Dowel type connections in laminated bamboo with multiple slotted-in steel plates

Thesis report

Delft University of Technology

world leading in bamboo

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Preface

To complete a two year education and obtain a master's degree at TU Delft, every student is required to do research in the form of a master thesis. This research is done individually and gives the student an opportunity to broaden his knowledge on a topic of his own choice.

For my bachelor thesis I did research on connections in strand woven bamboo. Back then, due to limited time, equipment and financial support, I never got to test the connections I intended to study. So it would seem only natural for me that, for my master thesis, I would want to finish the work started. Although this time, because of a different school, supplier of material and region, I used a different (but similar) material to form and test the connections. Doing research on connections made from a comparable material would give some closure to an otherwise unfinished (but nonetheless successful) project.

For my master thesis I studied the capacity and behaviour of doweled connections made from laminated bamboo. I determined the capacity of these connections at the Stevin laboratory at TU Delft and compared this capacity with a prediction I made by studying the material properties and strength parameters through an extensive literature study. During this undertaking I met a lot of interesting and knowledgeable people that were of great help to me in forming an answer to not only the main question of my thesis but also in coming up with solutions to various problems that occurred throughout the entire project. It goes without saying that I would like to thank each and every one of these people for the help they provided me. There are several people I would like to mention here as their help was invaluable and without them the project could not have been completed.

First of all, I want to thank my parents, Tosca Beuken and Jacques Debije, and the rest of my family for their continuous support, emotional as well as financial, their motivation, which helped me get through the most difficult periods of both this thesis and my entire education in Delft and for their trust and confidence in me to make the right decisions whatever happened. My next thanks goes out to my friends roommates who made my study here in Delft very memorable. In this, I would like to mention also Johan Hover who performed his thesis research alongside my own and faced many of the same problems, for which a fitting solution could always be found through close cooperation.

Thanks to all their questions and input all members of the committee contributed considerably to this thesis. The first member of the committee I would like to thank is my supervising professor Jan-Willem Van de Kuilen, who granted a lot of academic freedom whilst giving necessary guidance and criticism to not stray from course. Furthermore, my thanks goes out to my daily supervising teachers Peter de Vries and Wolfgang Gard from the timber section whose doors were always open for questions, guidance in finding solutions to encountered problems and discussion of found results. Further thanks goes to Arjan Van der Vegte from MOSO International B.V. for showing great interest in my research and providing me with the laminated bamboo on which my thesis was based and from which my test pieces were fabricated.

For the processing of the results, a statistical analysis was necessary. I would like to thank Geert Ravenshorst from the timber section and André Hensbergen from the EWI faculty for their help in deriving the correct method and formulas for the processing and adaptation of the found test results.

Special thanks goes out to all members of the wood workshop and Stevin Laboratory for their help with the correct execution of the tests, the necessary equipment for the attachment of the test pieces and the very accurate fabrication of all bamboo members and steel plates. Without John Hermsen and Fred Schilperoort this would not have been possible.

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J.J.B. Debije

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Summary

The main focus of this research was testing of dowel-type connections using slotted-in steel plates in laminated bamboo loaded parallel-to-grain. Since laminated bamboo is a relatively new material, a proper design standard and design formulas have not yet been established. Strength testing of this material is currently being done by a number of research institutes. Those researches have already resulted in a range of properties and strength parameters. To analyse the possibility of calculating laminated bamboo connections with these already obtained strength parameters using timber design principles, this research focussed on strength testing of a variety of connections and comparing the obtained test results to expected capacities calculated from such timber design formulas. To calculate the expected capacity, design formulas from EC5 were used. From EC5 also the spacing requirements (end, edge and dowel spacing distances) were adopted into the test piece design. Several connection variants were designed and tested. These variants all made use of one dowel of a constant steel grade and dowel diameter. The connection variants were designed such that results were obtained in every failure mode. This thus included testing of three variants of one slotted-in plate (modes 1, 2 and 3) and six variants with two slotted-in steel plates. Of these six variants three displayed failure mode 1 in the middle member and three displayed mode 3 in the middle member (and 1, 2, and 3 in the outer members). This variety in test specimens made it possible to not only compare the measured capacities to design codes but also to compare the capacity and behaviour of connections with multiple slotted-in plates to that of connections with only one slotted-in plate.

