Design characteristics, codes and standards of natural fibre composites

20

M.A. Alam[1], *S.M. Sapuan*[2], *M.R. Mansor*[3]
[1]Universiti Tenaga Nasional, Kajang, Selangor, Malaysia; [2]Universiti Putra Malaysia, Serdang, Selangor, Malaysia; [3]Universiti Teknikal Malaysia Melaka, Durian Tunggal, Malacca, Malaysia

20.1 Introduction

Nowadays, there is an emerging demand to upgrade the existing infrastructures all over the world. These are due to upgrade of design codes, mistakes in design calculation, improper detailing of shear reinforcement, construction errors or poor construction practices, insufficient shear reinforcement or reduction in steel area due to corrosion in the service environment. Since replacement for such deficient structures requires a huge amount of money and time, strengthening is the most acceptable way to rehabilitate those structures to increase their load carrying capacity and extend their service life.

Another drive towards upgrading the building and construction infrastructure is to improve the existing sustainability performances. Du Plessis (2007) stated that sustainable construction relates to the development and proper management of a healthy built environment with efficient use of resources based on ecological principles. Based on the LafargeHolcim (2016) Foundation report, as the total urban world population growth is nearing one million inhabitants per week, sustainable performance in the construction industry needs to be quickly addressed to cater for the increasing demand. Among the areas highlighted in a similar report for a greater sustainability effort in the construction industry included the design and management of buildings, material performance, construction technology and processes, energy and resource efficiency in building and operation and maintenance.

Apart from increasing demand due to the boost in the world population, the building and construction industry also plays a major stake in the total world energy usage. It is reported that the building lifecycle in the United Kingdom, which covers construction, operation and demolition consumed approximately 40% of the nation total energy use, which in consequence causes high emission pollution (Alwan et al., 2016). Elsewhere, the construction industry in China is reported to consume nearly 793.74 million tons of coal in 2007 alone, which contributes to approximately 29.6% of the nation's total energy consumption. The value significantly showed that the construction industry is an energy-intensive industry, which plays a vital role towards the need for a more efficient and sustainable use of energy (Hong et al., 2016).

Advanced High Strength Natural Fibre Composites in Construction. http://dx.doi.org/10.1016/B978-0-08-100411-1.00020-0

In conjunction to the material performance area, traditional engineering materials such as concrete and steel are often applied in the building and construction industry due to good mechanical properties and high reliability performances. However, due to the increasing environmental awareness by consumers, new alternative materials, which have higher recyclability, biodegradability and renewability impacts are introduced to substitute, either partially or entirely, the conventional materials. The use of steel as the reinforcement agent for structural applications is also being reduced in order to cater the depleting raw material source and high energy consumption during product manufacturing and waste management processes, which affect the stability of the raw material cost in the market and consequently impact the overall building and construction cost (Yahya et al., 2016).

Based on the aforementioned scenarios, many efforts have been made to increase the sustainability performance of current building and construction operations. One of the efforts is in term design of new construction structures using renewable and recyclable raw materials as a substitution to the current conventional construction materials. Within the pool of alternative materials being explored, natural fibre composites (NFCs) are among the candidate materials, which have sparked a high potential for many construction applications such as for the design of beams, door panels, decking, railing and window frames. Several notable advantages of NFCs for construction application is low raw material cost, low energy intensity requirement during manufacturing and high environmental friendly characteristics (such as renewable, recyclable and biodegradable) (Dittenber and GangaRao, 2012). In addition, the use of NFCs also offers additional low health side effects during use as compared to glass fibre, which is often linked with skin irritations and respiratory complications (Ardente et al., 2008).

Moreover the push towards improving the sustainability performance of buildings is also in action through the application of environmental conscious design methods. This can be observed through the introduction of many design guidelines and assessment methodologies for green buildings, such as the United States Leadership in Energy and Environmental Design (LEED) method, Canadian Building and Environmental Performance Assessment Criteria and Japanese Comprehensive Assessment System for Building Environmental Efficiency (Franzoni, 2011). In addition, new design methodologies, which resulted in the integration of conventional design guidelines and assessment methodologies, were also formed to further enhance the design process of green buildings throughout the planning, analysis and execution phases. Among the examples is the development of integrated Building Information Modeling (BIM) and LEED framework, which enabled design assistance and certification management processes to be performed concurrently (Wu and Issa, 2010). Furthermore, enhancement of the BIM-LEED method was also proposed through the integration of the cost estimation function to the existing design model, which is reportedly able to provide a more holistic approach in the conceptual design of the green building to designers and clients. The cost estimation function allowed the prediction of cost to obtain the green building certification, in addition to the information of the planned building rating performance prior to the actual construction process (Jalaei and Jrade, 2015).

Thus in this chapter, focus is given towards realizing a higher sustainability performance of current building and construction industry practices through design practices. Among the topics included are an overview of NFC design practices for sustainable construction and a new design model for shear strengthening of reinforced concrete (RC) beams using NFC. In addition, to demonstrate the applicability of the new proposed design model, a case study on the design of kenaf fibre reinforced polymer composites (KFRP) is also included at the end of this chapter for the shear strengthening of RC beams.

20.2 Overview of natural fibre composite applications for sustainable construction

The application of NFCs for sustainable construction was dated since 4000 BC by the Egyptian civilization through the use of straw as a reinforcement agent in clay bricks for housing development purposes. The combination of straw and clay to form the brick demonstrates the early application of composite materials made from natural resources, which was reportedly able to lower the building material cost as well as increase the structural performance of the material (Mansour et al., 2007). The use of natural fibre for mud brick building materials such as straw and coconut coir were also reportedly able to increase the initial conventional mud brick compressive strength and thermal insulation properties, as well as reduce the conventional mud brick weight (Khedari et al., 2005; Binici et al., 2005).

