J. Build. Mater. Struct. (2017) 4: 22-30 *Review Article*
DOI : 10.34118/jbms.v4i1.28

Biocomposite Bridge

Malschaert D

The Netherlands, The Hague University of Applied Sciences, Civil Engineering, Antea Group B.V.
* Corresponding Author: david.malschaert@gmail.com

Received: 11-07-2017 Accepted: 11-08-2017

Focus and restrictions. This paper focuses on the structural application of the material biocomposite in bridge building. No experimental tests were executed during this research. This paper is the result of two underlying reports: Literature research and applied research. These underlying reports are not published and are in possession of the author of this paper, The Hague University of Applied Sciences and Antea Group B.V.

Abstract. Biocomposite materials are becoming more interesting to use in infrastructural projects due to their biodegradable, renewable, recyclable and sustainable properties. With a relatively low density, it is an interesting building material regarding a bridge deck. When designing with biocomposite the following factors are important to consider: material design, fibre treatment, coating and manufacturing technique. A PLA-Bamboo biocomposite was applied to an existing design of a bridge deck made out of synthetic composite. Due to its randomly oriented fibres and its equally designed lamellae, the cross section was considered homogeneous and the stresses were calculated according to 'Hooke's law'. The unity checks were performed according to 'CUR 96' with an own devised material factor of 5,69. This factor was calculated in this study for biocomposites with untreated fibres. The calculations showed that the original material (synthetic composite) was not directly replaceable by the PLA-Bamboo biocomposite. An alternative design of the deck (deck height of 1 meter and doubled thicknesses of the skins and web plates, 40- and 10 mm) showed better results. This design complied for the unity checks for strength.

Key words: Biocomposite, Biofibre, Bioresin, Biobridge, Biobased structural application.

1. Introduction

At this moment, most of the bridges in the world are made out of the traditional materials: wood, steel and reinforced concrete. Developments in 'composite bridges' started roughly two decades ago. This new material has proven itself to be a strong and eco-friendly material. Another interesting material, when sustainability is an important factor, is biocomposite. Currently, there is no bridge in the infrastructure which is made out of biocomposite (according to the definition set out in this paper, see below). This brings up the following question: Is biocomposite a good alternative material for structural application regarding a small bridge?

Antea Group B.V. is interested in new and innovative materials for infrastructure with the circular design taken into account. With these design considerations, knowledge is gained about what is possible now and perhaps in the future.

In this paper the following definition is used in terms of biocomposite: *a composite where all of the elements of the construction (fibres, resins and optional core materials) exist out of 100% organic material, apart from a coating and fibre treatment.*

2. Methodology

This research is based on a literature review. No experimental tests were done during this research as mentioned in 'Focus and restrictions'. The literature used for this research is mainly adapted from published papers. With the knowledge of this literature review, an applied research was carried out. In this applied research, biocomposite was applied on a design of a synthetic composite bridge deck. The outcome of the calculations showed if biocomposite can be used on this design and where the weak spots are in the material regarding this application.

3. Pros and Cons

Due to the use of biological materials, biocomposite is biodegradable, renewable, recyclable and sustainable. These are important benefits in regards to the growing environmental awareness (Satyanarayana, 2009; Mohanty, 2000). With an eye on the increasing scarcity of other materials (e.g. oil for synthetic composites), biocomposite can be an alternative material in the future. Next to this biocomposite has a relatively low density and low coefficient of thermal expansion which reduces loads on the structure (Kalia, 2009). The relatively low density makes biocomposite an interesting building material for bridge decks. This reduction in weight could result in less deep foundation piles or even a shallow foundation. Biocomposite also has a wide range of materials (Nijssen, 2015). This variety gives the designer the opportunity to find the materials for his/her biocomposite which are most favourable for the project (low costs on raw materials, high mechanic properties, etc.).

