APPLICATION OF GLASS FIBRE REINFORCED POLYMERS FOR CLOSED FISH FARMING

Halvor Larsson Aga[1,2,3], Saeed Bikass[2] and Gloria Stenfelt[2]

[1] Department of Physics and Technology, University of Bergen, Postboks 7803, 5020 Bergen, Norway
[2] Department of Mechanical and Marine Engineering, Western Norway University of Applied Sciences, Inndalsveien 28, 5063 Bergen, Norway
[3] Ovum AS, Kanalveien 52c, 5068 Bergen, Norway

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ABSTRACT

Closed fish farms address some critical issues in the aquaculture of salmon, where farms made of glass fibre are an interesting alternative to other material choices. To be competitive on cost when comparing to traditional methods including open net pens, it is important to design a structure that is safe, yet effective in the use of materials. The selection of rules and failure criteria is an important factor to achieve the lowest possible use of material. One failure criterion is the maximum strain criterion, which may be suitable to address fibre failure. To investigate the impact of rule selection, a series of tensile strength experiments are carried out on composite test coupons. These are cut from plates of uni-axial E-Glass and vinylester produced by the vacuum assisted resin transfer method. Five experiments are used to obtain characteristic breaking strains. These are used to establish the allowable strain for two different sets of rules, additionally two alternative applications within each rule is investigated. The resulting allowable strains differs by a factor of almost three.

1 INTRODUCTION

Due to challenges in the aquaculture industry related to sea lice and fish escape [1], there is a drive for new technologies. One of these technologies are closed fish farms, which solve some significant issues. These include; avoiding sea lice by drawing water beneath the unit, which is below the level where the sealice live, collecting waste and preventing fish escape by solid walls. There are some examples of closed fish farms made of composites, notably glass-fibre reinforced polymers (GRP); Aquafarm Equipment's Neptun [2], and Ovum's Egget® [3]. Egget®, as shown in Figure 1, has an egg shape with a buoyancy collar. The pilot has an internal water volume of 1800 m^3, a height of 22 m, and a diameter of 15 m. The large sheets are made of E-glass layers in a quasi-isotropic layup combined with a sandwich core and moulded in vinylester. The application of GRP in an ocean environment result in many challenges, e.g. the production of such a large composite structure is complex to handle and it must withstand dynamic loads induced by waves. Another challenge is how to ensure the structural integrity of the unit at the lowest possible cost. Selection of the failure criterion, related parameters and margins can support effective material usage. There are many different failure criteria for composite materials, as shown by the worldwide failure exercise [4]. Some require many experimental properties, while the simplest require only a few. These include the maximum stress and maximum strain failure criteria. Multiple failure criteria may be required for a complete structural assessment. The aim of this paper is to establish characteristic maximum strains for use with the maximum strain criterion. We will compare the allowable strains based on two different sets of rules from DNV.

Figure 1 – Egget® during production (photo: Thomas Morel)

2 THE MAXIMUM STRAIN FAILURE CRITERION

The maximum strain criterion requires checking that the strains in a material do not exceed the allowable strain. Its earliest reference seems to be by Waddoup in [5], which the authors have not had access to, however it is mentioned in both [6] and [7]. The criterion may be defined by

$$\varepsilon \leq \varepsilon_a = \frac{\varepsilon_c}{\gamma} \ , \tag{1}$$

where ε is the actual strain at any place in the material, ε_a is the allowable strain, ε_c is the characteristic strain, the strain which an individual breaking strain exceeds the value with a given probability, and γ is a reserve factor. For some composite structures, a check of the maximum strain is important to ensure material strength, and it may even represent the main structural assessment of strength for fibre failure. This is usually done for every ply. A simplification can be made for structures with strength in all planar directions (quasi-isotropic layups), where it is sufficient to investigate the ultimate strain in the corresponding directions. In [8] this is called the simplified strain criterion, and two central requirements to apply it is that there is minimum 12.5% fibres in each 45° material direction and that the strain failure limit is set to 1.2%, and the shear strain limit is set to 1.6%.

