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Reliability Assessment of Flax/Epoxy Composites for Structural Applications

By

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Thesis for the degree of Doctorate of Philosophy

May 2019

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Abstract

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Due to environmental challenges it is important to investigate potentially more sustainable materials. One material with particular promise includes flax fibre reinforced composites which the literature proposes have excellent specific Young's moduli and is already being used in a number of applications. However the large variability in the fibres' properties is seen as major drawback to their use in structures and indicates a need to determine how the laminate properties vary. In addition, the limited assessments conducted at the structural scale demonstrate a change in behaviour in comparison to conventional composites. This indicates a requirement to perform further structural level assessments to see how this change in behaviour might affect the reliability of a flax structure.

In this thesis the reliability of flax fibre/epoxy composite structures is assessed to compare them to current E-glass/epoxy ones and determine whether they can be a suitable alternative. First the impact of the high variability in fibre mechanical properties on the laminate properties is evaluated by testing: 95 yarn specimens, resulting in a coefficient of variation of 18.6% for the Young's modulus, 20 cloth specimens and 122 laminate specimens, for which the coefficient of variation of the Young's modulus decreases to 5.08%. This shows that flax fibre reinforced epoxy composites have comparable variability to synthetic based composites and demonstrates that flax fibre reinforced composites have reproducible properties at the macroscale level. However, the behaviour at the laminate scale differs from standard composites with a larger difference in laminate properties than expected. Simulations are performed to assess the behaviour of flax at structural scale which demonstrate a change in structural response between flax and standard composites, with flax experiencing higher stresses than expected for a lower Young's modulus but the same topology. This behaviour is then captured in a computationally efficient analytical model of a grillage; it is generally shown to predict the stress to within 5% of an FEA model. In this analysis

flax is shown to be more sensitive to transverse Young's modulus than standard composites and a better characterisation of this property is required. The capabilities of flax at the structural scale are then investigated using reliability analysis to generate flax structures with an equivalent safety to those in E-glass, accounting for the change in behaviour. An extensive literature review of flax laminate mechanical properties is performed to define their range and variations. These values are used to simulate probabilities of failure which demonstrate that flax structure needs to be 2.4 times heavier than the E-glass structure to have an equivalent mean stress to mean strength ratio. It concludes that flax fibres might be used in some applications but cannot replace E-glass in volume constrained structures.

Further investigations should be conducted before flax fibre reinforced composites can be safely considered for structural applications, this includes: a better characterisation of the transverse and compressive properties, improvements in the manufacturing techniques likely to be used for large structures to improve the fibre volume fraction, a wider range of structures to determine if the sensitivity to transverse properties is grillage specific and confirmation of these findings through structural scale experiments.

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Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

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Blanchard, J.M.F.A., Sobey, A.J. and Blake, J.I.R., Multi-scale investigation into the mechanical behaviour of flax in yarn, cloth and laminate form, Composites Part B, 2016, vol. 84, pp. 228-235

Blanchard, J.M.F.A., Mutlu, U., Sobey, A.J. and Blake, J.I.R., Modelling the different mechanical response and increased stresses exhibited by structures made from natural fibre composites, Composite Structures, 2019, vol. 215, pp. 402-410

Blanchard, J.M.F.A. and Sobey, A.J., Comparative design of E-glass and flax structures based on reliability, Composite Structures, 2019, vol.225, In Press

Signature:		Date:	

Acknowledgements

The author would like to thank her supervisors, Dr. Adam Sobey and Dr. James Blake for their guidance, time and support during all these years. The author also would like to thank Paul Bossens from Isolutions for providing additional computers to run the final simulations.

The author would like to thank Prof. Philippa Reed and Dr. Hom Dhakal for their help as examiners to improve this work and to kindly agree to examine the thesis at very short notice. The author also would like to thank Prof. Mark Spearing for his advice and guidance during the project.

The author would like to thank her parents for their constant support.

Finally the author would like to thank Lloyds Register Educational Trust for funding part of this project.

Definitions and Abbreviations

Retting: process employing the action of bacteria and moisture on plants to dissolve or rot away part of the cellular tissues surrounding bast fibre bundles and facilitate the separation of the fibres from the stem.

Hackling: process of splitting and straightening flax fibres to remove the fibrous core and impurities.

Scutching: process of separating the impurities from the fibres.

E: Young's modulus

CoV: Coefficient of variation

FEA: Finite Element Analysis

CLPT: Classical Laminate Plate Theory

STDEV: Standard deviation

TS: Tensile strength

UD: Unidirectional

RTM: Resin Transfer Moulding

Nomenclature

E_1	Longitudinal Young's modulus
E_2	Transverse Young's modulus
E_c	Composite Young's modulus
E_f	Fibre Young's modulus
E_m	Young's modulus of the matrix
F	Empirical grillage factor
G_{12}	Shear modulus
P_f	Probability of failure
S_{12}	Shear strength
V_f	Fibre volume fraction
V_m	Matrix volume fraction
W_f	Fibre weight fraction
W_m	Matrix weight fraction
X_c , X_t	Longitudinal compressive and tensile strengths
Y_c, Y_t	Transverse compressive and tensile strengths

ε_1	Strain 1
ε_2	Strain 2
η_d	Fibre diameter distribution factor
η_l	Fibre length distribution factor
η_o	Fibre orientation distribution factor
κ	Fibre area correction factor
ν_{12}	Poisson's ratio
ρ_c	Density of the laminate
ρ_f	Density of the fibres

Chapter 1 Introduction

1.1 Sustainable replacement for fibre reinforced composites

There is a rising demand for more sustainable materials. Whilst fibre reinforced composites are increasingly used for structural applications they can have an adverse environmental impact, both during manufacturing and at the end of life of the structure. E-glass is the most commonly used material and represents 87% of the 8.7 million tonnes of the global composite market, Shah [1]. The ability to replace some or all of these composites with sustainable alternatives will provide a cleaner environment both through reduced energy in production, where a flax fibre mat takes less energy to produce, 9.55 MJ/kg, than an E-glass fibre mat, 54.7 MJ/kg, Joshi et al. [2], and to reduce problems of recyclability at end of life, Mahboob et al. [3], as illustrated in Figure 1.

Figure 1: E-glass vessel abandoned near the Mediterranean [4]

The demand for environmental sustainability has led to an increasing interest in natural fibre reinforced composites, which is reflected in the high number of publications on this topic with 765 journal papers published on flax fibre laminates alone in the top 4 composite journals (Composite Science and Technology, Composites Part B, Composites Part A and Composite Structures) in the last 5 years. This interest is partly because of the natural fibres lower environmental impact during production and improved biodegradability at the end of life but they also have a number of other beneficial properties: they are widely available; have a low density, leading to high specific properties; are easy to handle and process; are non-abrasive on tooling and present no health risks for the production workers as demonstrated by Wambua et al. [5], Bensadoun et al. [6], Ali et al. [7], Kersani et al. [8] and Shah [1].

There are a number of promising natural fibres such as flax, hemp, jute or bamboo. However, flax is considered to be the leading contender to replace E-glass due to its higher mechanical properties combined with low weight [3] [9] [10] [11] [12]. Furthermore, flax fibres are easily grown in Europe with large quantities available and therefore a good choice as a sustainable material for the European composite industry [9] [13] [14]. Their low cost is also cited as an additional advantage, [12] [3] [10], despite the cost of natural fibres still being higher than E-glass [15]. In addition their good acoustic and thermal insulation and enhanced vibration absorption can provide benefits in certain applications [11].

The interest in natural fibre reinforced composites is driven by environmental awareness but safety and structural longevity are key concerns if these materials are going to be a successful replacement. Therefore, natural alternatives must have a mechanical performance that is comparable to standard composites if they are going to be successful. A number of authors show that this is the case as the low density of flax fibres leads to the specific properties being equivalent or better to E-glass [3] [11] [16] [17] [18] [19] [20] [21] [22] [23] [24]. In addition the literature often assumes that high specific properties at the fibre scale give high laminate mechanical properties. Therefore, a number of authors propose that flax fibre reinforced composites have the potential to be used in structural applications [25] [26] [27] [18] [14] [10] [28] [12] [29], but investigations at the structural scale to support this assumption are limited.

These interesting properties and potential have led to growth in the market size of natural fibre composites from 43,000 tonnes of natural fibres used for composite reinforcement in the EU in 2003 to around 315,000 tonnes in 2010 [30]. According to the author this figure represents 13% of the total fibres used by the composite industry, including glass and carbon, and this explosive consumption indicates a wider usage in the near future, Yan [30]. There is a need for more sustainable materials and EU regulations on end of life vehicles [31] which has pushed the automotive industry to adopt natural fibre reinforced composites, Bensadoun et al. [6]**,** where lightweight components can be produced with natural fibre reinforced composites and reduce the carbon emission and fuel consumption of the vehicle, Bensadoun et al. [6]. Therefore, natural fibre reinforced composites are already used in mass production by the automotive industry but mainly for non-structural parts such as interior door panels, dashboards and seat backs, often manufactured with short randomly orientated fibres and compression moulding, Fortea-Verdejo et al. [32], Martin et al. [33], Yan [30], Ahmad et al. [34] and Shah [35]. For commercial applications, over 95% of natural fibre reinforced composites produced in the EU are for the automotive industry, Shah et al. [1]. Recently a few sporting applications: bicycle, surfboard, skis presented by Pil et al. [36], prototype sailing dinghies, [37], [38] , [11], and a research project on wind turbine, Shah et al.

[39]; use flax fibre reinforced composites for load bearing structures and there is a growing interest to investigate their potential for structural applications, Shah [35] and Hänninen et al. [40].

However, as highlighted by Mahboob et al. [3], the adoption of flax fibre reinforced composites for load bearing applications by the industry is prevented by a lack of confidence in their structural performance and the number of challenges associated with the development of new materials. A number of issues are identified in the literature as limiting factors for structural applications and presented in Table 1.

Table 1: Issues for flax fibre reinforced composites at the structural scale identified in the literature

Issues for structural scale applications	References
Perceived variability at the fibre scale	Mahboob et al. [3] Philips et al. [41] Van de Weyenberg et al. [42], Aslan et al. [43] Lefeuvre et al. [44],
Difficulties to predict laminate properties with fibre data	Shah et al. [45] , Madsen et al. [46], Hristozov et al. [47] and Hänninen et al. [40],
Poor fibre/matrix interface	Yan et al. [25], Charlet and Beakou [13], Kersani et al. [8],
Limited durability and high moisture uptake	Dhakal et al. [48], Yan et al. [25], Assarar et al. [49] and Hristozov et al. [47],
Limited data on fire behaviour	Shah [35]
Inadequate understanding of the processing and manufacturing requirements	Shah [35]
Lack of testing standards	Moothoo et al. [50], Bensadoun et al. [51], Haag and Müssig [52]

As seen in Table 1, a number of concerns are raised in the literature which need to be investigated for the utilisation of flax fibre reinforced laminates at the structural scale. However, modelling of a flax structure in intact conditions might be beneficial before all these more detailed elements are investigated.

1.2 Research aim and objectives

The aim of the project is to investigate whether flax fibre reinforced composite materials can be an alternative to conventional composites for structural applications. This aim will be met through a number of objectives:

- Conduct a literature review to identify the current understanding of the relationship between flax material properties and their structural response.
- Determine the mechanical properties and the variability of flax through experimental testing at different scales, from yarn up to laminate scale.
- Model the structural response of flax fibre reinforced composites.
- Compare the reliability of stiffened structures manufactured with flax or E-glass reinforced composites.

1.3 Research novelty

The novelty in this study is to perform a reliability assessment of a structure made of flax fibre reinforced composites allowing a comparison with standard E-glass composites. This is achieved by understanding the impact of the flax fibres' variability on the laminate properties, establishing whether this is an issue for structural response, and deriving distributions for the key material properties which are required for structural assessment. Modelling flax fibre reinforced laminates at structural scale, where a different structural behaviour is identified and a new analytical model of a grillage structure is developed to consider this specific behaviour at the structural scale. These allow the ability to assess the reliability of flax structures for the first time.

1.4 Scope of work

This thesis focuses on one type of material: flax fibre reinforced epoxy composite materials. Flax fibres are selected among all the natural fibres available in the market for their good mechanical properties for composite applications, low density, low cost and wide availability in Europe which is important to preserve the ecological advantages as shown by Charlet and Beakou [13] and Dittenber and GangaRao [12]. For structural applications, flax long fibres are preferred. To have a better understanding of the fibres' behaviour within the laminate, epoxy is selected as a conventional matrix with well-defined and stable properties. In addition, epoxy and flax fibres have good interface properties as demonstrated by Shah et al. [53], Seghini et al. [54] and Coroller et al. [55]. The project focuses on structural assessment in intact conditions as the structural behaviour needs to be investigated first. Large structural experiments are scoped out for expense and time constraints.

1.5 Outline of the study

The literature relating to flax composites' properties through the scales: fibre, laminate and structural, will first be reviewed in chapter 2 to define the novelty, followed by the research methodology of the thesis in chapter 3. The multi-scale experimental results of the flax fibre reinforced laminate's mechanical properties at the yarn, cloth and laminate scales will be presented in chapter 4, to demonstrate the impact of the fibre's variability on the laminate properties. A model of a flax stiffened structure is developed which demonstrates a change in behaviour in chapter 5 that is then captured in a rapid analytical model. The safety of flax structures is then demonstrated in chapter 6 using a reliability analysis. Chapter 7 discusses and proposes potential avenues for future research before being summarised in chapter 8.

1.6 Publications

Journals:

Blanchard, J.M.F.A., Sobey, A.J. and Blake, J.I.R., Multi-scale investigation into the mechanical behaviour of flax in yarn, cloth and laminate form, Composites Part B, 2016, vol. 84, pp. 228-235.

Blanchard, J.M.F.A., Mutlu, U., Sobey, A.J. and Blake, J.I.R., Modelling the different mechanical response and increased stresses exhibited by structures made from natural composites, Composite Structures, 2019, vol. 215, pp. 402-410.

Blanchard, J.M.F.A. and Sobey, A.J., Comparative design of E-glass and flax structures based on reliability, Composite Structures, 2019,vol. 225, In Press.

Conferences:

Blanchard, J.M.F.A., Sobey, A.J. and Blake, J.I.R., Reliability analysis of natural composite for marine structures, International Conference on Lightweight Design of Marine Structures 2015, Glasgow

Blanchard, J.M.F.A., Sobey, A.J. and Blake, J.I.R., Assessing the feasibility of natural composite for structural applications, 17th European Conference on Composite Materials, 2016, Munich

Blanchard, J.M.F.A., Sobey, A.J. and Blake, J.I.R., Research needs and future potential for natural fibre composites in structural applications, 20th International Conference on Composite Materials, 2017, Paris

Chapter 2 Literature review

A large number of studies are published on flax fibres and flax reinforced composites with 765 papers published in the 4 top composite journals in the last 5 years but only 4 at the structural scale. A literature review of the field is conducted with a focus on the utilisation of flax fibres in structural applications. The literature review is split between different scales: fibre, laminate and structure to understand the gaps in the research relating to the influence of the fibre and laminate scales on the structural response.

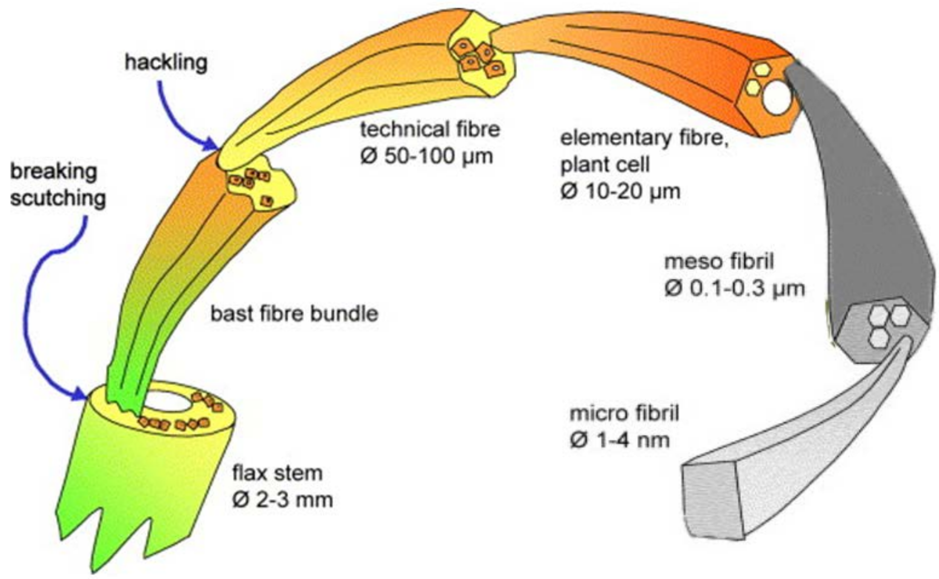


Figure 2: Relationships between scales of flax [56], with the reviewed constituents in colour

Flax fibres are extracted from plant stems and have a complex structure with different types of fibres presented in Figure 2 [57] [58] [59] and in order of size consist of: elemental fibres, technical fibres and yarns. This is one of a number of ontologies to describe the physiology of flax fibres with many different terms in the literature used by different authors. The smallest constituent investigated is the elemental fibres which are made up of continuous filaments with a limited length, Bensadoun et al. [51]. These elemental fibres are glued together with pectic cement in groups of 10 to 40 to form technical fibres, creating long fibres which are discontinuous where the elemental fibres join, Bensadoun et al. [51] and Thomason et al. [60]. During production, technical fibres are extracted from the stem of the plant after breaking, scotching and hackling. Elemental fibres can then be separated from these technical fibres by applying chemical and mechanical treatments, Rask et al. [59]. For composite reinforcements, yarns are produced by twisting together several technical fibres which can be partially separated into elemental fibres. Yarns are therefore composed of both elemental and technical fibres, Rask et al. [59] and the structure of a flax yarn is presented in Figure 3.

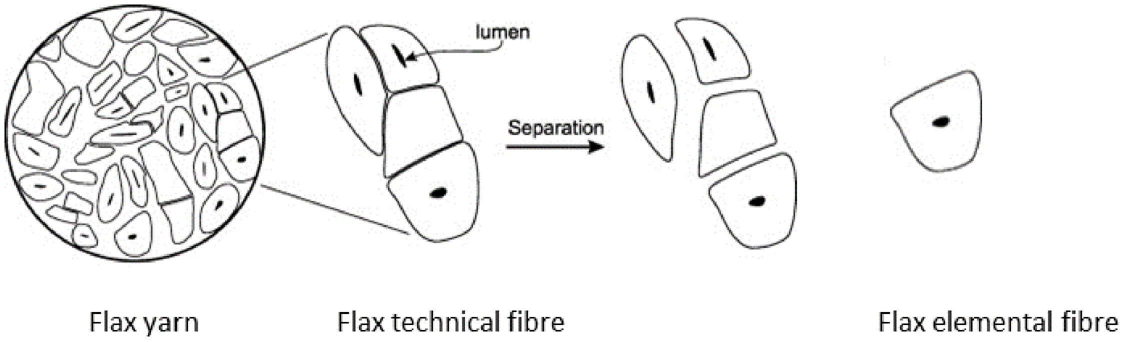
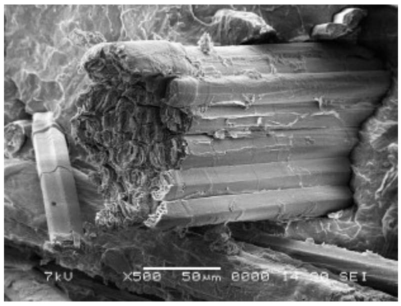


Figure 3: Schematic illustration of the cross-sections of flax yarn, technical and elemental fibres showing the relationship between them. Adapted from Rask et al. [59]

Yarns are then twilled into a cloth which can be infused with resin to construct a laminate. The definitions for flax fibres at different scales are shown in Table 2 but the difference between flax technical fibres and flax bundles is rather vague in the literature.

Table 2: Definition of the different natural fibre reinforced composite components

Scale	Definition	
Elemental fibre	Continuous short filament obtained by separating technical fibres by applying chemical and mechanical treatments which are extracted from the stem of the plant. [59] Synonym: Single fibres	
Technical fibre	Technical fibres flax fibres are composed of several elementary fibres glued together by pectin cement to create a discontinuous long fibre [51] [13] Synonym: “bundles” also called technical fibres [61]	 Technical flax fibre in a laminate [62]
Yarn	Group of elemental and technical fibres twisted together. [59] [63]	
Cloth	Texture produced by weaving or knitting yarns together to obtain directionally tailored properties. [63] Synonym: Fabric	
Laminate	Layers of cloth bonded together with a matrix. Synonym: Composite	

2.1 Fibre and yarn scales

The flax fibre literature is reviewed to determine what gaps are missing to evaluate the suitability of flax for structural applications. The review starts by exploring the literature related to flax fibres and yarns as the components of a laminate, investigating the available mechanical properties and characterising the behaviour of these fibres.

2.1.1 Mechanical properties of flax fibres

A number of studies present the mechanical properties of flax fibres with a large majority at the elemental scale. Baley [64] is one of the first authors, in 2002, to describe the composition, structure, density and defects of elementary flax fibres before considering their tensile mechanical properties. Since then a number of other studies have added to the available mechanical properties of elemental flax fibres which are presented in Table 3.

Table 3: Tensile mechanical properties of elemental flax fibres from the literature

Reference	Number of specimens tested	Young's modulus		Tensile strength		Ultimate strain	
		Average (GPa)	CoV (%)	Average (MPa)	CoV (%)	Average (%)	CoV (%)
Baley [64]	-	54	28	1339	36	3.27	26
Baley and Bourmaud [65]	**2954**	53	16	945	21	2.07	22
Charlet et al. [66]	90	54	54	1253	49	2.50	44
Charlet et al. [67]	122	63	57	1250	56	2.30	48
Bourmaud et al. [68]	90	54	27	1215	41	2.24	26
Bensadoun et al. [51]	50	57	23	791	40	1.80	28
Aslan et al. [43]	30	31	52	974	43	3.00	22
Andersons et al. [69]	260	34-42	30-35	520-880	34- 46	1.71 -2.70	26 - 37

The longitudinal Young's modulus, strength and strain of flax fibres are well characterised with average properties determined from a large number of specimens by different authors from different laboratories; the largest individual study is conducted by Baley and Bourmaud [65] with 2954 specimens tested. The Young's modulus ranges from 31 GPa to 63 GPa, the breaking strength from 520 MPa to 1339 MPa and the ultimate strain from 1.71 to 3.27%. However, the variability in mechanical properties is large with a coefficient of variation as high as 57% for the Young's modulus, 56% for the breaking strength and 48% for the ultimate strain and even the lowest coefficients of variation, 16% for the Young's modulus, is high.

Only a few studies determine other mechanical properties such as compression, transverse properties or Poisson's ratio. A compressive strength of 1300 MPa for elemental flax fibres is determined by Bos and Donald [56]. This work is extended by Bos et al. [9] who calculate the compressive strength of single flax fibres to be equal to 1200 MPa with a variation of 31%. The mean Poisson's ratio of flax fibres is calculated from UD laminate experiments and the rule of mixtures by Scida et al. [22]. The apparent Poisson's ratio of flax fibres is equal to 0.498 according to this study. The shear modulus of flax fibres is back calculated from laminate properties by Baley et al. [70] and equal to 2500 MPa. However, the relationship between fibre and laminate properties is not straightforward for flax fibre reinforced laminates.

There is a trend in the literature to state that the specific properties of flax fibres are comparable to E-glass and therefore flax fibres are a promising substitute for composite applications; [22], [71], [72], [73], [74], [75], [33], [16], [17], [18], [19], [20], [21], [23] and [24]. Thuault et al. [76] state that flax fibres approach the values of carbon fibres if the bending stiffness is considered and conclude that these comparisons highlight the potential of flax fibres for structural components. However, few studies compare the mechanical properties of flax fibres and E-glass with experiments and the results are presented in Table 4.

Table 4: Comparison between flax and E-glass fibre properties

Reference	Young's Modulus		Breaking strength	
	Flax	E-glass	Flax	E glass
Coroller et al. [55]	57.1 GPa	70.3 GPa	1135 MPa	1765 MPa
Lefeuvre et al. [71]	55.3-58.9	70.3-77.8	970 to 1109 MPa	1940-2319 MPa

Lefeuvre et al. [71] show that the variation in strength properties is higher for flax with a value of 38% compared to 22% for E-glass. Both Coroller et al. [55] and Lefeuvre et al. [71] highlight the advantages of the flax fibres' low density compared to glass fibres and therefore the interesting specific properties. The high specific stiffness of flax fibres is also highlighted by Baley and Bourmaud [65] who demonstrate that elemental flax fibres have an average specific tensile stiffness and breaking stress results comparable, or sometimes better, than E-glass fibres. Poilane et al. [77] also find that the specific stiffness of flax and E-glass are similar by using the median values from the literature. However, even if the specific stiffness is comparable, Goudenhooft et al. [78], Lefeuvre et al. [44] and Shah [1] find that the specific strength is lower with a specific strength of 523 MPa cm^3/g for flax compared to 748 MPa cm^3/g for E-glass, Lefeuvre et al. [44].

This shows that flax fibres have a lower Young's moduli than E-glass but when density is taken into account they have a comparable specific stiffness. However, the strength values are low and therefore even the specific strength is lower than E-glass which can be an issue for structural applications. Despite the low strength the literature generally still argues that flax fibres are a sustainable replacement for E-glass with comparable properties and that the lack of uptake is related to the variability of the fibres.

During the characterisation of the mechanical properties the flax fibres exhibit a different behaviour compared to E-glass. Coroller et al. [55] show a non-linear section in the stress-strain curves of the elemental flax fibres compared to the quasi linear behaviour of E-glass fibres illustrated in Figure 4.

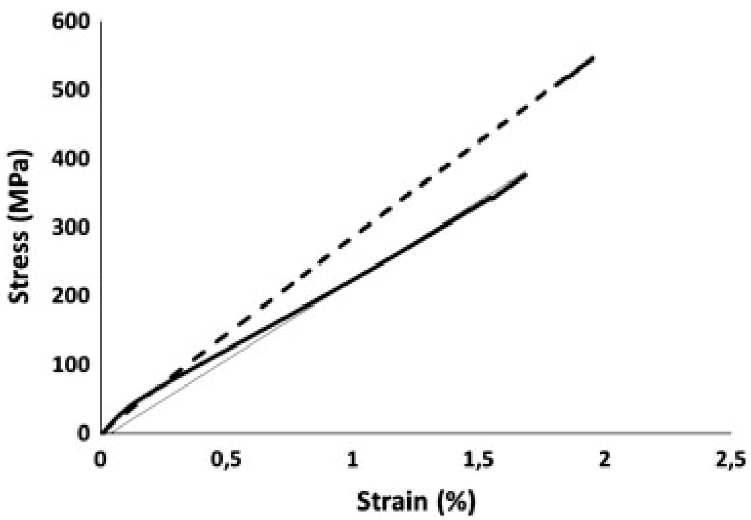


Figure 4: Tensile stress–strain behaviour of unidirectional composite reinforced by glass (▬ ▬) or flax (Hermes) (▬), Coroller et al. [55]

Lefeuvre et al. [79] identify 3 different stress-strain curves: linear, bi-linear, with two distinct linear sections, and one linear section followed by an increase in the tangent modulus. These differences in behaviour between specimens are also noticed by Aslan et al. [43] who present the tensile stress-strain curves of elemental flax fibres and two different behaviours are observed: linear or non-linear. It is also found that the mechanical properties of the non-linear specimens are lower than the nearly linear specimens with a Young's modulus equal to 24.2 GPa compared to 33.1 GPa and a tensile strength of 641 MPa compared to 760 MPa. Aslan et al. [43] found that the different behaviours are correlated with the number of defects and the difference in processing, with highly processed fibres having more defects and therefore these fibres more exhibiting a non-linear behaviour. The fibres with a linear section followed by an increase in the tangent modulus have the highest properties independent of the varieties. A third behaviour categorised with two different behaviours is also shown with a non-linear region for low strain values which is qualified of a elasto-visco-plastic deformation followed by a linear region with an elastic behaviour; [51], [69], [75], [80], [81], [82] and [45]. The non-linear region is explained by the authors and Aslan et al. [43] by the reorganisation of the cellulose microfibrils within the cell wall of elemental fibres. However, Andersons et al. [83] find that the stress-strain curves of elemental flax fibres are different between the specimens tested ranging from linear elastic, agreeing with Zafeiropoulos et al. [73], to strain hardening. Bensadoun et al. [51] find that the stress-strain curves exhibit a non-linear behaviour and conclude that it is required to calculate two different Young's moduli with two stiffnesses depending on the strain region. The initial Young's modulus is equal to 57 GPa and is calculated for a strain between 0% and 0.1% which decreases in the strain region 0.3-0.5% where it is equal to 44.5 GPa. On the other hand, Charlet et al. [66] find an initial modulus of 54 GPa and a final Young's modulus of 62 GPa. Bourmaud et al. [81] investigate 7 different flax fibre varieties cultivated between 2002 and 2008 and the stress-strain curves all show a non-linear region in the early stage of loading followed by an elastic linear region. Therefore, the authors conclude that the variety or year of cultivation does not affect the tensile behaviour.

A more complex behaviour is noticed by Coroller et al. [55] and Charlet et al. [84] who find that the tensile stress strain curves of elementary flax fibres can be divided in three sections: an initial linear part until 0.3% strain followed by non-linear part from 0.3 to 1.5% strain and a final linear part until failure. The tensile behaviour of flax fibres is more complex than the E-glass linear elastic typical stress-strain curves. An initial non-linear behaviour for low strains followed by a linear region is noticed by many authors. These changes in behaviour , with 5 different profiles for the stress-strain curve documented in the literature, makes the calculations of the Young's modulus and the values to use for modelling a complicated choice. The impact of the non-linearity on the calculation of the Young's modulus will be reviewed in section 2.1.3.

2.1.2 Influence of natural parameters on the variability

Flax fibres are a plant-based product and a number of studies, [60], [85], [86], [12], [42], [55], [87], [81], [88], [89], [65] suggest that the weather, location, harvesting conditions or genetics of the plants might be the cause of the large scatter in material properties. The impact of the weather, locations of the flax field, plant varieties, years, cultivation conditions and agricultural techniques on the fibre properties and variability are investigated by several authors and the findings are summarised in Table 5 with a complete version in Appendix A.

Table 5: Influence of natural parameters on the flax fibre properties

Natural factors	Mechanical properties	References
Time of cultivation	Statistically stable over years and not impacted by the weather conditions	[65], [44], [71], [90], [91]
	Impacted by the years of cultivation	[75] ,[81]
	Fibres exposed to hail have a lower tensile strength	[55]
Varieties	Mechanical properties are not impacted by the varieties	[65], [78]
	Mechanical properties are impacted by the varieties	[75], [55]
	Out of 4 or 7 varieties, depending on the study, the maximum and minimum stiffness values are for the same variety	[81], [92]
Location of fibres in the stems	Elemental fibres extracted from the middle of the stem have the highest properties followed by the top and the lowest properties for the bottom section	[82] [92] [93] [94]
Agricultural practice	High seeding rates decrease the mechanical properties	[95]
	Highly retted fibres have higher mechanical properties	[75] [33]

Flax fibres are a natural product agriculturally cultivated in varying weather conditions, with different amounts of: rain, hours of sun, temperature, soil pH or special climatic events such as hail depending on the years. The findings on the influence of the cultivation year and the impact of the variety selected on the fibre mechanical properties are contradictory and the spread of data is a major obstacle to draw firm conclusions. However, it is demonstrated that fibres extracted from the middle of the stem have the highest properties and highly retted fibres, fibres soaked in water to soften them, also demonstrate higher properties. These factors need to be considered for composite applications.

During the characterisation of the mechanical properties different authors tested enough specimens to model the statistical distribution of the mechanical properties of flax fibres and determined whether the natural growth factors and manufacturing process change the distribution of properties from the Normal distribution common for most materials. Coroller et al. [55] present the tensile properties of three different varieties of flax elemental fibres and the Weibull distribution is proposed and is validated to show a good fit for the tensile strength values with the Anderson-Darling test for E-glass and two varieties of flax fibres: Hermes and Marylin. However, one flax variety, Andrea, cannot be modelled with the Weibull distribution, which the authors put down to these fibres being exposed to hail during growth. Andersons et al. [83] also model the strength distribution with a two parameter Weibull distribution which approximates the experimental data for 3 different gauges length "reasonably well" according to the authors. The failure strain is also modelled with a modified two parameter Weibull distribution but the distribution parameters are highly scattered. Andersons et al. [69] state that the strength distribution of elemental fibres follows a modified Weibull distribution. However, Lefeuvre et al. [44] find that the tensile properties of 8 different flax fibre samples are normally distributed according to the Anderson-Darling test with 95% confidence. However, there is no evidence to show the superiority of the Weibull distribution over the Normal distribution and more experiments need to be conducted to find the best distribution to model fibre properties. The location of the flax on the stem and different growth conditions during cultivation lead to high variability of the flax fibres, but despite this a standard Normal distribution provides a good approximation to this behaviour in most cases.

2.1.3 Influence of experimental errors

The experimental errors associated with testing flax fibres and the absence of specific standards because of the relative novelty of the materials are cited as possible causes of the uncertainty and variability on the fibre's mechanical properties, Shah et al. [45] , Haag and Müssig [52] and Hughes [87]. The uncertainties can be caused by the type of fibres tested (elemental or technical), the testing parameters such as the gauge length and strain rate or how the results are analysed with the measurement of the cross-sectional area and strain range used for the calculation of the Young's modulus.

Fibres are tested at the elemental scale and at the technical scale, however the literature does not always state the type of fibres tested between elemental and technical fibres and it can contribute to the variability of mechanical properties available in the literature as highlighted by Depuydt et al. [96], Shah et al. [45] and Pickering et al. [97]. The difference in these properties is large where Bos et al. [9] find that the tensile strength of technical fibre strength is 57% the strength of elemental fibres tested at the same gauge length. Charlet and Beakou [13] find a similar difference with technical flax fibres strength 2 to 4 times lower than the strength of elementary fibres when the gauge length is longer than the mean length of elementary flax fibres. These lower properties of the technical fibres compared to elemental fibres are also demonstrated by Bensadoun et al. [51], Depuydt et al. [96], Shah et al. [45], Andersons and Joffe [98], Andersons et al. [69], Mahboob et al. [3] and Joffe et al. [99].

The determination of the cross-sectional area of flax fibres is required to calculate their strength and Young's modulus. A wide number of studies, [68], [69], [71], [73], [99], [79], [85], [90] and [100] assume that the cross sectional area of elemental flax fibres is circular. Using this assumption it is possible to calculate the fibre cross sectional area by measuring the diameter along the fibre length, [58], [69], [76], [55], [44], [82], [83], [84], [93], [94] and [101]. However, the flax fibres have a complex structure and elemental fibres have a polygonal cross sectional area [59], [63], [64], [9], [22], [72], [99], [88], [101] and [102]. In addition the diameter of flax fibres varies along the length, Scida et al. [22]. These measurements are important as the circular assumption overestimates the cross sectional area and underestimates the strength and stiffness properties calculated from fibre tensile tests as demonstrated by Haag and Müssig [52]. Shah et al. [45] also find that the circular assumption underestimates the strength and stiffness of the fibres by 40 to 70%. The approximations and inaccuracy in the cross sectional area determinations is also cited as a source of errors in the strength and Young's modulus calculations by [51], [68], [71], [97], and [103].

The influence of the circular assumption on the fibre cross sectional area is investigated by Aslan et al. [43] who compare the fibre cross sectional area determined from diameter measurement along the fibre length and a circular assumption with the true cross sectional area of the embedded fibres measured with a scanning electron microscope. The average cross-sectional area measured with a circular assumption is 39% higher than the true cross sectional area. Thomason et al. [60] also compare the cross-sectional areas measured with an average fibre diameter estimated from 4 microscopic images along the fibre length with the true fibre cross sectional areas determined from microscopic images of embedded fibres. The cross-sectional area values are scattered but the measurements based on fibre diameter fall outside the 95% confidence limit of the true cross-sectional area and are on average double the values obtained from the true cross sectional area measurements. The true cross sectional area is difficult to measure before testing as the fibre needs to be embedded in resin and cut at regular intervals along the length. Haag and Müssig [52] compare three different types of non-destructive measurement techniques applied on the same batch of technical flax fibres: flatbed scanning and optical microscopy, which are both 1D techniques, with a laser-based fibre dimensional analysis system to obtain 2D measurements of the cross sectional area by rotating the sample within the laser beam. These techniques are compared with the true cross sectional area data measured with SEM. A Fibre Area Correction Factor equal to 1.76 is proposed to take into account the elliptical shape of flax fibres. The strength shows variation of up to 300% for the same fibre depending on which of the 4 techniques is used to calculate the cross sectional area.

In addition to the measurement of the cross-sectional area the method used to determine the Young's modulus needs adapting due to the change in behaviour of the stress-strain curve. The Young's modulus is calculated with different standards depending on the studies and the complex stress-strain behaviour means that the strain intervals used for the calculations can have a large impact on the results. There are 5 main methods used to perform this calculation:

- The AFNOR standard NF T25-501-2 specifically designed for flax but only available in French to calculate the Young's modulus of flax fibres which is extracted by linearly fitting the last part of the stress-strain curves before rupture according to Keryvin et al. [88] and Lefeuvre et al. [79]. This method is used by a number of authors, [65], [71], [75], [33], [88], [91], [95] and [104].
- The ASTM C1557-03 standard used by Perremans et al. [105].
- The ASTM D 3379 standard used by Aslan et al. [43] and Andersons et al. [83].
- Pillin et al. [75] , Charlet et al. [93] and Alix et al. [106] use the slope of the linear part of the stress-strain curves.
- Thuault et al. [76] use the slope of the loading curve in the final deformation stage to measure the Young's modulus.

Comparing some of these different methods Lefeuvre et al. [79] calculate the Young's modulus for flax specimens with one linear section followed by an increase in the tangent modulus with three different techniques: the XP T25-501 standard, which corresponds to the slope of the stress-strain curve before rupture, the tangent modulus at the threshold point and the tangent modulus at rupture. The tangent modulus at rupture demonstrates slightly higher values than the standard Young's modulus and the tangent modulus at the threshold point is significantly smaller. The different methods used for the calculation of the fibre Young's modulus and the non-linear tensile behaviour complicate the calculations and the understanding of the flax fibres, with a possibility that this increases the range of different material properties seen in the literature.

2.1.4 Yarn and fabric mechanical properties

Due to the short length of the elemental flax fibres, the fibres are often twisted together to obtain yarns which can be transformed into continuous reinforcements for laminate applications. At the yarn scale, additional parameters specific to the yarn can impact the properties such as the twist and twist angle in addition to parameters impacting fibre properties. However even if it is a required step for the production of flax fibre reinforcements it also has an impact on the laminate properties. The yarn tensile mechanical properties determined by different authors are presented in Table 6.

Table 6: Yarn mechanical properties from the literature

Reference	Number of specimens tested	Tensile modulus		Tensile Strength	
		Mean (GPa)	CoV (%)	Mean (MPa)	CoV (%)
Masseteau et al. [103]	-	11.5	14.8	191.4	16.7
Huang and Netravali [63]	20	12.1	21	353	18.2
Chabba and Netravali [107]	20	8.5	23.4	312	24.5
Xue and Hu [74]	30			707	
Yan et al. [85]	10	16.4	2.4	145.4	5.8

The yarn mechanical properties are less studied than the elemental and technical fibre scales and demonstrate lower properties compared to elemental and technical fibres with a mean Young's modulus between 8.5 and 16.4 GPa and breaking strength between 145.4 and 707 MPa. These low mechanical properties are explained by a different failure mechanism between the yarn and elemental single fibre by Yan et al. [85]. The mechanical properties within the same study are scattered with coefficients of variations up to 24.5%. Chabba and Netravali [107] justify the large variability by a variation of yarn diameters along the length which is also noticed by Mehmood and Madsen [14].The number of specimens tested in each study is also limited compared to testing conducted on smaller scales. Xue and Hu [74] find that the stress-strain curves present some sawtooth fluctuations caused by a step by step damage mode. Barbulée et al. [108] investigate the different failure mechanisms and the causes of the saw-tooth shape of the loading curves of flax slivers, described as a collection of disentangled and aligned technical fibres more or less bonded by bark residues or other tissues, under tensile loading. The acoustic emission data and optical microscopy analysis allow the authors to identify three types of damages: delamination in the bundles by breakage of the pectin links between ultimate fibres, delamination among adjacent bundles, successive ruptures of the bundles to explain the particular shape of the stress-strain curves.

2.1.5 Summary

Flax fibres and in particular, elemental and technical fibre scales are widely studied as shown in Table 7. There is a trend to say that flax fibre properties are equivalent to E-glass in the literature and experimental investigations demonstrate that elemental flax fibres have higher specific stiffnesses but lower specific strengths properties. However, the flax fibres' properties are scattered and the variability of the flax fibre properties is cited as a major drawback by a number of authors. This high variability in comparison to synthetic fibres is seen as an obstacle for composite applications and laminate properties predictions and an obstacle for structural applications for which reliable properties are required. The causes of this variability either due to their natural origins or the testing techniques are investigated. Flax fibres being a novel material, testing standards are commonly adjusted to consider the specificities of natural fibres and the different methods increase the spread of results. The cross sectional area measurement is often approximated with a circular assumption and causes inaccuracies and the non-linear stress-strain behaviours have an impact on the stiffness calculations. The comparison shows that technical fibres have lower mechanical properties than elemental fibres. Yarns properties are less studied though the available results show lower mechanical properties than at the fibre scale. The influence of the fibre properties at the laminate scale is reviewed in the following section.

Table 7: Summary of the literature at the elemental, technical fibre and yarn scales

Scales	Properties	References
Elemental and technical fibre	Tensile mechanical properties	[64] [65] [66] [67] [68] [51] [43] [69] [65], [44], [71], [90], [91] [75] [81] [55] [65], [78] [75], [92] [82] [92] [93] [94] [95] [33]
	Compressive mechanical properties	[56] [9]
	Comparison with E-glass	[71] [55] [71] [65] [77] [78] [44] [1]
	Statistical distribution	[55] [83] [69] [44]
	Comparison between elemental and technical fibres	[9] [13] [51] [96] [45] [98] [69] [3] [99]
Yarn	Tensile Mechanical properties	[103] [63] [107] [74] [85]
	Compressive mechanical properties	
	Comparison with E-glass	N/A
	Statistical distribution	

2.2 Laminate scale

Flax fibres are widely investigated at the fibre scale and demonstrate promising mechanical properties for utilisation in composite applications. However, as articulated by Shah et al. [45] “it is highly desirable to be able to predict composite properties (and behaviour) from data on fibre properties. This provides a cost-effective and time-saving route in developing optimised materials with reliable behaviour. Currently, this is not possible with plant fibres and PFRPs. This is in part due to the naturally variable, stochastic properties of plant fibres, but also due to serious lack of studies relating plant fibre properties to composite behaviour.” Therefore, the laminate mechanical properties of flax reinforced composites are reviewed in this section together with a comparison of flax fibre laminates and E-glass composites. The objective is to determine the capability of flax fibre reinforced laminates for structural applications and therefore the focus is on aligned flax fibre reinforced composites, ignoring chop strand mat.

2.2.1 Laminate mechanical properties

Laminates of flax are made from infusing resin into a series of cloths or fabrics. These fabrics are therefore the last scale at which flax can be considered without the resin, though there is limited literature at this scale. The fabrics are made by weaving together yarns. The influence of the yarns' twist factors on the cloth properties are investigated by Omrani et al. [109] who present the mechanical properties of three different weave fabrics made with yarns with different twist factors. The force strain curves can be divided into two parts with a first non-linear section associated with the yarn's alignment followed by a linear part which represent the extension of the yarns. The weaving process has an impact on the fabric mechanical properties with the high twisted fabric having lower mechanical properties.

A summary of the flax fibre reinforced laminate mechanical properties available in the literature is presented in Table 8.

Table 8: Range of mechanical properties for unidirectional flax laminates from the literature

Mechanical properties		References
Longitudinal Young's modulus (GPa)	11-36.1	[77], [110], [20], [55], [89], [103], [53], [111], [94], [3], [14], [112], [113], [114], [24], [26], [115]
Longitudinal tensile strength (MPa)	113-547	
Transverse Young's modulus (GPa)	3.06-5.6	[3], [116], [29], [112], [113], [24], [14], [26], [117], [62]
Transverse tensile strength (MPa)	7.51-38.8	
Compressive longitudinal modulus (GPa)	15.1-30	[115] , [118], [72], [3], [24]
Compressive longitudinal strength (MPa)	115.4-136.9	
Compressive transverse modulus (GPa)	5.7- 5.93	[3], [24]
Compressive transverse strength (MPa)	80 - 100	[3], [24]
Poisson's ratio	0.34-0.43	[29], [3], [112], [113], [24]
Shear modulus (GPa)	1.53-2.19	[70], [3], [112], [113], [24]
Shear strength (MPa)	17.7 -39.7	

The mechanical properties presented in Table 8 are determined with a limited number of specimens, different fibre volume fractions and manufacturing techniques which can partially explain the large range of properties available in the literature. Liang et al. [24] show that the coefficients of variation for flax laminate mechanical properties are generally below 5% and are comparable to the variation seen in E-glass. However, this variation is obtained from only 5 specimens and are not conclusive and the large variability in flax fibre reinforced composite mechanical properties is cited as a major drawback for their utilisation for high performance structural applications by Mattrand et al. [61].

Torres et al. [26] experimentally determine the statistical distribution of unidirectional flax/epoxy laminate mechanical properties based on 40 specimens for the longitudinal tensile properties and 37 specimens for the transverse properties which are compared to 47 carbon specimens. The authors conclude that the variability of longitudinal flax laminate properties is lower than the carbon equivalent, 5.5% compared to 9%, and also significantly lower than the reported values for single fibre properties. However, the transverse strength has a variation of 12.9%. The Normal distribution best fits the elastic modulus for all configurations while the 2-parameter Weibull distribution provides the best fit for strength and strain.

The longitudinal tensile properties of unidirectional flax laminates are well defined, as seen in Table 8, however the number of studies determining other mechanical properties required for structural assessment are limited as shown by Mahboob et al. [3]. An inventory of the mechanical properties for flax laminates is presented of values available in the literature with 22 sets of data for the longitudinal tensile properties but only 2 references for the transverse properties. Liang et al. [24] support this stating that the compression and shear properties are important but not common in the literature in agreement with Baley et al. [115] who comment that they are a potential limiting factor for structural applications.