A great disadvantage of biocomposite is the poor adhesion between fibre and matrix. This poor adhesion results in low mechanical properties of the biocomposite (Kalia, 2009). Because biocomposite is, in general, a hydrophilic material, it absorbs water. This water absorption significantly reduces the mechanical properties (Singh, 2000). The mechanical properties can also differ in respect to the climate of origin, harvest method, weather- and soil conditions (Kalia, 2009).

4. Important factors

Multiple important factors when designing a bridge out of biocomposite are discussed in this chapter.

4.1. Material design

When considering the design of the biocomposite the fibre orientation and fibre volume fraction are important aspects which can have a great positive impact on the mechanical properties of the biocomposite. (Shalwan & Yousif, 2013). In comparison with woven or randomly oriented fibres, unidirectionally oriented fibres (bundles) have a significantly higher tensile strength and stiffness in the axial direction. In this case, the strength and stiffness in the radial direction are determined by the resin (Nijssen, 2015). When concerning a bridge deck, the forces in the transverse direction are significantly lower than in longitudinal direction. Another option is to use different orientations for each layer in the biocomposite. In this case, the strength and stiffness in the axial and radial direction of the laminate can be influenced.

The fibre volume fraction is the ratio of the fibre content of the biocomposite. This fibre volume fraction can also be modified to gain a stronger biocomposite. A higher fibre volume fraction results in general in an increase in mechanical properties of the biocomposite; therefore, a high fibre volume fraction can be favourable when the biocomposite has a structural application (Shalwan & Yousif, 2013).

4.2. Fibre treatment

The use of natural fibres in a composite, results in poor adhesion with the matrix. Fibre treatment can clean and modify the surface of the fibre and thus improve the surface roughness. This treatment results in better adhesion with the matrix and ultimately higher mechanical properties of the biocomposite (Kalia, 2009).

Previous research shows that the chemical treatments organosilane and alkali increase the mechanical properties of the biocomposite considerably. Thermal-, plasma- and corona treatment (physical treatments) also have a strong positive influence on the mechanical properties of tensile strength and Young's modulus (Faruk, 2012).

4.3. Coating

Biocomposite is, in general, a hydrophilic material. Due to this, biocomposite is likely to absorb moisture. This moisture absorbance decreases the mechanical properties significantly (Singh, 2000). The effect of moisture absorbance on the strengths of a jute fibre composite is shown in Figure 1.

A hydrophobic coating on the biocomposite could prevent the absorption of moisture. The coating needs to resist moisture, UV-light, corrosion and low- and high temperatures in order to be applicable on a bridge. Polyesters are widely used as a coating material because they often have these properties.

