MASTER THESIS

CHARACTERIZATION OF CORE MATERIALS IN MARINE SANDWICH PANELS EXPOSED TO SLAMMING LOADS

VERSION 0.9

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ABSTRACT

Design regulations for sandwich panels and shear strength characterization of sandwich core materials are considered. The panels included are situated in the bottom hull of planning crafts, in common for these panels are that they all are designed with regard to slamming pressures.

An evaluation is performed where different regulations are compared to each other in regard to sandwich core characterizing methods. The evaluation is made for five different core materials and eight different design regulations.

An extended design study is made where sandwich panels are designed in two different ships, the panels are designed in different regulation with different core materials. These designs are based on Matlab implementations of sandwich panel design regulations with complementary optimization routines to enable panel weight minimization. The study includes a comparison between the regulations and the use of higher utilization of the core material shear strength. Also included is an investigation on how shear elongation and dynamic load testing characterization affects the sandwich panel design.

The result given by this work clearly shows that the characterization process of marine sandwich core materials could be improved. This leads to an investigation of a new way of characterizing the core material. This study uses the yield point as the material shear strength property. Included in the above mentioned study, is an investigation on how the safety factors used in the design regulation would be affected by the new characterization method.

ACKNOWLEDGMENT

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1. INTRODUCTION

Composite materials are being used to reduce the weight in ships. Weight reduction gives capabilities to reduce engine power corresponding to lower fuel consumption or the ability to carry more cargo [1]. This report focus on the sandwich materials that more commonly are used in high speed crafts. Sandwich panels in high speed crafts experience different types of loads and the ones situated in the hull bottom experience dynamic loads, also referred to as slamming loads. This report will focus on the sandwich panels that experience slamming loads.

The core material in a sandwich panel is mainly used to carry the shear forces acting on the panel and increase the stiffness of the panel. The core material in marine sandwich panels are often made of PVC and SAN foams. When exposed to quasi static loads these materials are highly ductile and show a non linear behavior past yield, when exposed to dynamic loads the core materials show strain rate dependence.

Previous studies, e.g. [2], have shown that there are large differences in how sandwich core material properties are regarded in different design regulations. Only one of the regulations included in this study use a characterization method which tests the panels for dynamic loads [3]. Other regulations [4]-[10] use a quasi static characterization method. These methods often give a sandwich panel design which depends on the core shear strength in the panel [11].

Some of the characterization methods using quasi static testing of the core give higher knockdown factors for cores with high shear elongation [5] and [6]. However previous studies have shown that some core materials with high shear elongation perform poorly when it comes to dynamic testing [12] and low cycle fatigue tests [13].

Studies have also shown that core materials subjected to quasi static shear testing, when exposed high deformations, will not only experience pure shear which results in that the calculations method to derive shear strength is no longer accurate [14].

The aim of this report is to investigate if and how the consideration of sandwich core material properties in design regulations could be improved to enable better utilization of the shear strength in the sandwich core material.

The report consists of a study where sandwich panels are designed according to different regulations. The design restrictions are evaluated for each regulation in regard to sandwich theory. The study also includes an increased utilization of the shear strength for the core material and how this would affect the panel design in regard to strength, stiffness, stability and weight of the panel. The result of this study includes suggestions on how the classification societies and certification bodies could improve their design rules.

As a result of the mentioned study a new way of characterizing the core material is investigated. This new characterization could lead to the use of dynamic properties of the core material. Previous studies have shown that when sandwich core materials start to yield they transfer the loads to the face laminates [15]. This is why an investigation will be performed on how a new type of characterization method could be used where the yield stress defines the core materials shear strength instead of the ultimate shear stress. Previous studies confirm that the characterization methods that classification societies use in their design regulations could be improved by using the yield point [16] and they also show that core materials with high ductility shall be favored [17], but to which extent is not yet known. Studies also show that some core materials subjected to dynamic loads will have increased shear yield stress and that some of the materials will get a reduced strain to failure [18]. This study will show how the new way of characterizing the core material will affect the safety factors used in the DNV design regulation for high speed crafts [3].

DNV-HSLC has a unique way of characterizing sandwich core materials situated in sandwich panels that experience slamming pressures. They use a four point bending test (ASTM C393) [19] and apply a dynamic load of 65 MPa/s. By using this method dynamic property of the core materials are acquired. DNV only allows the use of these properties if the material shall be disadvantaged by a bad dynamic performance. This report will show a design of a sandwich panel with the use of dynamic properties from a material that performs well under dynamic loads.

2. PROBLEM STATEMENT

Partners in this thesis project were DIAB, which is a sandwich core manufacturer and Det Norske Veritas (DNV), which is a classification society.

This master thesis project began with two questions:

1. How come sandwich core materials are judged differently in design rules for ship construction? - DIAB

2. "How are other structural properties such as bending, buckling and deflection affected by the use of maximum shear strength"? - DNV

To be able to answer these questions sandwich panels in two different ships with different loads and materials were designed with different design regulations. The location of the panels was chosen so that the panels would be designed against slamming pressures.

2.1. SLAMMING LOADS

Ships that travel the water are exposed to forces due to waves and winds. Some of these ships experience damaged on the hull structure after leaving port. The reason for this could be that these ships are not designed to withstand the forces that they are exposed to.

The lighter and the faster a ship becomes the higher aerodynamic and hydrodynamic forces it will experience. Slamming loads are hydrodynamic loads acting on a ship when experiencing a slam from a wave impact as seen in Figure 1. This report focuses on sandwich panels in high speed crafts designed with slamming loads.

Figure 1. High speed boat subjected to slamming loads.

Slamming loads are a localized pressure pulses travelling over a limited part of the hull for a very short time. They are created when the forward part of the hull strikes the water. The magnitude of these pressures are due to wave heights/length and vessel/panel sizes. Extensive research of slamming loads is an ongoing work at the center for naval architecture at KTH e.g. [20] – [22]. For high speed crafts these panels are most likely to be built in a sandwich construction.

2.2. SANDWICH PANELS

A sandwich panel consists of three layers, two faces and a core, as illustrated in Figure 2. The faces are primarily carrying the bending moments and are usually made of high performing materials such as carbon fiber reinforced epoxy. The core is primarily carrying the shear forces and is usually made of a light plastic foam material. The use of sandwich panels give some advantages, such as high stiffness and strength to weight ratio, thermal and acoustic isolation, high energy absorption and buoyancy [23]. Extensive research activities on sandwich and composite materials are an ongoing work at KTH, e.g. [24] – [26].

Figure 2. Sandwich panel cross section.

Different design regulations are used to design sandwich panels that shall withstand slamming loads. These regulations are given by classification societies or international standards and they differ in the way they characterize the core materials.

2.3. CLASSIFICATION SOCIETIES AND INTERNATIONAL STANDARDS

"Classification is a system for safeguarding life and property at sea, and the environment due to operational consequences."-DNV

Classification societies establish and maintain technical standards for construction and operation of ships. This means that they set the technical rules that ships are designed by and they also survey the construction of ships. They periodically survey ships to ensure that they continue to meet within their rules. Ships designed by these rules are often larger than 24 meters.

Classification of ships is necessary for especially the ship owners but it is also important for

- National authorities
- Insurance firms
- Yards
- Finance institutions

When designing ships smaller than 24 meters certification standards can be used. These regulations are given by classification societies or international standards that provide a certification service for the small craft industry. The certification aims at providing an appropriate safety level for the ships, their intended application and design limitations.

The common name "design regulations" in this report is used for technical rules of ship building given by the classification societies and international standards.

3. REVIEW OF DESIGN REGULATIONS AND CHARACTERIZATION METHODS

This review was performed to understand how different classification and certification societies characterize core materials in marine sandwich panels. Different design regulations, core materials and laminates were investigated.

3.1. DESIGN REGULATIONS

The regulations were reviewed to understand which regulations would be beneficial to use when performing the study.

The comparison is done for different design regulations. All the regulations regard high speed craft but two of these regulations are only used for ships with a length up to 24 meters. The comparison provides an overview of how the regulations defines ships that are applicable for the regulations and a comparison of how the regulations characterize the sandwich core materials used to design bottom sandwich panels exposed to slamming loads.

The following classification rules were reviewed:

- DNV, High Speed, Light Craft and Naval Surface Craft, 2010.07
- American Bureau of Shipping, Guide for Building and Classing High-Speed Craft, 2010.01
- Lloyd Register, Rules and Regulations for the Classification of Special Service Craft, 2008.07
- Bureau Veritas, Rules for the Classification of High Speed Craft, 2002.02
- Germanischer Lloyd, Special Craft, High Speed Craft, 2002.02
- Registro Italiano Navale, Rules for the Classification of High Speed Craft, 2002.02

Bureau Veritas, Germanischer Lloyd and Registro Italiano Navale regulations for classifications of high speed crafts has been established together as members of UNITAS.

Two regulations for smaller ships up to 24 meters were also used in the study:

- DNV, Standard for Certification No. 2.21 Craft, 2010.04
- International Standard ISO 12215, 2000.09

The applicable ships for these types of classification regulations are given by the tables below.

Table 1. Applicable ships for classification regulations

Society	**High speed definition**	**Light craft definitions (tons and meters)**
ABS-HSC	$V/\sqrt{L} > 2.36$	$L < 130\ m\ (mono\ hull)$
DNV-HSLC	$7.16\ \Delta^{0.1667}$	$\Delta < 0.13\ LB^{1.5}$
LR-SSC	$7.16\ \Delta^{0.1667}$	$\Delta < 0.04\ LB^{1.5}$
UNITAS	$7.16\ \Delta^{0.1667}$	None

Table 2. Applicable ships for regulations

Regulation	**Applicable boats**
DNV-CRAFT	$6 < L < 24\ m\ and\ V < 45\ knots$
ISO	$L < 24\ m$

The ONUK MRTP33 Fast Patrol Crafts hull and superstructure are constructed to DNV HSLC classification see Figure 3.

Figure 3. ONUK MRTP33 Fast Patrol Craft [27].

3.2. MATERIAL CHARACTERIZATION

The societies use two main methods when characterizing shear strength for core material in sandwich panels subjected to slamming loads. The ultimate shear strength is given by standard test methods for shear properties of sandwich core materials, these certification methods are ASTM C273 [28] or ISO 1922 [29].

Both certification methods load the core in shear and the load shall be applied until 100 % shear failure in the core occurs. The shear strength is then given by

$$\tau = \frac{F}{A} \quad (1)$$

were F is the maximum force applied during the test and A is the area of the specimen (initial length times initial width).

In addition to these methods some of the regulations include the shear elongation in their assessments and one of the regulations use a dynamic factor given by how well the core material perform when subjected to dynamic loads. This dynamic factor is given by certification method ASTM C393.

Different regulations apply different knockdown factors (KDF) on the ultimate shear strength given by the certification methods. Applying KDF corresponds to applying safety factors (SF), see equation 2.

$$KDF = \frac{1}{SF} \quad (2)$$

In table 3 the certification methods and knockdown factors are shown for each regulation. Here $\hat{\gamma}$ is the shear elongation, τ_u is the minimum ultimate shear stress of the sandwich core material given on the type approval certificate, τ_{ud} is the minimum ultimate dynamic shear stress of sandwich core material under slamming type load given on type approval certificate and τ_{br} is the shear breaking strength of the core material $(\tau_{br} = \tau_u)$.

Table 3. Certification methods and knockdown factors

Class rule	Certification method	KDF
DNV-HSLC	ASTM C273 Dynamic ASTM C393	$0.4\,\tau_{ud}$
ABS-HSC	ASTM C273	$0.4\,\tau_u\ if\ \hat{\gamma} < 40\%$ $0.55\,\tau_u\ if\ \hat{\gamma} > 40\%$
LR	ISO 1922/ ASTM C393	$0.3\,\tau_u$

UNITAS	ISO 1922/ ASTM C393	$0.33\ \tau_{br}$
DNV-CRAFT	ASTM C273	τ_u
ISO-12215	ISO 1922	$0.55\ \tau_u\ if\ \ \hat{\gamma} < 35\%$ $0.65\ \tau_u\ if\ \ \hat{\gamma} > 35\%$

As can seen in Table 3, ABS-HSC and ISO-12215 use the shear elongation to define the core material shear strength and apply different knockdown factors depending on the magnitude of the shear elongation.

DNV-HSLC is the only regulation that takes in to consideration the dynamic load acting on the sandwich panel. They state that "Experience and material test have shown that some core materials or qualities have lower strength and more scatter under dynamic loads than for static loads" and they also use a minimum core density requirement for cross-liked PVC cores which is not allowed to use for densities less than 130 kg/m^3. Because of this DNV multiplies the ultimate shear strength given from ASTM C273 with the dynamic reduction factor (cd).

$$cd = \frac{dynamic\ test\ values}{static\ test\ values} \tag{3}$$

The dynamic test value is given by a four point bending test ASTM C393 which applies a load with a load rate giving a shear stress rate of 65 MPa/s. The same four point bending test is then done with a quasi-static load. If the dynamic strength is higher than the static strength, the dynamic reduction factor is set to 1.0 otherwise it is given by the equitation above. The minimum ultimate dynamic shear strength of core material is given by

$$\tau_{ud} = cd \cdot \tau_u \tag{4}$$

DNV – CRAFT states "For core material in bottom panels of planning craft documentation of dynamic properties may be required", if this means that they use the same method as in DNV-HSLC is not established.

3.2.1 Discussion

Only DNV-HSLC of the regulations discussed above use dynamic loading to investigate how the core material behaves when subjected to slamming loads. If the magnitude of this dynamic test loads is relevant to the loads that the panel actually is subjected to is not completely investigated. Studies have shown that the actual slamming pressure can be much higher than the value DNV subscribes. But the strain rate dependency of core materials may be of a type that 65 MPa is enough to give the material a fair judgment. The 130 kg/m^3 restriction DNV-HSLC uses is discussed under 6.3.3 Discussion.

ISO-12215 and ABS-HSC uses the shear elongation at break to decide how much of the shear strength of the core materials that will be used when design panels subjected to slamming loads. When discussing with ISO-12215 regulation makers why the use shear elongation at break to characterize the core following answer was told:

"About considering shear elongation at break, we consider that with a "ductile" core, in case of unpredicted shock (or elongation) we prefer having cores that yields and allow the sandwich to make "bump" before breaking. (There was an impressive popular Airex pub some years ago showing an Airex sandwich plate on which a truck has rolled on and which had a bump, but the core was apparently not broken)."

Also discussed was why they use 35 % of the shear elongation at break to divide core materials in to tow different groups:

"I am not an expert at all in ISO 1922, and we just choose the 35% elongation to separate "classical "Airex 62-80 from "classical" reticulated PVC."

The conclusion of this discussion is that they believe; core materials that lack high shear elongation do not forgive the mistakes. Cores with low shear elongation will break while subjected to high impact loads while cores with high shear elongation instead will plasticize and create a bump in the sandwich panel.

Design simulations were made to further investigate how the design regulations and characterization methods affect the sandwich panel design.

3.3. CORE MATERIALS

Sandwich core materials exposed to quasi static loads show a high ductile behavior and a non linear behavior past yield. When exposed to dynamic loads the core materials also shows strain rate dependence. This is why it is difficult to characterize the material and why the regulations use different approaches to do this.

Core materials used in this study were

DIAB

- Divinycell H (cross-linked PVC)

GURIT

- Corecell M-foam (SAN)
- Corecell A-foam (SAN)

AIREX BALTIC, 3A Composites

- Airex C70 (cross-linked PVC)
- Airex R63 (linear PVC)

Here PVC stands for polyvinyl chloride and SAN for styrene acrylonitrile. The difference between these materials is that linear PVC and SAN foams show a slightly more ductile behaviour when subjected to static loads past yield.

For more information regarding core materials see Appendix A.

To compare how much of the shear strength in the core material that is used in the regulations one density of each material was chosen. The densities were chosen to be as close to each other as possible and fulfilling the minimum density demands from DNV-HSLC. Figure 4 shows how much of the shear strength that is allowed to use when designing a core materials in DNV-HSLC regulation $(0.4\ \tau_{ud})$. The entire comparison can be seen in Appendix B.

