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Faculteit Industriële Ingenieurswetenschappen

master in de industriële wetenschappen: bouwkunde

Masterthesis

Experimental evaluation of the mechanical properties of bamboo reinforcement for reinforced concrete beams

Stef Theysmans
Ruben Van Meensel
Scriptie ingediend tot het behalen van de graad van master in de industriële wetenschappen: bouwkunde

PROMOTOR :
Prof. dr. ir. Jose GOUVEIA HENRIQUES

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Foreword

This master's thesis represents the culmination of our academic journey at UHasselt - KU Leuven, as industrial construction engineers. The research presented in this thesis investigates the feasibility of using bamboo as an alternative reinforcement material for concrete beams in regions where steel is scarce or expensive. This endeavour has involved a series of experiments, in which new knowledge was gained and conclusions could be drawn.

We would like to thank our supervisor, prof. dr. ir. Jose Gouveia Henriques, for his professional guidance throughout the year. Furthermore, we would also like to thank dr. ing. Rik Steensels for assisting in the lab.

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Abbreviations

BBGRC	-	Bamboo Bitumen Grooves Reinforced Concrete
BBRC	-	Bamboo Bitumen Reinforced Concrete
BBSRC	-	Bamboo Bitumen Steel Reinforced Concrete
BRC	-	Bamboo Reinforced Concrete
PC	-	Plain Concrete
SRC	-	Steel Reinforced Concrete

Abstract

This thesis explores the feasibility of using bamboo as an alternative reinforcement material for concrete beams in regions where steel is scarce or expensive. The study investigates the mechanical properties and performance of bamboo in comparison to traditional steel reinforcement in concrete structures. Through experimental tests, including bending and pull-out tests, the study evaluates the resistance of bamboo reinforced concrete beams in bending, including the characterization of the bamboo concrete bond.

Bamboo is found to be a promising material due to its high tensile strength, sustainability, and cost-effectiveness. However, challenges related to its variability in quality, bonding with concrete, and long-term durability are identified. Therefore, this study compares the performance of different types of concrete beams: plain concrete, steel reinforced concrete, bamboo reinforced concrete and bamboo with steel reinforced concrete.

The results show that the adhesion of bamboo to concrete can be improved by using bitumen but especially by adding grooves. Bamboo reinforced beams are stiffer compared to unreinforced beams creating a greater margin of safety. A hybrid reinforcement of bamboo and steel is a more economical and realistic solution that has potential. A pure bamboo reinforcement with grooves is also a solution that is promising and approaches the performance of steel. Further research will be needed to prevent the bamboo from slipping by looking more closely at the influence of the grooves.

Abstract in het Nederlands

Deze scriptie onderzoekt de haalbaarheid van het gebruik van bamboe als alternatief wapeningsmateriaal voor betonnen balken in regio's waar staal schaars of duur is. De studie onderzoekt de mechanische eigenschappen en prestaties van bamboe in vergelijking met traditionele stalen wapening in betonconstructies. Door middel van experimentele testen, waaronder buig- en uittrekproeven, evalueert dit onderzoek de weerstand van bamboe gewapende betonnen balken tegen buiging, inclusief het karakteriseren van de bamboe betonhechting.

Bamboe blijkt een veelbelovend materiaal te zijn vanwege de hoge treksterkte, duurzaamheid en kosteneffectiviteit. Er zijn echter uitdagingen met betrekking tot de variabiliteit in kwaliteit, de hechting met beton en de duurzaamheid op lange termijn. Met die reden vergelijkt deze studie de prestaties van verschillende soorten betonnen balken: ongewapend beton, staalgewapend beton, bamboegewapend beton en bamboe-met-staal-gewapend beton.

De resultaten tonen aan dat de hechting van bamboe aan beton kan worden verbeterd door bitumen te gebruiken maar vooral door groeven toe te voegen. Bamboe versterkte liggers zijn stijver in vergelijking met ongewapende liggers waardoor een grotere veiligheidsmarge ontstaat. Een hybride wapening van bamboe en staal is een meer economische en realistische oplossing die potentieel heeft. Ook een pure bamboe wapening met groeven is een oplossing die de werking van staal benadert. Verder onderzoek is nodig om de invloed van de groeven te bekijken.

1 Introduction

When thinking of standard construction in Europe, the first image that comes to mind is concrete construction. Many skyscrapers are therefore constructed from reinforced concrete to support the weight of these structures, but in many countries these raw materials are not easily available and they also carry a price tag that many third-world countries cannot afford. As a result, residents of these countries will not have the option of building with traditional reinforced concrete. Therefore, third-world countries will have to look for local resources that can be used to add extra strength to concrete. Bamboo is a promising material that has good properties for use in construction applications.

To reinforce concrete beams, steel is standardly used. The steel is meant to absorb the tensile forces in the beam, as concrete has a low tensile strength. So, to replace steel with an economical alternative, a material that also has a high tensile strength like bamboo should be considered. In many countries, bamboo is present in large quantities, so bamboo is a cheaper alternative than steel. Whether bamboo is a realistic substitute for steel as a reinforcement, the characteristic properties of bamboo must first be considered.

Replacing steel reinforcement with one made from bamboo would be a much better economic option in countries with tropical and subtropical climates. Think of countries located in Asia, Africa and South America. In collaboration between UHasselt and Jimma University in Ethiopia, this thesis looks at the properties of bamboo and how it will be applied as reinforcement in concrete beams. As an initial research for UHasselt, which is a follow-up to a master's thesis from 2022-2023, bending tests will be conducted with four types of concrete beams: unreinforced, steel reinforced, bamboo reinforced and a combination of steel and bamboo reinforced. The bending tests will be conducted in two scales. Furthermore, pull-out tests will be done. And a type of bamboo reinforcement with grooves will be used to see if this affects adhesion. The ultimate goal is to see if it is realistic to reinforce beams with bamboo.

2 Traditional concrete

2.1 Unreinforced concrete

Concrete is one of the most widely used materials in the world. The type of concrete varies from country to country according to the materials available. As a result, the type of gravel and its grain distribution will vary, the cement quality and its strength and mainly the reinforcement depends on the availability of steel at the site.
In order to match the study as closely as possible with the research in Ethiopia, these factors need to be considered and weighed if it is feasible to reproduce these specific characteristics of the concrete during the experiments.
Jimma University used the following raw materials as the concrete composition:

- CEM I 42.5 N,
- natural river sand 0/4.75,
- crushed stone aggregate 4/20,
- no admixtures,
- concrete workability: 30-50 mm (slump test).

Jimma University itself has obtained a strength of $f_{cm,cube} = 38\ N/mm^2$. Based on this strength, the concrete composition will be made to get a comparable concrete composition and a representative testing. The strength of the concrete corresponds to a C25/30 commonly used in Ethiopia [1], however, this is not the case in Western countries.

2.2 Reinforced concrete with steel

Concrete is a material that has very good properties when it comes to compressive forces. The tensile force of concrete is ten percent of the compressive force, which is why steel is used as reinforcement to absorb the tensile forces in the material. If a beam is loaded at the top by a point load, the beam will have a compressive zone at the top and a tensile zone at the bottom. The two zones will be separated by the neutral axis. In the tensile zone, the tensile force of concrete will be neglected and only the tensile force of the reinforcement will be calculated. To better represent these zones and the stresses, Figure 1 is shown [2].

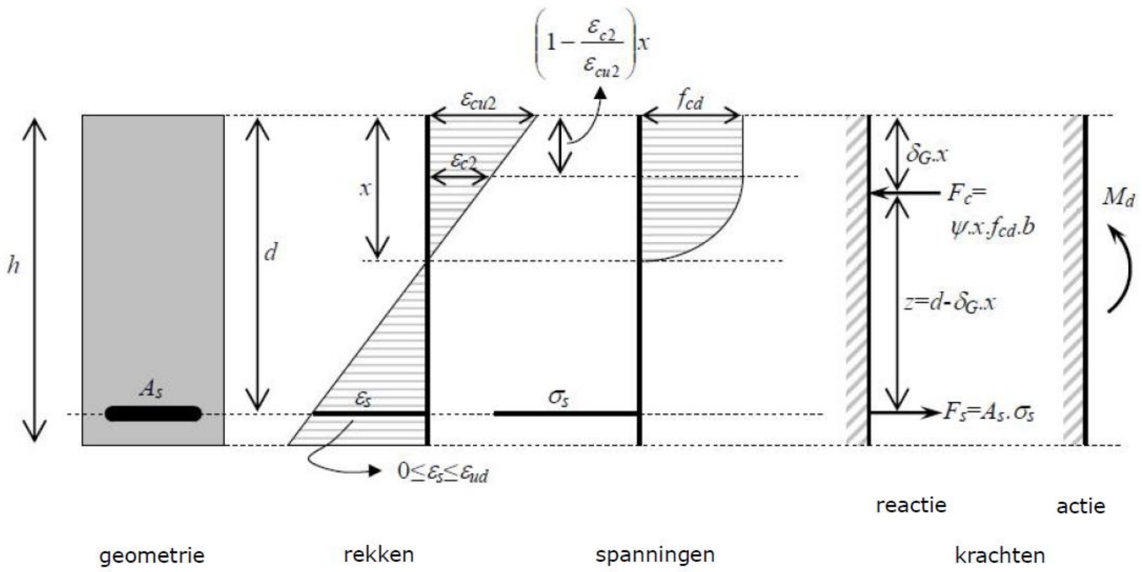

Figure 1: Strain, tension and forces diagram [2]

For a single reinforced beam, the dimensions are shown in Figure 1, where h is the height of the beam, d is the effective height (the distance between the reinforcement and extreme concrete fibre under compression) and x is the concrete pressure height. The steel and concrete will elongate, represented by ε_s and ε_{c2} respectively. The stresses in the concrete and steel cause a force represented by F_c and F_s. These two forces will be balanced by the resisting moment M_d. Using these diagrams, two equations can be formulated:

Translational equilibrium (compressive force in concrete= tensile force in steel):

$$F_c = F_s \quad (1)$$

Rotational equilibrium (resisting moment= applying moment):

$$M_d = F_c * z = F_s * z \quad (2)$$

Substitution of the torque arm:

$$z = d - 0.4x \quad (3)$$

Enter formula (3) in (2):

$$M_d = F_s * (d - 0.4x) \quad (4)$$

Formula for the concrete compression height:

$$x_u = \frac{A_s f_{yd}}{0.8 b f_{cd}} \quad (5)$$

Formula (4) and (5) are used to calculate the steel reinforcement and will later also be used to calculate the bamboo reinforcement. The formulas assume that there is no slip between steel and concrete and that the dimensions of the cross-section remain constant. They actually mean that the compressive force in concrete will be as great as the tensile force in the steel. The tensile force in the steel is equal to the reinforcement area in the cross-section of the concrete beam times the steel tension. This stress, in turn, can be determined using Hooke's law. A very important aspect is whether the steel reinforcement yields, to get to most economic reinforcement. The steel will yield when it is between its yield strength limits $\varepsilon_s = 0.2174$ - 1%. This means that the reinforcement is in areas 2a and 2b [2]. These areas are based on the relationship between the strain in the steel and concrete, see Figure 2. Zone 1 is bounded by a limit, the left limit being centric strain. The right-hand limit is the maximum compressive force in the concrete while the strain in steel remains maximum. This zone can be divided into 1a and 1b where in 1a no compression in concrete takes place and in 1b it does. Zone 2 is the zone where maximum compression in concrete is reached and steel switches from tension to compression. With zone 2a where steel experiences strain only and in 2b the steel is under compression.

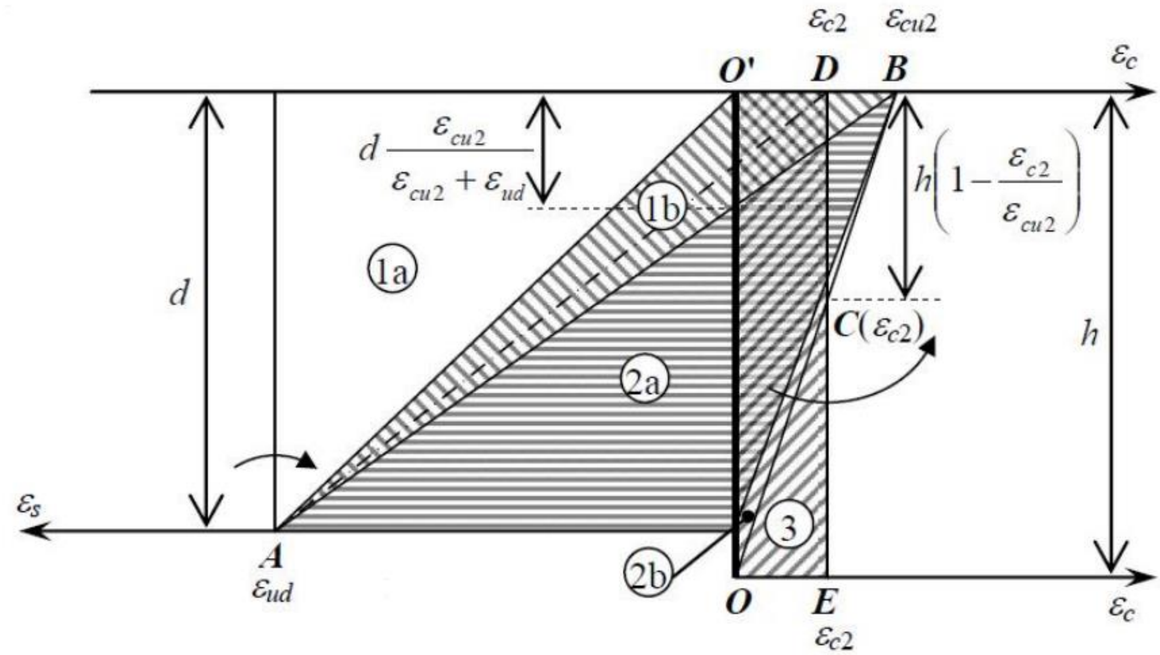

Figure 2: Different zones [2]

3 Bamboo

3.1 Mechanical properties of bamboo

UHasselt has already conducted initial research in collaboration with Jimma University [3]. The research was to investigate whether using bamboo would be a good substitute for steel to see if it would be possible to reinforce concrete beams with bamboo.

Since there is a collaboration with Jimma University, the original intention of the research is to use local bamboo species in Ethiopia. There are two species present in Ethiopia, namely Oxytenanthera abyssinica Munro (lowland bamboo) and Yushania alpina k.Schum (highland bamboo). But a disadvantage of these two species is that once mature, they have a diameter larger than 40mm, which is not appropriate for reinforcement in concrete. It is possible to harvest Yushania Alpina in a young stage, so its diameter varies between 25 mm and 30 mm. With this, this bamboo species can be used to carry out experiments on a large scale. To carry out smaller tests an alternative species was chosen named Arundinaria amabilis (Tonkin). Tonkin is a bamboo variety available with a diameter between 8 and 12 millimetres. Because of this, the previous research is based on Tonkin and this research is going to expand on this and look at the effective use of Tonkin and concrete.

3.1.1 Bamboo vs steel

Bamboo and steel are two fundamentally different materials used in numerous applications because of their unique properties. For example, bamboo is a natural material that can be planted and harvested. Steel, on the other hand, is an industrially produced material obtained by melting iron ore. Steel can be produced in any shape, unlike bamboo, which is limited by its original shape.

When the mechanical properties [4] are examined in more detail, more differences are observed. The mass density of bamboo strongly depends on the species, but generally varies between 500 and 800 kg/m^3. The mass density of steel is 7800 kg/m^3. So a big difference in mass density occurs. The characteristic strength of bamboo ranges between 30 and 50 MPa, while the tensile strength of steel ranges between 400 and 550 MPa. Bamboo thus falls short of steel in terms of strengths. The E-modulus ratio of steel and bamboo is ten indicating that bamboo will undergo greater elongation under the same stress [3].

When looked further in terms of environment, bamboo stands out above steel. Bamboo is a sustainable material, as it grows quickly and has minimal impact on the environment. Steel, on the other hand, requires a lot of energy to be produced; the raw materials have to be processed before it can be used. As a result, the environmental impact here is greater.

Steel and bamboo both have their advantages and disadvantages. Choosing the right bamboo species here will be important to achieve a good result. The next section will elaborate on the choice of the right bamboo species in this regard.

3.1.2 Mechanical properties of Tonkin

In previous research at UHasselt [3], tests were carried out using Tonkin. Tonkin has a smaller diameter which is necessary to use as reinforcement. In this research [3], tests were done on the density of the bamboo, which varies between 579 and 904 kg/m³. Tonkin thus has an average density of 748 kg/m³. As indicated in 3.1.1, the density of bamboo varies between 500 and 800 kg/m³ [4], so this confirms the results for Tonkin. This study cites that the values are wildly different from each other, this can be explained by the fact that bamboo is a natural material and so each piece of bamboo can vary in dimensions.

In previous research [3], it is noticeable that the values for tensile strength and modulus of elasticity are lower than those from the literature. In this research there were problems in fixing the specimens to the machine, and often this slipped. The obtained values were taken as lower limits. However, a relationship can be observed between tensile strength and density. Thus, the specimens with higher density show higher tensile strength. For the tensile tests, the specimens show a linear stress behaviour up to ±0.3% strain, after this the stress increases less strongly until they fail under brittle fracture.

During the pull-out tests, the bond strength was determined between bamboo and concrete. The tests have shown that the bond strength increases by 14% if a knot is present in the specimens [3]. However, many of the pull-out tests failed so the results cannot be fully used. This is because during the pull-out tests, the bamboo was crushed by the clamps which were used. This took place even before slip occurred in the concrete. However, it can be observed that the successful specimens with a knot give similar results. This is a consequence of the anchoring provided with the knot.

During the study [3], bending tests were also carried out on bamboo sticks. For the bending tests on Tonkin without a knot with a diameter of nine to ten millimetres, a maximum bending stress of 86.83 MPa is obtained on average. If specimens with a knot are used, a maximum bending stress of 78.38 MPa is observed on average. The major difference between the specimens without a knot and with a knot is the behaviour that occurs after obtaining the maximum bending stress. The specimens without a knot split after reaching the maximum bending stress, this allows them to still absorb stresses after this. The splitting of these specimens is shown in Figure 3. The specimens with knots completely break in two, so they can no longer absorb stresses. The fracture in these samples is shown in Figure 4.

Figure 3: Splitting of bamboo without a knot after bending test [3, p. 80]

Figure 4: Breaking of bamboo with a knot after bending test [3, p. 81]

3.1.3 Mechanical properties of Yushania Alpina

Yushania Alpina is a species of bamboo that grows locally in Ethiopia. Research has been conducted on this bamboo species to analyse its properties. The density of Y. Alpina varies between 630 and 650 kg/m³ [5]. The tensile strength for 1-year-old T. Alpina is 326 ± 30 MPa. The bamboo becomes even stronger when it is 2 years old, then the tensile strength is 386 ± 36 MPa [6]. These strengths are obtained by doing bending tests on bamboo fibres.

3.1.4 Coating of bamboo

Unlike steel reinforcement bars, which have a ribbed edge which improves adhesion with concrete, a problem arises in the adhesion of bamboo with concrete. The adhesion between the materials is important for the transmission of forces. Without the friction between the reinforcement and concrete, the tensile forces occurring in the concrete are not absorbed by the reinforcement and the usefulness of reinforcement is lost.

When reinforced concrete fails under tension, three different phases occur in relation to slippage between the reinforcement and concrete [7]. The first stage is the friction stage, the static friction force captures all the shear load and the slip is relatively small. The slip phase (slip stage) is the second phase, here the load overcomes the maximum static friction force and slip does start to occur in contrast to the first phase. From here on, the reinforcement no longer contributes to the tensile strength of the structure because the bond is completely lost. The last stage is the pressure stage, now all the load is carried on the connection of the reinforcement with the structure which is irrelevant to the pure bond between reinforcement and concrete.

Bamboo has a smooth surface and does not have the ability like steel to be formed into a shape with ribs for improved adhesion. Furthermore, the corrosion that occurs in steel improves the adhesion, so this is another disadvantage of bamboo where no corrosion occurs. These factors make adhesion between concrete and bamboo more complicated as traditional reinforcement. For this type of reinforcement, the friction is not expressed by the coefficient of friction but by the pull-out strength of the bamboo from the concrete. This has been done to take into account all the influencing factors. The pull-out strength is going to be determined in this research with the first type of experiment because the pull-out strength varies as a function of the type of bamboo and the concrete strength.

Since the concrete contains a lot of water, and since bamboo is a hygroscopic material, it will absorb water and it will expand. Once the concrete and bamboo begin to dry, the bamboo will shrink again and its adhesion to concrete will be reduced. This makes the coating important so that the bamboo will no longer absorb water. Also, the fact that bamboo is biodegradable can worsen the adhesion in the long run.

The difference in expansion coefficients can cause cracks to form in the concrete, which creates another risk. Insects such as termites can tear through concrete with a size of 0.8 mm [8]. As a result, the bamboo is not adequately protected by the concrete and measures will be required. There is also a relationship between insect attacks and the level of starch and moisture content of the bamboo [9], [10]. The starch level can be lowered by dehydration of the material, which will reduce the moisture content. Lowering the moisture content also has the effect of making bamboo less vulnerable to fungal attacks, and this is the case when the moisture content is below 15% [9]. The physical and mechanical properties also increase as the moisture content decreases. If bamboo is treated correctly against fungi and insects, the reinforcement can serve longer compared to steel. By soaking bamboo in boric acid for 3 days, the bamboo reinforcement is still in satisfactory condition after 15 years [10].

Another disadvantage of bamboo is its resistance to highly alkaline environment. When Portland cement is used, a strong alkaline environment is created with usually a pH higher than twelve in the pore water. This will ensure that no corrosion will occur on the steel of the reinforcement. However, bamboo is not resistant to an alkaline environment. This will alter the surface and cell structure of the material. Also, a loss of 50% of tensile strength can occur if bamboo is treated with highly alkaline water for a year [8].