A good thermal insulation property using NFCs was also reported by Khedari et al. (2004). In their study, three types of NFCs were applied to produce low thermal conductivity particleboard products using durian peel fibres, coconut coir fibres and hybrid durian peel/coconut fibres. The feasibility of using the NFC materials was able to conserve energy usage when applied as insulating materials for wall and ceiling sections inside the building. Furthermore, they also point out that the NFC particleboards can also be used as furniture material, which increases the diversity of application of the NFCs towards higher usage of agricultural waste. Elsewhere, Binici et al. (2014) reported similar thermal insulation building material applications using NFCs. In their report, two types of natural fibres were used, which are sunflower stalks and cotton textile waste, to form the NFC materials, while epoxy resin was applied as the matrix material. Both NFC insulation materials showed acceptable mechanical and thermal performance, which successfully satisfied the Turkish TS 805 EN 601 insulation material application standard. The NFC developed also reportedly contributed to reducing agrowaste scenarios for the country.

Besides that, feasibility on the application of NFCs for building and residential structural flooring materials was also investigated. Burgueño et al. (2004) reported the production of cellular beams and panels made from hemp/unsaturated polyester composites and flex/unsaturated polyester composites. Their study revealed that both NFC materials showed equal performance in terms of allowable pressure load for flooring applications compared to commercial grade flooring materials. Moreover, Burgueño et al. (2005), in another report, showed that the use of hybrid NFCs was also able to further enhance the structural properties of cellular plate products for housing panel applications. The hybrid NFC cellular plate was fabricated from short hemp fibres as sandwich plate core material, while jute fibres in a mat form as the outer and inner skin of the sandwich plate structure. Mechanical characterization results showed that the hybrid natural fibre reinforced unsaturated polyester composite cellular plate has a higher modulus of elasticity value as compared to E-glass fibre reinforced unsaturated polyester composites. In addition to that, Li and Xian (2012) also reported on the application of unidirectional hemp reinforced epoxy composites for civil structural beam products. In their report, an NFC beam prepared using a prior mercerization process to the hemp fibres was able to increase the flexural strength and flexural modulus of the composite materials.

Among the many applications of NFC for building and construction, based on a literature review, concrete is the type of product most heavily associated with NFC. In general, concrete is the most applied building material in the construction industry due to its superior mechanical and physical properties, which enable it to handle very high compressive loads, while at the same time offer advantages such as great flexibility to be manufactured in many geometrical shapes, incombustible, affordable and highly available source of material (Aprianti et al., 2015). Concrete is produced through the combination of three main constituents, which are cement, water and aggregates (in both fine and coarse forms). Despite the advantages, conventional concrete materials also have significant drawbacks in terms of negative environmental impacts, such as high carbon dioxide (CO_2) emission release during the manufacturing stage and high energy consumption (Mo et al., 2016). Therefore in order to cater the limitation, many studies have been made to incorporate natural fibres as a filler material to the cement, a replacement for the aggregates and as a reinforcement to the concrete. The role of natural fibres as supplementary cementitious materials is to reduce the Portland cement volume in forming the concrete, which helps to reduce the overall concrete cost and decrease CO_2 emissions. On the other hand, the use of natural fibres also improved the ductility, toughness and impact resistance of the concrete when used as reinforcement materials through reducing the brittleness of the cement (Onuaguluchi and Banthia, 2016). Various sources of natural fibres are investigated as alternative materials in concrete formulation, which can be grouped into two categories: those from farming or agriculture waste and those from commodity crops. Examples of the agriculture waste type of natural fibres, which have been applied to formulate green concretes and other building materials, are coconut coir, rice husk, palm oil fuel ash, bagasse, wood chips, bamboo leaf ash, banana, wheat straw, barley straw and sisal; while natural fibre resources from commodity crops used in similar green concrete applications are kenaf, jute and hemp plants (Pacheco-Torgal and Jalali, 2011; Senaratne et al., 2016; Yan et al., 2016).

As shown in earlier examples, there are many utilizations of NFCs in sustainable construction applications. It should be noted that the process of converting the raw material into a successful product in not a trivial task and involves various stages along the whole product development process. Based on the Pugh Total Design method, the development process of any product can be summarized into six main stages, which are market analysis, development of design requirements in the form of product design specifications, conceptual design, detail design, product manufacturing and finally sales of the finished product (Pugh, 1991). During the conceptual design stage of the product, the material selection process is performed to define the appropriate type of material which can be used to construct the product. In a sustainable construction point of view, decision making on the best type of material need to be systematically and scientifically conducted for specific building and applications, so the final candidate material will be able to deliver the expected performance in term of product functionality and safety, while at the same time providing the best environmental performance in terms of lower greenhouse gas emissions and energy usage (González and Navarro, 2006).

The direct linkage between material selection and sustainable construction can be observed through the inclusion of material selection activity as one of the six key areas involved in the LEED green building rating and certification system (Gurgun et al., 2015). The use of renewable, recyclable and biodegradable raw material resources such as NFCs can provide a higher score in the green building assessment process and finally contribute to a higher total rating for the desired building. The positive impact in the green building certification process is also one of the driving factors why designers and building owners are increasing the presence of NFC materials in the construction industry (Castro-Lacouture et al., 2009).

Material selection involves the consideration of many criteria from various stakeholders and the presence of multiple material alternatives for an intended product, which need to be considered by the decision makers. Kibert (2008) stated that among the challenges faced in the sustainable material selection process are a high variety of products and materials which need to be evaluated individually and assembled as building components, varying assessment of product parameters and inadequate information of the manufacturing process. In another report, Akadiri (2015) revealed that other challenges in material selection for construction also included factors such as perception of extra costs being incurred by utilizing the green materials, lack of material information for the selection process and perception of extra time incurred by using green materials. On the other hand, the assessment of selection criteria also involved many considerations. Akadiri and Olomolaiye (2012) stated that among the selection consideration in sustainable material selection in a building project are utilization of less resources, the use of renewable and recyclable resources, and materials with the lowest environmental impact throughout the whole product life cycle.