To make the best use of the available material and have as little wasted bamboo as possible, the test specimens were equipped with equal connections at both ends. So that when loaded, actually two results could be obtained. One of these results was the capacity of the connection that failed. The other result was the knowledge that the other connection was, at least, stronger than the measured capacity. The use of such symmetrically loaded specimens however also causes the average of all measured capacities to be somewhat lower than normal, since half of the fabricated connections were stronger and are still intact. To overcome this, a method was devised which was adopted into the result analysis and by which the measured capacities were adjusted so that a representative value for all connections was obtained.

From the comparison of the adjusted test results and design codes then was concluded that all of the tested variants had a capacity that was well above the EC5 value. This confirmed that the design of connections in laminated bamboo can safely be done using the design principles of EC5 for timber. Although further research is necessary to determine the necessary minimum end and edge distances for laminated bamboo. Since all mode 1 specimens failed, due to splitting and shear, at a relatively lower capacity and mode 2 and 3 specimens had a relatively higher capacity and showed more embedment deformation, the connections benefit from a larger end distance.

The benefits of using multiple slotted-in plates were investigated in three ways:

- First of these three was comparing the found capacity of connections in which a second slotted-in plate and a third bamboo member were added to the connection (the middle member thickness was of course increased for this, so that the slotted-in plates were symmetrically loaded.). The effects of this were researched by adding such a second plate to two different single plated variants (failure modes 1 and 3). The resulting strength increase was found to be lower than double the strength of a connection using only one slotted-in plate. The ratio of strength increase for both of these variants was quite similar. This would suggest that, like using multiple dowels in a row, additional slotted-in plates in a connection can influence the capacity of the other slotted-in plates and that such connections are affected by an effective number of plates.
- The second way was looking into the effects of plate placement. In a connection using multiple sotted-in plates the placement of these plates does not necessarily have to be such that the plates are symmetrically loaded. The members at each side of the plates can have a different thickness or occurring failure mode. This of course affects the capacity of the entire connection. It was found that, when a failure mode of lower

deformation capacity (i.e. first failing) was placed in the middle of the connection, the capacity of the connection was higher than when the first failing members were put at the outside of the connection. When the outside members fail first the horizontal support of the slotted-in plates vanishes and the plates become free to slide over the deforming dowel. When this happens, the deformation will rapidly increase with only a marginally increasing capacity. The slotted-in pates will eventually be loaded out-of-plane and, since they are usually not designed for this, start deforming. The most likely scenario in this case is that the slotted-in plates will bend and the dowels will ultimately slide out of the plates resulting in a sudden failure of the connection. This effect is not studied in this research since the slotted-in plates were to remain intact.

- The third way was not initially anticipated in the test piece design but was done by comparing the found capacities of a one and two slotted-in plate variant that had the most similar connection thickness. Inserting an extra slotted-in plate in an existing connection or in a design of a connection in which the total connection thickness is kept constant can result in a capacity increase without affecting the slenderness. From the test results is concluded that the extra slotted-in plate can increase the connections' strength capacity but also drastically decrease its deformation capacity. Since the extra plate caused the bamboo members in between the plates to become thinner also the occurring failure mode changed. This resulted in a higher strength relative to connection thickness and a lower final deformation.

Final recommendations are to investigate a possible effective number of slotted-in steel plates by also testing connection variants using three slotted-in plates. Of course in this further research extensions can be made by testing multiple dowels or dowel diameters, different materials or even more specimens to reduce the natural variation in test results to get a more accurate number of effective slotted-in plates.