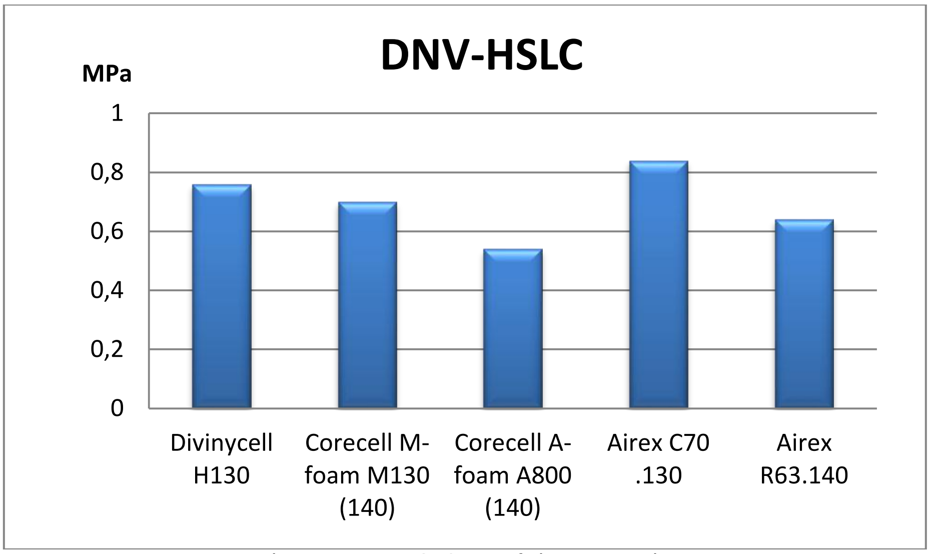


Figure 4. DNV-HSLC use of shear strength.

3.4. LAMINATES

Two different laminates were reviewed, carbon fiber – vinyl ester and glass fiber – vinyl ester. Both have a quasi-isotropic lay-up of [25% 0, 25% 90, 25% ± 45] and have been used in previous studies at KTH [1]. They were chosen so that a realistic sandwich panel design could be performed since carbon fibre often is used to design high speed crafts and glass fibre more commonly is used when designing crafts in DNV-CRAFT and ISO-12215 regulations. The report will also show how laminates are characterized by the design regulations and which effect this has on the actual sandwich panel. The laminate properties are given in Table 4.

Table 4. Laminate properties [1].

Fiber layup	$E\ (MPa)$	$G\ (MPa)$	$\sigma\ (MPa)$	τ (MPa)	$\rho\ (kg\ /m^3)$	v^f
Carbon	38000	14000	300	115	1476	0.6
E-Glass	15800	6000	247	95	1865	0.5

4. STUDIED VESSELS AND PANELS

Two different panels in two different ships were designed to conduct this study. The location of these panels was decided based on previous studies showing that these bottom areas experience the highest slamming pressures acting on the hull [1].

4.1. TTB 2000

One of the crafts studied was the TTB 2000, which is a Swedish patrol boat see Figure 5. The studied panel was situated with a distance from the aft perpendicular of 12.8 meters. The panel size was given by previous studies of the structural arrangement of this boat in regard to sandwich design [1]. The longest side of the panel was 1.6 meters and the shortest was 0.6 meters. The main particulars for the boat are given in Table 5, taken from the design specification according to FMV [31].

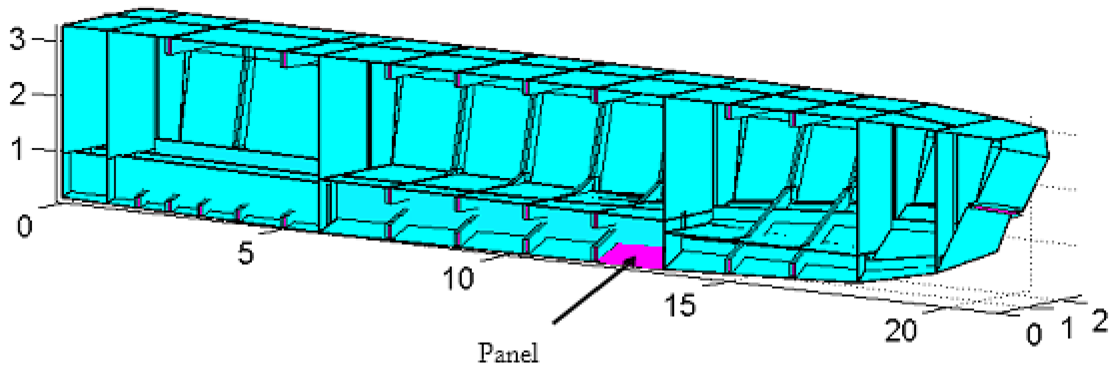


Figure 5. TTB 2000 structural arrangement [1].

Table 5. Main particulars TTB 2000.

Definition	Symbol	Value
Length over all	L	23.85
Length design waterline	Lwl	20.05
Length between perpendiculars	Lpp	20.05
Beam	B	5.1
Approximate design waterline breadth	Bwl	4.5
Draught design waterline	T	0.97
Estimated draught L/2	$T0$	0.7
Displacement	Δ	48.2
Speed in knots	V	35
Deadrise angle at LCG	β_{cg}	20
Deadrise angle sandwich panel	β_{xx}	25.5
Design acceleration	acg	20.11
Longest side of panel	a	1.6
Shortest side of panel	b	0.6
Service area restriction notation DNV-HSLC		R3

4.2. DIAB 38

The other craft studied was a 38 foot yacht seen in Figure 6. The studied panel was situated with a distance from the aft perpendicular of 6 meters. The panel size was determined by structural arrangement given by DIAB as where the main particulars seen in Table 6.

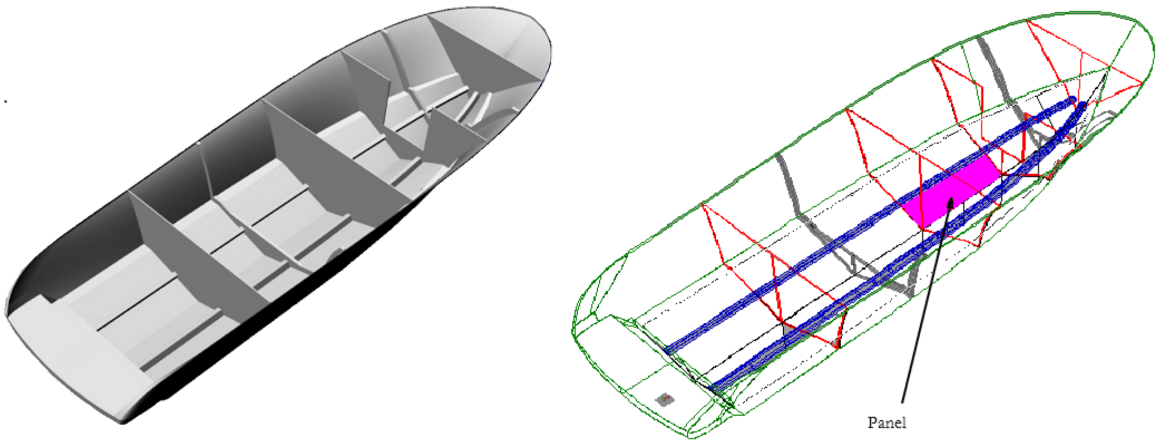


Figure 6. 38 foot yacht.

Table 6. Main particulars 38 foot yacht.

Definition	**Symbol**	**Value**
Length over all	L	11.6
Length design waterline	Lwl	9.5
Length between perpendiculars	Lpp	9.5
Beam	B	2.8
Draught design waterline	T	0.7
Estimated draught L/2	$T0$	0.5
Displacement	Δ	8
Speed in knots	V	35
Deadrise angle at LCG	β_{cg}	21
Deadrise angle sandwich panel	β_{xx}	26.5
Longest side of panel	a	2
Shortest side of panel	b	0.55
Service category	B	
Dynamic load factor	n_{CG}	4.5

5. COMPARISON OF DESIGN RESTRICTION IN REGULATIONS

5.1. INTRODUCTION

The focus in this study is DNV-HSLC, DNV-CRAFT and ISO-12215 regulations. It is important to understand that DNV-HSLC is a classification rules, that DNV-CRAFT and ISO-12215 are certification standards and which types of ships that are applicable for these regulations. These three regulations were chosen because they use different characterization methods and they fulfill the objectives in the design study see 6.1 Introduction.

The focus in this comparison is to show how the restrictions for hull structure design of a sandwich panel differ for different design regulations. Stiffness, strength and stress restrictions are analyzed for all three regulations in regard to sandwich theory.

5.2. SANDWICH THEORY

A short introduction to sandwich theory is presented to better understand how the design regulation uses design restriction and from where these restrictions can be derived.

5.2.1. Structural loads & Failure modes

The structural loads acting on a sandwich beam / panel exposed for a distributed pressure are transverse forces (T) and bending moments (M).

$$T = kqb \tag{5}$$

$$M = kqb^2 \tag{6}$$

Here k is a value given by both the ratio between the longest and the shortest side of the sandwich panel (a/b) and dependent on which type of boundary condition that is applied. q is the design pressure which is a distributed pressure working on the entire panel.

When designing a sandwich panel exposed to a distributed pressure the four most critical failure modes are taken in to consideration:

1. Core shear
2. Face fracture
3. Face wrinkling
4. Maximum deflection

5.2.2. Sandwich theory and design restrictions

One thing that makes sandwich structures special is that the Young's modulus E varies through the cross section. This is why the flexural rigidity (EI), used in the ordinary beam theory, cannot be used here. The flexural rigidity for sandwich beams (D) is given by the Timoshenko beam theory. The parameters are shown in Figure 7.

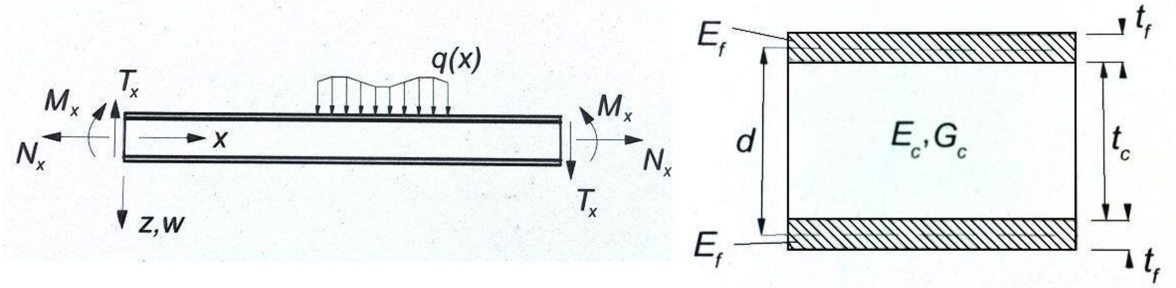


Figure 7. Sandwich beam and cross section [23].

$$D = \int Ez^2 dz = \frac{E_f t_f^3}{6} + \frac{E_f t_f d^2}{2} + \frac{E_c t_c^3}{12} = 2D_f + D_0 + D_c \quad (7)$$

$2D_f = flexural\ rigidity\ from\ faces$

$D_0 = flexural\ rigidity\ due\ to\ stainer\ contribution\ for\ the\ faces$

$D_c = flexural\ rigidity\ form\ core$

For a sandwich with thin faces, $t_f << t_c$, and weak core, $E_c << E_f$, the flexural rigidity can be approximated as

$$D = \frac{E_f t_f d^2}{2} \quad (8)$$

When a sandwich beam is subjected to a lateral load see Figure 8, the stresses in the face and the core are

$$\sigma_f = \frac{M_x z E_f}{D}\ for\ \frac{t_c}{2} < |z| < \frac{t_c}{2} + t_f \quad (9)$$

$$\sigma_c = \frac{M_x z E_c}{D} \approx 0\ for\ |z| < \frac{t_c}{2} \quad (10)$$

and the shear stress in the core is

$$\tau_c(z) = \frac{T_x}{D}\left(\frac{E_f t_f d}{2} + \frac{E_c}{2}\left(\frac{t_c}{4} - z^2\right)\right) \quad (11)$$

The maximum shear stress for a sandwich beam with a symmetrical layup will occur at the neutral axis $(z = 0)$. The maximum shear stress for the face will occur at the same place as the minimum shear stress for the core, in the interface between the face and the core.

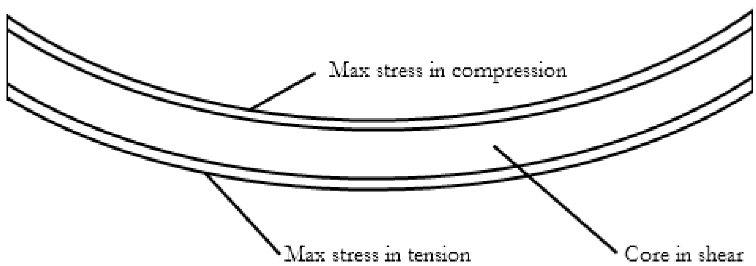


Figure 8. Sandwich in beam bending.

When assuming thin faces and weak core as previous assumption the face stress and the core shear stress becomes

$$\sigma_f = \pm \frac{M_x}{t_f d} \quad (12)$$

$$\tau_c = \frac{T_x}{d} \quad (13)$$

The stresses are shown in Figure 9 in terms of real stresses and stresses due to approximations.

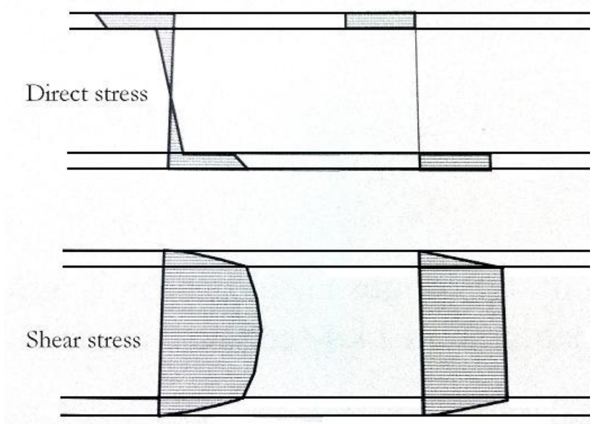


Figure 9. Stress distribution in sandwich beam with and without approximations [23].

The deformation (w) that appears while bending a sandwich beam consists of two parts: deformation due to bending (w_b) and deformation due to shear (w_s).

$$w = w_b + w_s \tag{14}$$

The deformation due to shear is dependent on the shear stiffness (S). The shear stiffness is derived using the following approximations $t_f << t_c$, $E_c << E_f$ and that the shear modulus for the face (G_f) is large.

$$S = \frac{G_c d^2}{t_c} \tag{15}$$

Here G_c is the shear modulus for the core.

The total deformation in a simply supported sandwich beam subjected to a distributed load can be written as

$$w_b = \frac{qL^3}{24D}[(L-x) - 2(L-x)^2 + (L-x)^3] \tag{16}$$

$$\frac{w_s}{dx} = \frac{T}{S} - \gamma_0 \frac{t_c}{d} \Rightarrow w_s = \frac{qL}{2S} \tag{17}$$

$$w = w_b + w_s \Rightarrow w = \frac{qL^3}{24D}[(L-x) - 2(L-x)^2 + (L-x)^3] + \frac{qL}{2S} \tag{18}$$

Here γ_0 is the in plane part of shear angle. $\gamma_0 = 0$ if the sandwich beam is either clamped or if the boundary condition gives symmetry.

Figure 10 describes some of the reaction forces acting on a sandwich panel when subjected to a distributed pressure.

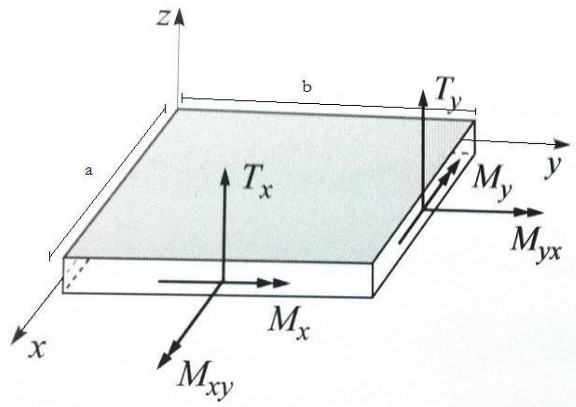


Figure 10. Reaction forces sandwich plate [30].