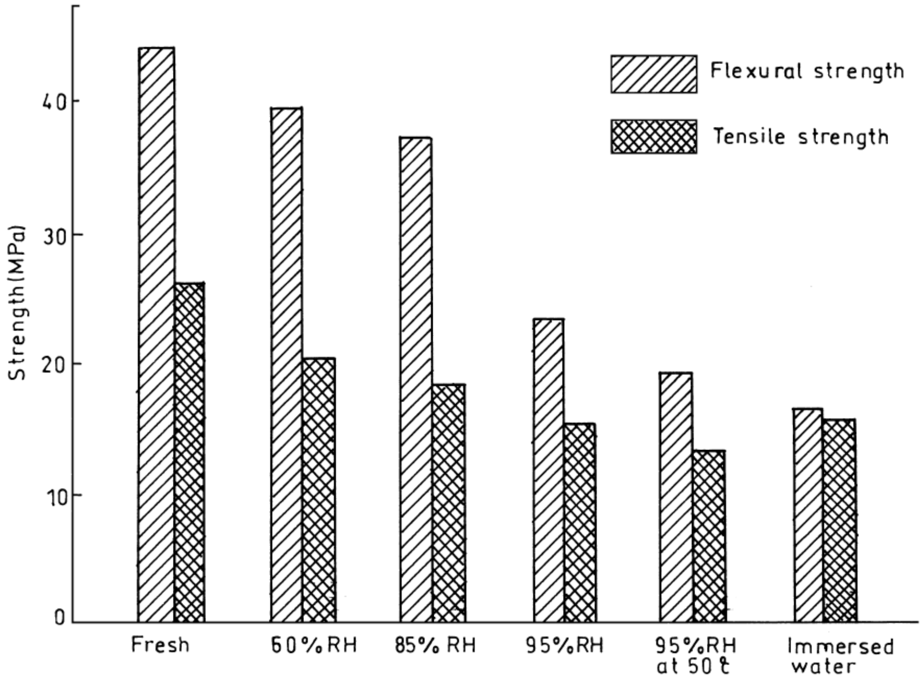

Fig 1. The effect of humid conditions on strengths of a jute composite (Singh, 2000).

4.4. Manufacturing techniques

Biocomposite can be manufactured using traditional composite manufacturing techniques, e.g. compression moulding, vacuum infusion, pultrusion and mixing (Faruk, 2012). Of these techniques mixing has a low quality as result, contrary to the others mentioned (Nijssen, 2015).

Vacuum injection or compression moulding is best when the bridge consists of a small number of parts. Figure 2 illustrates the process of vacuum infusion. Pultrusion can be used to make piles for deep foundation or structural profiles. In the latter case, the structure is constructed out of many parts which increase building time.

When a core material is used (in the case of a sandwich biocomposite) wet lay-up, prepreg lay-up or the adhesive bonding method can be used (Karlsson & Aström, 1996).

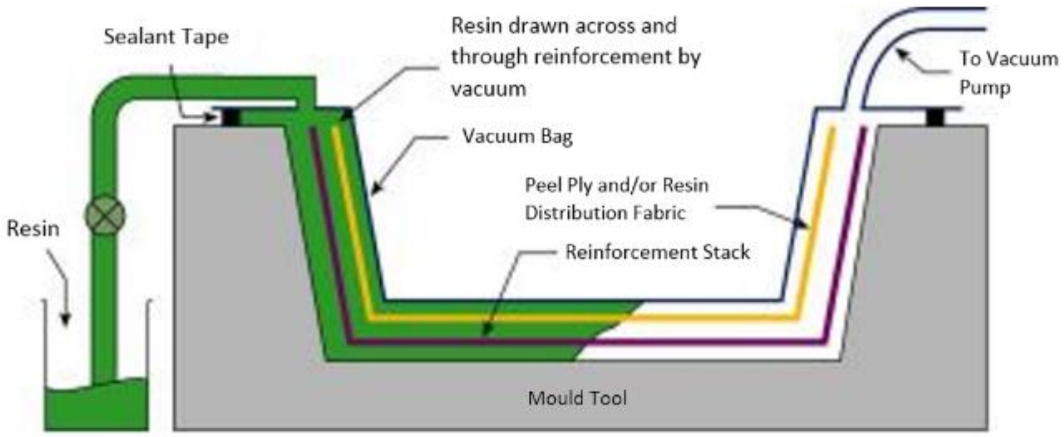

Fig 2. Vacuum infusion proces (Gent, 2014).

5. Bridge deck design

To test the structural application of the biocomposite material, it was applied to an existing bridge deck design. This design was originally made out of glass fibre reinforced polyester resin (synthetic composite).

5.1. Geometry

The deck is made out of a sandwich structure with 20 mm thick skins. The deck has a length of 16 meters and has 5 mm thick (centre distance 200 mm) web plates in both longitudinal- and transverse direction. The cross section of the deck is illustrated in Figure 3.

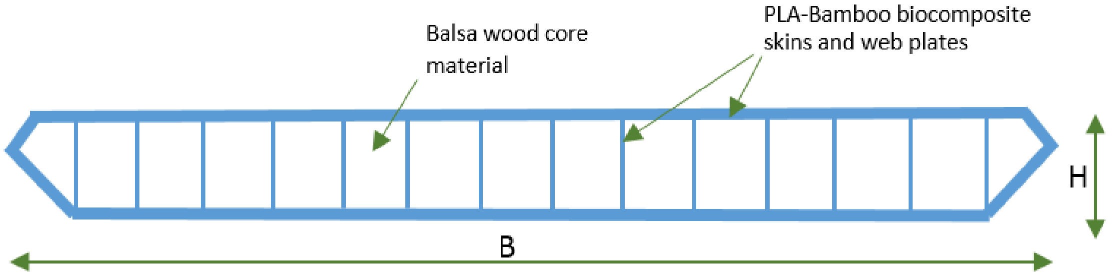

Fig 3. Cross section deck. Where: B=4500mm, H=460mm.