Samenvatting

Dit onderzoek focust zich voornamelijk op het testen van penverbindingen door het gebuik van een staalplaat als middelste element in gelamineerd bamboe met de belasting in richting van de vezel. Gelamineerd bamboe is een vrij nieuw materiaal op de Europese markt en een juiste ontwerpnorm met geldende ontwerpformules ontbreekt nog. Het testen van alle sterkte eigenschappen van dit materiaal wordt op dit moment door verschillende onderzoeksinstanties gedaan. Deze onderzoeken richten zich op het achterhalen van de sterkte parameters door het uitvoeren van labbroeven volgens testmethoden voor hout. Om te controleren of de ontwerpprincipes voor houtverbindingen ook toepasbaar zijn op bamboeverbindingen, wordt in dit onderzoek gekeken of de capaciteit van gemaakte bamboeverbindingen overeenkomt met de capaciteit die voorspeld wordt aan de hand van rekenregels voor houtverbindingen. De rekenregels die in dit onderzoek gebruikt worden zijn afkomstig uit Eurocode 5. Uit deze Eurocode zijn ook alle minimale rand- en eindafstanden gehanteerd bij de fabricage en het ontwerp van de proefstukken. Verschillende verbindingsvarianten zijn ontworpen en beproefd. Deze varianten maakten allen gebruik van één stalen pen van eenzelfde staalsoort en diameter. De tesvarianten waren zodanig ontworpen dat ieder faalmechanisme optrad en werd gemeten. Hierbij waren drie varianten gemaakt met één staalplaat (faalmechanismen 1, 2 en 3) en zes varianten met twee staalplaten. Van de varianten met twee platen trad bij drie mechanisme 1 op in het middelste element en bij drie trad mechanisme 3 op in het middelste element. De buitentste elementen wisselden per variant tussen faalmechanismen 1, 2 en 3. Deze verscheidenheid aan testvarianten maakte het mogelijk om niet alleen de gemeten capaciteiten met de berekende capaciteiten te vergelijken maar ook om de capaciteit en het gedrag van een verbinding met twee staalplaten te vergelijken met dat van een verbinding met maar één staalplaat.

Om het ter beschikking gestelde materiaal zo optimaal mogelijk te benutten en zo min mogelijk bamboe te verspillen waren alle proefstukken voorzien van een identieke verbinding aan beide uiteinden van het proefstuk. Op deze manier kunnen bij het testen twee resultaten per proefstuk worden bekomen. Het eerste resultaat is de capaciteit van de bezweken verbinding en het tweede resultaat is de wetenschap dat de andere, nog intacte, verbiding in ieder geval sterker is dan de zojuist gemeten waarde. Het gebruik van zulke symmetrisch belaste proefstukken brengt echter ook een moeilijkheid met zich mee. De verkregen gemiddelde capaciteit van alle proefstukken is in werkelijkheid namelijk lager dan het echte gemiddede van alle verbindingen. Dit omdat de helft van de gemaakte verbindingen sterker was en daardooor intact is gebleven en niet gemeten. Om deze meetfout recht te trekken is een methode moeten worden ontwikkeld waarmee de gevonden capaciteiten omerekend konden worden zodat een waarde werd verkregen die representatief is voor alle verbindingen.

Door een vergelijking te maken tussen de omgerekende testresultaten en de verwachte waarde op basis van de ontwerpformules uit EC5 was daarna geconcludeerd dat alle testvarianten een capaciteit hadden die ruim boven de berekende waarde lag. Dit stelde vast dat het ontwerp van verbindingen in gelamineerd bamboe op een veilige manier gedaan kan worden door gebruik te maken van de ontwerpregels voor hout uit Eurocode 5. Aanbevolen wordt echter om meer onderzoek te verrichten naar de minimaal benodigde rand- en eindafstanden voor gelamineerd bamboe. Dit omdat alle varianten van faalmechanisme 1 splijtgedrag toonden of bezweken op afschuiving bij een capaciteit die relatief lager lag terwijl varianten van mechanismen 2 en 3 juist op een relatief gezien hogere capaciteit uitkwamen en hierbij ook meer stuikvervorming vertoonden. Een grotere eindafstand zou dan eventueel een voordelig effect kunnen hebben.

De voordelen van het gebruik van meerdere staalplaten zijn op drie verschillende manieren onderzocht:

- De eerste van deze manieren was het vergelijken van de capaciteitstoename van een verbinding waarbij een tweede staalplaat en een derde bamboe element aan de verbinding werden toegevoegd (het middelste bamboe element werd hierbij ook verdikt zodat de staalplaten aan beide kanten even zwaar belast werden). Het effect van deze uitbreiding op een verbinding werd onderzocht voor twee verschillende enkelplatige varianten (faalmechanismen 1 en 3). De resulterende capaciteitstoename voor de

verbindingen met twee staalplaten was minder dan de dubbele capaciteit van een verbinding met maar één staalplaat. De verhouding in de krachtstoename voor beide varianten was vrij overeenkomstig. Dit zou suggereren dat, net als bij het gebruik van meerdere pennen in een rij, additionele staalplaten in dezelfde verbinding invloed hebben op de capaciteit van de andere platen en dat bij verbindingen als deze rekening moet worden gehouden met een effectief aantal staalplaten.