2.1 DNV Rules for High-Speed and Light Craft

An example of application of a maximum strain criterion can be seen in the DNV rules for high-speed and light craft (HSLC) [9]. It contains a separate chapter on Fibre Composites in the section for Hull Structures. These rules are relevant for high speed and/or light craft, and it must be noted that particularly with regards to the loading, this rule may not be relevant for Egget® in all respects. The rule permits the use of either default material properties or by material properties obtained by qualification testing. Qualification testing in this context means establishing the material data from experiments by following given procedures, while default material properties are tabulated in the rule. Among these properties is the allowable tensile strength, which is 1.2% for E-Glass. Alternatively, qualification tests may be carried out, where a minimum of five successful tests must be performed for each property. The mechanical strength, F_r, is calculated by

$$F_r = \bar{\mu} - 2.4\sigma\ , \tag{2}$$

Where μ is the individual mechanical strength from a test and $\bar{\mu}$ is the mean mechanical strength of the tests

$$\bar{\mu} = \frac{1}{n}\sum_{i=1}^{n} \mu_i \tag{3}$$

and σ is the standard deviation

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(\mu_i - \bar{\mu})^2\ . \tag{4}$$

Here, n is the number of tests and $\mu_i$is the individual test result. We assume that F_r can be taken as characteristic breaking strain and that μ, $\bar{\mu}$ and σ then relates to the ultimate strain in the experiments. To arrive at allowable strain, the characteristic breaking strain is divided by a reserve factor. For laminates this is set to 3. In the following we will investigate both the allowable strain based on default values (1.2%/3 = 0.4%) and allowable strain based on testing.

3.2 DNV ST-C501 Composite Components

A more general and comprehensive set of rules is the DNV ST-C501 – composite components (C501) [10]. This is can be used to design any composite component. The characteristic value of any material property is obtained by

$$x_c = \bar{x} - k_m\hat{\sigma}, \tag{5}$$

where x_c, $\bar{x}$ and $\hat{\sigma}$ are the characteristic value, mean and standard deviation of the variable x, which in our case is taken as ε for strain. The structure is classified in a reliability class from A to D, where the target annual probability of failure is known. Table 1 shows the reliability class, its corresponding annual probability of failure P_f and a statistical factor k_m, which is used in Equation 5 for five tests, both for any material and for materials that are well known. The standard defines this as a material combination with an E-glass or PAN carbon fibre, with polyester, Epoxy or vinylester resin, having a maximum strain exceeding 1.5 times the maximum strain of the fibre and that fibre and matrix must have been available in the market for more than five years. Further, the production process must be either vacuum assisted resin transfer moulding or filament winding and the curing schedule of the supplier of the resin must be adhered to.

Reliability class	P_f	k_m	$k_m{}^*$
A	10^{-3}	2.5	2.3
B	10^{-4}	2.9	2.3
C	10^{-5}	3.5	2.4
D	10^{-6}	4.4	2.5

* Known materials

Table 1 – Target annual Probabilities of Failure (P_f) and statistical factor (k_m) for five tests for Different Reliability Classes [10]

When it comes to the reserve factor, C501 includes both load effect and resistance in this. It is possible to use statistical models to establish it, or simplified ones can be selected from tables. These tables include both reliability class and the coefficient of variance. The coefficient of variance is calculated by dividing the standard deviation by the mean of the property, breaking strain in our case. Also loading is considered, however this is not the topic of this paper. Table 2 shows the simplified partial factor for the different Reliability classes.

Reliability class	COV< 10%	10%<COV<12.5%	12.5%<COV
A	1.2	1.3	1.4
B	1.3	1.4	1.6
C	1.5	1.6	2.0
D	1.7	1.9	2.5

Table 2 - Simplified Partial Factors from C501 [10]

In the following of this work both values for allowable strains based on any material and known material will be calculated.