A number of studies investigate the properties of the laminates manufactured from these cloths but there is some disagreement over the comparison of their properties with E-glass. For example Lebrun et al. [89] state that the mechanical properties of unidirectional flax reinforced laminates are almost equivalent to unidirectional E-glass composites. Whereas Pil et al. [36] state that the longitudinal stiffness of flax laminates coincides with E-glass but the specific stiffness is higher and the bending stiffness is only 15-25% lower than that of carbon fibre composites. To compare the materials a number of authors use almost equivalent volume fractions, defined as a difference below 2%. Oksman [119] finds that laminates reinforced with “high quality” bio technically retted flax fibres manufactured via RTM are 26% stiffer than E-glass with an average Young’s modulus of 39 GPa compared to 31 GPa for E-glass and Mehmood and Madsen [14] find that the specific Young’s modulus of flax is 23 GPa/g/cm^3 compared to 20 GPa/g/cm^3 for E-glass. However, there is still some disagreement with Duc et al. [120] finding that the flax laminates are 43% less stiff than E-glass with a specific Young’s modulus 18% lower than E-glass. Coroller et al. [55] compare the tensile properties of UD flax laminates made with three different varieties of fibres with UD E-glass laminates and find that flax laminates with the highest properties have a Young’s modulus of 31 GPa compared to 34 GPa for E-glass but the flax variety with the lowest Young’s modulus is 35% less stiff than E-glass. However, all these authors conclude that flax laminates have lower strengths with values 65% to 34% lower than E-glass. These results show that some flax fibre reinforced laminates might be able to reach comparable stiffness properties to E-glass but it cannot be assumed without testing and the strength is significantly lower. Furthermore, even if comparing flax and E-glass laminate properties at equivalent fibre volume fractions is interesting to evaluate the effect of the fibre properties at the laminate scale, the fibre volume fractions used are often in the low range, 40% for Duc et al. [120], 45% for Coroller et al. [55], 48% for Oksman [119] , for E-glass laminates.

Using more realistic values for the volume fraction, Hristozov et al. [47] compare the mechanical properties of UD flax and E-glass reinforced laminates manufactured by hand lay-up and achieve a fibre weight fraction of 28% for flax compared to 58% for E-glass and therefore different mechanical properties with an average breaking strength of 207.42 MPa for flax compared to 865.35 MPa for E-glass and a Young’s modulus of 21.94 GPa for flax compared to 37.37 GPa for E-glass. Shah et al. [53] also obtain different fibre volume fractions for flax and E-glass laminates manufactured with resin infusion with 26.9-29.9% for flax compared to 42.6% for E-glass. The lower volume fraction of flax laminates reduces the mechanical properties to below those of E-glass but it highlighted that the density of flax laminates is 40% lower than E-glass and therefore the flax reinforcement showing the highest properties have a specific tensile modulus similar to E-glass but that the specific strength is still 40 to 60% that of E-glass. The mechanical properties of flax laminates are compared to E-glass and presented in Table 9.

Table 9: Comparison between flax and E-glass mechanical properties from the literature

Mechanical properties	Flax	Eglass	V_f (%)	References
Longitudinal flexural modulus of UD laminates (GPa)	19.51	20.80	25%	[121]
Longitudinal flexural strength of UD laminates (MPa)	182	450	25%	[121]
Transverse tensile modulus of UD laminates (GPa)	3.62	5.98	21.5%	[62]
Transverse tensile strength of UD laminates (MPa)	12.6	15.2	21.5%	[62]
Longitudinal compressive modulus of UD laminates (GPa)	30[1]	33[2]	50 wt%	[72]
Longitudinal compressive strength of UD laminates (MPa)	119 62	595 300	50 wt% 25%	[72] [121]
In plane shear modulus for UD laminate (GPa)	1.4	1.72	55%	[70]
In plane shear strength for UD laminate (MPa)	30.72 39.7	50.3 51.4	55% 43%	[70] [24]
in-plane shear modulus (GPa)	1.96	3.44	43%	[24]
Compressive modulus for [0/90] laminates (GPa)	13.0	27.3	43%	[24]
Compressive strength for [0/90] laminates (MPa)	98	405	43%	[24]
tensile modulus for [0/90] laminates (GPa)	14.5	21.9	43%	[24]
Tensile strength for [0/90] laminates (MPa)	170	380	43%	[24]

A number of studies investigate the properties of the laminates manufactured from these cloths but there is some disagreement over the comparison of their properties with E-glass. It is seen that at equivalent fibre volume fractions unidirectional flax laminates reinforced with some type of flax fibres can compete with E-glass in terms of longitudinal stiffness but cannot compete in strength and these fibre volume fractions are often lower than expected for E-glass laminates. The lower density of flax fibres is often cited as an advantage in terms of specific properties but the lower

[1] 1 specimen tested
[2] 1 specimen tested

fibre volume fraction of flax laminates reduces the difference in density to 26% at the laminate scale according to Liang et al. [24]. The flexural modulus is found to be equivalent between both materials by Goutianos et al. [121] but the flexural strength, transverse and compressive properties are lower and more data are required. Even if the longitudinal tensile properties of unidirectional flax reinforced composites are widely defined in the literature, the transverse, compressive and shear properties required for structural assessment and modelling tools are less common. Only a few studies determine all of the required properties. Most of the studies are conducted with a limited number of specimens, the lowest being 1 for the compressive stiffness determined by Bos et al. [72]. Mahboob et al. [3] use a minimum of three specimens which is not enough to gain confidence in the results.

At the fibre scale, the behaviour is non-linear and different to a typical E-glass stress-strain curve. The stress-strain relationship is also investigated at the laminate scale to see how this affects the laminate showing a similar non-linear behaviour in most cases. A number of experiments show that the stress-strain relationship of UD laminates can be divided into two regions with an initial linear elastic deformation up to a knee point followed by a drop of strain showing a difference between flax and E-glass laminates. [24], [77], [89], [113], [112]. The second region is classified as non-linear by Monti et al. [112] and Cherif et al. [113], quite linear by Liang et al. [24] and as viscoelastoplastic by Poilane et al. [77].The yield point and associated drop of strain is seen at different points. Lebrun et al. [89] find a yield point between 0.1% and 0.2%, Monti et al. [112] find a value of 0.11% and Liang et al. [24] find a knee point for a strain between 0.2 and 0.3%. Different explanations for the non-linear behaviour are put forward based on different observations. Poilane et al. [77] compare different matrices which do not present a yield point and conclude that it is caused by the flax reinforcement exhibiting a plastic deformation after a short quasi elastic region. Monti et al. [112] explain the non-linear behaviour by the non-linear response of flax fibres and Shah et al. [122] find that the non-linear behaviour is more pronounced as the fibre volume fraction increases. Berges et al. [29] conclude that the origin at the microstructural scale of this behaviour remains an open question in the scientific community.

However, Haggui et al. [123], Mahboob et al. [3] and Perremans et al. [23] find that the stress strain curves of flax laminates can be divided into three different parts with an initial linear region referring to elastic and reversible mechanical behaviour followed by a second non-linear transition stage and finally a linear and relatively inelastic behaviour. The initial linear part is observed up to 0.1% strain by Haggui et al. [123], 0.2-0.25% strain by Mahboob et al. [3] and Perremans et al. [23]. The third region starts after 0.35% strain according to Mahboob et al. [3]. The first region represents the initial elastic behaviour of the material followed by a visco-elastoplastic deformation of the amorphous components within the flax fibres and the orientation change of the microfibrils to align with the loading axis according to Perremans et al.[23]. The final linear region of the curves indicates that the re-orientation of the microfribrillar with the flax fibres is completed according to Mahboob et al. [3] whereas Perremans et al. [23] explained it by the accumulation of damages until final fracture.

Whilst most results show a non-linear behaviour that is different from standard composites Duc et al. [120] find that carbon, E-glass and flax UD laminates behave in a similar manner, with an initial linear elastic region followed by a point of inflection and a non-linear region at high strains. The difference between the materials is the transition which occurs at 0.6% strain for carbon and E-glass compared to 0.2% for flax. A non-linear behaviour is also found for the stress strain curves of UD specimens tested in the transverse directions [24], [3], [113], [116] and [123] and for compressive stress-strains curves by Liang et al. [24].

In terms of stiffness behaviour, Shah [124] investigate the stiffness ‘evolution’ during monotonic and progressive cyclic loading on two different flax reinforcements. The stiffness variation is separated into two regions with a dramatic reduction of stiffness in the order of 30-50% of their initial stiffness up to an applied strain of 0.4%. After this point, the stiffness stays constant. In comparison, E-glass has a reduction in stiffness of only 3% up to 0.4% strain and stiffness reduction of up to 10-15% around failure. The behaviour is also different between E-glass and flax with flax exhibiting a drastic drop in stiffness but thereafter stabilized and glass exhibits a gradual linear decrease in stiffness as the applied strain is increased. However, progressive cyclic loading experiments find that the initial stiffness is recovered and exceeded by up to 20% when the strain is released.

The mechanical behaviour and associated stress-strain curves of flax specimens is different to E-glass with a non-linear behaviour. Because of the non-linearity seen in the stress-strain curves of flax fibre reinforced laminates and the change of slope after the yield point, the strain range selected to calculate the Young’s modulus can have a significant impact on the result. The calculation of the Young’s modulus can therefore be questioned and especially the range of strain used to determine the value. Therefore a number of methods to calculate the Young’s modulus have been determined with a review of the different procedures used in the literature shown in Table 10.

Table 10: Different strain ranges used in the literature to calculate the Young's modulus

Strain ranges	Standard	References
0.05% and 0.25%	ISO standard 527-1 or 527-4 [125]	[24], [113], [101], [115], [126], [94], [127], [128]
0.1 to 0.3%	ASTM STANDARD D 3039/3039M [129]	[130], [85], [131], [18], [26], [21]
Slope of the linear portion		[123], [132]
Initial linear elastic domain		[49], [112], [77], [8]
0.1-0.2%		[41]
0.05% and 0.15%		[120]
0.01 and 0.10%		[14]
0.025-0.10%.		[124], [45], [53], [122]
0.3-0.5%.		[19]

The ISO 527-4 standard is described as non-appropriate for flax fibre reinforced laminates by Cadu et al. [133], Berges et al. [29] and Campana et al. [110] because of the non-linearity of the stress-strain curves with an inflection in the strain range used to calculate the Young's modulus. Cadu et al. [133] state that the standard will underestimate the value for the Young's modulus and Campana et al. [110] state that the value will be incorrect. Shah [124] proposes that the residual stiffness calculated from the second linear section of the curve might be a more appropriate value for the design of components made of flax fibre reinforced composites. The different methods used in the literature to calculate the Young's modulus where some consider the non-linear behaviour of flax laminates while some do not, can increase the variability in mechanical properties but also overestimate them if the first linear section is used for calculations.

To overcome the bi-linear behaviour different authors calculate two different moduli before and after the decrease in stiffness and the results are presented in Table 11.

Table 11: Young's modulus calculated at different strain rates

Strain range initial modulus	Initial modulus (GPa)	Strain range second modulus	Second modulus (GPa)	References
Before yield point	15.97	After yield point	10.86	[89]
0% and 0.1%	26.6	0.3% and 0.5%	20	[11]
0.01-0.15%	32.9	0.4% until failure strain	19.6	[29]
0.05 and 0.25% ISO STANDARD	17.9	0.5 and 0.8%	12.9	[110].

The tensile behaviour and associated stress-strain curves of flax fibre reinforced laminates are different to E-glass with a non-linearity. The two standards, ISO 527 and ASTM D3039 specify a range of strain to determine the Young's modulus but the inflection point of the flax laminate stress-strain curves is often in the same range. Therefore, some authors use a smaller strain values to calculate the Young's modulus in the linear section of the curve. However as the yield point is for low strain values and causes a large decrease in stiffness, Shah [124], this common practice can be questioned. The initial stiffness values are larger than the modulus calculated after the yield point and therefore the stiffness values available in the literature are likely to be higher than what can be expected in real life applications.

2.2.2 Comparison between fibre and laminate properties

The flax fibre scale is widely studied but the link between fibre and laminate properties is not well established. The influence of the fibre location in the stem on the UD laminate properties is studied by Charlet et al. [82], as it has a large impact on the fibre properties. The lowest fibre mechanical properties are found for flax fibres originating from the bottom part of the stem are used to manufacture a laminate with a Young's modulus of 11.1 GPa compared to 16.7 GPa for laminates manufactured with fibres originating from the middle section of the stem, which have the highest properties. This result is confirmed by Lefeuvre et al. [94] who compare the properties of laminates reinforced with flax fibres originating from the bottom, middle or top sections of the stem and demonstrate that the highest properties, E = 63.4 GPa (Young's modulus) and TS = 940 MPa (tensile strength), are obtained with the laminate reinforced with fibres coming from the middle section, followed by the top section, E = 50.8 GPa and TS = 760 MPa, and the bottom section which demonstrate the lowest properties, E = 48.4 GPa and TS = 590 MPa.

The influence of the variety of flax fibres used to manufacture laminates is investigated by Coroller et al. [55] who compare the tensile properties of laminates reinforced with 3 different varieties of elemental flax fibres: Hermes, Andrea and Marylin. At the fibre scale, Marylin fibres have the highest mechanical properties (E = 57.1 GPa / TS = 1135 MPa) followed by Hermes fibres (E = 48.9 GPa / TS = 1066 MPa) and Andrea (E = 48.3 GPa / TS = 841 MPa). At the laminate scale Marylin still demonstrates the highest stiffness, 34 GPa, compared to 28 GPa for Andrea and 26 GPa for Hermes but not the highest strength, despite the laminates being manufactured with similar fibre volume fractions. Hermes, which is 93% individualised, or more separated from each other, has the highest breaking strength, 408 MPa, followed by Marylin which is 69% individualised, 364 MPa, and Andrea which is 74% individualised, 290 MPa. Therefore, it can be concluded that the individualisation of the fibres has a significant impact on strength at the laminate scale but cannot be investigated at the fibre scale.

Haag et al. [27] analyse the influence of the year of cultivation of flax fibres on the laminate properties on ten different varieties cultivated over two consecutive years and find that the stiffness of laminates manufactured with flax fibres grown in 2012 are significantly lower than the stiffness of laminates manufactured with flax grown in 2013 for 7 out of 10 varieties. The authors conclude that the weather has a significant influence on the laminate properties. The influence of the variety on the laminate mechanical properties is also investigated based on the median values over two years and without taking into account the scatter of data. Out of the 10 varieties tested, Diane shows above average performance while Evea and Hermes demonstrate below average properties in both years. No conclusion could be drawn for the 7 other varieties.

Flax fibres have reasonable mechanical properties and specific properties in the range of E-glass properties however, the laminate properties are lower than E-glass and lower than expected from the fibre properties, though these results are not conclusive. Different factors which are seen as negatively influencing the laminate properties are investigated in this section. These studies show that the fibre scale mechanical properties have an influence on the laminate, such as the location of the fibre on the plant stems. Other parameters, such as the fibre individualisation, have a significant impact on the laminate properties and can only be investigated at this scale.

2.2.3 Fibre volume fraction

The fibre volume fraction plays a key role in the laminate mechanical properties however flax fibre laminates exhibit lower values than laminates manufactured with E-glass, Goutianos et al. [121]. Hristozov et al. [47] find a fibre weight fraction of 28% for flax compared to 58% for E-glass panels both being manufactured by hand lay-up. This low fibre volume fraction is caused by the low packability of flax fibres according to Madsen et al. [46]. Similar findings are presented by Shah et al. [53] who obtain a fibre volume fraction below 30% for flax panels compared to 43% for similar E-glass panels manufactured by resin infusion, even if the void content is similar for both materials with values between 0.5-2%. The authors conclude that this lower fibre volume fraction is a setback for flax composites and an increase in fibre volume fraction will substantially improve the properties. The relationship between the fibre volume fraction and the mechanical properties is also widely studied.

Charlet et al. [66] find that the tensile modulus of unidirectional flax laminates increases quasi-linearly with an increase in fibre volume fraction when in the 10% to 40% range. This is also demonstrated by Baley et al. [115] for the range 20% to 60% and Shah et al. [122] in the range 6.1% to 32.5%. Habibi et al. [117] find that the longitudinal tensile and flexural properties of unidirectional flax reinforced epoxy increase linearly with an increase in fibre volume fractions for 20%, 30% and 40%. This is supported by Hepworth et al. [134] who find that an increase in fibre volume fraction leads to an increase in Young's modulus up to a fibre content value of 68% after which the properties decrease from 22.45 GPa at 68% to 21.3 GPa at 80% fibre volume fraction; though the quantity of data is limited. Aslan et al. [135] also find that the stiffness reaches a plateau before decreasing for fibre weight fractions above 60%.

Charlet et al. [82] find yet another behaviour where the strength is higher than the linear prediction for volume fraction between 20% and 30% and lower than the linear prediction above 40%; though the strain is quasi constant for all volume fractions tested above 15%. This is confirmed by Shah et al. [122] showing a constant strain from 24% onwards. Oksman [119] finds that the strength reaches a plateau for volume fractions between 42 and 47%. However, a decrease in strength is found for volume fractions above 48.2% by Mehmood and Madsen [14] and this is supported by Hepworth et al. [134] where an increase in fibre volume fraction leads to an increase in breaking strength up to a fibre content value of 68% after which the properties decrease from 216 MPa at 68% to 187 MPa at 80% fibre volume fraction; though the quantity of data is limited.

The reasons for the lower fibre volume fraction achieved in flax laminates but also the drop in properties for higher fibre content are investigated by numerous authors. A higher porosity content is found in flax laminates compared to E-glass by Madsen et al. [136], which is caused by the presence of a lumen, the complex fibre/matrix interface, the heterogeneous form of flax fibres which restricts the impregnation, and the low packing ability, which limits the maximum obtainable fibre volume fractions. Based on the geometry of the plant and assuming that the flax yarns follow a square packing arrangement, Shah et al. [122] derive a maximum obtainable fibre volume fraction equal to 33.1% for UD laminate manufactured with flax yarns with a twist of 50 tpm.

Mehmood and Madsen [14] find that the porosity increases when the fibre volume fraction is increased. However, this is contradicted by Aslan et al. [135] where the porosity content of the flax yarn laminates manufactured with hot press are investigated at different fibre volume fractions and it is demonstrated that the porosity slightly increases at low volume fractions up to the transition stage which is at a weight fraction of 61.1% and 67.6% for the panels manufactured. Above the transition stage, the porosity increases dramatically as the volume of the matrix is not sufficient to fill the space between the highly packed fibres, the fibre volume fraction is constant but the matrix volume fraction decreases with a non-linear trend. These statements are contradicted by Shah et al. [122] who find that even though the void content seems to be generally higher for larger fibre volume fractions, there is no clear correlation between fibre volume fraction and porosity as the highest void content is at V_f equal to 24.0%, the middle value of the 5 different fibre volume fractions: 6.1%, 17.8%, 24.0%, 27.3% and 32.5% which were investigated. However, microscopic observations allow Shah et al. [122] to conclude that for low fibre volume fractions, voids form within the yarn whereas for higher fibre volume fractions, voids form between yarns. However, the fibre volume fractions are increased by adding layers and therefore the laminate with the lowest fibre volume fraction is manufactured with one layer compared to 5 layers for the highest value. The number of layers used can therefore have an influence on the type and content of porosity.

The volume fraction of flax fibre reinforced laminates cannot be measured with conventional techniques used for synthetic fibres such as matrix digestion in acids or matrix burn off tests as these methods severely degrade the fibres and produce inaccurate and unreliable results as found by Mahboob et al. [3]. Therefore, different methods are used to determine the fibre volume fractions of flax laminates.

A common approach is to determine the fibre volume fraction of flax laminates based on the weight measurements and density of the constituents and the laminate, [51], [66], [22], [24], [89], [113], [119], [53], [112], [26], [29], [122], [133], [137], [138] and [139]. Torres et al. [26] and Baets et al. [19] assume that the laminate contains no void for the calculations of the fibre volume fraction. According to Torres et al. [26], it is an important simplification but Baets et al. [19] state that the void content is low from the results of a qualitative microscopic evaluation of the porosity. Martin et al. [111] compare the fibre volume fraction calculated with a weight and density approach with values measured from SEM images for 4 samples and find similar results.

However, Oksman [119] highlights that this method gives an approximation of the fibre volume fraction as flax fibres are hollow and the lumen is not filled with the resin, leading to a larger volume of air in the flax compared to standard composites. Hepworth et al. [134] also find with microscopic observations that the resin does not penetrate into the cell lumens or into the fibre bundles. Bambach [139] states that the calculated fibre volume fraction may be considered as an upper bound estimate as it is possible that the fibres are compressed under vacuum because of their lumen core and therefore the fibre density may increase slightly during fabrication. Madsen and Lilholt [140] support this, finding that the lumen in most of the fibres collapse during manufacture. Monti et al. [112] determine the void content in the specimens with the difference between theoretical and measured densities of the composites measured in water with Archimedes principles, it ranges between 2.5 and 7.5%.

Flax laminates have a lower fibre volume fraction than standard composites. While a number of authors find that an increase in fibre volume fraction leads to improved mechanical properties as expected based on the rule of mixtures; some find that at high fibre volume fraction the properties decreases. Due to the specific nature of flax fibres, laminate fibre volume fraction cannot be determined with standard methods and different techniques and assumptions are used in the literature which has an impact of the range and accuracy of data available.

2.2.4 Manufacturing issues

The manufacturing of flax fibre reinforced laminates introduce several challenges and the production technique has a significant impact on the fibre volume fraction and mechanical properties achieved. Hand lay-up which is a common manufacturing technique for cheap structural parts is difficult to use for flax laminates and produces low fibre volume fractions, between 18 and 23%, Haggui et al. [123] and Muralidhar [141]. In fact, flax fibres float up in the resin before curing because of their low density and tend to swell according to Hepworth et al. [134]. The authors conclude that to obtain fibre volume fractions above 20%, pressure needs to be applied during curing reducing the benefits of the low cost. Due to the low fibre volume fraction achievable with hand lay-up, more expensive closed mould techniques are widely used in the literature to manufacture flax composites as demonstrated by Shah [1]. However, even if compression moulding can produce higher fibre volume fractions, it is unlikely to be used for structural parts. There are also issues when using close mould manufacturing techniques due to the bulkiness of the flax fibres, Shah et al. [39]. During the manufacture of a small wind turbine made of flax/polyester composite via Light Resin Transfer Moulding it is found that closing the tool after laying the fabric is difficult. Resin infusion is therefore more likely to be used for large parts, Shah et al. [122] and Shah [1], even if the fibre volume fractions obtained are low, below 30% for flax panels compared to 43% for similar E-glass panels, Shah et al. [53]. To obtain higher fibre volume fractions, prepreg followed by autoclave could be considered, Shah et al. [53] and Shah [1]. The resin penetration is another issue associated with manufacturing flax laminates as found by Hepworth et al. [134] who notices that the mechanical properties of flax laminates manufactured with fast curing epoxy decrease by up to 50% compared to slow curing matrix as rapid curing might not allow the resin to penetrate between fibres as effectively. The viscosity of the resin also has an impact and Shah [1] states that thermosets are more suitable than thermoplastics due to their lower viscosity and better compatibility with plant fibres.

As the majority of flax fibre reinforced laminates are manufactured with expensive techniques such as compression moulding, hot press and autoclave with the possibility to change curing and post curing parameters, their influence on the mechanical properties, fibre volume fraction and void content is investigated. An increase in pressure during curing improves the Young's modulus and strength of the manufactured laminates, [41], [133], [135] and [138]. A pressure increase improves the fibre volume fraction; [1] [135] and [138], from 38% at 1 bar compared to 51% at 5 bars, Cadu et al. [133]. An increase in curing pressure decreases the void content according to Li et al. [21] but increases the void content according to Cadu et al. [133].

2.2.5 Yarn weave fabric

Due to their short length, flax elemental fibres are often twisted together to obtain a longer reinforcement in the form of yarns and yarn weave fabrics are often used for manufacturing flax laminate composites. Liu and Hughes [16] and Misnon et al. [142] highlight their advantages, the randomisation of fibre defects, the improved alignment of the yarns and the possibility to reach higher fibre volume fraction using better yarn packing. However, the utilisation of woven fabrics introduces twist into the fibres and the fabric crimp can lead to poor resin penetration. The crimp of the yarns can reduce the tensile modulus of the composites according to Xue and Hue [74] and as stated by Xiong et al. [143], Baets et al. [19], Shah [1] and Bar et al. [144], the twist can reduce the mechanical properties as it provides a misalignment of the fibres to the composite loading axis. Therefore, it is important to investigate the impact of the yarn utilisation on the laminate properties.

Duc et al. [120] find that at equivalent fibre volume fraction, the Young's modulus and strength are lower for weave flax fabric reinforced composites. The difference is explained by higher crimps in the flax woven fabric compared to E-glass fabric. The effects of crimp on the tensile properties of woven flax is also investigated by Phillips et al. [41] who find that the percentage of crimps in the laminate have a negative effect on the laminate tensile properties with up to a 51% decrease in strength for a 6% increase in crimp level.

In addition to the crimp in flax fabric, the influence of the yarn twist on the laminate properties is investigated by a number of studies, Omrani et al. [109], Baets et al. [19], Shah et al. [53] find that the laminate manufactured with high twisted fabric have lower mechanical properties in comparison to low twist yarn reinforcements. However, Goutianos et al. [121] obtain the highest laminate mechanical properties with medium twist yarn reinforcement between laminates manufactured with yarns with a twist of 29 turns/m, 47 turns/m and 58 turns/m. Another issue with twisted yarn reinforcements used in laminates is the low resin penetration as demonstrated by Goutianos et al. [121], Baets et al. [19], Li et al. [21], Chabba and Netravali [107].

2.2.6 Poor interfacial properties

The mechanical properties of composite materials are mostly influenced by the constituents' material properties such as the fibre and the resin but also by the interface to effectively transfer the load between the matrix and the fibres, Marrot et al. [101]. As highlighted by Le Duigou et al. [145], Meredith et al. [18] and Liang et al. [24] flax fibres are hydrophilic and most conventional resins are hydrophobic resulting in poor interface properties. The poor interface properties are even cited as a limitation for structural applications by Seghini et al. [54].

Shah et al. [53] find that E-glass specimens tested have a 20% to 30% higher interlaminar shear strength compared to flax epoxy composites. Coroller et al. [55] determine the interfacial shear strength with microbond tests between flax fibres and an epoxy matrix and find a value of 22.3 MPa in comparison to 37.2 MPa for E-glass/epoxy concluding that a real adherence is shown between flax fibres and epoxy even if the link is weaker than the glass/epoxy bond. The weaker interlaminar properties are explained by Liang et al. [24] who observe flax fibre pull-out with almost no matrix residue on the fibres in comparison to E-glass specimens which demonstrate a stronger adhesion between E-glass fibres and the matrix. Intra fibre separation is another type of damage found in flax reinforced laminates where the primary and secondary fibre cell wall interface is weak with comparable adhesion to fibre/matrix properties. The observation reveals that the increase of the mechanical properties of flax fibre reinforced epoxy composites is correlated to the improvement of the interfacial adhesion between natural fibres and the matrix.

Fibre treatments are shown to be expensive and some are toxic, removing the cheap and environmentally friendly aspect of using natural fibres, Shah [1]. Unoptimised fibre treatments can reduce the fibre strength by up to 50% and there is no agreement in the literature on the treatment parameters to use. In addition improving the interfacial properties can lead to reduced impact properties. The author concluded that the utilisation of fibre treatment to improve the mechanical properties of natural fibre reinforced composites to be used for structural applications is discouraged as they increase price with potentially little or no benefit to mechanical properties, Shah [1].

2.2.7 Damage

Of increasing interest has been the manner in which flax fibres are damaged and break, which is different to E-glass composites. Haggui et al. [123] have identified 4 classes of damages for the unidirectional and 0/90° laminates and 3 classes for the ±45° and transverse unidirectional specimens. The first class can be associated with the mechanisms of matrix micro cracking, the second class to fibre/matrix debonding, the third class, fibre pull out which is the last event for 45 and 90° specimens, and the fourth class for longitudinal and 0/90° specimens is the rupture of the specimens and is attributed to fibre and bundle breakage. Shah et al. [53] document the failure mode of unidirectional flax fibre reinforced epoxy laminates in tension showing that they have a flat brittle fracture surface with little fibre pull out resulting from matrix crack growth transverse to the fibre direction.

Koh and Madsen [127] investigate the applicability of 4 common strength based failure criteria: Tsai Hill, Tsai Wu, Hashin and Puck criterion to predict the failure of multi directional flax fibre reinforced composites. The failure criteria are compared with tension and compression experimental data from UD and multidirectional laminates. The authors define failure as the ultimate strength that the laminate can sustain. The parameters of the 4 criteria are optimised with a minimisation algorithm to fit the equations of the criteria to the experimental data. The authors conclude that the Tsai-Hill theory gives the highest error of 20% and does not fit the experimental data. However, the experimental properties are determined with limited number of specimens, 3 in the longitudinal transverse directions and in longitudinal compression and only 2 specimens for transverse compression.

2.2.8 Summary

The literature relating to flax fibres at the laminate scale is summarised in Table 12. The longitudinal mechanical properties of flax fibre reinforced laminates are well characterised with a stiffness approaching the stiffness of E-glass but the strength of flax laminates is lower. The number of studies investigating the transverse, compressive and shear properties are limited in comparison to the data available for the longitudinal properties. The number of specimens tested is also limited for the large majority of the data available. As it is seen at the fibre scale, the non-linear fibre behaviour translate to non-linear stress-strain curves at the laminate scale. This non-linearity creates difficulties when calculating the Young’s modulus with different strain ranges used by different authors and the ASTM or ISO standards often modified. Due to this it is likely that the stiffness of flax laminates is therefore overestimated. The studies investigating the relationship between fibre scale and laminate scale properties are limited but the laminate properties are lower than expected from the fibre scale data. These low mechanical properties at the laminate scale can be explained by issues specific to flax fibre reinforced composites. Flax laminates properties are impacted by the low fibre volume fraction which can be obtained.

Table 12: Summary of the literature at the laminate scale

Scales	Properties	References
Laminate	Tensile longitudinal properties	[77], [110], [20], [55], [89], [103], [53], [111], [94], [3], [14], [112], [113], [114], [24], [26], [115]
	Transverse, compressive or shear mechanical properties	[116], [29], [112], [113], [14], [26], [117], [62] [115] [118], [72], [3], [24] [70],
	Tensile behaviour	[24], [77], [89] [113], [112] [123], [3] [23] [120], [116] [123] [24] [124]
	Statistical distribution	[26][3]
Fabric	Tensile Mechanical properties	[109]
	Compressive mechanical properties	
	Comparison with E-glass	
	Statistical distribution	
Yarn/fabric	Relationship between yarns and fabric properties	[109][4]
Yarn/laminate	Influence of yarn properties on the laminate properties	

[3] Published in 2017
[4] Published in 2017

2.3 Structural scale

It is important to be able to compare the properties of flax fibre reinforced laminates with the different materials already used and widely available. Shah [35] compares natural fibre reinforced composites with conventional materials using Ashby-type charts to help in the design process. Ashby charts are presented in Figure 5. The author concludes that natural fibre composites performed exceptionally well against equivalent glass composites for stiffness, both absolute and specific, and therefore can be a potential alternative to glass composites in stiffness critical applications but not in strength critical applications.

2.3.1 Comparison of key material properties

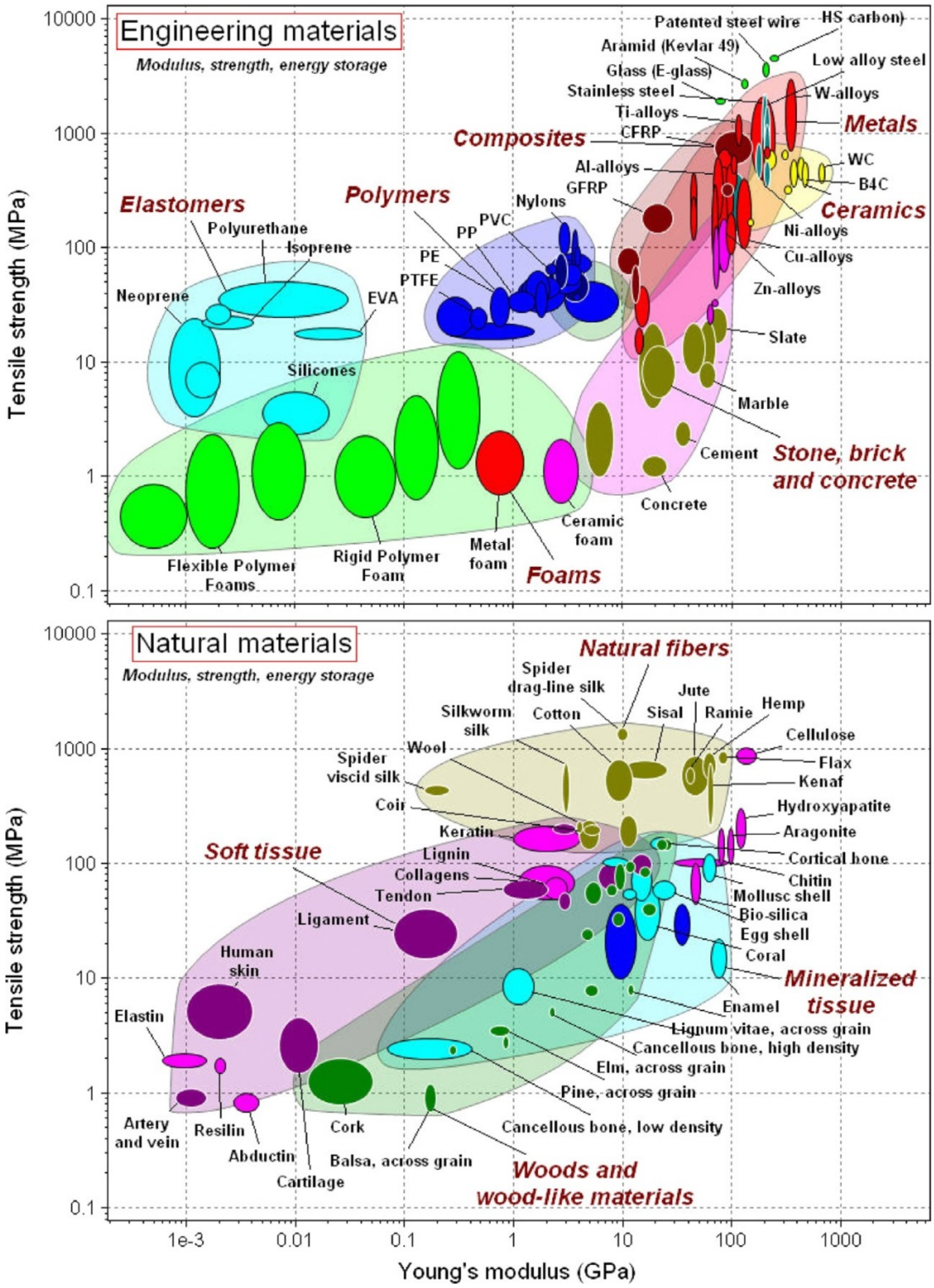


Figure 5: Ashby plot illustrating the Young's modulus and tensile strength of traditional engineering materials and natural materials from [146]

A number of authors: [18], [27], [14], [25] and [26]; propose that flax reinforced laminates have the potential to be used for structural applications based on coupon scale data from experiments or review of the literature. However, flax laminates have a different behaviour both at the fibre and laminates scales to E-glass with the potential that this can be transferred to the larger scale. The limited studies conducted at the structural scale are reviewed.

2.3.2 Structural applications

Some papers suggest that the study is conducted at the structural scale, such as Bodros et al. [147], which compares the tensile properties of flax reinforced laminates with E-glass composites and conclude that flax fibre reinforced PLA composites can act as a substitute to glass fibre composites for structural applications under tensile loading. However, the reinforcement is a random short fibre mat and the mechanical properties are therefore low with the highest Young's modulus values below 10 GPa and the highest breaking strength below 100 MPa, indicating that these applications are not highly loaded and therefore not primarily structural. Lau et al. [148] and Dittenber and GangoRao [12] present review papers of natural fibre composites for structural scale applications and identify the challenges such as the variability in mechanical properties, high moisture content, poor fibre/resin interface and manufacturing difficulties but the mechanical properties are not investigated nor is the structural behaviour. Dittenber and GangoRao [12] state that the fibre variability can lead to problems in natural fibre reinforced epoxy composites especially if they are used as primary structural components. The key issues which need to be investigated for developing natural fibre composites at the structural scale are reviewed by Shah [1]. The issues with manufacturing large parts made of natural fibre composites are reviewed. The author conclude that more Ashby plots for different parameters are needed for an increase uptake of natural fibre reinforced composites. This review is based on laminate scale and review the different issues well known for flax fibre composites in light of structural scale applications however, structural analysis is not included.

Pil et al. [36] present a few current applications of flax fibre at larger scale. Flax is used in sporting goods, tennis rackets, surfboards, skis and furniture mainly to reduce vibration and is used in combination with other materials which provide the structural support. More structural applications exist such as components of a bicycle frame or the monocoque structures for e-scooters. However, even if flax is starting to be used in consumer goods it is not for their mechanical properties but for other considerations such as sustainability or damping.

The engineering applications at the structural scale are limited. Shah et al. [39] compares a small wind turbine made of flax/polyester composites and an identical structure made of E-glass composite to investigate the feasibility of flax structures. It demonstrates that the flax structure is 10% lighter than the identical E-glass structure due to the lower density of flax fibres compared to E-glass fibres. However, even if the mass of flax fibres is lower, 4.2 kg, than E-glass, 7.7 kg, the resin accounts for 38% of the E-glass blade mass but 46% of the flax blade mass, explained by the lower fibre volume fraction of flax and some resin rich regions. The flax structure meets the industrial regulations for wind turbine blades, however, the stiffness of the flax blade is lower than the E-glass blade with a 40% higher tip deflection under Normal operation loads. For the worst case loading, the flax blade is more flexible with a tip deflection of 2025 mm compared to 743 mm for E-glass. Flax has a different structural behaviour compared to E-glass with the tip displacement increasing at a constant rate with load for the E-glass blade, the tip displacement increases at an increasing rate with the load for flax. The failure mode of the flax blade is different than the failure mode of the E-glass blade. While the E-glass blade fails by cracks at the blade root followed by extensive delamination, the flax blade fails 1m along the blade length at the location of change in the stacking sequence which is a possible stress concentration. Initially, matrix cracking/peeling is observed, which is a sign of resin richness, followed by compressive loads on the top surface which buckled. Further loading led to complete buckling, delamination and collapse of the blade. Cost is also an issue with the material costs for flax fibre reinforced composite structures being three times higher than the conventional structure. The authors conclude that flax fibres can replace E-glass in small wind turbine blade applications but more studies are required at the structural scale.

Castegnaro et al. [114] built a sailing dinghy made of flax epoxy and balsa wood. The authors state that the spread of laminate properties needs to be balanced with large safety factors for structural design. The authors noticed a 20% weight reduction for a similar stiffness based on an FEA model compared to an equivalent wooden dinghy. The boat was launched in 2012 and had not suffered structural failure when the paper was published in 2017. The authors conclude that bio-composite materials can be employed as structures in the nautical field.

Bambach [149] presents the compressive properties of plate and channel sections made of flax reinforced epoxy laminates and different plate thicknesses are compared. It is shown that even if the mechanical properties of the laminates are low, the buckling and post buckling response is stable and therefore suitable for light structural applications for the thicker specimens. However, the theoretical buckling stress exceeds the experimental values and the model needs to be improved for natural composites with more experimental data. Bambach [139] also investigates the feasibility of using channel sections made of flax fibre reinforced laminates to replace steel studs in a residential building applications based on their compression properties. The flax channel sections are geometrically optimised with 7 different configurations and 2 different thicknesses tested in pure compression. The flax reinforcement is 2*2 twill, hand lay-up with epoxy. For comparison, steel and timber studs used in residential buildings are also tested. If the steel studs are considered as a benchmark with a compression strength of 12.7 kN for the non-load bearing case with a thickness of 0.55 mm and 41.0 kN for the load bearing case with a thickness of 1.15 mm, all the flax channel geometries considered can meet the non-load bearing steel studs compressive load and the thicker laminates, 4.8 mm, can compete with the load bearing studs with a compressive force of 59.4 kN and 69.2 kN for two different geometries. However, the authors highlight that the flax channels are substantially less stiff and serviceability requirements need to be considered. The flax sections are also much thicker and only one specimens was tested for each configuration. Urbaniak et al. [150] compare the compressive behaviour of channel sections made of flax laminates and E-glass laminates by modelling a compressive experiment set up with FEA. A different buckling mode is observed between the E-glass and flax specimens and the authors conclude that experimental validation will be interesting.

2.3.3 Deriving material properties for structural modelling

The rule of mixtures is widely used to predict the longitudinal properties of unidirectional flax laminates, [55], [94], [101], [107], [111], [112] and [8].

To test the accuracy of the method, a number of authors [3] [122] [51] [50] [66], [45], [53] [82], [14], use the rule of mixtures to back calculate flax fibre properties from laminate properties and compare the prediction with fibre mechanical properties. The comparison for the Young's modulus is presented in Figure 6 and for the strength in Figure 7. Bensadoun et al. [51] back calculate the technical fibre properties from one batch using the rule of mixtures and laminate properties manufactured and tested by 5 different laboratories with elemental fibre properties determined experimentally. The initial back calculated Young's modulus is equal to 59.8 MPa compared to 57.0 GPa for experimental elemental fibres, Figure 6, but the back calculated strength is much lower with 527 MPa compared to 791 MPa, Figure 7. Shah et al. [53] back-calculate the fibre properties from laminate properties manufactured with epoxy and polyester matrixes with the rule of mixtures. For "high quality" flax yarns, the back calculated fibre properties decrease by 20% when used in an epoxy matrix compared to polyester whereas for the low quality flax fibres, the properties are 6% higher in epoxy compared to polyester. These results demonstrate the resin might also influence the results.

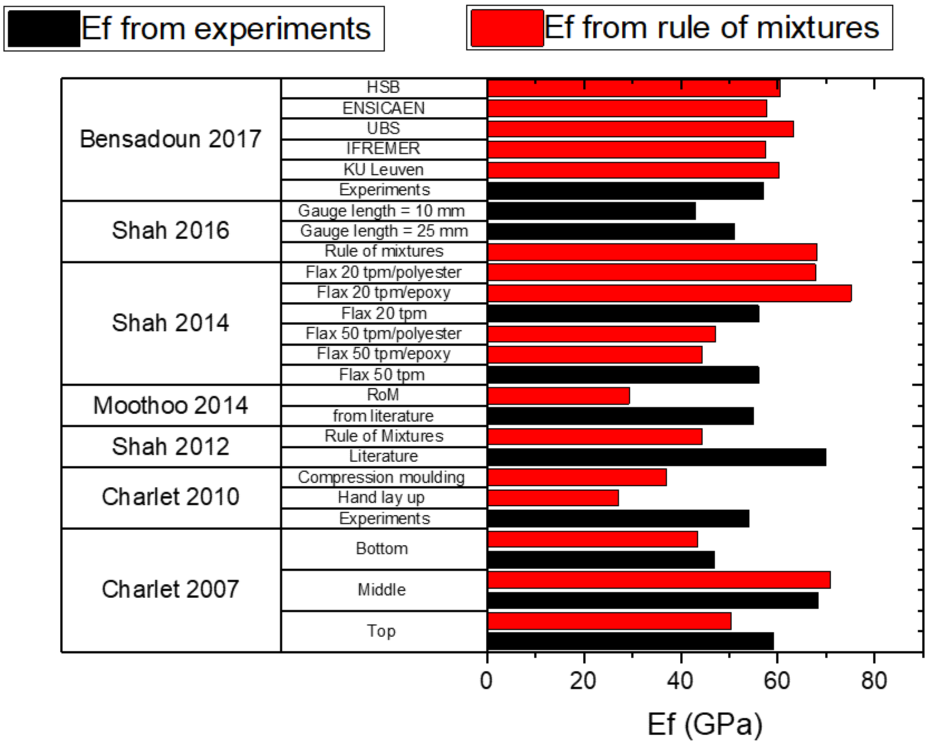


Figure 6: Comparison between fibre Young's modulus determined with experiments and back calculated with the rule of mixtures

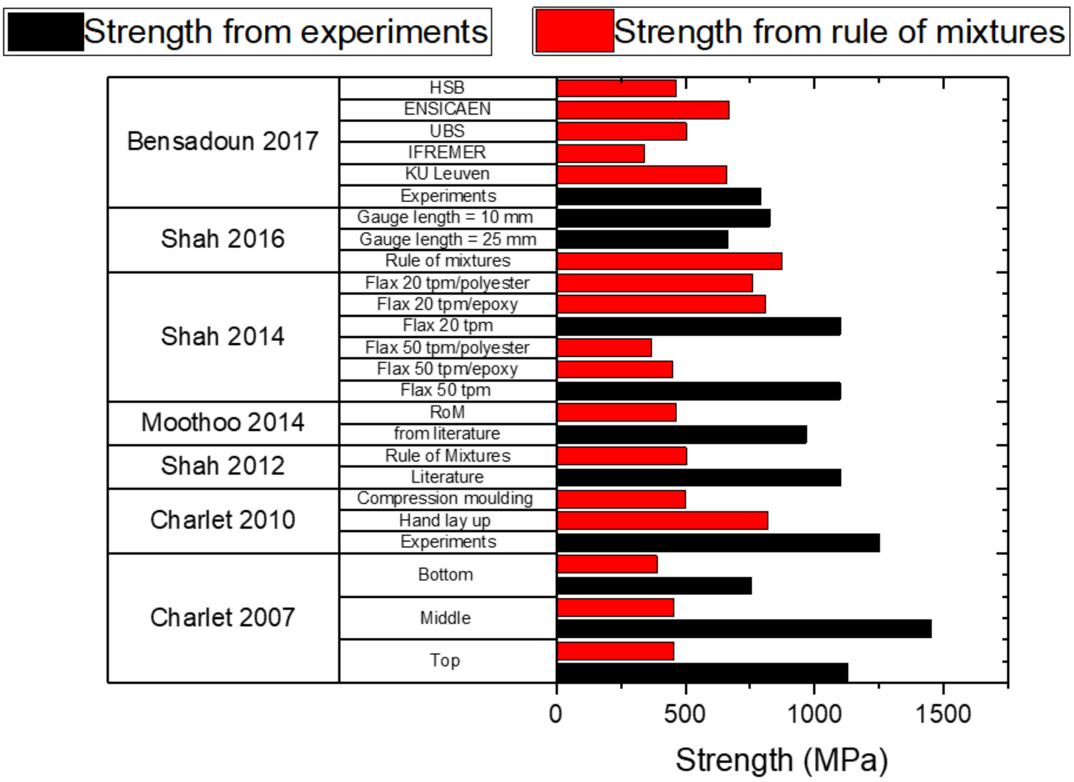


Figure 7: Comparison between fibre strength determined with experiments and back calculated with the rule of mixtures

The rule of mixtures cannot accurately predict fibre properties from laminate properties. One of the reasons highlighted by Charlet et al. [66] and Charlet et al. [82] is that laminates are manufactured with technical fibres which are known to have lower properties that the elemental fibres tested but Charlet et al. [66], Charlet et al. [82] and Bensadoun et al. [51] compare back calculated properties with elemental fibre properties. In addition, Charlet et al. [82] state that the elemental fibres tested tend to be the strongest available for practical reasons. Shah et al. [45] attribute this difference between experimental data and prediction to the experimental errors in fibre tensile tests and composites experiments and the suitability of the rule of mixtures for natural fibre composites. The possible errors on the rule of mixtures side are: the non-uniform fibre properties and their high variability, the misorientations in the reinforcement especially if yarns are used, damages of the fibres due to processing, flax fibres and flax composites behaviour is not entirely elastic. The authors conclude that more research need to be conducted on the rule of mixtures but in the meantime, design with flax composites must be based on laminate data.