Therefore, to use bamboo as a building material, a coating will have to be applied to be able to improve the adhesion and thus improve the strength properties. According to [8], there are favourable effects for the adhesion and strength of bamboo splints after treating them with epoxy-based adhesives. The average bond strength of untreated bamboo splints is 0.13 MPa. If bamboo is treated with Sikadur 32 adhesive, the strength increases to 0.59 MPa. This gives a significant difference with untreated bamboo.

To obtain similar bending behaviour to steel, a bamboo reinforcement ratio of 8% [8] is required for uncoated bamboo. If a coating of Sikadur 32 glue is applied, this ratio is still only 1.4%. If this ratio is compared with the reinforcement ratio of steel, which is 0.89%, coated bamboo comes much closer. This proves that a coating is necessary to come close to the properties of a steel reinforcement.

Thus, the untreated bamboo is vulnerable to numerous phenomena that will have a consequence on the strength properties of bamboo as a structural material. This especially for bamboo as reinforcement in concrete. This makes treatment of the bamboo essential to ensure the desired performance and longevity. This can be seen in Table 1. This table shows the positive effect of coatings on bamboo.

Table 1: Bonding strength of bamboo segment subjected to pull-out test [9, p. 643]

Treatment	Bond strength of treated bamboo τ_b	Bond strength of untreated bamboo τ_b/τ_{bnt}
Without treatment	0.52	1.00
Negrolin + sand	0.73	1.40
Negrolin + sand + wire	0.97	1.87
Sikadur 32-Gel	2.75	5.29
Steel	3.25	6.25

As can be seen in Table 1, a coating consisting of negrolin and sand improves the strength of treated bamboo segments 1.40 times compared to untreated bamboo. If a steel wire is added around the bamboo, this factor becomes 1.87 times stronger than untreated bamboo. If a Sikadur 32-Gel is used as discussed earlier, the strength of treated bamboo segments will improve 5.29 times compared to untreated bamboo. This result comes close to the bonding strength of steel and shows that a treatment will be necessary to get results similar to steel reinforcement.

3.2 Reinforced concrete with bamboo

The aim of this research is to look at the possibility of reinforcing concrete with bamboo. Whether bamboo effectively contributes to the load-bearing capacity of a structure and also to see on what scale this technique can be applied.
Previous studies quickly reveal many potential problems. The use of bamboo as reinforcement brings out durability, strength and stiffness issues [8]. The fact that it is an anisotropic material and has different failure modes depending on the direction makes it difficult to predict the failure modes. Also, bamboo does not have radial fibres which will make it vulnerable to shear in the longitudinal direction and to compression and tensile failure in the transverse direction [8]. During the failure of a beam reinforced with steel, the ductile failure mode of steel will allow fractures to be established before the beam will fail completely. Since bamboo fails under brittle fracture, this will not be the case and will be less safe in case of structural failure. Against the easy workability of steel, making rebar braces from bamboo is not easy and the joints are less reliable as welded and bent steel bars.

The ratio of the area of the reinforcement to the concrete has an influence in relation to the load-bearing capacity of the concrete. In theory, no reinforcement will be placed in the compression zone as the concrete absorbs the compressive force here. Then again, in the tensile zone, the tensile force of the concrete will be neglected. However, the concrete will serve to link the concrete of the compression zone to the reinforcement. One study obtained 3% as the ideal ratio in accordance with Brazilian construction restrictions [8]. More focused on the aspect of safety for preventing brittle failure after cracking, 3.5% is recommended [8]. This does assume that the bonding properties are similar to bamboo and concrete. A higher percentage is needed if the properties are poor.

In study [10], bending tests have already been performed on concrete beams with a length of 1.2 m. Four different test specimens were used, a concrete beam without reinforcement (PCC), a beam with steel reinforcement (RCC), a beam where bamboo partially replaced the steel reinforcements (PRS-BRC) and a beam fully reinforced with bamboo (FRS-BRC). The RCC beam consists of 2 x 12 mm steel bars at the bottom and 2 x 10 mm steel bars at the top. For PRS-BRC, the top bars are replaced with 2 x 12 mm bamboo bars. The stirrups for RCC and PRS-BRC consist of 8 mm steel bars at 125 mm c/c. For FRS-BRC, the reinforcement consists of 2 x 16 mm bamboo bars at the bottom and 2 x 16 mm bamboo bars at the top. The stirrups consist of 12 mm bamboo bars. To ensure grip between the bamboo and the concrete, a steel wire of 1 mm in diameter is tied around both ends of the bamboo specimens. During the tests, the first crack load, ultimate load, yield load and the deflection were measured. The results of these tests are shown in Figure 5 and Figure 6.

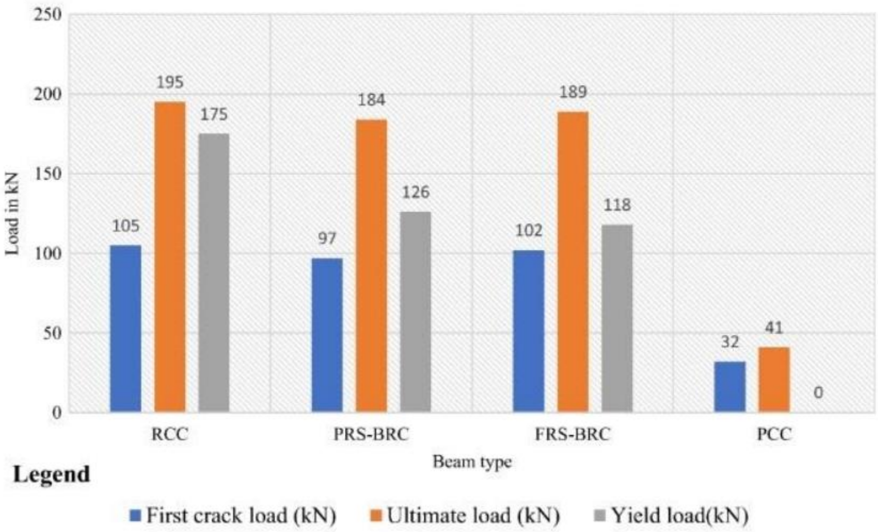

Figure 5: Maximum load per beam type [10, p. 9]

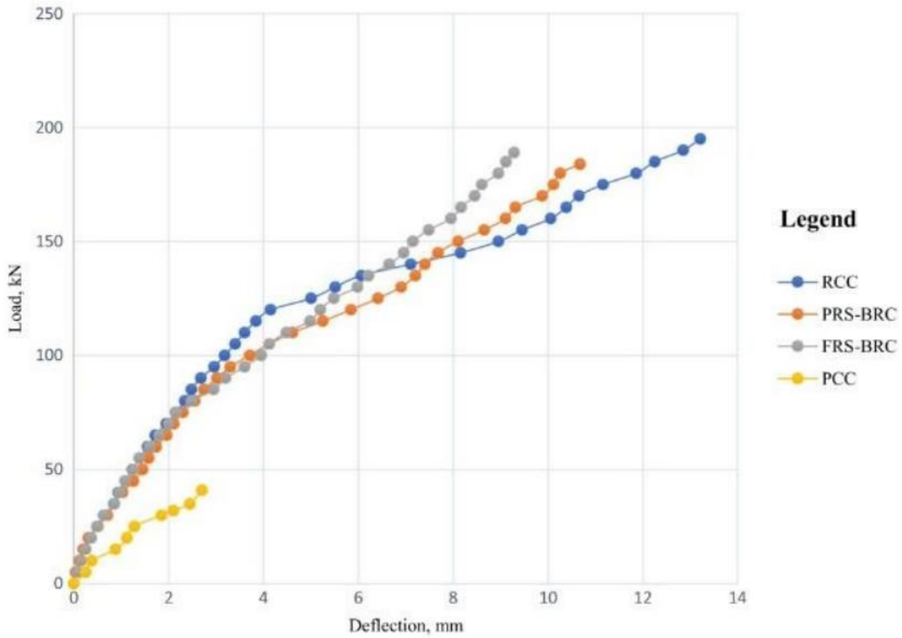

Figure 6: Load in function of deflection [10, p. 10]

Figure 5 and Figure 6 show a decrease of 8.25%, 5.98% and 38.89% of the first crack load, ultimate load and the yield load of PRS-BRC compared to RCC. For the results of the FRS-BRC there is a decrease of 2.81 %, 3.17 % and 48.31% in comparison with RCC. Judging from the results, the first crack load and ultimate load barely decrease when bamboo is used as reinforcement instead of steel. Yield load on the other hand drops dramatically, with a beam fully reinforced with bamboo losing almost fifty percent of its yield strength compared to steel. Another interesting result is the deflection of the first crack. A deflection of 4.1 mm is measured with RCC, but for the FRS-BRC a deflection of 3.7 mm. The fact that bamboo is a brittle material and exhibits less elongation than steel can be seen in these results and is the reason why less bending can be absorbed by a concrete beam reinforced with bamboo. However, it is a great improvement over a beam without reinforcement because then the deflection is only 1.2 mm which is 1/3 of a bamboo reinforced beam. The data shows that while bamboo-reinforced beams can carry higher loads than PCC beams, they fall short when compared to RCC beams, especially in terms of deflection characteristics at various stages (first crack, ultimate and yield). The research suggests that bamboo reinforced concrete can be used in low-rise buildings where the load will be minimum. To see the effect on the maximum load, the ratios were calculated between the ultimate load of the three different reinforcements with that of the unreinforced beams. The ratio of steel reinforcement to unreinforced concrete is $\frac{F_i}{F_{pc}} = 4.75$. For the reinforcement consisting of steel and bamboo, this is $\frac{F_{ib}}{F_{pc}} = 4.49$. And for full bamboo reinforcement, $\frac{F_b}{F_{pc}} = 4.61$.

In research [10], the deflection ductility factor method was used to determine the ductility of the beams. This ductility is the ratio of the ultimate deflection and the yield deflection. The ductility can also be based on energy, here the ratio is between the energy at ultimate state and at yield stage. The results are shown in Figure 7.

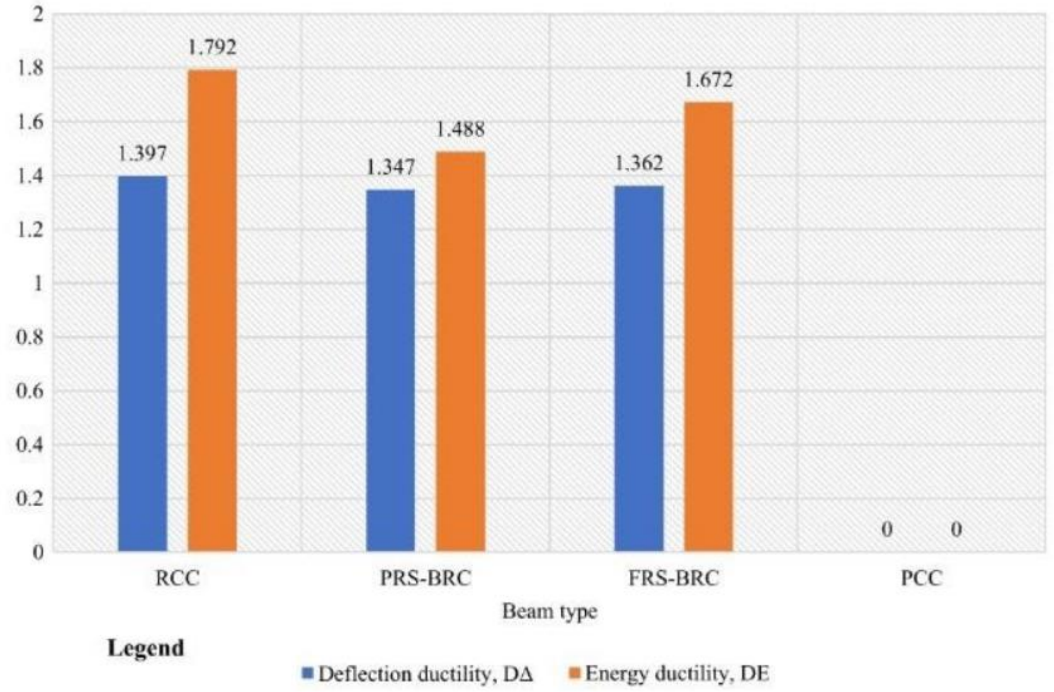

Figure 7: Ductility of the beam types [10, p. 12]

It can be seen from Figure 7 that the ductility of FRS-BRC is closer to RCC. It also shows that complete replacement of steel reinforcement has a higher ductility than partial replacement of steel reinforcement. The addition of the bamboo reinforcement has a great advantage in terms of safety, as failure of the beam requires a large displacement against an unreinforced beam.

A study at the Fukuyama University has shown that the crack pattern for bamboo reinforced beams is the same as for steel reinforcement [11]. By performing three-point bending tests on concrete beams reinforced with bamboo and steel, a similar cracking pattern was demonstrated, shown in Figure 8.

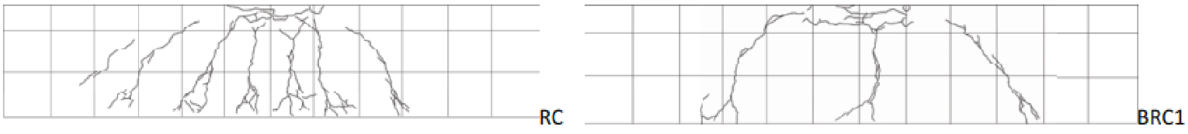

Figure 8: Cracking pattern of steel and bamboo reinforced beam [11, p. 2969]

Figure 8 shows that multiple cracks take place across the beam facing the gripping force. With an unreinforced beam, this would be a single crack that would break the beam in two. The results of the bending test show that the maximum applied force is almost double for a steel reinforcement as for a bamboo reinforcement. The steel reinforced beam achieved a maximum force of 76.3 kN while two bamboo reinforced beams achieved 40.1 kN and 40.5 kN [11]. The way the reinforcement and bending resistance were calculated is not given in the paper.

Study [12] investigates the influence of specimen shapes, presence of knots and bark on tensile strength with consideration of moisture content. As a result, the tensile strength of bamboo decreases when the bark is removed and the number of knots increases. They also recommend a moisture content of 12% at 28 days of the open air-dried process because the tensile strength will decrease when the moisture content will rise. Pull-out test shows that the roughness of the surface of the bamboo can double the bond strength, the roughness depends on the type of bamboo. Three-point bending tests were conducted on six beams, of which two beams reinforced with steel (SCB) and the other four beams with bamboo (BVCB and BHCB) using two types of bamboo: Bambusa Vulgaris Vittata (BV), Bambusa Heterostachya (BH). The result of the bending test is shown in Figure 9.

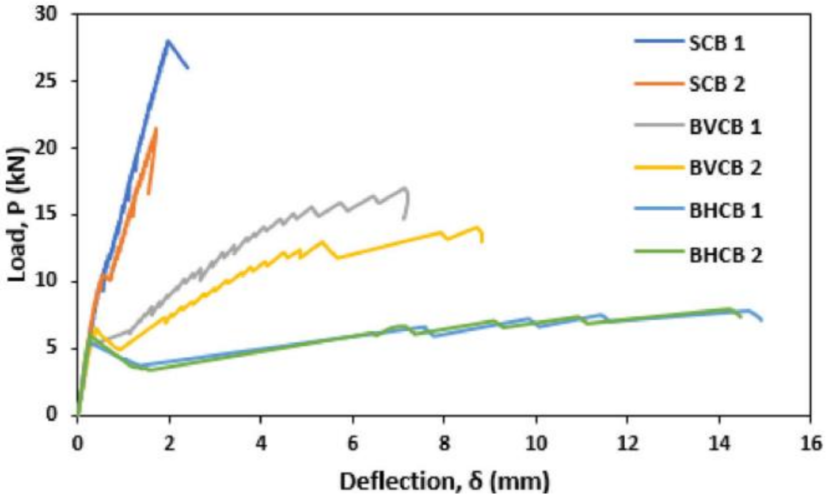

Figure 9: Results three-point bending tests [12, p. 14]

The results show that the steel reinforced beams can carry loads up to 30 kN in comparison to the two bamboo species which are limited to 8 kN and 15.5 kN. The striking difference between the bamboo species is that the bamboo species with the best bond strength but the lowest tensile strength can withstand the high load even though all six beams were expected to withstand the same load. This is why they point out that there is no code of practice for calculating bamboo reinforcement yet. Another striking fact is that bamboo requires a large deflection for the fallen beam. One of the bamboo species has four times more deflection than steel and the other species as much as seven times which means that bamboo reinforced beams are more ductile than the beams with steel.

To get a better bonding between the bamboo and the concrete, different types of patterns can be applied on the surface of the bamboo. Study [13], examines the bond strength by conducting pull-out tests. These are done on pure bamboo, bamboo with steel wire and bamboo with semi circular corrugations. The bamboo here consists of large bamboo canes divided into smaller strips with a thickness of 19 mm. Figure 10 shows the bamboo strip with wire wrapping and Figure 11 shows the bamboo strip with semi circular corrugations. Figure 12 shows the results from the bonding tests.

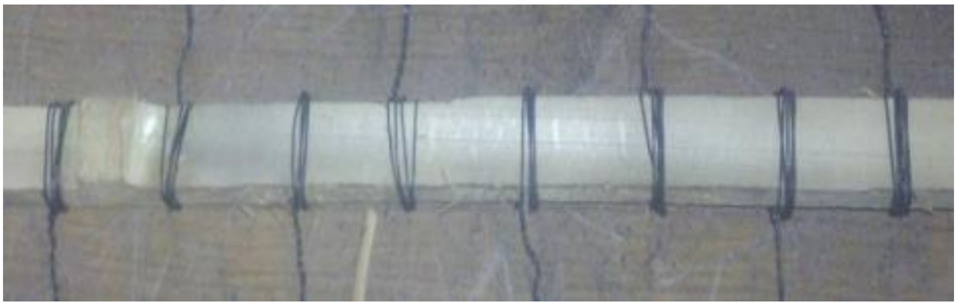

Figure 10: Bamboo strip with wire wrappings [13, p. 8]

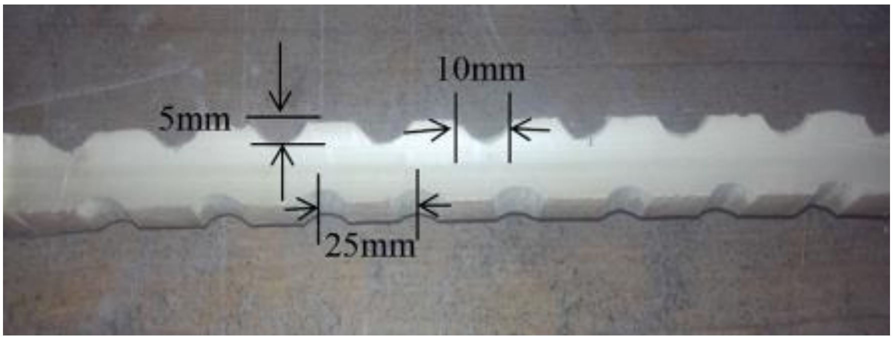

Figure 11: Bamboo strip with semi circular corrugations [13, p. 8]

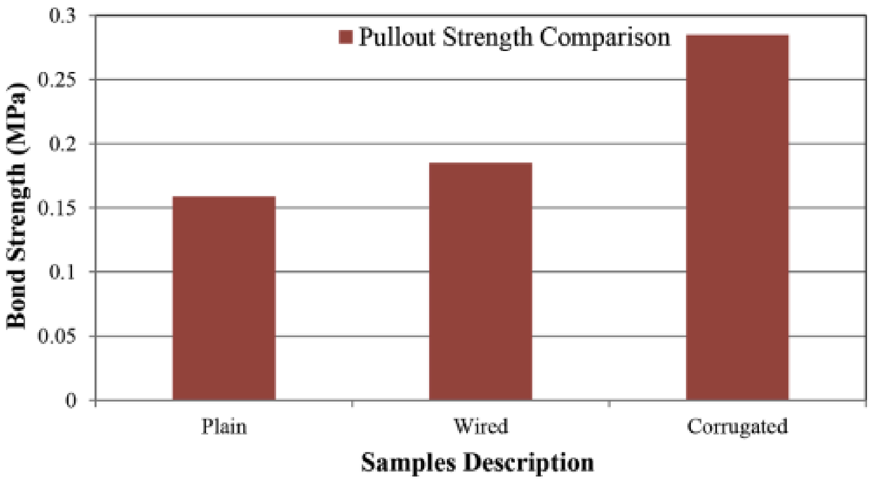

Figure 12: Bonding strengths of various types of bamboo strips [13, p. 8]

Figure 12 shows that the wire wrappings and semi-circular corrugations improve the bonding strength of the bamboo. To test whether this better bond strength also affects the strength of the beam, this study [13] made eight reinforced concrete beams, two of which had bamboo strips of each type and two with steel. Four-point bending tests were carried out on these. The results obtained are shown in Figure 13.