If the panel is simply supported the maximum deflection and bending moments appear in the middle of the panel at $(x, y) = (a/2, b/2)$ while the maximum transverse forces T_x are acting at $(0, b/2)$ and $(a, b/2\ )$and T_y at $(a/2, 0)$ and $(a/2, b)$. For a clamped panel the maxiumum transverse forces and bending moments will apperar on the edges at $(0, b/2)$, $(a, b/2\ )$ and at $(a/2, 0)$, $(a/2, b)$.

The core shear stress (τ_c) and the stress in the face laminates (σ_f) that a sandwich panel experience are given by:

$$\tau_{cx} = \frac{T_x}{d} \tag{19}$$

$$\tau_{cy} = \frac{T_y}{d} \tag{20}$$

$$\sigma_{fx} = \pm\frac{M_x}{t_f d} \tag{21}$$

$$\sigma_{fy} = \pm\frac{M_y}{t_f d} \tag{22}$$

The maximum shear will then be the larger of τ_{cx} or τ_{cy} and the maximum face stress the larger of σ_{fx} or σ_{fy}.

When designing a sandwich panel that is situated for a distributed pressure four different design restrictions are taken in to consideration from the failure modes mentioned.

By using equation (5), (6) and (19)-(22), four design restrictions can be presented

$$1. Core\ shear\ \ \tau_{c,max} = \frac{T_{max}}{d} \Longrightarrow \tau_{c,max} = \frac{kqb}{d} \leq \hat{\tau}_c\eta \tag{23}$$

$$2. Face\ fracture\ \ \sigma_{f,max} = \frac{M_{max}}{t_f d} \Longrightarrow \sigma_{f,max} = \frac{kqb^2}{t_f d} \leq \hat{\sigma}_f\eta \tag{24}$$

$$3. Face\ wrikling\ \ \sigma_{f,max} = \frac{M_{max}}{t_f d} \Longrightarrow \sigma_{f,max} = \frac{kqb^2}{t_f d} \leq \hat{\sigma}_{f,cr}\eta \tag{25}$$

$$4. Maxium\ deflection\ \ w_{max} = w_{b,max} + w_{s,max} \Longrightarrow w_{max} = \frac{kqb^4(1-v^2)}{D} + \frac{kqb^2}{S} \leq \widehat{w}\eta \tag{26}$$

Here ^ indicates maximum allowed stresses and deflection, η is the knockdown factor used and $\sigma_{f,cr}$ is the stress given by the Hoff's method that is used when designing against face wrinkling.

$$\sigma_{f,cr} = 0.5\sqrt[3]{E_f E_c G_c} \tag{27}$$

As mentioned before these design criteria are the same criteria that DNV-HSLC uses when designing a sandwich panel situated in the bottom hull of a high speed craft. However DNV-HSLC also uses criteria's involving the thickness of the face laminates by giving a restriction on how much reinforcement is needed in the skin laminates on the sandwich panel.

5.3. SANDWICH PANEL DESIGN RESTRICTIONS IN DIFFERENT REGULATIONS

The comparison of the design restriction is made in regard to sandwich theory. The restrictions are used by the regulations to make sure that the panel will handle the loads which it is subjected to during the panel life time. The restrictions for each regulation are shown in Table 7.

Table 7. Regulation restrictions.

Restriction on	**DNV-HSLC**	**DNV-CRAFT**	**ISO-12215**
Laminates	Minimum reinforcements in laminates	Minimum face thickness	Minimum sandwich skin fiber mass
Core	Minimum core density for panels subjected to slamming loads		
Laminate bending strength	Maximum normal stress in skin laminates	Minimum section modulus	Minimum section modulus
Local laminate buckling strength	Critical local buckling stress		Critical local buckling stress
Panel stiffness	Maximum allowed deflection	Minimum moment of inertia	Minimum moment of inertia
Core shear strength	Maximum core shear stress	The shear strength of core material shall be not less than	Thickness required by shear load capabilities

It is interesting to see that DNV-HSLC uses restrictions directly corresponding to sandwich theory where the calculations can be based on three different boundary conditions: fixed edges, partially fixed edges and simply supported edges. For slamming loads in the hull bottom partially fixed edges are stipulated. They also use a minimum core density requirement which says "Core material used in areas exposed to bottom slamming shall be type approved by the society for such use. Cross – linked PVC foam core materials for use in such areas shall normally have a density not less than $130\ kg/m^3$".

5.3.1 Laminates restriction

The laminate restrictions differ for the regulations. DNV-HSLC uses the minimum amount of fiber reinforcements (W).

$$W \geq W_0\left(1 + k\,(L-20)\right)\left[\frac{g}{m^2}\right] \tag{28}$$

where W_0 and k are depending on which fiber type that is used and were the panel is situated. For ships less than 20 meters $W = W_0$.

DNV-CRAFT states that the thickness of skin laminates of sandwich panels shall not be less than

$$t_{s\,min} = \frac{k\,t_{1\,min}}{f_c}\ [mm] \tag{29}$$

where k is depending on which structural member the panel is situated in,

$$t_{1\,min} = (t_0 + kL)\sqrt{f_b} \tag{30}$$

$$f_c = 0.94 + 0.12\ \sigma_c \tag{31}$$

$$f_b = 130/\sigma_{bu} \tag{32}$$

k and t_0 is depending on the length of the craft, were the panel is situated, and the speed of the craft. σ_{bu} is the bending strength of laminate and σ_c is the compressive strength of the core material.. Due to the use of compressive strength in the core material it could be possible that DNV-CRAFT implements the restriction for local buckling in the thickness requirement.

ISO gives the thickness requirement by minimum sandwich skin fiber mass in the outer skin as

$$W_{OS} = k_{DC} \cdot k_4 \cdot k_5 \cdot k_6 \cdot (0.1\ Lwl + 0.015)\ \left[\frac{kg}{m^2}\right] \tag{33}$$

where k_4 is the minimum skin location factor ($k_4 = 1$ for hull bottom), k_5 is the skin fiber type factor and k_6 is the sandwich minimum skin care factor.

In Figure 11 all laminate restrictions are shown both with a glass fiber and carbon fiber laminate for each regulation for different lengths of ships.

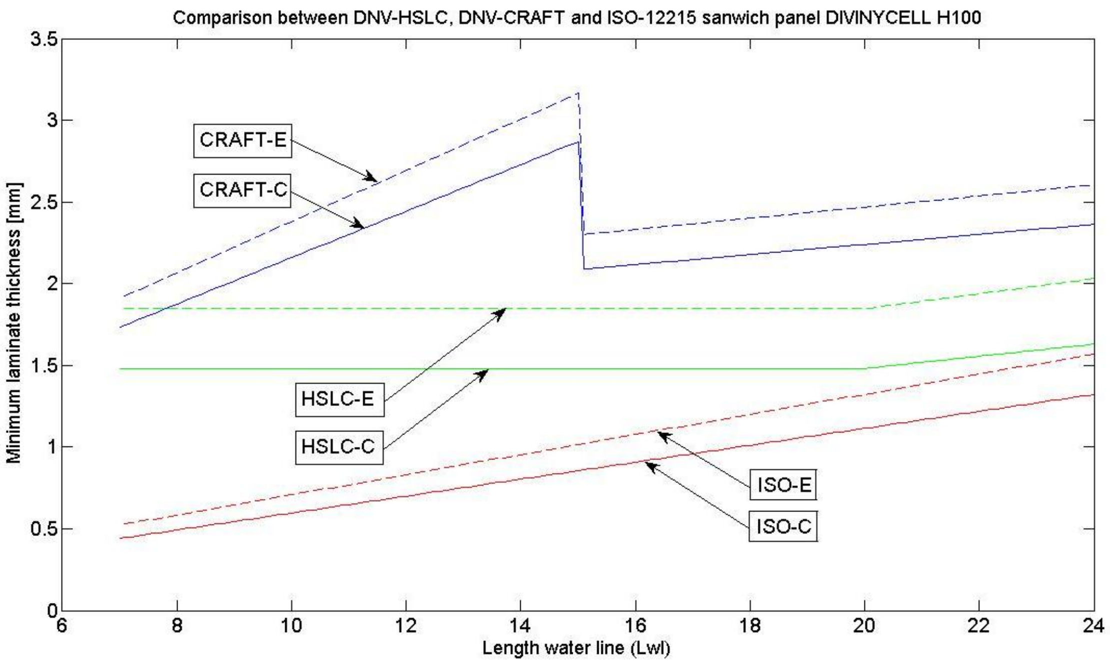


Figure 11. Thickness requirement depending on length HSLC, CRAFT, ISO

The thickness restriction given by DNV-CRAFT for ships under 15 meters is very high. The speed that was used for these results was 35 knots. If the ship would travel in 24 knots the curves would merge. Even for ships over 15 meters the thicknesses for DNV-CRAFT is higher than for the other regulations.

5.3.2 Face strength and core shear strength

The face strength and core shear strength restrictions were compared to each other and sandwich theory with a knockdown factor of 0.33. This comparison was made by using aspect ratios from the sandwich panel situated in TTB 2000. The boundary condition used for DNV-HSLC was partially fixed edges because this boundary condition is used for bottom panels exposed to slamming loads. The boundary condition used for sandwich theory was chosen to be clamped because this is more comparable to partially fixed than simply supported.

In Table 8 this comparison is shown, here b and s represent the shortest side of the panel, W and SM the section modulus and t_s the thickness of the core material. Other variables not mentioned are used to define the boundary conditions and the aspect ratio. Values describing the boundary condition and aspect ratios are inserted so that the equations can be simplified and compared to each other. The face strength equations shows how much more/less stress that is allowed in the laminate and the shear strength equations shows how much more/less shear strength that core material need to have in comparison to sandwich theory.

Table 8. Strength restrictions (All restrictions is transformed to give stresses in MPa when using unites given by regulations).

Maximum normal stress in laminates HSLC	**Minimum section modulus to maximum allowed laminate stress CRAFT**	**Minimum section modulus to maximum allowed face stress ISO-12215**	**Maximum stress in face laminate Sandwich Theory KDF=0.33**
$\sigma_n = \frac{160 \cdot p \cdot b^2}{W} C_N. C_1$ $\Downarrow$ $\sigma_{nu} = \frac{160 \cdot p \cdot b^2}{W \cdot 0.3} 0.46$ $\Downarrow$ $\sigma_{nu} = \frac{p \cdot b^2}{W} \cdot 245$	$W = \frac{0.04 \cdot p \cdot s^2 \cdot 80}{\sigma_{nu}}$ $\Downarrow$ $\sigma_{nu} = \frac{0.04 \cdot P \cdot s^2 \cdot 80 \cdot 100}{W}$ $\Downarrow$ $\sigma_{nu} = \frac{P \cdot s^2}{W} \cdot 320$	$SM_o = \frac{b^2 \cdot {k_C}^2 \cdot P \cdot k_2}{6 \cdot 10^5 \cdot \sigma_{dto}}$ $\Downarrow$ $\sigma_{ut} = \frac{b^2 \cdot 1 \cdot P \cdot 0.5 \cdot 100 \cdot 10^6}{0.5 \cdot 6 \cdot 10^5 \cdot SM_o}$ $\Downarrow$ $\sigma_{dto} = \frac{P \cdot b^2}{SM_o} \cdot 167$	$\sigma_{nu} = \frac{p \cdot b^2}{W} \cdot 228$
Maximum to minimum core shear stress HSLC	**Minimum core shear stress CRAFT**	**Thickness requirement by shear load capabilities ISO**	**Minimum core shear stress Sandwich Theory KDF=0.33**
$\tau_c = \frac{0.52 \cdot p \cdot b}{d} C_s$ $\Downarrow$ $\tau_u = \frac{0.52 \cdot p \cdot b}{d \cdot 0.4} \cdot 0.94$ $\Downarrow$ $\tau_u = \frac{p \cdot b}{d} \cdot 1.22$	$\tau_u = \frac{1.5 \cdot f_{T1} \cdot P \cdot s}{d}$ $\Downarrow$ $\tau_u = \frac{1.5 \cdot 0.97 \cdot P \cdot s}{d}$ $\Downarrow$ $\tau_u = \frac{p \cdot s}{d} \cdot 1.46$	$t_s \geq \sqrt{k_C} \frac{k_{SHC} \cdot P \cdot b}{1000 \cdot \tau_d}$ $\Downarrow$ $\tau_u = 1 \frac{0.487 \cdot P \cdot b \cdot 1000}{1000 \cdot t_s \cdot 0.55}$ $\Downarrow$ $\tau_u = \frac{P \cdot b}{t_s} \cdot 0.89$	$\tau_c = \frac{p \cdot b}{d} \cdot 1.45$

DNV-HSLC and ISO-12215 consider the local buckling of the panel using Hoff's method as an addition to the laminate strength criteria ref. equation 27.

What can be seen in Table 8 is that ISO-12215 applies the lowest safety factors in regard to sandwich theory and that DNV-CRAFT applies the highest.

5.3.3 Stiffness

To see how the stiffness restrictions in the regulations differs the restriction for maximum moment of inertia for DNV-CRAFT and ISO-12215 were converted to a maximum allowed displacement restriction like in DNV-HSLC.

DNV-HSLC gives the maximum allowed displacement as

$$w_{max} < b \cdot 0.02\ [mm] \tag{34}$$

DNV-CRAFT uses the maximum moment of inertia of a 1 cm wide sandwich strip

$$I = 0.0364 \cdot f_i \cdot p \cdot s^3\ [cm^4] \tag{35}$$

where

$$f_i = 0.97 \cdot \frac{7000}{E_n} \cdot 0.5 \tag{36}$$

E_n is the modulus of elasticity for the laminates in tension or compression in $[MPa]$, p is the design pressure in $[kN]$ and s is the shortest side of the panel in $[m]$.

ISO-12215 uses the maximum moment of inertias of a 1cm wide sandwich strip

$$I = \frac{b^3 \cdot k_C{}^3 \cdot P \cdot k_3}{12 \cdot 10^6 \cdot k_1 \cdot E_{io}}\ [cm^4] \tag{37}$$

where k_C is the curvature factor, k_3 is the panel aspect ratio factor, k_1 is the sandwich bending deflection factor and E_{io} is the mean moduli for the inner and outer skin in $[MPa]$, P is the design pressure in $[kN]$ and b is the shortest side of panel in $[mm]$.

By using the scantlings of the panel situated in TTB 2000 and the following assumptions

$$\begin{Bmatrix} L = s = b \cdot 10^{-3}\ (shortest\ side\ of\ panel) \\ E_f \cdot 10^6 = E_n = E_{io}\ (Face\ moduli) \\ q \cdot 10^3 = p = P\ (Design\ pressure) \end{Bmatrix}$$

and that the stiffness requirement is not depending on the core properties a conclusion was made that if the requirement shall be converted to a deflection requirement the shear deflection shall not be taken into consideration, no core material properties are used in the equations. By using sandwich theory and using deflection equation below for a beam with boundary condition clamped the moment of inertia was derived to a deflection restriction.

$$w_{max} = \frac{QL^3}{24D}\left[(L-x) - 2(L-x)^2 + (L-x)^3\right] = \frac{QL^3}{384D} \Longrightarrow \frac{QL^3}{384E_f I} \tag{38}$$

The moment of inertia from the two regulations used in the sandwich deflection equation gives the two following maximum allowed deflection restrictions.

$$w_{max,CRAFT} < b \cdot 0.021 \quad (39)$$

$$w_{max,ISO} < b \cdot 0.019 \quad (40)$$

5.4. DISCUSSION

All regulations use almost the same design restrictions for sandwich panel design all though DNV-HSLC uses almost exactly the same equations as sandwich theory.

What is surprising to see is that the speed dependency in DNV-CRAFT restriction for minimum laminate thickness, this dependency for crafts up to 15 meters has survived Nordisk Båt Standard and is still used by DNV-CRAFT. This speed dependency results in that the laminate thickness will have a peak at 15 meters and for crafts above 15 meters the laminate thickness will be reduced see Figure 11. DNV has to change this speed dependency so that a reasonable laminate restriction is given by the regulation. It is interesting that ISO-12215 gives a restriction for laminate thickness that is very low. This laminate thickness is given from the demand of minimum sandwich skin fiber mass in the outer skin which also covers uncertainties of how the laminate is manufactured. But it can be questioned that crafts with laminates as thin as ISO-12215 subscribes will have a sufficient design.