Monti et al. [112] compare the Young's modulus of UD flax laminate tested experimentally and equal to 23.3 GPa with value determined with the rule of mixtures and fibre properties from the supplier data. They show that the rule of mixtures predictions are accurate. However, this conclusion needs to be mitigated as the fibre volume fractions are estimated between 35% and 45% for the experimental data and the rule of mixtures stiffness predictions are therefore between 23 GPa and 29 GPa. The inaccuracy in the fibre volume determination prevents clear conclusions on the accuracy of the rule of mixtures.

Marrot et al. [101] and Martin et al. [111] compare predicted properties with laminate properties at different fibre volume fraction. Lefeuvre et al. [94] compare predicted properties with laminate properties for fibres from different parts of the stem and Coroller et al. [55] uses fibres from 3 different varieties. All these studies find that the rule of mixtures can accurately predict the stiffness of the laminate with an error between -6% and 2.3% except for one case according to Coroller et al. [55] but the strength is overestimated compared to the strength determined from laminate experiments with errors up to 78.3%, Coroller et al. [55]. To counteract the inaccuracy in strength prediction, Marrot et al. [101] derive an efficiency factor based on the repartition of the fibres in the laminates with a value between 0.43 and 0.84 depending on the fibre volume fraction, varieties of flax fibres and types of matrix. An efficiency factor, k, to illustrate the fibre individualisation rate on the strength prediction is also derived by Coroller et al. [55] but the derivation is not presented and the value of k varies for each configuration from 0.54 to 0.72. Martin et al. [111] find that a k value of 0.65 gives the best fit to the experimental data whereas Lefeuvre et al. [94] derive an efficiency factor k varying from 0.53 to 0.40 depending on the fibre location in the stems. Martin et al. [111] conclude that the inaccuracy of the rule of mixtures for strength prediction is caused by the fibres being in bundles form in the laminates, the scattering of fibre properties and the low individualisation of the fibres. While Marrot et al. [101] explain that the lower strength values can be explained by the poor separation and repartition of the fibres.

Chabba and Netravali [107] use the rule of mixtures to predict laminate properties of unidirectional flax yarn reinforced composites based on yarn properties determined experimentally. In this case the rule of mixture overestimates both the stiffness and strength compared to laminate experiments with a Young's modulus of 3.9 GPa and strength of 145 MPa compared to 2.24 GPa for the Young's modulus and 126 MPa for the strength from experiments. The authors explain the difference by the resin shrinkage during curing which caused the yarn to be in longitudinal compression after the curing and during tensile testing. Kersani et al. [8] also find that the rule of mixtures overestimates the stiffness with measured Young's modulus 22% lower than the estimations. However the prediction is based on fibre properties from the literature and not on fibre tests conducted with the same reinforcement as the fibre used in the prepregs.

To improve the prediction of these material properties Madsen and Lilholt [140] present a corrected version of the rule of mixtures. The correction is a modification of the fibre volume fraction to include porosity. The porosity is divided into two components: porosity caused by processing such as fibre/matrix interface porosity and porosity caused by a structural mechanism. The difference between the rule of mixtures and the corrected version is small up to a fibre volume fraction around 50% where the corrected rule of mixtures deviates from the linear rule of mixtures. Compared to experimental results, the corrected rule of mixtures improves the mechanical properties prediction for laminates with high fibre volume fraction and high porosity content, however the range of fibre volume fractions used for the validation is limited and more data are required. The technique is expensive as the determination of the porosity parameters requires extensive testing. The transverse properties are overestimated by both the corrected and Normal rule of mixtures.

Shah et al. [53] investigate the value used in the rule of mixtures for the fibre length efficiency factor defined as "the ability of the fibre to transfer strength and stiffness to the composite" with the Kelly-Tyson's model based on the critical fibre length of flax fibres which is found to be between 0.28 and 0.35 mm. The values for both length efficiency factor, η_l, for strength and stiffness are very close to 1. The authors also assumed that the fibre orientation efficiency factor, η_o is equal to 1 for flax yarn reinforced laminates.

2.3.4 Summary

There are limited assessments of flax fibre reinforced composites at the structural scale. Those that have been performed exhibit a different behaviour at the structural scale compared to conventional composites. No assessment of the safety of these composites has been compared to the same structures made from conventional materials, such as E-glass.

Performing the structural analysis is made difficult as the prediction of the material properties is inaccurate. The rule of mixtures, is accurate for synthetic fibre reinforced composites and therefore it is commonly used for predicting the properties of natural fibre, even if all the assumptions are not always met. However, the accuracy of the rule of mixtures for these applications is questionable and therefore laminate properties must be derived experimentally.

2.4 Summary from the literature

Flax fibre mechanical properties are widely characterised, as summarised in Table 13, and many studies conclude that their mechanical properties are comparable to E-glass fibre mechanical properties but are highly variable which prevents their use as a structural material.

This review of the studies conducted on the material characterisation at the fibre, yarn, cloth and laminate scales showed that the fibre mechanical properties demonstrated a large variability partially caused by an inaccurate measurements of the cross sectional area. However, the specific properties of flax fibres were higher than glass fibres, an encouraging result for their application in composite structures.

The laminate mechanical properties are well studied but statistical distribution and variabilities are not investigated. The mechanical properties are lower than E-glass especially the strength properties. The different causes for the lower properties such as the low fibre volume fraction, the different manufacturing techniques, fibre defects, yarn twist, poor interfaces and void contents are investigated together with possible improvements. However, the yarn and cloth scales show less characterisation. The determination of the properties based on testing one material across multiple scales, including the cloth scale, has not been performed on flax fibre reinforced composites.

Even if studies at the fibre or laminate scales conclude that flax fibre reinforced composites are suitable for structural applications, the number of studies at the structural scale are rather limited and demonstrate a change in structural behaviour compared to conventional composites. The change in structural behaviour requires different modelling techniques and adaptation of the failure criteria. The commonly used rule of mixtures cannot accurately predict the properties for natural composites and laminate scale mechanical properties are required for structural analysis.

There are no safety assessments for natural composite structures, which are commonly performed for structures made of conventional composites.

The coloured areas in Table 13 highlight the areas that need investigation to determine if flax fibre reinforced composite can replace conventional composites for structural applications.

Table 13: Summary of natural fibre reinforcement characterisation studies at different scales

Scales	Properties	Flax
Fibre	Tensile properties	[33] [43] [44] [54] [51] [64] [65] [66] [67] [68] [69] [71] [75] [78] [81] [82] [90] [91] [92] [93] [94] [95]
Yarn	Tensile properties	[63] [74] [85] [103] [107]
Cloth	Tensile properties	[74] [109]
Composite	Tensile properties	[3] [14] [20] [24] [53] [55] [77] [89] [94] [103] [110] [111] [112] [113] [114] [26] [115]
	Fibre volume fraction	[14] [66] [82] [115] [119] [122] [111] [134] [135]
	Fibre/matrix interface	. [145] [18] [24] . [53]. [55]
Structure	Structural response	[39] [149] [139] . [150]
	Safety Assessment	
Multi-scale	Mechanical properties fibre/laminate	[107] [50] [66]
	Mechanical properties Yarn/cloth/laminate	

Chapter 3 Methodology

To investigate the potential for flax fibre reinforced composites as a replacement for conventional composites in structural applications, the safety of flax structures is determined. A reliability analysis is therefore conducted to predict the probability of failure for the structure. To perform this analysis an accurate but fast model is required to replicate the structural behaviour while material properties and their variabilities are necessary inputs for this model. The relationships between these sections are shown in Figure 8.

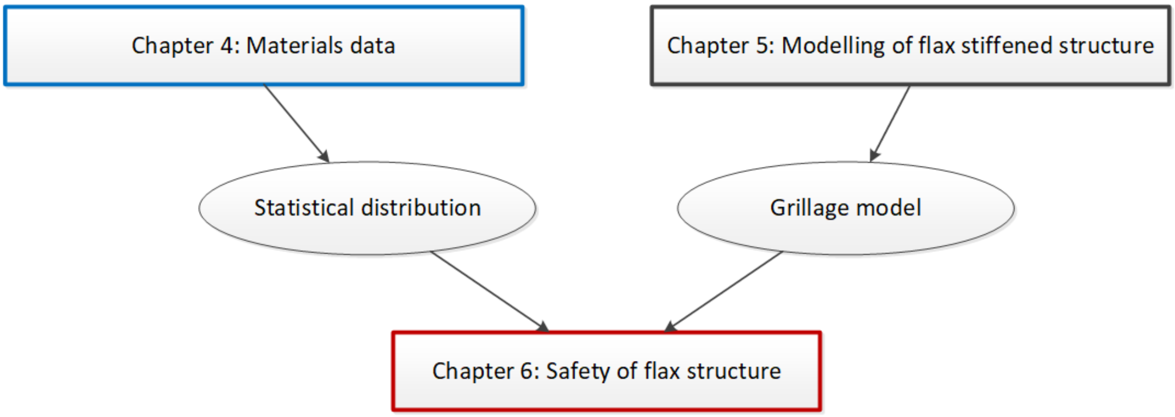


Figure 8: Reliability framework in relation to thesis chapters

3.1 Material characterisation

To define how the overall structural performance is affected by the high variations between flax fibres, the variability of flax laminate and its constituents is investigated at different levels: yarn, ply and laminate. The steps between elemental fibres and yarns are not investigated as this has already been widely studied as shown in the literature review, Chapter 2, for example Aslan et al. [43], Andersons et al. [69] and Thomason et al. [60]. However, there is a lack of literature investigating flax composites at larger scales and so the smallest scale investigated is limited to the yarn. Furthermore, laminates are often manufactured from yarn or technical fibres rather than elemental fibres but the relationship between these constituents and laminate properties is not as well studied in comparison to elemental fibres and laminate scales.

Therefore, flax fibre reinforced composites and their constituents are tested experimentally at yarn, cloth and laminate scales. A large number of specimens are tested to identify statistical distributions for the mechanical properties. 95 yarn specimens are tested in tension and the yarn true cross sectional area is measured under a microscope for 100 specimens. 20 cloth specimens are tested in tension to study the influence of the yarn variability on the cloth mechanical properties. Finally, the experimentally determined tensile and flexural properties of 95 laminate specimens are compared with the predicted behaviour of flax composites from the natural rule of mixtures developed by Virk et al. [151]; using different assumptions for the yarn cross sectional area and the yarn tensile test data. The influence of the scale at which the fibre properties are determined: elemental, technical fibres or yarns, for laminate properties predicted with the rule of mixtures is also investigated.

The multi-scale characterisation of the flax reinforced composite mechanical properties determines the influence of the fibre's variability on the laminate properties, and demonstrate a change in behaviour between laminates reinforced with flax fibres and standard composites. Importantly it shows that the variability in laminate properties is similar to standard composites, and not an inhibitor to using flax composites.

3.2 Structural model

The structural response of natural composites is investigated with modelling techniques rather than experiments to study the behaviour of large structures at low cost.

The change in behaviour already seen at the laminate scale for flax fibre reinforced composites needs to be investigated and accurately modelled at larger scales and a representative grillage structure from the maritime industry is selected. However, the simple analytical approach, Navier grillage method, taken from Vedeler [152] and originally derived for steel to model a top hat grillage structure is not accurate to model the structural response of flax fibre reinforced composites. This is due to the low stiffness of flax fibre reinforced composites which leads to a change in behaviour at the structural scale, not seen for standard composites. The analytical model needs to be adjusted to accurately predict this behaviour and the stress of flax grillage structures. Therefore, an empirical factor is derived to take into account the material properties of composite materials compared to the original formula derived for steel and to calculate layer by layer stresses. Therefore, Classical Laminate Plate theory is applied to the crown element of the stiffeners, the location of maximum stress on a grillage structure. The empirically derived equation is validated with an FEA model developed by Mutlu and presented in Blanchard et al. [153] for different cases. The model is verified by:

- Comparing a flax structure to conventional fibre reinforced composites; E-glass, Kevlar, Carbon and High Modulus Carbon fibre reinforced epoxy composites, to investigate the change in structural behaviour of natural fibre reinforced composites.

- A parametric study of different grillage topologies for a range of dimensions likely to be seen in industrial applications: different plate length and aspect ratio, number of stiffeners, stiffener height and stiffener widths.

The empirical model allows rapid and accurate prediction of stresses through the laminates for grillage structure made of standard composites and low stiffness materials such as flax fibre reinforced composites.

3.3 Reliability analysis

The feasibility of flax reinforced composites for structural applications is then investigated with a risk-based design approach. The analytical model developed to model the stress behaviour of a grillage structure made of flax fibre reinforced laminates is used to run a reliability analysis of flax and E-glass grillage structures with a representative range of mechanical properties and coefficients of variation from the literature.

The reliability analysis is performed using a Monte-Carlo simulation which can be divided into the following steps:

- A randomly distributed set of input variables for the material properties is generated using representative values from the literature and statistical distribution determined with experiments from Chapter 4.
- The pressure applied on the structure is randomly generated and follows a Weibull distribution.
- Ply by ply stresses and deflection are calculated with the analytical model developed in Chapter 5.
- The maximum stresses are compared to the limit state functions to determine if the stresses are outside the failure envelope and if the structure has failed. Tsai and Zinoviev failure criteria from the World Wide Failure Exercise are selected with parameters determined for flax laminates by Koh and Madsen [127].

The simulations are run until 10^9 unless if the probability of failure has reached convergence previously. The convergence criteria requires the difference between each of the last three runs and the average of the last three runs to be within 5% difference.

The reliability analysis is conducted for a flax structure with the same volume as E-glass and for a flax structure with the same mass as E-glass to consider the advantageous low density of flax fibre in comparison to E-glass fibres. A feasibility study to determine the dimensions and mass of a flax structure as safe as the E-glass structure is also run to determine the industrial feasibility of flax for structural applications in a specific application and the additional mass or volume penalties if the change is made.

Chapter 4 Multi-scale investigation into the mechanical behaviour of flax

The tensile mechanical properties of elemental flax fibres are well documented in the literature but demonstrate a high variability which is seen as a major drawback for the utilisation of flax fibre reinforced composites at the structural scale. However the influence of the fibre variability on the laminate mechanical properties is not well understood.

The aim of this chapter is to investigate the influence of flax fibre variability on the laminate properties and understand the relationship between the yarn, cloth and laminate scales. This is conducted with experimental testing at multiple scales from yarn up to the laminate. The steps between elemental and technical fibres are not investigated as this has already been widely studied in the literature; therefore, the smallest scale investigated is the yarn. The link between the fibre and yarn properties and the laminate properties is then investigated using the rule of mixtures.

4.1 Experimental methodology

Flax fibres from a single batch are used for the majority of the study with a second batch used to record the load and displacement of the cloth. A woven balanced cloth (0°/90°) called “FlaxPly” made by LINEO in Belgium is used throughout the study and described in Table 14.

Table 14: Manufacturer’s description of the cloth

Fibre areal density (g/m^2)	222.1
Yarn linear density (Tex)	104.2
Weave style	Twill (2/2)
Yarns/cm (warp direction)	10.2
Yarns/cm (weft direction)	10.1

The matrix is composed of a Gurit Prime 20 LV Epoxy resin mixed in 100:26 ratio by weight. An epoxy matrix is selected for its well-known mechanical properties which allows focus on the fibre reinforcement, helping to isolate the uncertainty in the fibre properties. Epoxy resins also demonstrate better compatibility with flax fibres and improved interfaces, as demonstrated by Shah et al. [53], Seghini et al. [54] and Coroller et al. [55]. 7 identical panels of 8 layers of

"FlaxPly"/Epoxy composite are manufactured to test the laminate material properties. Resin infusion is preferred for good mechanical properties and consistent properties across the plate. A visualisation of the set-up is presented in Figure 9. Whilst other methods provide a higher fibre volume fraction resin infusion is widely used in industry for fibre reinforced composites as a good compromise between the quality and cost [154] [155] [156]. The infusion process is followed by vacuum consolidation for at least 8 hours, and a cure time at ambient temperature of 24 hours. Panels are then placed in the oven for post curing for 16 hours at 50 °C, as recommended by the resin supplier, to improve the mechanical properties.

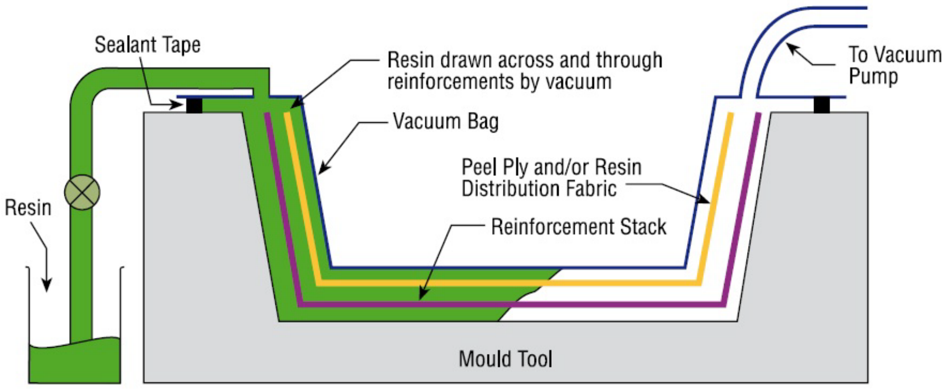


Figure 9: Resin infusion process used to manufacture flax reinforced laminate panels [157]

4.1.1 Yarn experiments

The breaking strength of the yarns is determined with two different methods. It is calculated with the linear density of the yarns and expressed in Newtons/tex according to the traditional standard, BS ISO 3341:2000 [158], but also with the fibre cross sectional area to obtain a breaking strength in MPa that can be used to relate the yarns' mechanical properties to the laminate properties.

To calculate the breaking strength in Newtons/tex the linear density, defined for a yarn as the mass of a 1000 m length, is required. To find the linear density 121 yarns are cut to 600 mm and are weighed using a Mettler AE 240 scale with a precision of 10^{-5}g, these specimens are then tested under tension. The variability of the linear density along the yarn is also determined by dividing one yarn into 100 specimens of 1cm length to be able to compare the variability within a yarn to that across multiple yarns. The yarns for the test are collected from a woven cloth and separated with care by hand using yarns from both the transverse and longitudinal directions.

To determine the stress in MPa in each yarn, the cross sectional area needs to be measured. This is performed using an Olympus microscope BX41M-LED. The 100 yarn specimens are embedded into an epoxy matrix and are then polished using progressively finer grit, 120-1200, in order to make accurate observations. The angle between the yarn and the observed surface is measured and specimens not perpendicular to the surface are discarded. The cross sectional area of the yarn is observed at a magnification of 20. The images obtained are transferred into the Image J software which is automatically calibrated against measurements from an objective micrometer. As no accurate non-destructive method is found to determine the cross sectional area of a yarn before testing, an average cross sectional area is used for the stress calculations based on these measurements.

To obtain the tensile mechanical properties of the yarns, 95 specimens are tested in tension according to BS ISO 3341:2000 [158] using an Instron 5569 with a load cell of 2 kN. The yarns are tested at a rate of 200 mm/min using radiused clamps and a gauge length of 500 mm. The breaking strength is measured according to BS ISO 3341:2000 [158] and calculated as the tensile breaking force per unit linear density of the unstrained specimen. The standard for yarns BS ISO 3341:2000 [158] does not specify the strain range at which the tensile modulus of yarns needs to be calculated. Therefore, the strain values are determined by scaling the strains used to calculate the standard composite tensile modulus.

The scaling is performed by multiplying the strains at which the standard composite tensile modulus is determined, ε_1 = 0.05% and ε_2 = 0.25%, as referred to in the ISO standard BS EN ISO 527-1:2012 [159], by the ratio of the flax composite breaking strain to the flax yarn breaking strain. This leads to higher values for the strains, ε_1 = 0.09%, and ε_2 = 0.46%, at which the yarn tensile modulus is determined. The strain is calculated from the cross-head displacement of the INSTRON 5569.

4.1.2 Cloth experiments

The properties at the cloth scale are studied and linked to the yarn's properties. The flax fibre used in this analysis has a manufacturer specified cloth density of 222.1 g/m^2. However, to obtain a more accurate result, a 10 cm x 10 cm cloth sample is cut by hand and split into 100 specimens of 1cm^2, as seen in Figure 10, which are used to evaluate the variability in the cloth density.

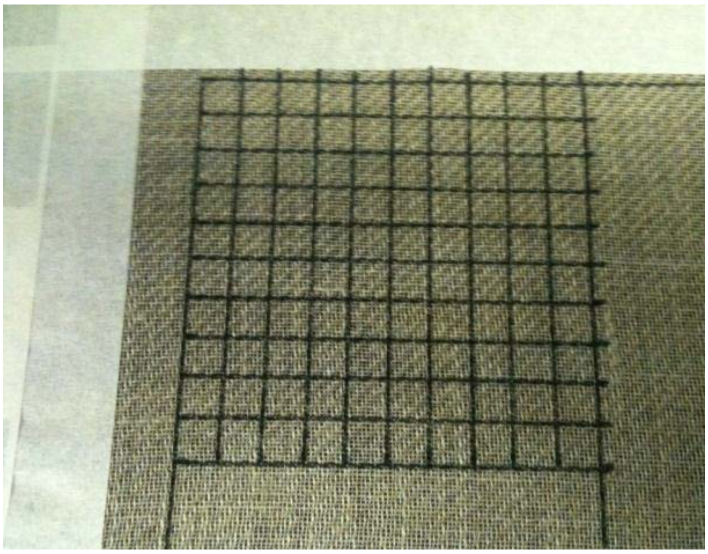


Figure 10: Preparation of the specimens for the cloth density test

Following the density determination, 20 specimens of cloth are tested in tension to determine the tensile breaking force according to BS ISO 3342:2011 [160]. Fewer cloth specimens are tested as the distribution at this scale is considered to be less important as the reduction in variability at the laminate level shows the fibre variability is less influential at higher scales. However it is important to investigate the properties that link the yarns' results to the laminate. The specimens are tested using an Instron 5569 machine at a rate of 200 mm/min with a 50 kN load cell. The specimen's dimensions are 1300 mm long and 75 mm wide. To avoid slippage a standard length cannot be used and radiused clamps are used instead of the flat clamps described in the standard. To further prevent the specimen slipping each end of the specimen is covered with a thick layer of tape which is assumed to have no effect on the final results. Load and extension are recorded but the gauge length cannot be accurately determined due to the utilisation of the radiused clamps. The set-up for the cloth tensile test is presented in Figure 11.

Figure 11: Tensile test of a cloth specimen

To determine the correlation between the yarn breaking force and the cloth breaking force, the number of yarns for each specimen in the longitudinal direction is counted by eye, 22 cm from the edge at both ends, a distance corresponding to the end of the gauge length. An average of both values is then calculated for each specimen.

4.1.3 Laminate experiments

The fibre volume fraction of flax fibre reinforced laminates cannot be accurately measured with conventional techniques used for synthetic fibres such as matrix digestion in acids or matrix burn off tests as it severely damages the fibres [3]. Therefore, the fibre volume fraction is defined by the constituent weights and densities assuming no void content which is a common approach in the literature, [137] [89] [26] [119] [139]. Whilst this introduces some variation and uncertainty it is assumed that this would be minimal across the specimens, due to systematic variation. A void content of 2.36% is found by Cihan et al. [15] for the same flax reinforcement resin infused with epoxy showing this is a reasonable assumption. Each specimen is measured and weighed using a Mettler AE 240 scale, precision of 10^{-5} g, before the tensile test, and the dimensions are based on a mean value calculated from 3 measurements for each specimen and dimension.

122 specimens, with no end tabs, are tested in tension according to the Standard BS EN ISO 527-4:1997 [161] using an Instron 5569 machine with a 50kN load cell and flat grips. The specimens are on average 25.32 mm wide (CoV = 1.84%), 249.8 mm long (CoV = 0.49%) determined with a Vernier calliper, and on average are 4.31 mm thick (CoV = 4.36%) measured with a micrometer at different

locations. The breaking strength, breaking strain and Young's modulus are determined according to the standard. The strain used for the calculation of the Young's modulus is obtained with a 50 mm extensometer placed at the middle of the specimen gauge length but the strain at failure is determined with the cross-head displacement of the machine.

101 specimens are tested in flexure according to the ASTM Standard D 7264/D 7264M-07 [162] using a span to thickness ratio of 20:1 and a three point bending arrangement. The tests are performed with an Instron 5569 machine equipped with a 50 kN load cell and the set-up is presented in Figure 12.

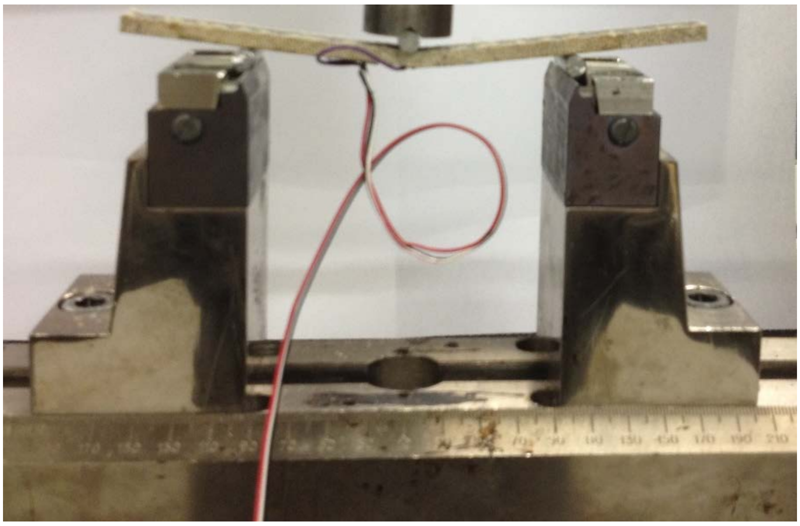


Figure 12: Flexural test set-up

The specimens are on average 4.50 mm thick measured with a micrometer at three different locations. The breaking strength is determined according to equation (1),

$$\sigma = \frac{3PL}{2bh^2}, \qquad (1)$$

where:

- σ : Stress at the outer surface at mid-span, MPa,
- P: Applied force, N,
- L: Support span, mm,
- b: Width of beam, mm,
- h: Thickness of beam, mm.

The flexural strain is calculated according to equation (2),

$$\varepsilon = \frac{6\delta h}{L^2}, \qquad (2)$$

where:

- ε: Maximum strain at the outer surface, mm/mm,
- δ: Mid-span deflection, mm,
- L: Support span, mm,
- h: Thickness of beam, mm.

To calibrate the strain derived using the cross-head displacement measurement which has an unknown accuracy, 10 extra specimens are instrumented with strain gauges. The error between the measurement from the strain gauges and the cross-head displacement allows the accuracy of the cross-head displacement to be determined and the derivation of a correlation factor. This correlation factor is equal to 1.0948 and the strain from equation (2) is multiplied by this factor to reduce the error in the predicted strain as it was not practically feasible to test 101 instrumented specimens.

The flexural modulus is calculated as shown in equation (3) and the recommended strain range of 0.002 with a start point of 0.001 and an end point of 0.003 is followed according to the standard,

$$E_f^{chord} = \frac{\Delta\sigma}{\Delta\varepsilon}, \qquad (3)$$

where:

- E_f^{chord}: Flexural chord modulus of elasticity, MPa,
- Δσ: Difference in flexural stress between the two selected strain points, MPa,
- Δε: Difference in strain between the two selected strain points.

4.2 Multi-scale material properties

The experimental results found during the testing of the yarns, cloths and laminates are presented in the following sections. These multi scale results allow a better understanding of the relation between the yarn, cloth and laminate levels. The results for the densities, cross sectional areas and tensile strengths are presented alongside the distributions for these properties. Flexural properties for the laminate level are also included.

4.2.1 Yarn

The linear density values for the 1 cm specimens and 600 mm specimens are summarised in Table 15 to investigate the difference in variability within a yarn and between different yarns.

Table 15: Statistical results of the yarn linear density

	Yarn fineness (tex) (length: 1cm) 100 specimens	Yarn fineness (tex) (length: 600 mm) 121 specimens
Mean	143	132
STDEV	35.2	16.7
CoV (%)	24.6	12.6
Min	67	92.8
Max	232	173

The linear density within the yarn is more variable with a coefficient of variation of ≈25%, compared to the linear density between yarns with a coefficient of variation of ≈13%. It demonstrates that the variation in density within a yarn is larger than the density between different specimens. The yarn linear density determined for each 600 mm specimens is used to determine the breaking strength in Newtons/tex.

The determination of the cross sectional area is required to calculate the yarn breaking strength in MPa and it is calculated based on measurements of 100 yarns. The variables associated with the freehand tool Image J software and the cross sectional area based on the elliptical and circular formula are compared in Table 16 with a representational microscopic image of a typical yarn cross-sectional area presented in Figure 13.

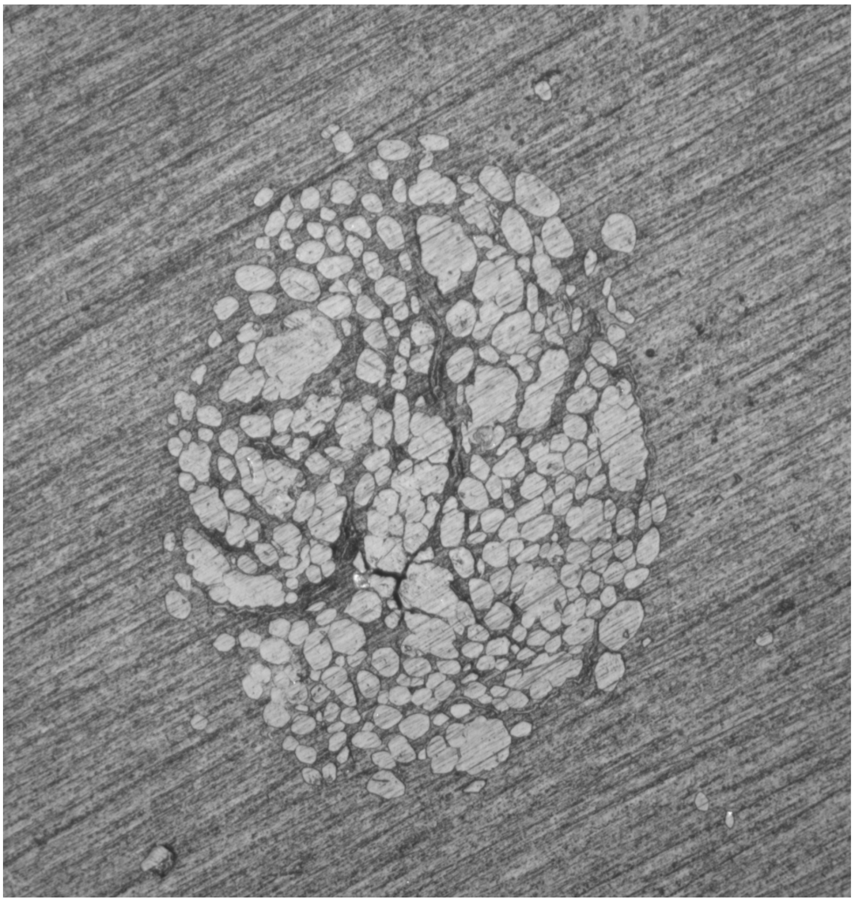


Figure 13: Cross-sectional area of a flax yarn (observed at a magnification of 20x)

Table 16: Statistical analysis of yarn cross sectional areas (mm^2)

	Freehand tool	Ellipse formula	Circle formula, using:		
			Minor diameter	Major diameter	Mean diameter
Mean	0.101	0.090	0.080	0.115	0.097
STDEV	0.024	0.024	0.025	0.037	0.028
CoV (%)	24.1	26.7	31.2	31.9	28.9
Min	0.052	0.043	0.038	0.052	0.046
Max	0.159	0.146	0.153	0.228	0.168

The cross sectional area calculated using the freehand tool is deemed more accurate as it follows the exact shape of the cross section. The mean results using the elliptical estimate are within 11% of the freehand tool results, conservatively underestimating the cross sectional area by a small mean value. The circular formula's mean value based on the minor diameter is further from the freehand tool results underestimating the cross-sectional area by 21% whereas the circular formula's mean value based on the major diameter overestimates the cross-sectional area by 14%. The circular formula's mean value based on the mean diameter underestimates the cross-sectional area by 4%. This large variability between the circular formula based on the minor, major or mean diameter shows that a single measurement of the diameter is not reliable. The coefficient of variation demonstrates that the fibre measurement using the freehand tool has a ≈24% variation about the mean and the elliptical formula has a variation of ≈27% about the mean whereas the circular methods show a greater variability as shown in Table 16. Therefore, even if the free hand tool measurement is the most accurate, the elliptical approximation is considered to be a more suitable alternative compared to the circular assumption to estimate the cross sectional area with a non-destructive technique or where a more cost effective and less time consuming method are required. The elliptical approximation has a smaller variation with a closer mean value and is considered to be a more suitable alternative to estimating the cross-sectional properties.

The cross sectional area results and the linear density are used to calculate the tensile properties of the yarns. The stress and strain are calculated using the load and extension recorded during the experiments with the cross sectional area data already recorded. The stress-strain curves calculated for the 95 specimens tested are shown in Figure 14.

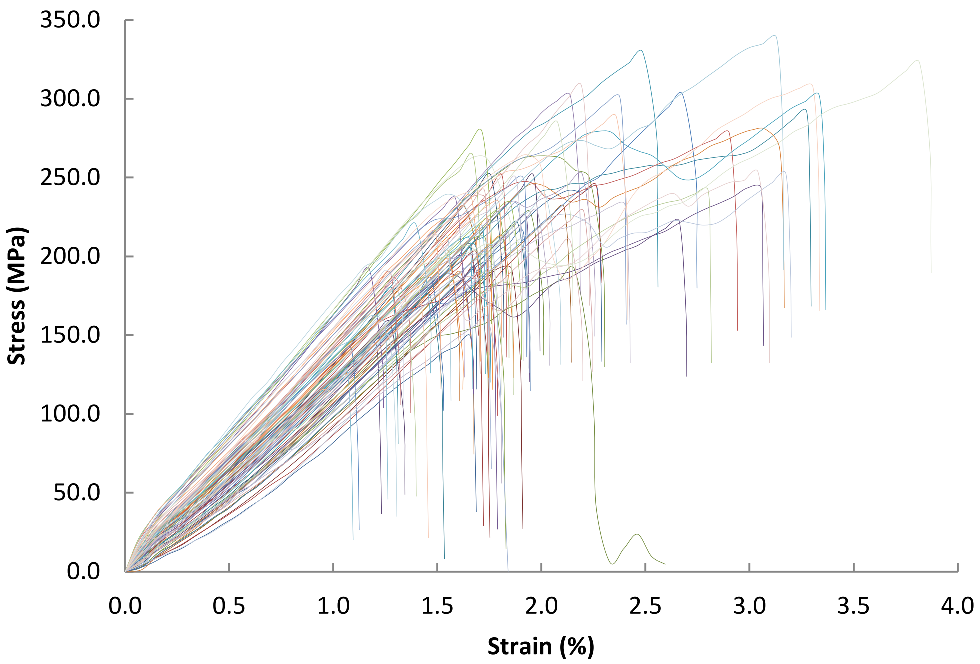


Figure 14: Stress-strain curves for 95 flax yarns of 500 mm gauge length under tension.

The curves show a high variability in the yarns' mechanical properties in terms of breaking elongation and breaking stress. The stress-strain curves for 3 yarns representing distinctive behaviours are detailed in Figure 15.

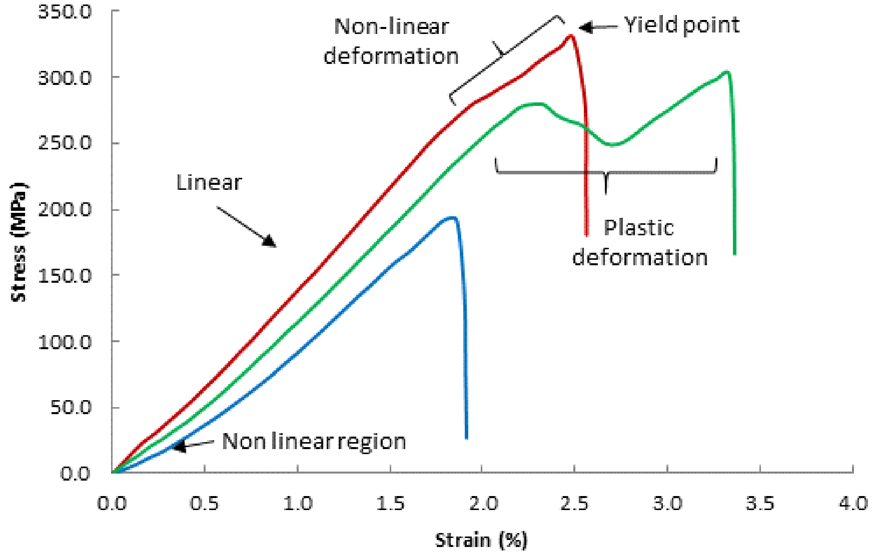


Figure 15: Typical stress-strain curves for flax yarns of 500 mm gauge length under tension

Some specimens exhibit a yield point followed by non-linear deformation before the final breaking point, represented by the green curve in Figure 15. This non-linear region corresponds to successive ruptures of the fibres contained within the yarn. Some specimens have a non-linear behaviour at the start of the test that can be caused by fibre rearrangement within the yarn, represented by the blue curve in Figure 15. Some specimens have a linear behaviour for the majority of the test followed by an inflection point and plastic deformation before failure, represented in red in Figure 15. Similar behaviours are reported for flax yarns by Xue and Hue [74] and flax tows by Moothoo et al [50] and Barbulée et al. [108]. The resulting mean values for the mechanical properties are summarised in Table 17.

Table 17: Yarn tensile test data based on 95 specimens

	Gauge Length (mm)	Breaking Force (N)	Tensile Breaking Stress (MPa)	Breaking Strength (N/tex)	Tensile Modulus (GPa)
Mean	501	22.6	224	0.17	11.4
STDEV	1.83	4.59	45.5	0.03	2.11
CoV (%)	0.37	20.3	20.3	16.0	18.6
Min	497	11.6	115	0.10	6.38
Max	508	34.1	339	0.23	16.7

The weakest yarn breaks at a load of 11.6 N and the strongest at 34.1 N showing that the flax yarns are exhibiting a high variability, as expected. The statistical distribution of the yarn's tensile modulus is presented in Figure 16. The experimental data can be assumed to follow a Normal distribution with a confidence of 95% as shown by the chi-square test for goodness of fit with χ^2 = 3.9728 and therefore smaller than the critical value for α = 0.05 of 15.51 [163].

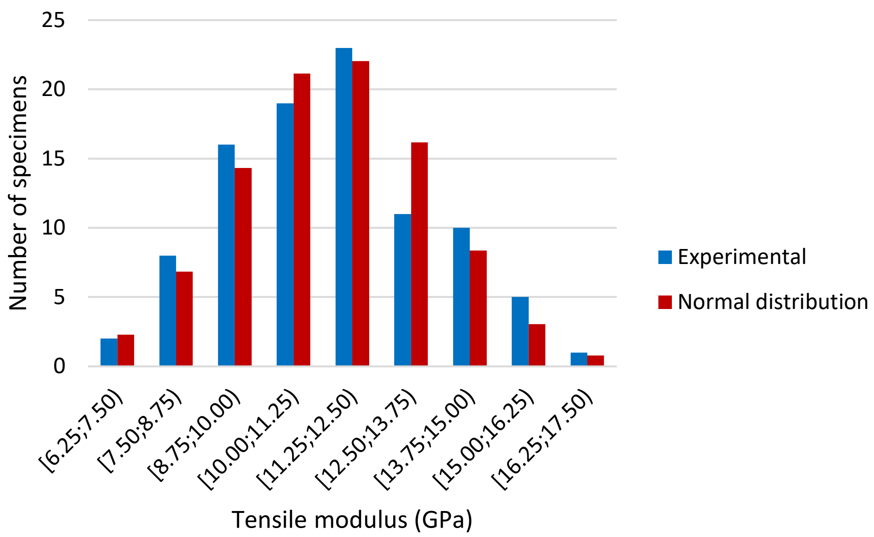


Figure 16: Statistical distribution of the tensile modulus for 95 yarns

Whilst it is assumed that the high variability from the yarns comes from the variation in the material, the yarns tested have to be separated from the cloth and, even if the manipulation is performed with great care, it is possible that yarns may be damaged during the process. Prior damage may have occurred in the manufacturing process or these yarns contain elemental fibres that have been damaged during growth. The yarns also suffer from variability in cross sectional area and using the mean value may have an effect on the stress calculation. The variability in the yarns' fineness (Table 15) is lower than that found in the tensile mechanical properties. The combination of the variability in the cross sectional area and the yarn's linear density can explain part of this but it appears that mechanical properties of the elemental fibres still have an important influence at the yarn scale. Chabba and Netravali [107] find a lower Young's modulus with a higher coefficient of variation, 23.4%, based on a smaller number of flax yarn specimens, 20. However, the apparent diameter measured along the length is used to calculate the cross sectional area and therefore leads to inaccurate results for the stress, which is calculated using this value.

4.2.2 Cloth

The variability at the yarn scale is still significant, but reduced, and therefore the influence of the yarn properties at the cloth scale is investigated in the following section to see if the trend continues. The statistical distribution of the cloth density, obtained from weighing 100 specimens, is summarised in Table 18. The cloth density given by the manufacturer is 222.1 g/m^2 and the mean value found for the cloth density is 283 ± 23.9 g/m^2. Differences between the manufacturer value and calculated value might be explained by the small size of the specimens tested and also the coating applied by the manufacturer on the fibres. The value found by experimentation is used for the calculations of the fibre weight fraction. The results show that there is a large difference in the coefficients of variation for the yarns' linear density, 25%, and for the cloth's, 8%, which shows a trend of reduced variation at larger scales.

Table 18: Statistical values of the flax cloth aerial density based on 100 specimens

	Cloth aerial density (g/m^2)
Mean	283
STDEV	23.9
CoV (%)	8.43
Min	233
Max	342

The breaking force is found from the cloth tensile test and the load-extension curves for the 20 specimens tested are shown in Figure 17.

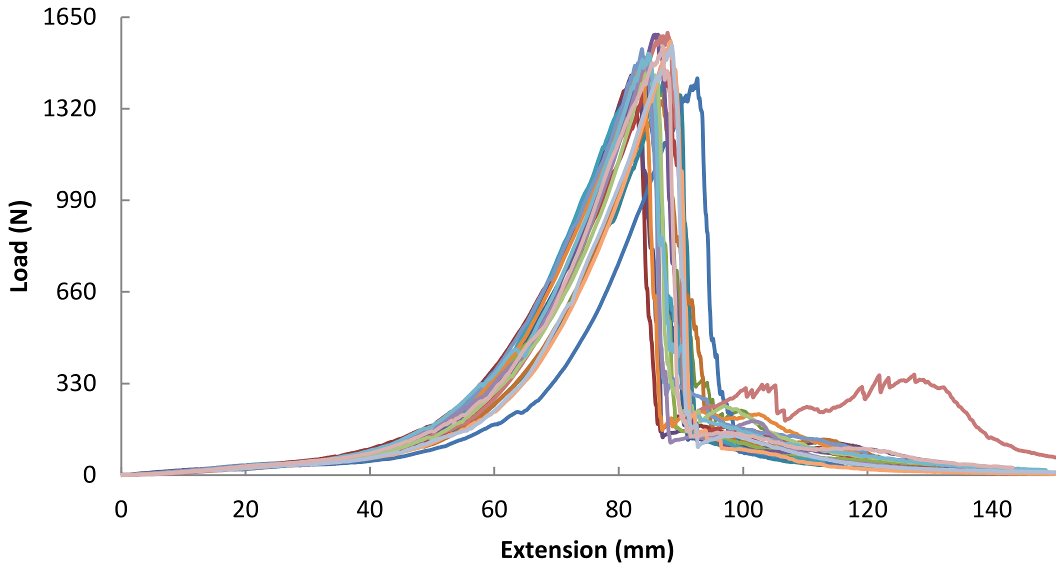


Figure 17: Load-Extension curves for 20 cloth specimens tested in tension

The load-elongation curve is once again not linear at the start of testing. As the yarn tensile testing progresses the cloth extends and changes the organization of the yarns breaking into a wave pattern within the gauge length as seen in Figure 18.

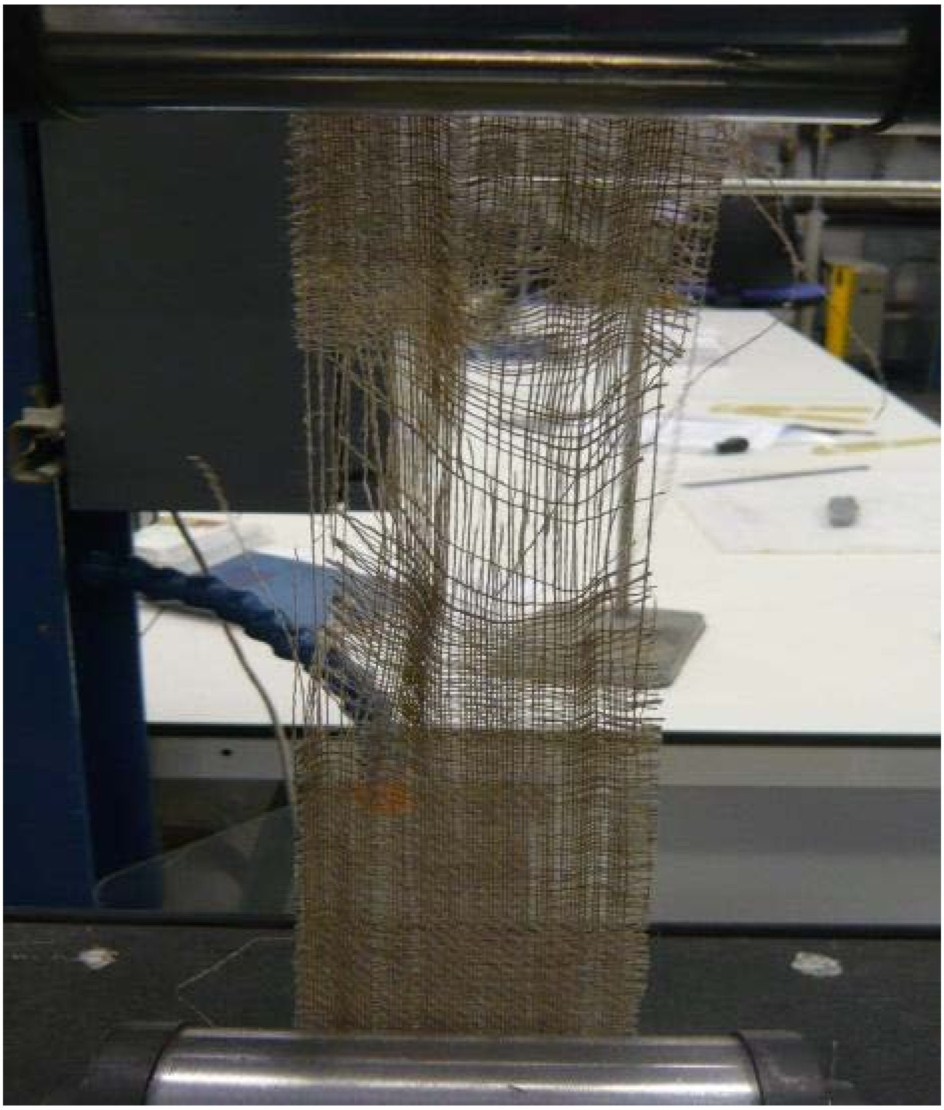


Figure 18: Cloth tensile failure

The cloth starts to break at the point carrying the highest stress and the load is redistributed along the remaining yarns. The starting point for the break is not the same for each specimen but can be seen to always be in the middle of the gauge length. Table 19 summarises the results for the tensile breaking force.