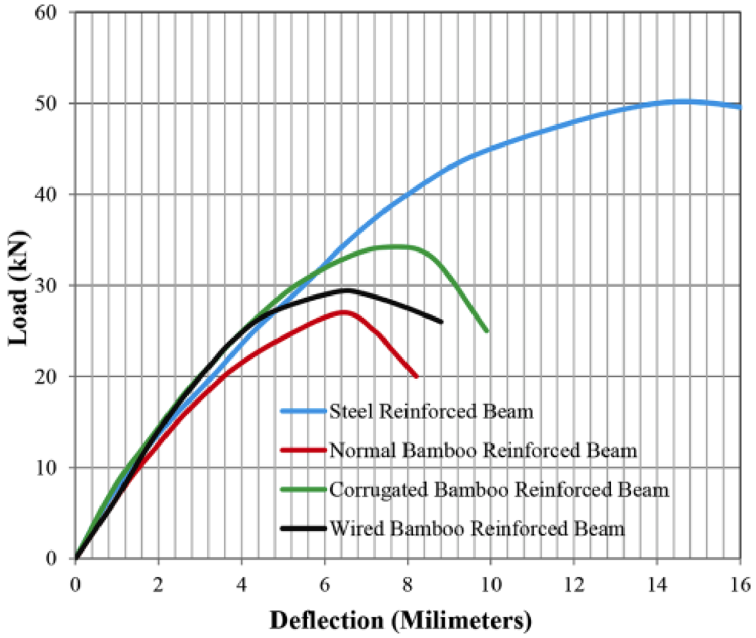

Figure 13: Load deflection curves for various concrete beams [13, p. 10]

What can be concluded is that the ductility of the corrugated bamboo reinforced beam is the highest among the bamboo reinforced beam types. When it comes down to comparing the ultimate loading capacities with plain bamboo, the wired samples show an improvement of 11% and the corrugated samples show an improvement of almost 80% [13].

4 Experimental program

4.1 Description

To determine if bamboo is a real possible replacement for steel, three types of tests will be conducted. Two types of bending tests on concrete beams and one type of test to determine the bonding strength between bamboo and concrete which is needed to characterise materials and load transfer mechanics. The first bending test consists of a three-point bending test on plain concrete, bamboo and steel reinforced concrete beams with a length of almost 1 m. The second bending test will be a four-point bending test on bamboo with bitumen, bamboo with bitumen and grooves, bamboo with bitumen in combination with steel and steel reinforced concrete beams with a length of around 2.5 m.

Table 2 shows the tests which will be executed.

Table 2: Number of tests

	Test 1: Adhesion	Test 2: Three-point bending	Test 3: Four-point bending
Plain concrete		2	
Steel reinforcement		2	1
Steel and bamboo reinforcement with bitumen			1
Bamboo reinforcement without bitumen	6	2	
Bamboo reinforcement with bitumen	3	2	1
Bamboo reinforcement with bitumen and sand	3		
Bamboo reinforcement with bitumen and grooves			1
Cubes	12		3

4.2 Characterization of the materials

4.2.1 Steel

The type of steel that will be used is standard reinforcement, with dimensions varying according to what is needed.

4.2.2 Bamboo

As bamboo, two different types of bamboo are used, which are described in paragraphs 3.1.2 and 3.1.3. Here, Tonkin will be used for Test 1 and Test 2. For Test 3, Y. Alpina will be used.

4.2.3 Concrete

Furthermore, a concrete composition will have to be made. The same type of concrete will be used for all the tests. It is chosen to obtain a concrete similar to the concrete used at Jimma University, as discussed in 2.1. The concrete will need to have a compression strength $\left(f_{cm,cube}\right)$ of 38 N/mm². Furthermore, a CEM I 42.5 N will be used to produce such concrete. To determine the water-cement factor, the following formula of Walz will be used.

$$f_{cm,cube} = 0.46 * f_{cm,cem} * \left(\frac{1}{\frac{w}{c}} - 0.06\right) \qquad (6)$$

If this formula is converted to the w/c factor, the following is obtained.

$$\frac{w}{c} = \frac{1}{\frac{1}{0.46} * \frac{f_{cm,cube}}{f_{cm,cem}} + 0{,}06} = \frac{1}{\frac{1}{0.46} * \frac{38}{58} + 0.06} = 0.67 \qquad (7)$$

So this indicates a w/c factor of 0.67. Since this is high, a w/c factor of 0.60 will be used. Furthermore, a 1-2-3 ratio is going to be used. This means that for every kg of cement, 2 kg of sand and 3 kg of gravel will be used. So for each bag of cement, this gives the values which can be seen in Table 3. In this table, volume rates will also be elaborated.

Table 3: Composition of concrete for one bag of cement

Material	Mass (kg)	Mass density (kg/m^3)	Volume (m^3)	Total volume (m^3)	Volume percentage (%)
Cement (CEM I 42.5 N)	25	3115 [14]	0.0080	0.1032	8
Water	15	1000	0.0150		15
Sand (0/4)	50	1500 [15]	0.0333		32
Gravel (4/16)	75	1600 [16]	0.0469		45

To estimate the volume of concrete that can be formed with one bag of cement, the mass density is taken into account. The mass densities of different materials are listed in Table 3. Then the masses are divided by the mass densities to get a volume. A total volume can then be obtained. If the volumes are divided by the total volume, the volume percentage of each material can be calculated which can be used in further elaborations.

The volume percentages are multiplied by the required volume of concrete, in this way the volumes of the different materials are obtained. When this is multiplied by the mass density, the required mass is obtained. Since the volume of concrete obtained with the cement is an estimate, a margin is made on the required volume of concrete. With these calculations, a surplus of cement bags is determined for conducting the tests.

4.2.4 Cube tests

To test the obtained strength of the concrete, different cube tests will be executed. During the pouring of the concrete, these cubes are made. These cubes have dimensions of 150x150x150 mm. Figure 14 shows the cubes after decasting done the day after pouring.

Figure 14: Cubes

The test specimens for the pressure tests can be seen in Figure 14. For test series one and two, twelve cubes are formed together; for test series three, three cubes are formed separately. As can be seen in Figure 14, several edges of the cubes have broken off, which can be explained by stripping the cubes too early.

The cubes are stored in the same way as the test pieces. Each testing day, three cubes are tested. Table 4 shows the average results of the strength of the cubes for test series one and two.

Table 4: Results of the cubes for serie one and two

Testing day	Average strength (MPa)	Average mass (kg)
19 days	30.14	7.588
28 days	34.06	7.587
Bending tests (62 days)	37.27	7.702
Pull-out tests (82 days)	40.66	7.639

As shown in Table 4, the strength on the day of the bending tests matches well with the 38 N/mm² to be obtained, the strength on the day of the pull-out tests is 1.66 N/mm² stronger than the strength that has to be obtained.

During test series three, a collaboration was made with other research from Jimma University to produce the concrete at the same time. To avoid producing too much concrete for just the pressure tests, only a total of three pressure tests were conducted for series three. This compression test was performed after 28 days and the results are shown in Table 5.

Table 5: Results of the cubes for serie three

Testing day	Average strength (MPa)	Average mass (kg)
28 days	42.84	7.654

As can be seen in Table 5, at 42.84 MPa, there is a deviation from the desired values of 38 MPa. This also means that there is a small deviation with the results of series two. This should be taken into account that series three will obtain greater compressive and tensile strengths than first desired.

4.3 Adhesion

4.3.1 Pull-out specimen description

The bond strength tests serve to characterise the load transfer between the two materials. It will measure the force that is needed to break the connection between the bamboo and the concrete and to what extent the bamboo slips.

The specimens consist of two concrete bars which are connected with a bamboo stick. During the pull-out tests, both concrete bars are pulled without damaging the bamboo itself by the clamps. In total there are four different types of specimen depending on the used type of bond. From every type there are three specimens.

All the specimens are shown in Figure 16. The different types of specimen are:

- clean bamboo without a knot in the concrete bars (a, Figure 17);
- clean bamboo with bitumen without a knot in the concrete bars (b, Figure 17);
- clean bamboo with bitumen and sand without a knot in the concrete bars (c, Figure 17);
- clean bamboo with a knot in every concrete bar (d, Figure 17).

The dimensions of the specimen are:

- cross section bar: 45x45 mm,
- length of each concrete bar: 210 mm,
- length of the bamboo: 300 mm.

These dimensions can be seen in Figure 15.

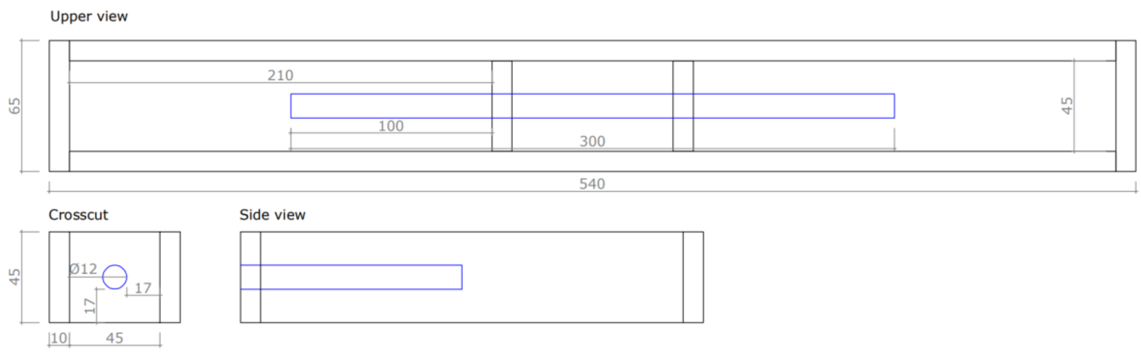

Figure 15: Pull-out test specimen dimension

The distance between the two bars is 100 mm which means that the bamboo is fixed into the concrete along a length of 100 mm along each side. This leaves a length of 110 mm of plain concrete. The clamps for pulling on the specimens are placed over a length of 100 mm over the plain concrete area of the bars. A transition area of 10 mm is placed so that the compressive strength required for clamping in the specimens is not going to affect the clamping of the bamboo stick.

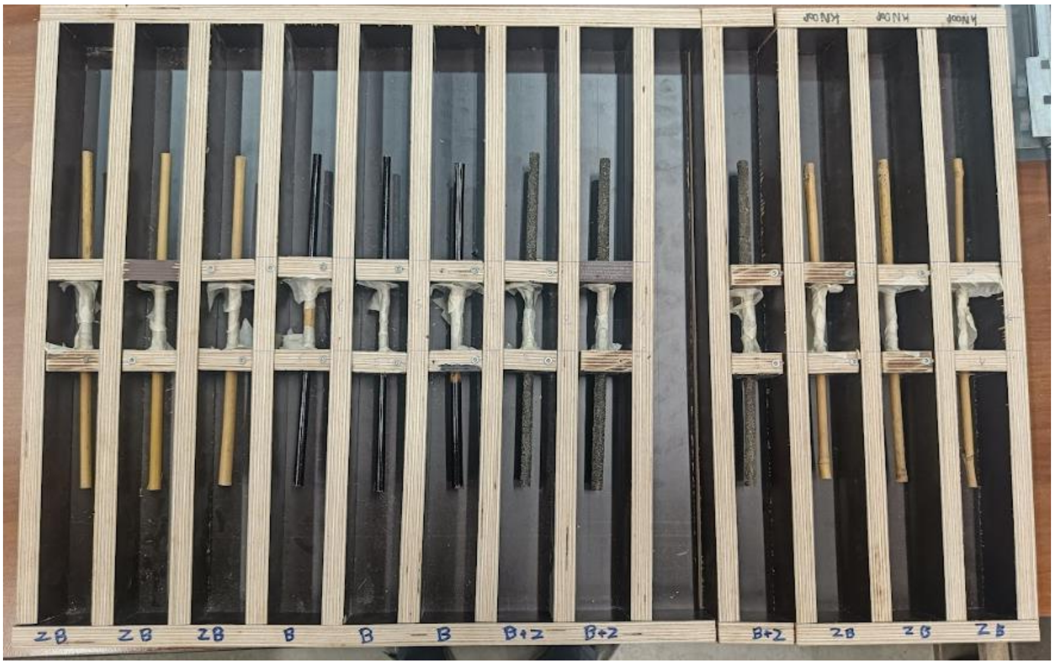

Figure 16: All types of specimen

Figure 17: Type of specimen a-b-c-d

For concrete, the same composition as explained in paragraph 4.2.3 was used. This concrete was then poured into the specimens and after at least 28 days, they were uncasted. The uncasted specimens are shown in Figure 18.

Figure 18: Uncasted specimens pull-out tests

4.3.2 Pull-out test

The specimens for the pull-out test are clamped to both concrete bars of the specimen. Each side is fixed with clamps over a length of 10 cm. The clamping is not too tight so that the concrete is damaged but also tight enough so that the specimen does not slip in the clamps. After starting the test, the clamps move at a speed of 0.05 mm/s apart. During the displacement, the force is measured and the displacement itself. The pull-out test setup is shown in Figure 19.

Figure 19: Pull-out test setup

4.4 Small span beams subject to bending

4.4.1 Small concrete beam description

To have a first impression of bamboo's contribution to the flexural strength of a concrete beam, test pieces are made with a length of 95 cm. Eight test pieces in total were tested, including two test pieces with plain concrete (PC - Plain Concrete), two original reinforced beams with steel (SRC - Steel Reinforced Concrete), two reinforced with bamboo (BRC - Bamboo Reinforced Concrete) and two reinforced bamboo beams coated with bitumen (BBRC - Bamboo Bitumen Reinforced Concrete). The dimensions of these specimens are shown in Figure 20.

The dimensions of the cross section of the beam in theory are 20 cm by 20 cm. This is based on the dimensions of a mesh reinforcement, the mesh is used as transverse reinforcement. This reinforcement is used for the steel reinforced beams as well as the two types of bamboo reinforced beams. Which means that only the longitudinal reinforcement is out of bamboo. The type of bamboo is based on a previous master thesis [3] and the type is Arundinaria amabilis (Tonkin).

The dimensions of the materials used are:

- transverse reinforcement consisting of:
    - steel S500: 8 x (15x15 cm), $\phi = 5\ mm$ (SRC, BRC, BBRC).
- longitudinal reinforcement consisting of:
    - steel S500: 4 x 90 cm, $\phi = 8\ mm$ (SRC),
    - bamboo: 10 x 90 cm, $\phi = 10 - 12\ mm$ (BRC, BBRC).

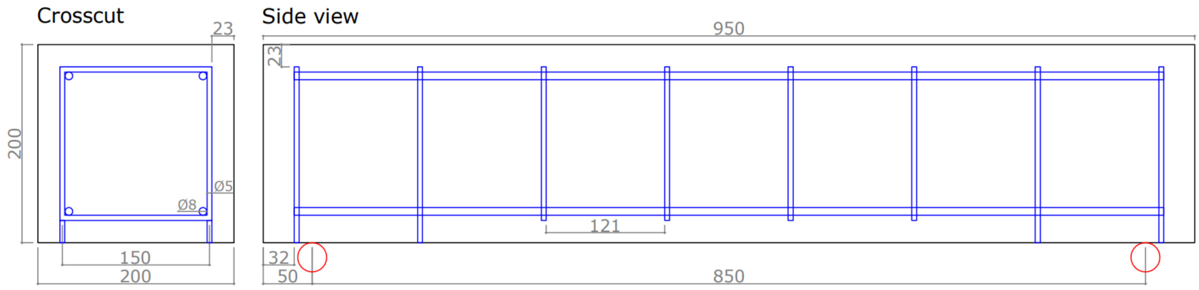

Figure 20: Dimensions of the reinforcement cage (SRC)

For SRC, in total there are four steel bars in the longitudinal reinforcement. The bottom two are for improving the tensile strength of the beam and the other two are for the construction of the cage. Which are shown in Figure 21.

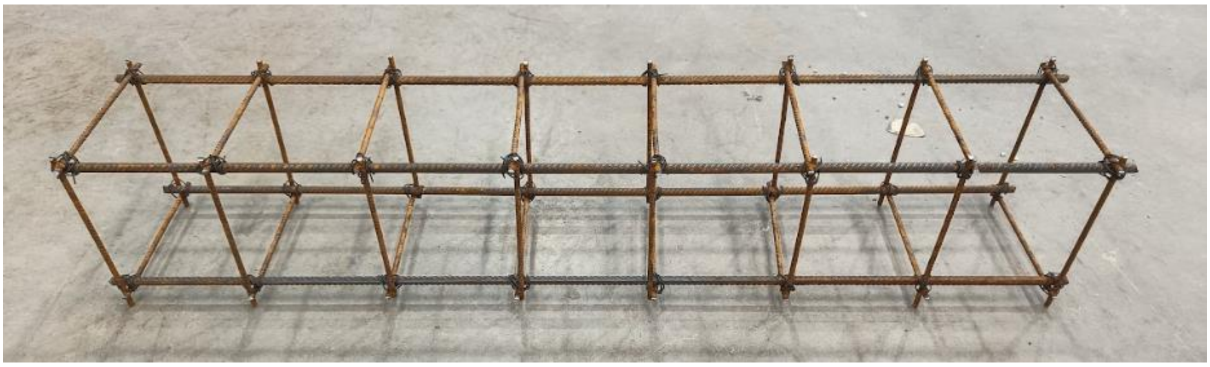
Figure 21: Reinforcement cage for SRC

The total amount of the bamboo that is needed for BRC and BBRC is calculated so that the bending resistance of the beams reinforced with bamboo and steel are comparable. The average tensile strength of a bamboo stick is 5217 N, this value is taken from the 2022-2023 thesis [3]. Eight bamboo sticks are needed to achieve a similar tensile strength to steel and two for the construction of the cage. This can be seen in Figure 22. There are large inaccuracies in the calculation, the diameter of each stick varies from stick to stick and also according to the location of the stick. Also, the tensile strength, the amount of knots and the diameter of the knots will vary per individual stick.

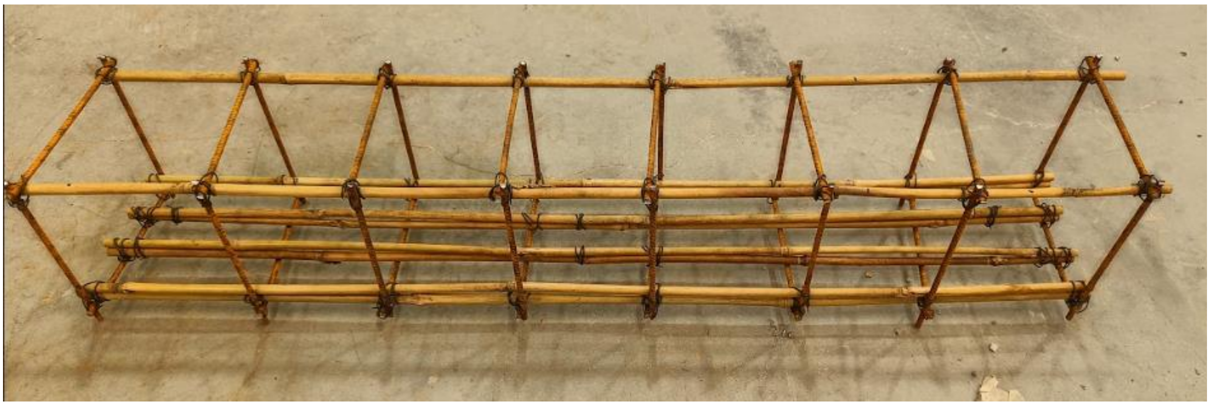
Figure 22: Reinforcement cage for BRC

To improve the bonding between the bamboo sticks and the concrete, a coating of bitumen has been used. The bitumen used is a roof primer. The bitumen coating has been used only on the bamboo and so only on the longitudinal reinforcement, this can be seen in Figure 23.


Figure 23: Reinforcement cage for BBRC

The reinforcement cages can now be placed in a self-made formwork. This formwork is made of plywood with one base plate and screwed-on sides. Thus, one large formwork is formed in which the eight beams can be formed. This formwork with the reinforcement cages can be seen in Figure 24.

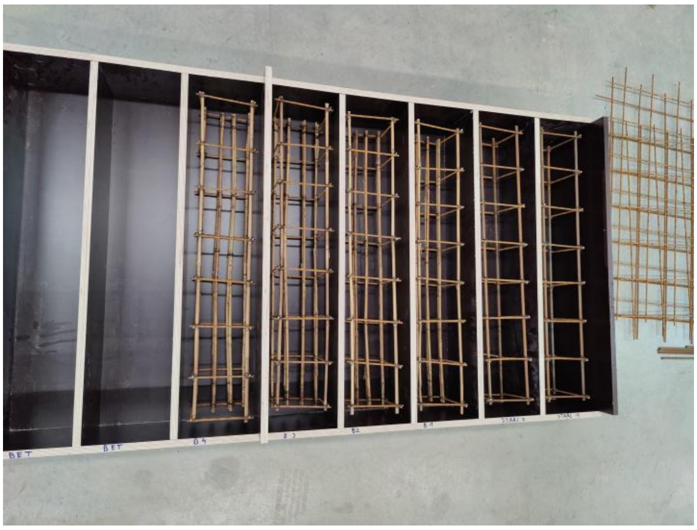

Figure 24: Formwork for the small beams

With the formwork and reinforcement cages ready, the concrete can be made with the concrete composition described in paragraph 4.2.3 and being poured into the formwork. After demoulding the beams, the dimensions of the beams are checked for deviations. The different dimensions can be found in Appendix A: Small span beams. The demoulded beams can be seen in Figure 25.

Figure 25: Demoulded small beams

4.4.2 Three-point bending test

A three-point bending test is used to determine the maximum force that can be applied on the concrete beams. Due to the force placed in the middle of the beam, the greatest bending moment will take place here and the reinforcement will experience the greatest tensile force at this location at the bottom of the beam. During the test, not only the force required to cause the beam to fail but also the displacement of the beam required to cause the failure is measured.
The important part of the test is that the beam is going to fail due to a lack of bending resistance and not due to a lack of shear resistance. The setup that is being used is shown in Figure 26.

Figure 26: Three-point bending test

The force of the machine, shown in Figure 26, increases at a rate of 500 N/s. The gauge that records the displacement is connected to the pressure point. The test pieces were painted along the sides with a white coating to capture the crack pattern.