3 EXPERIMENTS

The test setup consists of an Instron 8810 test rig with an extensometer and a 100kN load cell. The experiments are carried out at the Western Norway University of Applied Sciences (HVL), as shown in Figure 2. Vacuum assisted resin transfer moulding is used to prepare a flat plate consisting of two layers of uni-directional E-glass fibres with fibre-weight of 650g/m^2 in vinylester. From this plate, the test specimens are cut to length and width of approximately 250 mm and 15 mm. The long side is parallel to the fibre direction. The average thickness is 1.22 mm with a standard deviation of 0.05 mm. These are clamped directly into the testing rig. The breaking strain is generated for each experiment as the maximum strain measured. The ISO527-5 [11] is used as a reference for the testing setup.

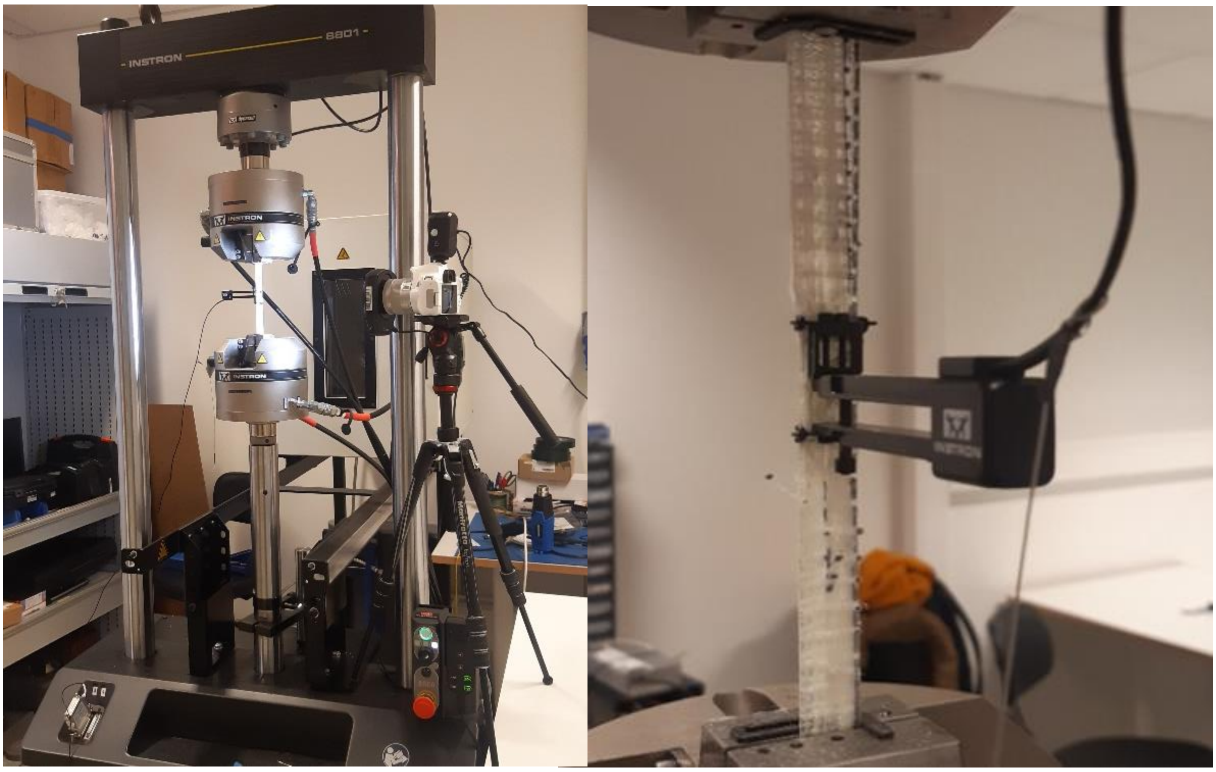

Figure 2 - Overview of the experimental setup with the testing rig on the left and an example test specimen after failure on the right