5.2. Materials

Extensive research was done on the mechanical properties of different biocomposites. There was only one biocomposite to apply to this design. This biocomposite exists out of a PLA resin with bamboo fibres. The fibres are untreated and the fibre volume fraction has a value of 38% (fibre weight fraction=30%). The properties, except the shear strength and the interlaminar shear strength (ILSS), were extracted from 'CES Edupack 2016, sheet: PLA(30% natural fiber)'. The shear strength was calculated according to 'Von Mises' theory ($\tau_{max}=\sigma_Y/\sqrt{3}$) (Anderson, 2005). The ILSS of a PLA-Bamboo biocomposite or any other biocomposite, could not be adopted from the available literature. This value was adapted from a synthetic composite (glass fibre reinforced polyester), knowing that the actual value can be much lower. An assumption could not be made for this value due to the missing of research in this area. This makes the calculations in this research incomplete. Table 1**Erreur ! Source du renvoi introuvable.** presents the used properties in this study of a PLA-Bamboo biocomposite.

Research has shown that the adhesion between core material and skins is poor. The core material is therefore not included in the calculations. The function of the core material is only practical (mould in manufacturing). Balsa wood can be used as core material. This and the PLA-Bamboo biocomposite is shown in Figure 3.

Table 1. Properties PLA-Bamboo biocomposite.

Property	Value	Unit
Fibre orientation	Random	[-]
Fibre volume fraction	38.0	[%]
Density	1.30	[g/cm^3]
Tensile strength	57.0	[MPa]
Compressive strength	88.9	[MPa]
Shear strength	32.9	[MPa]
Interlaminar shear strength	20.0	[MPa]
Young's modulus	5.23	[GPa]
Shear modulus	1.89	[GPa]
Poisson's ratio	0.39	[-]
Glass temperature	53.0	[°C]

5.3. Calculation method

It has been proven that the traditional 'rules of mixtures' (ROM) are not directly applicable on biocomposite (Facca, Kortschot, & Yan, 2006) (Facca, Kortschot, & Yan, 2007). The calculated values differ significantly from the experimental values. Because of this, the use of experiments for determining the mechanical properties of a biocomposite is inevitable. The next problem in designing with biocomposite is to calculate the occurring stresses. Three methods where considered.

5.3.1. Classical laminate theory

The 'classical laminate theory' (CLT) is a theory that calculates the elongations and stresses in lamellae individual. The fibre orientations may differ from one another. For the use of the CLT, the thickness in the cross section must remain the same. This is not the case in the design of the deck (Figure 3). In addition, the shear forces are not included in the CLT (Nijssen, 2015). Due to these reasons, the classical laminate theory cannot be used for this research.

5.3.2. Inhomogeneous cross section

Because the cross section of biocomposite exists out of two different materials with different strength and stiffness properties, it can be considered an inhomogeneous cross section. The adhesion between fibre and matrix must be perfect for this method. This is because the strength and stiffness of the materials are taken into account separately. The interaction between fibre and matrix is not included. The adhesion between fibre and matrix is very unpredictable for biocomposites (Faruk, 2012). Because of this unpredictability, the method based on a inhomogeneous cross section is not a good method to calculate the stresses in a biocomposite.