4.5 Longer span beams subject to bending

4.5.1 Longer concrete beam description

After the information gained from the adhesion tests and 3-point bending tests, larger-scale tests can be carried out. A total of four beams will be tested: one beam with only steel reinforcements (SRC - Steel Reinforced Concrete), one with a combination of steel and bamboo with bitumen (BBSRC - Bamboo Bitumen Steel Reinforced Concrete), one with bamboo and bitumen (BBRC - Bamboo Bitumen Reinforced Concrete) and one with bamboo and bitumen which has grooves (BBGRC - Bamboo Bitumen Grooves Reinforced Concrete).

The beams have a cross section with a width of 20 cm and a height of 30 cm. For the transverse reinforcement, custom-made stirrups were used. The cross section with the transverse reinforcement can be seen in Figure 27. For the longitudinal reinforcement with bamboo, an average has been taken for the diameter.

The dimensions of the materials used are:

- transverse reinforcement consisting of:
    - steel S500: 14 x (15x25 cm), $\phi = 6\ mm$ (SRC, BBSRC, BBRC, BBGRC).
- longitudinal reinforcement consisting of:
    - steel S500: 4 x 2.4 m, $\phi = 12\ mm$ (SRC),
    - steel S500: 4 x 2.4 m, $\phi = 6\ mm$ (BBSRC),
    - bamboo: 3 x 2.4 m, $\phi = 29.8\ mm$ (BBSRC),
    - bamboo: 6 x 2.4 m, $\phi = 27.9\ mm$ (BBRC),
    - bamboo: 6 x 2.4 m, $\phi = 24.9\ mm$ (BBGRC).

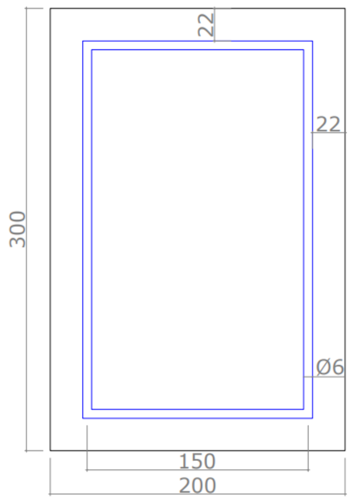

Figure 27: Cross section with transverse reinforcement

For SRC, a total of four steel bars are present as longitudinal reinforcement. The bottom two are for improving the tensile strength of the beam and the other two are for the construction of the cage. This can be seen in Figure 28.

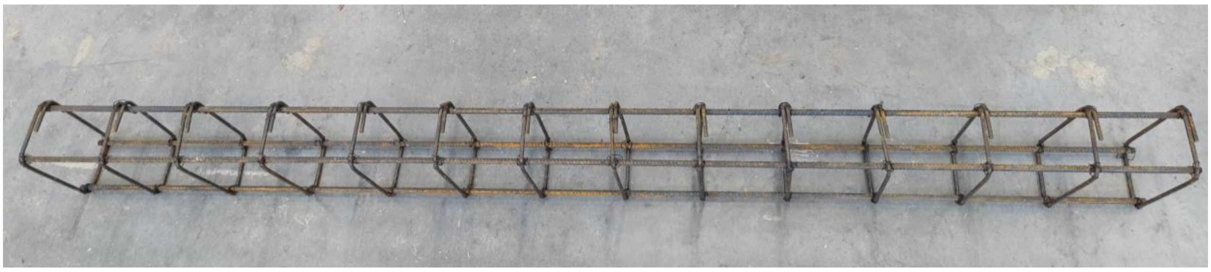

Figure 28: Reinforcement cage for SRC

For BBSRC, four steel bars are present as longitudinal reinforcement along with three bamboo bars. This bamboo is arranged so that two bars with the thick side are on the same side as the thin side of the other bar. This ensures that the reinforcement is distributed and not all large diameters are on one side. The bamboo bars are localised at the bottom of the reinforcement, as this is where the tensile forces will occur. With one bamboo bar between the two steel bars and the other two bamboo bars above the steel bars of the corner. This can be seen in Figure 29.

Figure 29: Reinforcement cage for BBSRC

For BBRC, six bamboo bars are used. Here, the bamboo is also arranged in a way so that the large diameters are not all on the same side of the reinforcement. The placing of the bamboo bars, with two bars in the corner of the transverse reinforcement. The other two bamboo bars, above the other two to respect the concrete cover because there is not enough distance in between the bars of the corners. This can be seen in Figure 30.

Figure 30: Reinforcement cage for BBRC

For BBGRC, the same arrangement as for BRC was used. However, grooves have been made in the bamboo to see if this affects the bending strength. This can be seen in Figure 31.

Figure 31: Reinforcement cage for BBGRC

To apply the grooves shown in Figure 31, a uniform way was devised to apply the grooves the same way everywhere. Thus, four grooves occupying 25% of the thickness of the stick were applied, each about 1 cm wide over a distance of 60 cm from the sides of the sticks. This was done by starting at the end and then applying a groove every 10 cm if possible. If there is a knot in the way, this distance is increased. So in an ideal situation, the grooves are within 50 cm and at worst within 60 cm from the side.

Next, all bamboo bars are coated with bitumen before being placed in the formwork. Spacers are used to hold the bamboo in place. This can be seen in Figure 32.

Figure 32: Formwork for the large beams

With the formwork and reinforcement cages ready, the concrete can be made with the concrete composition described in paragraph 4.2.3 and being poured into the formwork. After demoulding the beams, the dimensions of the beams are checked for deviations. These different dimensions can be found in Appendix B: Longer span beams. The demoulded beams can be seen in Figure 33.

Figure 33: Demoulded large beams

4.5.2 Four-point bending test

A four-point bending test is used to determine the maximum bending resistance of the concrete beams. The outer supports are 2.4 m apart. At the centre of these supports, there are two load points, with a distance of 88 cm between them, that transmit a force to the specimen. During the test, the force required to cause the beam to fail is measured from the two load points. The displacement is also measured at the two load points and in the middle of the beam. The setup that is being used is shown in Figure 34.

Figure 34: Four-point bending test

The force of the machine, shown in Figure 34, increases manually, this by gradually increasing the hydraulic pressure of the two pistons simultaneously. Figure 35 shows where the different forces and supports are located. All the dimensions are in mm.

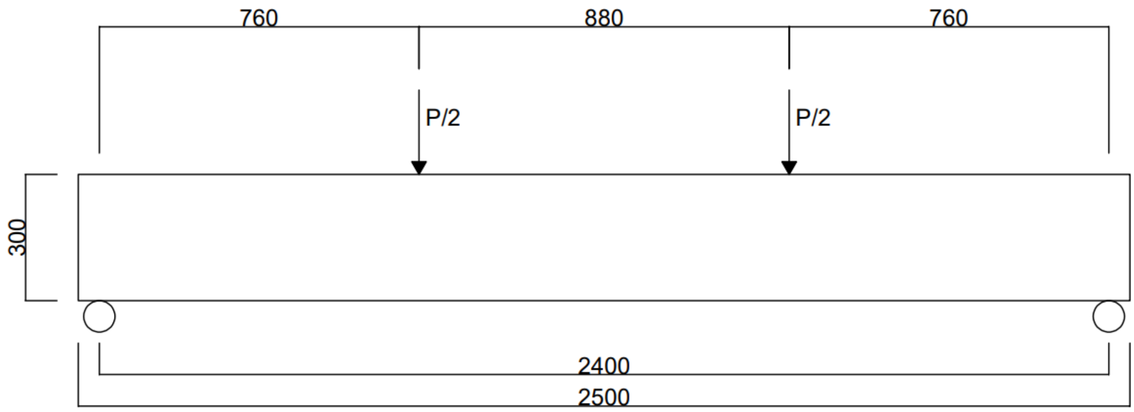

Figure 35: Location of the forces and supports

5 Experimental results

5.1 Pull-out test results

To determine the bond strength of bamboo with concrete, four types of specimens were designed, each of which three were tested. Three of the four types are bamboo without a knot in the concrete bars. These three then vary further whether no coating, bitumen coating or bitumen coating with sand was used. The last type is clear bamboo with a knot along each end of the bamboo stick located in the concrete bars. The results of the pull-out tests are shown in Table 6. With the second column showing the maximum force during the test. Using this force and the contact length between bamboo and the concrete, the maximum force per contact length is shown in column three. The last column lists the nominal deformation at maximum force. The formulas used to calculate the last two columns are the following.

Maximum force per contact length:

$$\sigma_{max} = \frac{f_{max}}{r^2 * \boldsymbol{\pi} * \frac{l_1 + l_2}{2}} \; (N/mm^2) \tag{8}$$

$with$
$r = \; radius\ of\ the\ bamboo\ in\ mm$
$l_1 = \; length\ of\ the\ bamboo\ in\ the\ first\ concrete\ bar\ (mm)$
$l_1 = \; length\ of\ the\ bamboo\ in\ the\ second\ concrete\ bar\ (mm)$
$f_{max} = \; maximum\ force\ applied\ on\ the\ specimen\ (N)$
$\sigma_{max} = \; maximum\ force\ per\ contact\ length\ (N/mm^2)$

Table 6: Results pull-out test

Specimen	Maximum force (N)	Maximum force per contact length (N/mm²)	Nominal deformation at maximum force (%)
Clear bamboo 1	189.74	0.06	1.14
Clear bamboo 2	241.50	0.08	0.10
Clear bamboo 3	365.69	0.12	8.79
Bitumen coating 1	3854.36	1.23	0.67
Bitumen coating 2	3005.69	0.95	0.57
Bitumen coating 3	4800.48	1.58	0.48
Bitumen and sand coating 1	1190.20	0.37	0.25
Bitumen and sand coating 2	1271.27	0.40	0.33
Bitumen and sand coating 3	1142.77	0.37	0.77
Clear bamboo with knot 1	5045.43	1.72	2.33
Clear bamboo with knot 2	2696.07	0.87	0.86
Clear bamboo with knot 3	3048.82	0.96	0.84

To account for minor deviations with differences between the length of the bamboo sticks in the concrete, the length of each bamboo stick was measured before pouring the concrete. After the obtained results of the maximum force, this force was related to the bond surface of the bamboo with the concrete. This is shown in the second column in Table 6. To get a clear relationship, the maximum applied force per specimen is on the following graph, which can be seen in Figure 36.

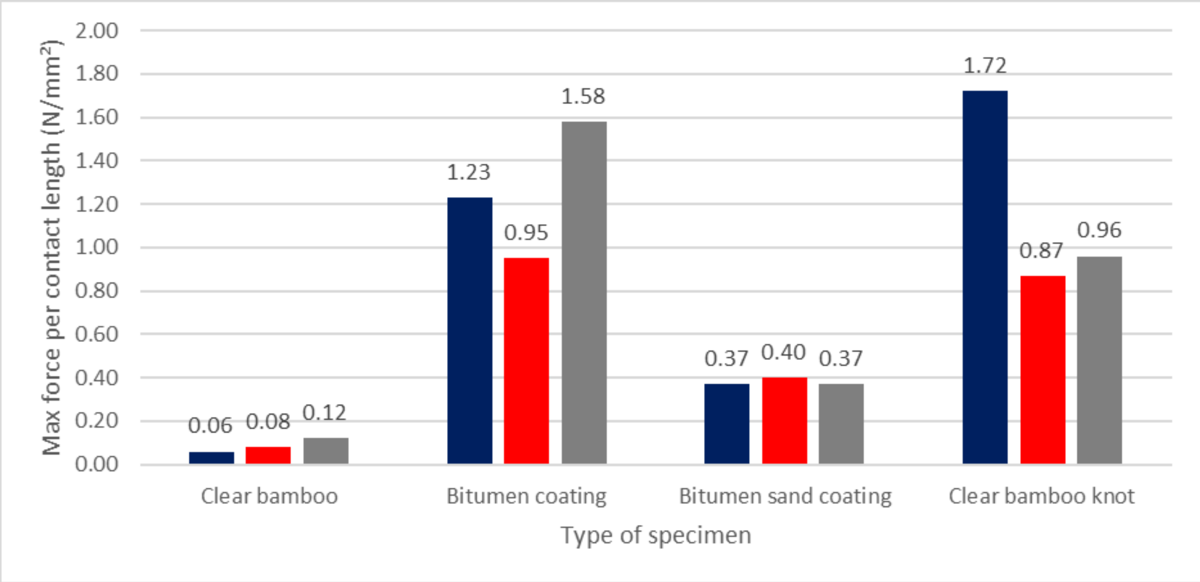

Figure 36: Results of pull-out tests

For adhesion with clear bamboo, a minimum of 0.06 N/mm² adhesion strength is obtained that the bamboo has with concrete. The maximum is 0.12 N/mm². The reason why the maximum is double the minimum is due to the thickness of the bamboo stick. After failure of the specimen, it can be seen that the bamboo stick becomes thicker as the end of the stick, this will cause extra friction. The thicker end can also be seen in the necessary displacement that is required to reach maximum force. After 29 mml deformation, the force is reached as the thicker end piece is pulled through a thinning passage which creates increasing resistance. If compared with Table 1, discussed in paragraph 3.1.4, it can be seen that the results for bamboo without treatment, with a value of 0.52 N/mm² [9], gives a higher bond strength than the results obtained in Figure 36. The lower result could be due to the handling of the delicate specimens and the smooth surface of Tonkin.

It can also be seen after failure that the contact surface between the bamboo and the concrete was a smooth surface. This can be seen in Figure 37.

Figure 37: Contact surface

With a maximum bond strength of 1.58 N/mm², it is clear that bitumen coating has a positive impact. In fact, the maximum bond strength is 13 times that of clear bamboo. This improvement corresponds to the improvement from Table 1 using Sikadur-32. Here an improvement of 5.29 times that of untreated bamboo was obtained. The greater improvement in this study is possibly due to the small bond strength of the untreated bamboo. It does show that bitumen effectively have a good influence on adhesion. The lower values for specimen 'Bitumen coating 2' was to be expected in advance. Before the test, slippage could be detected in the specimen, the cause may be the demoulding of the specimen.

The average bond strength of the bitumen with sand coating is 0.38 N/mm². The addition of the sand has a negative effect on adhesion, contrary to what was expected, but still has a positive effect compared to clear bamboo. The adhesion is 1/4 of the maximum adhesion with bitumen coating alone. The sand granules will lose adhesion faster than the concrete with the bitumen. Once the adhesion is gone, only the adhesion between the concrete and bitumen will withstand the force but with the addition of the sand, this contact area is reduced and so the adhesion strength will be lower. A possible solution is to mix the sand with the bitumen before applying the coating. During this study, the bitumen was applied first and then the sand, this makes sure the sand is not completely surrounded by bitumen. Thus, the contact surface between the concrete and the sand do not contain bitumen, so the breakdown of the grains takes place faster. Also, research [9] as discussed in paragraph 3.1.4 used a coating with sand. In this research, different coatings have been used with Negrolin+sand having the lowest improvement in bond strength. With only an improvement of 1.40 times the original bond strength, this is in trend with this research. Thus, it can be concluded that sand has an adverse effect as a coating.

The influence of a knot in the concrete can be seen in the last type of specimen. Although there is a big difference between the values, it is clear that a knot for clear bamboo will provide all the bond strength. The maximum value for specimens with knots is 1.72 N/mm². This is 14 times the maximum value for clear bamboo without knots. This also confirms the 14% [3] improvement a knot has on the bond strength between bamboo and concrete, cited in paragraph 3.1.2. Although the thickness difference between the bamboo rod and the knots must be taken into account. For specimen 'clear bamboo with knot 2-3', the values are 0.87 N/mm² and 0.96 N/mm², respectively. After failure of the specimens, it was clearly seen that the diameter of the knots did not differ much from the rod diameter. This again shows how difficult it is going to be to use bamboo in practice, there will always be a safety factor to take into account for the amount of knots and the variation of the thickness of the knots. Also, the values are not representative because the bond strength is included by the knot only. The strength should not be represented over the whole surface of the bamboo but rather the amount of knots per length. Figure 38 shows the failure of the concrete bar, where the concrete broke at the height of the knot.

Figure 38: Knot in concrete bar

In comparison to research [8], as discussed in 3.1.4, where an average bond strength of 0.13 MPa was found for untreated bamboo, this research has an average bond strength of 0.09 MPa. Using Sikadur 32+ increased the adhesion to 0.59 MPa for research [8]. Making the adhesion 4.5 times stronger. In this study, the greatest average improvement in adhesion strength is for the bitumen coating with 14.5 times the adhesion strength. Research [9] also uses a Sikadur 32 gel and here achieves an improvement of 5.29 times the original bond strength. However, it must be taken into account that the original bond strength is 0.52 MPa which is six times the average bond strength of this study. Also, the maximum bond strength with this coating reaches 2.75 MPa which is more than double the bond strength achieved with bitumen.

To better understand the results, the force measured during the tests is shown as a function of specimen deformation. This is shown on the following four graphs, Figure 39 - Figure 42, representing the three specimens by type.

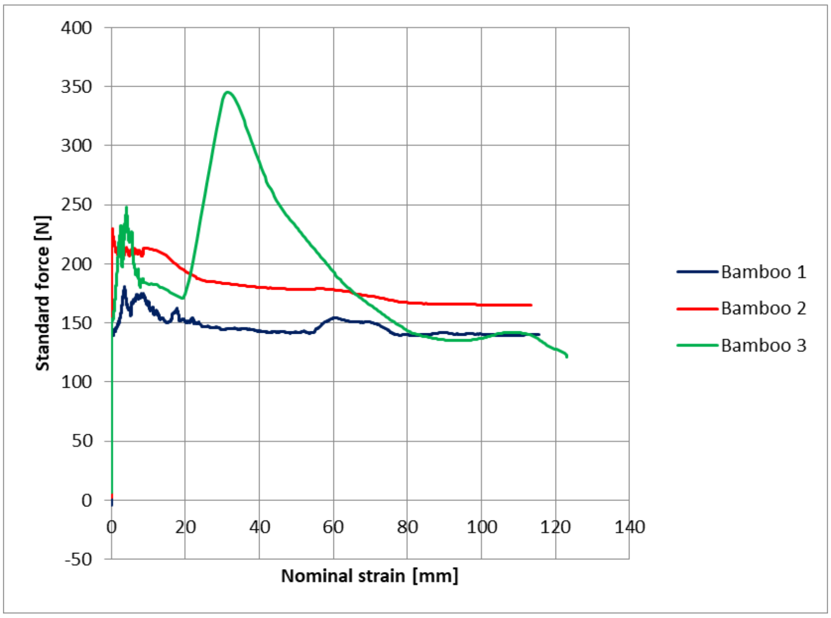

Figure 39: Clear bamboo

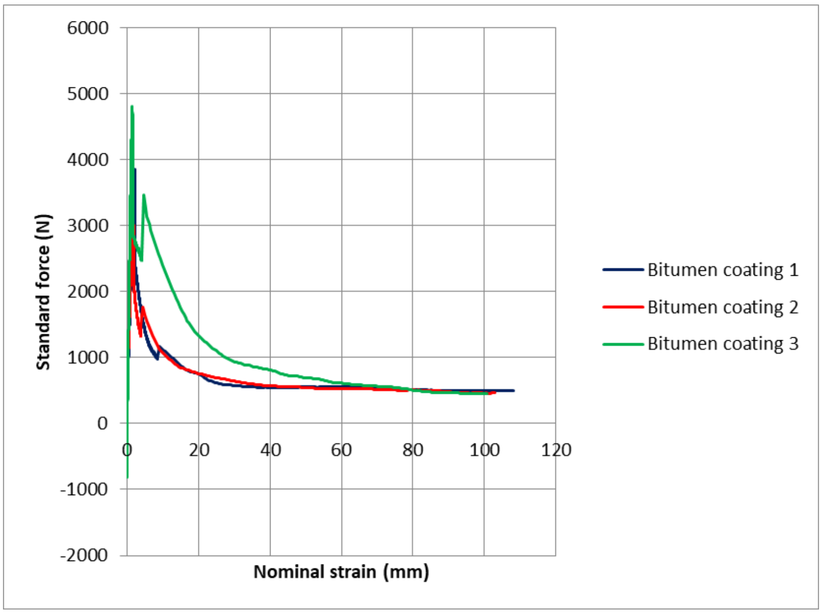

Figure 40: Bitumen coating

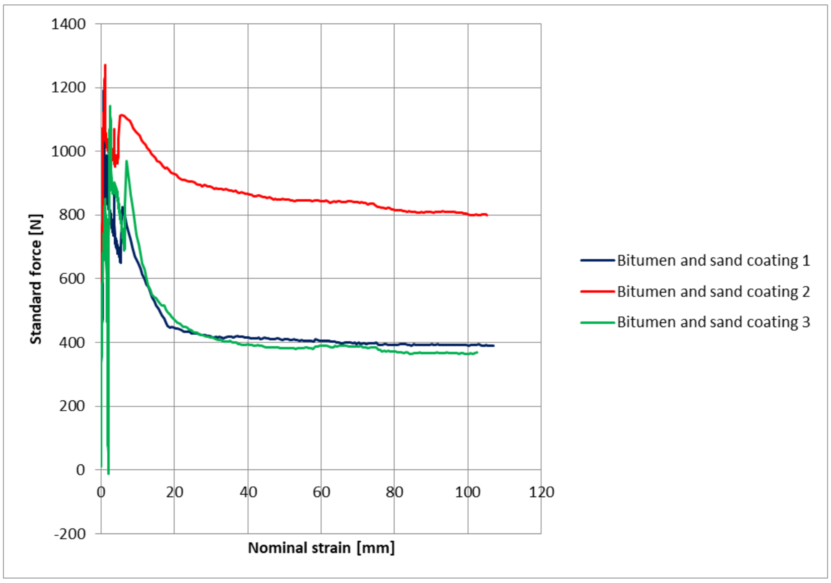

Figure 41: Bitumen and sand coating

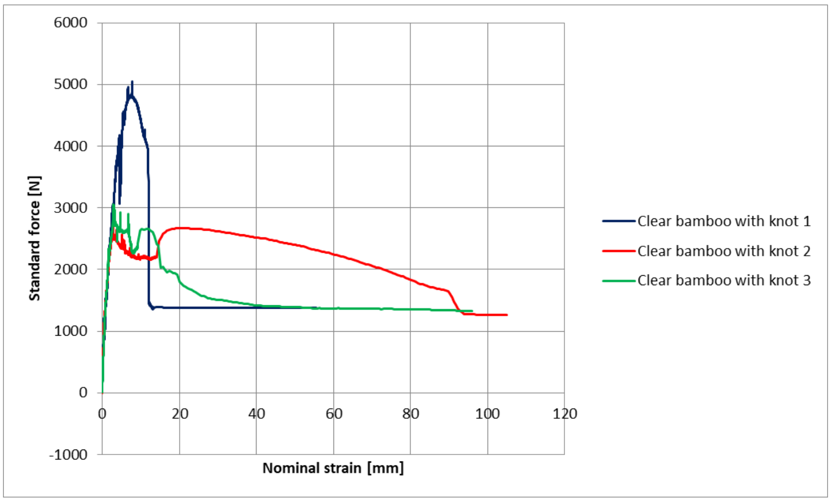

Figure 42: Clear bamboo with knot

If Figure 39 - Figure 42 are compared, a general course can be observed. The general course of the force as a function of deformation is a steep increase in force at the beginning of the test where the maximum force is immediately reached. After this, the bond breaks and slip begins to occur between the bamboo and the concrete. Here local peaks and drops occur over a very short deformation period. Shortly after this, the final strength is reached which is much lower than the maximum strength. The ultimate strength remains constant for the rest of the deformation and shows that the bond is completely gone and not regained. On this general tendency, it can be noted that in Figure 39 an exception can be seen. Here after the first peak a valley can be seen after which maximum strength is experienced. This can be linked to the fact that the thickness of the bamboo stick thickened towards the end as mentioned earlier.