All regulations use a safety margin in their design and DNV-CRAFT applies the highest safety factor for maximum face strength and core shear strength compared the other regulations. ISO-12215 applies very low safety factors. The reason for this is probably that ISO-12215 is a regulation with focus on leisure crafts while DNV-CRAFT focus more on commercial crafts like work boats, small ferries etc.

The stiffness restrictions for DNV-CRAFT and ISO-12215 are not based on any properties for the core material. This leads to the conclusion that stiffness criteria for HSLC are more accurate due to the fact that the deflection in sandwich theory is dependent of laminate and core properties. This leads to larger safety against maximum deflection in the DNV-HSLC due to the fact that the deflection in sandwich theory has a core shear dependency.

6. DESIGN STUDY

6.1 INTRODUCTION

The design pressures and restrictions for the three regulations were implemented in Matlab so that sandwich panels could be designed. The panels were designed with two different laminates and five different core materials so that the following objectives could be achieved.

- Understand how DNV-HSLC and DNV-CRAFT correlate to each other for ship sizes that correspond to the lower limit for DNV-HSLC and upper limit for DNV-CRAFT.
- Evaluate the design of sandwich panels subjected to slamming loads with higher knockdown factors for core shear strength in DNV-HSLC.
- Compare the characterization methods of core materials for DNV-CRAFT and ISO-12215 and see how this effects the scantlings of the sandwich panels exposed to slamming pressures.

6.2 DESIGN PRESSURES

To design the sandwich panels the highest design pressure acting on the panels is derived from the different regulation.

The design slamming pressure for DNV-HSLC is given by the following equation.

$$P_{sl} = 1.3k_l \left(\frac{\Delta}{nA}\right)^{0.3} T_0^{\ 0.7} \frac{50-\beta_x}{50-\beta_{cg}} a_{cg} \ \left[\frac{kN}{m^2}\right] \qquad (41)$$

A is the design load area, n the number of hulls and k_l a longitudinal distribution factor given by the location of the panel. Every panel situated in the bottom hull forward of mid ships has $k_l = 1$. Variables and values for TTB 2000 are given by Table 5.

The DNV-CRAFT regulation gives the design pressure by the following equation

$$P_s = PF_s \cdot k_{ls} \cdot k_\beta \cdot k_a \qquad (42)$$

These parameters are all based on semi empirical methods were PF_s is a pressure factor given by speed and length of the boat, k_{ls} the longitudinal distribution factor depending on speed, length and situation of panel, k_β the correction for dead rise angle and k_a the area reduction factor considering the size of the panel.

The design pressure given by the ISO-12215 regulation is

$$P_{BMP} = P_{BMP\ BASE} \cdot k_{AR} \cdot k_L \qquad (43)$$

where

$$P_{BMP\ BASE} = \frac{0.1\, m_{LDC}}{Lwl \cdot B} \cdot \left(1 + k_{DC}^{\ 0.5} \cdot n_{CG}\right) \qquad (44)$$

k_{AR} is the area reduction factor which takes into account the variation of pressure due to panel size, k_L the body type factor ($k_L = 1$ for bottom panels), m_{LDC} the displacement in kg and k_{DC} the design category factor. The design pressure for ISO-12215 is depending on the size of the panel, main particulars of the boat, situation of panel, and design category factor which is given by the sea state the boat shall operate in. Variables and values for DIAB 38 are given in Table 6.

The design pressure in DNV-CRAFT is only depending on the speed and length of the boat and the dimension and location of the bottom panel. The design pressure for DNV-HSLC and ISO-12215 is depending on the service restriction / design category factor.

DNV-HSLC design pressures are depending on the design acceleration while DNV-CRAFT pressures are the same for different accelerations, design accelerations included in this study can be seen in Table 9 with resulting design pressures. TTB 2000 was built with a design acceleration of 2g, 2.8g was chosen as this design acceleration gives corresponding design pressures in the regulations and 4g was chosen as it is not likely to design a craft like TTB 200 towards a higher design acceleration.

Table 9. TTB 2000 design pressures.

Regulation	$\boldsymbol{acg = 2g}$	$\boldsymbol{acg = 2.8g}$	$\boldsymbol{acg = 4g}$
DNV-HSLC design pressure $[kN/mm^2]$	53	74	105
DNV-CRAFT design pressure $[kN/mm^2]$	74	74	74

The design pressures used in the study of the 38 foot yacht was derived from both regulations. In this study only one design pressure was chosen, where the design load $n_{CG} = 4.5$ is given but in Table 10 two can be seen. This was made to demonstrate which design load in ISO-12215 that corresponds to DNV-CRAFT design pressure. 4.5 was chosen because it was given along with the main particulars of the boat see Table 6.

Table 10. 38 foot yacht design pressure.

Regulation	$\boldsymbol{n_{CG} = 3.8}$	$\boldsymbol{n_{CG} = 4.5}$
ISO-12215 design pressure $[kN/mm^2]$	49	57
DNV-CRAFT design pressure $[kN/mm^2]$	49	49

6.3 SANDWICH PANEL DESIGN TTB 2000

Two different panel designs were made in TTB 2000. Panels were designed for the comparing study between DNV-HSLC and DNV-CRAFT where panels were designed with different densities for only one core material. Panels were also designed for different knockdown factors in DNV-HSLC to see how this would affect the panel design.

6.3.1 Comparison DNV-HSLC & DNV-CRAFT

The sandwich panels were designed with the carbon fiber laminate given by Table 4. The core material used was DIVINYCELL H80 – H200.

Figure 12 shows the resulting scantlings restrictions for a sandwich panel according to the DNV-HSLC and DNV-CRAFT regulations. The design of the panel was optimized in regard to lowest weight. Laminate thickness and core thickness was varied so this could be achieved. The differences in scantlings between the panels were due to the difference in the design pressure, restrictions for core shear strength and minimum laminate thickness. The design pressures used to perform this design is given in Table 9 where 2 g design acceleration is the design acceleration given by the design specification [31], 2.8 g design accelerations corresponds to the design pressure given by DNV-CRAFT and 4 g is an approximate maximum design acceleration for which a craft like this could be designed.

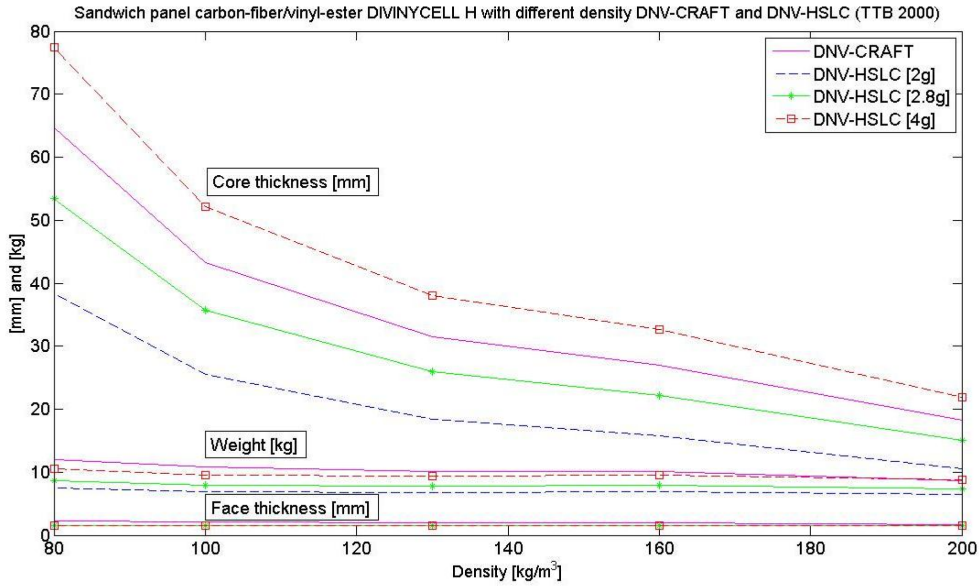


Figure 12. Sandwich panel CRAFT and HSLC, with different design accelerations

Important to notice is that even though the panel will be designed with highest design acceleration of 4g the sandwich panel will be lighter in DNV-HSLC than in DNV-CRAFT, this is due to the thicker minimum laminate thickness requirement used by the DNV-CRAFT regulation.

The design restrictions used by the two regulations which are acting on the panel design can be seen in Figure 13 and Figure 14. The x-axis shows different core densities for Divinycell H and the y-axis shows how much of each design restriction that is used. It is easy to see that the core shear strength restriction is dominating in both panels and that the laminate strength restrictions are in second place. Important to remember is that the minimum restriction for the laminates is working as well.

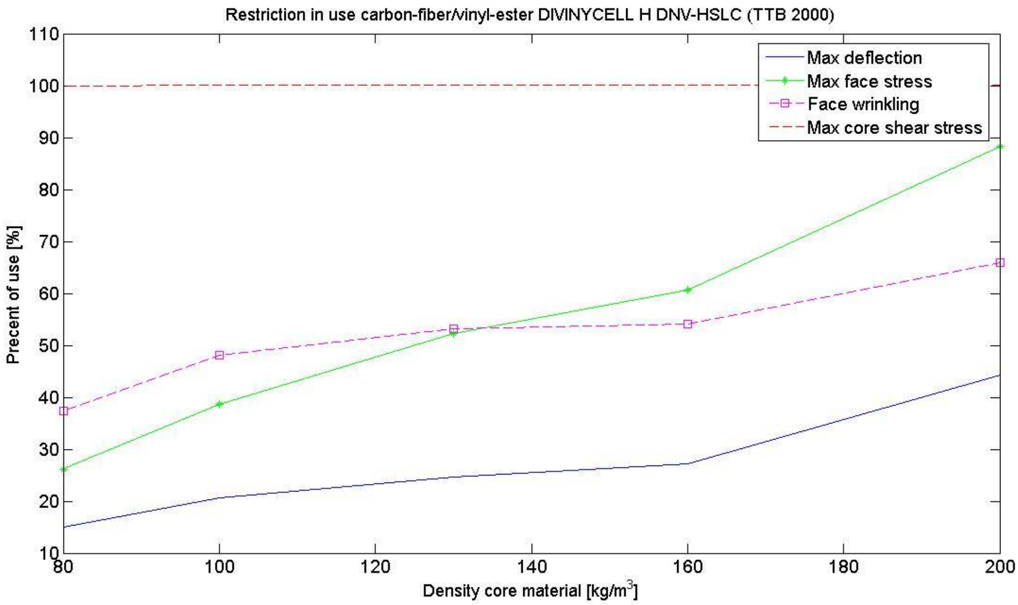


Figure 13. Sandwich panel restriction HSLC design acceleration 2.8 g

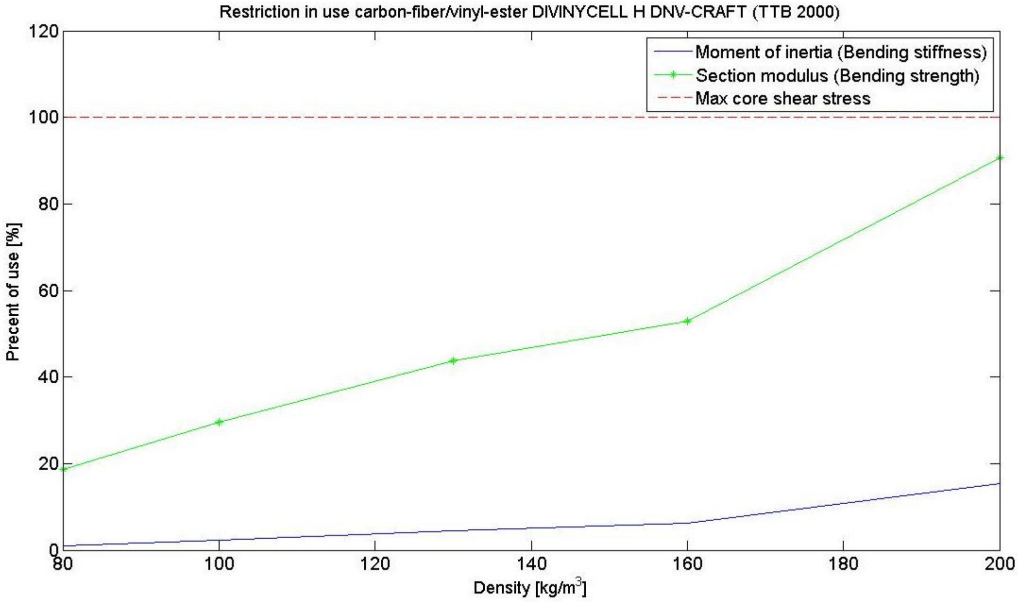


Figure 14. Sandwich panel restriction CRAFT

The figures show core material with core densities from $80\ -200\ kg/m^3$, but due to fact that the panel is exposed to slamming loads the minimum core density given by the DNV-HSLC regulations is $130\ kg/m^3$. But the panel was designed with lower densities so possible effect of a design with a low density could be seen.

6.3.2 Use of higher knockdown factor DNV-HSLC

The knockdown factor for the core material shear strength was increased from 0.4 to 0.65 in the DNV-HSLC regulation which would approximate going from a safety factor of 2.5 to 1.5. This was done for a panel with core material Divinycell H130. The results can be seen in Figure 15, which shows that an increase in the knockdown factor will have significant impact on the core thickness. When the knockdown factor has reached approximately 0.51 the decrease in core thickness is stalled due to the fact that a lower core thickness will give a higher stress in the laminates which make the face wrinkling restriction to be used.

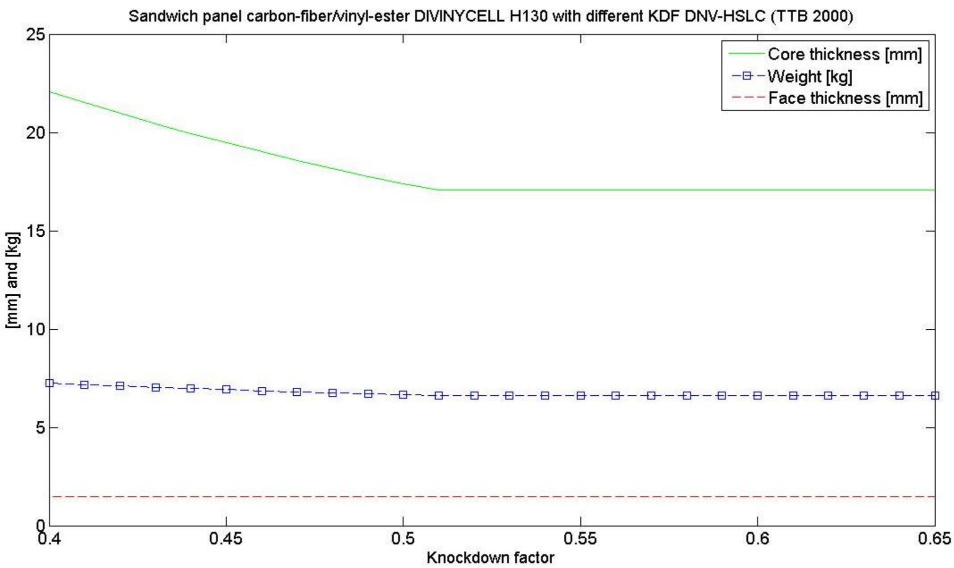


Figure 15. Sandwich panel scantlings due to increased knockdown factor.

The restriction used, as seen in Figure 16, shows that after the knockdown factor was increased to approximately 0.5 the design went from being ruled by the core shear stress to face wrinkling. Due to the weight optimization this will not lead to changes in the panel design between 0.5 and upwards.