5.3.3. Homogeneous cross section

In this method it is assumed that the properties in the entire cross section of the structure are equal. In order to ensure this, the lamellae must be equal to each other as well. This includes, fibre volume fraction and fibre orientation. When a material has a homogeneous cross section, 'Hooke's law' can be applied. In order to calculate according to Hooke's law, a linear relation is needed in the stress-strain curve of the material (Welleman, 2011). Studies have proven that the stress-strain curve of a biocomposite increases linearly to a maximum fibre volume fraction of 50% (Ochi, 2007; Akil, 2011; Shin, 1989).

A biocomposite is manufactured in lamellae, due to this the adhesion between these lamellae needs to be strong enough. These lamellae are not included in the design of a homogeneous cross section but the adhesion will be checked according to CUR 96 (see Table 4, interlaminar shear stress). For these reasons, the method based on a homogeneous cross section is a good method to calculate the stresses in a biocomposite. This method was used for this study.

5.3.4. Standards

Several standards where used for calculating the structural safety of the deck. The 'Eurocodes' where used for the design of the loads and the safety factors. The unity checks where performed according to 'CUR 96'. This is a recommendation (not a standard) for designing structures with glass fibre reinforced synthetic resins (CUR, 2003). The reason that CUR 96 was used is because of the absence of a standard (or recommendation) on biocomposite and the absence of a standard on synthetic composite.

For this study, the material factor was adapted for the use of CUR 96. This factor was distracted from differences between calculated values of the tensile strength and young's modulus according to the ROM and the experimental values.

The highest calculated factor in Table 2 has a value of 5.69 and counts for all biocomposites with untreated fibres which are produced according to the following methods: vacuum injection, compression moulding, prepregs and pultrusion. Calculating the inverse of this factor gives a 0.18 strength correction factor.

Table 2. Determination material factor (Graupner, 2009; Ochi, 2007).

Property	Measured	Calculated	Unit	Factor
Tensile strength	41	224	MPa	5.46
Tensile strength	58	330	MPa	5.69
Tensile strength	53	241	MPa	4.55
Young's modulus	4242	4740	MPa	1.12
Young's modulus	8064	5990	MPa	0.74
Young's modulus	7139	6369	MPa	0.89
Tensile strength	131	178	MPa	1.36
Tensile strength	211	297	MPa	1.41

6. Results

6.1. Stresses and unity checks

Table 3 presents the occurring stresses in the deck by position (see Figure 4).

Table 3. Stresses in deck.

Position	$\sigma_{N,max}$ [MPa]	$\sigma_{M,1,max}$ [MPa]	$\sigma_{M,2,max}$ [MPa]	$\tau_{v,max}$ [MPa]	$\tau_{w,max}$ [MPa]
1	0.11	30.39	0.70	0.00	0.12
2	0.11	0.00	0.73	7.28	0.12

Where:

σ_N = Stress as a result of axial force
$\sigma_{M,1}$ = Stress as a result of a moment in axial direction
$\sigma_{M,2}$ = Stress as a result of a moment in radial direction
τ_V = Stress as a result of shear force
τ_W = Stress as a result of torsion

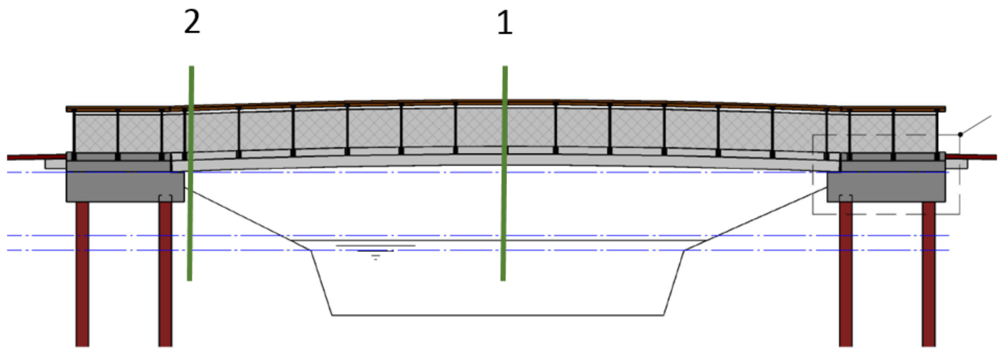

Fig 4. Positions in deck (heester, 2015).