For Figure 40 and Figure 41, the general trend is followed for all samples. Figure 42 gives a different view. All three samples do not follow the standard trend but all show different deviations. 'Clear bamboo with knot 1' withstood the greatest maximum force and reached this force immediately at the beginning of the trial. Once the maximum load is reached the force drops to its final strength. The large drop is due to the breaking of the concrete. 'Clear bamboo with knot 2' first shows the general tendency after which adhesion is regained and the maximum is reached. This shows that once the bond is broken it can still be regained from the thickening of the bamboo stem by the knots. The last specimen of this category shows irregular increases and decreases after reaching the maximum. This indicates that the knots are providing adhesion again but the difference between the diameter of the stem and knot is not large enough.

The conclusion is that a way of adhesion improvement is needed, as also discussed in 3.1.4. Adding bitumen helps with improving the adhesion but then sand should not be used. The surface of bamboo is to smooth that the friction between pure bamboo and concrete is negligible. The only bond strength is obtained from the thickening of the knots. Without an applicable solution that is feasible in practice and does not risk reliability, the use of bamboo has no added value despite the good material properties of the material itself.

5.2 Three-point bending test

To see the effect of the bamboo reinforcement, the results for maximum strength are compared between the four types of specimens. The amount of reinforcement for the beams was calculated in advance so that no matter what type of reinforcement was used, the maximum load would be the same. The results obtained are shown for each specimen in Figure 43.

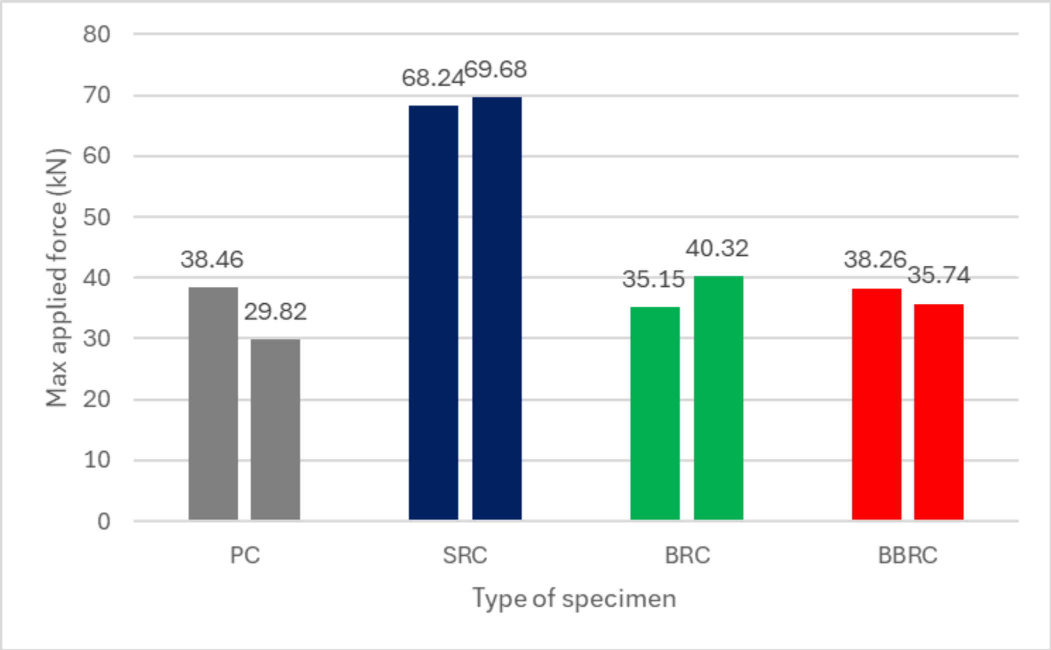

Figure 43: Max applied force for each specimen

The results show that the bamboo reinforcement does not add to the maximum allowable load on a concrete beam. The values are similar for PC, BRC and BBRC. The values have large deviations, for example, between PC1 and PC2 there is a difference of 8.64 kN. Because of this, it cannot be said whether bamboo reinforcement has a positive influence on bending strength. The desired strength is not achieved for the bamboo reinforcement, nor is there any difference in strength between the bamboo reinforcement with or without bitumen. With these results of maximum strength, similar results were obtained to the study at Fukuyama University [11], which is described in 3.2. Where the beams with steel reinforcement absorb almost double the force of those with bamboo reinforcement.

During the bending test, force and deflection were measured together. Using the force as a function of deflection, the deformation behaviour of the beam is shown. It can also be seen how ductile or brittle the beams behave against each other. For the eight tests, the graphs can be seen in Figure 44.

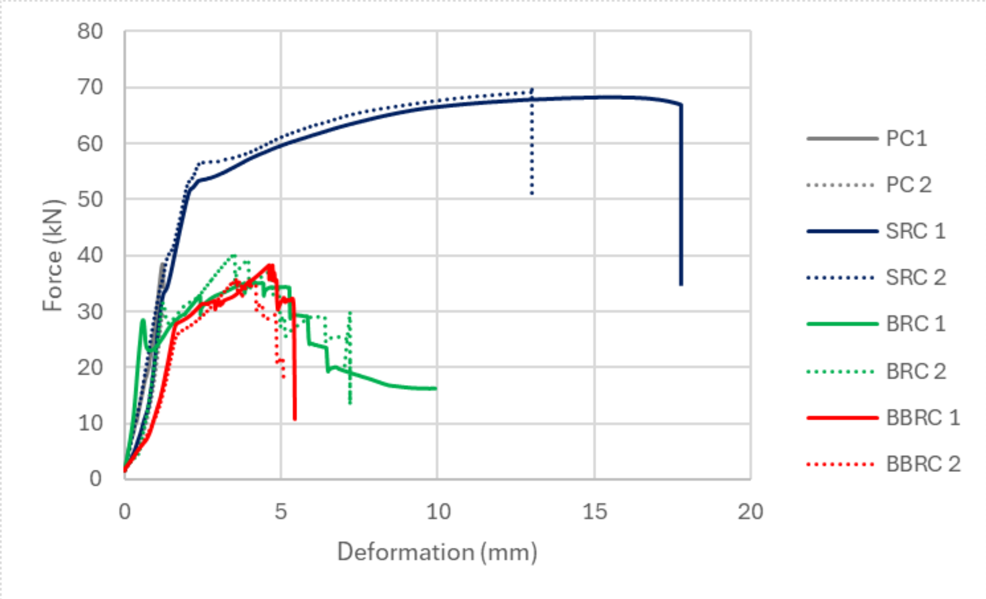

Figure 44: Force in function of deformation for all tests

Figure 44 shows all eight tests which gives an overview of the force-deflection behaviour and consequently, the impact of the use of different types of reinforcement. The graph clearly shows that SRC can handle the largest force. In addition, it can be seen that the strength values of bamboo and concrete are close to each other as discussed earlier. Only there is a big difference with the ratio of deformation between plain concrete and bamboo. What is clear from the graphs is that concrete only shows an elastic deformation and has a brittle fracture when it reaches its maximum strength. Unlike bamboo, the deflection will increase further. During the increase in deflection, the strength goes down in steps after reaching its maximum. Between the two different bamboo reinforcements, there is also a difference in the gradient of the graph. After the linear gradient of the beam, there is a difference between BRC and BBRC. For the reinforcement without bitumen, a decrease in force takes place just after the elastic deformation, after which the force will increase again and reach the maximum force. With BBRC, there will be no decay and the maximum applied force will be reached immediately after the elastic deformation. This shows that the better bonding of the bitumen helps with decreasing the slip. But prior to this there is development of cracks, as it can be seen, the load does not decrease but when cracks occur the stiffness lowers visibly. This is also the case for BRC.

The graph in Figure 44 will now be divided to provide a better discussion of the results. First, Figure 45 shows only the graphs for the plain concrete beams.

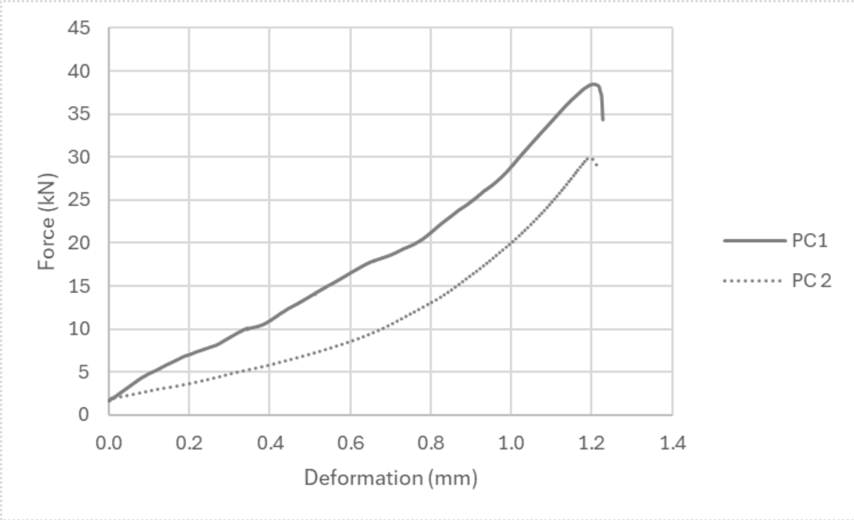

Figure 45: Force in function of deformation for PC-beams

As can be seen in Figure 45, the gradient only shows elastic deformation until the beam breaks brittle. Both beams break after a deformation of 1.2 mm. The cracking pattern for the plain concrete is shown in Figure 46.

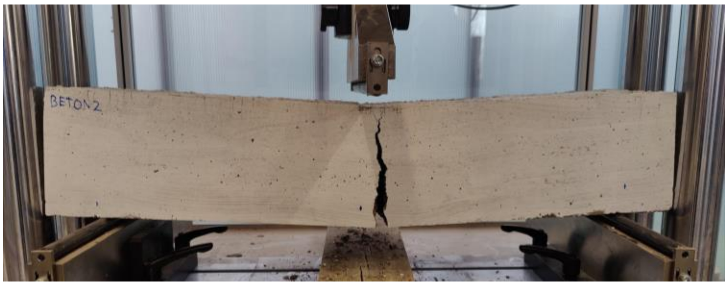

Figure 46: Cracking pattern of PC

As can be seen in Figure 46, the cracking pattern consists of a single crack that breaks the beam in two and is located at the middle of the beam which corresponds to the position of the maximum bending moment.

Next, Figure 47 shows the graphs for the beams with steel reinforcement.

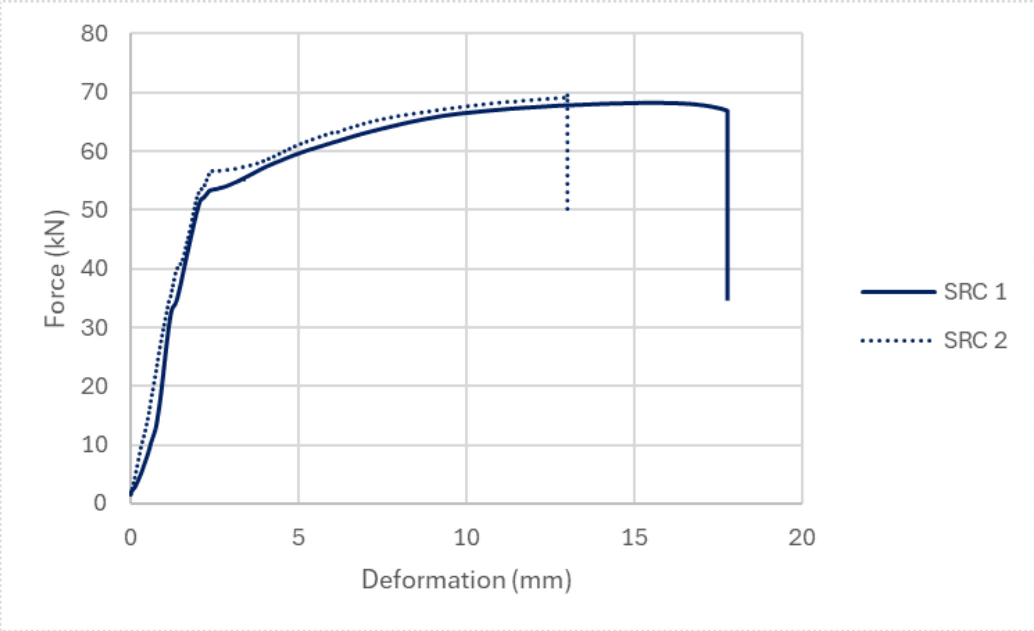

Figure 47: Force in function of deformation for SRC-beams

As can be deduced from Figure 47, the deflection of SRC beams proceeded in two parts. In the first part, the beam behaves linearly up to a force of 55 kN. After the elastic deformation, the reinforcement in the beam starts yielding and a different force distribution occurs. During the plastic deformation, the force only goes up by 15 kN but the deformation goes up by 15.2 mm for SRC 1 and 10.6 mm for SRC2 which is 85% and 81% of the total deformation. During this section, the fractures in the concrete are going to occur and the reinforcement is going to flow until necking takes place in the steel bars, this will lead to the ultimate failure of the beam. This ultimate failure results in the reinforcement breaking, which can be heard with a bang during testing. The necking of the steel reinforcement is shown in Figure 48. This is followed with breakage.


Figure 48: Necking of steel reinforcement

The cracking pattern of the steel reinforced concrete beams can be seen in Figure 49.

Figure 49: Cracking pattern of SRC

As can be seen in Figure 49, the cracking pattern consists out of multiple cracks. This confirms the study by Fukuyama University [11] discussed in section 3.2 and shown in Figure 8.

Next, Figure 50 shows the graphs for the beams with bamboo reinforcement.

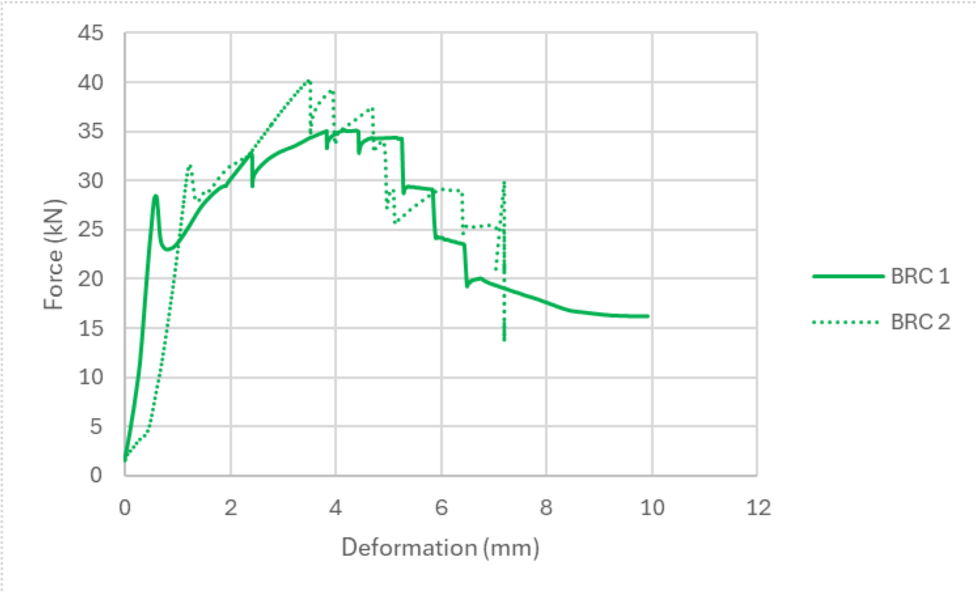

Figure 50: Force in function of deformation for BRC-beams

As can be seen in Figure 50, the course of the BRC beams has first an elastic deformation, the difference with the SRC is that the bamboo starts cracking when it is activated. At the beginning of the activation of the bamboo, a redistribution of the forces on the bamboo reinforcement takes place after the cracking of the concrete. This causes a drop in the applied load to occur and then the deformations continue where slip of the bamboo occurs. This can be seen by the different jumps in the graphs. After reaching the maximum load, the force starts to decrease in steps. This is again due to the slipping of the bamboo sticks in the concrete. The slipping happens in pieces, the reinforcement regains its bond through the knots. The final failure will happen after the breakage of one or more bamboo sticks or when the reinforcement cannot regain its bond through the knots. This breakage can be seen in Figure 51. BRC 1 reaches a deformation of 10 mm and BRC 2 a deformation of 7.2 mm.

Figure 51: Breakage of the bamboo reinforcement

The cracking pattern of the bamboo reinforced concrete beams can be seen in Figure 52.

Figure 52: Cracking pattern of BRC

As can be seen in Figure 52, the cracking pattern consists out of a single crack, which contradicts the research of the Fukuyama University [11]. They indicate that the cracking pattern is the same for steel and bamboo reinforcement. Multiple cracks should be present in both. However, only one crack is present here. This can be explained by the poor adhesion provided by the bamboo reinforcement.

Next, Figure 53 shows the graphs for bamboo reinforced concrete with bitumen.

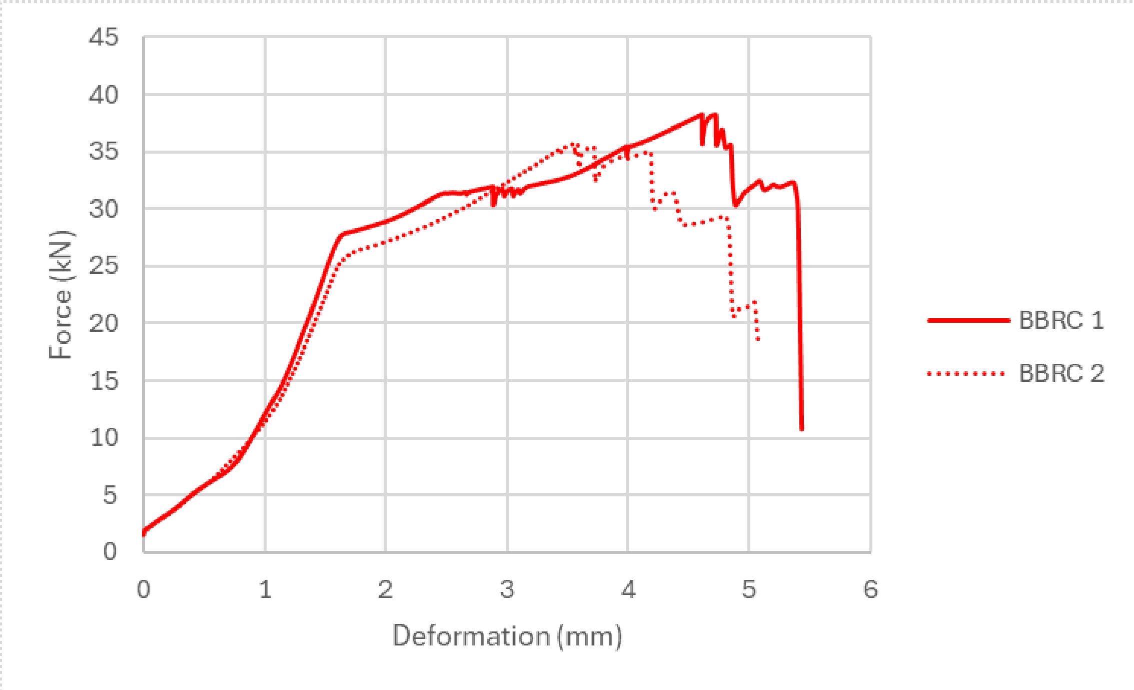

Figure 53: Force in function of deformation for BBRC-beams

The graphs of the BBRC beams, which can be seen in Figure 53, show a different course after elastic deformation. The force experiences no decrease and cracking of the bamboo occurs immediately. After reaching the maximum force, the decrease in force goes back down in steps. Thus, the transition of the forces from the concrete to the reinforcement is more gradual courtesy of the better adhesion due to the bitumen layer. Also, there are fewer steps in the decrease of force and the steps are also smaller. BBRC 1 and BBRC 2 achieved a deformation of 5.4 mm and 5 mm, which are lower than the deformations of BRC 1 and 2.

Figure 54 shows the breakage of one of the reinforcement bars.