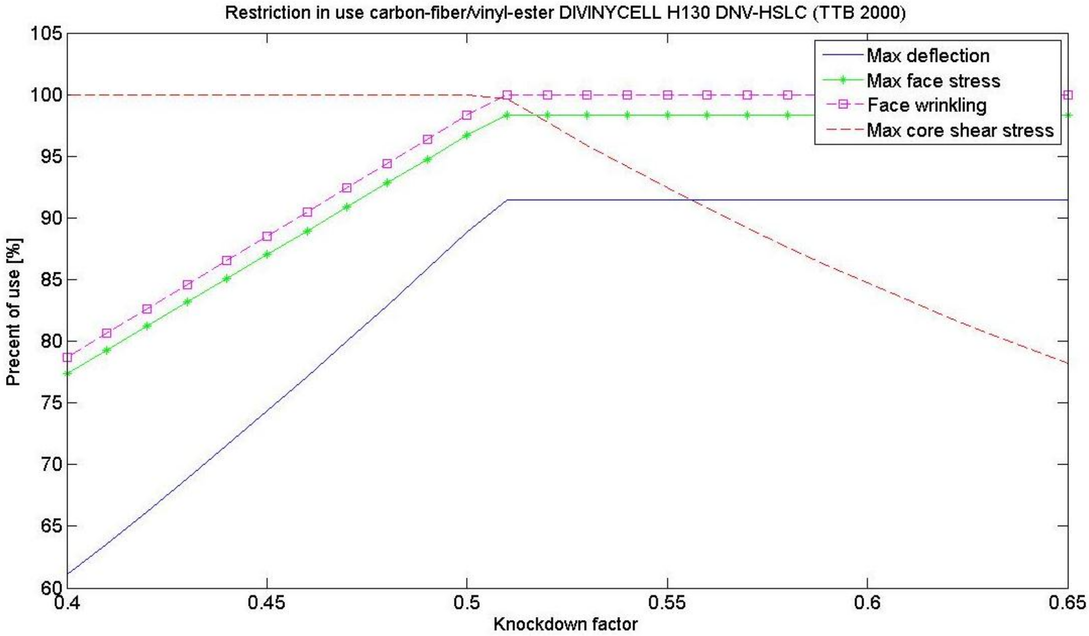


Figure 16. Restriction used for panel design with increase in knockdown factor.

6.3.3 Discussion

Section 2 in chapter 4 in DNV-CRAFT "DESIGN LOADS" gives design pressures for bottom panels subjected to slamming loads that correspond to panels designed with a design accelerations of 3g in the other regulations, as seen in Table 9. And panels designed by HSLC with almost two times the amount of slamming pressure as CRAFT will only get slightly heavier. It can clearly be seen that DNV-CRAFT is more conservative in their design of composite hulls due to the use of high safety factors in their design restrictions of sandwich panels.

For this particular sandwich panel in TTB 2000 it seems like the most beneficial core material density to use is 130 kg/m^3 because this gives the lightest sandwich panel. And for this core the rising knockdown factor will have an impact on the thickness. A sandwich panel designed with a core with a lower density 100 kg/m^3 will be depending on the maximum core stress criteria. If the knockdown factor is increased to 0.5 the weight will be the same as for H130 but the panel for this core will be thicker.

The effect of using a higher knockdown factor is important to consider because this can give a lighter bottom structure in the ship. The reason that DNV uses relative low knockdown factor could lay in uncertainties in, load predications, material structures such as in homogenizes core materials, design and material production.

As seen in these panel designs there is nothing that supports the restriction of forbidding the use of cross-linked core materials with densities lower than 130 kg/m^3. In discussions with DNV the questions from were the restriction of not letting cross-linked PVC core materials to be used under densities of 130 kg/m^3 for sandwich panels exposed to slamming loads was answered.

"I cannot find the written background for this requirement, but assume it was related to the ductility of the material supported by test results – and that some decisions were made w.r.t. a lowest accepted density. At that time we did not have the slamming fatigue test included to our Type Approval Programme, but any materials passing the test criteria may in principle be used despite the density is lower than 130 kg/m3."

Maybe the most important factor is how the core material development has resulted in improved core materials. The regulation was written in the mid 1990 but the development of core materials has continued since then. This is why it is of great importance to the core material manufacturers that the regulations update the design rules of sandwich panels so that sandwich, as a construction material, could be competitive on the market. By introducing the dynamic test this is exactly what DNV has done. But how well does this test compare to actual slamming loads? To understand this material testing has to be done. Read more in 7.3 Recommendations-material testing

6.4. SANDWICH PANEL DESIGN DIAB 38

The study regarding the design comparison of characterizing of core materials was performed for all five core materials. The sandwich panels were designed in the DIAB 38 which is a leisure craft and the panels were designed with glass fiber laminate.

6.4.1 Comparison DNV-CRAFT & ISO-12215

The panel in the 38 foot yacht was designed using five different core materials and the glass-fiber laminate according to Table 4. The design of the panel was optimized in regard to lowest weight. Laminate thickness and core thickness was varied so this could be achieved The scantling restrictions for the panels designed according to DNV-CRAFT and ISO-12215 for DIVINYCELL H as core material can be seen in Figure 17.

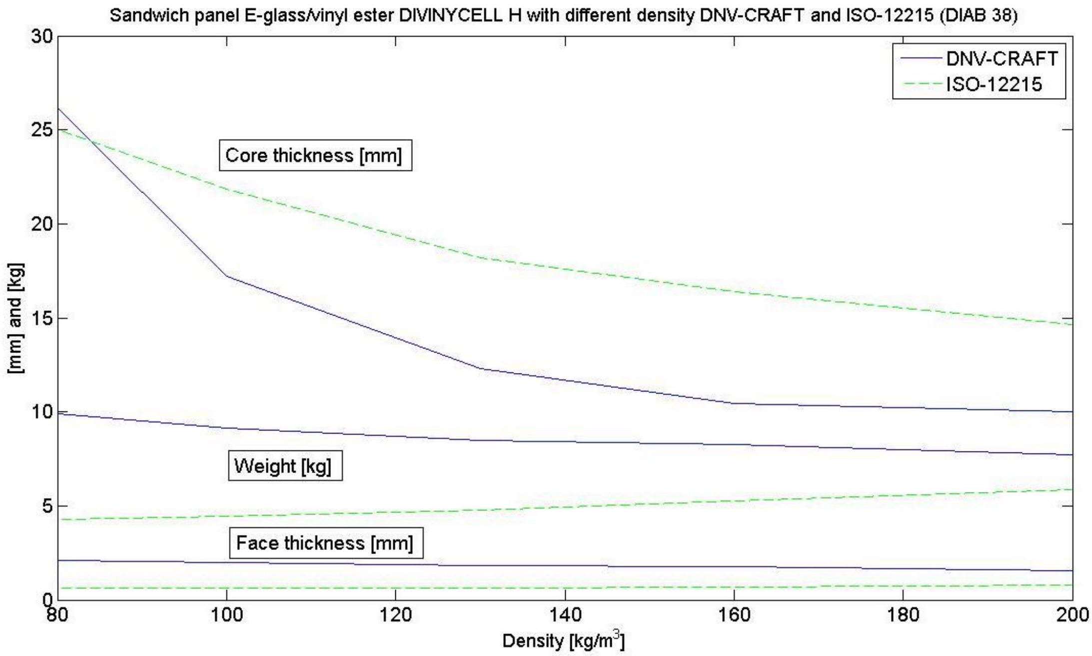


Figure 17. Comparison between sandwich panel designed by DNV-CRAFT and ISO-12215.

The difference in the scantlings was based on the fact that even thought the safety factor for the shear load restriction given by ISO-12215 was less than the safety factor for the minimum core shear stress given by DNV-CRAFT, the stress and wrinkling for ISO-12215 becomes the governing restriction due to the low minimum face thickness given by skin fiber mass, as seen in Figure 18. This leads to a higher core thickness and lower weight for ISO-12215, the DNV-CRAFT scantlings were given by the use of the minimum core shear stress and the minimum laminate thickness.

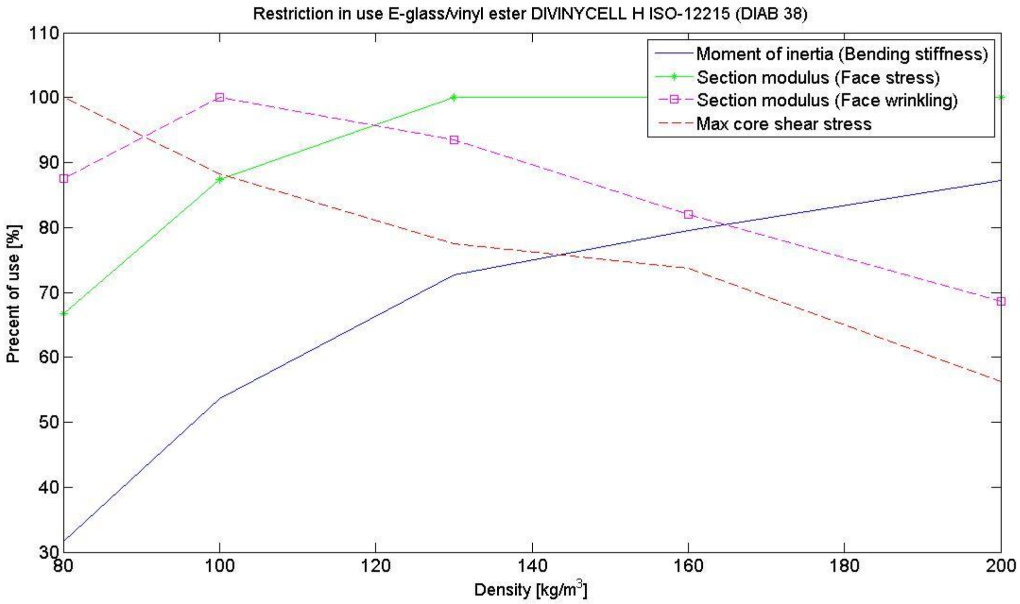


Figure 18.Design restriction sandwich panel ISO-12215.

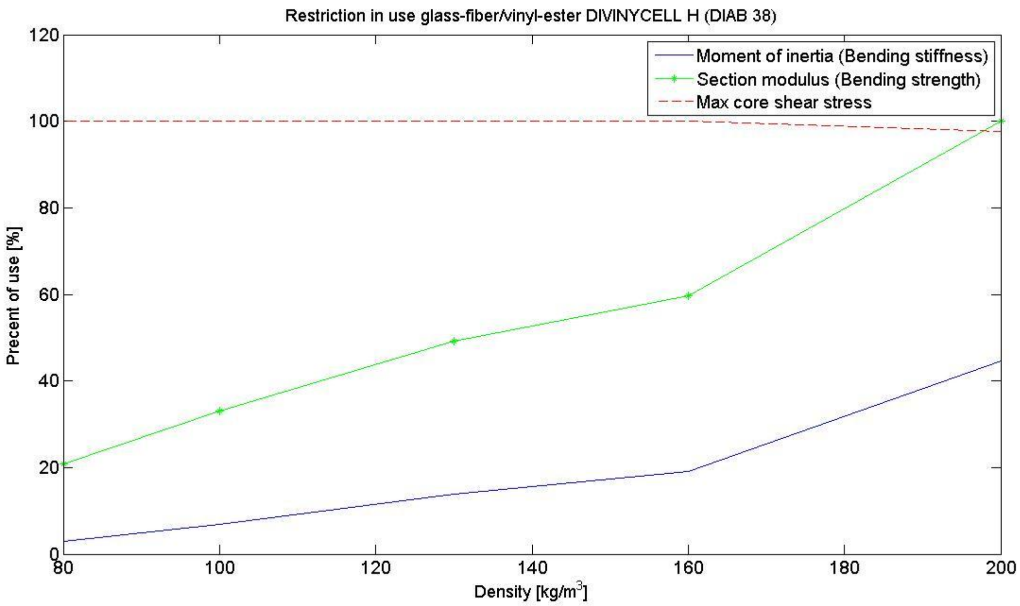


Figure 19. Design restriction sandwich panel DNV-CRAFT

6.4.2 Effects of core material characterization

Sandwich panels were designed with different core materials to see the effects of core material characterization in ISO-12215 see Figure 20. The benefit of this characterization is that core materials with a shear elongation over 35 % as Corecell M, Corecell A and AIREX R63 are given a knockdown factor of 0.65 instead of 0.55.

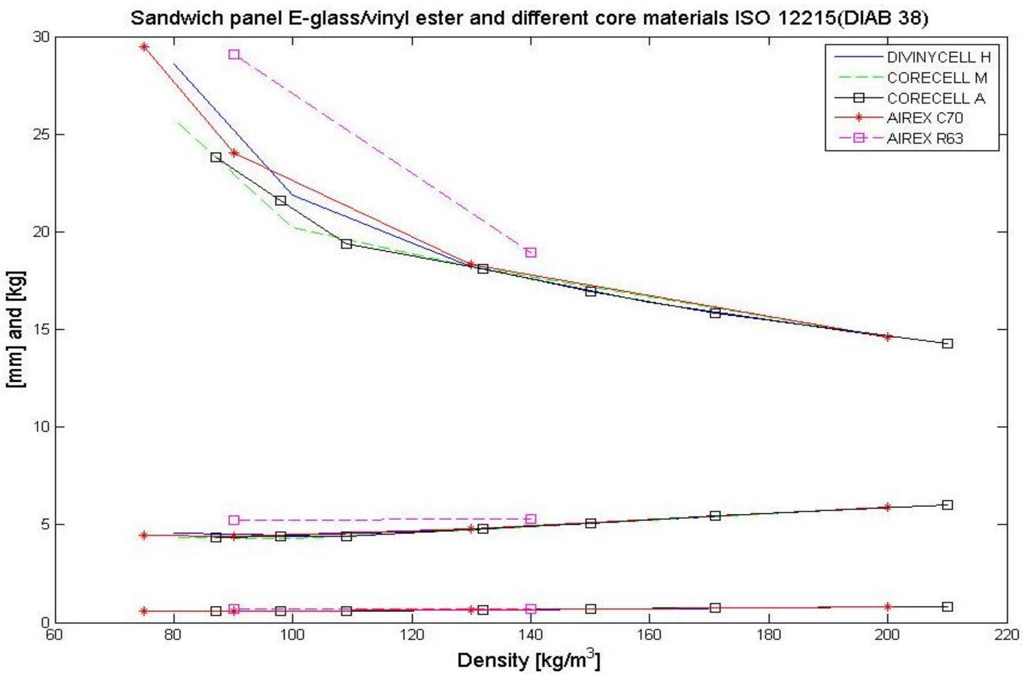


Figure 20. Sandwich panel design different core materials ISO-12215.

The governing restriction for the panel design in ISO-12215 with densities $80 - 130\ kg/m^3$ was critical face wrinkling stress. This restriction is based on the Hoff´s equation which is depending on two core material properties, Young's modulus and the shear modulus. Corecell M and Corecell A has high shear modulus in comparison to the other core materials which gives a lower core thickness see Figure 20. For densities $130 - 210\ kg/m^3$ the face strength requirement is governing which means that panels designed with different core materials and the same laminate will have the same core and face thickness.

The governing restrictions for the panel design in DNV-CRAFT are core shear strength and minimum thickness in laminate criteria. Because the regulations do not benefit special core materials the designed panels are depending on the shear strength of the core materials. Panels designed with core materials with high shear strength will have lower core thickness and weigh less see Figure 21.

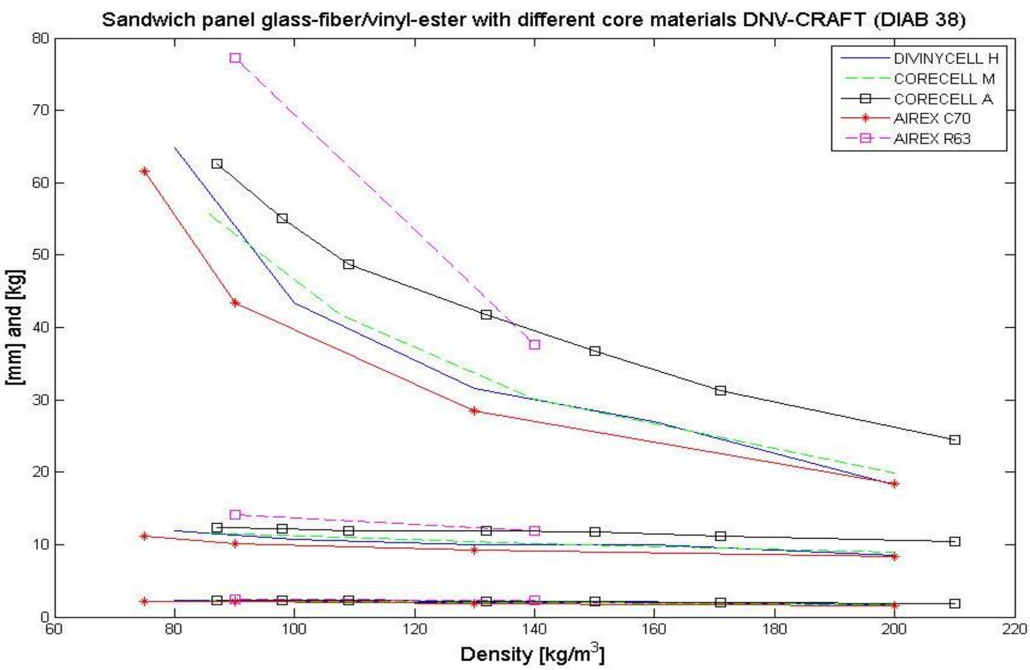


Figure 21. Sandwich panel design different core materials DNV-CRAFT.