- De tweede manier was het onderzoeken van de plaatpositionering. In een verbinding met meerdere staalplaten hoeft de positionering van de platen niet per se zo te zijn dat de platen exact symmetrisch belast worden. De verschillende houtelementen aan weerszijden van de staalplaten kunnen immers een verschillende dikte en daarmee ook een ander faalmechanisme hebben. Dit zal dan uiteraard een effect hebben op de capaciteit van de hele verbinding. Door het vergelijk van verschillende testvarianten werd bevonden dat als een faalmechanisme met een lagere vervormingscapaciteit (i.e. een eerder falend mechanisme) in het midden van de verbinding werd geplaatst, de capaciteit van de verbinding uiteindelijk hoger uitviel dan wanneer het eerder falend mechanisme aan de buitenkant van de verbinding werd geplaatst. In het geval dat een van de buitenste elementen eerst faalde en als het ware van de verbinding werd verwijderd viel namelijk ook de horizontale steun voor de staalplaat weg. Hierbij werd het voor de staalplaat mogelijk om over de steeds vervormende pen te schuiven. Als dit gebeurde nam ook de vervorming van de totale verbinding sterk toe zonder ook een significante toename in belasting. Uiteindelijk heeft dit tot gevolg dat de staalplaten niet meer in hun vlak belast worden en zullen gaan buigen. Een situatie waarop de staalplaten normailiter niet berekend zijn, met het gevolg dat deze zullen gaan vervormen. Het meest waarschijnlijke scenario in dit geval is dat de gebruikte staaplaten zo ver zullen gaan vervormen dat de pen ten slotte uit de gaten zal schuiven en de verbinding abrupt los zal shieten. Deze situatie is in dit onderzoek echter niet onderzocht omdat de staalplaten immers nog voor andere proefstukken benodigd waren en intact moesten blijven.
- De derde manier waarop de effecten van meerdere staalplaten is onderzocht was niet voorafgaand aan de proeven meegenomen in het ontwerp van de proefstukken. Deze manier besloeg het vergelijken van de capaciteit van twee verbingingen met een zo veel mogelijk overeenkomstige totale verbindingsdikte. De toevoeging van een extra staalplaat in een al bestaande verbinding of een te ontwewrpen verbinding zonder de totale verbindingsdike aan te tasten kan een voordelig effect hebben op de sterkte capaciteit van die verbinding zonder de slankheid hiervan aan te tasten. Uit de testresultaten was af te lezen dat de toevoeging van een extra staalplaat kan zorgen in een toename van de verbindingssterkte maar tegelijkertijd ook kan zorgen voor een afname van de vervormingscapaciteit. Het gebruik van de extra staalplaat had namelijk tot gevolg dat de omliggende elementen dunner werden, met als consequentie dat ook het optredende faalmechanisme veranderde. Dit resulteerde in een verbinding met weliswaar een hogere sterkte in verhouding tot de totale verbindingsdikte maar ook een verbinding met een relatief lage vervormingscapaciteit.

Aanbevolen wordt om verder onderzoek te verrichten naar een mogelijk effectief aantal staalplaten door middel van ook beproevingen uit te voeren op verbindingen met drie staalplaten. Dit vervolgonderzoek kan uiteraard uitgebreid worden met het testen van bijvoorbeeld meerdere stiften of stiftdiameters, verschillende materialen of zelfs een verhoging van het aantal proefstukken om de natuurlijke variatie in testresultaten te verlagen en tot een meer accuraat effectief aantal te komen.

1 Introduction

Nowadays concepts such as renewable and environmentally friendly become more and more important. These concepts are especially momentous in the construction industry, where vast amounts of building materials are utilized. In the near future a shortage of raw building materials such as steel and wood could be expected. Renewable resources will become of utmost importance. Renewable means that the used building materials will have to be able to be manufactured without causing a burden on the environment. The use of bamboo as a construction material could be a solution to this problem.