Despite the process complexity, there are several methods to assists designers in performing the material selection process in sustainable building and construction applications. Govindan et al. (2016) demonstrated the use of a hybrid multicriteria decision making (MCDM) method in performing brick material selection for the UAE construction industry. The hybrid MCDM method is comprised of the Decision Making Trial and Evaluation Laboratory method, the Analytic Network Process method and the Technique for Order Preference by Similarity to an Ideal Solution method to analyse and rank the best candidate material among the given alternatives for the desired application. Besides that, a new approach in the building material selection process involving economic, social and environmental aspects was also applied using the Analytic Hierarchy Process (AHP) method by Cuadrado et al. (2016). The use of the AHP tool in the new Integrated Value Model for Sustainable Assessment method proposed in their study also included additional sustainability criteria such as employee safety, product functionality and corporate image. Furthermore, the Simple Additive Weighing and AHP methods were also applied for the material selection for dwelling house construction. Three main selection criteria were included in the analyses, which are cost, environmental impacts and qualitative aspects (such as project duration) (Medineckiene et al., 2010). Apart from that, a new model of decision making framework was also developed to assist decision makers in similar material selection process. Zavadskas et al. (2005) developed a web-based decision support system for construction material selection, which incorporated various selection criteria such as price, product geometry, availability, supplier information and delivery methods. Among the reported advantages of the decision support system is the integration of a search mode for information as well as a web-based selection tool.

The outcome of the material process also gave a direct impact to the end-of-life stage of the product. Various disposal options during the product's end-of-life stage will contribute to varying environmental performance such as emission type and amount generated, as well as the energy use during the disposal process (Dodoo et al., 2009; Silvestre et al., 2014). For example, the selection of wood as the construction material in the conceptual design stage will open for two disposal options for the wood-based product, which are either incinerated or land filled. In consequence, the disposal option made for the product, if the type of materials used are not carefully taken into consideration, will give effect to either positive or balanced greenhouse gas performance to the environment (Ortiz et al., 2009).

20.3 Design of natural fibre composites for shear strengthening of reinforced concrete beams

In general, reinforced concrete (RC) beams fail in flexure or shear. In order to take full advantage of the potential ductility of the RC members, it is desirable to ensure the flexural failure rather than shear since shear failure is sudden, brittle and catastrophic in nature, which occurs with no advance warning of distress. Thus shear strengthening of an RC beam is crucial to increase the shear capacity of the shear-deficient beams. There have been a series of studies in the past for the shear strengthening of RC beams using externally bonded carbon fibre reinforced polymer (CFRP) laminates (Alam et al., 2016; Alsayed and Siddiqui, 2013; Bae et al., 2013; Barros and Dias, 2006; Belarbi and Acun, 2013; Costa and Barros, 2010; Dias and Barros, 2011; Dong et al., 2013; Jumaat and Alam, 2009; Koutas and Triantafillou, 2013). However, CFRP laminates were found to be less effective for shear as compared to flexure in strengthening of RC structures. As per the ACI design guideline, the maximum CFRP strain of 0.004 could be used in the design for the shear strengthening of an RC beam, which is 30% of its ultimate capacity. However, the actual design strain of CFRP laminate could be lower, as compared to 0.004, to avoid premature debonding failure based on the proposed guideline of ACI (2002).

It is noted that the effective strain of CFRP laminate is found to be 0.0013, which is almost 10% of the ultimate strain of CFRP laminate. Alam et al. (2016) also investigated that the design strain of CFRP laminate could be used around 0.0017, which is almost 14% of the ultimate capacity of CFRP laminate to prevent the debonding of laminate. Thus the strengthening of a reinforced concrete beam for shear using CFRP laminate would not be the economical choice. Hence low strength NFC materials such as kenaf fibre reinforced polymer (KFRP) laminate could be used for shear strengthening of reinforced concrete beams.

Kenaf fibre has been used in a composite plate for nonstructural applications over the last decade (Elsaid et al., 2011; Rassmann, 2010; Shibata et al., 2006; Bernard et al., 2011; Rassmann et al., 2011; Huda et al., 2008; Ghani et al., 2012). Most of the research works were found to be on the development of a biodegradable kenaf fibre composite plate with low strength. In general, the tensile strength of kenaf fibre composite plates was found to be lower as compared to CFRP laminate. However, the position and amount of fibres in the composite plate would have a significant effect to enhance the tensile strength of the laminate. Recently, development of NFC plates for potential application in shear strengthening of an RC structure has been carried out by Alam et al. (2015a,b, 2016). Thus a systematic guideline to design an RC beam for shear strengthening using a KFRP plate is vital. The subsequent sections in this chapter will mainly focus on the design parameters of a KFRP plate for shear strengthening of an RC beam based on Euro Code-2 (EC2, 2004).

20.4 Proposed design model for shear strengthening of reinforced beam using kenaf fibre reinforced polymer laminate

In general, an externally bonded shear strengthened beam failed due to the debonding of laminate with lower strain as compared to yield strength of shear reinforcement (Alam et al., 2016). However, because of lower stiffness, the debonding strain of KFRP laminate could be higher as compared to yield strain of shear reinforcement. Thus the dimension of KFRP laminate for shear strengthening of a reinforced concrete beam could be obtained through the new proposed guideline as shown in the following section.