6.4.3 Discussion

The biggest difference in the regulations is that CRAFT gives a larger thickness in the restriction for minimum laminate thickness which leads to a much higher panel weights. The reason for this, as mentioned before could be that ISO-12215 is a regulation with focus on leisure crafts while DNV-CRAFT focus more on commercial crafts like work boats, small ferries etc.

In discussions with scantling experts and DNV personal it was found that the general opinion seems to be that the thickness given by ISO-12215 is so thin that it is impossible to use sandwich panels given by their minimum requirement. This results in, when designing a sandwich panel in the DIAB 38, the characterization method for core materials is not used instead face wrinkling and face stress restrictions are governing in the design.

A panel design with a laminate thickness of 2 mm was also performed for ISO-12215. 2 mm represents a more realistic laminate thickness which is often used by ships in these sizes. With this laminate thickness the maximum core shear stress restriction was governing which leads to that the characterization method is used. Results of this design can be seen in Appendix C.

7. CORE MATERIAL CHARACTERIZATION USING YIELD POINT & USE OF DYNAMIC REDUCTION FACTOR ABOVE 1.0

An alternative characterization method was investigated. This method uses the core material yield point to define the shear strength of core material.

Today sandwich panels are designed so that the core materials never will experience stress above yield but they are characterized using the shear strength breaking point. This alternative characterization for core materials will use the yield point instead of the breaking point to characterize the material and will remove uncertainties as values for shear elongation and stress past yield.

Previous studies have shown that materials tested in the certification methods not only experience shear stresses when loaded to high elongation above yield, they also experience tensile stresses [14]. This alternative characterization method will give a shear strength property only depending on the shear strength of the core material.

Also investigated was allowing the dynamic reduction factor in DNV-HSLC to be used to a value greater than 1.0. This will show the effects in sandwich panel design when allowing a core material use its increased strength properties when loaded dynamically.

Materials included in this study were DIVINYCELL HP80 – HP200 and Airex R63.80.

7.1. YIELD POINT EXTRACTION METHODS

The materials were chosen because raw data from ASTM C273 certification method was available at KTH composite testing libratory, this data was used to compare two different extraction methods for the yield point.

The 2 % method uses a 2% offset of the elastic region of the stress / strain curve to define the yield point, as seen in Figure 22, while the elastic – plastic method uses the tangent of the elastic and the plastic region and then uses the intersection of these two lines to define the yield point, as seen in Figure 23.

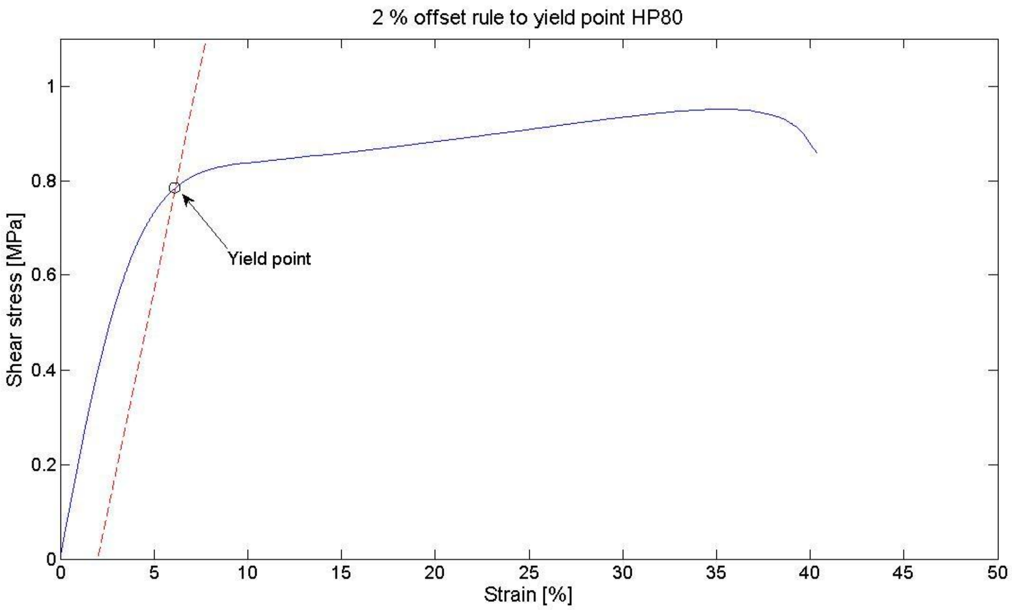


Figure 22. 2 % offset method.

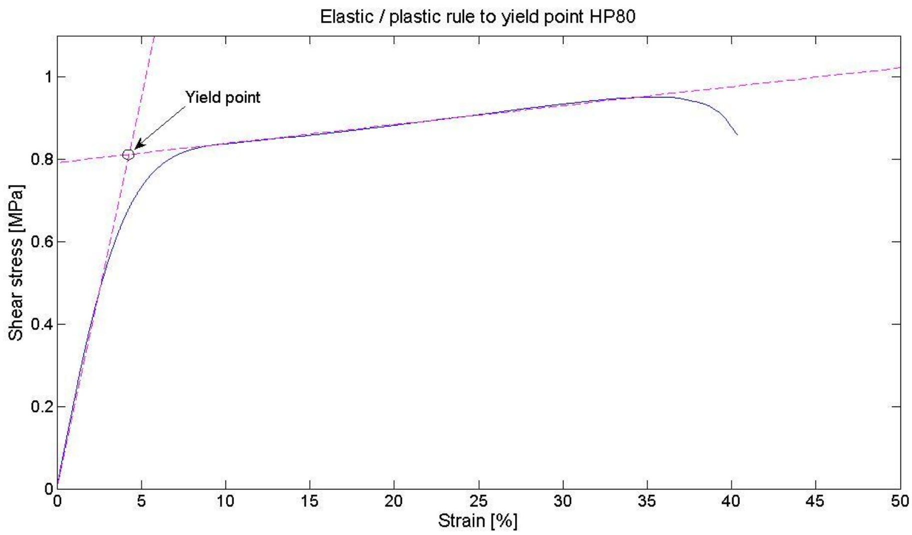


Figure 23. Elastic / plastic method.

These two methods were compared using core materials with densities of 80 kg/m3. The materials were made of different material structures, the HP80 is a cross-linked PVC material while the Airex R63.80 is a linear PVC material. The comparison can be seen in Figure 24 and Figure 25 where the yield point is extracted for both methods in both materials.

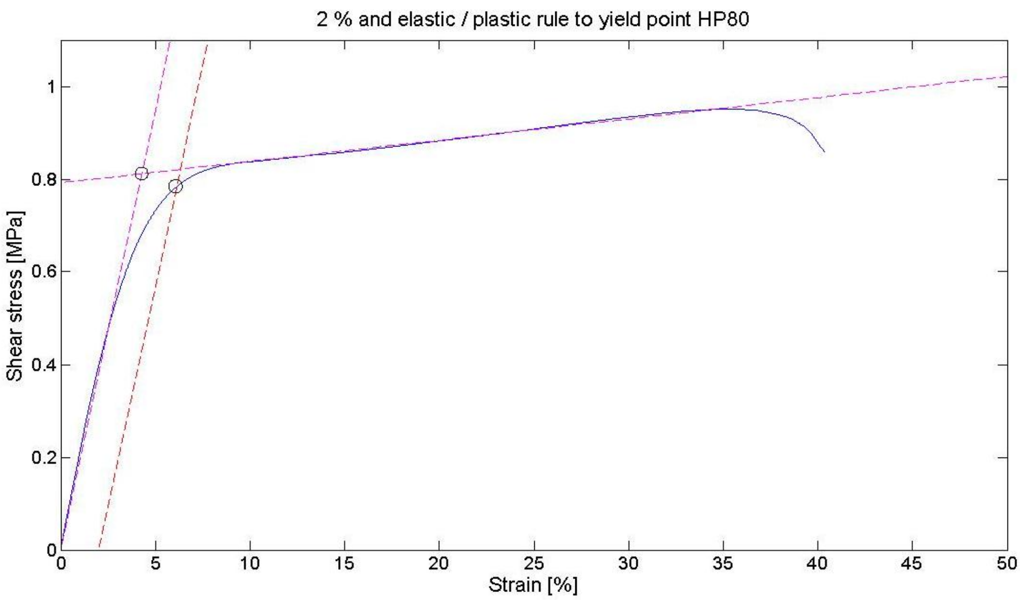


Figure 24. HP 80 yield point extraction.

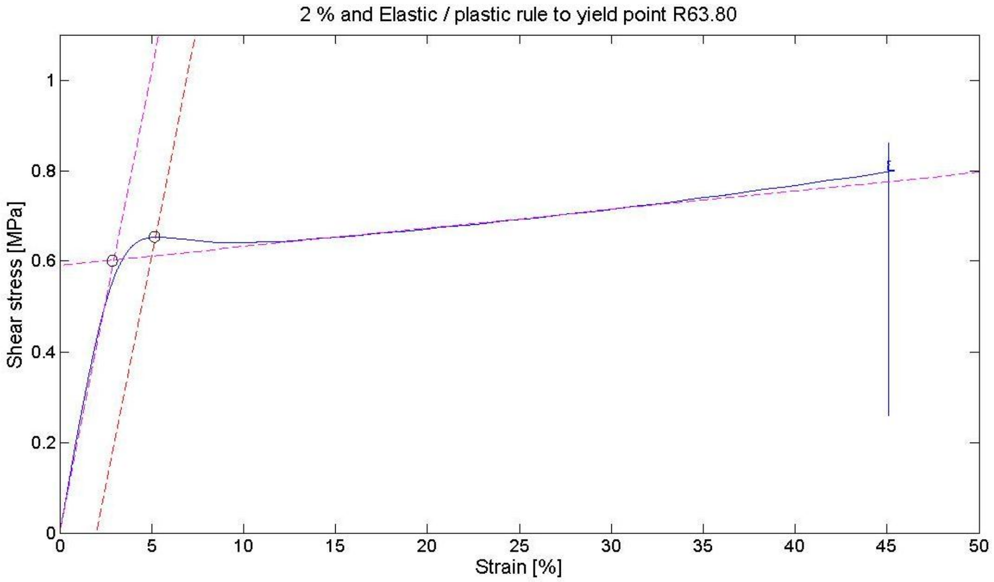


Figure 25. Airex R63.80 yield point extraction.

The result of the extracted yield point is given in Table 11.

Table 11. Result of extraction methods.

Materials	2 % method	Elastic / plastic method
Divinycell HP 80	0.78 MPa	0.81 MPa
Airex R63.80	0.65 MPa	0.60 MPa

It is clear that one of the different material structures benefits from different extraction methods, due to the differences in the stress strain curves. The 2 % method is more accepted as it is used by the ASTM C237 certification method but still an evaluation of the extraction methods could be performed by using repeated loading material testing which is described in 7.3 Recommendations-material testing

7.1.1 Effects in the DNV-HSLC regulation

To see how this alternative characterization method would affect the regulations in terms of knockdown factors the ratio yield point / breaking point was extracted from the 2 % method and converted in to yield percentages of ultimate strength for each material and density see Table 12.

Table 12. Percent yield of ultimate.

Material (X-PVC)	Yield in percentages of ultimate strength
HP80	83.6 %
HP100	81.2 %
HP130	78.0 %
HP160	81.5 %
HP200	77.3 %
Material (linear-PVC)	
Airex R63.80	82.1 %

If the used shear strength in the regulation shall be the same as in the actual characterization method using the shear strength breaking point the knockdown factor in the DNV-HSLC has to be increased with approximately 25%.

7.2 DYNAMIC REDUCTION FACTOR

The dynamic reduction factor (cd) is a factor used by DNV to characterize core material exposed to slamming loads. The factor is mentioned in 3.2. Material characterization and given by the following equation.

$$cd = \frac{dynamic\ test\ values}{static\ test\ values} \tag{45}$$

Maximum allowable shear stress for core materials situated in sandwich panels exposed for slamming loads in DNV-HSLC is given by the following equation.

$$\tau_c = KDF \cdot cd \cdot \tau_u \tag{46}$$

As previously described the dynamic reduction factor is used to a value of 1.0 or lower. To see the effects of allowing a higher dynamic reduction factor a panel is designed with a dynamic reduction factor of 1.2 for Divnycell H core materials. This is demonstrated in Figure 26. The dynamic factor of 1.2 was given from a Technical report by DNV [32] where Divinycell H100 and H250 were dynamically tested by ASTM C393 see Table 13.

Table 13. Dynamic tests of Divinycell H [32].

Test	Static test Shear Str. / Defl. MPa / mm	Slamming test Shear Str. / Defl. MPa / mm
H100 core w/o joint	1.48 / 49	1.82 / 17
H100 core w/joint	1.49 / 35	1.57 / 9
H250 core w/o joint	4.82 / 39	6.14 / 31
H250 core w joint	5.00 / 34	6.06 / 20

The quota for the values of the slamming test divided by the static test was given guideline value of 1.2 so that the design could be preformed for different densities.

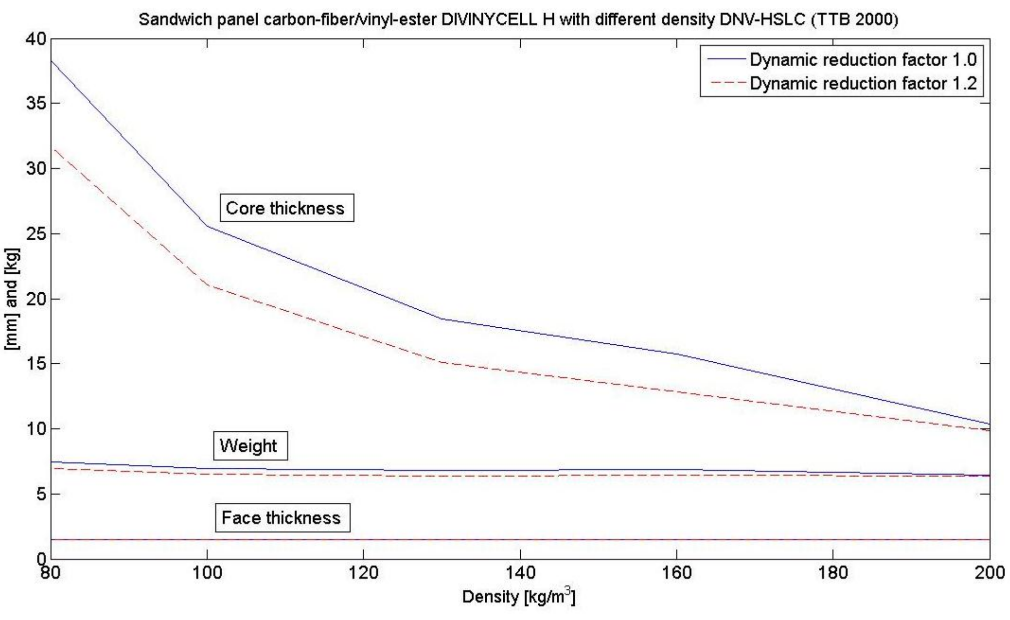


Figure 26. Design of sandwich panel in DNV-HSLC with different reduction factors.

It can be seen that for this types of panels in these ships the use of the dynamic property has an influence. The weight of the panel can be decreased with almost 1 kilogram and the core thickness reduced with 25%.

This would also lead to a larger difference between the core materials where core materials that performs well under dynamic loading will get a benefit. It will also lead to a development of core materials towards better handling of slamming pressures. Differences in panel designs in the DNV-HSLC regulation for a core material that would benefit from this type of characterization and a core material that is unfavorable are large, as seen in Figure 27.