1.1 Background information

This research is conducted on behalf of TU Delft and supported by the Dutch office of MOSO International B.V. which has its main office in Zwaag. MOSO International B.V. specialises in innovative and trendsetting products made of MOSO bamboo and has several offices all over the world. MOSO is the Chinese word for the bamboo species "Phyllostachys edulis". The products made out of MOSO are divers and are applied in all sorts of applications like flooring & floor covering, panels & panel covering materials and decking.

Recent developments within MOSO B.V. also include prospects for the use of bamboo engineered products in structural applications in Europe (e.g. roofing structures). LCA assessment shows that bamboo has positive aspects compared to wood (Vogtländer, 2010):

- It can grow in areas where foresting of wood is not possible, and it grows fast;
- it can replace tropical hardwood, so it can mitigate the decrease of tropical forest area;
- it can support the local economies in the third world.

Not only compared to wood bamboo has several benefits. In 2004 Murphy et al. found that bamboo has a much smaller environmental impact and is up to 33% cheaper than competitor products such as masonry. Bamboo is a material with strong prospects in the 21st century (Trujillo, 2009).

For certain applications a standard product is not well suited. In those cases MOSO International B.V. can deliver products that are custom made. For example: MOSO supplies the bamboo veneer for the dashboards of various BMW models and delivered 200.000m² of bamboo ceiling panels (which comply with the strictest fire resistance norms in Europe) for the Barajas airport in Madrid. Thanks to this innovative product development MOSO has evolved into the European market leader in the field of bamboo.
In its permanent strive for innovation MOSO actively collaborates with several acknowledged research and normalisation institutes such as TU Delft, NEN and CEN and is currently investigating the material properties of laminated bamboo and strand woven bamboo (SWB). The material properties of these types of bamboo are obtained via intensive testing. Based on interpretation of these test results design formulas can be established. The collection of these formulas will then be the basis of the European norm for bamboo.

1.2 Current state of affairs

Bamboo is a typical example of a promising new material that fits the bill when trying to live up to today's standards. With its high tensile strength thanks to its all parallel-to-axis fibers and low self-weight it can very well become a serious competitor for traditional building materials like steel and timber on the western market.
While designing in bamboo is mentioned in the codes (NEN-ISO 22156:2004), bamboo, as a structural application, is not often used in building design within (western) Europe. A better understanding of the material is still required in order to use it in a safe and reliable manner. Since bamboo is a relatively new material in Europe, the material properties are under investigation and proper design codes still have to be established. Several researchers (e.g. (Trujillo, 2009); (Yu, H.Q., Jiang, Z.H., Hse, C.Y., Shupe, T.F., 2008)) investigated the strength properties of round bamboo culms and their tests resulted in high parallel-to-fiber strength (tension as well as compression) but weak perpendicular-to-fiber behaviour (Trujillo, 2009). This might make bamboo's tensile strength difficult to exploit when

applying round culms in the design. It would be beneficial to consider not only round bamboo culms but also engineered bamboo products (e.g. laminated bamboo) when designing a structure. And with the help of modern technology the traditional use of raw bamboo culms is not the only nor the most effective application (Xiao, Y., Shan, B., Yang, R.Z., Li, Z., Chen, J., 2014).

Many engineered bamboo products are already available (like laminated bamboo, SWB and glubam) and various strength properties have been investigated (e.g. (Sinha, A., ASCE, A.M., Way, D., Mlasko, S., 2013), (Wei, Y., Jiang, S.H.X., Lv, Q.F., Zhang, Q.SH., Wang, L.B., Lv, Z.H.T., 2011), (Xiao, Y., Shan, B., Yang, R.Z., Li, Z., Chen, J., 2014)). However, most likely due to the lack of a general applicable testing standard for (engineered) bamboo products the strength properties resulting from tests show a lot of variation depending on the researcher and the applied testing method (Debije, J.,Hover, J., 2015). In this respect, for tests on bamboo materials, most researchers perform tests according to their national testing standards for (hard)wood. Research does suggest that connection design in bamboo could potentially be tackled using timber design principles (Trujillo, 2009).

China has a patented structural laminated bamboo product on the market known as Glubam®. This product has seen several uses of structural application in pedestrian bridges, roadway bridges and houses. All tests required for the use of Glubam (fire, systemic, connection and strength) on the Chinese market have been done according to the Chinese standards (Vos, 2015). In 2015 Robert-Jan Vos did his master thesis on the design of a residential building of multiple floors made from laminated Guadua bamboo. The goal of his thesis was to design a residential building made from laminated Guadua bamboo. For this thesis he did basic testing of some properties of laminated Guadua bamboo. However, for a general structural calculation he had to make an assumption with respect to the strength of the connections. He assumed the connections were strong and stiff enough to carry all loads and the deformations were according to the codes.