Table 19: Statistical values of the cloth tensile breaking force

	Tensile breaking force (N)
Mean	1491
STDEV	62.4
CoV (%)	4.0
Min	1348
Max	1594

The cloth breaking load variation is smaller than that found for the yarn tensile test. The coefficient of variation for the yarn breaking force is 20% and 4% for the cloth. This difference is caused by the load being carried by the adjacent yarns in the case where weak yarns break and this does not dramatically change the mechanical properties. It is assumed that the difference in terms of variability between the linear density of the yarn, which is high, and cloth, which is lower, can be related to the differences found in the variation of the mechanical properties at these scales. The number of cloth specimens tested is considerably smaller compared to the number of yarn specimens tested which can influence the coefficient of variation. To investigate the correlation between the yarn and cloth mechanical properties, tests are performed to determine the number of yarns per specimen. For each specimen there is a mean of 71.6 with a maximum of 74 and a minimum of 69 yarns found from 20 specimens at 2 separate locations. This shows that the variability in the number of yarns in the specimens is relatively low which helps to explain, together with the variability in density, the low variation in the cloth tensile properties.

An approximation for the relationship between cloth and yarns can be calculated from the breaking load of the cloth divided by the number of yarns in a specimen. The mean value for the cloth breaking load is 1491 ± 62.4 N. Assuming that only the longitudinal yarns are carrying a load during tensile testing, the load carried by each yarn is 21N. The mean value for the tensile breaking force found from the yarn tensile test is 22.6 ± 4.59 N. This approximation shows that the transverse yarns are not carrying any significant load.

4.2.3 Laminate

The influence of the yarns variability on the cloth properties is assessed, showing a reduction in variability, but the influence of the fibre reinforcement on the mechanical properties of a composite laminate needs to be established.

The fibre volume fraction is determined based on 122 specimens from 7 plates, and detailed in Table 20. The cloth density is presumed from testing to be 283 ± 23.9 g/m^2 , the flax density is assumed to be 1450 kg/m ^{3} [137] and the matrix density equal to 1089 kg/m^3 [164].

Table 20: Statistical values of the fibre weight and volume fractions for the 8 layer flax/epoxy laminates

	Breadth (mm)	Length (mm)	Thickness (mm)	Volume of the specimen v_c (mm^3)	Fibre weight fraction W_f (%)	Matrix weight fraction W_m (%)	Density of the laminate ρ_c (kg/m^3)	Fibre volume fraction V_f (%)
Mean	25.32	249.8	4.31	27300	44.1	55.9	1220	37.2
STDEV	0.467	1.21	0.19	1700	1.88	1.88	6.44	1.8
CoV	1.84	0.49	4.37	6.23	4.27	3.38	0.53	4.8
Min	24.19	247.0	4.03	24740	41.0	51.3	1210	34.3
Max	26.14	253.3	4.65	30210	48.7	59.1	1240	41.6

The mean fibre volume fraction is 37.24 ± 1.8 %; it is calculated assuming no void content and so the obtained result is a non-conservative estimate. The value is low compared to that expected for glass fibre reinforced composites manufactured with resin infusion, for example ISO 12215-5 advises a value of 58% [165]. This is expected due to the current difficulties with infusing natural fibres and is comparable to the fibre volume fraction seen in resin infusion for UD flax fibre reinforced epoxy composites, for example the value of 40% found by Van de Weyenberg et al. [137]. The stress-strain curves for the 122 specimens tested in tension are shown in Figure 19.

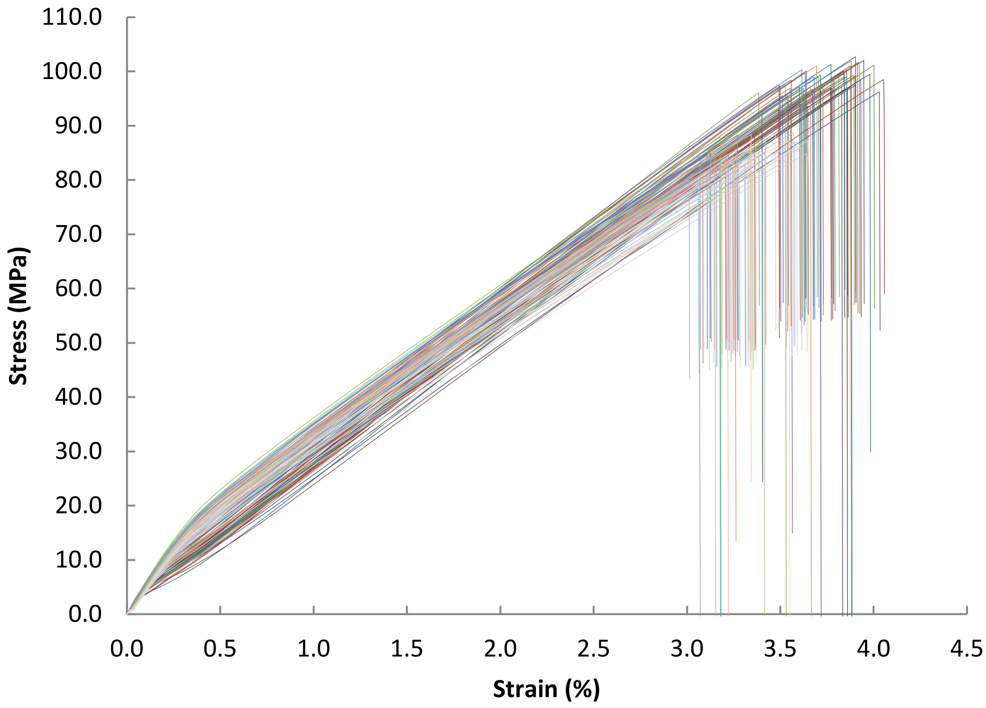


Figure 19: Stress-strain curves for 122 composite specimens tested in tension

The variability in the stress-strain curves seen at yarn scale is considerably reduced at the laminate scale. The stress-strain curves can be considered to be linear elastic before brittle failure occurs but the start of the experiment is difficult to interpret and some specimens present a bi-linear behaviour. Typical stress-strain curves are presented in Figure 20.

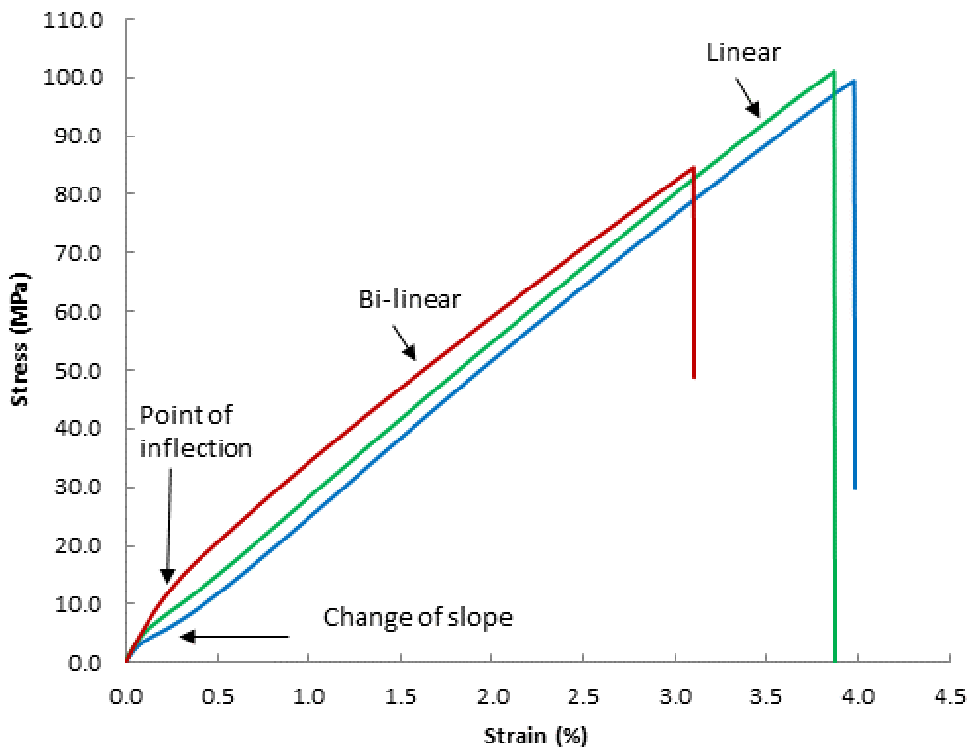


Figure 20: Typical stress-strain curves for composite specimens tested in tension

Three different behaviour of the laminates are shown, similarly to the yarn, but the variation in behaviour is smaller. The red curve represents laminates with a bi-linear behaviour with a point of inflection at low strains, below 0.5%, a similar behaviour is also seen by Cherif et al. [113]. The green curve is linear throughout the test whereas the blue curve represents a change of slope at the beginning of the test at strains around 0.1%, similar to the concave downward slope up to the maximum load exhibited by experiments performed by Xue and Hu [74]. A different behaviour, not seen in these experiments, is demonstrated by Liang et al. [24] who find that the curves have two knee points, one at 0.2-0.3% strain corresponding to the slope changing point of the 0° layers and the second one at 0.5-0.6% strain attributed to the failure of the 90°plies. The resulting tensile properties of the specimens are detailed in Table 21.

Table 21: Statistical values of the tensile properties for the 8 layer flax/epoxy laminates

	Breaking strength (MPa)	Breaking Strain (%)	Young's modulus (GPa)
Mean	90.9	3.50	8.18
STDEV	7.18	0.27	0.42
CoV (%)	7.90	7.73	5.08
Min	78.9	3.01	7.45
Max	103	4.05	9.31

The mean breaking strength is 90.9 ± 7.18 MPa and the coefficient of variation is lower than seen at the yarn level, 7.90%. The Young's modulus is 8.18 ± 0.42 GPa which is low compared to the E-glass fibre reinforced composites but has a comparative level of variation, 5.08 % compared to the variability from Sriramula and Chryssanthopoulos [166] which is between 1 and 10% depending on the manufacturing process. The statistical distribution of the laminate's Young's modulus is presented in Figure 21 The experimental data can be assumed to follow a Normal distribution with a confidence of 95 % as shown by the chi-square test for goodness of fit with $\chi2 = 9.41$ and therefore smaller than the critical value for $\alpha = 0.05$ of 15.51 [163], though the match is less strong than at the yarn scale.

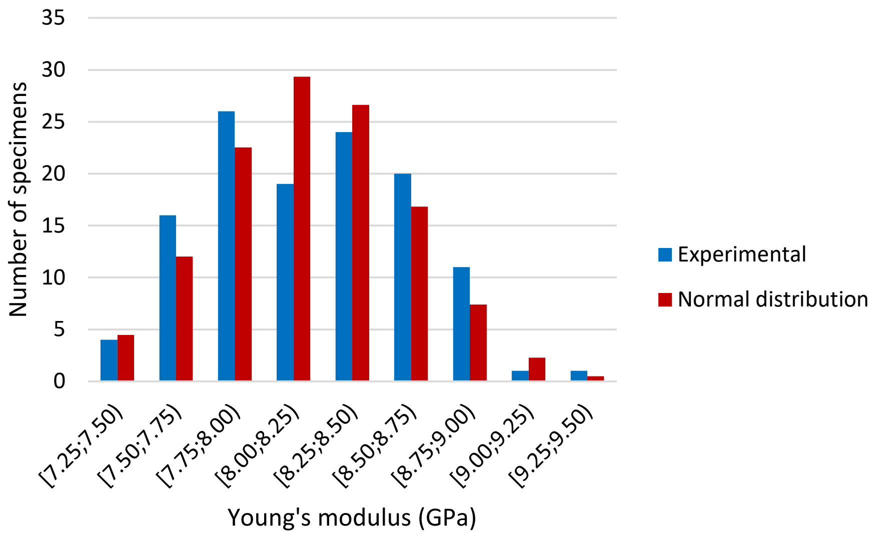


Figure 21: Statistical distribution of the Young's modulus for the 122 laminate specimens

The flexural properties are also determined for comparison with the tensile behaviours. The stress and strain are calculated according to standard ASTM D 7264/D 7264 M [162] using the load and extension recorded during the experiments. The comparison between the strain recorded by the strain gauges and the strain calculated with the cross-head displacement of the machine demonstrates that the strain calculated with the cross-head displacement underestimates the flexural modulus by 9.77 % compared to the strain recorded by the strain gauges. A correlation factor is therefore applied to the non-instrumented specimens. The stress-strain curves for the 101 specimens tested in flexure are shown in Figure 22.

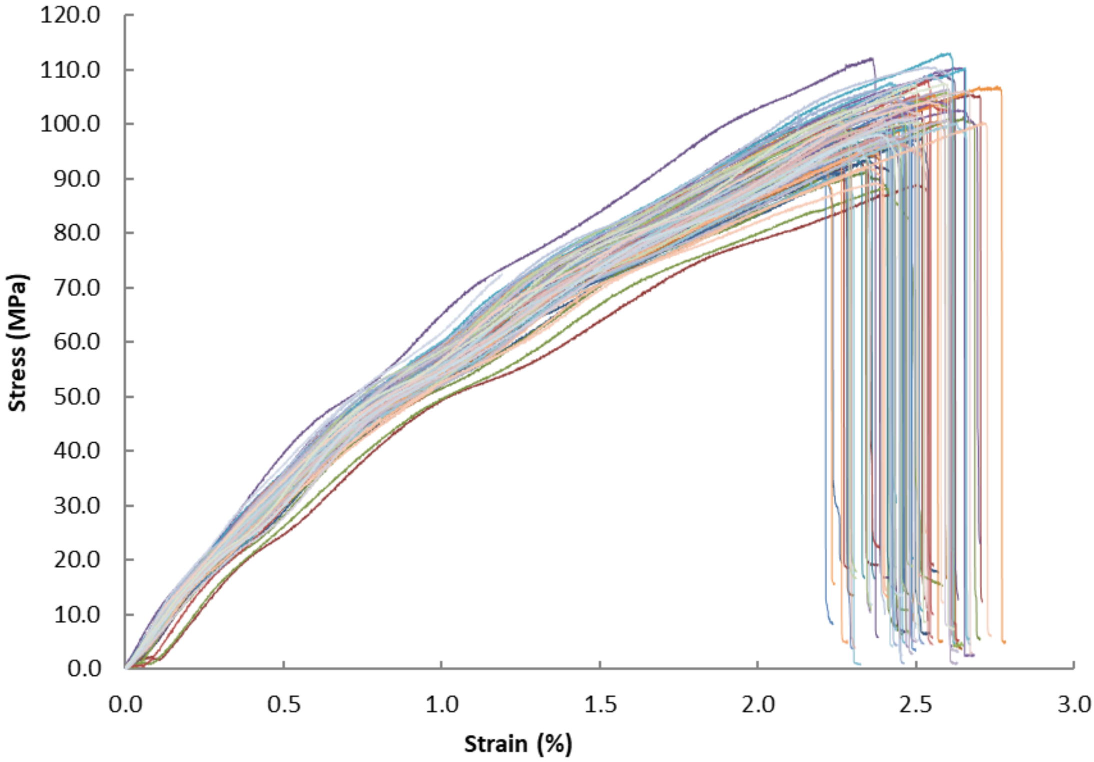


Figure 22: Stress-strain curves for 101 specimens tested in flexure

The variability in stress-strain curve seen at yarn scale is considerably reduced in the laminate. The flexural properties of the specimens are detailed in Table 22.

Table 22: Statistical values of the flexural properties for the 8 layer flax/epoxy laminates

	Flexural strength (MPa)	Flexural Strain (%)	Flexural modulus (GPa)	
			cross-head displacement	Strain gauge factor
Mean	101.0	2.4	6.87	7.55
STDEV	5.4	0.13	0.64	0.70
CoV (%)	5.3	5.2	9.34	9.34
Min	88.3	2.1	5.37	5.89
Max	113.0	2.8	8.36	9.17

The mean breaking strength is 101 MPa, the flexural modulus is 7.55 GPa and the coefficient of variation is lower than seen at the yarn level, 9.34% but higher than the variability found for the Young's modulus. This flexural modulus is low compared to glass fibre reinforced composites. The statistical distribution of the flexural modulus is presented in Figure 23.

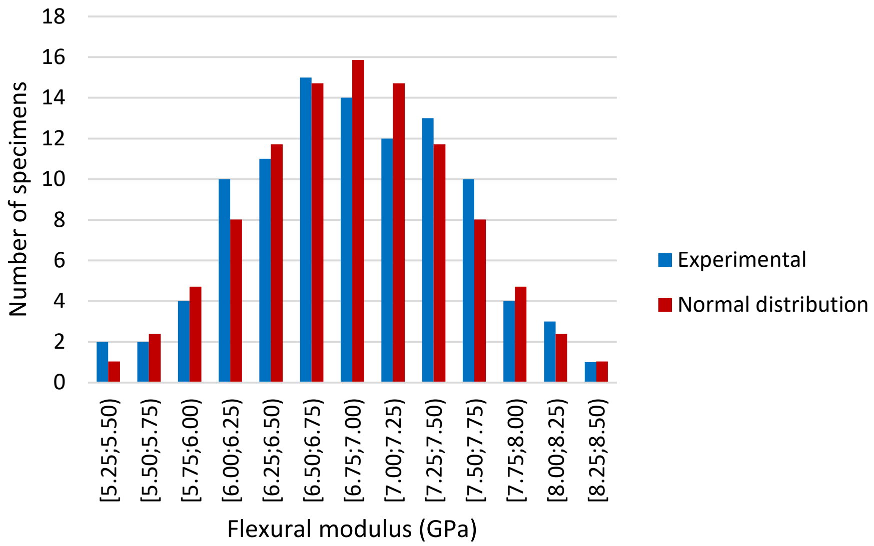


Figure 23: Statistical distribution of the flexural modulus of 101 flax/epoxy laminate specimens

The flexural modulus is normally distributed with a 95% confidence according to the Chi square test for goodness of fit with $\chi^2 = 3.23$ and smaller than the critical value of 21.03 for $\alpha = 0.05$ [163]. The mechanical properties of flax fibre reinforced composites are encouraging and the low variability compared to the yarn stage shows an increase in the reliability of the composite at the laminate stage giving comparative variability to E-glass.

4.3 Rule of Mixtures analysis

To investigate the influence of yarn mechanical properties at the laminate scale, the composite Young's modulus from experiments is compared with theoretical predictions derived with the rule of mixtures as shown in equation (4) with the addition of an orientation factor, η_o, to take into consideration the utilisation of balanced woven fabric at the laminate scale,

$$E_c = \eta_o E_f V_f + E_m V_m. \tag{4}$$

The validity of this rule of mixtures for flax fibre reinforced composites is questioned in the literature. Recent studies, summarised by Summerscales et al. [167], concerning natural fibres have shown that the rule of mixtures need to be modified for natural composites as the assumptions concerning the uniformity of the fibres does not stand. Therefore, experimental laminate data are also compared with an improved rule of mixtures derived by Virk et al. [151] for natural composites and presented in equation (5),

$$E_c = \kappa \eta_d \eta_l \eta_o E_f V_f + E_m V_m, \tag{5}$$

where κ is the fibre area correction factor based on jute, η_d is the fibre diameter distribution factor, η_l is the fibre length distribution factor and η_o is the fibre orientation distribution factor.

The natural rule of mixtures derived by Virk et al. [151] is based on the assumption that the standard rule of mixtures is not accurate for natural fibre reinforced composites because of an overestimation of the fibre cross sectional area, which leads to an underestimation of the fibre mechanical properties during testing. Therefore, the natural rule of mixtures is used to investigate the accuracy of the different assumptions about the fibre cross sectional area in the calculation of a theoretical Young's modulus and compared to the experimental laminate properties.

The natural rule of mixtures as described by Virk et al. [151] compensates for the variability in cross sectional area by using a fibre area correction factor, denoted κ, which compensates for the inaccuracy resulting from measuring the cross sectional area based on a circular assumption and an apparent diameter. The fibre area correction corresponds to the ratio of the apparent cross sectional area to the true cross sectional area [20]. To determine the accuracy of this natural rule of mixtures the Young's modulus is calculated using a circular assumption, based on minor, major and mean diameter measurements, which are compared to an elliptical estimate for the fibre cross sectional area. These are compared to the freehand tool as the most accurate method.

The fibre diameter distribution factor, η_d, is assumed equal to 1 as shown by Virk et al. [151] when the reinforcements is characterised and the fibre length distribution factor, η_l , is assumed equals to 1 as demonstrated by Madsen et al [46] for continuous fibres. The fibre orientation distribution factor is determined from Krenchel [168] as shown in equation (6),

$$\eta_o = \sum_n \alpha_n \cos^4 \theta_n \ , \qquad (6)$$

where α_n is the proportion of fibres oriented at a fibre angle θ_n relative to the applied load direction and is equal to 0.5 as the flax fibre is a balanced woven roving material oriented at 0° and 90°. A matrix modulus given by the manufacturer, Gurit [164], of 3.2 GPa is used with the mean fibre value from testing of 11.40 GPa. The mean composite tensile moduli obtained with the rule of mixtures and modified rule of mixtures for natural composites in comparison with experimental data are shown in Table 23.

Table 23: Comparison of the composite Young's modulus calculated with the different rule of mixtures

	Standard Rule of Mixtures	Natural Rule of mixtures (Circular)			Natural Rule of Mixtures (Ellipse)	Natural Rule of Mixtures (Freehand)
		Minor diameter	Major diameter	Mean diameter		
K	N/A	0.7959	1.1446	0.9625	0.8907	1
η_d	N/A	1	1	1	1	1
η_l	N/A	1	1	1	1	1
η_o	0.5	0.5	0.5	0.5	0.5	0.5
E_f (GPa)	11.396	11.396	11.396	11.396	11.396	11.396
E_m (GPa)	3.200	3.200	3.200	3.200	3.200	3.200
V_f (%)	37.24	37.24	37.24	37.24	37.24	37.24
E_c (GPa)	4.130	3.697	4.437	4.051	3.898	4.130
Error (%)	-49.527	-54.820	-45.777	-50.499	-52.362	-49.527

From the results in Table 23, it is possible to see that the tensile modulus error estimate is -49.5% for the original rule of mixtures, -52.4% for the ellipse and ranging from -54.8% to -45.8% for the circular estimate, compared to the experimental data from the 122 specimens. The natural rule of mixtures described by Virk et al. [151] is a widely used technique, despite being derived for jute. However, when the cross section is measured accurately using the true cross sectional area based on the freehand tool measurement, the fibre cross sectional area factor is 1 and in this case the natural rule of mixtures under predicts the composite' modulus by 49.5%. More accurately determining the cross-sectional area of the fibres does not improve the prediction and the poor performance of the rule of mixtures must be related to other physical properties.

The reasons for these inaccuracies in the rule of mixtures are inconclusive in the literature. The fibre orientation factor is taken as 0.5 as 50% of the fibres are in the longitudinal direction and 50%

are in the transverse direction from the loading but the interaction between longitudinal and transverse fibres due to the weaving effect is not considered. The interface between flax fibres and the matrix is of a lower quality than in conventional fibre reinforced laminates which can impact the validity of the rule of mixtures for flax fibre reinforced composites. The bi-linear, or 3 stage behaviour, of flax fibre tensile stress-strain curves can also impact the laminate predictions.

Another issue in the applicability of the rule of mixtures raised by Shah et al. [45], is the scale at which the mechanical properties of the reinforcement needs to be measured between elemental, technical fibres or yarns as the difference in mechanical properties between the constituents is large. A literature review of flax fibre properties at the elemental, technical fibres and yarns scale is conducted to determine representative average mechanical properties at each scales and determine the impact of the reinforcement scale for laminate properties predicted with the rule of mixtures. A review of the longitudinal Young's modulus for flax fibre at the elemental fibre, technical fibre and yarn scale is presented in Figure 24.

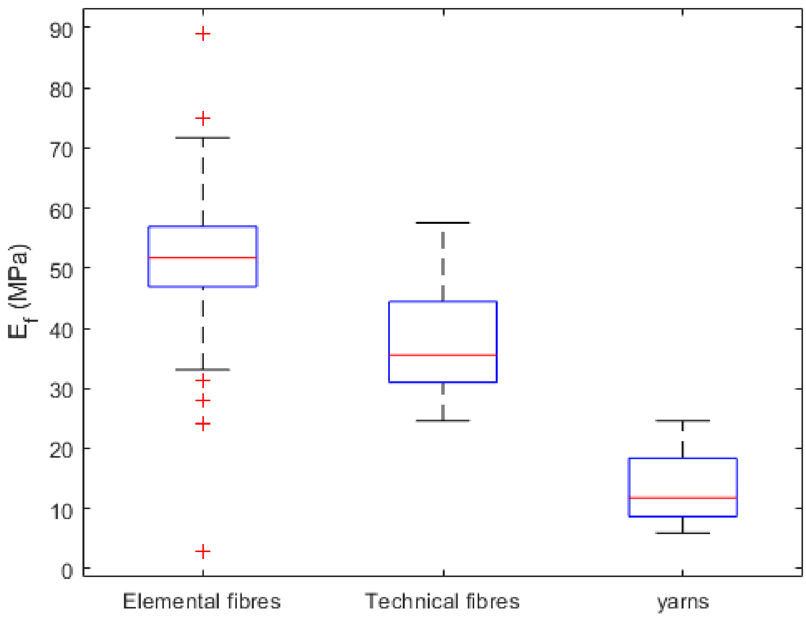


Figure 24: Fibre Young's modulus from the literature [Appendix B]

The number of points for each box plot are 6169 data points for the Young's modulus at the elemental scale, 642 points at the technical scale and 130 points at the yarn scale, meaning that the properties of flax fibres are well characterised. The set of data with references is presented in Appendix B. The fibre stiffness decreases as the scale increases with a mean Young's modulus of 51.96 GPa at the elemental scale, 38.35 GPa at the technical scale and 13.51 GPa for the yarns, shown in Figure 24. The values in the literature are widely spread with the lowest value equal to 2.88 GPa and the highest value equal to 89 GPa both being for elemental fibres but these are considered as outliers. The laminate properties estimated with the rule of mixtures with fibre properties at different scale in comparison to experimental properties are presented in Table 24.

Table 24: Comparison of the laminate Young's modulus predicted with the rule of mixtures for different reinforcement scales and laminate experimental stiffness

	Elemental fibre Literature	Technical fibre Literature	Yarn Literature	Yarn (experiments)
$E_{f\,(mean)}$ (GPa)	51.96	38.35	13.51	11.40
E_m (GPa)	3.2	3.2	3.2	3.2
V_f (%)	37.24	37.24	37.24	37.24
E_c (GPa) rule of mixtures	11.68	9.15	4.52	4.13
E_c (GPa) experimental	8.18	8.18	8.18	8.18
Error (%)	42.8	11.86	-44.74	-49.53

The large difference in mechanical properties between elemental, technical fibres and yarns are reflected in the theoretical calculations of the laminate stiffness. The rule of mixtures estimations are highly influenced by the scale at which the fibres are tested with the laminate stiffness overestimated by 42.8% if elemental fibre are tested or underestimated by 44.7% if yarns data are used in the calculations. Based on the mean values for the fibre properties at the different scales from the literature, the laminate properties need to be calculated with fibre properties measured between the technical fibre and yarn scales but according to Shah et al. [45], the laminate properties are accurately predicted with the rule of mixtures if the fibre properties are measured between the elemental and technical fibre scales. These results highlight the difficulties in predicting flax laminate properties with the rule of mixtures using fibre properties and the low confidence in the models relating fibre and laminate properties due to the numerous uncertainties. Mechanical properties determined at the laminate scale are therefore used for the structural investigations.

4.4 Summary

The scope of work can be broadly divided into the following categories:

- The determination of flax fibre yarn, cloth and laminate mechanical properties by experimental testing.
- The influence of the yarn variability on the laminate mechanical properties.
- Investigation into the calculation of cross sectional area of yarns with different assumptions (circular, elliptical or true cross sectional area) for decreased variability in the mechanical properties.
- Comparison of laminate properties determined with experiments and the rule of mixtures for different fibre cross sectional area and reinforcement scales assumptions.

Research conducted into flax fibres demonstrates that the elemental fibres' mechanical properties are variable and an obstacle to the utilisation of flax fibre reinforced composites for structural components. To estimate the influence of the yarn variability on the composite mechanical properties the cloth breaking load is determined. It is shown that the breaking load of the cloth is broadly equal to the breaking load of a yarn multiplied by the number of yarn in a cloth specimen and that the variability in cloth specimens is considerably reduced compared to the variability at the yarn stage. Current opinion, such as those reported by Dicker et al. [169], highlights that natural fibres exhibit high variability but the results shown here demonstrate that this variability is not significantly higher than other composite materials already used for structural applications at the laminate scale. The fibre volume fraction is low compared to standard composites manufactured using resin infusion and any improvement in the fibre volume fraction will increase the mechanical properties, though the volume fraction obtained for these experiments is similar to the value obtained by Van de Weyenberg et al. [137]. This indicates that further research into the production methods for flax reinforced composites must be investigated. It should still be underlined that the tensile modulus, 8 GPa, and flexural modulus, 6 GPa, show that the stiffness of the composite is low. The stiffness is determined for a strain range between $\varepsilon_1 = 0.05\%$ and $\varepsilon_2 = 0.25\%$ according to the standard BS EN ISO 527-4:1997 [161] but the linear behaviour of the stress-strain curves of flax reinforced laminates at the beginning of loading is debatable and can influence the calculations of the stiffness. This low modulus is partially caused by the high breaking strain of the composite but is counteracted, to some extent, by the high thickness of the plies increasing the flexural rigidity of the material.It is shown that the yarn cross-sectional area cannot be assumed to be circular and leads to inaccuracy in the final mechanical properties. The elliptical estimate tends to underestimate the cross sectional area by 11% but shows a similar coefficient of variation compared to the true cross sectional area based on the freehand tool measurement. The circular estimates are highly influenced by the diameter used for the calculations but always show a higher variability. The elliptical estimate can therefore be used instead of the commonly used circular assumption to predict the properties more accurately in time or budget constrained experiments.

Finally, a comparison of the rules of mixtures is made to help the investigation into these properties, advocated by Summerscales et al. [167]. The influence of the scale at which the fibre properties are determined on the laminate predictions is also investigated. It is found that the rule of mixtures underestimates the mechanical properties by 50% and the natural rule of mixtures proposed by Virk et al. [151] underestimates the properties by between 46% to 55% depending on the cross-sectional area assumptions and is therefore not reliable for flax fibres. This is because the rule relies on the assumption that the inaccuracy of the cross-sectional area measurements is resulting in the errors from the rule of mixtures. More accurate measurements of the cross sectional areas are used to obtain the mechanical properties and show that this inaccuracy is probably not the case and that a variable based on physical properties may be more appropriate. In addition, the laminate stiffness properties predicted with the rule of mixtures are highly influenced by the scale at which the fibre properties are determined with an overestimation of 43% if elemental fibres are used up to an underestimation of 50% if yarns are used. Accurate predictions can be determined if the fibre properties between the technical fibre and yarn scales are used but this result is contradicted by Shah et al. [45]. This demonstrates the difficulties in laminate property prediction based on the rule of mixtures for flax fibre reinforced composites. Numerous other factors at the fibre scale such as the fibre test parameters, strain range used for the Young’s modulus, twist angle and misorientation of the reinforcement can influence the results as shown by Shah et al. [45] who also questioned the applicability of the equation for natural composites. Therefore, laminate properties should be used for the structural analysis.

Chapter 5 Modelling the mechanical response of stiffened structures made of flax fibre reinforced composites

5.1 Introduction

The large variability of flax fibre mechanical properties is viewed in the literature as a major obstacle for their utilisation at the structural scale. This variability is reduced to a coefficient of variation, which is comparable to E-glass at the laminate scale, as demonstrated in chapter 4. However, the relationship between fibre and laminate properties differs from standard composites. Even if flax fibre properties can be comparable to E-glass, Yan et al. [25] and Baets et al. [19], the difference in mechanical properties at the laminate scale is larger and flax fibre composites suffer from lower fibre volume fractions. Currently the behaviour of composite structures is well understood but structural assessments of components made of flax fibre reinforced laminates are limited and those studies that have been performed demonstrate a change in structural response. Alkbir et al. [170], Shah et al. [39] and Bambach [148] conclude that component level analysis must be assessed before flax can be used in structural applications and to understand whether current structural analysis methods are appropriate for flax fibre reinforced composites.

Due to the complexity of composite materials it is useful to have computationally efficient tools to explore the structural design space at an early stage. To reduce the mass, grillages are commonly used in large composite structures; a typical grillage arrangement, taken from the marine industry, is presented in Figure 25. However, the accuracy of rapid analytical grillage methods, designed for steel structures are unknown for composite structures and in particular low stiffness flax fibre reinforced composites.

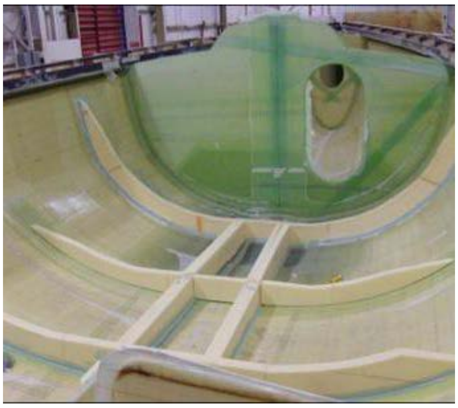


Figure 25: Composite grillage structure inside a leisure boat before layup

Despite a good understanding about the behaviour of composite structures, there are few available methods to model them. Finite Element Analysis (FEA) is the standard, but is more suited for use in the detailed design stages. At an early stage of the design it can be time consuming and authors, such as Toal and Keane [171] and Forrester and Keane [172], propose using it in conjunction with surrogate models. However, Jin and Jung [173] summarise that these methods can impose some inaccuracies, are limited to problems with around 30 variables and still require a number of time consuming FEA simulations. The accuracy of these surrogates is also dependent on the sampling plan requiring the user to have some expertise using these tools, Liu et al. [174]. To counteract these issues there is the development of methods that provide a rapid assessment of structures such as Vescovini and Bisagni [175] who developed an analytical method for assessing the post-buckling behaviour of composite stiffened panels. Akbulut and Sonmez [176] point to the necessity to be able to assess out-of-plane loads, as well as in-plane loads, developing a method for analysing plates but not extending this to more complex structures. Analytical approaches for modelling flax composites are therefore considered to allow easy incorporation into the Monte Carlo Simulation used for the later reliability analysis.

5.2 Analytical structural assessment

5.2.1 Navier grillage method

A number of authors: Maneepan et al. [177], Sobey et al. [178], [179], [180], [181], [182] Blake et al. [183], Yang et al. [184], Xue et al. [185] and Liu et al. [174], utilise the Navier grillage method to assess stiffened structures in applications which require computationally intensive methodologies, such as optimisation and reliability assessments. The method provides a rapid assessment of top-hat stiffened structures, a common topological representation for composite structures which reduce the mass of large composite structures and compensate for the poor torsional rigidity. Elastic equivalent properties are often used to represent composite materials, and therefore layer by layer stresses are ignored, but the accuracy of this adjustment is unknown and is investigated first.

The Navier grillage model, taken from Vedeler [152], calculates the deflection, w, with equation (7) for a grillage under simply supported boundary conditions,

$$w = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} f_{mn} \sin\frac{m\pi x}{L} \sin\frac{n\pi y}{B}, \tag{7}$$

where length, L, in the x-direction is stiffened with transverse stiffeners, N_T, running perpendicular to the x-axis and the breadth, B, in the y-direction is stiffened with longitudinal stiffeners N_L, running perpendicular to the y-axis. The value for the coefficient f_{mn} is calculated with equation (8) for odd wave numbers *m* and *n,* in this case up to a value of 11,

$$f_{mn} = \frac{16PLB}{\pi^6 mnE} \frac{1}{m^4(N_L+1)\frac{I_L}{L^3} + n^4(N_T+1)\frac{I_T}{B^3}}, \tag{8}$$

where *P* is a uniform pressure applied to the panel*, E* are the elastic equivalent properties*,* I_L the second moment of area in the longitudinal stiffener and I_T the second moment of area in the transverse stiffener. From the deflection, the longitudinal bending moment, M_L, at longitudinal position x and transverse position y is calculated with equation (9),

$$M_L = -EI_L\left(\frac{\partial^2 w}{\partial x^2}\right)_{yi} = EI_L \frac{\pi^2}{L^2}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} m^2 f_{mn} \sin\frac{m\pi x}{L}\sin\frac{n\pi y}{B}, \tag{9}$$

similarly the transverse bending moment, M_T, is determined with equation (10),

$$M_T = -EI_T\left(\frac{\partial^2 w}{\partial y^2}\right)_{xi} = EI_T \frac{\pi^2}{B^2}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} n^2 f_{mn} \sin\frac{m\pi x}{L}\sin\frac{n\pi y}{B}. \tag{10}$$

For fibre reinforced composite structures, the material properties for the Navier grillage model are defined using elastic equivalent properties taken from Datoo [186]. The reduced stiffness terms Q_{11}, Q_{12}, Q_{22} and Q_{66} are calculated as shown in equations (11), (12), (13) and (14):

$$Q_{11} = \frac{E_1}{(1-\nu_{12}\nu_{21})}, \tag{11}$$

$$Q_{12} = \frac{\upsilon_{21}E_1}{(1-\upsilon_{12}\upsilon_{21})} = \frac{\upsilon_{12}E_2}{(1-\upsilon_{12}\upsilon_{21})}, \tag{12}$$

$$Q_{22} = \frac{E_2}{(1-\nu_{12}\nu_{21})}, \tag{13}$$

$$Q_{66} = G_{12}. \tag{14}$$

Then, the transformed reduced stiffness terms, $\overline{Q_{ij}}$, for a given ply angle are obtained with equations (15), (16), (17), (18), (19) and (20),

$$\overline{Q_{11}} = cos^4\theta\, Q_{11} + sin^4\,\theta * Q_{22} + 2 * cos^2\,\theta\, sin^2\,\theta * Q_{12} + 4 * \; cos^2\theta\, sin^2\theta * Q_{66} \tag{15}$$

$$\begin{aligned}\overline{Q}_{12} &= \cos^2\theta\sin^2\theta * Q_{11} + \cos^2\theta\sin^2\theta * Q_{22} + \\ &(\cos^4\theta + \sin^4\theta) * Q_{12} - 4\cos^2\theta\sin^2\theta * Q_{66}\end{aligned} \tag{16}$$

$$\begin{aligned}\overline{Q_{16}} = cos^3\theta\sin\theta * Q_{11} - \cos\theta\, sin^3\,\theta * Q_{22} + (\cos\theta\, sin^3\theta - cos^3\,\theta\, sin\theta) * Q_{12} + \\ 2(\cos\theta\, sin^3\theta - cos^3\theta\sin\theta)Q_{66}\end{aligned} \tag{17}$$

$$\overline{Q_{11}} = sin^4\theta\, Q_{11} + cos^4\,\theta * Q_{22} + 2 * cos^2\,\theta\, sin^2\,\theta * Q_{12} + 4 * \; cos^2\theta\, sin^2\theta * Q_{66} \tag{18}$$

$$\begin{aligned}\overline{Q_{26}} = cos\theta\, sin^3\,\theta * Q_{11} \; - cos^3\,\theta\sin\theta * \; Q_{22} + (cos^3\,\theta\sin\theta - cos\theta\, sin^3\,\theta) * \; Q_{12} \\ + 2(cos^3\,\theta\, sin\theta - \cos\theta sin^3\,\theta)Q_{66}\end{aligned} \tag{19}$$

$$\begin{aligned}\overline{Q}_{66} &= \cos^2\theta\sin^2\theta * Q_{11} + \cos^2\theta\sin^2\theta * Q_{22} - \\ 2 * &\cos^2\theta\sin^2\theta * Q_{12} + (\cos^2\theta - \sin^2\theta)^2 * Q_{33}\end{aligned}. \tag{20}$$

The extensional stiffness terms, A_{ij}, are calculated with equation (21),

$$A_{ij} = \sum_{k=1}^{N} t(\overline{Q_{ij}})_k \tag{21}$$

where t is the ply thickness, k is the ply number and i, j are the principal directions.

For the membrane mode, the elastic equivalent properties are calculated with equation (22)

$$E = \frac{A_{11}A_{22}\,A_{66} + 2A_{12}A_{26}A_{16} - A_{22}A_{16}^2 - A_{66}A_{12}^2 - A_{11}A_{26}^2}{(A_{22}A_{66} - A_{26}^2\,)t}. \tag{22}$$

.

The maximum stresses, $\sigma_{L,T\,max}$, on the crown elements in each stiffener can then be derived from the moment, $M_{L,T}$, and calculated with equation (23),

$$\sigma_{L,T\,\max} = \frac{M_{L,T} Z_{L,T}}{I_{L,T}}, \tag{23}$$

where $Z_{L,T}$ is the vertical distance of the centroid of an element to the neutral axis and $I_{L,T}$ the second moment of area.

5.2.2 Validation of the model

The Navier grillage model is verified against the grillage studied by Clarkson [187] using a displacement method, which is assumed to be more accurate but is more computationally expensive. The grillage is constructed from steel and has 4 longitudinal and 4 transverse top hat stiffeners. The dimensions of the grillage are summarised in Table 25.

Table 25: Dimensions of the Navier grillage

		Dimensions (mm)
Longitudinal and transverse stiffeners	Web height	254
	Crown width	127
	Flange width	127
	Web thickness	9.144
	Crown thickness	18.288
	Flange thickness	18.288
Grillage	Length	3810
	Breadth	3810

A uniform pressure load of 137.9 kPa is applied on the structure and the stress and deflection are recorded at the intersection of the longitudinal and transverse stiffeners at the centre of the grillage. The results are presented in Table 26.

Table 26: Verification of the Navier grillage model

	Clarkson [187]	Navier grillage
Deflection (mm)	9.63	9.86
Stress (MPa)	165.52	170.24

The verification shows that the Navier grillage method can accurately predict the deflection and maximum stresses within a stiffened plate made of steel. To study a grillage structure made of fibre reinforced composites, the elastic equivalent properties need to be used. The elastic equivalent elastic properties are verified against various examples by Datoo [188] with different fibre orientations for the membrane mode and the bending mode.

The Navier grillage model is compared to a Finite Element Analysis presented in Blanchard et al. [153], whose accuracy is satisfactorily validated against experiments. The comparison of the analytical grillage model to the FEA shows that the Navier grillage method underestimates the maximum stresses for the composite structures with a 30% error, as shown in Table 27, as the change in material properties isn't accounted for. An adaptation to the Navier method is required for a rapid assessment of composite grillages.

Table 27: Comparison of grillage methods for steel and composite structures

Model	Stress (MPa)	
	Steel	Carbon/epoxy composites
FEA [153]	170.61	246.17
Navier grillage	171.46	171.46

5.3 Empirical improvement for composite grillages

5.3.1 Development of the formula

To derive an improved formulation of the Navier grillage model for composite structures, topologies and materials, representing values from large structural applications, are analysed using a verified FEA model. To calculate layer by layer stresses Classical Laminate Plate Theory is applied to the crown element of the stiffeners, the location of the maximum stress on a grillage structure. The moments in the direction of the stiffener, $M_{x,L}$ for the longitudinal direction or $M_{x,T}$ for the transverse direction, are calculated with the grillage equations, (3) and (4). These are divided by the empirically derived factor, *F*, and the stiffener width, *a*, before being implemented into the Classical Laminate Plate Theory, shown for the longitudinal and transverse directions in equations (24) and (25),

$$M_{x,L} = -\frac{EI_L}{aF}\left(\frac{\partial^2 w}{\partial x^2}\right)_{y_i}, \tag{24}$$

$$M_{x,T} = -\frac{EI_T}{aF}\left(\frac{\partial^2 w}{\partial y^2}\right)_{x_i}. \tag{25}$$

The empirical factor, *F,* is calculated to reduce the error in the stresses found between the Finite Element Model and the grillage analytical model for the standard materials: E-glass, Kevlar and Carbon. A second order polynomial regression analysis is then performed using a least squares fit to determine the equation for the empirical factor, *F,* as a function of E_1/E_2 which is calculated as shown in equation (26) with E_1 and E_2 being the longitudinal and transverse Young's modulus of the laminate,

$$F = 0.003\left(\frac{E_1}{E_2}\right)^2 - 0.1202\left(\frac{E_1}{E_2}\right) + 3.9721. \tag{26}$$

The resultant forces and moments acting on the laminate are then used to calculate the strains and curvatures using standard constitutive equations with equation (27) [189]:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}, \quad (27)$$

where , N_x and N_y are the normal forces per unit length, N_{xy} is the shear force, M_x, M_Y and M_{xy} the resulting moments per unit length $\varepsilon_x^0, \varepsilon_y^0, \gamma_{xy}^0$ are the middle-surface strains and κ_x , κ_y, κ_{xy},, middle-surface curvatures.