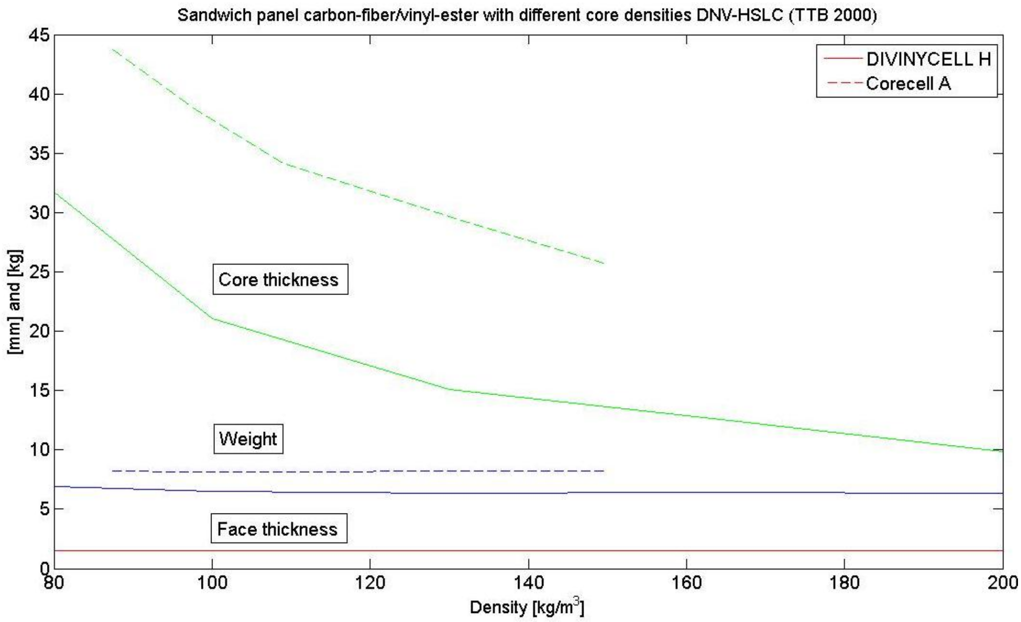


Figure 27. Panel design in DNV-HSLC with different dynamic factors for two different core materials.

Here Divinycell is given a dynamic factor of 1.2 while Corecell A is given the factor 0.85 which is given from the DNV type approval test for this core material.

7.3 RECOMMENDATIONS-MATERIAL TESTING

Material testing can be conducted further to evaluate this new characterization method and the dynamic test performed by DNV. These tests could have three main objectives: investigating how accurate the yield point extraction methods are, investigating how core materials would react when subjected to a dynamic load more similar to a slamming load and investigating the strain rate dependency of the core materials.

7.3.1 Quasi-static testing

The yield point extraction methods can be evaluated with repeated loading tests, as seen in Figure 28. Repeated loading will load – unload the material in several cycles with increasing strain to discover when the material is starting to plasticize and permanent deformations have accrued. These results can be compared to both the 2 % and the elastic / plastic method to verify the accuracy in these different methods. Already established is that these two methods benefit core material differently and by performing this test the methods could be evaluated.

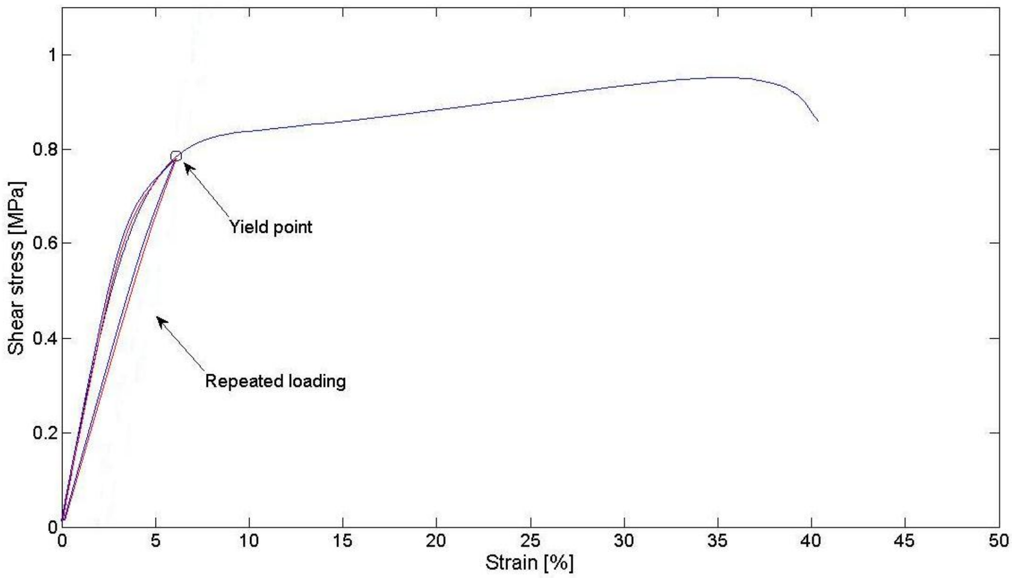


Figure 28. Repeated loading of core material.

Also interesting to investigate is how core material will react when subjected to repeated quasi-static testing to the yield point. Ten years ago core material broke after 6 -12 tests [16]. The tests will show if the development of core materials has given core materials with increased fatigue properties.

7.3.2 Dynamic testing

The main objective for the dynamic test is to evaluate if the dynamic test method that DNV uses for core materials is relevant to use for core materials situated in sandwich panels exposed to slamming loads.

Figure 29 shows Airex core material loaded dynamically with different strain rates using ASTM C393 test method, this is the same procedure DNV-HSLC uses when testing core material dynamically. A more realistic way to perform dynamic tests can be to load the material to the dynamic yield point and then unload it slowly as an actual slamming pressure. The result of this test will give two possible scenarios. Either the core material will return within the elastic region of the material and return to the original shape or it will plasticize. If the core will keep the material properties the use of the dynamic properties like a dynamic reduction factor to a value greater than 1.0 can be justified.

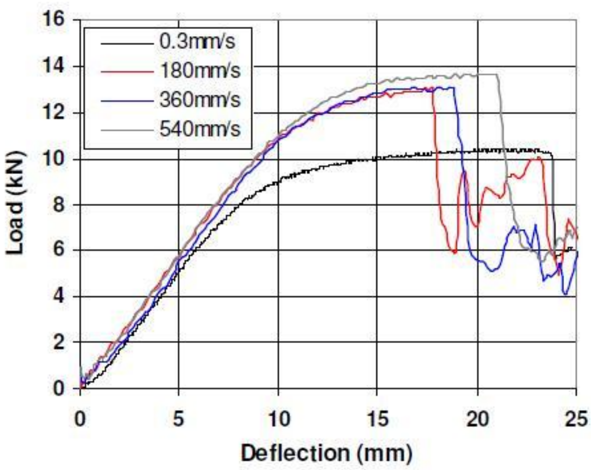


Figure 29. Load – deflection graphs for different strain rates
Airex C70.130 [11].

The dynamic yield point is usually higher than the static breaking point for materials that have an increase in material properties when dynamically loaded, as seen in Figure 29. The strain rate dependency in the material can also be seen and represented by the red curve which shows the core shear stress rate given by DNV to be 65 MPa/s. The blue curve is twice as high and the grey curve three times as high. This clearly show that the strain rate dependency of the material properties will not change as much after 65 MPa/s but it may be possible to lower this rate so that results with enough accurateness can be performed at lower strain rate.

8. CONCLUSION

The differences in sandwich panel design between the design regulations are rather big. The design regulations use different knockdown factors in their sandwich panel designs, this is caused by the different types of crafts the regulations targets. Low knockdown factors are applied to work boats and small ferries etc. while high knockdown factors are applied to leisure crafts.

Different opinions for which material property that give core material the ability to handle slamming loads are the reason why different regulation uses different characterization methods. One opinion is that the core materials should have a high shear elongation to be able to withstand slamming loads and the regulations using this method befit those core materials buy giving them higher knockdown factors. DNV-HSLC opinion is instead to reduce the knockdown factors for core materials that perform badly when exposed to dynamic testing.

When designing a sandwich panel in DNV-HSLC with an increased use of the shear strength for the core material a significant reduction in core thickness will be achieved but this will not lead to a big weight reduction of the panel. By designing the panel with the goal to keep the weight as low as possible the reduction will only occur if the shear strength requirement is ruling in the panel design.

Great uncertainties to how well core materials perform when exposed to slamming loads are introduced when characterizing the core materials by the ultimate shear strength where quasi static load is applied. These uncertainties are given by the difference in the core material structure, in this report, SAN, linear – PVC and cross linked PVC materials where investigated. Some of the uncertainties in the characterization of shear strength in core materials can be removed by using a characterization method were the yield point is used to define the core materials shear strength.

9. DISCUSSION

It is important that development of classification and certification regulations for composite materials is progressing towards the goal of making crafts lighter without jeopardizing the safety. This can be done by using improved design restrictions and more precise characterization methods.

DNV has been trying to improve their design regulation by introducing a dynamic test to characterize the core materials capabilities to withstand slamming loads. But this characterization method will not test the material for actual slamming loads, due to the fact that slamming loads never will progress until total failure in the core has accrued. But by doing this DNV is pushing the development forward towards designing crafts with greater knowledge and understanding of the core materials.

REFERENCES

1. Stenius I, Rosén A, Kuttenkeuler J, On structural design of energy efficient small high-speed craft, Marine Structures (2011), doi:10.1016/j.marstruc.2011.01.001
2. Burman M, Rosén A and Zenkert D, Spectrum Slam Fatigue Loading of Sandwich Materials for Marine Structures, Int. Conf. on Sandwich Structures ICSS9, Pasadena, USA, June 2010.
3. DNV, High Speed, Light Craft and Naval Surface Craft, 2010.07
4. DNV, Standard for Certification No. 2.21 Craft, 2010.04
5. International Standard ISO 12215, 2000.09
6. American Bureau of Shipping, Guide for Building and Classing High-Speed Craft, 2010.01
7. Lloyd Register, Rules and Regulations for the Classification of Special Service Craft, 2008.07
8. Bureau Veritas, Rules for the Classification of High Speed Craft, 2002.02
9. Germanischer Lloyd, Special Craft, High Speed Craft, 2002.02
10. Registro Italiano Navale, Rules for the Classification of High Speed Craft, 2002.0
11. Battley M and Lake S, Designing Composite structures for slamming Loads, 2nd High Performance yacht design Conference, Auckland, 14-16 February, 2006.
12. Reuterlöv S, Slamming Test of Different Foam Core Materials, Presented at JEC/SAMPLE Europe, International Conference 2007.
13. Islin R, Lake S and Battley M, Low Cycle fatigue of Composite Sandwich foam Cores, 3rd High Performance Yacht Design Conference, Auckland, 2-4 December, 2008.
14. Battley M and Burman M, Characterisation of ductile Core Materials, 8th International Conference on Sandwich Structures, 2008.
15. Salih N. Akour, Hussein Z. Maaitah, Effect of Core material Stiffness on Sandwich panel behavior Beyond the Yield Limit, Proceeding of the World Congress on Engineering 2010 Vol II, June –July, 2010, London U.K.
16. Zvanik M, Shear Properties of Structural Polymer Foams, Sandwich Construction 5, Proc. 5th Int. Conf. on Sandwich Construction, Zurich, Switzerland, September 2000.
17. Hayman B, Hoffman P, McGregor D, Noury P, Non-Linear Core Behavior in Sandwich Panels For High Speed Crafts. FAST 2001: 4th-6th September 2001, Southampton, UK.
18. L. Buene, A.T Echtermeyer, B. Hayman, O.E Sund and B. Engh, Shear Properties of GPR Sandwich Beams Subjected to Slamming Loads, A.S veritas Research and Det Norske Veritas Classification A/S, HØvik, Norway.
19. ASTM C393-00, Standard Test for Flexural Properties of Sandwich Constructions.
20. Garme K., Rosén A., Experimental Pressure Investigation on a High-Speed Craft in Waves, Proceedings International Conference on Hydrodynamics of High-Speed Craft, RINA, UK, 2000.
21. Rosén A., Loads and Responses for Planing Craft in Waves, PhD Thesis, TRITA-AVE 2004:47, ISBN 91-7283-936-8, Division of Naval Systems, KTH, Stockholm, Sweden, 2004.
22. Garme K., Rosén A., Kuttenkeuler J., In Detail Investigation of Planing Pressure, Proc. Hydralab III Joint Transnational Access User Meeting within the European Commission 6th framework, Hannover, Germany, 2010.
23. Zenkert D, An Introduction to Sandwich Structures (Student edition).
24. Burman, M., " Sandwich Materials in Buildings" The 16th SICOMP Conference on Manufacturing and Design of Composites, Säröhus, Gothenburg, Sweden. 30-31 May, 2005.
25. Burman M., Rosén A., Zenkert D., Spectrum Slam Fatigue Loading of Sandwich Materials for Marine Structures, 9th Int. Conf. on Sandwich Structures, ICSS9, CalTech, Pasadena, USA, 2010.
26. T. Allen, M. Battley, I. Stenius, Experimental Methods For Determining Shear Loads In Sandwich Structures Subjected To Slam Loading, 9th International Conference on Sandwich Structures, California Institute of Technology, Pasadena, California, USA, 2010.
27. http://www.yonca-onuk.com, 2011-11-27.

28. ASTM C273-00, Standard Test Method for Shear properties of Sandwich Core materials.
29. ISO 1922:2001, Rigid cellular plastics, Determination of shear strength.
30. Sundström B, Handbok och Formelsamling i Hållfasthetslära, Institutionen för hållfasthetslära KTH, april 1999.
31. FMV, Fartyg Fartgsbyrån, Specifikation för Trupptransportbåt 2000, 1999-06-10.
32. Technical Report Divinycell International AB, Testing of Sandwich Panel, Report No. 2007-3086.

APPENDIX A – CORE MATERIALS

Core material properties given by DNV certificate.

Divinycell H (cross-linked PVC)

Properties	Test Method	H60	H80	H100	H130	
Tensile strength	ASTM D 1623	1,5	2,2	2,5	3,5	MPa
Tensile modulus	ASTM D 1623	57	85	105	135	MPa
Compressive strength, 23°C	ASTM D 1621	0,7	1,15	1,65	2,4	MPa
Compressive modulus, 23°C	ASTM D 1621	60	80	115	145	MPa
Shear strength	ASTM C 273	0,63	0,95	1,4	1,9	MPa
Shear modulus	ASTM C 273	16	23	28	40	MPa
Shear elongation	ASTM C 273	10	15	25	30	%
Density	ASTM D 1622	54	72	90	117	kg/m^3
Slamming grade testing, shear strength	ASTM C393	-	-	-	-	MPa

Properties	Test Method	H160	H200	H250	
Tensile strength	ASTM D 1623	4,0	6,3	8,0	MPa
Tensile modulus	ASTM D 1623	160	210	260	MPa
Compressive strength, 23°C	ASTM D 1621	2,8	4,5	6,1	MPa
Compressive modulus, 23°C	ASTM D 1621	175	265	350	MPa
Shear strength	ASTM C 273	2,2	3,2	3,9	MPa
Shear modulus	ASTM C 273	50	65	81	MPa
Shear elongation	ASTM C 273	30	35	35	%
Density	ASTM D 1622	145	180	230	kg/m^3
Slamming grade testing, shear strength	ASTM C393	-	-	6.0	MPa

Remarks:

Airex C70 (cross-linked PVC)

Properties	Test Method	C70.48	C70.55	C70.75	C70.90		
Density	ISO 845	43	54	72	90	kg/m^3	msmv
Tensile Strength	ISO 527	0.8	1.0	1.6	2.2	MPa	msmv
Tensile Modulus	ISO 527	28	35	50	65	MPa	msmv
Compressive Strength (23°C)	ISO 844	0.5	0.75	1.1	1.7	MPa	msmv
Compressive Modulus (23°C)	DIN 53421	35	55	80	110	MPa	msmv
Shear Strength	ISO 1922	0.5	0.7	1.0	1.4	MPa	msmv
Shear Modulus	ASTM C393	14	18	24	34	MPa	msmv
Shear Elongation, at break	ISO 1922	8	10	10	12	%	msmv