20.4.1 Design strain of kenaf fibre reinforced polymer laminate

The debonding strain of an externally bonded plate could be obtained based on the proposed guideline of Alam et al. (2015a), as shown in Eq. (20.1):

$$\varepsilon_{\mathrm{KFRP,debonding}} = \frac{(d-d')w_{\mathrm{KFRP}}F_{\mathrm{bu}}}{A_{\mathrm{KFRP}}E_{\mathrm{KFRP}}} = \frac{F_{\mathrm{bu}}(d-d')}{t_{\mathrm{KFRP}}E_{\mathrm{KFRP}}} \tag{20.1}$$

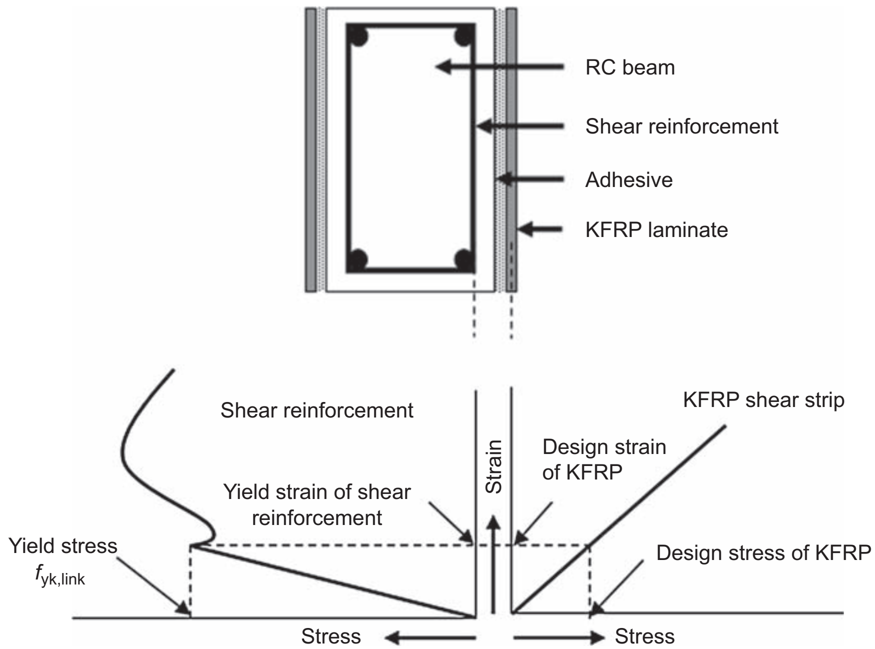

Figure 20.1 Strain compatibility between shear link and kenaf fibre reinforced polymer laminate.

The shear reinforcement of the beam will start to yield if the debonding strain of the externally bonded plate is higher than the yield strain of shear reinforcement. In that case the design strain of KFRP laminate would be the yield strain of shear reinforcement because of strain compatibility nature between shear reinforcement and KFRP laminate, as shown in Fig. 20.1. Thus the design strain of KFRP laminate would be Eq. (20.2):

$$\varepsilon_{\text{KFRP,design}} = \varepsilon_{\text{y,link}} = \frac{f_{\text{y,link}}}{E_{\text{s}}}; \quad \text{when} \;\; \varepsilon_{\text{KFRP,debonding}} \geq \varepsilon_{\text{y,link}} \tag{20.2}$$

20.4.2 Design shear force of kenaf fibre reinforced polymer laminate strengthened beam

The maximum flexural capacities of all beam specimens could be theoretically predicted using Eqs. (20.3)–(20.5), based on EC2 (2004):

$$M = \text{Tz} = 0.87A_{\text{s}}f_{\text{yk}}\left[d - \frac{0.45A_{\text{s}}f_{\text{yk}}}{f_{\text{ck}}b}\right] \tag{20.3}$$

where,

$$x = \frac{A_s f_{yk}}{0.567 f_{ck}(0.8)b} = \frac{A_s f_{yk}}{0.45 f_{ck} b} \tag{20.4}$$

$$z = d - 0.4x = \left[d - \frac{0.45 A_s f_{yk}}{f_{ck} b}\right] \tag{20.5}$$

Thus the maximum design shear force of the beam can be calculated using Eq. (20.6):

$$V_d = V = \frac{M}{\text{Shearspan}}; \quad \text{if } V_d > V, \text{the beam will fail by flexure} \tag{20.6}$$

if $V_d < V$,

Shear strengthening is not possible without the enhancement of the flexural capacity of the beam

20.4.3 Required dimension of kenaf fibre reinforced polymer laminate for shear strengthening of reinforced concrete beam

Shear force resisted by shear link is first calculated using Eq. (20.7) as:

$$V_{y,\text{link}} = 0.87 A_{s,\text{link}} f_{y,\text{link}} N \tag{20.7}$$

where N is the number of shear link that could be obtained using Eq. (20.8) (shown in Fig. 20.2

$$N = \frac{[d - d']\cot\theta}{s} \tag{20.8}$$

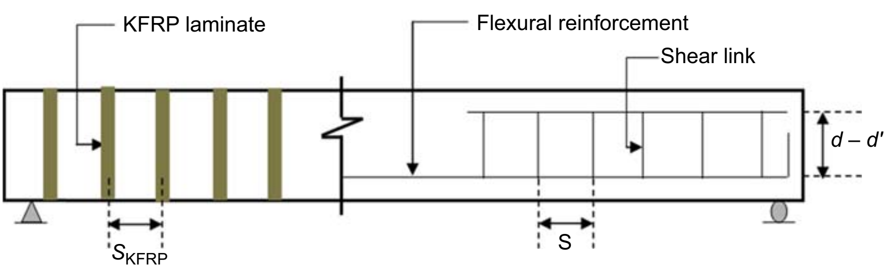

Figure 20.2 Details of a shear strengthened beam.