The stresses in Table 4 must be checked according to CUR 96 (CUR, 2003).

Table 4. Unity checks (CUR, 2003).

UC	Position	
[1]	Tensile stress in fibre direction	1
[2]	Compression stress in fibre direction	1
[3]	Tensile stress perpendicular to fibre direction	2
[4]	Compression stress perpendicular to fibre direction	2
[5]	Shear stress in cross section	2
[6]	Interlaminar shear stress	2
[7]	Combined stress (tensile)	1
[8]	Combined stress (compression)	1

Table 5 shows the calculated UC-values of each unity check. Only the maximum UC-values are given for each unity check.

Table 5. Unity checks by design.

	H	t_1	t_2	Unity check							
	[mm]	**[mm]**	**[mm]**	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**
Original design	460	20	5	4.23	2.71	0.10	0.06	1.75	2.88	17.92	7.37
Alternative design	1000	40	10	0.89	0.57	0.02	0.01	0.43	0.70	0.79	0.33

Due to the randomly oriented fibres the stresses are checked in longitudinal (1 and 2) and transverse (3 and 4) direction of the deck. With a highest calculated unity check of 17.92, the original design of the bridge deck does not comply when a PLA-Bamboo biocomposite is used as material. The values of the unity checks can decrease when a different biocomposite is used or when fibre treatment is applied. This increases the mechanical properties and gives an opportunity to apply a lower material factor.

6.2. Alternative design

An adjustment on the design of the cross section of the deck can decrease the occurring stresses. For this study the thickness of the skins and web plates where doubled (40- and 10 mm) and the height of the deck was increased up to 1.0 meters (+ 117%, see Table 5 and Figure 5). The design of the biocomposite remained unchanged due to the lack of information about the properties of biocomposites. The highest unity check of 0.89 was calculated. This shows that this biocomposite can be applied, but extreme adjustments must be done to the design. A different biocomposite may show better mechanical properties and results in which no (extreme) adjustment to the design of the cross section are necessary.

7. Conclusions

Several conclusions have been made during this research on the structural application of biocomposite on a bridge.

1. In comparison with synthetic composite, biocomposite has lower mechanical properties (tensile strength biocomposite: ca. 60 MPa, synthetic composite: ca. 200 MPa). The unity checks in the deck complied for strength with an adjustment, when the synthetic composite was replaced by a PLA-Bamboo biocomposite. The geometry of the deck (height and thicknesses) needed to be doubled (height + 117%, thicknesses + 100%) in the reference design.
2. Biocomposite has a linear stress-strain curve up to a maximum fibre volume fraction of 50%.
3. With a safety factor of 5.69, CUR 96 can be used as recommendation for designing with biocomposites with untreated fibres.
4. In comparison with other building materials (steel, concrete, synthetic composite etc.), biocomposite is eco-friendlier, biodegradable and it does not deplete other materials like iron and oil (in synthetic composite). The relatively low density (ca. 1.3 g/cm^3, steel: ca. 7.9 g/cm^3) makes biocomposite an interesting building material for bridge decks. Due to these benefits, biocomposite can be a good alternative building material.
5. The design of the biocomposite (fibre orientation and fibre volume fraction) and fibre treatment are important factors regarding the mechanical properties of the biocomposite.

Biocomposite can be manufactured using traditional composite manufacturing techniques like vacuum infusion, compression moulding and pultrusion.