Or in the contracted form presented in equation (28),

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon^0 \\ \kappa \end{Bmatrix}. \quad (28)$$

The resultants forces and moments are obtained from the grillage model and the matrix needs therefore to be inverted to calculate the middle-surface strains, ε^0, and middle-surface curvatures, κ, as presented in equation (29),

$$\begin{Bmatrix} \varepsilon^0 \\ \kappa \end{Bmatrix} = \begin{bmatrix} A' & B' \\ B'^T & D' \end{bmatrix} \begin{bmatrix} N \\ M \end{bmatrix}. \quad (29)$$

The curvatures and strains are calculated from the extensional stiffness matrix, [*A*], the extensional-bending coupling stiffness matrix, [*B*], and the bending stiffness matrix, [*D*]. The crown is assumed to be in pure bending and therefore the normal forces per unit length, N_x and N_y, and shear force, N_{xy}, are assumed to be negligible and set to 0. The width to height ratio of the cross section is assumed to be small; this means that the lateral curvature is induced only due to the effects of Poisson's ratio and therefore transverse bending moment per unit length, M_y, is also set to 0. The extensional-bending coupling matrix, [*B*], relates in-plane strains to bending moments and curvatures to in-plane forces; the laminate is symmetric and therefore the [*B*] matrix is also set to 0. With these assumptions, equation (29) can be modified into equation (30),

$$\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} = \begin{bmatrix} A'_{11} & A'_{12} & A'_{16} & 0 & 0 & 0 \\ A'_{21} & A'_{22} & A'_{26} & 0 & 0 & 0 \\ A'_{16} & A'_{26} & A'_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & D'_{11} & D'_{12} & D'_{16} \\ 0 & 0 & 0 & D'_{21} & D'_{22} & D'_{26} \\ 0 & 0 & 0 & D'_{16} & D'_{26} & D'_{66} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ M_x \\ 0 \\ 0 \end{bmatrix}. \tag{30}$$

The strains from equation (30) can then be converted to stresses in the k^{th} layer of the crown laminate using equation (31),

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}_k = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}, \tag{31}$$

where z is the ply centroidal value and τ_{xy} is the shear stress. The stresses in each layer is calculated by rotating to the fibre and matrices coordinates with equation (32),

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix}_k = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta & \left(\cos^2\theta - \sin^2\theta\right) \end{bmatrix}_k \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \tag{32}$$

The stresses in the longitudinal and transverse directions are determined for each layer of the crown.

5.3.2 Verification of the Classical Laminate Plate Theory

The classical laminate plate theory is validated against Datoo [188] and two case studies by Nettles [190]. The first example consists of a 4-ply laminate with a [0°/45°/45°/0°] stacking sequence subjected to a tensile stress resultant of 87563.42 N/m, shown in Figure 26.

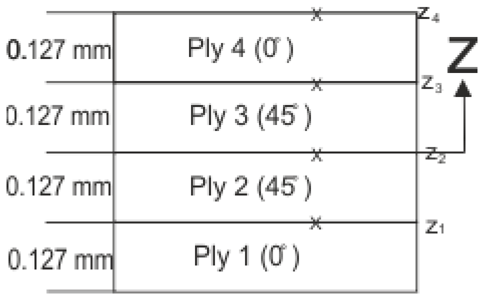


Figure 26: Laminate sequence for the verification of the CLPT

The results are summarised in Table 28.

Table 28: Verification of the stress matrix in the principal material directions for a tensile stress resultant of 87563.42 N/m

	layer 1	layer 2	layer 3	layer 4
σ_1 (MPa)	304.28	28.33	28.33	304.28
$\sigma_{1\ Nettles}$ (MPa)	304.84	28.59	28.59	304.84
Error (%)	-0.18	-0.88	-0.88	-0.18
σ_2 (MPa)	-0.34	12.47	12.47	-0.34
$\sigma_{2\ Nettles}$ (MPa)	-0.33	12.49	12.49	-0.33
Error (%)	3.92	-0.23	-0.23	3.92
τ_{12} (MPa)	-7.93	-20.05	-20.05	-7.93
$\tau_{12\ Nettles}$ (MPa)	-7.94	-20.08	-20.08	-7.94
Error (%)	-0.02	-0.15	-0.15	-0.02

The second case consists of the same laminate subjected to a bending moment in the 0° fibre direction of 22.24 N-m/m. The stresses into the principal material directions and the associated errors are detailed in Table 29.

Table 29: Validation of the stress matrix in the principal material directions for a bending moment of 22.24 N-m/m

	layer 1	layer 2	layer 3	layer 4
z (mm)	-0.127	0.000	0.127	0.254
σ_1 (MPa)	-287.95	0.00	56.26	575.91
$\sigma_{1\ Nettles}$ (MPa)	-287.84	0.00	55.81	575.71
Error (%)	0.04	0.00	0.81	0.03
σ_2 (MPa)	1.78	0.00	8.97	-3.57
$\sigma_{2\ Nettles}$ (MPa)	1.83	0.00	8.94	-3.57
Error (%)	-2.71	0.00	0.39	-0.08
τ_{12} (MPa)	3.38	0.00	-20.12	-6.76
$\tau_{12\ Nettles}$ (MPa)	3.38	0.00	-20.15	-6.73
Error (%)	-0.02	0.00	-0.15	0.39

The errors for the longitudinal and transverse stresses are negligible with the largest error being an underestimation of 2.7% for the transverse stress occurring in the top layer. The Classical Laminate Plate Theory is therefore giving accurate and satisfactory results and could be implemented into the crown element of the grillage. The verification and the close or matching results of the Classical Laminate Plate Theory is giving confidence to the model which will be used to analyse the structural behaviour of a grillage structure made of different fibre reinforced composite materials.

5.4 Demonstration of the empirical formula

To demonstrate the accuracy of the empirical formula, the stresses predicted by the modified grillage model are compared to Finite Element Analysis stresses, presented in Blanchard et al. [153], for different composite materials from natural fibres, representing the lowest Young's modulus feasible for structures, to high modulus carbon fibre reinforced composites, representing the highest end of the Young's modulus spectrum. Different grillage topologies are also investigated by varying: the number of stiffeners, the plate length, the stiffener height, the stiffener width and the plate aspect ratio.

5.4.1 Base case

A base case is defined as a square grillage composed of 4 equally spaced longitudinal stiffeners and 4 equally spaced transverse stiffeners as shown in Figure 27. The total length and breadth of the panel is 3810 mm and the dimensions of the stiffeners are presented in Figure 28.

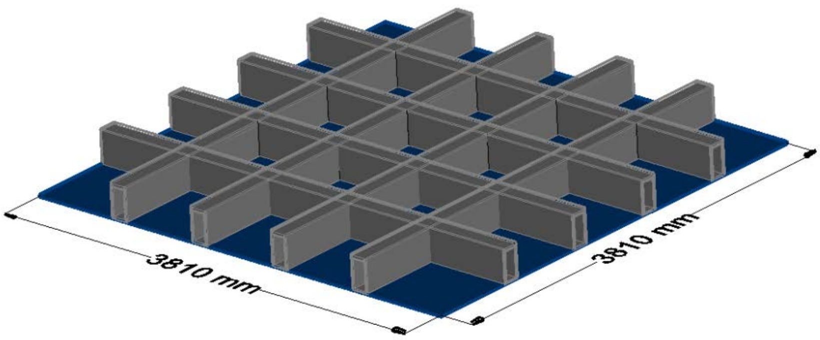


Figure 27: Base case grillage definition

A uniform pressure of 137.9 kPa is applied to the structure. The crown element of the stiffeners are formed of 10 layers with a $[0\ 90\ 0\ 90\ 0]_S$ lay-up. The web and plate elements are composed of 8 layers with a $[0\ 90\ 0\ 90]_S$ lay-up.

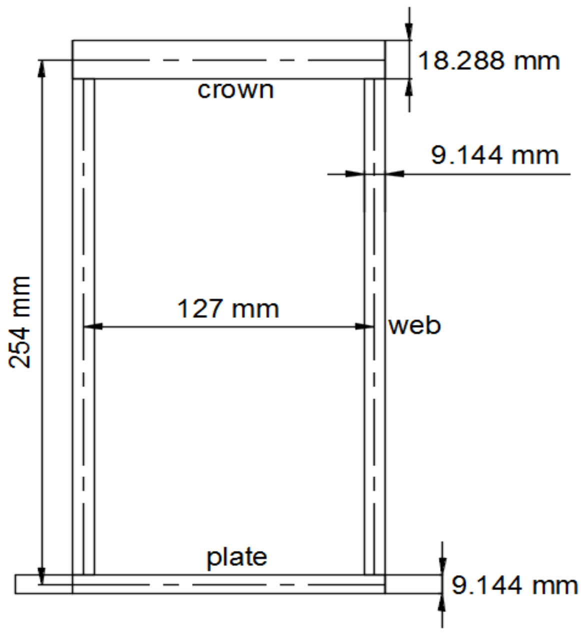


Figure 28: Dimensions of the base case stiffener

The base case is used to determine the influence of the material properties on the empirical factor in section 5.2 and sensitivity to topological changes in section 5.3. The response of grillage structures are modelled using different fibres representing a range of composite materials with low to high moduli: low modulus (LM) flax, flax, E-glass, Kevlar, carbon and high modulus (HM) carbon, which are reinforced with epoxy. The material properties are presented in Table 30.

Table 30: Material properties for the case studies

	(LM) Flax/ epoxy	Flax/ epoxy	E-glass/ epoxy	Kevlar/ epoxy	Carbon/ epoxy	HM carbon/ epoxy
E_1 (MPa)	22300	29700	43000	75000	172400	300000
E_2 (MPa)	4200	4800	8000	6000	6900	12000
ν_{12}	0.35	0.36	0.28	0.34	0.25	0.3
G_{12} (MPa)	1970	2190	4000	2000	3450	5000
F	3.42	3.34	3.41	2.94	2.84	2.84
Ref.	[113]	[113]	[191]	[192]	[193]	[192]

5.4.2 Influence of the material properties

The base case topology is assessed and compared to stresses calculated from the FEA model, presented in Figure 29 where the line splits area A, representing low stiffness flax fibre composites, from area B, representing standard moduli composites.

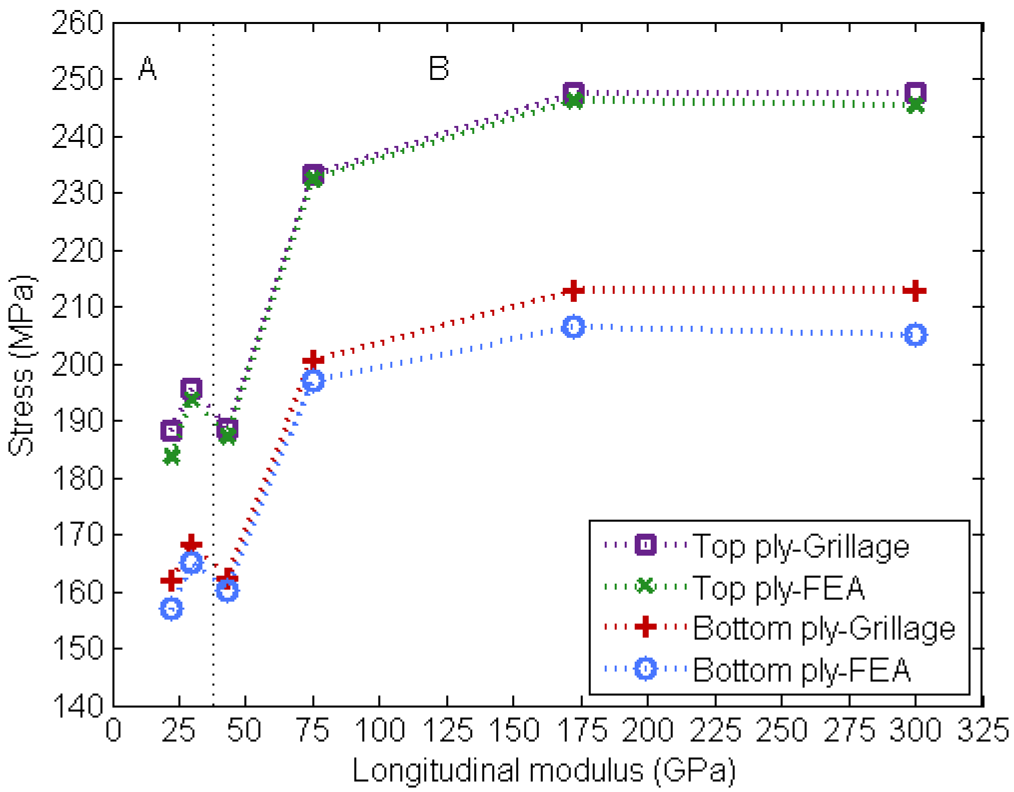


Figure 29: Comparison between stresses obtained from FEA [153] and empirical grillage model for different material properties

As the material properties change from low Young's Modulus to high the rate of change of the stress varies. At high values the stress decreases slowly, with a small variation between the two types of carbon. There is an increase in this rate for lower moduli, Kevlar and E-glass, before a small increase in stress for the higher modulus flax before decreasing again for the lower modulus flax. This demonstrates a different response for the lower stiffness materials as they are more sensitive to the value of E_2, small changes in this value make a much larger change to the structural response.

When modelling this change in behaviour the Navier grillage model does not consider the impact of the material properties on the stress prediction and so is incapable of giving the correct response. This is heavily influenced by the ratio of E_1 to E_2; which is reflected in the empirical factor, *F*, in equation (14). The model is validated for the different materials and the calculated values for the empirical factor are shown in Table 30. The addition of the empirical factor allows accurate predictions of these stresses, in comparison to FEA, for all the materials tested. The maximum stresses, in the outer layer of the laminate, have an error smaller than 2.5% for all the materials down to 0.3%; the absolute mean error is 1.0% across all the material properties for the top ply. To demonstrate the accuracy through the thickness the inner layer is also compared where the stresses are overestimated but with all the errors below 3.8% and the lowest error is 1.3%.

5.4.3 Topological factors

To compare the behaviour of flax and carbon the response is determined over a range of topologies suitable for large composite structures by varying the number of stiffeners; the plate, length and aspect ratio, and the stiffener, height and width. The material properties are presented in Table 30 and the stresses in the top ply are compared, as they represent the maximum stress and show a similar accuracy to the bottom ply. The stresses for the bottom ply for both carbon and flax fibre reinforced composites are presented in appendix C.

The effect of changing the number of stiffeners in both the longitudinal and transverse directions is evaluated from values of 2 to 5 stiffeners, also changing the stiffener spacing. The comparison between the FEA and the empirical grillage model is shown in Figure 30.

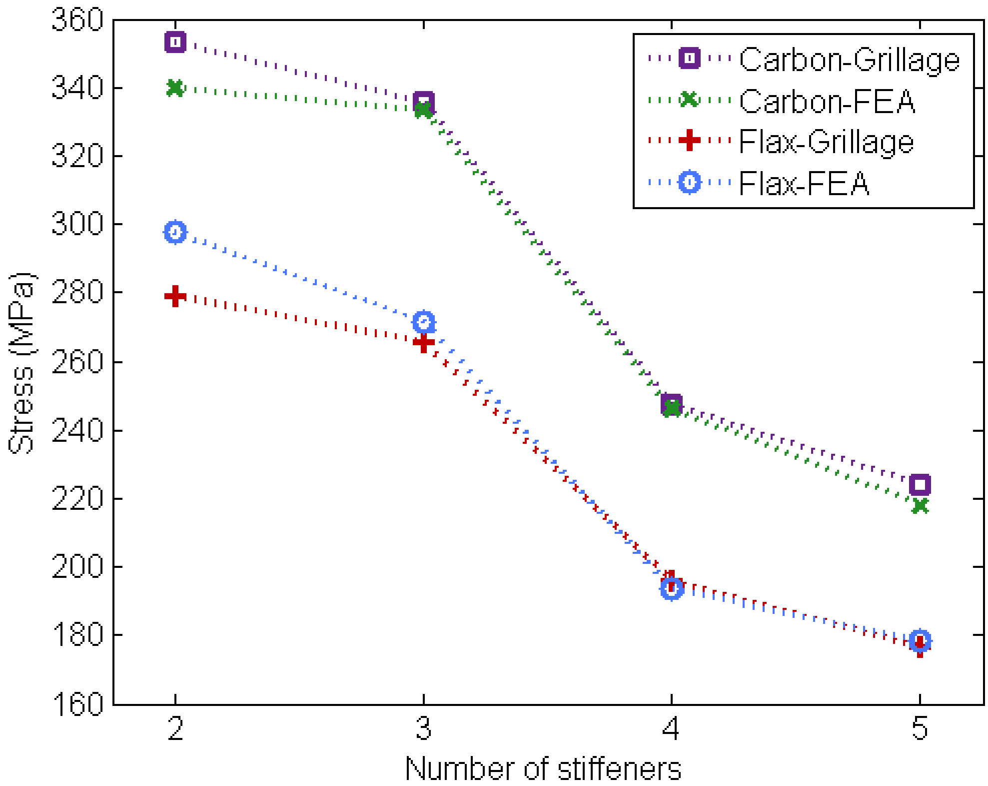


Figure 30: Comparison between top ply stresses obtained with FEA [153] and empirical model for varying number of stiffeners

At low numbers of stiffeners the stresses are relatively high with only a small decrease between 2 and 3 stiffeners. There is a larger drop when there is an increase of stiffeners between 3 and 4 because the stress is taken at the intersection between the stiffeners, not the centre of the plate, followed by another small decrease between 4 and 5. The grillage model overestimates the stresses on the top ply for carbon with a mean error of 2.0% whereas for flax this is only the case for 4 stiffeners with an absolute mean error across the entire range of 2.6%. The largest errors, 4.1% for carbon and -6.2% for flax, are both for the smallest number of stiffeners, also giving the largest stiffener spacing. This is considered to be a wide spacing for large composite structures, at a distance of 1270 mm, and taking an example from leisure boatbuilding would be treated as exceptional by ISO 12215-5 [194] as it is over the maximum stiffener spacing of 500 mm. The minimum error is 0.5% for carbon and -0.8% for flax.

Square plates with different areas are investigated by increasing the length and width from 2000 mm to 4000 mm in increments of 500 mm; meaning that the stiffener spacing ranges from 400 mm to 800 mm. The stresses predicted by the FEA and calculated with the empirical grillage model are compared in Figure 31.

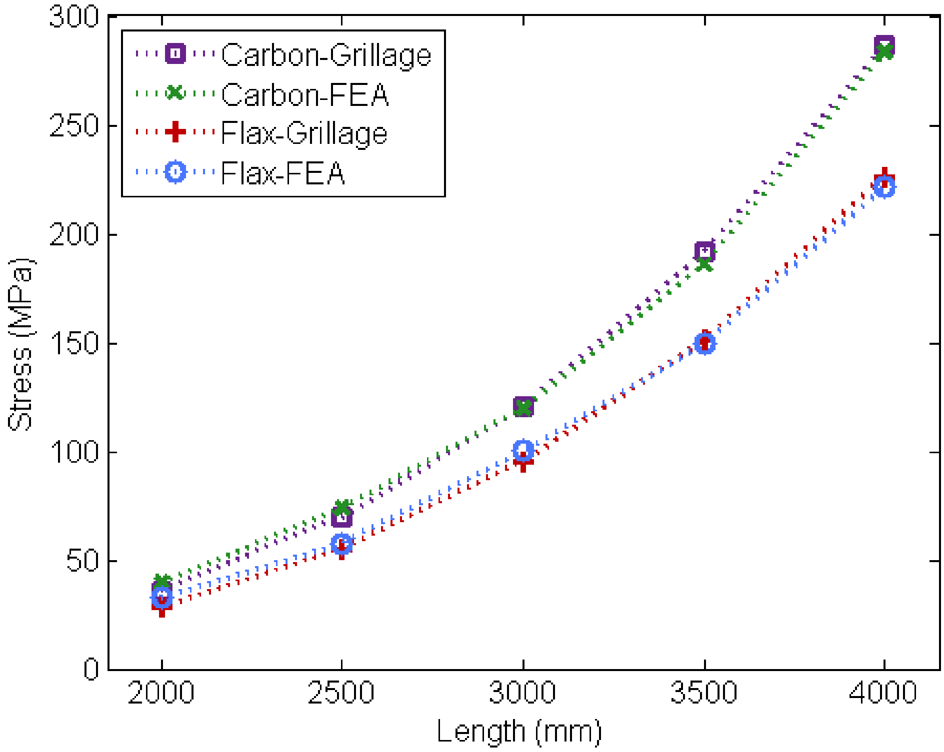


Figure 31: Comparison between top ply stresses obtained with FEA [153] and empirical model for varying areas of plate

The maximum stresses on the outer layer of the stiffeners are accurately predicted by the grillage model for lengths and widths above 2000 mm, with a maximum error of -5.2% for carbon and -4.3% for flax. However, for lengths and widths below this the error is higher, -10.0% for carbon and -14.5% for flax. However, this gives an absolute difference in stress of 4 MPa for carbon and 4.8 MPa for flax, and so it is still judged to have a reasonable accuracy. The minimum error for carbon is 0.8% and 1.3% for flax and the absolute mean error is 4.0% for carbon and 5.5% for flax.

The base case is extended for rectangular panels with aspect ratios from 1 to 3, in increments of 0.5. The width is kept constant, equal to 2000 mm, and the length varies from 2000 mm to 6000 mm. The structure is composed of 2 equally spaced stiffeners in the longitudinal direction and 4 equally spaced stiffeners in the transverse direction. The stresses predicted by the FEA and the empirical grillage results are presented in Figure 32.

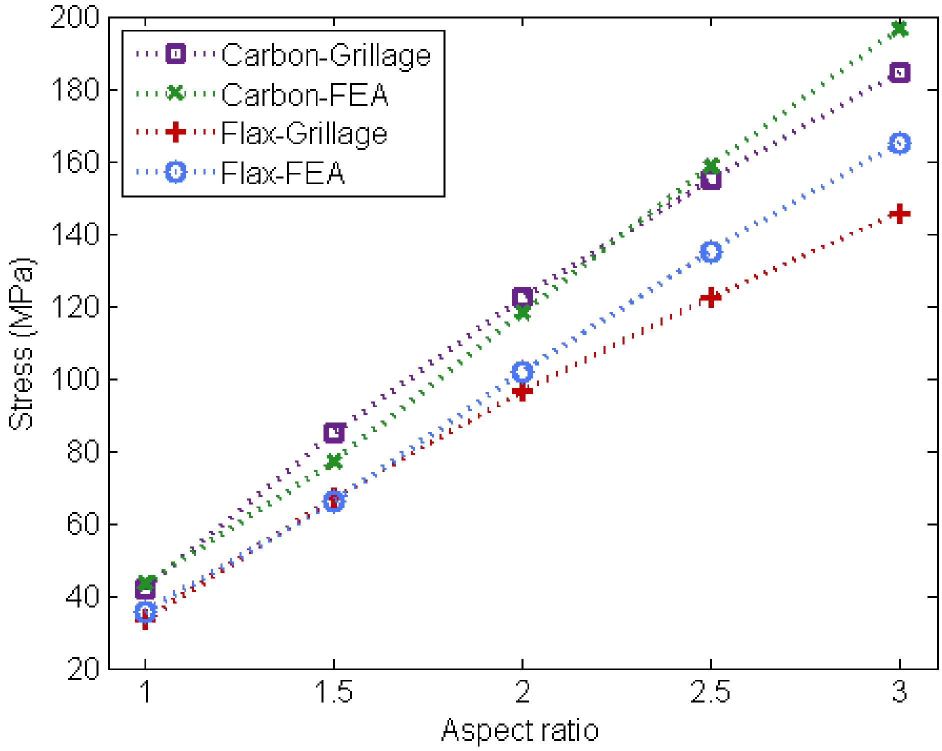


Figure 32: Comparison between top ply stresses obtained with FEA [153] and empirical model for varying aspect ratios

The stress increases almost linearly from a square plate to the largest aspect ratio of 3 where the carbon case has a slight S shape across the range but the flax is straighter. For carbon, the maximum stresses on the outer ply of the laminate are overestimated by the grillage for aspect ratios 1.5 and 2 whereas these are underestimated for aspect ratios 1.0, 2.5 and 3.0; the absolute mean error is 5.2%. The maximum error is an overestimation of 10.4% for an aspect ratio of 1.5 and the minimum error is an underestimation of -2.4% for an aspect ratio of 2.5. For flax, the grillage underestimates the maximum stresses for all the aspect ratios except for an aspect ratio of 1.5, which shows a minimum error of 1.6%. The absolute mean error is 7.0% and the maximum error is -11.7% for the largest aspect ratio, 3. Therefore, the empirical formula is judged to have a good accuracy at aspect ratios below 3 for both materials. The base case is extended for a range of stiffener heights from 100 mm to 250 mm in increments of 50 mm, varying the height to width ratio of the stiffeners, and the results are presented in Figure 33.

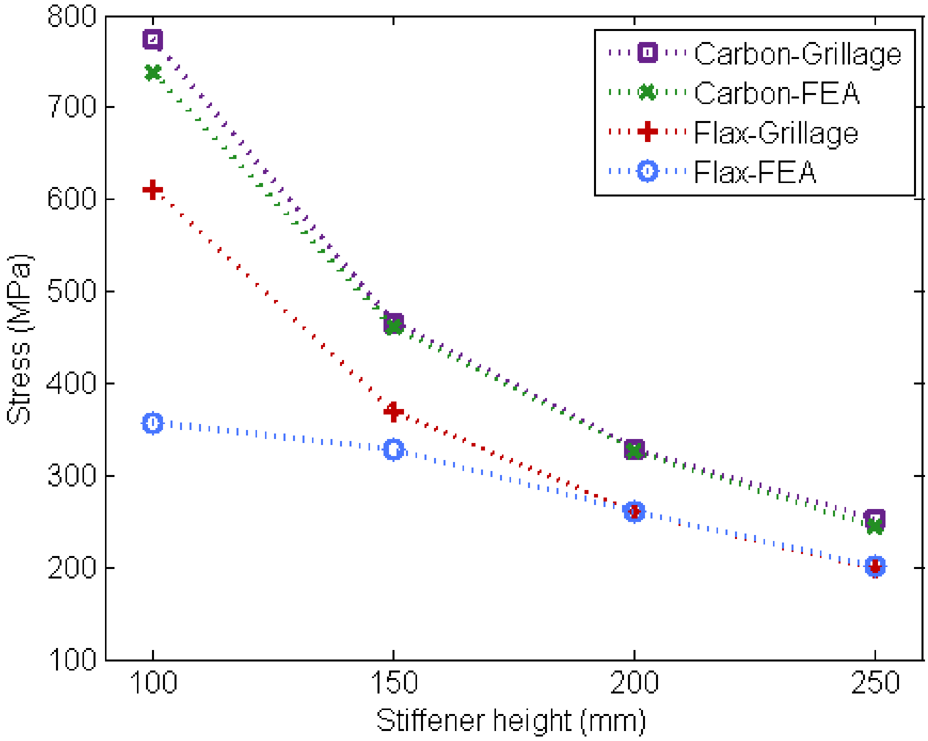
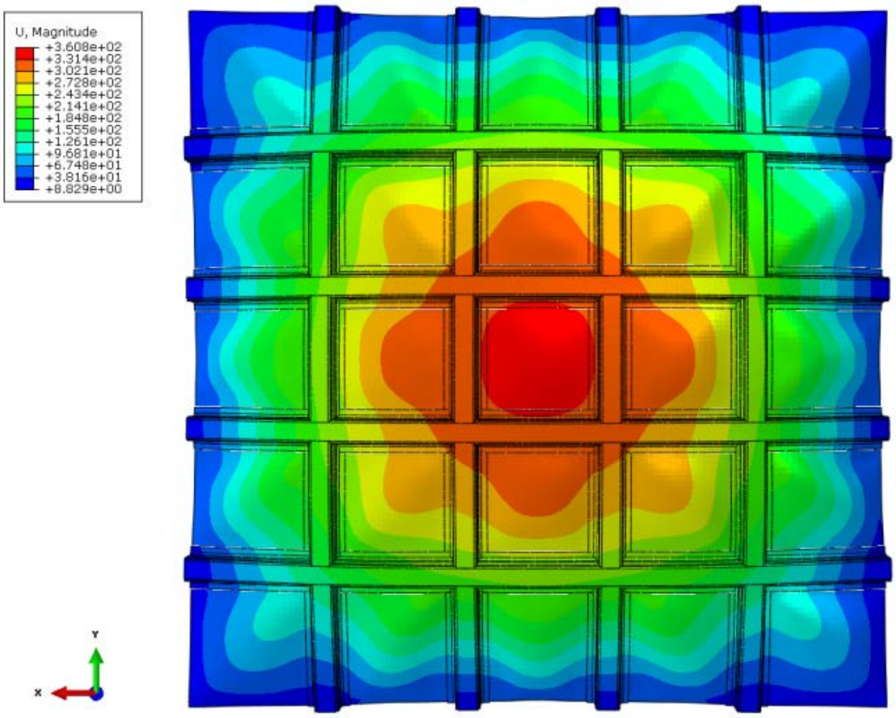


Figure 33: Comparison between top ply stresses obtained with FEA [153] and empirical model for varying stiffener heights

For the FEA carbon case the stress values initially decrease steeply at lower stiffener heights with a reduction in this trend for the largest stiffener sizes; this trend is followed by the analytical model. The FEA flax case has a smaller change in stress between the highest and lowest values, showing a change in behaviour between the two materials. The maximum stresses are overestimated by the grillage model compared to the FEA prediction for carbon with an absolute mean error of 2.6%, showing good accuracy. For flax, the empirical model overestimates the maximum stresses for 100 and 150 mm as it has a different trend but accurately predicts the stress for 200 and 250 mm. The absolute mean error is 21.1% due to the high error at 100 mm, which has a maximum error of 71.0% for flax compared to 4.9% for carbon and is 4.5% without this value. However, for these values the stiffener height is reduced to below the width, 127 mm, which is uncommon in practice. As the stiffener height is reduced the flax structure changes behaviour in the FEA model from local bending dominated to global bending dominated, but this non-linearity is not predicted in the analytical model leading to a higher discrepancy. Along with this change in bending there is a difference in the distribution of stresses. For the local bending cases, the carbon grillages and the taller stiffened flax grillages, the stresses are predominantly along the continuous stiffeners but in the global bending case the stresses are proportional in both directions; which reduces the magnitude of the increase in stress. The change is perceptible for the 150 mm tall flax stiffened plate but not for any carbon panels as they have a higher Young's modulus and therefore structural rigidity. The deflection FEA contour plots for the 100 mm high flax stiffened plate are presented compared to the 250 mm high grillage in Figure 34, and for carbon in Figure 35, to illustrate this response. The minimum error is -0.1% for flax and 0.7% for carbon.

(a)



(b)

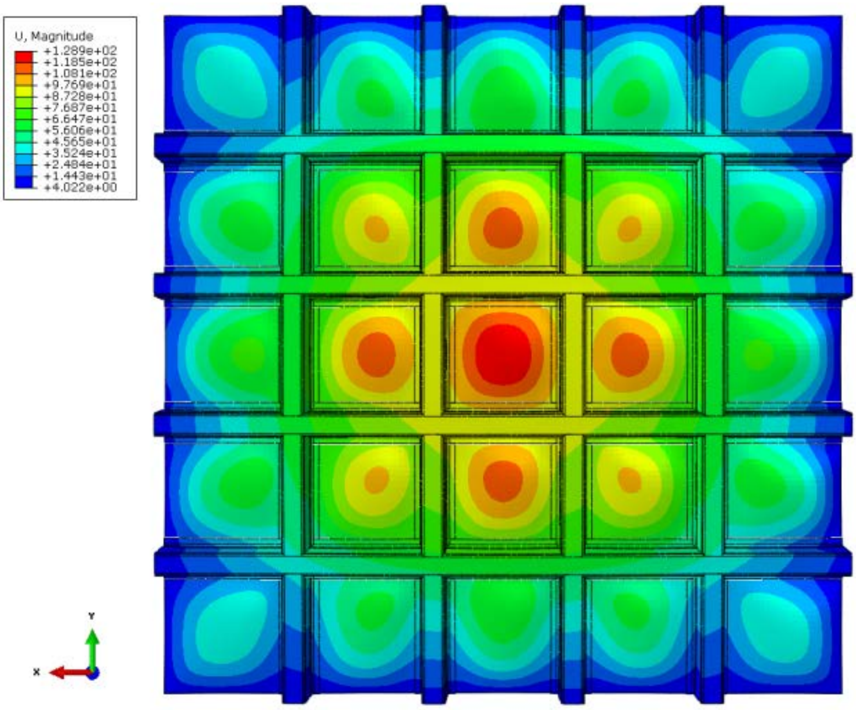
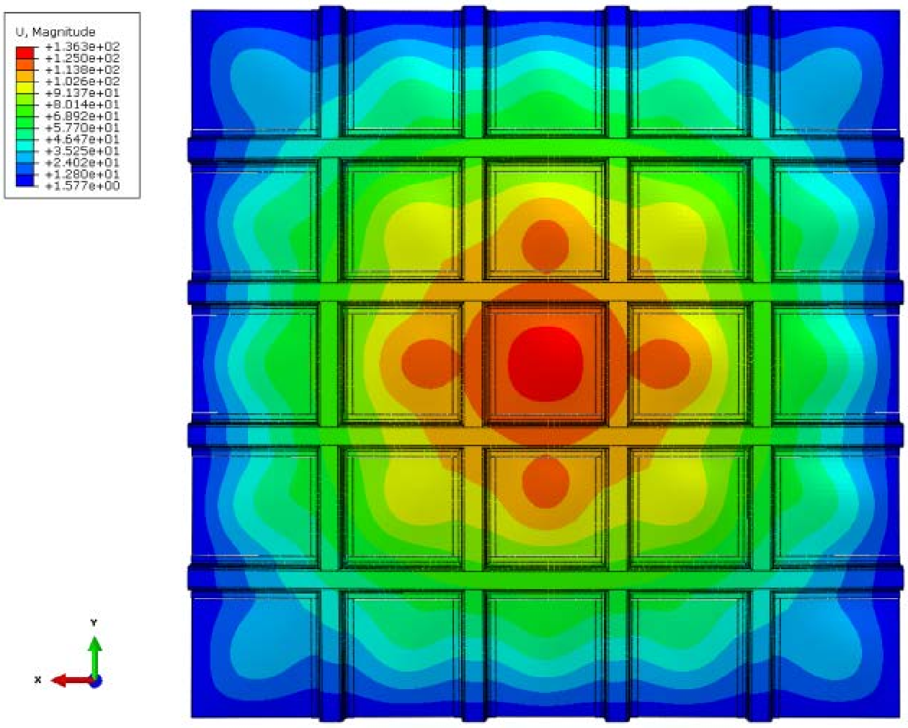


Figure 34: FEA deflection contour plots of the flax grillage for a stiffener height of (a) 100 mm and (b) 250 mm from [153]

(a)



(b)

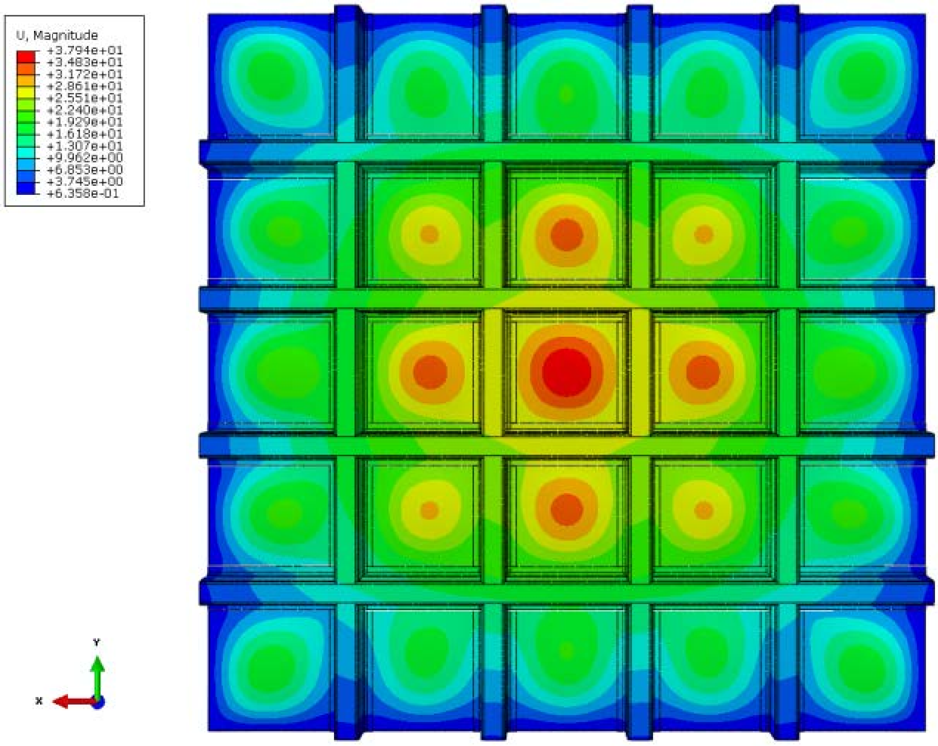


Figure 35: FEA deflection contour plots of the carbon grillage for a stiffener height of (a) 100 mm and (b) 250 mm from [153]

The stiffener width is also varied from the base case for values from 100 mm to 250 mm in increments of 50 mm. The comparison between stresses predicted by the FEA and the grillage results are presented in Figure 36.

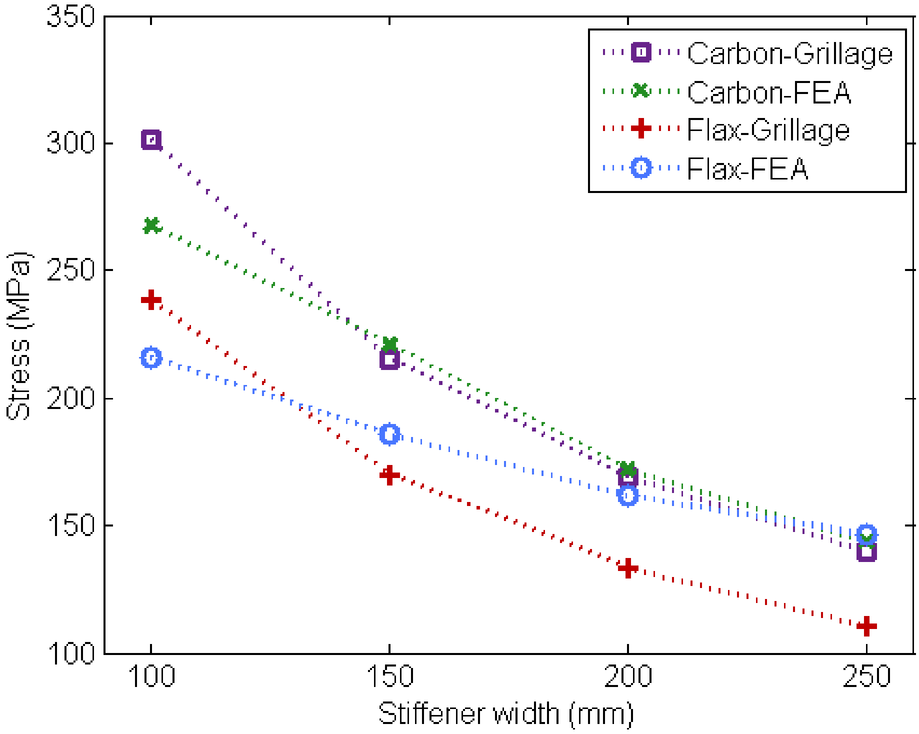


Figure 36: Comparison between top ply stresses obtained with FEA [153] and empirical model for varying stiffener widths

The maximum stresses are underestimated by the grillage model, except for a width of 100 mm, with an absolute mean error of 4.9% for carbon and 15.2% for flax. The maximum error for carbon is 12.6% for a width of 100 mm which is reduced to -1.7% minimum error at 200 mm. Whereas the maximum error for flax is for a width of 250 mm, -24.7%, with a minimum error of -8.4% at 150 mm. The carbon and flax results follow different trends, showing a change in behaviour. However, according to Blanchard et al. [153], the FEA model with a stiffener width of 100 mm does not converge for flax because of some local instabilities in the simulation. An automated stabilisation is added to the analysis where the dissipated energy fraction is employed using as low a value as possible with a convergence at 2.0×10^{-5}. An initial damping factor 2.1×10^{-9} is calculated and a default accuracy tolerance of 0.05 is used throughout the simulation with an adaptive scheme. Since the flax demonstrates a smooth curve it is assumed that this make a minimal difference to the results. The stiffener width and height are therefore deemed to be acceptably accurate between aspect ratios of 1 and 2.

5.5 Modelling capabilities and implications for flax composites

There is a need to study flax at the structural level to understand the mechanical behaviour, as underlined by Bambach [148] and Shah et al. [39], but these studies are limited in number. As part of understanding flax behaviour at the structural scale it is important to evaluate if the available models, such as Navier grillage, are accurate for flax fibre reinforced laminates. The original Navier grillage model is found to be inaccurate for all composites and an empirical addition is made which captures the change in structural response for composite grillages. For most of the cases the errors are low, defined here as having a maximum error less than 5% compared to FEA. In the topological cases the predictions are accurate but in some cases the empirical formula has reached the limits of its capabilities, meaning for more extreme topological cases the formulation might not be accurate.

Of the limited literature looking at natural fibres at a structural level Bambach [139] showed the applicability of these materials to form light structural applications, but with no comparison to the response of standard composites. Shah et al. [39] investigated flax wind turbine blades demonstrating that at structural scale flax had lower mechanical properties than E-glass. For the E-glass blade the displacement–load curve is linear but for flax the low stiffness produces a different, non-linear, response and the blades are found to fail differently. This work expands on these conclusions by showing that flax has a different structural response compared to conventional composites and can demonstrate an increase in stress for a reduction in Young's modulus. This is because these lower modulus materials are more sensitive to changes in E_2. Topologically, changes to the plate show limited differences in behaviour between conventional composites and flax. However, changes to the aspect ratio of the stiffener showed substantial differences in behaviour. This is interesting and isn't captured in other analyses of flax, but will further inhibit the suitability of these materials for structural applications as they can exhibit higher than expected stresses. While the results are not conclusive they indicate a requirement for more studies at the structural level including experimental analysis at this scale and the investigation of a wider range of structural elements. Furthermore, flax laminates exhibit a non-linear behaviour where the initial stiffness decreases by up to 50% between the initial strain profile and values above 0.4% strain, as demonstrated by Shah [124]. This behaviour has an impact on the calculation of the Young's modulus where current values taken from the literature are likely to be determined at lower strains and therefore higher than expected at structural scale. A lower stiffness is likely to exacerbate the difference in behaviour between the carbon and flax structures already seen for the extreme cases with a larger range of flax grillages exhibiting a different behaviour than would be expected in comparison to their current standard composite counterparts.

In addition to the implications for the difference in behaviour for natural composites the accuracy of the method is further assessed for standard composites. E-glass cases are also simulated and the detailed results are presented in Appendix C. They exhibit similar relationships to carbon between stress and input parameters, with some discrepancies. For the stiffener width they exhibit errors above 5% for values larger than 175 mm; with a maximum error of 22% at the extreme value of 250 mm. In comparison to carbon, the errors for changes in stiffener number are lower, remaining at 3% or below. For the stiffener height the E-glass demonstrates good accuracy over most of the range but with higher errors at the lower values; by 100 mm this error is already high, 48%. For E-glass the aspect ratio errors are higher, 40-50%, meaning that for less stiff materials a square approximation is required. The effect of the different numbers of layers in the crown, ranging from 8 to 18 layers, is also investigated for carbon and the detailed results are presented in appendix C. The empirical grillage model is conservative with the largest errors for symmetric laminates, which overestimates the stress with an error of 8.9% for the 16 layer case. The non-symmetric layups have a lower error, which is maximum at 15 layers with a value of 6.7%. Different plate and crown thicknesses are also investigated where the maximum stress is accurately predicted for topologies where the crown is thicker than the plate. When the crown and plate thicknesses are equal the error increases to -6.8%. When the crown becomes thinner than the plate the error is larger. The error is maximum when the crown is 50% thinner than the plate, -8.8%, which is an unusual configuration as it is assumed that the crown will be thicker than the plate in most applications. This demonstrates the general applicability of the method beyond natural composites.

5.6 Summary

Natural fibre composites are increasingly investigated as a sustainable replacement to standard composites. Despite this the numbers of investigations at the structure scale are limited, meaning their mechanical response isn't understood and neither is the applicability of current analytical methods. An analytical method, Navier Grillage theory, is therefore compared to FEA [153] for flax, E-glass and carbon showing poor accuracy even for standard composites. This method is empirically modified demonstrating an accuracy generally below 5% compared to FEA for a parametric study bounded by topologies and material properties commonly used in large composite structural applications. The flax and carbon FEA analysis demonstrate a change in response with an increase in stress for a reduction in Young's modulus. This is because these lower modulus materials are more sensitive to changes in E_2, and it is recommended that further effort is put into more rigorously defining these values and its relationship to E_1. Changes to the aspect ratio of the stiffener also show substantial differences in behaviour between flax and traditional composites.

Chapter 6 Can flax safely and efficiently replace E-glass in structural applications?

6.1 Potential for flax structures

Flax fibre reinforced composites are seen across the literature as a potential replacement to E-glass for structures. However, investigations at the structural scale are limited and flax fibre reinforced composites demonstrate a change in behaviour at the structural scale compared to standard composites with an increase in stress for flax grillage compared to E-glass or carbon fibre reinforced structures as seen in chapter 5. Therefore, to further explore the feasibility for flax fibre structures, it is important to determine how this change in structural behaviour affects their safety in comparison to E-glass. A reliability assessment reflects current industry best practice for structural design and so an analysis is performed on a secondary structure taken from a marine application.

A literature review of flax fibre reinforced epoxy laminate mechanical properties is conducted to gain a better understanding of the currently available materials and determine a realistic range of mechanical properties. An assessment is made of the structure as if it was made from a flax fibre reinforced epoxy composites and compared to an E-glass equivalent. Material properties are taken from the literature, comparing the structural integrity of the panel across the full range of values found in the literature. The influences of these material properties and manufacturing techniques on the structural properties are then investigated. To perform the analysis, Monte Carlo simulation is combined with the analytical grillage model successfully validated for flax reinforced epoxy composites in chapter 5.

6.2 Analysis of material properties from the literature

Due to the range of mechanical properties seen in the academic literature for composites, especially flax fibres, it is important to establish a realistic set of data, to ensure they represent properties likely to be seen in industry. A review is performed of both the available mechanical properties for flax and E-glass fibre reinforced laminate properties, to establish a benchmark reference for the reliability exercise.

6.2.1 Data collection method for flax and E-glass laminate mechanical properties

A set of criteria is defined to determine which data should be selected for consistency and to objectively remove some academic studies which provide unrealistic properties. The main selection criteria for both materials are the same, with some additional ones specific to flax due to the larger quantity of literature exploring techniques to improve the properties which have not proven to be industry ready. For flax composites, a large majority, 73%, of the papers were published in the last 5 years. For E-glass, the data have a larger spread with 44% of the papers published in the last five years and the oldest reference published in 1981. However, within the limited available literature the year of publication has no influence on the properties and is stable with time. The following general rules are followed:

- UD reinforcement is selected for this study to reduce the variability associated with different types of reinforcement and to obtain the highest mechanical properties. However purely unidirectional fabrics do not provide enough data and so fabrics with a minimum of 90% of the fibres in the longitudinal direction are also included.
- All the laminates have to be reinforced with a similar matrix to isolate the fibre properties from the matrix. Epoxy resin is selected for this exercise as the most data is available while also exhibiting good compatibility with flax and E-glass fibres. Furthermore, the high properties of epoxy resins help flax laminates reach their full potential.
- If different fibre volume fractions are tested in the same study, only the highest volume fraction is selected to represent the best attainable mechanical properties for industrial applications.
- All the manufacturing techniques are considered except pultrusion, due to the different geometries of the resulting specimens.
- If different numbers of layers or different manufacturing techniques are compared, all data are included to cover a range of manufacturing processes.
- Data presented in graphs for which it is difficult to obtain exact numbers and non-peer reviewed sources are not considered. Non-experimental data are also discarded.