As per EC2 requirements, at the failure stage, concrete is ignored to resist the shear force. Only shear links resist the shear force. Thus the shear resisting capacity of the unstrengthened beam is calculated using Eq. (20.9). Eqs. (20.10) and (20.11):

$$V_{\mathrm{y,link}} = 0.87 A_{\mathrm{s,link}} f_{\mathrm{y,link}} \left[\frac{(d - d')\cot\theta}{s} \right] \tag{20.9}$$

Shear force needs to be resisted by KFRP laminate,

$$V_{\mathrm{KFRP}} = V_d - V_{\mathrm{link}} \tag{20.10}$$

$$\text{Shear force resisted by KFRP strip} = 0.67 A_{\mathrm{KFRP}} E_{\mathrm{KFRP}} \varepsilon_{\mathrm{KFRP,design}} \tag{20.11}$$

Assuming the safety factor of KFRP laminate is 1.5, which is similar with concrete. Further research is required to develop a safety factor of KFRP laminate using Eqs. (20.12)–(20.14):

$$\begin{aligned} &\text{Shear force resisted by two sided laminate} \\ &= 2(0.67) A_{\mathrm{KFRP}} E_{\mathrm{KFRP}} \varepsilon_{\mathrm{KFRP,design}} = \frac{1.34 A_{\mathrm{KFRP}} E_{\mathrm{KFRP}} f_{\mathrm{y,link}}}{E_{\mathrm{s}}} \end{aligned} \tag{20.12}$$

$$V_{\mathrm{KFRP}} = V_d - V_{\mathrm{link}} = \frac{1.34 A_{\mathrm{KFRP}} E_{\mathrm{KFRP}} f_{\mathrm{y,link}}}{E_s} N_{\mathrm{KFRP}} \tag{20.13}$$

where,

$$N_{\mathrm{KFRP}} = \frac{[d - d']\cot\theta}{s_{\mathrm{KFRP}}} \tag{20.14}$$

Thus the required cross-sectional area of a single KFRP shear strip can be calculated using Eq. (20.15):

$$A_{\mathrm{KFRP}} = \frac{E_{\mathrm{s}} s_{\mathrm{KFRP}} (V_d - V_{\mathrm{link}})}{1.34 E_{\mathrm{KFRP}} f_{\mathrm{y,link}} (d - d')\cot\theta} \tag{20.15}$$

20.4.4 Theoretical model to predict the shear capacities of beam specimens

The shear capacities of control and KFRP laminate strengthened beams could be predicted using the proposed Eqs. (20.16) and (20.17), respectively:

$$V_{\mathrm{CB}} = A_{\mathrm{s,link}} f_{\mathrm{t,link}} \left[\frac{(d - d')\cot 45}{s} \right] \tag{20.16}$$

$$V_{SB,KFRP} = A_{s,link} f_{t,link} \left[\frac{(d - d')\cot 45}{s} \right] + 2A_{KFRP} E_{KFRP} \varepsilon_{KFRP,design} \left[\frac{(d - d')\cot 45}{s_{KFRP}} \right] \quad (20.17)$$

20.5 Design example: case study on shear strengthening of kenaf fibre composite reinforced concrete beam

20.5.1 Design descriptions

A 150 × 300 × 2300 mm full-scale reinforced concrete beam was fabricated with 2−16 mm flexural reinforcement and 6 mm shear reinforcement of 110 mm spacing. The beam was supported using a roller with the span of 2 m. It was tested for two-point load with the shear span of 650 mm. The properties of materials are shown in Table 20.1. The beams need to be strengthened for shear using KFRP laminate for its maximum capacities.

20.5.1.1 Flexural capacities of beams

Using Eq. (20.2), as stated in the previous section, the flexural capacities of beams is calculated as:

$$M = \mathrm{Tz} = 0.87A_s f_{yk} z = (0.87)(402)(550)\left[261 - \frac{0.45(402)(550)}{(25.6)(150)}\right]$$

$$= 45.23 \text{ kN.m}$$

Total failure load,

$$P = 2V_d = \frac{2M}{L_s} = \frac{2(45.23)}{0.65} = 140 \text{ kN}$$

Table 20.1 Design parameters

Beam	Concrete strength	Shear link	Flexural reinforcement	KFRP laminate
$b = 150$ mm $h = 300$ mm $d = 261$ mm $d' = 39$ mm	$f_{cu} = 32$ MPa $f_{ck} = 25.6$ MPa $\beta = 0.28$	$f_{t,link} = 556$ MPa $s = 110$ mm $f_{y,link} = 520$ MPa $A_{s,link} = 47.5$ mm^2 $E_s = 200$ GPa	$f_{yk} = 550$ MPa $f_{tk} = 654$ MPa $A_s = 402$ mm^2	$t_{KFRP} = 6$ mm $E_{KFRP} = 11.4$ GPa $S_{KFRP} = 110$ mm

Design shear force,

$$V_d = \frac{140}{2} = 70 \text{ kN}$$

20.5.1.2 Design strain of kenaf fibre reinforced polymer laminate

The design strain is first calculated by determining the yield strain of the shear reinforcement and the debonding strain of the KFRP laminate:

Yield strain of shear reinforcement,

$$\varepsilon_{\text{y,link}} = \frac{f_{\text{y,link}}}{E_{\text{s}}} = \frac{520}{200000} = 0.0026$$

Debonding strain of KFRP laminate,

$$\varepsilon_{\text{KFRP,debonding}} = \frac{F_{\text{bu}}(d - d')}{t_{\text{KFRP}} E_{\text{KFRP}}} = \frac{1.58(261 - 39)}{(6)(11400)} = 0.00512 > \varepsilon_{\text{y,link}}$$