Figure 54: Breakage of the bamboo with bitumen reinforcement

The cracking pattern of the bamboo reinforced concrete beams with bitumen can be seen in Figure 55.

Figure 55: Cracking pattern of BBRC

As can be seen in Figure 55, the cracking pattern consists out of multiple cracks. With this, the same fracture pattern is present here as with steel reinforcement. This confirms the study of the Fukuyama University [11], shown in Figure 8. So the bitumen here provides better adhesion, making the cracking pattern similar to that of steel.

Now that all graphs by species have been discussed, the graphs can still be discussed among themselves to see clear differences between the materials. Figure 56 and Figure 57 show a comparison between the different bamboo reinforced beams, with and without bitumen, and the plain concrete beams.

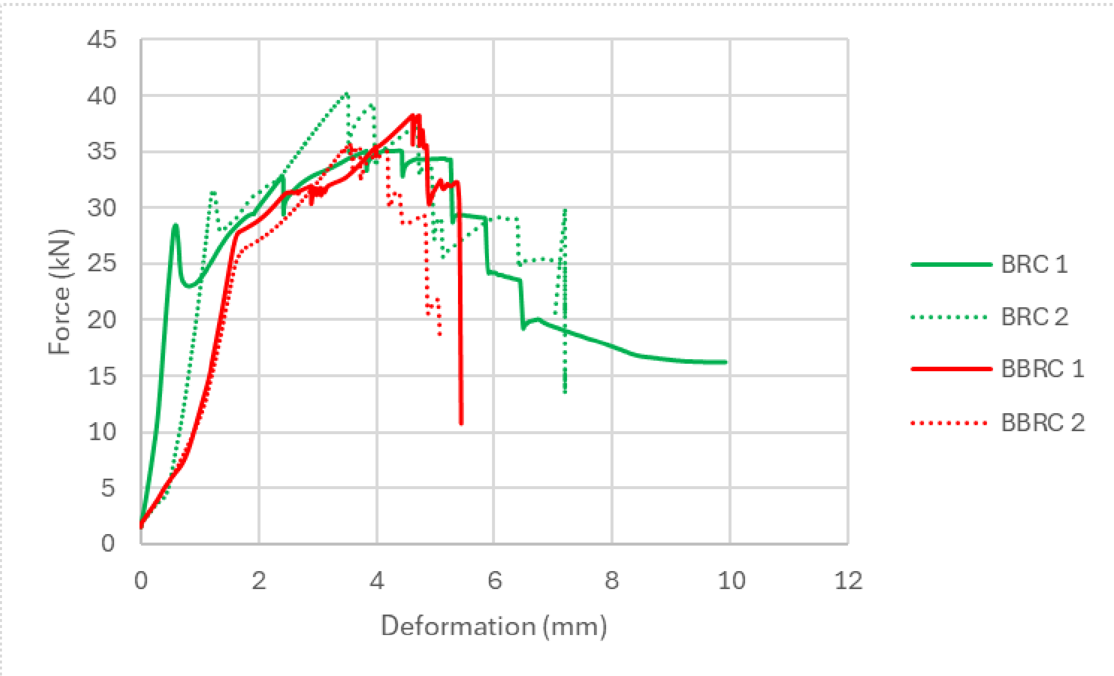

Figure 56: BRC and BBRC beams compared

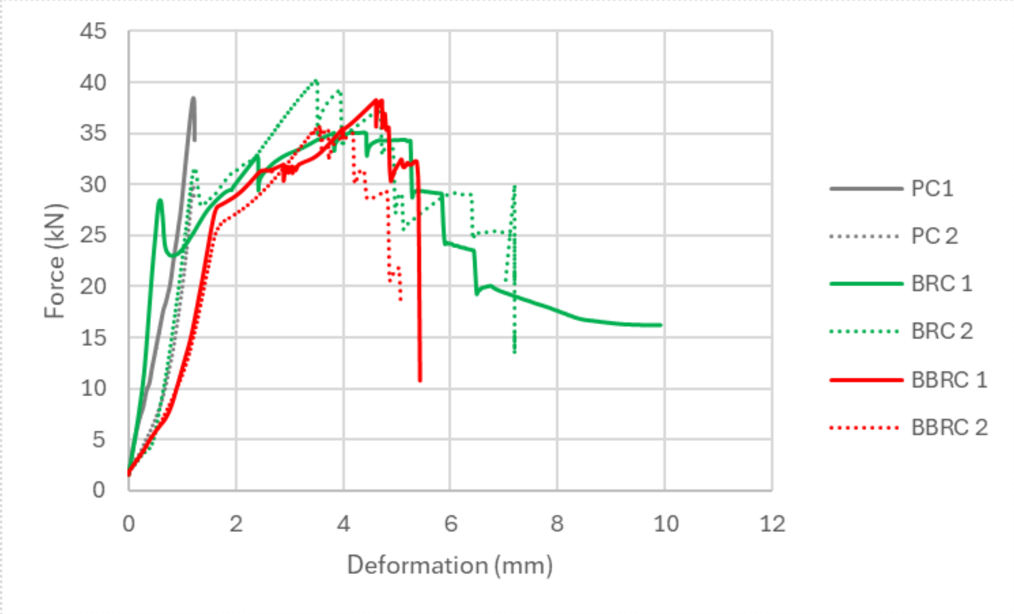

Figure 57: PC, BRC and BBRC beams compared

The following can be concluded from Figure 56 and Figure 57. The bamboo reinforcement has a positive influence on the total force that the beam can absorb and on the deformation that is required for the failure of the beam. BRC1, BRC2, BBRC1 and BBRC2 have resistance to a force that is 118%, 133%, 124% and 117% compared to PC 2. This is not the force that was calculated beforehand, this becomes clear when the force is compared with the steel reinforcement. SRC1 resisted a force that was 233% greater in comparison to PC2.

The influence of the bamboo has a greater impact on the deflection of the beam. Here, the deflection of BRC1, BRC2, BBRC1 and BBRC2 is 833%, 600%, 450% and 417%, respectively, compared with PC2. This means that the bamboo reinforced beams will no longer show brittle fracture and have a greater safety margin because the failure of the beam is faster to detect due to the fractures in the concrete. Also, the beams can absorb more energy because the area under the curves is larger than for an unreinforced beam. The interesting part is that BRC 1 and 2 have a larger deformation than BBRC 1 and 2. The lower deformation can be explained by the fact that the reinforcement has better cooperation with the concrete while BRC undergoes greater deformation under very low force due to continued slippage of the bars in the concrete.

These data show that adding a bitumen coating has no contribution on the load-bearing capacity and deflection of the beam. Due to the large amount of uncertainties, it is unclear whether the coating has an effect on the load-bearing capacity. The amount of knots per stick, the diameter of the bamboo reinforcement and the tensile strength of a bamboo rod varies from stick to stick and also over the length of the rod which gives a greater uncertainty and can cause large differences between similar types of reinforcements.

Using the areas under the previous functions, the ductility of the beams can be determined based on the energy. Only the steel reinforcement will obtain a yield strength and have a plastic deformation. For the bamboo reinforcement, the loss of stiffness is due to cracking in the concrete. For these the maximum force will be taken as the end point of the elastic stage, where the bamboo will start to slip. Table 7 shows the absorbed energy. Here the absorbed energy is divided into the elastic and total energy. Besides these, there are also two ratios shown. The first ratio is to see how ductile the beams respond, where the total absorbed energy is divided by the elastic absorbed energy. The second ratio is to compare how much more energy the beams can absorb compared to an unreinforced beam, PC1 to be precise. For this, the total absorbed energy of the beam in question is divided by the total absorbed energy of PC1.

Table 7: Absorbed energy three-point bending test

Type of specimen	Elastic absorbed energy	Total absorbed energy	Ratio total over elastic energy	Ratio total absorbed energy of PC1 to the different specimens
PC1	21.34	21.34	1.00	1.00
PC2	16.23	16.23	1.00	0.76
SRC1	88.18	1070.17	12.14	50.15
SRC2	83.84	765.83	9.13	35.89
BRC1	121.66	252.89	2.08	11.85
BRC2	97.03	214.10	2.21	10.03
BBRC1	116.17	143.08	1.23	6.71
BBRC2	76.15	122.21	1.60	5.73

Examining Table 7, it can be seen that the PC beams are completely elastic, with a total over elastic ratio of 1, and thus break very brittle as discussed before. After breaking, the beam will move, but there will be no more force on it. Looking further at the SRC beams, it can be seen that with a ratio of 12.14 and 9.13, the beams absorb a large amount of energy in the plastic range, which makes the response ductile in comparison to the others.

When the results for the beams reinforced with bamboo are compared, there are a number of things which are noticeable. First, it can be seen that the total absorbed energy for the BRC beams is larger than that for the BBRC beams. This can also be deduced from Figure 56. Furthermore, it can be seen that the ratios of the BRC beams, 2.08 and 2.21 respectively, are similar to each other and the ratios of the BBRC beams, 1.23 and 1.60 respectively, are also similar to each other. The BBRC beams can handle less deformations, so the total absorbed energy will be lower than that of BRC beams, and thus the ratio will also be lower.

If the ratios are compared between steel and bamboo beams, it can be seen that the ratios of the SRC beams are around five times larger than those of the BRC beams and around eight times larger than those of the BBRC beams. However, the ratios of bamboo do show a difference with the ratios for PC beams. This does show that the bamboo has a positive effect on the energy absorbed by the beams but does not come close to the energy of what the SRC absorbed.

The last column of Table 7 shows a comparison with the total absorbed energy of PC1. With this column, it is possible to compare how much more energy the beams with reinforcement can absorb. As can be seen in this column, the SRC beams show a very large factor, e.g. SRC 1 can absorb 50 times more energy than PC1. The two BRC beams show smaller ratios, but similar to each other, they absorb around ten times more energy than PC1. The BBRC beams show even lower ratios, they absorb around six times more energy than PC1.

If the ratios of the total energy over the elastic energy from Table 7 are compared with research [10] which can be seen in Figure 7, as described in 3.2, there are different aspects that stand out. Only SRC and BRC out of Table 7 can be compared with the energy ductility from RCC and FRS-BRC from Figure 7, as the same methods were used. First, it is already noticeable that the result for RCC with 1.792 [10] is smaller than the result for SRC with 12.14 and 9.13. So this means that SRC has a much larger plastic area compared to the elastic area and is thus more ductile than RCC. This is also already noticeable in the various graphs. For example, the graph of RCC in Figure 6, is more linear, while in the graphs of SRC in Figure 47, there is a clear transition from elastic to plastic with a large plastic area. For the bamboo beams, the results are more similar. For instance, for FRS-BRC with 1.672 [10], a similar result is present as for BRC with 2.08 and 2.21. However, the results for BRC are slightly higher, but this is also due to the deformations that continue to occur after the maximum, when the force starts to decrease, this can be seen in Figure 50. For FRS-BRC, there are no significant jumps present in the graph, shown in Figure 6, which means that little to no slip is present here and therefore it is possible to speak of a pure plastic zone in contrast to the BRC beams. The differences here are also due to different concrete and steel grades and different construction of beams and reinforcement. So, with this in mind, these differences are not considered problems and will vary from experiment to experiment.

To represent the influence of reinforcement and to compare with other research, the ratio of the maximum load of the different reinforcement types to the unreinforced beam was calculated. The ratio between the SRC and PC is $\frac{F_i}{F_{pc}} = 2.02$, BRC and PC is $\frac{F_B}{F_{pc}} = 1.11$ and the last ratio is between BBRC and PC with $\frac{F_{BB}}{F_{pc}} = 1.08$. In research [10] a ratio of 4.75 was achieved for the steel reinforcement and for the bamboo reinforcement a ratio of 4.61 with the unreinforced beam, as described in 3.2. These ratios are close to each other in contrast to this study where the ratio of steel is about double that of the two bamboo types. This shows a great contrast, research [10] makes the use of bamboo as reinforcement seem possible while this result does not substantiate this claim.

5.3 Four-point bending test

5.3.1 Force flow by beam

As a final result of the four-point bending test, the following results were obtained: the two different loads per pressure point, the deformation at each pressure point and the deformation at the centre of the beam. First, the forces of the pressure points are shown as a function of the deformation at that pressure point. Figure 58 shows the graph for the beam reinforced with bamboo and bitumen.

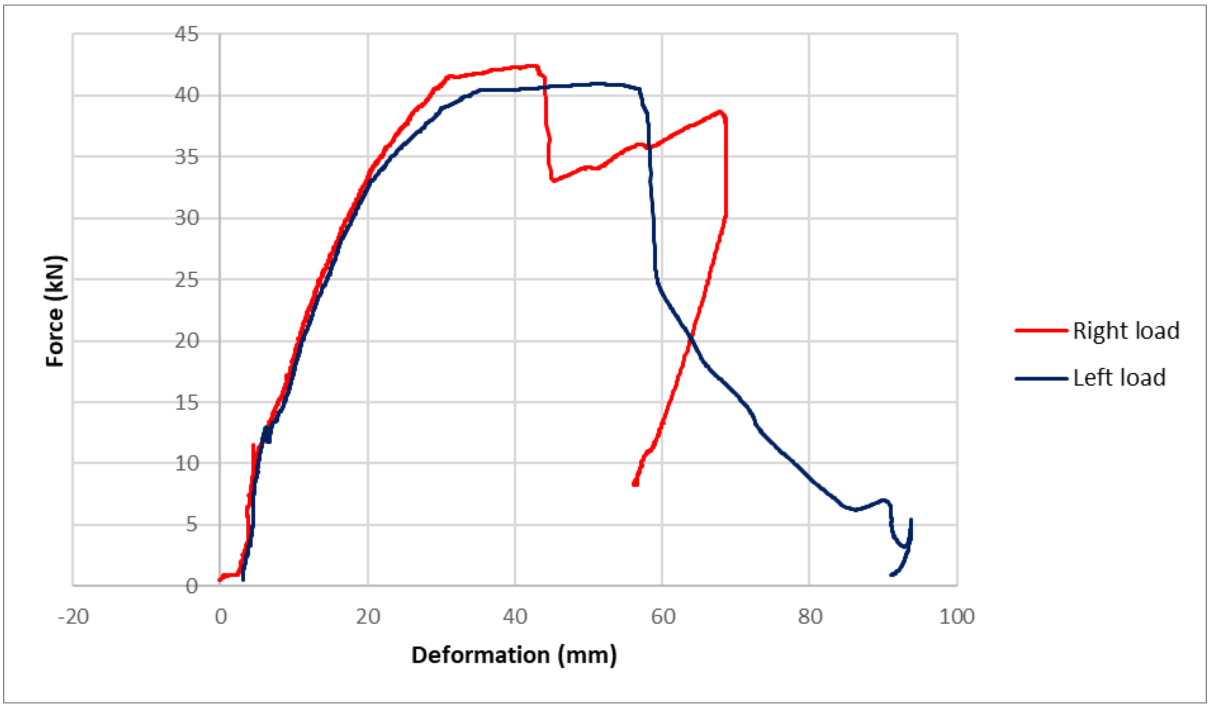

Figure 58: Results of BBRC

Figure 58 shows the course of the left and right pressure point. The course of both forces is very uniform with an increase which is followed by a plane where the maximum value is reached of 42.42 kN in the right pressure point. After reaching the maximum, a steep drop follows in which the pressure points move apart. The right pressure point goes back to experiencing an increase in load after a deformation of 45.8 mm. Here a local maximum of 38.5 kN will be found after a deformation of 68 mm. However, the left point will not experience an increase and will continue to decrease. This difference can be explained by the eccentricity of the bamboo due to the large inequalities of the reinforcement. The large permanent deformation in the left point is an indication that this is where beam failure will occur. It is noticeable that the maximum force of the left pressure point is lower than the right point with a value of 40.9 kN. But the left pressure point has undergone a large deformation of 58 mm for this purpose.

The cause of the local decrease in the right pressure point can be explained by a new force distribution in the reinforcement. Two causes can account for this, the first cause can be by the breaking of a bamboo stick causing the drop to take place. After this, a new force distribution will take place in the reinforcement causing a local maximum to be reached. A second cause is based on test series two. The possibility of slip between concrete and bamboo can cause a drop to take place and by regaining adhesion a new increase in strength can be noticed. The failure of the BBRC beam can be seen in Figure 59.

Figure 59: Bending of the BBRC beam

Figure 59 shows the presence of a large crack on the left side of the beam as has been concluded from Figure 58. This crack is the critical crack that caused the beam to fail. Apart from this crack, only small cracks are present at the right pressure point. Figure 60 shows a close-up of the failure of the bamboo reinforcement.

Figure 60: Close-up failure of the bamboo reinforcement

Figure 61 shows the graph of grooved bamboo with bitumen reinforcement.

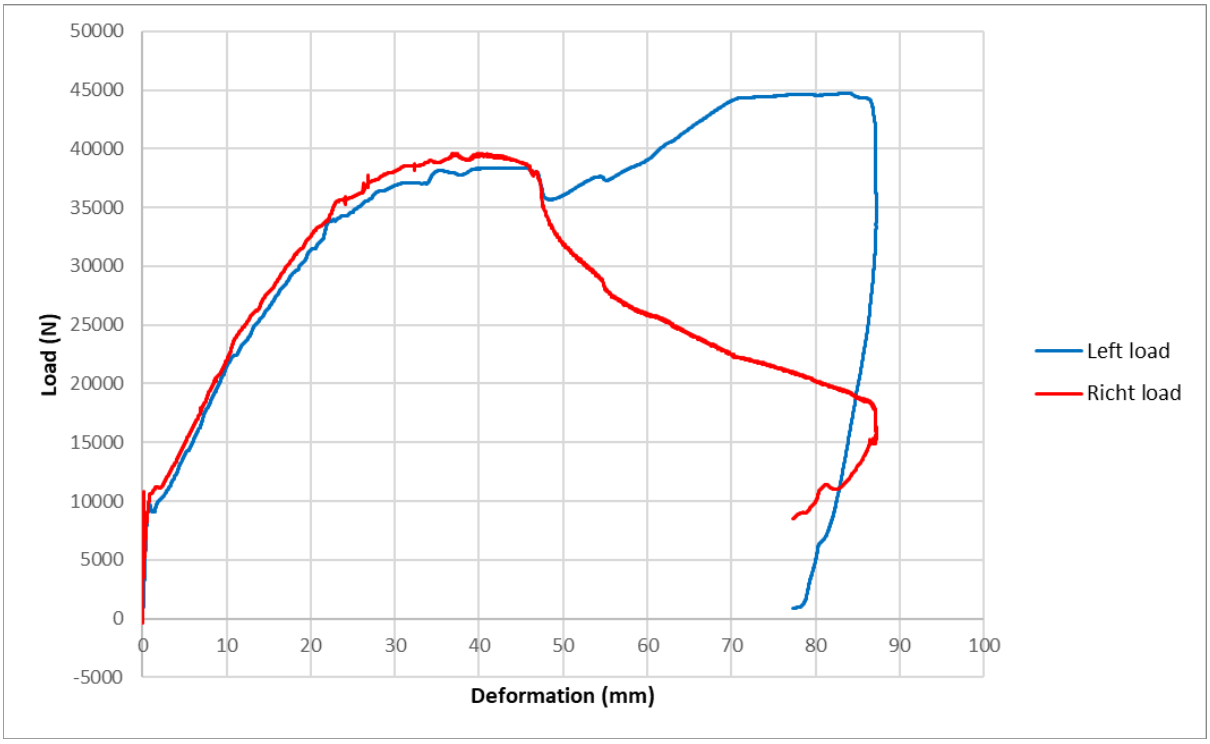

Figure 61: Results of BBGRC

Figure 61 shows the course of both pressure points. Here it can be seen in the beginning that both pressure points show a similar course up to a deformation of about 38 mm at a force of 35.6 kN in both pressure points. After this, the load in the left point increases to a maximum of 44.76 kN at a deformation of 84 mm after first experiencing a small decrease. This indicates that there is a shift in the force distribution in the reinforcement. The right load keeps experiencing a steep decrease, without a small drop. The large deformation in the right point makes it clear where the fracture is taking place. After reaching the maximum in the left pressure point, it can be noticed that not only the force decreases toward zero but also reduces the deformation of the beam. The failure of the beam happens after the bamboo reinforcement breaks or when the bond between the bamboo and the concrete disappears. When the bamboo reinforcement breaks, the tension is lost in the bamboo reinforcement and since this is elastically deformed under bending the reinforcement tends to return to its original shape. This is not the case with steel reinforcement since it has undergone plastic deformation and is going to retain its final shape.

Figure 62 shows the bending of the BBGRC beam.

Figure 62: Bending of the BBGRC beam

Figure 62 shows the presence of a critical crack on the right side of the beam. In contrast to BBRC, the other cracks are located more towards the middle of the beam, rather than under the left pressure point. Figure 63 shows a close-up of the failure of the grooved bamboo reinforcement, in which it can be seen that the bamboo is split.

Figure 63: Close-up failure of the grooved bamboo reinforcement

Figure 64 shows the gradient for the reinforcement combination of bamboo with bitumen and steel.