A large number of studies for flax laminates investigate various fibre treatments to improve the properties of the laminates. The effects of these chemical treatments on the laminate properties are inconsistent: Van de Weyenberg et al. [42] , Acera Fernandez et al. [116] and Shah [1]; or costly for industrial applications: Meredith et al. [18], Coroller et al. [55] and Shah [1]. Therefore, data based on the utilisation of chemical treatments such as Alkaline, stearic acid and silane solutions are discarded. Reinforcements subjected to mild treatments: water, cellulose based binder and fibres used as received with possible treatments applied by manufacturers are included as the influence of these treatments on the average properties is negligible.

Flax reinforcements subjected to heat treatments before manufacturing are included as heat treatments are commonly used and applicable in an industrial context. The influence of heat treatments on the average properties is investigated and statistically negligible.

Initially 60 papers for flax laminate properties and 34 papers for E-glass laminate properties are selected. From the initial selection, 7 papers are discarded for flax and 3 papers for E-glass as the data did not meet the criteria. The final set of data represents up to 273 tested specimens for the flax laminate and 49 data points for E-glass for the most available material property, Young's modulus. However, this is reduced to 3 tested specimens for the compressive strength, the least available material property.

Representative values for the mechanical properties and the coefficients of variation are determined by statistical analysis. All the data meeting the above conditions are collated into a box plot. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. These outliers are then discarded as they are not considered to be representative of the values likely to be seen in industry. The outliers plotted in the graphs are removed for the calculations of the average, minimum and maximum values. However, since most of the specimens are manufactured within a laboratory environment it is likely that they still represent optimistic values compared to what might be seen within industry. The mean, minimum and maximum values are then calculated to be used in the analysis to represent the range of properties it might be possible for industry to replicate. This is repeated for the coefficient of variation (CoV). In addition to the outlier the coefficient of variations associated with a data point for which the mechanical property is considered as an outlier are also discarded for the coefficient of variation calculations.

6.2.2 Flax/epoxy mechanical properties

The mechanical properties for unidirectional flax/epoxy laminates are presented in Table 31, where ([X1]-[X2]) represents multiple references citing the same value. The longitudinal Young's modulus of flax fibre reinforced UD epoxy composites is well characterized with 33 references and 58 different tests conducted, representing 273 data points. However, not all of the other properties are as well documented with 11 references for the transverse Young's modulus and 4 references for the longitudinal compressive strength. The limited number of references for these properties prevents the definition of a realistic range. The fibre volume fraction is well characterized with 43 references but this large number is influenced by the number of manufacturing techniques available and is discussed further in section 6.2.4.

Table 31: Average (Avg), minimum (Min) and maximum (Max) mechanical properties for flax/epoxy from the literature

Material Properties	Avg.	Min	Max	# of data points	# of refs. included	Refs. included	Discarded Refs.
Longitudinal Young's modulus E_1 (GPa)	25.42	11.86	40.10	58	33	[26] [24] [42] [55] [127] [103] [89] [82] [134] [20] [94] [111] [28] [3] [132] [21] [77] [29] [113] [195] [118] [53] [110] [137] [19] [8] ([119]- [196]) [120] [11] [117] [112] [114]	[121][5] [74][6] [23][7] [48][8] [72][9] [77][10] [82][11]
Transverse Young's modulus E_2 (GPa)	4.20	2.70	5.58	17	11	[24] [42] [127] [28] [3] [29] [113] [137] [117] [112] [114]	[116][12]
Shear modulus G_{12} (GPa)	2.01	1.86	2.19	9	5	[24] [28] [3] [113] [138]	[112][13] [138][14]

[5] Fabric described as UD but only 67% of the fibres in the 0° direction
[6] Unknown resin
[7] Range of values given for E_1
[8] Fabric described as UD - ribs 4/4
[9] Specimens fabricated by pultrusion
[10] Specimens made of FUD115 prepreg are discarded as the weft/wrap ratio is 1/8
[11] One data point of the study (fibres from bottom location) was discarded by the box plots as a minimum outlier
[12] Fabric described as UD but weft/ wrap ratio is 84/16 wt%
[13] Discarded by the box plot as a minimum outlier
[14] Data from test 11 was discarded by the box plot as a maximum outlier

Poisson's ratio v_{12}	0.36	0.34	0.37	10	5	[28] [3] [29] [113] [112]	[22][15] [24][16] [8][17]
Longitudinal tensile strength Xt (MPa)	255.14	113.00	408.00	55	31	[26] [42] [55] [127] [89] [82] [134] [20] [94] [111] [3] ([24] - [197]) [21] [77] [29] [113] [118] [53] [110] [137] [19] [8] ([119] - [196]) [120] [11] [117] [112] [114] [198]	[121][18] [74][19] [48][20] [72][21] [77][22]
Transverse tensile strength Y_t (MPa)	24.81	4.50	36.53	16	10	[24] [42] [127] [3] [29] [113] [137] [117] [112] [114]	[116][23]
Longitudinal compressive strength X_c (MPa)	127.50	110.00	136.90	4	4	[24] [127] [3] [118]	[72][24]
Transverse compressive strength Y_c (MPa)	85.31	76.00	100.00	3	3	[24] [127] [3]	N/A
Shear strength S_{12} (MPa)	39.34	32.00	45.60	6	4	[24] [3] [138] [70]	[112][25]

[15] Discarded by the box plots as maximum outliers
[16] Discarded by the box plots as maximum outliers
[17] Discarded by the box plots as maximum outliers
[18] Fabric described as UD but only 67% of the fibres in the 0° direction
[19] Unknown resin
[20] Fabric described as UD - ribs 4/4
[21] Specimens fabricated by pultrusion
[22] Specimens made of FUD115 prepreg are discarded as the weft/wrap ratio is 1/8
[23] Fabric described as UD but weft/ wrap ratio is 84/16 wt%
[24] Specimens fabricated by pultrusion
[25] Discarded by the box plot as a minimum outlier

Fibre volume fraction (%)	43.64	19.70	65.00	69	43	[22] [26] [24] [42] [55] [127] [103] [89] [82] [134] [20] [94] [111] [28] [3] [132] [21] [77] [29] [113] [195] [118] [53] [110] [137] [19] [8] [119] [196] [120] [11] [117] [197] [70] [51] [49] [199] [133] [200] [201] [202] [203] [204]	[112][26] [121][27] [74][28] [77][29] [51][30] [205][31] [116][32]

Table 31 shows that the range of mechanical properties is large, especially for the longitudinal Young's modulus where the maximum value is 57% larger and the minimum value is 53% lower than the mean. The minimum value of 11.86 GPa seems particularly low especially considering that the specimens were manufactured with compression moulding but it is not considered as an outlier statistically. A large range of data is also seen for the tensile strengths in both directions. The minimum value for the transverse strength is particularly low, 82% lower than the mean, even though these specimens were cured in an autoclave for which higher properties can be expected. The range for compressive data is smaller and can be attributed to the large influence of the resin on compression properties. For many of the properties there is still not a large enough quantity of points to gain confidence in the values, despite coming from multiple references. The fibre volume fraction varies with a minimum value of 19.7% and a maximum value of 65%. The substantial variation in fibre volume fraction might be explained by the different manufacturing techniques and the influence of the manufacturing techniques is investigated in more details in section 6.2.4. The coefficients of variation from the literature for variation in flax/epoxy mechanical properties are presented in Table 32.

[26] Range of volume fraction
[27] Fabric described as UD but only 67% of the fibres in the 0° direction
[28] Unknown resin
[29] Specimens made of FUD115 prepreg are discarded as the weft/wrap ratio is 1/8
[30] Specimens fabricated by manual pultrusion were discarded
[31] Specimens fabricated by filament winding are discarded
[32] Fabric described as UD but weft/ wrap ratio is 84/16 wt%

Table 32: Average (Avg), minimum (Min) and maximum (Max) coefficients of variation for flax/epoxy laminate mechanical properties from the literature

CoV (%)	Avg.	Min.	Max.	# of data points	# of refs. included	References included	Discarded refs.
Longitudinal Young's modulus E_1	6.62	1.28	16.37	55	31	[26] [24] [42] [55] [127] [103] [89] [82] [134] [20] [94] [111] [3] [21] [77] [29] [113] [195] [118] [53] [110] [19] [8] ([119]- [196]) [120] [11] [117] [112] [114] [204]	[77][33] [48][34] [72][35] [82][36] [82][37]
Transverse Young's modulus E_2	5.49	2.38	8.96	12	8	[24] [42] [127] [3] [29] [113] [117] [112]	[116][38] [29][39] [42][40]
Shear modulus G_{12}	6.69	2.90	9.64	8	4	[24] [3] [113] [138]	[112][41] [138][42]
Poisson's ratio ν_{12}	4.41	2.70	8.33	9	4	[3] [29] [113] [112]	[24][43] [8][44]

[33] Specimens made of FUD115 prepreg are discarded as the weft/wrap ratio is 1/8
[34] Fabric described as UD - ribs 4/4
[35] Specimens fabricated by pultrusion
[36] One data point of the study (fibres from bottom location) was discarded by the E1 box plots as a minimum outlier and the associated CoV is discarded
[37] One data point of the study (fibres from middle location) was discarded by the CoV box plot as a maximum outlier
[38] Fabric described as UD but weft/ wrap ratio is 84/16 wt%
[39] Data described as "DRY MTT2" is discarded by the box plot as a maximum outlier
[40] Data described as "Film Stacking" is discarded by the box plot as maximum outlier
[41] The data for G_{12} is discarded by the box plot as a minimum outlier and the associated CoV is discarded
[42] One data for G_{12} (test 11) is discarded by the box plot as a maximum outlier and the associated CoV is discarded
[43] The data for ν_{12} is discarded by the box plot as a maximum outlier and the associated CoV is discarded
[44] The data for ν_{12} is discarded by the box plot as a maximum outlier and the associated CoV is discarded

Longitudinal tensile strength Xt	6.87	0.17	14.81	50	28	[26] [42] [55] [127] [89] [82] [134] [20] [94] [111] [3] ([24] - [197]) [21] [77] [29] [113] [118] [53] [19] [8] ([119] - [196]) [120] [11] [117] [112] [114]	[77][45] [48][46] [72][47] [94][48] [204][49]
Transverse tensile strength Y_t	3.87	1.08	10.00	14	8	[24] [42] [127] [3] [29] [113] [112] [114]	[116][50] [117][51]
Longitudinal compressive strength X_c	3.16	1.47	4.02	3	3	[24] [3] [118]	[72][52] [127][53]
Transverse compressive strength Y_c	7.68	4.00	12.45	3	3	[24] [127] [3]	N/A
Shear strength S_{12}	5.04	2.99	8.31	6	4	[24] [3] [138] [70]	[112][54]

The mean values for the coefficient of variation for the different properties are between 3.16% and 7.68% and the maximum coefficient of variation reported is 16.37% for the longitudinal Young's modulus. The minimum values reported are low, especially the minimum value for flax tensile strength variation of 0.17% and appears to be unrealistically low. These specimens are manufactured with prepreg and autoclave curing, which is an unrealistically expensive technique for low cost structures, and only three specimens are tested. The influence of the number of specimens tested on the variations is difficult to determine but for all of the minimum and

[45] Specimens made of FUD115 prepreg are discarded as the weft/wrap ratio is 1/8
[46] Fabric described as UD - ribs 4/4
[47] Specimens fabricated by pultrusion
[48] Data described as "bottom of the stem (h = 12.5 cm)" is discarded by the box plot as a maximum outlier
[49] Discarded by the box plot as a maximum outlier
[50] Fabric described as UD but weft/ wrap ratio is 84/16 wt%
[51] Discarded by the box plot as a maximum outlier
[52] Specimens fabricated by pultrusion
[53] Coefficient of variation stated as 0%
[54] The data for S_{12} is discarded by the box plot as a minimum outlier and the associated CoV is discarded

maximum values reported the number of specimens is alternatively 3, 5 or not stated and is an indicator that more experiments are required to determine an accurate range of coefficients of variation for future analysis.

6.2.3 E-glass/epoxy mechanical properties

The unidirectional E-glass/epoxy mechanical properties are presented in Table 33. The number of references for E-glass laminates is limited with 17 data points for the longitudinal Young's modulus which is the most studied mechanical property compared to 55 data points for flax laminates. Though the lowest number of data points is higher, with 6 points for the transverse compressive and shear strengths.

Table 33: Average (Avg), minimum (Min) and maximum (Max) mechanical properties for E-glass/epoxy from the literature

Material Properties	**Avg.**	**Min.**	**Max.**	**# of data points**	**# of refs. included**	**References included**	**Discarded refs.**
Longitudinal Young's modulus (E_1) GPa	40.97	31.00	53.48	17	19	[55] [53] [120] [119] [206] [207]([208]- [209])([210]- [211]- [212]) [213]([214]- [215]) [216] [217]([218] - [219]) [220]	[221][55] [222][56] [223][57] [224][58]
Transverse Young's modulus (E_2) GPa	12.31	9.03	17.70	11	13	[207] ([208]- [209]) ([210]- [212]) ([214]- [215]) [216] [217] ([218] - [219]) [220] [225]	[222] [224] [221]

[55] Reference discarded because the resin is unknown
[56] Reference discarded because the experiment is unknown
[57] Data discarded by the box plot as a maximum outlier
[58] Reference is discarded because the data are FEA inputs rather than experimental data

Shear modulus (G_{12}) GPa	5.04	3.19	6.00	9	12	[207] ([208]- [209]) ([210] - [212]) ([214]- [215]) [216] [217] ([218] - [219]) [220]	[222] [224] [221]
Poisson's ration (ν_{12})	0.289	0.250	0.326	9	12	[207] ([208]- [209]) ([210] - [212]) [213] ([214]- [215]) [216] [217] ([218] - [219])	[222] [224] [221]
Longitudinal tensile strength (X_t) MPa	1014.31	514.20	1280.00	16	18	[55] [53] [43] [120] [119] [206] ([208]- [209]) ([210] - [211] - [212]) [213] ([214]- [215]) [217] ([218] - [219]) [223] [226]	[222] [224] [221]
Transverse tensile strength (Y_t) MPa	46.61	35.00	59.00	9	11	([208]- [209]) ([210] - [212]) ([214] - [215]) [217] ([218] - [219]) [225] [226]	[222] [224] [221]
Longitudinal compressive strength (X_c) MPa	635.29	487.00	800.00	7	8	([210] - [212]) [213] ([214] - [215]) [217] [218] [226]	[222] [224] [221]
Transverse compressive strength (Y_c) MPa	128.82	114.00	145.00	6	7	([210] [212]) ([214]- [215]) [217] [218] [226]	[222] [224] [221]
Shear strength (S_{12}) MPa	67.09	49.51	98.00	6	7	[70] ([208]- [209]) ([214]- [215]) [217] [226]	[222] [224] [221]

Fibre volume fraction (V_f) %	54.42	40	66.4000	21	20	[55] [53] [119] [120] [70] [200] [206] [210] [211] [214] [215] [217] [225] [220] [227] [228] [229] [230] [231] [232]	[233][59]

The mechanical properties of the E-glass laminates are higher than the properties of the flax laminates, with a smaller range of mechanical properties seen in the literature. The longitudinal Young's modulus has a minimum value 24% lower and a maximum value 31% higher than the mean. However, the longitudinal tensile strength has a larger range with the minimum value 49% lower and a maximum value 26% higher than the mean. The minimum value of 514 MPa for the longitudinal tensile strength is obtained with specimens manufactured via resin transfer moulding and a targeted fibre volume fraction of 40% which is low for E-glass. The values for the fibre volume fraction are consistent with a minimum value of 40% and a maximum value of 66.4% even though the specimens are manufactured with different manufacturing techniques. Representative coefficients of variation for the E-glass mechanical properties are presented in Table 34. For E-glass/epoxy laminates, only one reference is found for the coefficient of variation of the shear strength, longitudinal and transverse compressive strengths. Therefore the lowest and highest variation from the strength values found for the tensile strengths are used as representative.

[59] Data discarded by the box plot as a minimum outlier

Table 34: Average (Avg), minimum (Min) and maximum (Max) coefficients of variation for E-glass/epoxy laminate mechanical properties from the literature

CoV (%)	Avg.	Min.	Max.	# of data points	# of refs. included	Refs. included	Discarded refs.
Longitudinal Young's modulus (E_1)	4.87	2.92	6.78	6	7	[55] [53] [220] [119] [120] ([208]-[209])	[223][60] [218][61]
Transverse Young's modulus (E_2)	7.79	1.58	11.46	4	4	[225] [220] ([208]-[209])	[218]**
Shear modulus (G_{12})	4.32	4.32	4.32	1	1	[220]	[218]**
Poisson's ration (v_{12})	4.60	4.60	4.60	1	2	([208]-[209])	[218]**
Longitudinal tensile strength (X_t)	8.45	4.20	16.28	6	7	[55] [53] [119] [120] [223] ([208]-[209])	[218]**
Transverse tensile strength (Y_t)	9.34	7.13	13.20	3	3	[225] ([208]-[209])	[218]**

[60] The data for E_1 is discarded by the box plot as a maximum outlier and the associated CoV is discarded
[61] Or ** Data which includes the assumed CoV from Sanchez-Heres et al. [218]

Longitudinal compressive strength (X_c)	10.00	4.20***	16.28+	1	1	[218][62]	
Transverse compressive strength (Y_c)	10.00	4.20***	16.28+	1	1	[218][35]	
Shear strength (S_{12})	7.32	4.20***	16.28+	1	1	[70]	

*** lowest variation from strength values

+ highest variation from strength values

The mean coefficients of variation for E-glass laminate mechanical properties are between 4.32% and 10%. The minimum values are low, especially for the longitudinal and transverse Young's moduli at 2.92% and 1.58% respectively, which seems unrealistically low. The maximum variation is for the longitudinal tensile strength, with a coefficient of variation of 16.28%. These values are in accordance with Lekou and Philippidis [234] who determine the coefficients of variation for the mechanical properties of UD E-glass polyester manufactured by hand lay-up and obtain values between 8.94% to 24.90% based on 26 specimens. The values for the shear modulus and Poisson's ratio are based on one study and therefore may not be representative.

Flax composites are often seen as highly variable, however the coefficients of variation are similar to E-glass with all the mean values below 8% for flax compared to 10% for E-glass. This comparable variability at the laminate scale between flax and E-glass confirms the results from chapter 4 that there is little difference in variability at this scale. The maximum variability is also in the same range with a maximum value of 16.37% for the flax coefficient of variation compared to 16.28% for E-glass.

[62] No value are found in the literature except an assumption in Sanchez-Heres et al. [218]

6.2.4 Manufacturing techniques

Through the analysis of this data a wide range of values are shown for the different mechanical properties. To ensure that a reasonable spread of data is used the analysis combines values from number of different manufacturing techniques which influence the achievable fibre volume fraction and therefore the mechanical properties of the composites. A large range of manufacturing techniques from inexpensive hand lay-up to more expensive closed mould techniques are used to manufacture natural fibre reinforced composites and Figure 37 illustrates how much the fibre volume fractions are influenced by the manufacturing technique.

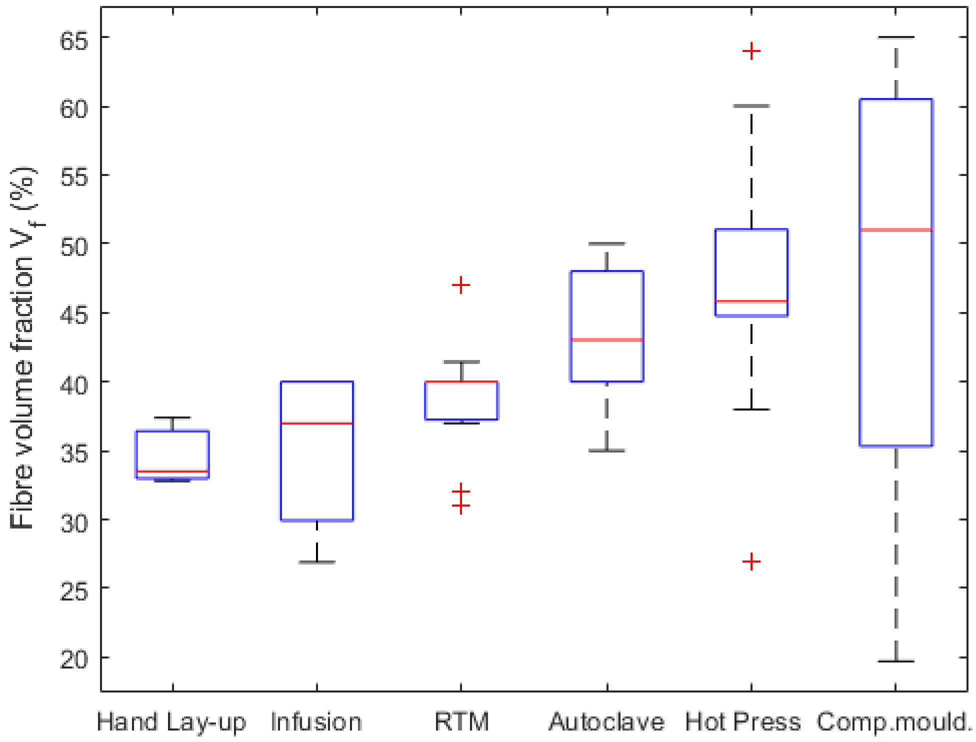


Figure 37: Fibre volume fraction (V_f) obtained for flax/epoxy laminates with different manufacturing techniques

It is expected that for improved manufacturing techniques the variability decreases but due to the large number of studies using expensive manufacturing techniques such as compression moulding, 13 studies, and hot press, 25 studies, compared to hand lay-up with only 3 references, it is difficult to determine the influence of the manufacturing techniques on the range of properties. Despite the difference in the mean value of the volume fraction between the specimens manufactured by hand lay-up and those manufactured by compression moulding, the lowest value, 19.70%, and highest value, 65%, are both for specimens manufactured with compression moulding. The large range of data for compression moulding can be explained by the difference in applied pressure between the different studies, which also substantially affects the cost of manufacture. A common issue in the literature is the low fibre volume fractions exhibited by natural fibre reinforced composites, Shah et al. [53]. This is supported by the analysis of the data with a mean volume fraction of 34.57% for flax epoxy composites manufactured with hand lay-up compared to 62.5% for E-glass. Higher fibre volume fractions, 47.46% and 47.65%, can be obtained with expensive manufacturing techniques such as compression moulding and hot press but these techniques are unlikely to be selected if the current structure is made of E-glass and replaced by flax as they will make the components too expensive. It is likely that large structural components will be manufactured using hand layup or resin infusion, with some more expensive applications autoclaving pre-preg laminates. As the fibre volume fraction influences the mechanical properties, the longitudinal Young's modulus obtained for different manufacturing techniques are presented in Figure 38.

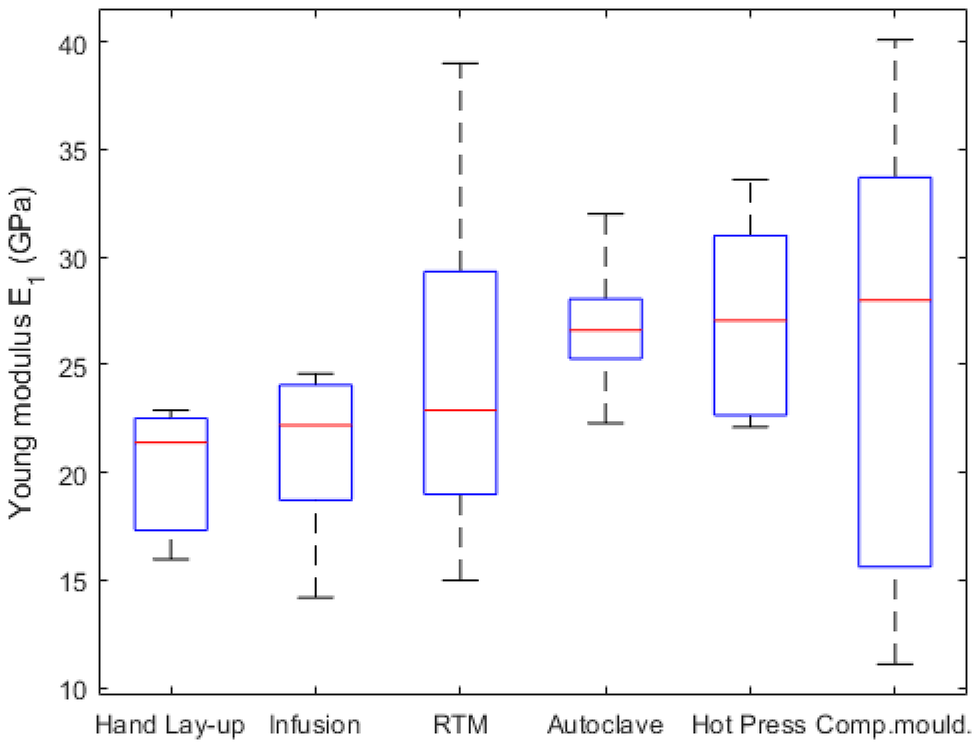


Figure 38: Flax/epoxy laminate longitudinal Young modulus E_1 (GPa) obtained with different manufacturing techniques from the literature

As expected the manufacturing technique has a large influence on the longitudinal Young's modulus with a mean stiffness of 20.1 GPa for hand lay-up and 27.1GPa for specimens manufactured by hot plate. This difference can be explained by the higher fibre volume fraction and lower void contents obtained with more expensive manufacturing techniques as an increase in pressure produces plates with lower porosities and higher mechanical properties as shown by Phillips et al. [41] and Li et al. [21]. The minimum, 11.1 GPa, and maximum value, 40.10 GPa, are both obtained by compression moulding, again showing a larger range than other techniques due to the number of pressures tested at and the large number of references using compression moulding. The range of coefficients of variation reported in the literature is similar for all manufacturing techniques with mean values around 5% except for compression moulding with a mean variation of 11%.The influence of the manufacturing techniques on the longitudinal breaking strength are presented in Figure 39.

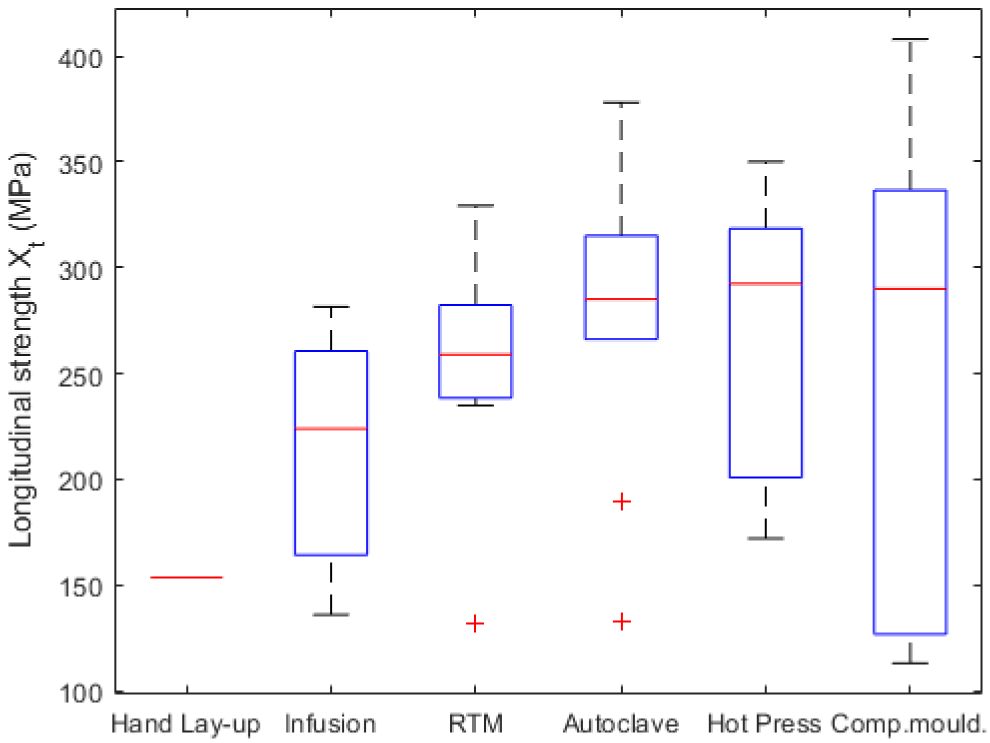


Figure 39: Longitudinal tensile breaking strength X_t (MPa) obtained with different manufacturing techniques for flax reinforced epoxy laminates from the literature.

The relationship between manufacturing techniques and the fibre volume fraction in Figure 38 and the longitudinal Young's modulus in Figure 39 is less clear for the longitudinal strength. The mean values for the longitudinal tensile strength ranges from 153.6 MPa for hand Lay-up to 296.44 MPa for laminates manufactured with autoclave. The maximum value of 408 MPa is obtained with compression moulding which shows the largest spread of strength values. The spread of data can also be caused by the larger number of studies, 13, using compression moulding as a manufacturing technique. Only one study uses hand lay-up as a manufacturing technique, meaning that the value may not be representative of values probable in industry. The mean values for the coefficients of variation reported in the literature are more spread than for the Young's modulus with a mean value of 2.7% for resin infusion compared to 8.6% for autoclave.

6.2.5 Summary

The mean flax laminate Young's modulus is 38% lower than the E-glass and the mean longitudinal tensile strength for flax laminates is 75% lower, a large drop in mechanical properties. These values show a much larger difference than when comparisons are performed at the fibre scale, where the majority of testing is currently performed in the literature. However, the variability of natural composites, which is often documented as being problematic, is similar to E-glass at the laminate scale. Most studies focus on the tensile Young's modulus but the longitudinal tensile strength has a higher impact on the probability of failure than the Young's modulus for a strength limit state as shown by Yang et al. [184] who find that the strength is the most influential parameter with a sensitivity factor of 0.72 compared to 0.14 for the fibre's modulus. Flax epoxy mechanical properties are well characterized in longitudinal tension but less characterized in the transverse direction, especially compression and shear; though these properties are less important for many structural applications. A large proportion of the data is for properties generated using more expensive manufacturing techniques, more commonly used to manufacture carbon structures which are unlikely to be replaced by flax but more realistic manufacturing options, like resin infusion, are poorly documented. A combination of these factors inflates the mechanical properties to values that are unlikely to be seen in industrial applications and provides an unfair analysis in comparison to flax at the material scale, though limited studies are performed to see how these differences effect the structural behaviour. Fibre scale properties are often used in the rule of mixtures to obtain laminate properties in initial calculations for standard composites [140]. However, for flax fibre laminates a number of authors, Charlet et al. [66], Shah et al. [45], Charlet et al. [82], Shah [1] and Moothoo et al. [50], investigate the accuracy of the rule of mixtures and it can be concluded that the obtained results are inconsistent. Despite this a large proportion of the literature focusses on fibre properties with 6169 data points for the Young's modulus at the elemental fibre scale. For structural applications, engineers and designers need reliable mechanical properties to implement in structural analysis and therefore laminate scale data are required.

6.3 Reliability analysis of natural composites for structural applications

6.3.1 Monte-Carlo simulation

The reliability analysis of a grillage structure is conducted to compare flax and E-glass fibre reinforced composites. Different techniques can be used for reliability studies such as Monte-Carlo simulations, First Order and Second Order Reliability methods. For this study, a Monte-Carlo simulation is selected based on the same method proposed by Sobey et al. [179]. It is an accurate technique which can solve complex problems and predict the future behaviour of structures for which the probability distributions of the basic variables are known [235]. The methodology is presented in Figure 40.

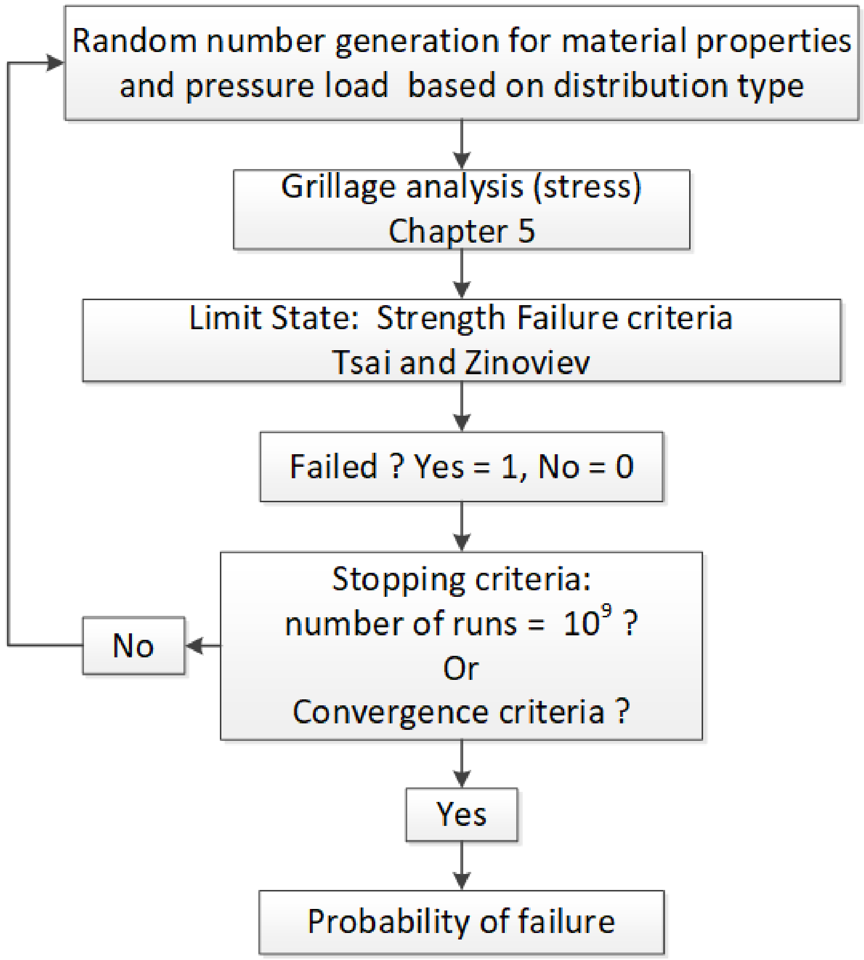


Figure 40: Reliability assessment method for composite grillages [293] [294]

The first step of the Monte-Carlo simulation is to populate the inputs for the first structural assessment. The material properties are generated using a normally distributed random seeding with mean values and coefficients of variation generated from the review of the literature. The tails are discarded, as shown in Palmer [236], to remove unrealistically high or low values. The pressure is also randomly generated with a mean value of 110 kPa, the design load for the application. It follows a Weibull distribution with a variation of 15% [179]. The structural response of the grillage structure, including the stresses, can then be calculated. This is performed according to a rapid analytical calculation used in Sobey et al. [179] with an updated formula developed by Blanchard et al. [153] which can account for the change in structural response exhibited by low stiffness materials such as flax; this approach has been shown to be within 5% accuracy of FEA based on the variable range used in the simulations. The third step it to compare the stresses to the failure criteria to determine if the grillage is failing based on first ply failure. The probability of failure is calculated from the total number of failed structures divided by the number of grillages assessed at that point. The simulations are stopped at 10^9 or when the probability of failure has converged, which is judged to be when the difference between the probabilities of failure at the last three orders of magnitude (10^n, 10^{n+1} and 10^{n+2}) and the average probability of failure for those three steps, are all smaller than 5%.

6.3.2 Failure criteria

The failure of the panel is determined using strength failure criteria recommended by the World Wide Failure Exercise: Liu and Tsai [237] and Zinoviev et al. [238], on a first ply failure approach. Whilst it is also recommended to utilise the Puck or Cuntze failure criteria in addition to these criteria neither is selected due to the large number of data required to accurately assess these criteria which is missing for natural fibres.

The Zinoviev failure criteria assume that the behaviour of the laminate is linear elastic up to failure. The ply remains elastic if the following conditions are fulfilled;

- $X_c \leq \sigma_1 \leq X_t$
- $Y_c \leq \sigma_2 \leq Y_t$
- $|\tau_{12}| \leq S$

Where X_t, Y_t are ultimate tensile stresses along and transverse to the fibres, X_c, Y_c are the equivalent characteristics in compression and S is the ultimate in-plane shear stress [238] [239]. These conditions determine a failure surface in the shape of a rectangular parallelepiped in the coordinates σ_1, σ_2, τ_{12} presented in black in Figure 41. When the stress in an isolated ply reaches any of the mentioned ultimate values, the ply fails and therefore the structure is considered to have failed. The Tsai failure criteria is calculated with equation (33), [240] [237];

$$\frac{\sigma_x^2}{X_t X_c} + \frac{2F_{xy}^* \sigma_x \sigma_y}{\sqrt{X_t X_c Y_t Y_c}} + \frac{\sigma_y^2}{Y_t Y_c} + \frac{\sigma_s^2}{S^2} + \left[\frac{1}{X_t} - \frac{1}{X_c}\right]\sigma_x + \left[\frac{1}{Y_t} - \frac{1}{Y_c}\right]\sigma_y = 1. \qquad (33)$$

When considering the Tsai-Wu criterion, previous results show that the nominal value of $F_{xy}^* = -0.5$ leads to good agreement for E-glass [237]. However for flax fibre reinforced epoxy laminates the failure envelope needs to be adjusted and the value of F_{xy}^* is set to 0 as optimised by Koh and Madsen [127]. The optimisation is based on limited experimental data with only 3 specimens for Y_t and X_c and 2 specimens for Y_c. To demonstrate the difference in behaviour with the change in F_{xy}^* the Zinoviev failure envelope is plotted in black and the Tsai failure envelope is plotted in light grey for E-glass in Figure 41 a) and flax in Figure 41 b) using the mean strength properties. The failure occurs when the response is outside one or both coloured regions.

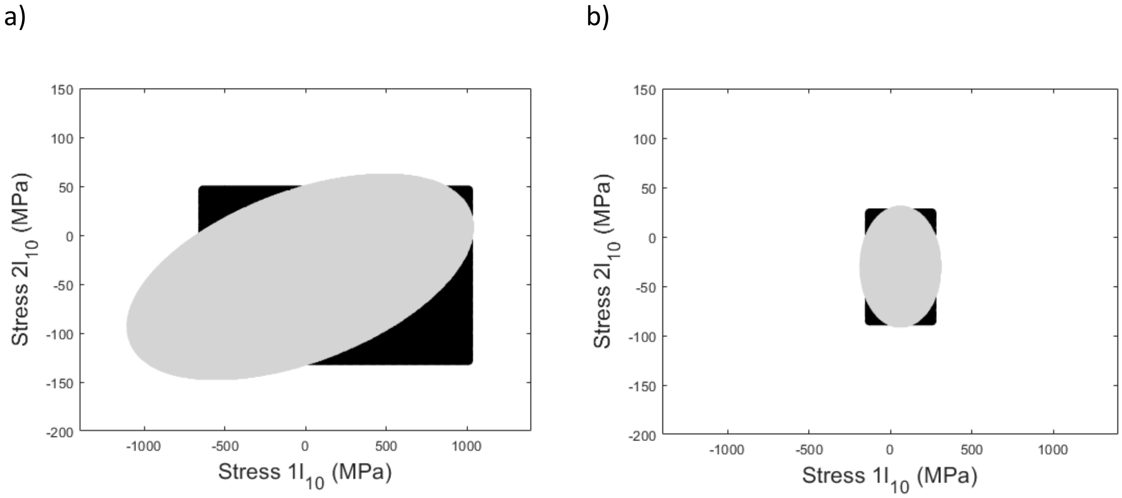


Figure 41: a) failure envelope for E-glass mean values b) failure envelope for flax mean values

The change in F_{xy}^* creates differences in the shape of the failure envelopes between the E-glass and flax laminates, with flax is more likely to fail in tension/tension and compression/compression but less likely to fail in tension/compression than E-glass. In this study, no failures are recorded in pure compression and most failures are recorded in pure tension with low transverse stresses. This means that for this application the difference in shape has a limited impact on the probability of failure of the structure. However, the Tsai failure criterion needs more refinement to ensure safe application of natural composites especially if complex loadings or lay-ups are utilised. The small size of the flax structure's failure envelope is clearly illustrated in Figure 41 due to the low strength of the material.

6.3.3 Grillage topology

A grillage structure, presented in Figure 42, is selected as a typical component in many structural applications. The stiffened plate is modelled using the Navier method grillage analysis taken from Vedeler [241] and empirically adapted for grillage structures made of composite materials by Blanchard et al. [153]. The adapted Navier grillage analysis calculates the deflection at intersecting points between longitudinal beams and transverse girders. The selected grillage topology is based on secondary stiffeners taken from a marine application and is composed of 2 identical longitudinal and transverse stiffeners, designed with a [0/90] symmetric lay-up. The material properties vary between the longitudinal and transverse stiffeners, to reflect the construction typical for the structures where stiffeners are constructed separately and post-cured to the plate. The geometry of the panel is fixed to identify the impact of the material properties rather than the geometric imperfections.

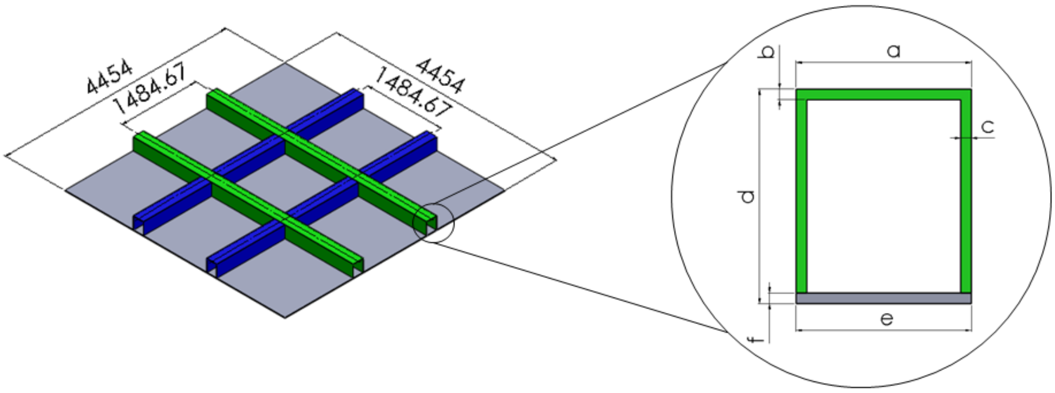


Figure 42: Grillage structure and stiffener dimensions

One of the main advantages of flax fibre reinforced composites is their low density compared to conventional composites, even if the lower fibre volume fraction reduces this benefit. To consider the difference in density between E-glass and flax fibre reinforced composites two design constraints are used: one where the volume of the two grillages is the same and one where the mass is equivalent, to show how to take advantage of the low flax density. For the volume constrained approach, the dimensions of both structures are identical and the flax/epoxy grillage is lighter because of the lower density of flax laminates. For the mass constrained approach, the thickness of the flax/epoxy laminate is increased equally on the plate and the stiffener's webs and crown to reach a mass comparable to the E-glass/epoxy grillage; the volume of the flax fibre reinforced epoxy composite structure is then larger than the E-glass/epoxy structure for the same mass. The dimensions, masses and volumes of the resulting grillages are presented in Table 35.

Table 35: Dimensions of the grillage structure

	E-glass/Epoxy	Flax/Epoxy (same volume)	Flax/Epoxy (same mass)
Crown width (mm) a	211	211	223.2
Crown thickness (mm) b	12.84	12.84	18.94
Web thickness (mm) c	12.84	12.84	18.94
Web height (mm) d	258	258	270.2
Flange width (mm) e	211	211	223.2
Plate thickness (mm) f	12.84	12.84	18.94
Length (mm)	4454	4454	4454
Volume (m^3)	0.40	0.40	0.60
Mass (kg)	755	508	754

The dimensions of the mass constrained flax/epoxy grillage structure is calculated with the average density of the composites for both materials, assuming no void content. V_f is the average fibre volume fraction selected as 54.42% for E-glass and 43.64% for flax reinforced epoxy from Table 31 and Table 33. A value of 1.089 g/cm^3 is used for the epoxy density based on the properties of the PRIME^{TM} 20 LV with fast hardener from Gurit. A representative value from the literature of 2.54 g/cm^3 is selected for the density of E-glass fibres [65] [90] [77] [233]. The variability in flax fibre densities available in the literature is large with values ranging from 1.287 g/cm^3 [242] to 1.59 g/cm^3 [14] measured with different methods. An average value for flax fibre density of 1.49 g/cm^3 is used based on experiments performed with 10 measurements by gas pycnometer by Amiri et al. [243] as this method is judged to be more accurate and less variable than others. From these values a density of E-glass fibre reinforced epoxy laminate is calculated equal to 1879 kg/m^3 and the density of flax fibre reinforced epoxy laminate is equal to 1264 kg/m^3.

6.4 Comparison of E-glass and flax composite structural properties

The reliability analysis of a flax structure is compared to a conventional composite to investigate the potential to replace E-glass with more sustainable materials in structural applications. Since the structure is originally taken from a marine application an acceptable range of probabilities of failure is defined based on those commonly seen in the marine industry where the target is between 10^{-4} and 10^{-6} as presented in Table 36. These values are set based on consideration of all failure modes, final failure including fatigue, and it is anticipated that the values in this analysis should therefore be considerably safer than these values, as only first ply failure is considered.

Table 36: Annual probability of failure in existing structures [244]

Type of Structure	Relevant Code	Annual P_f
Stiffened Flat Plates	NPD/DNV API RP2T	10^{-5}-10^{-4}
Stiffened Panels	API RP2T, RCC/API Bul-2U	10^{-4}
Stiffened Plates	API RP2T, RCC/API Bul-2U	10^{-3}

6.4.1 Equal volume

The probability of failures and deflections for grillage structures made of flax composites with the same volume as the E-glass grillage are presented in Table 37 and compared to the values for E-glass.

Table 37: Probability of failure for flax grillage with the same volume as E-glass

Variables	CoV	Flax P_f	Flax mean deflection (mm)	E-glass P_f	E-glass mean deflection (mm)
Min	Min	1.00E+00	466	0.00E+00	171
	Mean	1.00E+00		6.29E-06	
	Max	1.00E+00		7.46E-03	
Mean	Min	8.59E-01	227	0.00E+00	128
	Mean	9.07E-01		0.00E+00	
	Max	9.49E-01		9.51E-06	
Max	Min	6.90E-03	147	0.00E+00	96
	Mean	9.23E-02		0.00E+00	
	Max	3.83E-01		1.54E-06	

The probability of failure of the E-glass panel is low with almost all the configurations failing at 10^{-6} to less than 10^{-9} except for one case where the variables are set to their minimum and have the maximum coefficient of variation. This is below the probability of failure common in the marine industry, but this analysis only considers intact properties with no fatigue indicating that the minimum properties for the E-glass and the higher coefficients of variation might be unrealistic. The coefficients of variation have a large influence on the reliability of the structure especially when the mechanical properties are low as it can be seen in Figure 43. For high mechanical properties, the variation has no influence as even with the maximum coefficients of variation the mechanical properties are in the safe zone. However for lower mechanical properties closer to the failure limit, an increase in variability has a large impact.