Finally, the design strain of KFRP laminate is calculated as the following:

$$\varepsilon_{\text{KFRP(design)}=}\varepsilon_{\text{y,link}} = 0.0026$$

20.5.1.3 Required cross sectional area of kenaf fibre reinforced polymer laminate for shear strengthening of reinforced concrete beam

As per the proposed guideline, the cross-sectional area of CFRP laminate can be calculated based on Eq. (20.12) stated in the previous section. For conservative design, the shear crack inclination of the beam could be considered as 45°.

$$V_{\text{y,link(45)}} = 0.87 A_{\text{s,link}} f_{\text{y,link}} \left[\frac{(d - d')\cot 45}{\text{s}} \right]$$

$$= 0.87(47.5)(520) \left[\frac{(261 - 39)\cot 45}{110} \right]$$

$$= 43360 \text{ N}$$

$$= 43.36 \text{ kN}$$

$$A_{\text{KFRP}} = \frac{E_{\text{s}} s_{\text{KFRP}} (V_d - V_{\text{link}})}{1.34 E_{\text{KFRP}} f_{\text{y,link}} (d - d') \cot \theta} = \frac{(200000)(110)(70000 - 43360)}{1.34(11000)(520)(261 - 39) \cot 45}$$

$$= 345 \text{ mm}^2$$

$$= 6 \text{ mm} \times 57 \text{ mm} \approx 6 \text{ mm} \times 60 \text{ mm}$$

Thus from the earlier results of the analysis, the provided KFRP laminate was 6 mm × 60 mm × 300 mm with 110 mm spacing for shear strengthening of the beam.

20.5.1.4 Theoretical shear capacity of kenaf fibre reinforced polymer laminate strengthened beam

The theoretical shear capacity of the KFRP laminate for strengthened beam is calculated as:

$$V_{\text{t,link}} = A_{\text{s,link}} f_{\text{t,link}} \left[\frac{(d - d') \cot 45}{s} \right] = (47.5)(556) \left[\frac{(261 - 39) \cot 45}{110} \right]$$
$$= 53.3 \text{ kN}$$

$$V_{\text{KFRP}} = 2 A_{\text{KFRP}} E_{\text{KFRP}} \varepsilon_{\text{KFRP,design}} \left[\frac{(d - d') \cot 45}{s_{\text{KFRP}}} \right]$$

$$= 2(300)(11400)(0.0026) \left[\frac{(261 - 39) \cot 45}{110} \right] = 35.89 \text{ kN}$$

Hence the total shear force of the KFRP laminate shear strengthened beam is calculated as:

$$V_{\text{SB}} = V_{\text{y,link}} + V_{\text{KFRP}} = 53.3 + 35.89 = 89.2 \text{ kN}$$

while the shear failure load is 178.4 kN.

20.6 Conclusion

This chapter has revealed the design practices of NFCs towards achieving sustainable construction performance. It can be observed that the use of NFC can highly contribute to improve the sustainability of building and construction materials through its renewable, recyclable and biodegradable properties as compared to conventional materials for similar applications. The use of NFCs in structural building applications can be made feasible through a systematic design process, which encompassed areas of materials selection and design development. In addition, the proposed shear strengthening design model of an RC beam using an NFC model, as explained in this chapter, showcased a systematic design guideline for designers to apply it for future applications. Moreover, the practicability of the design model using KFRP laminate in the case study also provided a hands-on guideline for easy understanding to practitioners. Finally, the use of the proposed design model can also be expanded for various types of natural fibres to help designers explore the potential of other sources of reinforcement materials, such as agricultural waste materials, which could bring greater benefits for similar applications.

Nomenclature

$\varepsilon_{\mathrm{KFRP,debonding}}$	Debonding strain of KFRP laminate
d	Effective depth of beam
d'	Depth of compression reinforcement (top bar)
w_{KFRP}	Width of KFRP shear strip
F_{bu}	Bond strength of concrete
t_{KFRP}	Thickness of KFRP laminate
A_{KFRP}	Cross-sectional area of KFRP laminate
E_{KFRP}	Modulus of elasticity of KFRP laminate
$\varepsilon_{\mathrm{KFRP,design}}$	Design strain of KFRP laminate
$\varepsilon_{\mathrm{y,link}}$	Yield strain of shear reinforcement
$f_{\mathrm{y,link}}$	Yield strength of shear reinforcement
E_{s}	Modulus of elasticity of steel bar
M	Moment resisting capacity of beam
T	Tensile force of flexural reinforcement
Z	Moment arm
A_{s}	Cross-sectional area of flexural reinforcement
f_{tk}	Tensile strength of flexural reinforcement
f_{yk}	Yield strength of flexural reinforcement
f_{ck}	Concrete compressive strength based on cylinder test
b	Width of beam
x	Depth of neutral axis
V_d	Design shear force
L_{s}	Shear span
N	Number of shear links that resist shear
θ	Inclination of shear crack
s	Spacing of shear link
$V_{\mathrm{y,link}}$	Shear force of beam due to yielding of shear reinforcement
$A_{\mathrm{s,link}}$	Cross-sectional area of shear link
V_{KFRP}	Shear force resisted by KFRP laminate
N_{KFRP}	Number of KFRP laminate to resist shear (from one side of beam)
s_{KFRP}	Spacing of KFRP laminate
V_{CB}	Shear capacity of control beam
V_{SB}	Shear capacity of KFRP laminate strengthened beam
$f_{\mathrm{t,link}}$	Tensile strength of shear reinforcement
$V_{\mathrm{SB,KFRP}}$	Shear capacity of KFRP laminate strengthened beam

References

ACI Committee 440, 2002. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. ACI 440 (2R-02).

Akadiri, P.O., 2015. Understanding barriers affecting the selection of sustainable materials in building projects. Journal of Building Engineering 4, 86−93.