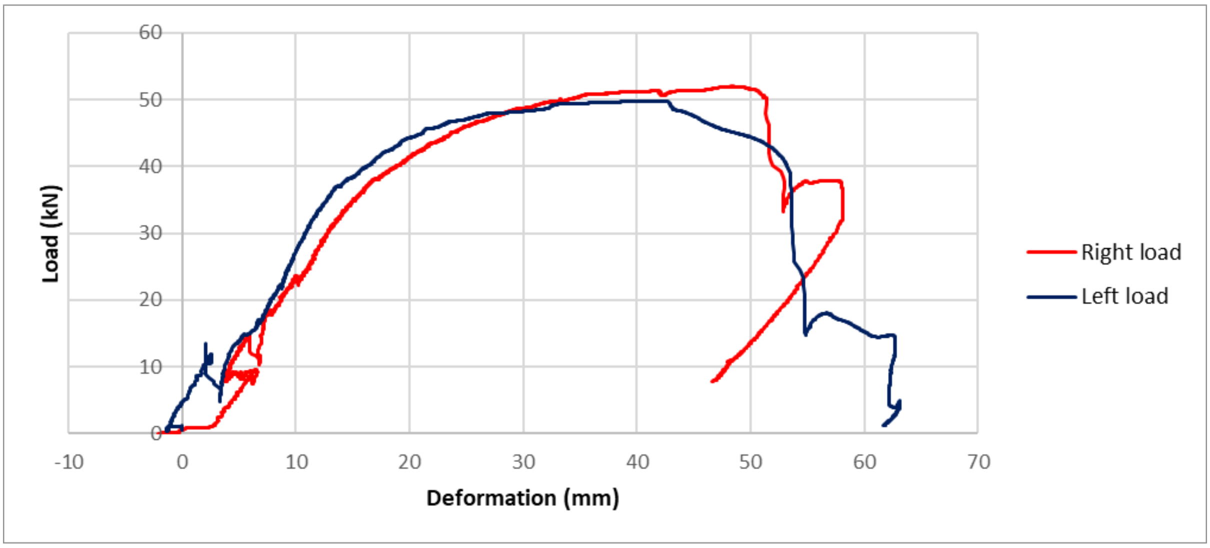

Figure 64: Results of BBSRC

Figure 64 shows a different course as the previous two. Initially during the increase in load, there are staggerings in the graph that are not expected. There is a constant interchange between the rise and fall of the force and deformation. This may be due to the inaccuracy of the test setup. After the unconstant trend, the same sequence takes place as in the previous two scenarios where both pressure points rise to their maximum load and reach a plateau. After reaching the maximums in both pressure points a drop in forces occurs. The course of both pressure points is similar because after the drop a small increase in force takes place after which the force tends to zero completely.
The maximum load is reached in the right pressure point with a force of 51.97 kN at a deformation of 46.64 mm. The largest final deformation is seen in the left pressure point while the deformation of the right point decreases again after failure of the beam like the previous tests.

The more similar course of both pressure points indicates that adding steel reduces the eccentricity of the reinforcement. Figure 65 shows the bending of the BBSRC beam.

Figure 65: Bending of the BBSRC beam

Figure 65 shows the presence of a critical crack on the left side of the beam. Similar to BBRC, the other cracks are located under the right pressure point. Figure 66 shows a close-up of the failure of the bamboo and steel reinforcement, in which the necking of the steel reinforcement is visible, while the bamboo reinforcement, located in the middle of the beam, is still intact. The bamboo reinforcement at the bottom of the beam did split.

Figure 66: Close-up failure of the bamboo and steel reinforcement

To compare these observations and results, Figure 67 shows the result of the steel reinforcement.

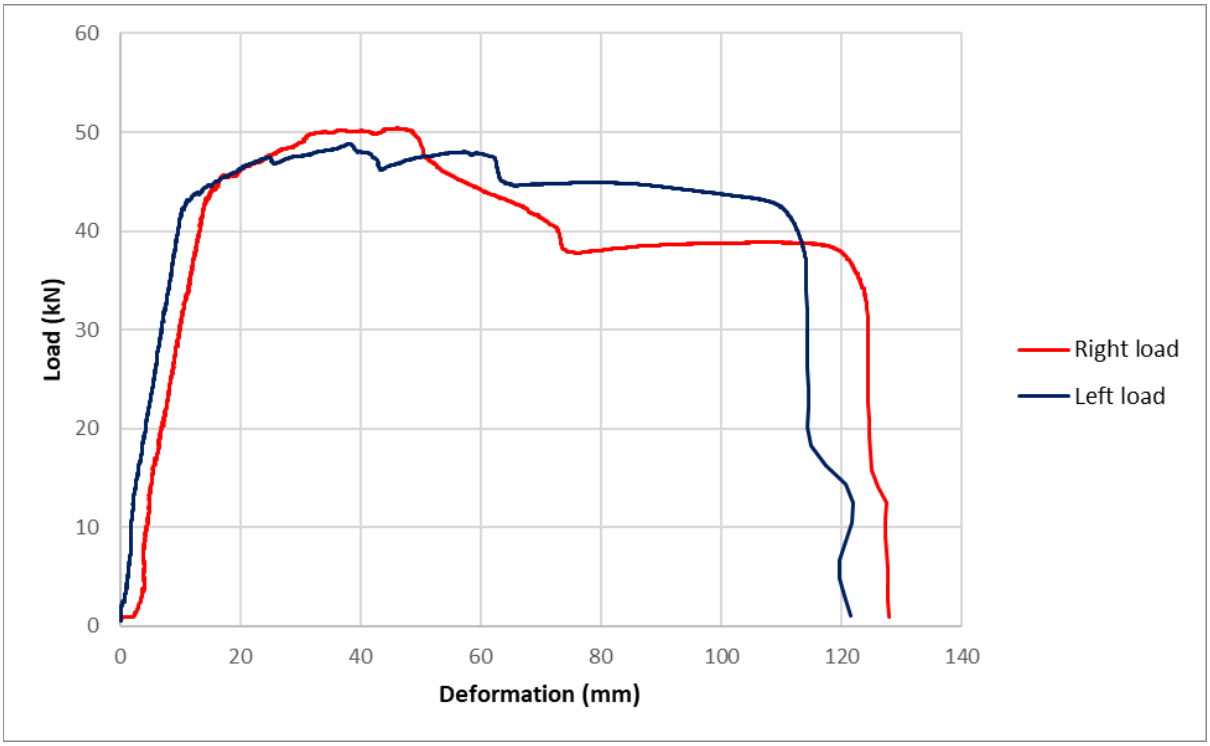

Figure 67: Results of SRC

The known course of a steel reinforcement is shown in Figure 67. The course of the forces is first linear until approximately a force of 42.8 kN after which the plastic region begins. A maximum load of 50.42 kN is reached after a deformation 46.1 mm in the right pressure point. After this, the forces in both pressure points gradually decrease until necking takes place in the reinforcement and a steep decrease takes place until the beam fails. The deformations in both points are almost similar to each other, the left point has an ultimate deformation of 121.51 mm and the right point 127.87 mm. This shows that similar deformation takes place between the pressure points during the entire test. After failure, there is also no reduction in the deformations at either of the two points like the previous three tests. Figure 68 shows the bending of the SRC beam.

Figure 68: Bending of the SRC beam

Figure 68 shows the presence of a critical crack in the middle of the beam. In this figure, it is clearly visible that all cracks occur in the middle of the beam between the two pressure points. Furthermore, it is clearly visible that there is pressure at the top of the beam. This can be seen by the horizontal crack located at the top of the beam. Figure 69 shows a close-up of the failure of the steel reinforcement, in which the necking of the steel reinforcement is visible.

Figure 69: Close-up necking of the steel reinforcement

5.3.2 Influence of the reinforcement

To consider the different workings of the reinforcements, the forces in the two pressure points were added together. This total force in kN was put as a function of the deformation at the centre of the beam in mm. The results for the four specimens are shown in Figure 70. However, it must be taken into account that the bending resistance of the four reinforcement types are different. The resistance of the reinforcements depends on the material used. For the bamboo reinforcement, the diameters of bamboo availability and how many sticks could fit in the beam were considered in order to respect the concrete coverage and still come as close as possible to the bending resistance of the steel reinforcement.

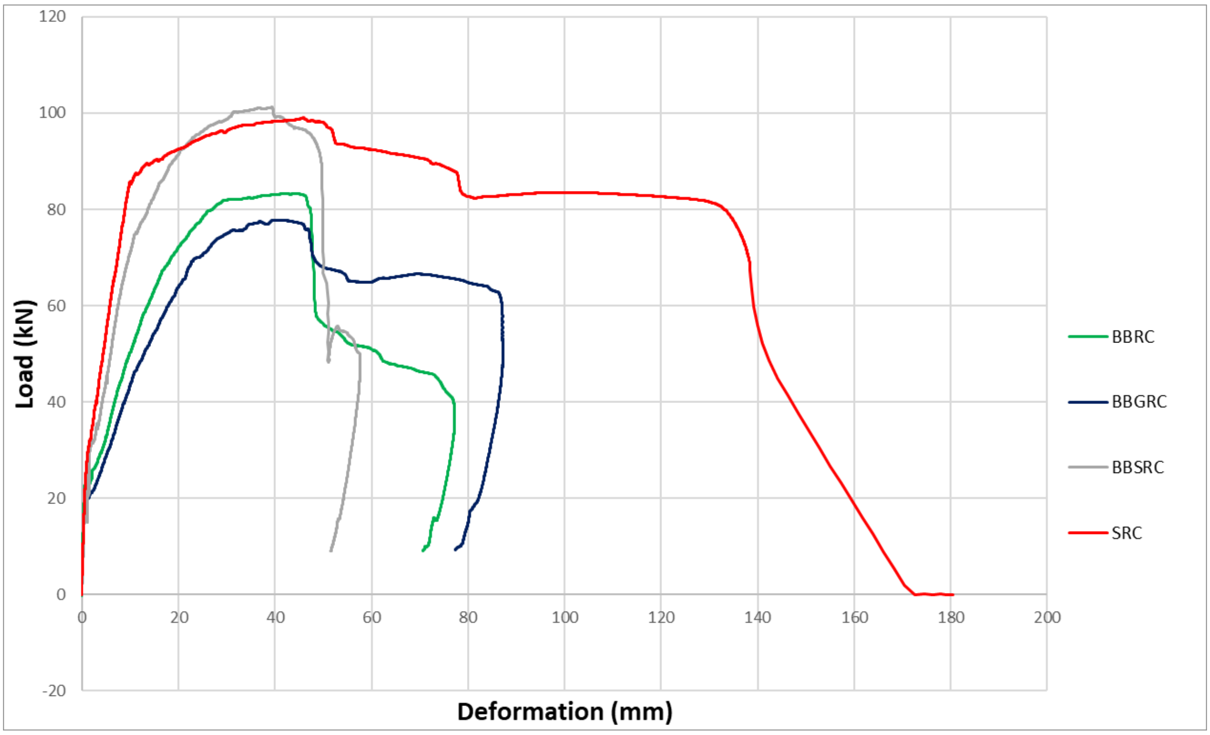

Figure 70: Total load for each type of reinforcement

As can be seen in Figure 70, the four functions all show a similar progression. After a steep rise, a maximum is reached after which a moderate decline takes place which is terminated with a sharp drop which happens by the failure of the beam. The red graph shows the result of the steel reinforced beam. The beam withstood a maximum load of 99.0 kN and has a total deflection of 172.5 mm. After reaching the maximum values, the force decreases in two stages: after reaching the maximum force until necking of the reinforcement and until the beam fails completely.

The combination of a steel and bamboo reinforcement provided the largest load. This beam withstood a maximum load of 101.1 kN. At the same time, this beam experienced the smallest deflection, which is a disadvantage. After a deflection of 57.62 mm, the beam failed. The drop in load is much sharper as this versus steel. After reaching the maximum, failure of the beam immediately follows. As seen in Figure 66, the steel reinforcement has failed, while the bamboo at the bottom split, but did not break. This indicates that the two reinforcement types complement each other and work together. Because of the smaller diameter of the steel reinforcement, smaller plastic deformation and faster necking is going to take place here in comparison with SRC. Once the steel failed, the bamboo had to take over. Since there is only one bamboo stick in the most critical zone, it was not able to fully absorb all the forces. The result is that the beam failed, with less deformations than the other beams. The maximal force to be absorbed is the highest among all the beams. Therefore, there is an added value in combining steel and bamboo reinforcement. However, the deformation still needs to be improved, and so does the energy the beam can absorb.

The result of the bamboo reinforcement is shown in green. Here it can be seen that there is a similar gradient to steel, only after reaching the maximum there is a greater decrease than SRC. After reaching the maximum, the beam seems to have lost its bending resistance but regains strength after a large decrease in strength. After this, the beam fails after a deformation of 77.2 mm. The maximum load on the reinforcement is 83.3 kN.

The last feature is the blue one and shows the result of the grooved bamboo reinforcement. Here it can be seen that a maximum is reached and immediately followed by a decrease. The maximum for the reinforcement is 77.8 kN which is lower than the bamboo reinforcement without grooves. This means that a lower maximum is reached in comparison with the bamboo reinforcement but a smaller decrease takes place afterwards. Also, the reinforcement with grooves experiences greater deformation with a maximum of 87.29 mm. This deformation is achieved after the decrease of the maximum and a plateau occurs where the force remains approximately constant and the deflection increases. To provide an overview, Table 8 shows the maximum load and deformation for each specimen.

Table 8: Overview of the maximum load and deformation

Specimen	Max load (kN)	Max deformation (mm)
BBRC	83.3	77.2
BBGRC	77.8	87.29
BBSRC	101.1	57.62
SRC	99.0	172.5

Table 8 gives an overview where some points stand out. The maximum force for a specimen is associated with the lowest deformation, this for BBSRC. SRC withstood the second highest load but has a deformation ratio of 0.45, 0.51 and 0.33 compared to BBGRC, BBGRC and BBSRC. Research [12] discussed in 3.2 has shown that certain bamboo reinforcements exhibit greater deformation of four to seven times the deformation of a steel reinforcement. This research does not agree with this determination and shows that a steel reinforcement is more ductile as a bamboo reinforcement contrary to what research [12] states.

If compared with Figure 13, discussed in 3.2. The forces and deformations in Figure 13 are smaller, but the same trend can be observed as in Figure 70. Steel reinforcement here also sticks out above the bamboo reinforced beams with maximum strength and deformation. When the bamboo reinforced beams are then compared, they show a slight deviation. The BBGRC beam cannot withstand a higher maximum force than BBRC. However, the grooved bamboo can withstand a greater force for longer and, in doing so, also a greater deformation, which is similar to Figure 13.

The formation of the first cracks was further observed during the tests. These values are shown in Table 9. These values are guide values and may therefore differ slightly from cracks that were already present but not well visible.

Table 9: First cracks during the tests

Specimen	Load (kN)
BBRC	30
BBGRC	36
BBSRC	35
SRC	48

Looking at the values in
Table 9, it is noticeable that the beams with bamboo reinforcement have similar results for initial cracking. Furthermore, SRC stands out above the rest, with a load of 48 kN for the first cracks. If compared with Figure 5, as discussed in 3.2, the loads for the first cracks are similar for RCC, PRS-BRC and FRS-BRC. The higher load for the first cracks of SRC in
Table 9, can be explained by the better adhesion and the higher ductility of the steel reinforcement.

Similar to the small beams in 5.2, the absorbed energy of the large beams can now be compared, this is shown in Table 10. Also in the four-point bending tests, there is slip between the bamboo and the concrete. The slip is less noticeable here, this may be due to the larger diameters with larger knots. As a result, for the bamboo reinforced beams up to the maximum load is considered elastic. The ratio is to see how ductile the beams respond, where the total absorbed energy is divided by the elastic absorbed energy.

Table 10: Absorbed energy four-point bending test

Type of specimen	Elastic absorbed energy	Total absorbed energy	Ratio total over elastic energy
BBRC	3076.19	4826.31	1.57
BBGRC	2394.90	5502.83	2.30
BBSRC	2298.86	4965.43	2.16
SRC	953.62	12032.08	12.62

When the results of Table 10 are analysed, several things are noticeable. First, SRC shows by far the highest total absorbed energy, but at the same time also the lowest elastic absorbed energy. This shows that steel can absorb a very large amount of energy in a plastic manner. Furthermore, the results of the beams reinforced with bamboo show similar results for the total absorbed energy, with BBGRC having the largest value of the three with a value of 5502.83. Furthermore, BBSRC and BBGRC absorb less elastic energy.

When looking at the ratios of total over elastic energy, similar results to the three-point bending tests from Table 7 can be seen. First, SRC with a value of 12.62 shows a similar result to SRC1 with 12.14. In both tests, the ratios for the steel reinforced beams are significantly higher than the others. In addition to SRC, BBRC from Table 10 can be compared with the BBRC beams (test series 2) from Table 7. For

BBRC (test series 3), the lowest ratio is obtained of the different beams, this with a ratio of 1.57. This shows a similar ratio to BBRC2 (test series 2), with a ratio of 1.60. Looking at the ratios of BBSRC and BBGRC (test series 3), similar ratios are obtained. So this means that the ratio of elastic absorbed energy to total absorbed energy is similar for both types of beams.

It can be concluded from these results that the grooves have a positive effect on the absorbed energy, but do not come close to the SRC beams, which absorb twice as much energy and have a ratio of total absorbed energy to elastic energy that is five times higher.

However, there are many uncertainties present:

- the formwork is homemade, which leads to deviations in the dimensions of the beams, which can be seen in Appendix B: Longer span beams;
- the bamboo has different sizes and different knot sizes, resulting in reinforcement that is not the same in each beam, which can be seen in Appendix B: Longer span beams;
- the concrete is homemade in batches of 0.3 m^3, which is not enough to fill all the beams at once, leading to various deviations per batch;
- the expected bending resistance of the beams are not equal because the reinforcement is not the same for the four species, therefore the energy absorbed by the four beams is not comparable.

However, efforts have been made to minimise these uncertainties as much as possible. For the deviations in the dimensions of the beams, a theoretical calculation has been done, this is further addressed in paragraph 5.3.3.To address the differences in dimensions of the bamboo sticks, the bamboo was arranged so that the thick and thin ends alternate on different sides of the beam to eliminate this difference as much as possible. For the various concrete compositions, each batch was made as closely as possible to the theoretical values from paragraph 4.2.3.

5.3.3 Comparison of experimental and theoretical values

To effectively consider the usefulness of the different types of reinforcements, this chapter presents the theoretical values for the bending resistance for each beam and compares this with the experimentally obtained values. This is necessary to filter out all the uncertainties since the resistance of the reinforcements differ among each other and cannot be compared in this way. The bending resistance of an unreinforced beam is first calculated in order to have a reference of the influence of the four reinforcement types and for comparison with other research. To calculate the bending resistance in case of a plain concrete beam the next formulas are used.

Average tensile strength [17]:

$$f_{ct,m} = 0.3 * (f_{ck})^{2/3} \ (MPa) \tag{9}$$

$$f_{ct,m} = 0.3 * (42.84)^{2/3} = 3.673 \ MPa$$

Bending resistance:

$$M_r = f_{ct,m} * \frac{b*h^2}{6} \ (Nmm) \tag{10}$$

By not using standard moulds for casting the beams, the dimensions of the beams differ. As a result, the bending resistance is calculated per beam and shown in Table 11. In column three, the maximum bending moment is calculated during the tests using the maximum force. The formula of the bending moment is shown below, this formula is based on the fact that the failure will occur between the two pressure points where the moment will be constant. Also the distance between the pressure point and the support is 760 mm which is used in the formula (x).

Bending moment:

$$M = 760 * \frac{P}{2} (Nmm) \tag{11}$$

With
$P = \ total\ force\ of\ both\ pressure\ points$

Table 11: Comparison moments with plain concrete

Type of specimen	Width beam (mm)	Height beam (mm)	$M_{r,plain}$ (Nmm)	Maximum force (N)	M_r (Nmm)	Ratio $\frac{M_r}{M_{r,plain}}$
BBRC	191.5	300.3	10833251	83271	31642980	2.92
BBGRC	223.5	293.7	12088427	77799	29563506	2.45
BBSRC	200.0	299.3	11238882	101163	38441940	3.42
SRC	192.5	299.0	10793345	99001	37620342	3.49

Calculating $M_{r,plain}$ takes into account the deviations in the width and height of the beams, these deviations can be seen in Appendix B: Longer span beams. This is necessary because while making the test specimens, for example, a deviation of 32 mm occurred in the width between BBRC and BBGRC. In the penultimate column, using the measured maximum force, the critical bending moment of the beams was calculated. With these values, the last column shows the ratio between the bending moment measured during the test and what the bending moment would be without the reinforcement.

At first glance, BBSRC seemed the most promising of the four types of reinforcements by resisting the greatest force. Now it turns out that this type of reinforcement has the second largest ratio to unreinforced concrete, the ratio is 3.42. When looking at SRC, there is a ratio of 3.49. The lower maximum force is due to the smaller width of the beam. The difference between the two types does not represent much compared with BBRC. This specimen has a ratio of 2.92 and thus has a 192% improvement in bending resistance. The lowest ratio is for BBGRC with a ratio of 2.45. Despite the lowest ratio, the flexural resistance did increase by 145% versus unreinforced concrete. So the addition of the grooves seems to cause a 47% decrease. The cause of this decrease can also be linked to the difference in bamboo diameter and by the difference of the diameter between the start and end point of the bamboo stick which will cause a difference in slip.

In comparison with the results of 5.2, the ratio of the steel reinforcement is improved in test series 3. Series 3 has a ratio of 3.49 by contrast with series 2 with a ratio of 2.02. The results of series 3 are more aligned with research [10] as described in 3.2, where a ratio of 4.75 is achieved. In the case of the bamboo reinforcement with bitumen a ratio of 2.29 is achieved in series 3 which is also higher than the ratio of 1.08 of series 2. In research [10] a ratio is achieved of 4.61 which is higher than the results of serie 3. Test series 3 are more in line with research [10] than series 2. The ratios between the two types of reinforcement are closer together for series 3 than series 2 in comparison with research [10]. The magnitudes of the ratio are not comparable between the studies as it depends on the concrete section and the amount of reinforcement used. But research [10] and the results of series 3 confirm that it is possible to use bamboo as reinforcement.

To account for the differences in reinforcement, the bending moment resistance is then calculated for each specimen. Formula (1) and (5) as discussed in 2.2 are used, additionally calculate formula (12) for moments equilibrium. Since the beam is double reinforced, formula (13) is for determining the addition of the compression reinforcement. Because of the four-point bending test, the moment between the two pressure points is constant and formula (14) can be used to determine the moment between these pressure points.