8. Recommendations

There are four recommendations made based on mechanical properties, material design, calculation method and time-dependent properties:

1. There is still too little knowledge about the properties of biocomposites. Most research currently done is about the tensile strength and Young's modulus of biocomposite. When designing a bridge, properties such as compressive strength, (interlaminar) shear strength, shear modulus and poisson's ratio are also important. More research on these properties is needed. With more research and thus knowledge about the mechanical properties of the biocomposite, it can also be possible to reduce the material factor calculated in this research.
2. The fibres flax, nettle, hemp, abaca and silk with a PLA resin can be a biocomposite with high mechanical properties. An organosilane-, alkali-, thermal-, corona- or plasma fibre treatment show good adhesion between fibre and matrix and thus results into higher mechanical properties of the biocomposite. The mechanical properties of these combinations must be studied.
3. More research on calculation the occurring stresses in biocomposites is needed. The 'Classical Laminate Theory' can be applied but has its limitations (shear strength and thickness in the cross section). A method based on a homogeneous cross section can only be used when the properties for each lamellae are equal to one another.

A bridge is mostly designed for numerous years. Because of this, the time-dependent properties are important. More research is needed to the creep- and fatigue behaviour of biocomposite. Also the effect of time on the Young's modulus must be studied.

9. References

Akil, H., Omar, M. F., Mazuki, A. A. M., Safiee, S. Z. A. M., Ishak, Z. M., & Bakar, A. A. (2011). Kenaf fiber reinforced composites: A review. Materials & Design, 32(8), 4107-4121.

Anderson, T. (2005). Fracture Mechanics - Fundamentals and Applications. Boca Raton: Taylor & Francis Group.

CUR. (2003). Aanbeveling 96, Vezelversterkte Kunststoffen in Civiele Draagconstructies. CUR.

Facca, A. G., Kortschot, M. T., & Yan, N. (2006). Predicting the elastic modulus of natural fibre reinforced thermoplastics. Composites Part A: Applied Science and Manufacturing, 37(10), 1660-1671.

Facca, A. G., Kortschot, M. T., & Yan, N. (2007). Predicting the tensile strength of natural fibre reinforced thermoplastics. Composites Science and Technology, 67(11), 2454-2466.

Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. Progress in polymer science, 37(11), 1552-1596.

Gent, U. O. (2014). Organizing your composite workshop. Retrieved from University of Gent: http://www.composites.ugent.be/home_made_composites/organizing_your_composite_workshop.html

Graupner, N., Herrmann, A. S., & Müssig, J. (2009). Natural and man-made cellulose fibre-reinforced poly (lactic acid)(PLA) composites: An overview about mechanical characteristics and application areas. Composites Part A: Applied Science and Manufacturing, 40(6), 810-821.

Heester, B. (2015). Definitief ontwerp. Brug over de Kleine Dommel te Eindhoven. Antea Group.

Kalia, S., Kaith, B. S., & Kaur, I. (2009). Pretreatments of natural fibers and their application as reinforcing material in polymer composites—a review. Polymer Engineering & Science, 49(7), 1253-1272.

Mohanty, A. K., Misra, M., & Hinrichsen, G. (2000). Biofibers, biodegradable polymers and biocomposites: an overview. Macromolecular materials and Engineering, 276(1), 1-24.

Nijssen, R. (2015). Composieten Basiskennis. Vereniging kunstofcomposieten Nederland.

Ochi, S. (2008). Mechanical properties of kenaf fibers and kenaf/PLA composites. Mechanics of materials, 40(4), 446-452.

Satyanarayana, K. G., Arizaga, G. G., & Wypych, F. (2009). Biodegradable composites based on lignocellulosic fibers—An overview. Progress in polymer science, 34(9), 982-1021.

Shalwan, A., & Yousif, B. F. (2013). In state of art: mechanical and tribological behaviour of polymeric composites based on natural fibres. Materials & Design, 48, 14-24.

Shin, F. G., Xian, X. J., Zheng, W. P., & Yipp, M. W. (1989). Analyses of the mechanical properties and microstructure of bamboo-epoxy composites. Journal of Materials Science, 24(10), 3483-3490.

Singh, B., Gupta, M., & Verma, A. (2000). The durability of jute fibre-reinforced phenolic composites. Composites Science and Technology, 60(4), 581-589.

Welleman, J., Dolfing, A., & Hartman, J. (2011). Basisboek Toegepaste Mechanica. Amersfoort: Thieme Meulenhoff.