Akadiri, P.O., Olomolaiye, P.O., 2012. Development of sustainable assessment criteria for building materials selection. Engineering Construction Architecture Management 19 (6), 666−687.

Alam, M.A., Hassan, A., Muda, Z.C., 2015a. Development of kenaf fibre reinforced polymer laminate for shear strengthening of reinforced concrete beam. Materials and Structures 49 (3), 795−811.

Alam, M.A., Alriyami, K., Jumaat, M.Z., Zakaria, C.M., 2015b. Development of high strength natural fibre based composite plates for potential application in retrofitting of RC structure. Indian Journal of Science and Technology 8 (15), 1−7.

Alam, M.A., Alriyami, K., Muda, Z.C., Jumaat, M.Z., 2016. Hybrid kenaf fibre composite plates for potential application in shear strengthening of reinforced concrete structure. Indian Journal of Science and Technology 9 (6), 1−7.

Alsayed, S.H., Siddiqui, N.A., 2013. Reliability of shear-deficient RC beams strengthened with CFRP-strips. Construction and Building Materials 42, 238−247.

Alwan, Z., Jones, P., Holgate, P., 2016. Strategic sustainable development in the UK construction industry, through the framework for strategic sustainable development, using building information modelling. Journal of Cleaner Production. http://dx.doi.org/10.1016/j.jclepro.2015.12.085 (in press).

Aprianti, E., Shafigh, P., Bahri, S., Farahani, J.N., 2015. Supplementary cementitious materials origin from agricultural wastes − a review. Construction and Building Materials 74, 176−187.

Ardente, F., Beccali, M., Cellura, M., Mistretta, M., 2008. Building energy performance: a LCA case study of kenaf-fibres insulation board. Energy and Buildings 40 (1), 1−10.

Bae, S.W., Murphy, M., Mirmiran, A., Belarbi, A., 2013. Behavior of RC T-beams strengthened in shear with CFRP under cyclic loading. Journal of Bridge Engineering 18 (2), 99−109.

Barros, J.A.O., Dias, S.J.E., 2006. Near surface mounted CFRP laminates for shear strengthening of concrete beams. Cement and Concrete Composites 28 (3), 276−292.

Belarbi, A., Acun, B., 2013. FRP systems in shear strengthening of reinforced concrete structures. Procedia Engineering 57, 2−8.

Bernard, M., Khalina, A., Ali, A., 2011. The effect of processing parameters on the mechanical properties of kenaf fibre plastic composite. Materials and Design 32, 1039−1043.

Binici, H., Eken, M., Dolaz, M., Aksogan, O., Kara, M., 2014. An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres. Construction and Building Materials 51, 24−33.

Binici, H., Aksogan, O., Shah, T., 2005. Investigation of fibre reinforced mud brick as a building material. Construction and Building Materials 19 (4), 313−318.

Burgueño, R., Quagliata, M.J., Mohanty, A.K., Mehta, G., Drzal, L.T., Misra, M., 2004. Load-bearing natural fiber composite cellular beams and panels. Composites Part A: Applied Science and Manufacturing 35 (6), 645−656.

Burgueno, R., Quagliata, M.J., Mehta, G.M., Mohanty, A.K., Misra, M., Drzal, L.T., 2005. Sustainable cellular biocomposites from natural fibers and unsaturated polyester resin for housing panel applications. Journal of Polymers and the Environment 13 (2), 139−149.

Castro-Lacouture, D., Sefair, J.A., Flórez, L., Medaglia, A.L., 2009. Optimization model for the selection of materials using a LEED-based green building rating system in Colombia. Building and Environment 44 (6), 1162−1170.

Costa, I.G., Barros, J.A.O., 2010. Flexural and shear strengthening of RC beams with composite materials − the influence of cutting steel stirrups to install CFRP strips. Cement and Concrete Composites 32 (7), 544−553.

Cuadrado, J., Zubizarreta, M., Rojí, E., Larrauri, M., Álvarez, I., 2016. Sustainability assessment methodology for industrial buildings: three case studies. Civil Engineering and Environmental Systems 33 (2), 1−19.

Dias, S.J.E., Barros, J.A.O., 2011. Shear strengthening of RC T-section beams with low strength concrete using NSM CFRP laminates. Cement and Concrete Composites 33 (2), 334−345.

Dittenber, D.B., GangaRao, H.V., 2012. Critical review of recent publications on use of natural composites in infrastructure. Composites Part A: Applied Science and Manufacturing 43 (8), 1419−1429.

Dodoo, A., Gustavsson, L., Sathre, R., 2009. Carbon implications of end-of-life management of building materials. Resources, Conservation and Recycling 53 (5), 276−286.

Dong, J., Wang, Q., Guan, Z., 2013. Structural behaviour of RC beams with external flexural and flexural−shear strengthening by FRP sheets. Composites Part B: Engineering 44 (1), 604−612.

EC2, 2004. General Rules and Rules for Building Eurocode 2: Design of Concrete Structures Part 1−1 1992-1-1.

Elsaid, A., Dawood, M., Seracino, R., Bobko, C., 2011. Mechanical properties of kenaf fiber reinforced concrete. Construction and Building Materials 25 (4), 1991−2001.

Franzoni, E., 2011. Materials selection for green buildings: which tools for engineers and architects? Procedia Engineering 21, 883−890.

Ghani, M.A.A., Salleh, Z., Hyie, K.M., 2012. Mechanical properties of kenaf/fiberglass polyester hybrid composite. Procedia Engineering 41, 1654−1659.

González, M.J., Navarro, J.G., 2006. Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact. Building and Environment 41 (7), 902−909.