Properties	Test Method	C70.130	C70.200	C70.250		
Density	ISO 845	120	180	225	kg/m^3	msmv
Tensile Strength	ISO 527	3.0	4.8	5.5	MPa	msmv
Tensile Modulus	ISO 527	95	140	160	MPa	msmv
Compressive Strength (23°C)	ISO 844	2.6	4.5	5.3	MPa	msmv
Compressive Modulus (23°C)	DIN 53421	145	240	280	MPa	msmv
Shear Strength	ISO 1922	2.1	3.2	3.8	MPa	msmv
Shear Modulus	ASTM C393	45	68	78	MPa	msmv
Shear Elongation, at break	ISO 1922	20	20	20	%	msmv

Airex R63 (linear PVC)

Density	ISO 845	kg/m³	Average *Typ. range*	60	90 *80 - 120*	140 *125 - 170*
Compressive strength perpendicular to the plane	ISO 844	N/mm²	Average *Minimum*	0.38	0.90 *0.70*	1.6 *1.3*
Compressive modulus perpendicular to the plane	DIN 53421	N/mm²	Average *Minimum*	30	56 *46*	110 *100*
Tensile strength in the plane	ISO 527 1-2	N/mm²	Average *Minimum*	0.90	1.4 *1.2*	2.4 *2.2*
Tensile modulus in the plane	ISO 527 1-2	N/mm²	Average *Minimum*	30	50 *45*	90 *80*
Shear strength	ISO 1922	N/mm²	Average *Minimum*	0.50	1.0 *0.8*	1.85 *1.60*
Shear modulus	ASTM C393	N/mm²	Average *Minimum*	11	21 *18*	37 *35*
Shear elongation at break	ISO 1922	%	Average *Minimum*	70	75 *70*	80 *75*
Impact strength	DIN 53453	kJ/ m²	Average	4.0	5.0	6.5
Thermal conductivity at room temperature	ISO 8301	W/m.K	Average	0.034	0.037	0.039

Corecell A (SAN)

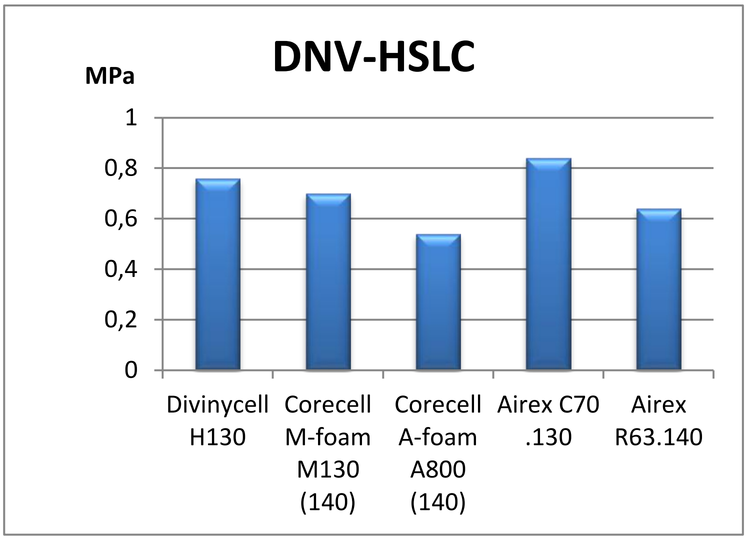
Properties	Test Method	A700	A800	A900	A1200	Unit	
Density (nominal)	ASTM D1622	132	150	171	210	kg/m³	msv
Density	ASTM D1622	125	140	161	200	kg/m³	msmv
Tensile strength	ASTM D1623	2,28	2,60	2,96	3,67	MPa	msv
Tensile strength	ASTM D1623	1,88	2,11	2,44	3,05	MPa	msmv
Tensile modulus	ASTM D1623	139	166	198	265	MPa	msv
Compressive strength	ASTM D1621-04	1,89	2,36	2,95	4,23	MPa	msv
Compressive strength	ASTM D1621-04	1,62	1,97	2,50	3,65	MPa	msmv
Compressive modulus	ASTM D1621-04	83	102	126	178	MPa	msv
Compressive modulus	ASTM D1621-04	68	83	104	149	MPa	msmv
Compressive modulus	ASTM D1621-73	113	141	175	251	MPa	msv
Compressive modulus	ASTM D1621-73	87	105	134	195	MPa	msmv
Shear strength	ASTM C273	1,70	1,95	2,25	2,82	MPa	msv
Shear strength	ASTM C273	1,45	1,64	1,92	2,43	MPa	msmv
Shear modulus	ASTM C273	51	60	71	93	MPa	msv
Shear modulus	ASTM C273	43	50	60	80	MPa	msmv
Shear elongation, at break	ASTM C273	61	58	55	49	%	msv
Heat resistance, % retention of shear strength, +63°C	ASTM C393		-		80	%	
Water resistance, % retention of shear strength	ASTM C393		-		>100	%	
Slamming grade testing, shear strength	ASTM C393		-		>2,07	MPa	msmv

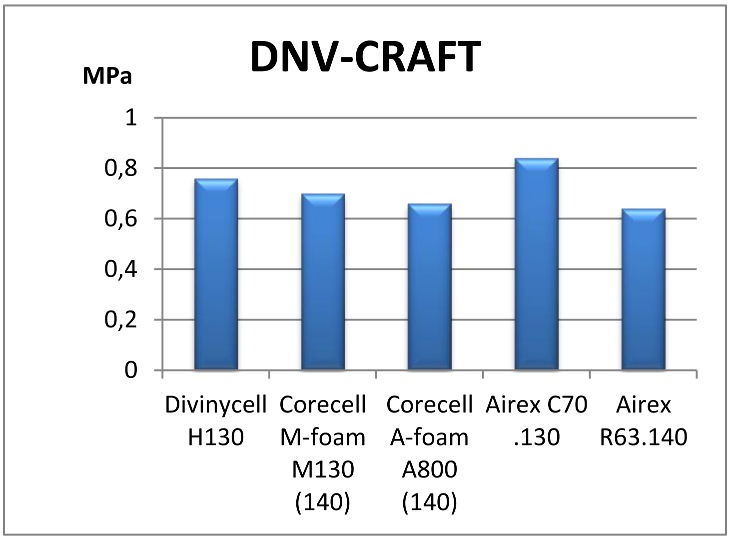
Corecell M (SAN)

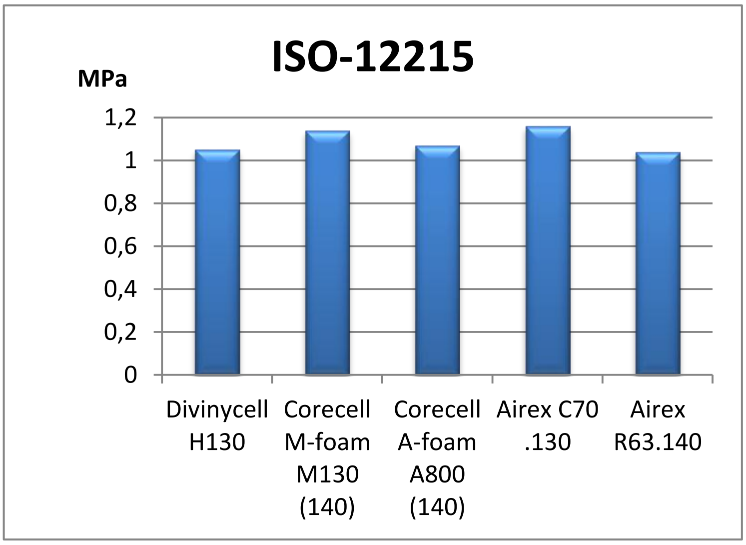
Properties	Test Method	M60	M80	M100	M130	M200	Unit	
Density (nominal)	ASTM D1622	65	85	107,5	140	200	kg/m^3	msv
Density	ASTM D1622	61	81	100	130	185	kg/m^3	msmv
Tensile strength	ASTM D1623	0,81	1,62	2,11	2,85	4,29	MPa	msv
Tensile strength	ASTM D1623	0,35	1,35	1,72	2,30	3,44	MPa	msmv
Tensile modulus	ASTM D1623	44	72	109	176	334	MPa	msv
Compressive strength	ASTM D1621-04	0,55	1,02	1,55	2,31	4,40	MPa	msv
Compressive strength	ASTM D1621-04	0,33	0,80	1,24	1,95	3,66	MPa	msmv
Compressive modulus	ASTM D1621-04	31	52	76	111	210	MPa	msv
Compressive modulus	ASTM D1621-04	21	42	62	94	168	MPa	msmv
Compressive modulus	ASTM D1621-73	45	71	107	170	317	MPa	msv
Compressive modulus	ASTM D1621-73	35	57	83	130	239	MPa	msmv
Shear strength	ASTM C273	0,68	1,09	1,45	1,98	2,95	MPa	msv
Shear strength	ASTM C273	0,55	0,96	1,26	1,75	2,64	MPa	msmv
Shear modulus	ASTM C273	20	29	41	59	98	MPa	msv
Shear modulus	ASTM C273	17	25	34	49	81	MPa	msmv
Shear elongation, at break	ASTM C273	53	58	52	43	20	%	msv
Heat resistance, % retention of shear strength, +45°C	ASTM C393	-	-	-	85	-	%	
Water resistance, % retention of shear strength	ASTM C393	-	-	-	93	-	%	
Slamming grade testing, shear strength	ASTM C393	0,76	-	-	2,3	-	MPa	msmv

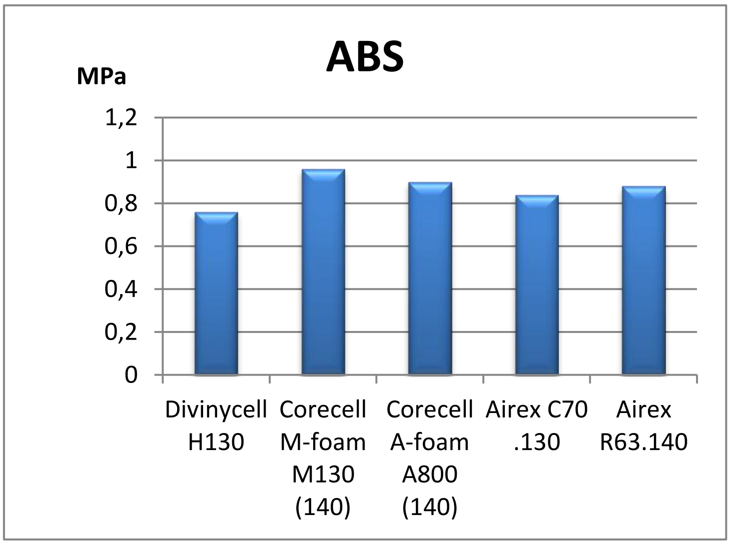
APPENDIX B – USE OF CORE MATERIALS IN DESIGN REGULATIONS

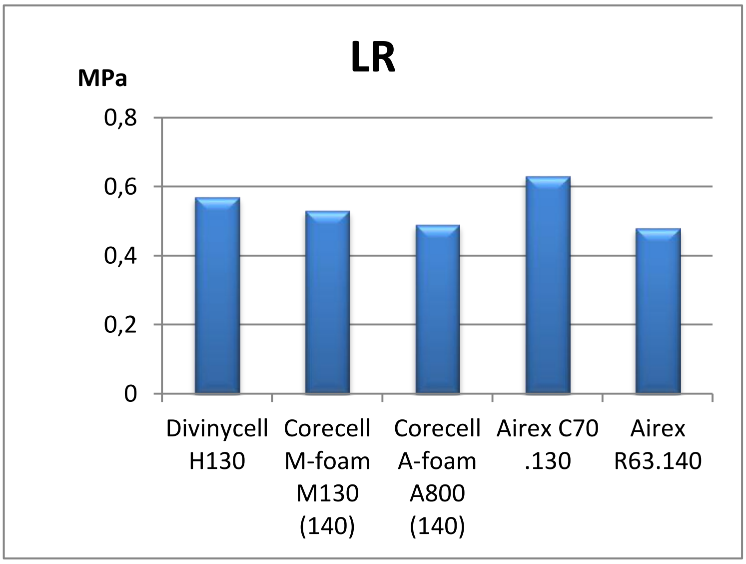
Uses of core material shear strength in different design regulations. Densities for the core materials were chosen to fulfill DNV-HSLC minimum core material density demand for sandwich panels exposed to slamming loads.

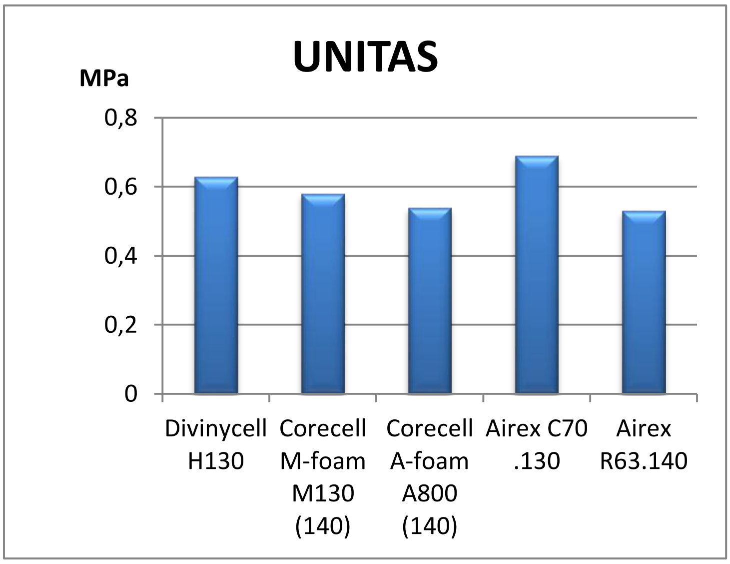






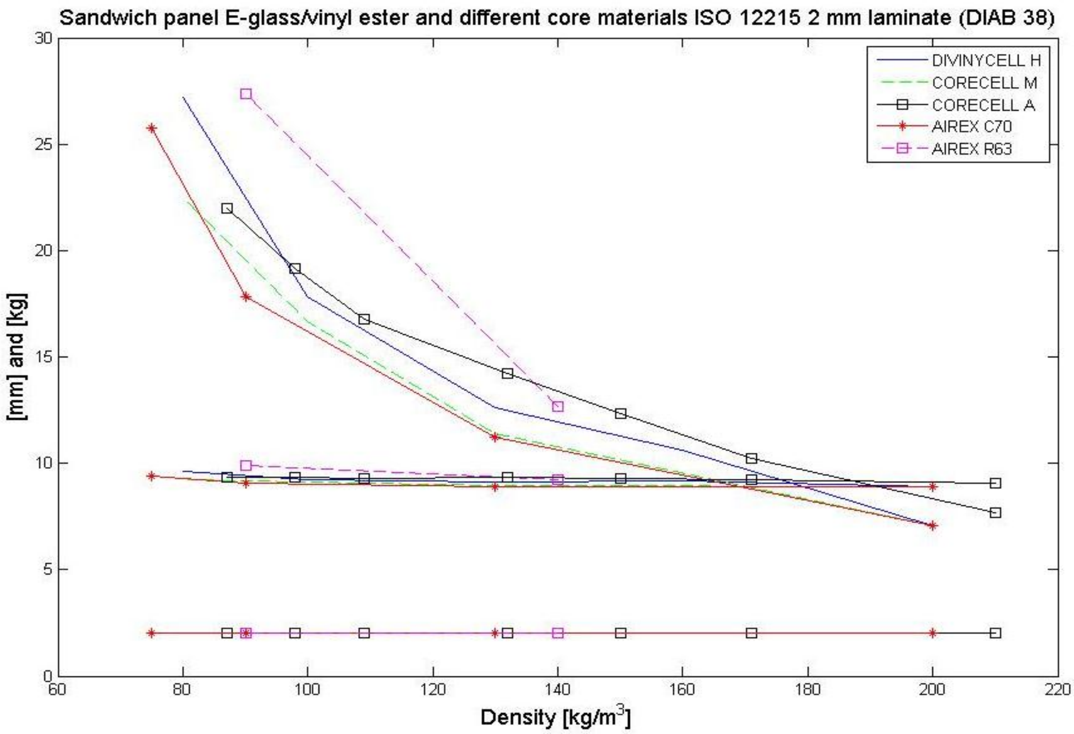






APPENDIX C – PANEL DESIGN ISO-12215 WITH 2MM LAMINATES

Panel design ISO-12215 with 2mm laminate thickness.



Restrictions working on panel with 2mm laminate thickness with core material Divinycell H.