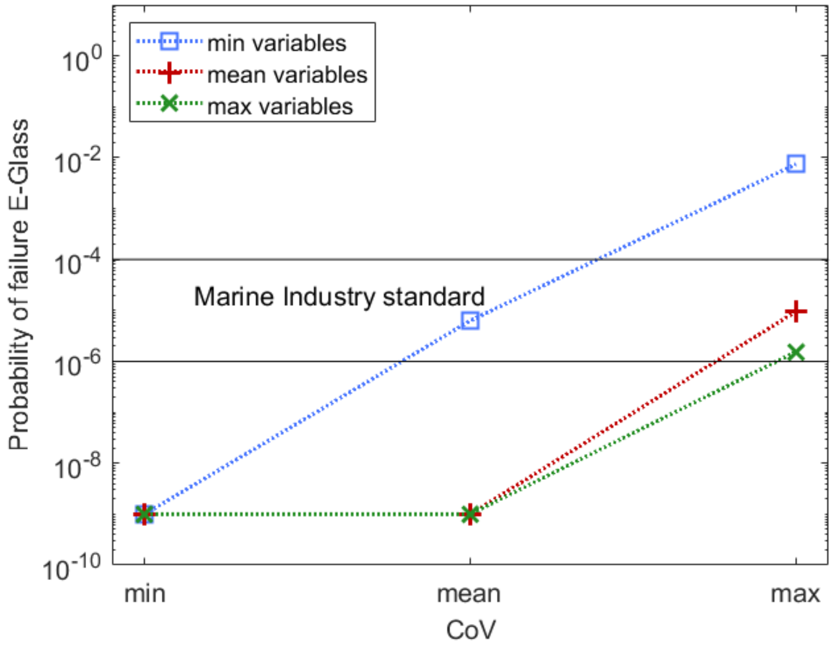


Figure 43: Probabilities of failure of E-glass structures for different mechanical properties and CoV

For a flax fibre reinforced epoxy structure with an equivalent volume to the E-glass structure, the probability of failure of the flax laminates are unacceptably high for all the cases and cannot provide a safe panel. The probability of failure is above 0.9 for the cases with minimum or average mechanical properties and 6.9×10^{-3} for the “safest” configuration, maximum properties and minimum coefficients of variation, despite this only being a first ply failure estimate. However, the panel made of flax is lighter than the E-glass equivalent and there are less volume constrained applications than mass constrained ones; therefore a mass constrained approach is investigated.

6.4.2 Equal mass

A grillage structure with the same mass as the E-glass structure, but a larger volume, is investigated to determine the feasibility of flax fibre reinforced laminates for structures constrained by mass. This is to take advantage of the low densities exhibited by flax fibres, giving them the greatest opportunity to be used in applications; the probabilities of failure and mean deflections are presented in Table 38 where the E-glass values remain the same as no changes are made to this structure.

Table 38: Probability of failure for flax grillage with the same mass as E-glass

Variables	CoV	Flax P_f	Flax mean deflection (mm)	E-glass P_f	E-glass mean deflection (mm)
Min	Min	9.99E-01	291	0.00E+00	171
	Mean	1.00E+00		6.29E-06	
	Max	1.00E+00		7.46E-03	
Mean	Min	9.40E-03	142	0.00E+00	128
	Mean	9.01E-02		0.00E+00	
	Max	3.71E-01		9.51E-06	
Max	Min	0.00E+00	92	0.00E+00	96
	Mean	1.15E-07		0.00E+00	
	Max	8.30E-03		1.54E-06	

The increase in thickness of the flax laminates, to match the mass of the E-glass structure, has a large impact on the probabilities of failure. The flax structure with the mean variables and mean coefficients of variation exhibit a decrease in probability of failure by a factor of 10. The large range of mechanical properties for flax translates to a large range of probabilities of failure, from unacceptable for the minimum variables cases to very safe for the maximum variables; a larger range than for the E-glass cases. Even if the probabilities of failure are higher than the E-glass mass equivalents the flax structures show some probability of failures below the 10^{-6} safety recommendation, though only for the cases with maximum mechanical properties. The influence of the variables and the coefficients of variation on the probabilities of failure are presented in Figure 44.

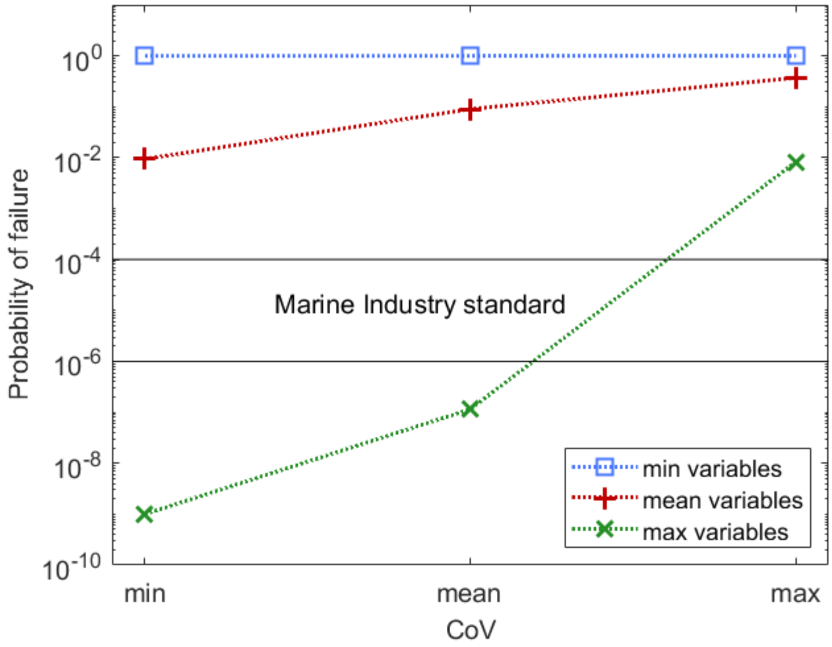


Figure 44: Probabilities of failure of flax structures for an equivalent mass to E-glass

In most cases the variability of the mechanical properties has a limited influence as the panels will fail due to the poor mechanical properties of the flax. However, in the case of the maximum mechanical properties the variability has a larger influence. It indicates that if the maximum properties with minimum coefficients of variation from the literature are reproducible, flax structures might be feasible for some applications as no failures occurred. However, these values are deemed to be quite unlikely, as they are generated in laboratory conditions. Whilst these values indicate some potential they do not exhibit an equivalent factor of safety as for the E-glass and therefore a flax structure is derived that is as safe as E-glass using the mean, minimum and maximum properties.

6.4.3 Feasibility study

The mass of the flax structure is increased to reach an acceptable probability of failure and give a more likely value of the mass of the structure required to have an equivalent safety, using the mean properties and coefficients of variation. Figure 45 demonstrates how the additional mass affects the probability of failure.

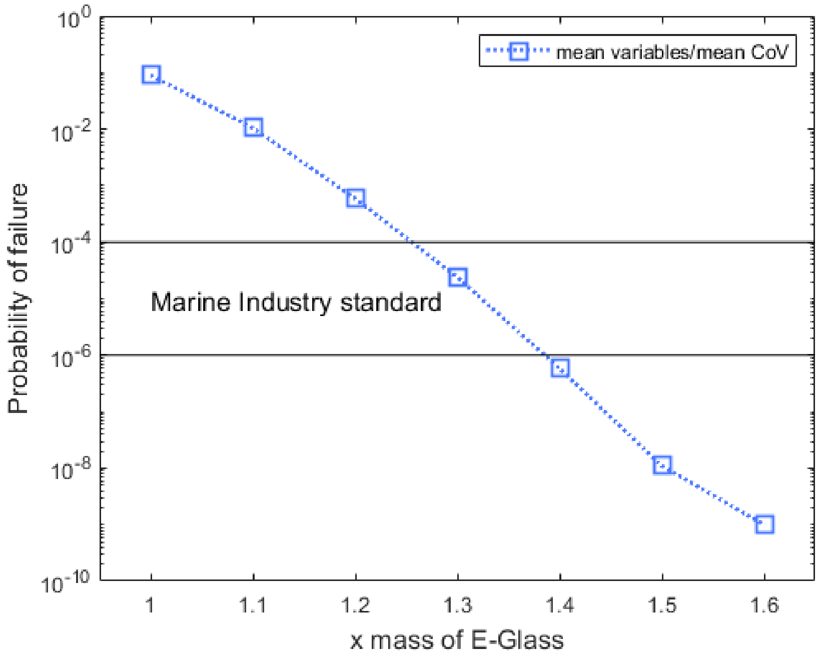


Figure 45: Probability of failure for flax structures with mean mechanical properties compared to the mass of the E-glass structure

For the mean flax mechanical properties and mean variability, the structure needs to be 30% heavier than the E-glass structure to meet the marine industry standard. However, at this mass the flax and E-glass structures are not equivalent with a probability of failure smaller than 10^{-9} for the E-glass panel compared to 2.52×10^{-5} for the flax panel. The flax panel needs to be 1.6 times heavier than E-glass to be equivalent in terms of probability of failure. However, due to the lower density of flax laminates compared to E-glass, the volume of the flax structure is 138% larger than the E-glass grillage, increasing the stiffener height from 258 mm to 292.4 mm and the thickness from 12.84 mm to 30.04 mm. As the probability of failure for the E-glass panel is smaller than 10^{-9}, it is difficult to determine how safe the E-glass structure is compared to flax as lower values make little statistical sense in real applications. Therefore, the mean stress to mean strength ratio after convergence is calculated for both structures. To obtain the same ratio, the flax structure needs to be 2.4 times heavier and 257% larger, 0.4 m^3 compared to 1.4 m^3, than E-glass, a considerable weight and volume increase.

The mean mechanical properties for flax laminate from the literature are likely to be higher than properties obtained in industry. Therefore, a feasibility study with the minimum mechanical properties and mean variation is also conducted to determine the mass of the structure required in comparison to E-glass to obtain an acceptable probability of failure. Figure 46 demonstrates how the additional mass affects the probability of failure.

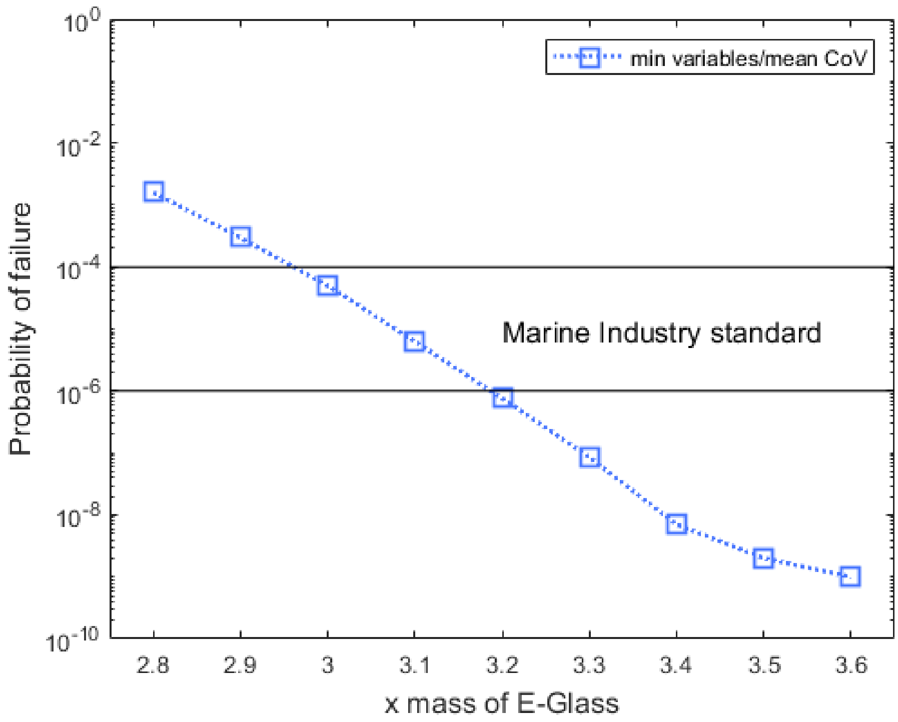


Figure 46: Probability of failure for flax structures with minimum mechanical properties compared to the mass of the E-glass structure

For the minimum mechanical properties and mean variability, the flax structure needs to be 3 times the mass of E-glass to meet the marine industry standard with a probability of failure equal to 4.97×10^{-5} but the flax structure needs to be 3.6 times heavier than E-glass to have an equivalent probability of failure, 10^{-9}. The increase in thickness is significant, 65.64 mm for flax in comparison to 12.84 mm for E-glass. Due to the low probability of failure of the E-glass structure, the mean stress to strength ratio is calculated for both structures to determine how reliable the E-glass structure is in comparison to flax and it is found that the flax grillage needs to be 4 times the mass of E-glass to have the same ratio which represents an increase in volume of 495% with a thickness of 72.54 mm for flax laminate in comparison to 12.84 mm for E-glass. It demonstrates that if the mean mechanical properties cannot be reproduced at the structural scale, the considerable increase in mass and volume to reach equivalent properties make it unrealistic.

If the maximum mechanical properties achievable for flax laminates are considered with mean variation, the structure needs to be 10% heavier than E-glass to have equivalent probability of failure but 1.7 times heavier to have an equal mean stress to mean strength ratio which represents an increase in volume of 152%; which is still a substantial increase.

6.4.4 Impact of manufacturing process on flax structural properties

The manufacturing process has a large impact on the mechanical properties obtainable for a given material. The impact of the manufacturing techniques and therefore the reliability of the structure for three commonly used manufacturing techniques for E-glass structures: hand lay-up, resin infusion and autoclave is investigated on the grillage with the same mass as E-glass. The tensile properties, E_1 and X_T are specific for each manufacturing process but due to a lack of data, and the low influence of the transverse and compressive properties on the reliability, the mean data from Table 31 are used for E_2, Y_T, X_C, Y_C, S_{12} for all three cases. The average coefficients of variation from Table 32 are used for all the mechanical properties as the quantity of data available specifically for these three manufacturing techniques is insufficient to obtain representative values. The probabilities of failure for the three different manufacturing techniques with mean variables and mean coefficients of variation are presented in Figure 47 together with the probability of failure obtained with the combined manufacturing techniques.

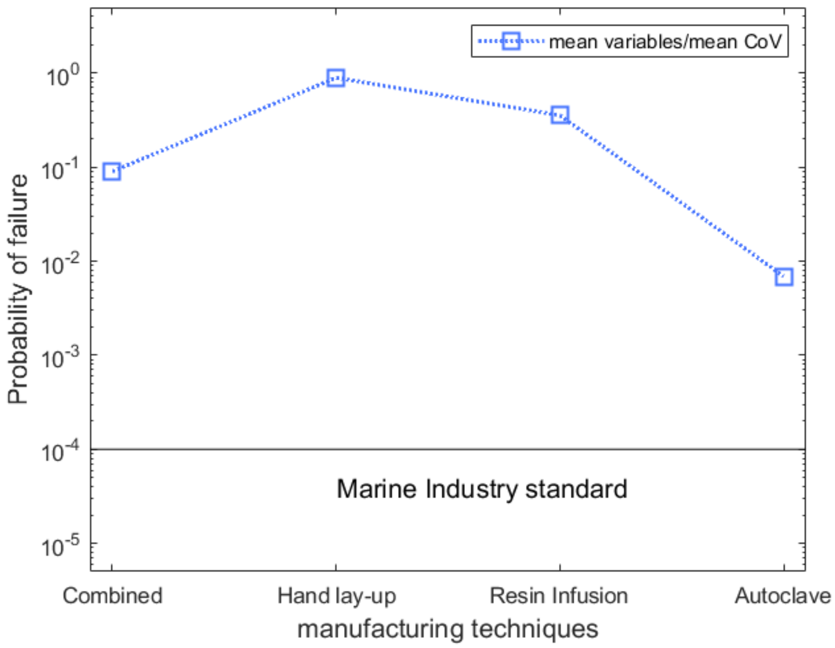


Figure 47: Probability of failure for a flax epoxy structure manufactured with hand lay-up, resin infusion and autoclave

Figure 47 shows that the number of studies using expensive manufacturing techniques for flax fibre reinforced laminates reduces the probability of failure from that derived from the combined manufacturing techniques. This results in a probability of failure which is lower than would be expected when considering hand lay-up and resin infusion. The panel manufactured with prepreg and autoclave curing has the lowest probability of failure equal to 6.9×10^{-3} which is still too high to be adequate for marine structures. Hand lay-up and resin infusion techniques which are widely used in the industry for E-glass structures are inadequate, therefore the estimates for the equivalent mass of 2.4 should be increased or the cost of these new sustainable structures will be substantially increased due to the utilisation of more expensive manufacturing techniques. It demonstrate the influence of the manufacturing techniques on the reliability of the structures and the importance to consider mechanical properties obtained with manufacturing techniques reproducible on an industrial scale for structures.

6.5 Discussion and limitations

There are a huge number of data points in the literature for flax fibre properties, 6000+. However, the specific structure of flax fibres means that the data cannot be used for predictions of the properties at larger scales as the Rule of Mixtures is too inaccurate. At the laminate scale the number of data points is reduced but the range of these values for each property remains large; this is especially the case for the Young's modulus and the strength in the longitudinal direction with 58 points and a minimum of 11.86 MPa and a maximum value of 40.10 MPa for Young's Modulus and with 55 points and a minimum value of 113 MPa and a maximum value of 408 MPa for the strength in the longitudinal direction. Whilst some properties are relatively well understood there is a lack of data for the transverse and compressive properties, with only 4 values, representing an average of a number of experiments, available in the current literature. The literature shows that the mechanical properties of flax laminates are lower than E-glass, 38% for the average longitudinal Young's modulus and 75% for the average longitudinal tensile strength, but that the variability of both materials is similar. Some of the values near the maximum and minimum still seem to be unrealistic, where the minimum tensile transverse strength of the flax, 4.5 MPa, is so small that some plies are failing transversely for the configuration with the minimum mechanical properties. In addition data is missing for the Poisson's ratio, the shear modulus and shear strength but the influence of these properties on the final failure of this application is small. Much of the data gives optimistic values compared to that likely to be seen in industry as it is obtained from expensive manufacturing techniques, with less data for hand lay-up and resin infusion manufacturing which are more realistic for structural applications. More studies on transverse and compressive properties are required for structural analysis and a better understanding of the properties likely to be seen in industry is also required.

The reliability analysis is based on strength only but many applications have a serviceability limit state based on deflection, which is typically harder to meet for composite materials. Under this limit state flax laminates cannot compete against E-glass for volume constrained applications where the mean deflection for the E-glass grillage is 128 mm compared to 227 mm for the flax grillage. Based on an equivalent mass, the deflection of the flax structure is only 11% higher than E-glass with a mean deflection of 142 mm because of the bulkier laminate; the flax structure needs to be 10% heavier than E-glass to have an equivalent mean deflection. Furthermore, as demonstrated by Shah [124], the Young's modulus has a bi-linear shape and the initial stiffness of flax laminates decreases by up to 50% above 0.4% strain. The Young's modulus data available in the literature is likely to be taken at lower strains and therefore the stiffness is higher than would be seen in structural applications, making this comparison difficult at this stage.

Studies at the fibre scale advertise flax fibre properties as equivalent to E-glass properties and therefore that both materials have equivalent mechanical properties at the laminate and structural scale. At the laminate scale, the focus is on the longitudinal Young's modulus properties for which the highest value for flax is almost equal to the average value for E-glass. However, the longitudinal tensile strength, which has a much bigger impact on the reliability, is low with a value of 255 MPa for flax compared to 1014 MPa for E-glass reinforced laminates and these reliability analyses demonstrate that the potential for flax fibres to be used for structural applications is lower than indicated by much of the literature. An increase in mass of a structure by 2.4 seems to be unrealistic for many industries, and there will be efficiency implications for structures that add this much weight with a possible gain in emissions larger than the gains in sustainability at manufacture. For non-structural applications, where the flax provides a lightweight option, then there are many benefits for these materials.

More research should be conducted on natural composite reinforced laminates before they can be safely considered for structural applications, especially at scales above the fibre. The structural behaviour of the material needs to be investigated with many more tests at the structural scale. The tensile transverse and compressive properties need to be investigated including their variability. Realistic material properties, likely to be reproducible by industry are required. Finally, the failure envelope used for this work for the flax structures is defined with the available knowledge but needs to be further investigated and represents a limitation of the work. The applicability of the World Wide Failure Exercise criteria to natural fibre composites must be validated with experimental data and mechanical properties obtained with realistic manufacturing techniques.

6.6 Conclusion

A number of studies in the current literature compare the mechanical properties of flax fibres with E-glass and conclude that since both fibres have equivalent properties that flax can be used for structural applications. However, the literature also shows that when composite laminates are manufactured from both materials that flax properties are lower than E-glass, especially the strength properties. Currently limited tests or modelling are performed at the structural scale to determine whether flax is capable of replacing E-glass, which is especially important due to the increasing literature showing that these materials behave differently. Therefore a reliability assessment is performed, with material properties selected based on the literature, comparing an E-glass stiffened structure taken from the marine industry with equivalents produced from flax. It is shown that the reliability of flax fibre reinforced structures is equivalent to E-glass when the flax structure is increased to 2.4 times the mass of E-glass, when using the mean properties from the literature. However, they are not a feasible replacement for volume constrained situations. The study is optimistic as the material properties considered here are for all manufacturing processes, to ensure that there is enough data, but when simulations using only the resin infusion properties for flax are considered the probabilities of failure increase. Recommendations are therefore that:

- Flax and E-glass structures are not equivalent, even where similar fibre properties are reported.
- Flax is widely studied in the literature, especially at the fibre scale, but this literature does not allow determination of the feasibility of flax materials for structural applications.
- The manufacturing processes considered in the literature are often the most expensive due to the lab-scale approach, and these are unlikely to be used in the structural applications where flax might replace standard composites.

Chapter 7 Discussion: limitations and given perspectives

The need for sustainable materials has led to a growing research interest for flax fibre reinforced composites. The potential for structural applications made from these materials is highlighted by a number of authors but investigations at the structural scale are limited [25] [26] [27] [18] [14] [10] [28] [12] [29]. A large part of the literature focuses on the fibre scale with their specific mechanical properties advertised as equivalent to E-glass [36] [22] [71]. Shah et al. [45], Charlet et al. [66], Kersani et al. [8] and Bensadoun et al. [51] demonstrate that the relationship between fibre properties and laminate properties is difficult to model, making these materials difficult to use, and there is a perception that the high variability in the mechanical properties of flax fibre reinforced composites is one of the main factors preventing their utilisation for structural applications.

Chapter 4 demonstrates that the large variability caused by the natural origins of the fibres and the experimental errors during the characterisation of their mechanical properties is not replicated at the laminate scale. The experiments show that the coefficients of variation are similar to E-glass laminates, below 8%, based on the tensile properties of 95 specimens. These laminate experiments also show that the mechanical properties are lower than expected and that the fibre mechanical properties, which are comparable to E-glass, are not transferred to the laminate scale. These low laminate properties can be partially explained by the low fibre volume fraction achievable for flax fibre reinforced laminates caused by the low packability of flax yarns.

The influence of the fibre properties on the laminate properties is investigated in chapter 4 using the rule of mixtures. The literature demonstrates that laminate properties cannot be predicted from fibre properties and that there is no clear explanation for why the rule of mixtures does not work. The influence on the laminate predictions of different assumptions: inaccuracy in the prediction of the fibre cross sectional area or scales at which the fibres properties are determined, are investigated but the results are inconclusive. However, it demonstrates that laminate mechanical properties data, rather than fibre scale studies, are required for modelling the structural response despite the literature being focused at this scale, 3596 specimens for fibres compared to 260 for laminates. At laminate scale the longitudinal properties are well defined in the literature but transverse, compressive, shear properties and Poisson’s ratio are also required for structural assessment.

In addition to the difficulties in predicting laminate properties based on fibre properties, flax fibres have a different behaviour compared to E-glass with non-linearity at low strains, Coroller et al. [55].

At the laminate scale, the non-linear stress-strain curve means that the initial stiffness decreases by up to 50% between the initial strain profile and values above 0.4% strain, as demonstrated by Shah [124]. The effect of this non-linear response needs to be investigated at the structural scale and its exclusion represents a limitation of the analytical model developed in chapter 5. Further work should be conducted to investigate this non-linear response. Different assumptions for the materials model could be compared such as using a bi-linear model, the Young's modulus of the initial slope, the Young's modulus of the final slope, a Young's modulus to the final failure point and potentially an elliptical approximation. There are also a range of shapes exhibited within the literature for this non-linear behaviour with different reductions in stiffness and different points at which this reduction occurs. Any models will therefore need to be compared across a range of stress-strain profiles and layups. Furthermore, at the laminate scale, the non-linear stress-strain curve means that the strain range used to determine the Young's modulus of the laminate has a large impact on the final results. It is therefore likely that the mechanical properties for flax fibre reinforced laminates available in the literature and used for the reliability assessment of flax stiffened structures in chapter 6 are overestimated in comparison to mechanical properties seen in real structures. The non-linear behaviour and its impact at the structural scale need to be better understood as it will make the prediction of structural response more expensive. For example the traditional pyramid of testing used in standard composites to save cost would currently not be possible as the behaviour at one scale cannot be transferred to the next scale up.

In addition to the non-linearity, flax fibre reinforced composites are shown to have a different structural behaviour in comparison to standard composites, which is not captured in the literature. It demonstrates that models used for standard composites need to be validated and their accuracy need to be determined before being used for the analysis of flax fibre reinforced composites at the structural scale. At the structural scale, flax fibre composites can demonstrate an increase in stress for a decrease in Young's modulus, which is unusual. In addition the transverse Young's modulus properties have a more significant impact on the structural performance. The results are not conclusive and need to be validated with additional experimental data and different structural components need to be investigated but it shows that some of the mechanical properties which have only a minor impact for standard composites, can have a significant influence for flax structures such as the transverse Young's modulus in the grillage model. In the future, different loading cases also need to be considered to determine the impact of other mechanical properties on the structural behaviour of flax fibre reinforced laminates, for example structural applications which exhibit large shearing.

Due to the relative novelty of the material and the current non-structural industrial applications, the failure envelope of flax fibre reinforced laminates is not well defined. There is limited literature to determine whether the World Wide Failure Exercise models are valid or what the parameters that go into these formula should be. While Koh and Madsen [127] investigate the applicability of Tsai-Hill, Tsai-Wu, Hashin and Puck failure criteria for flax fibre reinforced laminate to define a failure envelope, the values for the different coefficients are defined with an optimisation process and a limited number of experimental data. Also of concern is the low strength of the flax fibre laminates which leads to a small failure envelope. While the stiffness is widely used to compare flax reinforced composites with E-glass the low strength of flax laminates is much more of an issue for structural applications, clearly demonstrated in chapter 6 with a comparison between the failure envelope of E-glass and flax laminate based on mean mechanical properties from the literature. This work has been conducted with the knowledge available but the applicability of the World Wide Failure Exercise criteria to natural fibre composites must be further validated with experimental data.

The reliability analysis, conducted in chapter 6, demonstrates that the potential for flax fibres to be used for structural applications in the near future is lower than indicated by much of the literature. The increase in mass required to balance the lower strength and stiffness of the materials in comparison to conventional composites is large, with the flax grillage structure 2.4 times heavier than the E-glass equivalent in this particular example. Therefore, it is unrealistic for many industries with efficiency implications for structures that add this much weight. The additional weight could increase emissions above the improved sustainability at manufacture, especially in structures expected to operate for 10-20 years or more. The lower density of flax fibres in comparison to E-glass means that the increase in volume is even larger than the increase in mass. Flax fibre reinforced composites are therefore unsuitable for industrial applications constrained by volume such as the marine industry.

Despite the poor structural performance of flax fibre reinforced composites they are a relatively novel materials and improvements in their mechanical properties are still possible. A significant body of research is conducted on fibre treatments to improve the interface between flax fibres and the matrix with the objective to increase the laminate properties and improve the durability. Flax fibre reinforced composites suffer from low fibre volume fractions, especially if cheap manufacturing techniques are used such as hand lay-up or resin infusion, and so an improvement in the production and manufacturing techniques used for flax fibre reinforced composites could increase the fibre volume fraction and the mechanical properties of the laminates, as demonstrated by Shah [1]. An increase in material properties and the low densities exhibited by these materials might allow flax to be used for secondary structures in the future, with a will to incorporate sustainable materials. Furthermore, testing standards for the determination of the mechanical properties of flax fibre reinforced laminates are required to take into consideration the non-linear behaviour and the impact on the calculation of the Young's modulus. It should allow a reduction in the spread of results seen in the literature for natural fibre composites.

Chapter 8 Conclusion

There is a need for more sustainable materials. One of these is flax with the literature viewing these materials as a promising replacement to E-glass in composite applications. However, their structural capability is not well understood and their large variability in mechanical properties is seen as an obstacle for structural scale applications.

Therefore this thesis performs a reliability analysis of a flax structure for the first time to determine the suitability of flax for large structural applications. Three main steps are performed: first the impact of the fibre scale variability on the laminate properties is assessed, to determine if the variability is the main obstacle; then a structural analysis is performed and an analytical model is developed to accurately model the behaviour of flax fibre reinforced composite grillage structures; and finally, the safety of flax structures is investigated with a reliability analysis comparing the probability of failure of flax and E-glass grillage structures to determine the increase in mass and volume required for the flax structure to be equivalent to E-glass.

It is found that the large variability of flax fibre mechanical properties is not a problem at the laminate scale, with equivalent variation in mechanical properties for flax laminates and E-glass laminates. However, when they are part of a structure the flax fibre reinforced composites have a different behaviour to standard composites. A change in structural response is seen for flax fibre reinforced composites with an increase in stress for a decrease in stiffness. In addition, the transverse Young's modulus has a more significant impact on the structural response than in standard composites. This change in structural response means that the comparison between a flax and E-glass reinforced grillage structure demonstrates that the flax structure needs to be 2.4 times heavier than the E-glass structure to have an equivalent stress to strength ratio and an increase in volume of 257%. It is determined that current flax fibre reinforced composites cannot be used in structures constrained by volume and that for those constrained by mass that the penalty for their use is significant.

Further investigations should be conducted before flax fibre reinforced composites can be safely considered for structural applications. Future research should include: a better characterisation of the transverse and compressive properties; investigation into the non-linear behaviour of the tensile properties and its impact at the structural scale; improvements in the manufacturing techniques likely to be used for large structures, to improve the fibre volume fraction; a wider range of structures, to determine if the sensitivity to transverse properties is grillage specific and confirmation of these findings through structural scale experiments.

Appendix A Review of the impact of natural factors on flax fibre properties

Natural factors	Impact on mechanical properties	References
Time of cultivation	Statistically stable over 3 years even if two years are associated with a rain deficit	Lefeuvre et al. [44]
	No significant impact over 9 different years	Baley and Bourmaud [65]
	No significant impact over 4 different years	Lefeuvre et al. [71]
	41.0 GPa and 663 MPa in 2005 compared to 75.0 GPa and 1232 MPa in 2008 but only 9 specimens tested for 2005.	Pillin et al. [75] Bourmaud et al. [81]
	Reproducible mechanical properties over 4 consecutive years	Bourmaud et al. [90]
	The mechanical properties are not statistically different between field or greenhouse cultivation	Goudenhooft et al. [91]
	Fibres exposed to hail have a tensile strength of 841 MPa compared to 1066 MPa for fibres not exposed to exceptional weather conditions. The stiffness is similar for both batches but different varieties	Coroller et al. [55]
Varieties	Out of 12 different varieties including oleaginous fibres, the mechanical properties are not impacted	Baley and Bourmaud [65]
	Out of 4 different varieties the properties are not impacted	Goudenhooft et al. [78]
	Marylin variety has higher mechanical properties than Hermes and Andrea	Coroller et al. [55]
	Out of 7 varieties the mechanical properties are highly scattered but the maximum and minimum stiffness values are for the same variety over two different years	Bourmaud et al. [81]
	The average properties across 5 varieties of oleaginous fibres are lower than the average of 4 textile varieties	Pillin et al. [75]
	Out of 4 different varieties of flax fibres including one oleaginous type; the highest and lowest values are for the same variety but different locations in the stem.	Tanguy et al. [92]

Location of the fibres in the stems	Elemental fibres extracted from the middle of the stem have the highest properties followed by the top and the bottom	Charlet et al. [93]
	The breaking strength of 755 MPa for the bottom fibres compared to 1454 MPa for fibres coming from the middle section. The young's modulus varies from 46.9 GPa for the bottom part to 68.2 GPa for the middle section.	Charlet et al. [82]
	The mechanical properties are highest in the middle section followed by the top sections and then the bottom sections with the lowest stiffness ranging from 48.4 GPa for the bottom to 63.4 GPa for the middle. The strength varies from 590 MPa for the bottom to 940 MPa for the middle.	Lefeuvre et al. [94]
Agricultural practice	High seeding rate decrease the mechanical properties	Bourmaud et al. [95]
	Highly retted fibres have higher mechanical properties	Martin et al. [33] and Pillin et al. [75]

Appendix B Flax fibre mechanical properties from the literature

Rules:

- Fibres without treatment were included in the tables
- A distinction was made between elemental, technical and yarns flax fibres to investigate the impact of the scale on the mechanical properties.
- 1 in the number of specimens means that the number was not given

B.1 Elemental fibre properties

Materials : elemental flax fibres	# of specimens	Longitudinal Young's modulus (GPa)		Longitudinal tensile strength (MPa)		Longitudinal strain (%)		Refs.
		Mean	STDEV	Mean	STDEV	Mean	STDEV	
Elementary flax fibres, dew retted provided by Ekotex (Poland) Gauge Length = 5 mm	59	37	11	788	273	2.70	0.85	[69]
Elementary flax fibres, dew retted provided by Ekotex (Poland) Gauge length = 10 mm	83	42	14	718	290	2.40	0.89	[69]
Elementary flax fibres, dew retted provided by Ekotex (Poland) Gauge length = 20 mm	53	34	12	520	209	1.77	0.64	[69]
Elementary flax fibres, dew retted provided by Kraslava (Latvia) Gauge length = 5 mm	33	39	12	880	405	2.53	0.65	[69]

Elementary flax fibres, dew retted provided by Kraslava (Latvia) Gauge length = 20 mm	32	41	14	611	264	1.71	0.59	[69]
Single flax fibres provided by Ekotex (Poland) Green fibres with linear behaviour Gauge length = 5 mm Diameter = 18.9 ± 4.3 µm	30	31.4	16.2	974	419	3.00	0.65	[43]
Single flax fibres provided by Ekotex (Poland) Cottonized fibres with linear behaviour Gauge length = 5 mm Diameter = 18.4 ± 3.0 µm	15	33.1	11.6	760	392	2.27	0.63	[43]
Single flax fibres provided by Ekotex (Poland) Cottonized fibres with nonlinear behaviour Gauge length = 5 mm Diameter = 19.8 ± 3.6 µm	20	24.2	10.7	641	314	2.50	0.48	[43]
Single flax fibres, Hermes variety Gauge length = 10 mm (top of stem) Diameter = 19 ± 3.5 µm	36	59.1	17.5	1129	390	1.9	0.4	[82] [92]
Single flax fibres Hermes variety, 2003 Gauge length = 10 mm (middle of stem) Diameter = 19.6 ± 6.7 µm	37	68.2	35.8	1454	835	2.3	0.6	[82] [81]

Single flax fibres Hermes variety (bottom of stem) Gauge Length = 10 mm Diameter = 20.1 ± 4.1 μm	31	46.9	15.8	755	384	1.6	0.5	[82]
Single flax fibres (Melina variety, La Calira Company, Picardie France 2009) Gauge Length = 10 mm	71	54.7	11.7	856	354	1.8	0.8	[101]
Single flax fibres Variety : Ariane, 2002, Gauge length = 10 mm Diameter = 23 ± 5.7 μm	77	54.080	15.128	1339	486	3.27	0.84	[64] [81]
Elementary flax fibres, Marylin Fibres Cooperative de Teillage de Lin du Plateau du Neubourg (France) M309	110	56.7	13.6	1109	477	2.1	0.7	[44]
Elementary flax fibres, Marylin Fibres Cooperative de Teillage de Lin du Plateau du Neubourg (France) M175	74	55.9	12.6	1037	363	1.9	0.5	[44]
Elementary flax fibres, Marylin Fibres Cooperative de Teillage de Lin du Plateau du Neubourg (France) M416	64	53.4	12.9	948	337	1.9	0.6	[44]
Elementary flax fibres, Marylin Fibres	62	47.0	11.2	853	218	2.1	0.5	[44]

Cooperative de Teillage de Lin du Plateau du Neubourg (France)M055								
Elementary flax fibres, Marylin Fibres 33364.412.6 Cooperative de Teillage de Lin du Plateau du Neubourg (France)M283	75	59.5	17.0	1088	419	2.0	0.6	[44]
Elementary flax fibres, Marylin Fibres Cooperative de Teillage de Lin du Plateau du Neubourg (France) M004	55	64.4	12.6	1028	333	1.9	0.6	[44]
Elementary flax fibres, Marylin Fibres Cooperative de Teillage de Lin du Plateau du Neubourg (France) M575	59	59.1	15.3	1015	379	1.7	0.5	[44]
Elementary flax fibres, Marylin Fibres Cooperative de Teillage de Lin du Plateau du Neubourg (France) M470	54	56.2	16.7	935	364	1.8	0.5	[44]
Oleaginous Single flax fibres Gauge length = 10 mm Variety Hivernal 2006 (classical retting degree) Diameter = 12.9±3.3 μm	57	71.7	23.2	1111	554	1.7	0.6	[75]

Oleaginous Single flax fibres Gauge length = 10 mm Variety Alaska 2006 (classical retting degree) Diameter = 15.8 ± 4.1 µm	66	49.5	13.2	733	271	1.7	0.6	[75]
Oleaginous Single flax fibres Gauge length = 10 mm Variety Niagara 2006 (classical retting degree) Diameter = 15.6 ± 2.3 µm	71	45.6	16.7	741	400	1.7	0.6	[75]
Oleaginous Single flax fibres Gauge length = 10 mm Variety Everest 2006 (classical retting degree) Diameter = 21.2 ± 6.6 µm	76	48.0	20.3	863	447	2.1	0.8	[75]
Oleaginous Single flax fibres Gauge length = 10 mm Variety Olivier 2006 (classical retting degree) Diameter = 13.7 ± 3.7 µm	76	55.5	20.9	899	461	1.7	0.6	[75]
Oleaginous Single flax fibres Gauge length = 10 mm Variety Alaska 2006 (low retting degree) Diameter = 15.3 ± 5.4 µm	20	46.3	12.1	691	253	1.8	0.6	[75] [81]
Oleaginous Single flax fibres	9	41.0	12.5	663	307	1.8	0.4	[75] [81]

Gauge length = 10 mm Variety Everest 2005 (classical retting degree) Diameter = 16.9 ± 4.9 µm								
Oleaginous Single flax fibres Gauge length = 10 mm Variety Everest 2007 (classical retting degree) Diameter = 14.3 ± 5.1 µm	25	51.8	15.6	685	222	1.7	0.6	[75]
Oleaginous Single flax fibres Gauge length = 10 mm Variety Everest 2008 (classical retting degree) Diameter = 15.4 ± 5.1 µm	30	75.0	21.6	1232	554	2.1	0.8	[75] [81]
Elementary flax fibres Electra variety from Van Robaeys frères (Killem, France, 2007) Diameter = 15.8 ± 4.5 µm	45	51.1	15	808	342	1.60	0.45	[80]
Individual flax fibres from Dehondt Technology (Normandy, France, 2003) Variety Agatha Gauge length = 10 mm Diameter = 21.5 ± 5.3 µm Top of the stem	57	51	22	753	353	1.8	0.7	[93]
Individual flax fibres from Dehondt Technology (Normandy, France, 2003) Variety Agatha	45	57	29	865	413	1.8	0.7	[93] [81]

Gauge length = 10 mm (Middle of the stem) Diameter = 21.3 ± 6.3 µm								
Individual flax fibres from Dehondt Technology (Normandy, France, 2003) Variety Agatha Gauge length = 10 mm (Bottom of the stem) Diameter = 23.5 ± 7.9 µm	59	51	26	783	347	2.0	0.9	[93]
Single flax fibres (Normandy, France, 2003) Variety Hermes Gauge length = 10 mm	98	66.991	16.308	1057	462	2.2	0.8	[145]
Flax green elemental fibres (Normandy, France, 2004) Provided by Dehondt Technologies (Notre Dame de Gravenchon) Variety Hermes Gauge length = 10 mm Diameter = 17 ± 5 µm	58	36	15	670	315	3.5	1.1	[245]
Flax retted elemental fibres (Normandy, France, 2004) Provided by Dehondt Technologies (Notre Dame de Gravenchon) Variety Hermes Gauge length = 10 mm Diameter = 16 ± 4 µm	38	37	14	670	320	3.1	1.1	[245]

Elemental normally retted flax fibres Gauge length = 10 mm	25	43	14.19	925	398	2.9	1.65	[246]
Individual flax fibres retted in the field Variety : Ariane (Normandy) Gauge length = 10 mm Diameter = 21.57 ± 0.95 µm Fibres with diameter between 20 and 22.5	21	64.10	13.65	1499	346	2.93	0.74	[20]
Individual flax fibres retted in the field Variety : Ariane (Normandy) Gauge length = 10 mm Diameter = 23.86 ± 0.68 µm Fibres with diameter between 22.5 and 25	23	51.28	12.02	1317	529	3.34	0.71	[20]
Elementary flax fibres Hermes variety grown in Normandy, 2004 Gauge length = 10 mm	122	63	36	1250	700	2.3	1.1	[67]
Flax fibres from Lotteraner, Vienna, Austria Gauge length = 20 mm	20	40	19.2	904	326	1.4	0.2	[247]
Elementary flax fibres (France) Hermes variety, 2003	89	48.9	12.0	1066	342	2.8	0.8	[55]

Gauge length = 10 mm Diameter = 18.6 ± 3.9 µm								
Elementary flax fibres (France) Andrea variety, 2009 (hail) Gauge length = 10 mm Diameter = 18.1 ± 3.9 µm	59	48.3	13.8	841	300	2.2	0.8	[55]
Elementary flax fibres (France) Marylin variety, 2009 Gauge length = 10 mm Diameter = 13.9 ± 2.7 µm	99	57.1	15.5	1135	495	2.1	0.6	[55]
Single flax fibres grown in Nord Pas de Calais, 2011, from Van Robaeys Freres, Killem, France Alizee variety, Gauge length = 10 mm 1 day of retting Diameter = 14.0 ± 2.7 µm	50	38.6	17.3	792	374	2.2	0.7	[33]
Single flax fibres grown in Nord Pas de Calais, 2011, from Van Robaeys Freres, Killem, France Alizee variety, Gauge length = 10 mm, 9 days of retting Diameter = 14.5 ± 2.6 µm	50	48.6	11.8	935	317	2.2	0.7	[33]
Single flax fibres grown in Nord Pas de Calais, 2011, from Van Robaeys Freres, Killem, France	50	55.6	11.8	1036	270	1.9	0.5	[33]

Alizee variety, Gauge length = 10 mm 19 days of retting Diameter = 15.9 ± 2.5 µm								
Elemental flax fibres provided by CTLN Company (Le Neubourg, France) Marylin variety, 2003 Gauge length = 10 mm Diameter = 15.5 ± 2.7 µm	90	53.8	14.3	1215	500	2.24	0.59	[68]
Single flax fibres grown in Normandy (France) Alizee variety, 2007 Gauge length = 10 mm Diameter = 15.25 ± 3.07 µm	100	47.873	16.104	1012.8	391.2	2.31	0.72	[248]
Flax fibres, Normandy, provided by Vandecandelaere Company of the Depestele Group, 2011 Gauge length = 10 mm Diameter = 22.75 ± 6 µm	22	44	21	849	482	1.78	0.6	[249] [250]
Elementary Oleaginous flax fibres provided by the “Chambre d’Agriculture du Morbihan” Variety: Hivernal, 2006 Gauge length = 10 mm Diameter = 12.9 ± 3.3 µm	1	67.5	23.7	1119	490	1.9	0.5	[81]

Elementary flax fibres collected from the middle part of technical fibres, provided by Company "Cooperative de Teillage de Lin du Plateau du Neubourg" (CTLN, Le Neubourg, Normandy, France), 2009, Variety: Marylin M1_2009, Gauge length = 10 mm Diameter = 13.6 ± 2.5 µm	59	56.2	11.9	1197	452	2.2	0.7	[79]
Elementary flax fibres collected from the middle part of technical fibres, provided by Compagny Cooperative de Teillage de Lin du Plateau du Neubourg (CTLN, Le Neubourg, Normandy, France), 2009 Variety: Marylin M2_2009 Gauge length = 10 mm Diameter = 14.4 ± 3.2 µm	44	50.3	12.2	860	295	1.8	0.6	[79]
Elementary flax fibres collected from the middle part of technical fibres, provided by Compagny Cooperative de Teillage de Lin du Plateau du Neubourg (CTLN, Le Neubourg, Normandy, France), 2010 Variety: Marylin M1_2010	45	60.5	19.2	1128	471	2.1	0.5	[79]

Gauge length = 10 mm Diameter = 16.2 ± 4.2 µm								
Elementary flax fibres collected from the middle part of technical fibres, provided by Compagny Cooperative de Teillage de Lin du Plateau du Neubourg (CTLN, Le Neubourg, Normandy, France), 2010 Variety: Marylin M2_2010 Gauge length = 10 mm, Diameter = 15.1 ± 3.0 µm	41	48.9	11.5	936	263	2.1	0.5	[79]
Elementary flax fibres collected from the middle part of technical fibres, Normandy, France Variety: Hermes 2003 Gauge length = 10 mm Diameter = 21.0 ± 7.0 µm	47	66.5	36.3	1335	783	2.1	0.5	[79]
Elementary flax fibres collected from the middle part of technical fibres, Normandy, France Variety: Olivier 2003 Gauge length = 10 mm Diameter = 17.0 ± 3.7 µm	64	50.1	27.2	854	379	1.8	0.8	[79]
Elemental flax fibres collected from the middle part of the steam and cultivated on the Plateau	60	56	12	1197	452	2.2	0.7	[251]

of the Neubourg (Normandy, France) in 2009 and scotched by the company Cooperative de Teillage de Lin du Plateau de Neubourg (CTLN, Le Neubourg, Normandy, France) Variety: Marylin 2009 Gauge length = 10 mm Diameter = 14 ± 3 µm								
Elementary hackled flax fibres type Aramis harvested mature in 2013, Normandy and field dew-retted provided by Terre de Lin Company (France) Gauge length = 10 mm Diameter = 19 ± 3 µm	50	57	12.8	791	319	1.8	0.5	[51]
Elementary flax fibres from the Hermes variety Gauge length = 10 mm	90	54	29	1253	619	2.5	1.1	[252]
Marylin flax fibres grown in Plateau du Neubourg, Normandy France and provided by Tongxiang Sanshang Meixiang Co. Ltd., Zhejiang, China Diameter = 20.9 ± 2.7 µm	-	28.1	1.4	882.0	34.9	4.5	1.7	[253]
Flax fibres, variety Marylin (2003) cultivated on Plateau de Neubourg (Normandy, France)	70	45.2	12.9	789	276	2.4	1.1	[104]

provided by Coopérative de Teillage de Lin du Plateau de Neubourg (CTLN, France) Gauge length = 10 mm Diameter = 16.0 ± 2.7 µm								
Elemental flax fibres of Hermes variety harvested in Normandy in 2003 Gauge length = 10 mm Diameter = 10-20 µm	100	36.9	6.5	600	249	1.58	0.55	[88]
Elemental flax fibres, Eden variety, middle of the stem, Gauge length = 10 mm Diameter = 15.2 ± 2.6 µm	58	52.4	13.2	912	339	2.3	0.9	[92]
Elemental flax fibres, Alize variety, middle of the stem, Gauge length = 10 mm Diameter = 16.3 ± 4.8 µm	65	49.5	20	803	342	2.3	1.7	[92]
Elemental flax fibres, Olivier variety, bottom of the stem, Gauge length = 10 mm Diameter = 18.3 ± 5 µm	83	47.2	21.3	751	413	1.67	0.6	[92] [81]
Elemental flax fibres, Olivier variety, middle of the stem,	76	50.0	27.2	802	381	1.75	0.78	[92]