Govindan, K., Shankar, K.M., Kannan, D., 2016. Sustainable material selection for construction industry−a hybrid multi criteria decision making approach. Renewable and Sustainable Energy Reviews 55 (0), 1274−1288.

Gurgun, A.P., Komurlu, R., Arditi, D., 2015. Review of the LEED category in materials and resources for developing countries. Procedia Engineering 118, 1145−1152.

Hong, J., Shen, G.Q., Guo, S., Xue, F., Zheng, W., 2016. Energy use embodied in China's construction industry: a multi-regional input−output analysis. Renewable and Sustainable Energy Reviews 53, 1303−1312.

Huda, M.S., Drzal, L.T., Mohanty, A.K., Misra, M., 2008. Effect of fiber surface-treatments on the properties of laminated biocomposites from poly(lactic acid) (PLA) and kenaf fibers. Composites Science and Technology 68 (2), 424−432.

Jalaei, F., Jrade, A., 2015. Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. Sustainable Cities and Society 18 (0), 95−107.

Jumaat, M.Z., Alam, M.A., 2009. Effects of intermediate anchors on end anchored CFRP laminate flexurally strengthened reinforced concrete beams. Journal of Applied Sciences 9 (1), 142−148.

Khedari, J., Nankongnab, N., Hirunlabh, J., Teekasap, S., 2004. New low-cost insulation particleboards from mixture of durian peel and coconut coir. Building and Environment 39 (1), 59−65.

Khedari, J., Watsanasathaporn, P., Hirunlabh, J., 2005. Development of fibre-based soil–cement block with low thermal conductivity. Cement and Concrete Composites 27 (1), 111–116.

Kibert, C.J., 2008. Sustainable Construction: Green Building Design and Delivery, second ed. John Wiley & Sons, New Jersey.

Koutas, L., Triantafillou, T.C., 2013. Use of anchors in shear strengthening of reinforced concrete T-beams with FRP. Journal of Composites for Construction 17 (1), 101–107.

LafargeHolcim, 2016. Understanding Sustainable Construction. Retrieved on February 17, 2016 from: https://www.lafargeholcim-foundation.org/AboutPages/what-is-sustainable-construction.

Li, H., Xian, G., 2012. Mechanical property enhancement of flax fibre-based green composites for civil structural application. International Journal of Sustainable Materials and Structural Systems 1 (1), 95–103.

Mansour, A., Srebric, J., Burley, B.J., 2007. Development of straw-cement composite sustainable building material for low-cost housing in Egypt. Journal of Applied Sciences Research 3 (11), 1571–1580.

Medineckiene, M., Turskis, Z., Zavadskas, E.K., 2010. Sustainable construction taking into account the building impact on the environment. Journal of Environmental Engineering and Landscape Management 18 (2), 118–127.

Mo, K.H., Alengaram, U.J., Jumaat, M.Z., Yap, S.P., Lee, S.C., 2016. Green concrete partially comprised of farming waste residues: a review. Journal of Cleaner Production 117, 122–138.

Onuaguluchi, O., Banthia, N., 2016. Plant-based natural fibre reinforced cement composites: a review. Cement and Concrete Composites 68, 96–108.

Ortiz, O., Castells, F., Sonnemann, G., 2009. Sustainability in the construction industry: a review of recent developments based on LCA. Construction and Building Materials 23 (1), 28–39.

Du Plessis, C., 2007. A strategic framework for sustainable construction in developing countries. Construction Management and Economics 25 (1), 67–76.

Pacheco-Torgal, F., Jalali, S., 2011. Cementitious building materials reinforced with vegetable fibres: a review. Construction and Building Materials 25 (2), 575–581.

Pugh, S., 1991. Total Design: Integrated Methods for Successful Product Engineering, Wokingham. Addison-Wesley Publishing, England.

Rassmann, S., Paskaramoorthy, R., Reid, R.G., 2011. Effect of resin system on the mechanical properties and water absorption of kenaf fibre reinforced laminates. Materials and Design 32, 1399–1406.

Rassmann, S., Reid, R.G., Paskaramoorthy, R., 2010. Effects of processing conditions on the mechanical and water absorption properties of resin transfer moulded kenaf fibre reinforced polyester composite laminates. Composites Part A: Applied Science and Manufacturing 41 (11), 1612–1619.

Shibata, S., Cao, Y., Fukumoto, I., 2006. Lightweight laminate composites made from kenaf and polypropylene fibres. Polymer Testing 25 (2), 142–148.

Senaratne, S., Gerace, D., Mirza, O., Tam, V.W., Kang, W.H., 2016. The costs and benefits of combining recycled aggregate with steel fibres as a sustainable, structural material. Journal of Cleaner Production 112 (4), 2318–2327.

Silvestre, J.D., de Brito, J., Pinheiro, M.D., 2014. Environmental impacts and benefits of the end-of-life of building materials–calculation rules, results and contribution to a "cradle to cradle" life cycle. Journal of Cleaner Production 66, 37–45.

Wu, W., Issa, R.R., 2010. Application of VDC in LEED projects: framework and implementation strategy. In: Proc. CIB W-78 27th International Conference on IT in Construction, 15–19 November 2010. Cairo, Egypt.

Yahya, K., Boussabaine, H., Alzaed, A., 2016. Using life cycle assessment for estimating environmental impacts and eco-costs from the metal waste in the construction industry. Management of Environmental Quality: An International Journal 27 (2), 227−244.

Yan, L., Kasal, B., Huang, L., 2016. A review of recent research on the use of cellulosic fibres, their fibre fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering. Composites Part B: Engineering 92, 94−132.

Zavadskas, E.K., Kaklauskas, A., Banaitis, A., Trinkūnas, V., 2005. System for real time support in construction materials selection. International Journal of Strategic Property Management 9 (2), 99−109.