Moments equilibrium:

$$M_n = F_s * (d - 0.4 * x) \quad (12)$$

With

$F_s =$ tensile strength of steel reinforcement

$d =$ effective height

$x =$ concrete pressure height

Addition pressure reinforcement:

$$M_r = M_n + A_{s2} * f_{yd} * (d - d_2) \quad (13)$$

With

$M_r =$ bending moment resistance

$A_{s2} =$ surface pressure reinforcement

$f_{yd} =$ characteristic fluid strength

$d_2 =$ distance most compressed fibre to compression reinforcement

Moment between the pressure points:

$$M_r = 3 * \frac{P/2}{L} \quad (14)$$

With

$P = total\ force\ of\ both\ pressure\ points$

$L = distance\ between\ both\ pressure\ points$

With these formulas, the theoretical values for the maximum load are determined and compared with the experimental values. This is shown in Figure 71.

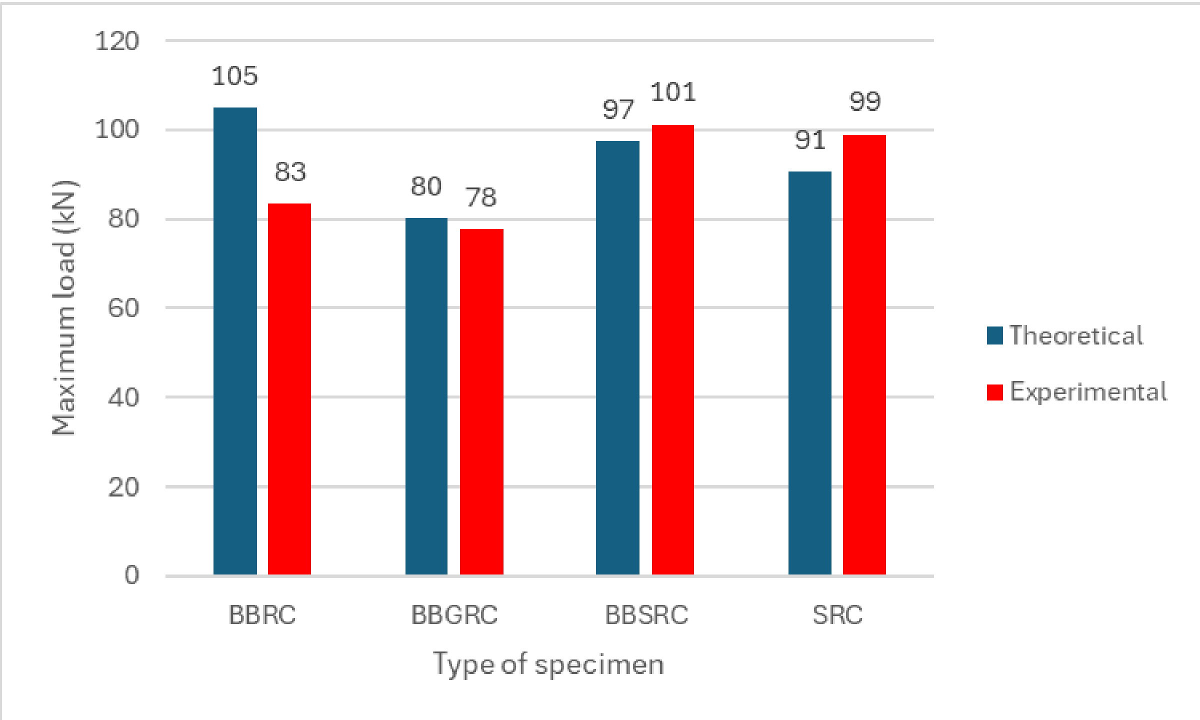

Figure 71: Maximum load theoretical vs experimental

Figure 71 shows the maximum loads per specimen obtained during the tests in red. In blue are the theoretical values obtained by calculations taking into account the dimensions of the beam, the amount of reinforcement and type of reinforcement used. For the types BBRC and BBGRC the theoretical values are greater than the experimental values. BBSRC and SRC have experimental values greater than the theoretical values. Due to the fact that BBRC and BBGRC have higher theoretical values than the experimentally determined values means that the calculations are not adequate for the bamboo reinforcements. However, since the calculations are the same for all four specimens, it is possible to look at the magnitude of the differences between the experimental and theoretical values to see the influence of the reinforcement and the differences between each other.

The largest difference between the theoretical and experimental values are seen at BBRC and have a difference of 22 kN. No safety margins were taken into account for the calculations, because of this it is possible that the experimental values are close to the theoretical values. The experimental values for BBGRC are 2 kN lower than the theoretical values which gives a good picture of the reality. BBSRC exceeds the theoretical values by 4 kN.

The experimental values for BBRC and BBGRC differ by 5 kN but with the theoretical values there is a difference of 25 kN. Despite the fact that Table 11 showed that BBGRC had a lower positive influence on bending resistance, it now appears that this type of reinforcement has a more effective effect as it is closer to the expected values. Thus, the lower positive influence of Table 11 is explained by the lower presence of reinforcement due to the smaller diameter of reinforcement sticks. The grooves in the bamboo will provide more effective working, which means that the experimental values are closer to the theoretical values. Because the slip is reduced by the grooves and an assumption of the formulas is that the slip between the reinforcement and concrete does not exist. The formulas used for steel reinforcement are reliable to use for bamboo reinforcement with grooves as well.

The fact that BBSRC has 2 kN more at the experimental values and 6 kN higher at the theoretical values in comparison with SRC means that the reinforcement is a more economical solution. Especially when it is remembered that BBSRC has only half as much steel reinforcement as SRC and the rest of the strength is achieved by bamboo. Adding the bamboo has a clear positive impact on the flexural resistance and a good cooperation with steel reinforcement emerges. If the strength of the beam is calculated using only the steel reinforcement without the bamboo stakes, BBSRC would be able to handle a maximum force of only 32.5 kN. This is a difference of 64.5 kN of maximum load gained by the bamboo reinforcement.

Inaccuracies on the calculations also play a role. Since a different type of bamboo was used between trial series two and three, the tensile strength of the bamboo for series three was determined via estimation. The tensile strength was determined by taking the ratio of the areas of the bamboo reinforcement of series two and three. Here the average area was taken of the bamboo stick over five different locations and with this the overall average was determined of all the reinforcement sticks of one specimen.

Another explanation why BBGRC better matches the theoretical values is the reduction of slip due to the change in diameter of the bamboo sticks, these different diameters can be seen in Appendix B: Longer span beams. If a ratio between the beginning and end of the stick is determined for each rebar, the narrowing of the bamboo can be considered. The results of the adhesion tests, as discussed in 5.1, showed that changing the diameter of the bamboo rebar along the length of the stick has a positive effect on adhesion. By determining for each rebar the ratio of the diameter at the thickest end to the thinnest end, it was found that BBGRC has a ratio of 1.42. A smaller ratio of 1.33 was determined for BBRC. This shows that BBGRC exhibits greater narrowing from the beginning to the end and confirms the determination of the adhesion tests.

To better understand whether it is possible to use the formulas of a steel reinforcement to calculate bamboo reinforcement, the following graph is shown. Here again per specimen the experimental values are shown and the theoretical expected values according to calculations as bespoken in Figure 71. Only in the theoretical values no safety factors were taken into account in order to be as close as possible to reality. To see the usefulness of the formulas, an additional category has been added in the graph where the theoretical values have been calculated with the safety factors for the material. Where $\gamma_m = 1.5$ for concrete and $\gamma_s = 1.15$ for steel were assumed. The results are shown in Figure 72.

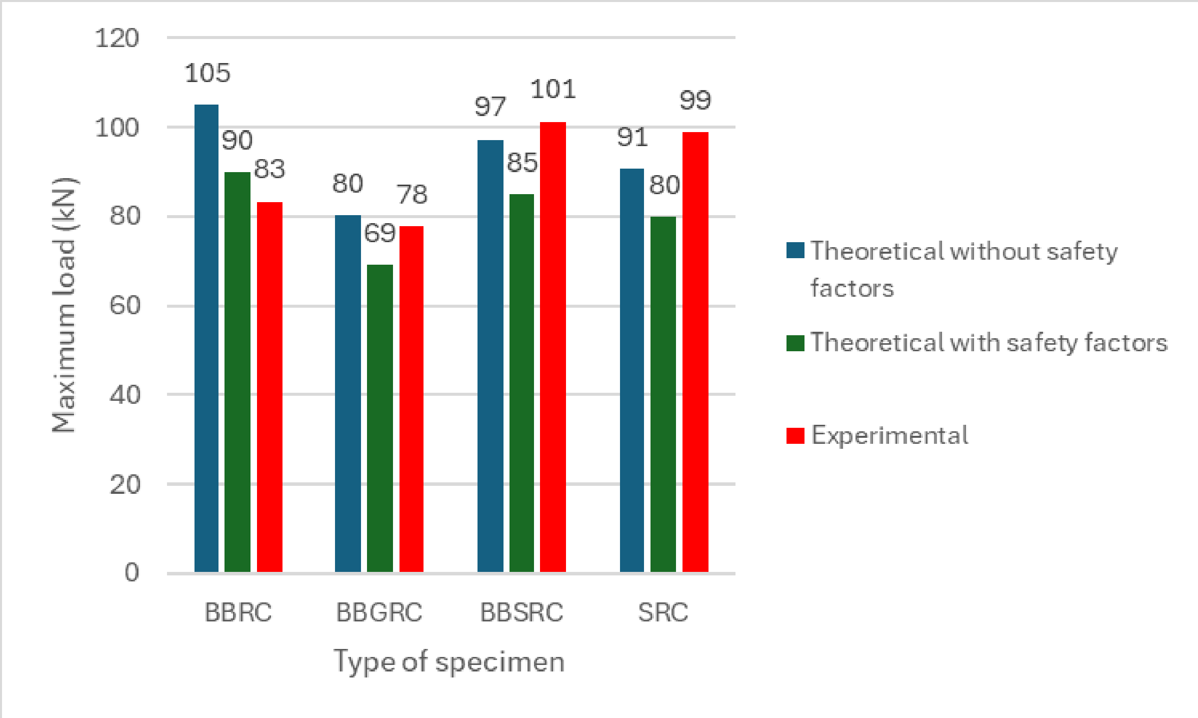

Figure 72: Comparison of the values with and without safety factors

As can be seen in Figure 72, by adding the safety factors, there are a total of three experimental values: BBGRC, BBSRC and SRC that do not compromise safety because the experimental values are higher than the theoretical values with safety factors. Of these, specimens BBSRC and SRC were already above the theoretical values without safety factors but the margin is greater for imprecision during practice. The only specimen that withstood a lower force as calculated was specimen BBRC. The beam withstood 7 kN less load than it could in theory. This again shows that the adhesion between the bamboo and concrete will cause slip and because of this, practice will differ too harshly from what is expected in theory and the formulas for steel will not be useful.

The fact that BBGRC is only sufficient if safety factors are used and this is not the case for the two beams where steel was used, shows that there is a lesser safety margin with a pure bamboo reinforcement with grooves. Since BBGRC does meet the calculated values with safety factors and BBRC does not, it does prove that the grooves have a positive influence on adhesion and the action is closer to that of steel reinforcement. It should be mentioned that the safety factor for the bamboo material is taken the same as for steel with $\gamma_s = 1.15$. Also, a total tensile force at which bamboo will fail has been used for the calculations of the compression reinforcement. In practice, the compression reinforcement will never experience this tensile force through bending only and because of this there is an overestimation on the calculation.

6 Conclusion

6.1 Adhesion

For the pull-out tests, clear conclusions can be drawn. The conclusion is that a way of adhesion improvement is needed. Adding bitumen helps with the adhesion between bamboo and concrete, the maximum bond strength is 13 times that of clear bamboo. The surface of bamboo is so smooth that the friction between pure bamboo and concrete is negligible. Besides the bitumen, the knots also provide adhesion, the maximum bond strength of a bamboo with a knot increases 14 times that of clear bamboo. However, the adhesion of the knots depends on the size of the knots, if the knots are almost the same size as the bamboo body, they do not add any value to the adhesion. This again shows how difficult it is going to be to use bamboo in practice, there will always be a safety factor to take into account for the amount of knots and the variation of the thickness of the knots.

For the pull-out tests with knots, no bitumen were present. Therefore, to further research, it may also be interesting of carrying out further tests where bitumen are applied as standard and more experiments are done with the dimensions of the knots and grooves. In addition, test pieces can be made where the bitumen are mixed with sand before application. Lastly, it may also be interesting to test the adhesion of steel with similar diameters as the bamboo, to be able to compare with steel as well.

6.2 Small span beams subject to bending

The results of the maximum applied force on each specimen show that the bamboo reinforcement does not add to the maximum allowable load on a concrete beam. The values are similar for PC, BRC and BBRC. Concrete only shows an elastic deformation and has a brittle fracture when it reaches its maximum strength. Unlike bamboo, the deflection will increase further. During the increase in deflection, the strength goes down in steps after reaching its maximum. The difference between BRC and BBRC here is that the force action is more uniform for BBRC and thus there is less slip between the bamboo and the concrete. BRC provides an improvement of 14.33 times the distortion compared to PC and BBRC an improvement of 8.67.

For the BRC beams, only one crack is present, which is similar to the brittle crack of PC. This can be explained by the poor adhesion provided by the bamboo reinforcement. Unlike BRC, BBRC does show a crack pattern consisting of multiple cracks, making it similar to steel. This shows that the influence of bitumen on the adhesion also affects the cracks. Because of the big impact on the deflection that the bamboo reinforcement has, the bamboo reinforced beams will no longer show brittle fracture and have a greater safety margin because the failure of the beam is faster to detect due to the fractures in the concrete.

The amount of knots per stick, the diameter of the bamboo reinforcement and the tensile strength of a bamboo cane varies from stick to stick and also over the length of the cane which gives a greater uncertainty and can cause large differences between similar types of reinforcements.

Energy absorption analysis revealed that the ratios of total absorbed energy to elastic energy of the SRC beams are around five times larger than those of the BRC beams and around eight times larger than those of the BBRC beams. This shows that the steel reinforcements are well activated and can absorb the tensile forces well. For bamboo, it is difficult to know if it has a fully plastic reaction after reaching its maximum, this due to the occurrence of slip. However, the ratios of total absorbed energy of PC1 to the different bamboo specimens do show an improvement of six times better for BBRC and ten times better for BRC. This indicates that the bamboo has a positive effect on the deformation that the beam can handle and thus the energy absorbed.

6.3 Longer span beams subject to bending

The force flow by beam shows that for the beams with bamboo one of the force points will experience no more increase after reaching its maximum force and will continue to decrease. This difference can be explained by the eccentricity of the bamboo due to the large inequalities of the reinforcement. This is visible during the tests by the failure of the beam not being in the centre, unlike SRC, where it is in the centre. For BBSRC, the course of forces and deformations is not completely similar, but here they diverge less dramatically than for BBRC and BBGRC. The course of both pressure points indicates that adding steel reduces the eccentricity of the reinforcement.

The combination of a steel and bamboo reinforcement provided the largest load. This beam withstood a maximum load of 101 kN. At the same time, this beam experienced the smallest deflection, which is a disadvantage. The steel reinforcement has failed, while the bamboo at the bottom split, but did not break. This indicates that once the steel failed, the bamboo had to take over, but since there is only one bamboo stick in the most critical zone, it was not able to fully absorb all the forces and as a result the beam failed, with less deformations than the other beams. The maximal force to be absorbed is the highest among all the beams. Therefore, there is an added value in combining steel and bamboo reinforcement. However, the deformation still needs to be improved, and so does the energy the beam can absorb.

It can be concluded from the experimental results that the grooves have a positive effect on the absorbed energy, but do not come close to the SRC beams, which absorb twice as much energy and have a ratio of total absorbed energy to elastic energy that is five times higher.

Using the calculated theoretical values for the maximum load per reinforcement type taking into account the material, diameter and quantity of bars of the reinforcement, the influence of the reinforcement can be observed. For SRC, experimental values of 99 kN were obtained where a load of 91 kN was calculated. This provides a good picture of reality. BBSRC has an experimental value of 101 kN with a calculated value of 97 kN. Here the margin is smaller but it can be concluded that the formulas are useful for a reinforcement that is a combination of bamboo and steel. What should be remembered is that BBSRC used half as much steel reinforcement as SRC and still obtained higher values. This allows this type of reinforcement to serve as a more economical solution. BBGRC and BBRC both have lower experimental values than the theoretical ones, which is not sufficient. Here BBGRC differs by 2 kN while BBGRC shows a difference of 22 kN between the experimental and theoretical values. This shows that due to the smaller reinforcement diameter, BBGRC offers a greater bending resistance and is closer to the action of steel. So the adhesion is improved by the grooves and with appropriate safety margins it can be confirmed that BBGRC is a possible solution to use as reinforcement.

6.4 Overall conclusion

In conclusion, although bamboo reinforcement showed some potential for improving ductility and energy absorption in concrete beams, its effectiveness in significantly improving maximum load carrying capacity remains uncertain. The use of bamboo reinforcement on a large scale has proven that a hybrid reinforcement of a combination with steel and bamboo offer a more economical solution. With only bamboo as reinforcement, making grooves in the bamboo reinforcement achieved better adhesion. The grooves make the operation of the reinforcement more similar to that of steel reinforcement and makes it possible to use as reinforcement. When looking at the tests on a smaller scale, there is no improvement in bending resistance and the reinforcement has only a limited addition to the deformation and absorbed energy. Based on the small-scale tests, the use of bamboo reinforcement is then not recommended.

Since it is a natural material, challenges such as variations in material properties and bond quality present obstacles to using the full potential of bamboo reinforcement in structural applications. Further research and development are needed to address these challenges and validate bamboo reinforcement as a viable alternative to steel reinforcement in concrete structures. Without an applicable solution that is feasible in practice and does not compromise reliability, the use of bamboo has no added value, despite the good material properties of the material itself. With this in mind, untreated bamboo can only be used for small structures, where there are no large forces on the beams. In contrast, a combination between bamboo and steel or pure bamboo with bonding enhancements such as grooves can absorb greater forces and can therefore be used for large structures with the necessary safety factors.

Further research can be conducted on finding the right ratio of steel/bamboo to offer the most economical solution when working with a hybrid reinforcement. To use bamboo alone as reinforcement, a deeper look can be taken at the influence of the grooves. The amount of grooves, the ideal thickness and length must be delved into in order to optimise adhesion but affect the strength of the reinforcement as little as possible.

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Appendices

Appendix A: Small span beams

Table 12: Deviations of the small span beams

Specimen	Length (cm)	Height (cm)	Average length (cm)	Average height (cm)
PC1	95.1	19.7	95.1	19.7
	95.1	19.9		
	95.1	19.6		
	95.2	19.7		
PC2	95.2	19.4	95.2	19.3
	95.1	19.8		
	95.4	19.1		
	95.2	18.9		
SRC1	95.5	19.9	95.4	19.9
	95.2	20.0		
	95.4	19.8		
	95.4	19.7		
SRC2	95.3	20.6	95.3	20.5
	95.3	20.2		
	95.3	20.6		
	95.4	20.5		
BRC1	95.2	20.7	95.3	20.6
	95.4	20.4		
	95.4	20.4		
	95.3	20.7		
BRC2	95.4	20.4	95.4	20.3
	95.3	20.0		
	95.4	20.3		
	95.4	20.5		
BBRC1	95.2	20.1	95.3	20.0
	95.4	19.8		
	95.3	20.2		
	95.1	20.0		
BBRC2	95.4	19.5	95.3	19.7
	95.2	19.1		
	95.4	20.3		
	95.3	19.9		

Appendix B: Longer span beams

Table 13: Deviations of the longer span beams

Specimen	Height (cm)	Width top (cm)	Width bottom (cm)	Length (cm)	Average height (cm)	Average width (cm)
BBRC	30.8	19.6	20.0	250	30.2	19.5
	29.9	18.9	19.8			
	30.3	18.7	19.6			
	29.9	19.0	19.9			
	30.0	19.6	19.8			
BBGRC	28.7	20.2	20.0	250	29.3	21.3
	29.1	22.8	19.9			
	29.3	24.0	20.7			
	29.7	23.8	20.5			
	29.5	20.2	20.6			
BBSRC	30.3	20.0	20.1	250	30.1	20.0
	29.9	21.0	19.0			
	30.1	21.3	18.7			
	29.8	21.1	18.8			
	30.6	20.1	19.8			
SRC	29.7	19.9	20.8	250	30.0	19.7
	29.9	18.8	20.3			
	30.3	18.5	20.0			
	29.9	18.8	19.8			
	30.0	19.9	20.3			

Table 14: Dimensions bamboo for the longitudinal reinforcement

Specimen	Location	Diameter 1 (mm)	Diameter 2 (mm)	Diameter 3 (mm)	Average diameter (mm)	Overall average diameter (mm)
BBRC	Bottom corner	22.4	23.6	32.9	26.3	27.9
	Bottom corner	27.9	25.5	21.1	24.8	
	Centre side	36.9	27.7	23.8	29.5	
	Centre side	33.3	28.8	25.8	29.3	
	Top corner	29.0	28.7	25.8	27.8	
	Top corner	33.0	29.4	27.4	29.9	
BBGRC	Bottom corner	29.0	25.1	22.1	25.4	24.9
	Bottom corner	31.7	25.2	23.9	26.9	
	Centre side	29.8	27.7	24.8	27.4	
	Centre side	17.2	22.1	28.4	22.6	
	Top corner	28.3	24.0	19.9	24.1	
	Top corner	29.4	22.2	17.9	23.2	
BBSRC	Centre bottom	37.3	32.1	28.9	32.8	29.8
	Centre side	31.3	28.7	25.8	28.6	
	Centre side	33.5	27.2	23.8	28.2	