4 RESULTS

The force vs strain curves are shown in Figure 3, the relation between force and strain is close to linear and the points of failure are close. The maximum strain is easily identified for each experiment and displayed in Table 1. From these values the mean, standard deviation and coefficient of variance is calculated and shown in Table 3. The low coefficient of variance underpins that the test specimens and experimental setup supports a high repeatability of the test. The production of the plates was in an industrial environment using vacuum assisted resin transfer and dissimilarity in the material between the test specimens are seen as a minor uncertainty. Since each specimen were manually cut, both the size and angles have a degree of uncertainty. A systematic uncertainty is the calibration of the extensometer and load cell of the tensile machine, for which no calibration record was available. From the statistical values the allowable strains are calculated, as seen in Table 4. For easy comparison Table 5 has been set up with an overview over the different rules, including a row with a comparison between the allowable failure strains relative to HSLC with default material values. The statistical coefficients (k_m) and reserve factors (γ) are selected from the corresponding rules.

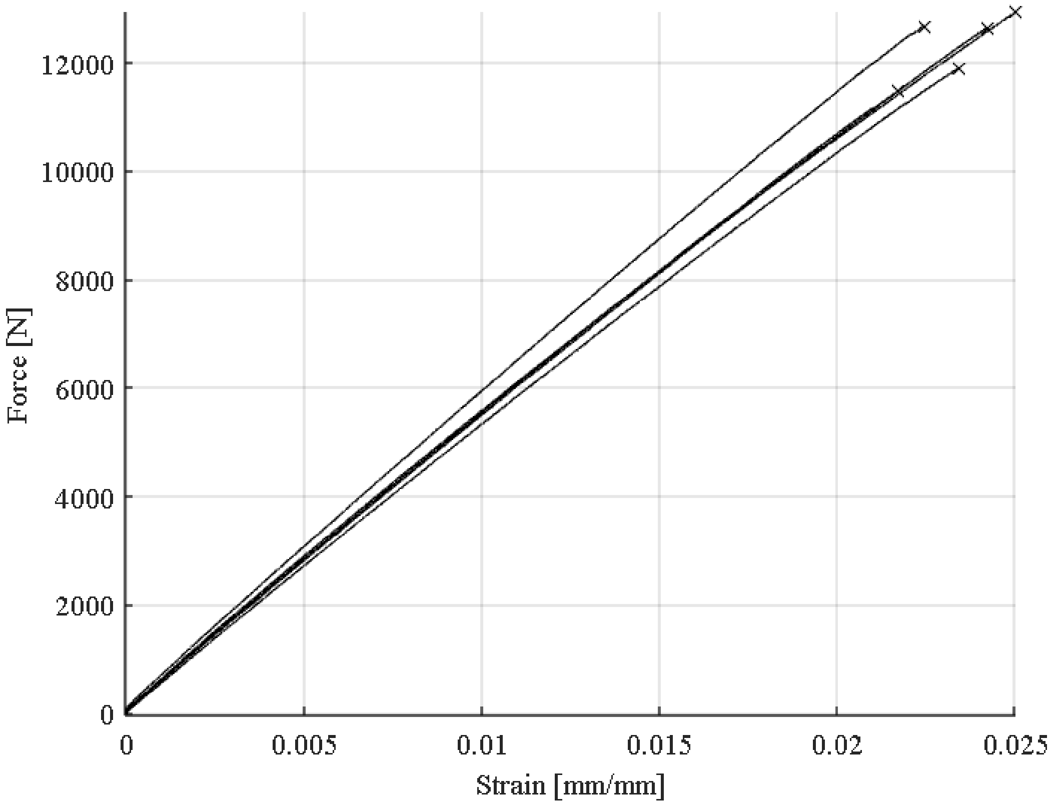

Figure 3 - Resulting force strain curves (

Test n	Breaking Strain ε_n
1	0.0242
2	0.0234
3	0.0250
4	0.0225
5	0.0217

Table 3 - Results of Each Tensile Test

Variable	Result
μ	0.0234
σ	0.0013
COV	0.0555

Table 4 - Results from tensile experiments

i	*Rule combination*	k_m	ε_c	γ	ε_{ai}	$\varepsilon_{ai}/\varepsilon_{a1}$
1	DNV HSLC with default strain	NA	0.0120	3	0.0040	1.00
2	DNV HSLC	2.40	0.0238	3	0.0067	1.68
3	DNV C501	4.40	0.0216	1.7	0.0103	2.58
4	DNV C501 with known materials	2.50	0.0237	1.7	0.0118	2.95

