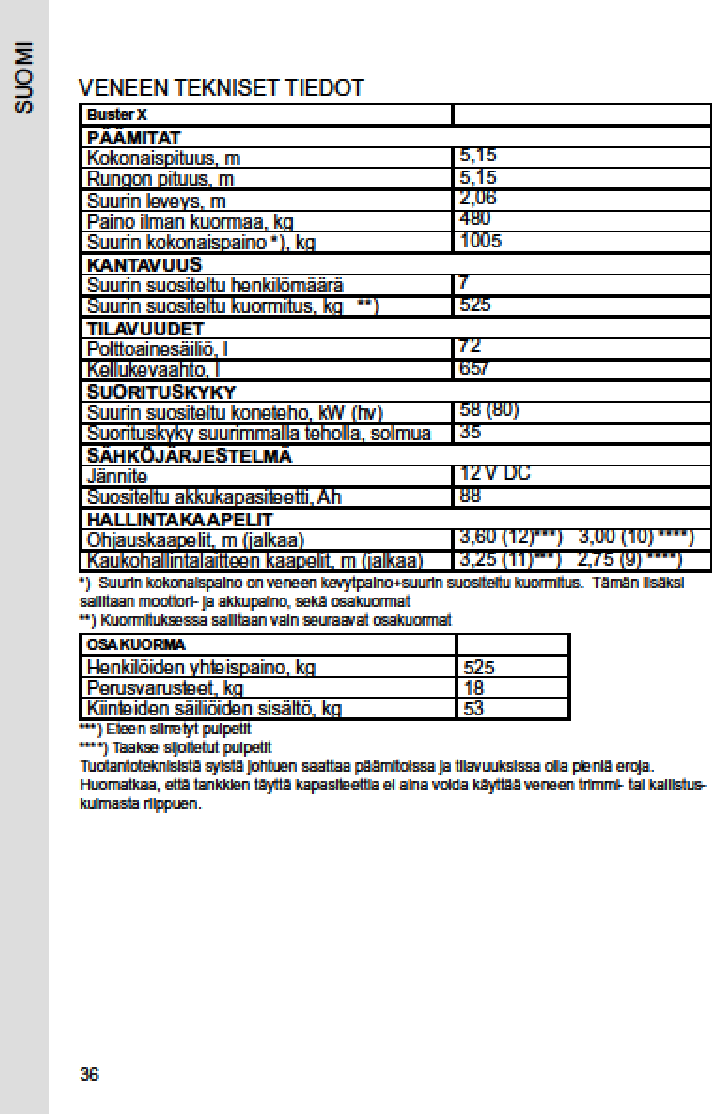
APPENDIX 2



VENEEN TEKNISET TIEDOT

Buster X	
PÄÄMITAT	
Kokonaispituus, m	5,15
Rungon pituus, m	5,15
Suurin leveys, m	2,06
Paino ilman kuormaa, kg	480
Suurin kokonaispaino *), kg	1005
KANTAVUUS	
Suurin suositeltu henkilömäärä	7
Suurin suositeltu kuormitus, kg **)	525
TILAVUUDET	
Polttoainesäiliö, l	72
Kellukevaahto, l	657
SUORITUSKYKY	
Suurin suositeltu koneteho, kW (hv)	58 (80)
Suorituskyky suurimmalla teholla, solmua	35
SÄHKÖJÄRJESTELMÄ	
Jännite	12 V DC
Suositeltu akkukapasiteetti, Ah	88
HALLINTAKAAPELIT	
Ohjauskaapelit, m (jalkaa)	3,60 (12)***) 3,00 (10) ****)
Kaukohallintalaitteen kaapelit, m (jalkaa)	3,25 (11)***) 2,75 (9) ****)

*) Suurin kokonaispaino on veneen kevytpaino+suurin suositeltu kuormitus. Tämän lisäksi sallitaan moottori- ja akkupaino, sekä osakuormat

**) Kuormituksessa sallitaan vain seuraavat osakuormat

OSA KUORMA	
Henkilöiden yhteispaino, kg	525
Perusvarusteet, kg	18
Kiinteiden säiliöiden sisältö, kg	53

***) Eteen siirretyt pulpetit

****) Taakse sijoitetut pulpetit

Tuotantoteknisistä syistä johtuen saattaa päämitoissa ja tilavuuksissa olla pieniä eroja. Huomatkaa, että tankkien täyttä kapasiteettia ei aina voida käyttää veneen trimmi- tai kallistuskulmasta riippuen.