Gauge length = 10 mm Diameter = 17.5 ± 3.6 µm								
Elemental flax fibres, Olivier variety, top of the stem, Gauge length = 10 mm Diameter = 20.7 ± 3.7 µm	61	54.5	32.5	960	692	2.0	1.2	[92]
Elementary flax fibres, grown in Normandy (France) provided by Dehondt Technology Hermes Variety Gauge length = 10 mm Diameter = 18.1 ± 3.9µm	40	55	17	995	345			[58] [84] [254]
Single flax fibres from Finflax (Oy) Finland Gauge length = 10,15 or 20 mm depending on the fibre length Diameter = 19 ± 5 µm	23	89	35	1100				[99]
Elementary flax fibres FinFlax Oy (Finland) Gauge length = 20 mm	56	64	21					[83]
Elementary flax fibres FinFlax Oy (Finland) Gauge Length = 10 mm	68	69	20					[83]
Elemental flax fibres, Bolchoi variety, cultivated in Saint Pierre le Viger in 2016 and provided by Terre de Lin (France)	50	54.7	13.2					[255]

Gauge length = 10 mm								
Elemental flax fibres		58.643						[256]
Dew retted flax (DR) Single fibres CERES Co. (Holland) 5 mm	30			906.4	246.3			[73]
Dew retted flax (DR) Single fibres CERES Co. (Holland) 8 mm	30			736.8	208.6			[73]
Dew retted flax (DR) Single fibres CERES Co. (Holland) 10 mm	30			602.6	198.4			[73]
Green flax (GR) Single fibres CERES Co. (Holland) 5 mm	30			678.9	216.2			[73]
Green flax (GR) Single fibres CERES Co. (Holland) 8 mm	30			523.7	175.3			[73]
Green flax (GR) Single fibres CERES Co. (Holland) 10 mm	30			468.3	211.6			[73]
Elemental flax fibres (JS2-33-1995, Cebeco, NL) 3 mm Standard decorticated	25			1522	400			[9]
Elemental flax fibres (JS2-33-1995, Cebeco, NL) 3 mm Hand decorticated (free of kink bands)	25			1834	900			[9]

Elementary flax fibres Gauge length = 1 mm Diameter = 26.6 ± 6.8 µm	48			1030	383			[257]
Individual green flax fibres Relative humidity = 30% Gauge length = 3.5 mm	15			677	425			[258]
Individual green flax fibres Relative humidity = 66% Gauge length = 3.5 mm	15			799	398			[258]
Individual green flax fibres Relative humidity = 30% Gauge length = 8 mm	15			619	461			[258]
Individual green flax fibres Relative humidity = 66% Gauge length = 8 mm	15			760	390			[258]
Individual single flax fibres (France) grown in 1995, dew retted Gauge length = 8 mm Diameter = 217 ± 113 µm		51.7	18.2	621	295	1.33	0.56	[259]
Single flax fibres Gauge length = 10 mm Diameter = 17.5 ± 4.2 µm	About 200	56	28	1099	558	2.3	0.9	[254]
Elementary flax fibres Gauge length = 10 mm Diameter = 23.0 ± 5.7 µm		54.080	15.128	1339	486	3.27	0.84	[257]
Single flax fibres	15	2.88		90.8				[260]

Elemental flax fibres from Institut Technique du Lin (France) Agatha Variety, middle of the stem Gauge length = 10 mm Diameter = 20.8 ± 5.9 µm	120	59	9.7	875.9	147.4	2.5	0.8	[261]
Flax fibres	25	66	22.2	1632.24	937	2.54	1.112	[262]
Elemental flax fibres grown in plateau of Le Neubourg (Normandy, France) from Company CTLN Variety, Marylin fibres, 2009 Gauge length = 10 mm Diameter = 14.8 ± 3.0 µm	248	55.3	13.0	1031	392	2.0	0.6	[71]
Elemental flax fibres grown in plateau of Le Neubourg (Normandy, France) from Company CTLN Variety, Marylin fibres, 2010 Gauge length = 10 mm Diameter = 15.8 ± 3.8 µm	137	53.3	14.1	970	318	2.1	0.6	[71]
Elemental flax fibres grown in plateau of Le Neubourg (Normandy, France) from Company CTLN	202	58.9	14.7	1020	351	2.0	0.5	[71]

Variety, Marylin fibres, 2011 Gauge length = 10 mm Diameter = 15.1 ± 3.4 µm								
Elemental flax fibres grown in plateau of Le Neubourg (Normandy, France) from Company CTLN Variety, Marylin fibres, 2012 Gauge length = 10 mm Diameter = 15.6 ± 3.1 µm	197	55.3	13.8	1109	333	2.2	0.7	[71]
Elemental flax fibres grown in Plateau de Neubourg (Normandy, France) in 2009-2012 and provided by CTLN Company Gauge length = 10 mm	11	57.5	0.3	1034	6	2.0	0.1	[90]
Elemental flax fibres provided by Terre de lin, cultivated in France in 2015, Saint Pierre le Viger, Normandy Variety : Liral Prince Gauge length = 10 mm Diameter = 21.4 ± 2.5 µm	87	41.2	10.3	878	28	2.40	0.60	[78]
Elemental flax fibres provided by Terre de lin, cultivated in France in	60	44.3	9.7	1089	365	2.53	0.51	[78]

2015, Saint Pierre le Viger, Normandy Variety : Ariane Gauge length = 10 mm Diameter = 17.5 ± 2.8 µm								
Elemental flax fibres provided by Terre de lin, cultivated in France in 2015, Saint Pierre le Viger, Normandy Variety : Eden Gauge length = 10 mm Diameter = 16.2 ± 3.0 µm	42	55.5	9.6	1175	288	2.46	0.40	[78]
Elemental flax fibres provided by Terre de lin, cultivated in France in 2015, Saint Pierre le Viger, Normandy Variety : Aramis Gauge length = 10 mm Diameter = 18.6 ± 2.9 µm	50	46.1	13.0	855	32	1.96	0.52	[78]
Elemental flax fibres provided by Terre de Lin, Normandy, France cultivated in 2016 at St Pierre Le Viger, Normandy, France Variety : Bolchoï Greenhouse cultivation Gauge length = 10 mm	50	56.3	15.1	1040	391	1.99	0.65	[91]

Diameter = 22.2 ± 4.1 µm								
Elemental flax fibres cultivated in 2016 at St Pierre Le Viger, provided by Terre de Lin, Normandy, France Variety : Bolchoï Field cultivation Gauge length = 10 mm Diameter = 23.5 ± 3.3 µm	50	54.7	13.2	1017	281	2.09	0.62	[91]
Elemental flax fibres cultivated in coastal region of Picardy, France in 2012 and provided by Van Robaeys Frères, Killem, France Variety : Alizée, scutched flax Gauge length = 10 mm Diameter = 14.1 ± 3.4 µm	60	47.0	15.7	937	400	2.0	0.6	[111]
Elemental flax fibres cultivated in coastal region of Picardy, France in 2012 and provided by Van Robaeys Frères, Killem, France Variety : Alizée, flax tows Gauge length = 10 mm Diameter = 14.0 ± 3.5 µm	60	50.8	15.7	870	342	1.8	0.5	[111]
Elemental flax fibres cultivated in Normandy,		48.4		590				[94]

2012 and provided by Terre de Lin Company Variety Eden Fibres extracted from the bottom of the plant (6 cm) Gauge length = 10 mm Diameter = 17.3 ± 2.7 µm								
Elemental flax fibres cultivated in Normandy, 2012 and provided by Terre de Lin Company Variety Eden Fibres extracted from the middle of the plant (35 cm) Gauge length = 10 mm Diameter = 16.7 ± 2.6 µm		63.4		940				[94]
Elemental flax fibres cultivated in Normandy, 2012 and provided by Terre de Lin Company Variety Eden Fibres extracted from the top of the plant (71 cm) Gauge length = 10 mm Diameter = 14.5 ± 2.5 µm		50.8		760				[94]
Elemental flax fibres cultivated in 2013 and provided by Terre de Lin, France Variety : Aramis Gauge length = 10 mm 1110 plants/m^2	50	51.2	18.1	850	359	2.14	0.82	[95]

Elemental flax fibres cultivated in 2013 and provided by Terre de Lin, France Variety : Aramis Gauge length = 10 mm 1697 plants/m^2	50	46.9	15.7	991	399	2.42	0.99	[95]
Elemental flax fibres cultivated in 2013 and provided by Terre de Lin, France Variety : Aramis Gauge length = 10 mm 2190 plants/m^2	50	39.8	17.5	630	337	1.87	0.83	[95]
Elemental flax fibres grown in 2012 provided by CTLN Company, Le Neubourg, France Variety : Marylin Bottom of the stem	46	47.2	18.1	872	437	2.1	0.8	[102]
Elemental flax fibres grown in 2012 provided by CTLN Company, Le Neubourg, France Variety : Marylin Middle of the stem	45	58.7	21.3	911	422	1.8	0.6	[102]
Elemental flax fibres grown in 2012 provided by CTLN Company, Le Neubourg, France Variety : Marylin Top of the stem	57	50.1	22.7	768	363	1.8	0.8	[102]

Elemental flax fibres obtained from the agricultural cooperative Terre de Lin and cultivated in 2013 at St Pierre le Viger, France Variety : Eden Bottom of the stem Gauge length = 10 mm Diameter = 21.3 ± 6.7 µm	60	51.3	27.9	884	542	3.0	1.4	[263]
Elemental flax fibres obtained from the agricultural cooperative Terre de Lin and cultivated in 2013 at St Pierre le Viger, France Variety : Eden Middle of the stem Gauge length = 10 mm Diameter = 19.8 ± 5.8 µm	46	68.9	24.6	1164	464	2.51	0.97	[263]
Elemental flax fibres obtained from the agricultural cooperative Terre de Lin and cultivated in 2013 at St Pierre le Viger, France Variety : TDL 25 Bottom of the stem Gauge length = 10 mm Diameter = 20.5 ± 4.9 µm	58	43.9	19.6	782	387	3.07	1.45	[263]
Elemental flax fibres obtained from the agricultural cooperative	55	55.6	23.0	1098	614	2.46	1.09	[263]

Terre de Lin and cultivated in 2013 at St Pierre le Viger, France Variety : TDL 25 Middle of the stem Gauge length = 10 mm Diameter = 18.8 ±4.3 µm								

B.2 Technical fibre properties

Materials: Technical fibres	**# of specimens**	**Longitudinal Young's modulus (GPa)**		**Longitudinal breaking strength (MPa)**		**Longitudinal strain (%)**		**Refs.**
		Mean	**STDEV**	**Mean**	**STDEV**	**Mean**	**STDEV**	
Green scutched and hackled technical long flax fibres Gauge length = 10 mm	25	33	6.6	893	259	3.8	0.76	[246]
Under retted scutched and hackled technical long flax fibres Gauge length = 10 mm	25	26	4.68	866	233.8	4.4	1.144	[246]
Normally retted scutched and hackled technical long flax fibres Gauge length = 10 mm	25	35	7.35	860	240.8	3.4	0.85	[246]

Materials: Technical fibres	**# of specimens**	**Longitudinal Young's modulus (GPa)**		**Longitudinal breaking strength (MPa)**		**Longitudinal strain (%)**		**Refs.**
		Mean	**STDEV**	**Mean**	**STDEV**	**Mean**	**STDEV**	
Green scutched and hackled technical long flax fibres Gauge length = 10 mm	25	31	10.85	793	309.3	4.1	1.19	[246]
Green hackled technical long flax fibres Gauge length = 10 mm	25	28	4.48	812	211.1	4.3	1.08	[246]
Under retted and hackled technical long flax fibres Gauge length = 10 mm	25	35	8.05	930	213.9	4.6	1.15	[246]
Normally retted and hackled technical long flax fibres Gauge length = 10 mm	25	36	9.36	719	244.5	3.1	0.78	[246]
Technical flax fibres from Wigglesworth fibres (Germany) Gauge length = 30 mm	3	57.53	5.12	649.67	285.55	1.07	0.4	[60]
Technical flax fibres from Wigglesworth fibres (Germany) Gauge length = 25 mm	3	56.47	3.04	641.33	368.71	1.01	0.51	[60]
Technical flax fibres from Wigglesworth fibres (Germany) Gauge length = 20 mm	3	51.43	1.96	812	176.23	1.25	0.33	[60]

Materials: Technical fibres	# of specimens	Longitudinal Young's modulus (GPa)		Longitudinal breaking strength (MPa)		Longitudinal strain (%)		Refs.
		Mean	STDEV	Mean	STDEV	Mean	STDEV	
Technical flax fibres from Wigglesworth fibres (Germany) Gauge length = 15 mm	3	45.9	2.55	723.67	149.91	1.1	0.3	[60]
Technical flax fibres from Wigglesworth fibres (Germany) Gauge length = 10 mm	3	38.43	2.17	613	75.74	0.95	0.02	[60]
Technical flax fibres Hermes variety, grown in Normandy (2004) Gauge length = 75 mm Diameter = 84 ± 20 µm	23	30	11	300	100	1.1	0.4	[106]
Technical flax fibres, long hackled fibres supplied by Lineo NV (FlaxTape R200) stored in an equilibrated room (50 ± 3% Relative Humidity, room temperature) Gauge length = 50 mm		41.6	2.3	457	94	1.59	0.35	[264]
Technical flas fibres sampled from FlaxTape 200 supplied by Lineo N.V. dried for 24h at 60°C and conditioned at 50% relative humidity and 21°C for 24 hours Gauge length = 50 mm		40	11	643	247	1.64	0.32	[96]

Materials: Technical fibres	# of specimens	Longitudinal Young's modulus (GPa)		Longitudinal breaking strength (MPa)		Longitudinal strain (%)		Refs.
		Mean	STDEV	Mean	STDEV	Mean	STDEV	
Technical flax fibres extracted from flax rovings (396 tex, 20 tpm) supplied by Safilin, France Gauge length = 10 mm, strain rate = 1mm/min	25	43.0	16.7	827	473			[45]
Technical flax fibres extracted from flax rovings (396 tex, 20 tpm) supplied by Safilin, France Gauge length = 25 mm, strain rate = 1mm/min	25	51.0	17.8	665	290			[45]
Technical flax fibres from Hungaro-ln Ltd, (kamarom, Hungary) Gauge length = 20 mm	50			613	442			[265]
Technical flax fibres from Hungaro-ln Ltd, (kamarom, Hungary) Gauge length = 40 mm	50			454	231			[265]
Technical flax fibres from Hungaro-ln Ltd, (kamarom, Hungary) Gauge length = 80 mm	50			264	127			[265]

Materials: Technical fibres	**# of specimens**	**Longitudinal Young's modulus (GPa)**		**Longitudinal breaking strength (MPa)**		**Longitudinal strain (%)**		**Refs.**
		Mean	**STDEV**	**Mean**	**STDEV**	**Mean**	**STDEV**	
Technical flax fibres (JS2-33-1995, Cebeco, NL) 25 mm	25			About 500				[9]
Technical flax fibres (JS2-33-1995, Cebeco, NL) 50 mm	25			About 500				[9]
Technical flax fibres (JS2-33-1995, Cebeco, NL) 100 mm	25			About 500				[9]
Technical flax fibres (JS2-33-1995, Cebeco, NL) 3 mm	25			About 850				[9]
Flax green technical fibres (Normandy, France, 2004) Provided by Dehondt Technologies (Notre Dame de Gravenchon) Variety Hermes, Gauge length = 75 mm Diameter = 135 ± 33 µm	19 to 90	31	12	305	120	1.3	0.4	[245]
Flax retted technical fibres (Normandy, France, 2004) Provided by Dehondt Technologies (Notre Dame de Gravenchon) Variety Hermes	19 to 90	32	12	310	120	1.1	0.4	[245]

Materials: Technical fibres	**# of specimens**	**Longitudinal Young's modulus (GPa)**		**Longitudinal breaking strength (MPa)**		**Longitudinal strain (%)**		**Refs.**
		Mean	**STDEV**	**Mean**	**STDEV**	**Mean**	**STDEV**	
Gauge length = 75 mm Diameter = 85 ± 20 µm								
Flax bundles Diameter = 0.133 ± 0.023 mm	59	24.610	3.213	451	78	1.92	0.19	[266]
Flax fibre bundles from "Flaxland", Gloucestershire, U.K. grown in 2011, top of the stem Gauge length = 40 mm Diameter = 100-300 µm	15			661.5	196.5			[267]
Flax fibre bundles from "Flaxland", Gloucestershire, U.K. grown in 2011, bottom of the stem Gauge length = 40 mm Diameter = 100-300 µm	15			699.9	182.8			[267]

B.3 Yarn properties

Materials: flax yarns	Number of specimens	Longitudinal Young's modulus (GPa)		Longitudinal breaking strength (MPa)		Longitudinal strain (%)		Refs.
		Mean	STDEV	Mean	STDEV	Mean	STDEV	
Flax yarns provided by Sachdeva Fabrics, Pvt. Ltd, New Delhi, India. Gauge length = 50 mm	20	12.1	2.541	353.0	64.246	5.0	0.655	[63]
Single flax yarns	10-15	5.9136	1.064	198.1	27.734	3.22	0.225	[154]
Flax yarns Gauge length = 254 mm	5	9.9	31	39.1	20			[260]
Flax yarns	95	11.4	2.11					[268]

Appendix C Additional results

C.1 Comparison of the stresses for the bottom ply of the laminate

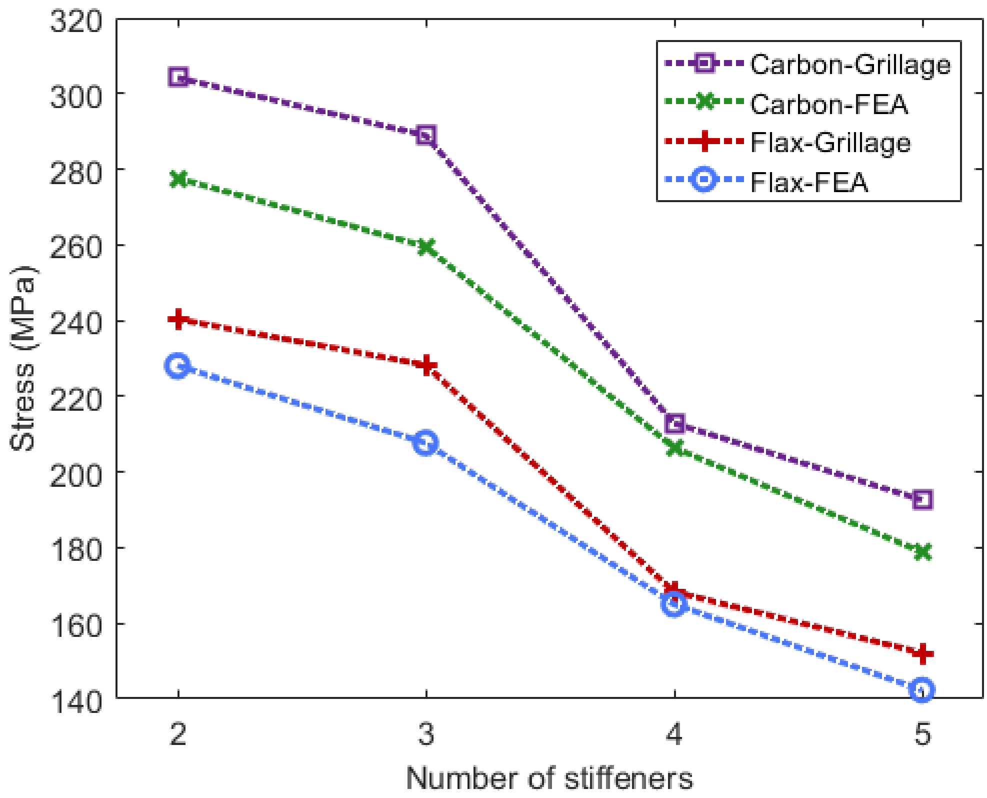


Figure 48: Comparison between bottom ply stresses obtained with FEA [153] and empirical model for varying number of stiffeners

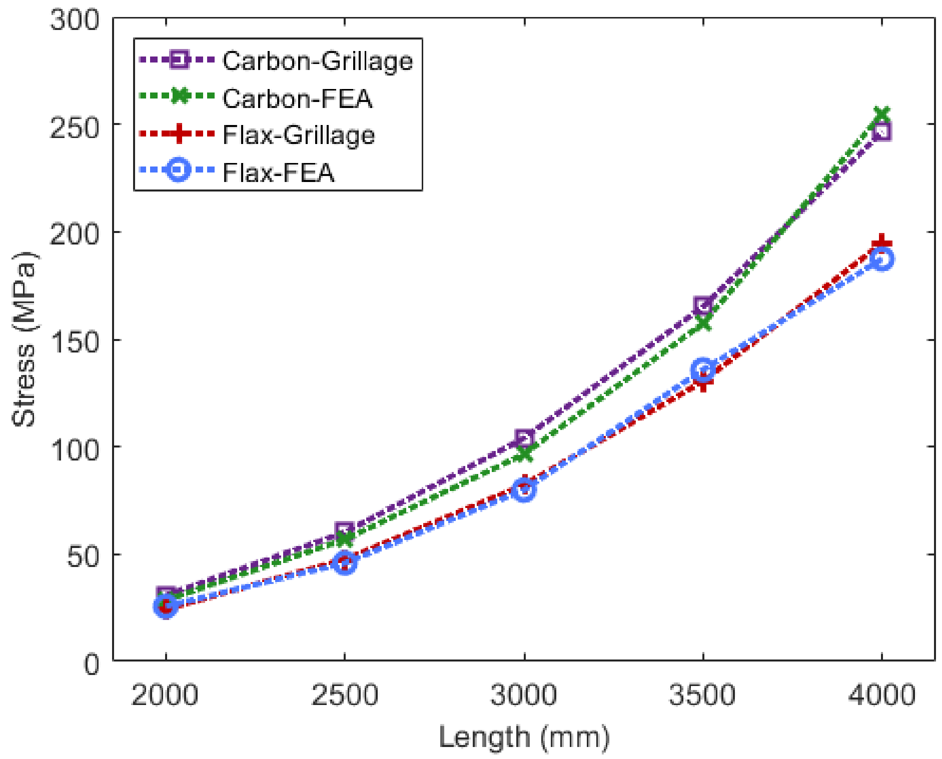


Figure 49: Comparison between bottom ply stresses obtained with FEA [153] and empirical model for varying areas of plate

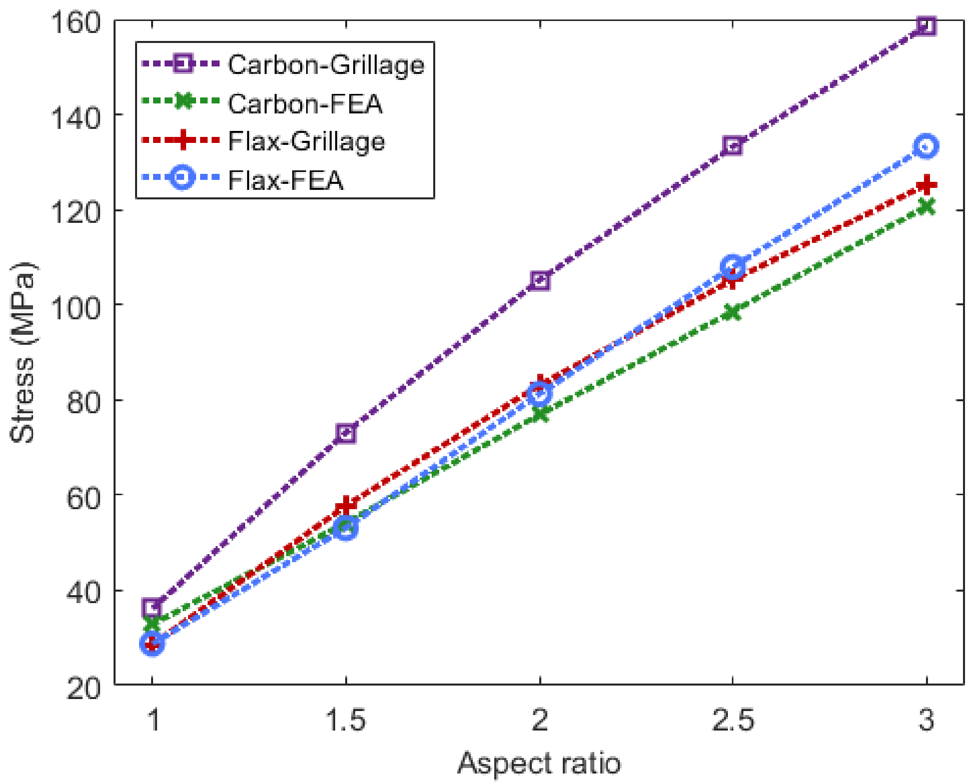


Figure 50: Comparison between bottom ply stresses obtained with FEA [153] and empirical model for varying aspect ratios

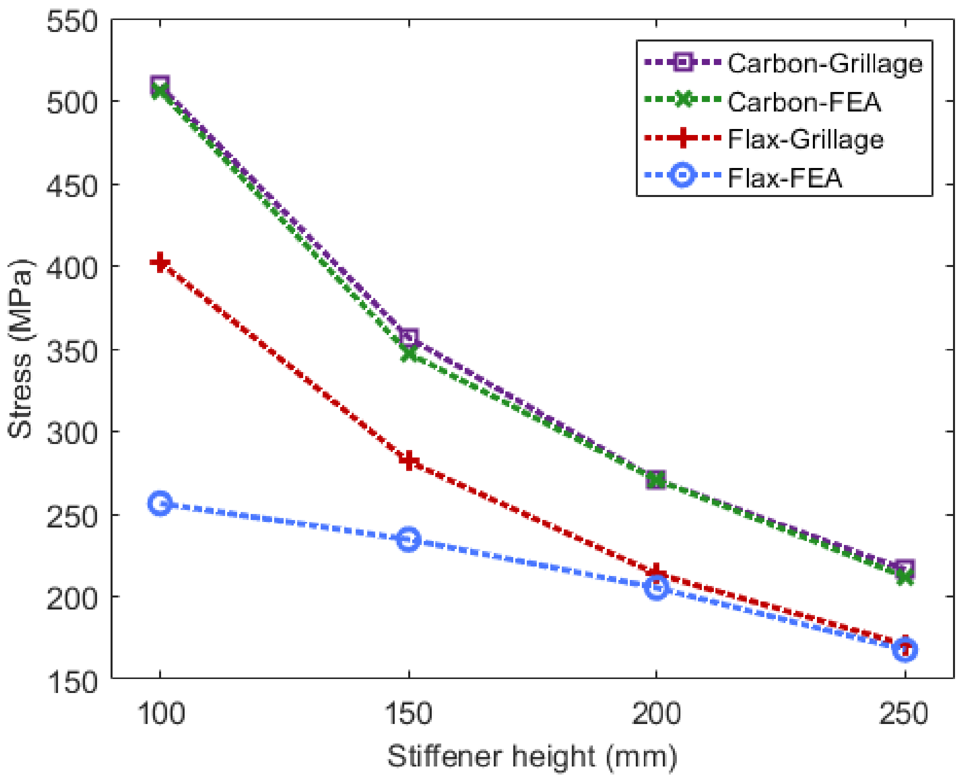


Figure 51: Comparison between bottom ply stresses obtained with FEA [153] and empirical model for varying stiffener heights

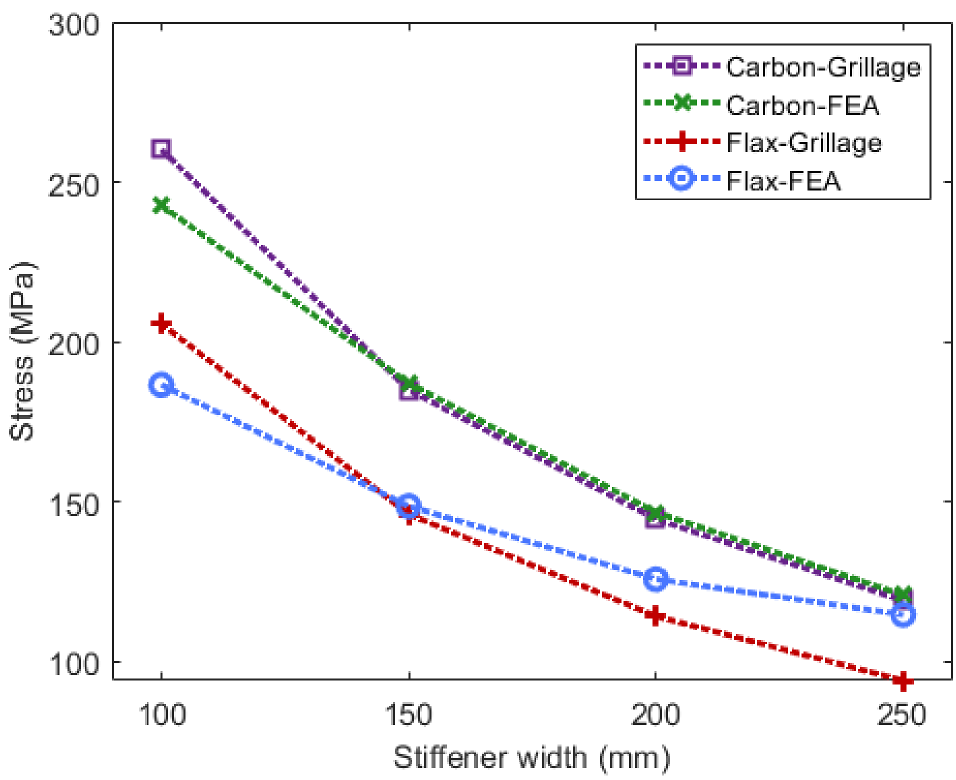


Figure 52: Comparison between bottom ply stresses obtained with FEA [153] and empirical model for varying stiffener widths

C.2 E-glass results

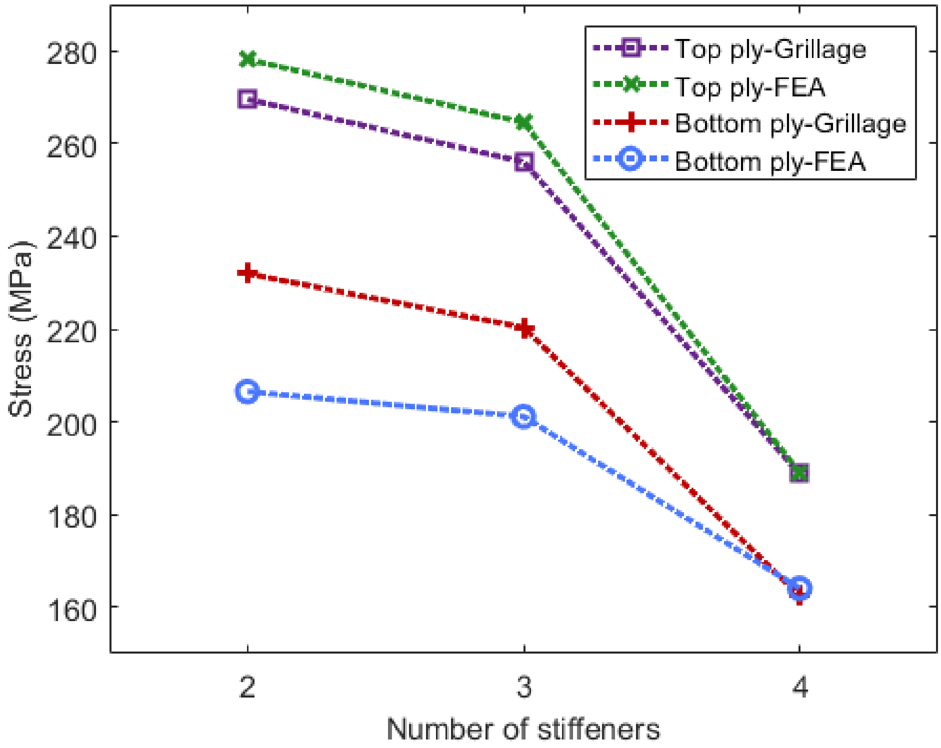


Figure 53: Comparison between stresses obtained with FEA [153] and empirical model for varying number of stiffeners on an E-glass structure

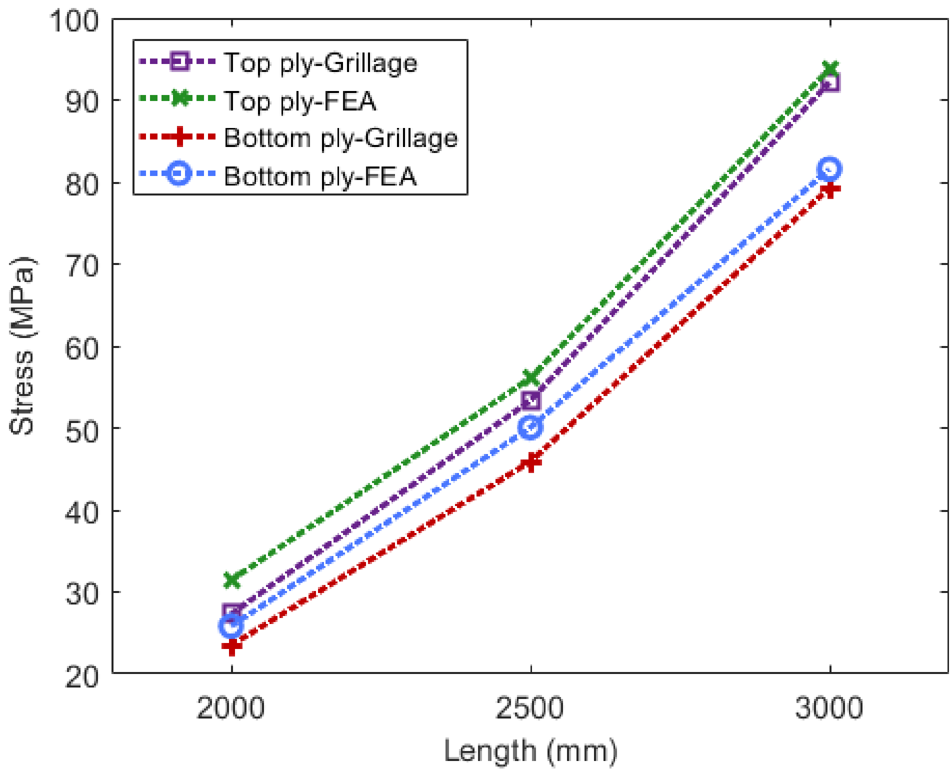


Figure 54: Comparison between stresses obtained with FEA [153] and empirical model for varying lengths on an E-glass structure

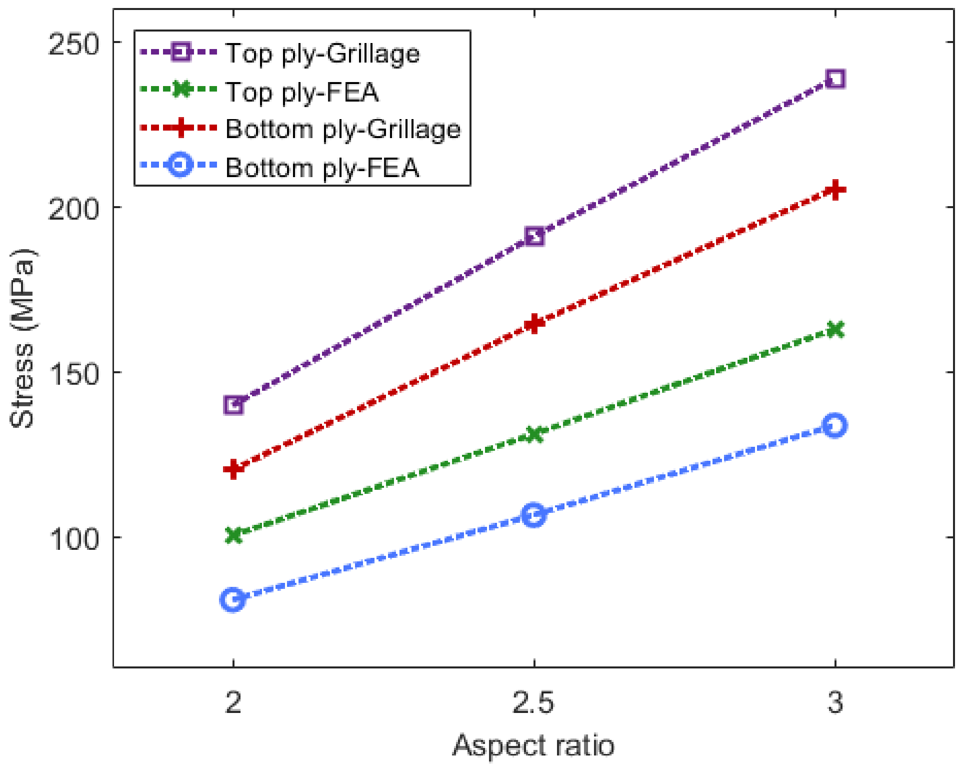


Figure 55: Comparison between stresses obtained with FEA [153] and empirical model for varying plate aspect ratio on an E-glass structure

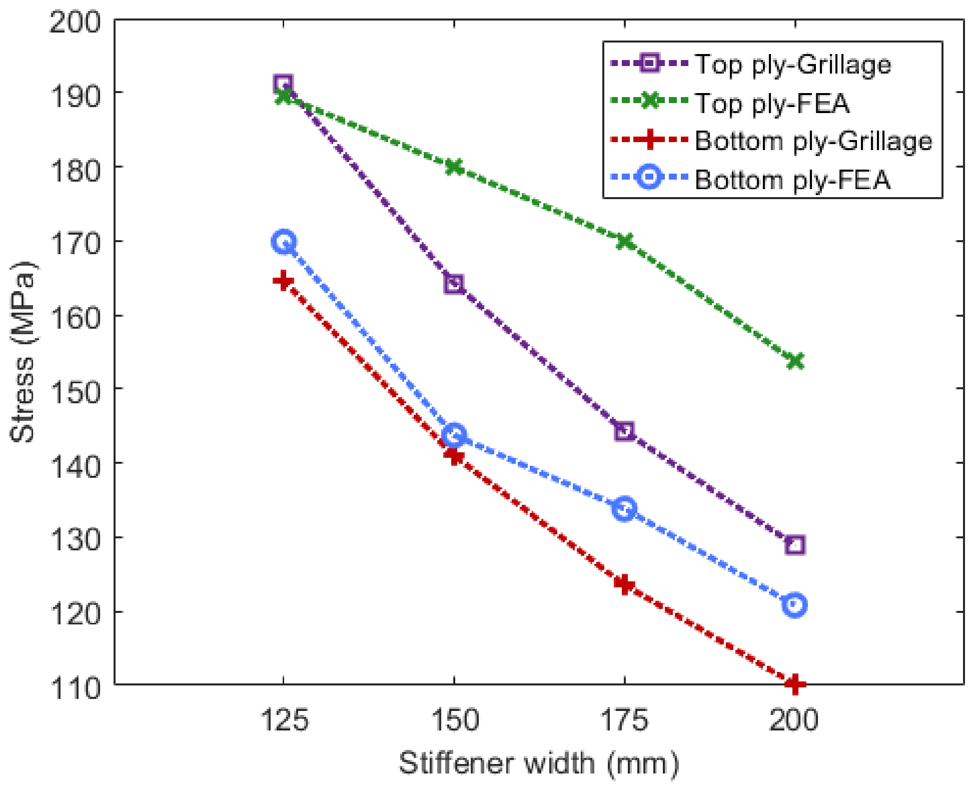


Figure 56: Comparison between stresses obtained with FEA [153] and empirical model for varying stiffener widths on an E-glass structure

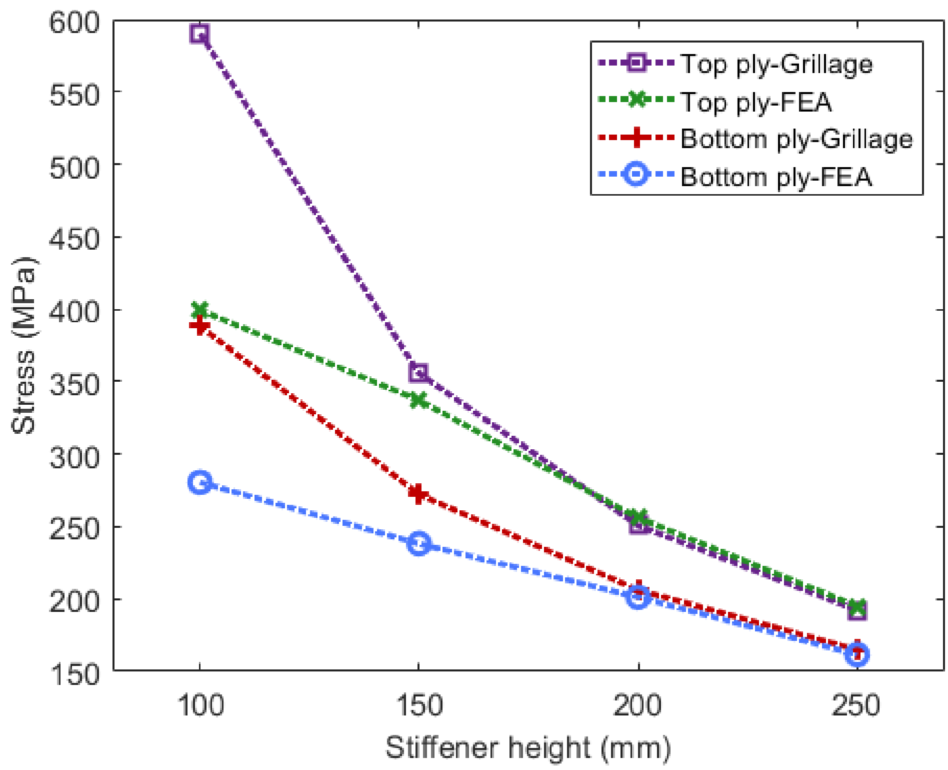


Figure 57: Comparison between stresses obtained with FEA [153] and empirical model for varying stiffener heights on an E-glass structure

C.3 Investigation into the accuracy of the analytical model for different parameters

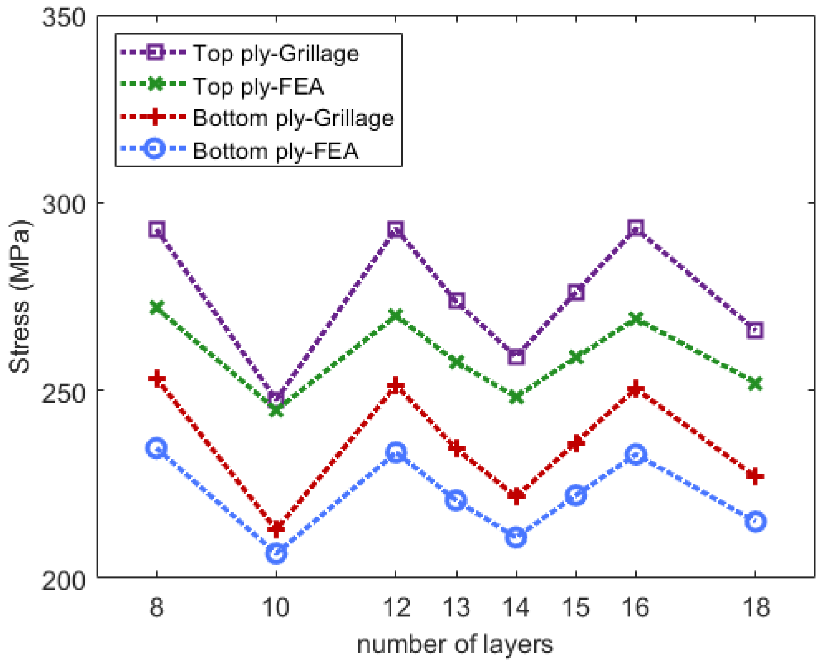


Figure 58: Comparison between stresses obtained with FEA [153] and empirical model for varying number of layers on a carbon structure

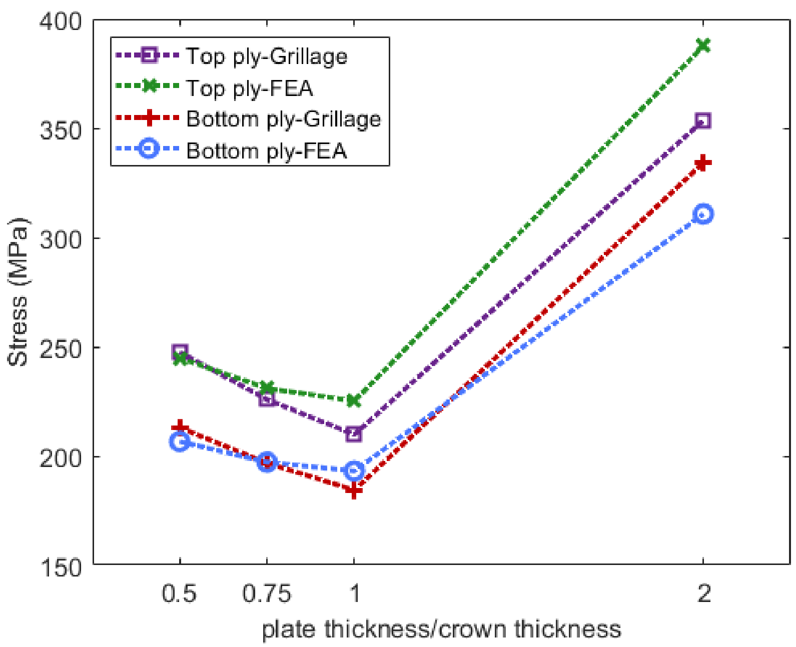


Figure 59: Comparison between stresses obtained with FEA [153] and empirical model for varying aspect ratio between the plate and crown thickness on a carbon structure

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