Table 5 – Calculation of Allowable Strain for Each Rule Application

It is evident that by applying the most advanced rule results in an allowable strain three times that of the least. The two intermediate rule combinations have allowable strains in the interval between these.

4 DISCUSSION

Table 5 shows that the allowable strain increases with the increase of requirements given by the rules. The difference between HSLC with standard material values and C501 with known materials is three. It is the impression that C501 considers only the fibre failure with the strain limit and that matrix cracking are handled in the other parts of the rule. HSLC is set up in a manner where micro cracking of the matrix is checked indirectly by the maximum strain criterion due to the high reserve factor, under the assumption that failure is fibre-dominant. By applying the C501 with known materials, the allowable strain is three times that of HSLC with default values. This may result in large overspend in material that the designer must be aware of when selecting the rule. On the other hand, the actual saving may not be that large when other effects are investigated which may lead to other failures before the allowable strain is reached. In the case of applying HSLC for a structure which is outside of its scope, it is important to investigate failures that may not be addressed. Even if HSLC seemingly contains conservative material data and large reserve factors, it cannot be ruled out that certain aspects may not be conservative without further investigations. By applying the C501 this is accounted for by the rule and so the structure can be designed to have appropriate reserve factors for each mode of failure. This may require a more rigorous design process, and for this reason the selection of rule is a trade-off between design effort and opportunities for optimising the structure. Because of this, a simpler design process based on large reserve factors may still be the choice for pilot projects.

5 CONCLUSION

The allowable strain by using C501 with known materials may be three times higher than the allowable strain by using HSLC with default material values, based on studies of the two sets of rules and example tensile testing.

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REFERENCES

[1] Grefsrud et al. RISIKORAPPORT NORSK FISKEOPPDRETT 2022 – RISIKOVURDERING, Havforskningsinstututtet, 2022

[2] NRK, Her løftes verdens største lukkede merd, 2015, https://www.nrk.no/vestland/her-loftes-verdens-storste-lukkede-merd-1.12622543

[3] TV2, Dette Egget skal vere med å revolusjonere lakseoppdretten, 2022, https://www.tv2.no/nyheter/innenriks/dette-egget-skal-vere-med-a-revolusjonere-lakseoppdretten/14780187/

[4] M. Hinton, P. Soden, and A.-S. Kaddour, Failure criteria in fibre reinforced polymer composites: the world-wide failure exercise. *Elsevier*, 2004.

[5] Waddoups, M. E., Characterization and design of composite materials. In *Composite Materials Workshop*, ed. S. W. Tsai, J. C. Halpin and N. J. Pagano. *Technomic, Connecticut*, 1968, pp. 254–308.

[6] Ever J. Barbero, Introduction to Composite Materials Design, *CRC Press*, 2018

[7] L.J. Hart-Smith, Predictions of the original and truncated maximum-strain failure models for certain fibrous composite laminates, *Composites Science and Technology*, 58, 1998, pp. 1151-1171 (doi: https://doi.org/10.1016/S0266-3538(97)00192-9).

[8] CROW, CROW-CUR Recommendation 96:2019 Fibre.reinforced polymers in buildings and civil engineering structures, 2019

[9] DNV, DNV-RU-HSLC Pt.3 Ch.4 Hull structural design, fibre composite and sandwich constructions, 2021

[10] DNV, DNV-ST-C501 Composite components, 2022

[11] Standard Norge, NS-EN ISO 527-5:2021, Plastics — Determination of tensile properties — Part 5: Test conditions for unidirectional fibre-reinforced plastic composites (ISO 527-5:2021), 2021