By means of contact with MOSO International B.V. it is clear that strength testing of laminated bamboo is not yet complete. In order to take advantage of MOSO laminated bamboo's full potential it has to be used in structural systems where the strengths of the material can be maximally utilised. For the determination of the strengths and weaknesses of the material (and thus to determine in what kind of constructions the material can best be used) MOSO ordered the Lignum Test Centre and the University of Cambridge to test the physical and mechanical properties of MOSO Outdoor Laminated Bamboo according to EN 408:2012. The results of these tests showed that laminated bamboo could be well suited in structural applications and the prospects for the near future are for instance roofing structures.

To get a beam of laminated bamboo approved for structural use they have asked TU Graz to do all the necessary tests needed for a basic European Technical Assessment (ETA) on a beam with dimensions 90x140 mm. Since in this basic testing a beam with set proportions is tested for a specific use, a large scale application of laminated bamboo beams in European constructions still requires a lot more knowledge of the material behaviour and the various strength/stiffness parameters.

As an example of this one could imagine a roofing structure made not out of beam elements but out of truss elements. Connections between truss elements are mostly axially loaded and may show different failure mechanisms than connections between beam elements, so prior to building a structure using truss elements, research of these kind of connections is essential.

MOSO has informed that for the ETA approval, additionally to the earlier performed physical and mechanical properties tests, testing of dowel type connections will be done. These connection tests include testing of the withdrawal strength and embedment strength as well as end and edge distances for connections using bolts and screws.

For a wide range of structural applications of laminated bamboo beams, also other aspects than the aforementioned properties need to be taken into account. For the design of a connection also the behaviour during failure and the different kind of failure modes need to be studied. Since the capacity of a connection is dependent on the failure mode that occurs per fastener and the (effective) number of fasteners used, these two properties need to be researched as well before a connection could be implemented in a structural application.

Research on one of these properties of laminated bamboo connections will be done at TU Delft by J. Hover alongside this research. In conjunction with J. Hover's research, who will focus on the effective number of fasteners, this

research will focus on the occurring failure modes and behaviour in laminated bamboo connections. While J. Hover will focus on multiple fasteners in a connection, this research will focus on multiple shear planes.
Research on several properties of engineered bamboo products in structural applications has been done by (Sharma, B.,Gatóo, A., Bock, M., Ramage, M., 2015). Their research showed that timber standards are increasingly used in bamboo research and industry to characterise the material and they observed that failure modes and strengths appear to be similar to timber (Sharma, B.,Gatóo, A., Bock, M., Ramage, M., 2015).

1.3 Research question and scope

The main research question of this thesis will be:

What are the strength properties parallel to fiber of laminated MOSO bamboo connections using multiple slotted-in steel plates and is there a possibility to predict their capacity using timber design formulas?

An addendum to this main research question is made by raising another question.

What are the benefits of using multiple slotted-in steel plates?

Laminated bamboo could be a promising material when it comes to large span roofing structures. Because of the relatively large ratio between strength and weight, laminated bamboo could be suitable for such structures and may even be favourable compared to other building materials. As the (near) future prospects for laminated bamboo concern, amongst others, roofing systems, this research will be confined to testing connections that are most likely to occur in these kind of structures.
For large spans of more than about 30 m, in timber structures, often truss structures are adopted. Usually, single or multiple slotted-in steel plates are used in combination with a number of dowels to form the truss nodes, as shown in Figure 1 – **Truss node with slotted-in steel plates**. Another common system is the roof truss with punched metal plate fasteners shown in Figure 2 - **Roof truss with punched metal plate fasteners** . Also metal stirrups placed in pairs at two opposite sides of the joint were very popular in the past and are still considered adequate and are frequently adopted. These are shown in Figure 3 **- Truss connection with metal stirrups** .
On the basis of the statements made by Sharma et al. (2015) concerning the similarities in the observed failure modes of timber and laminated bamboo it can be assumed that connection design used for timber trusses can also be applied in laminated bamboo trusses. Because toothed-plate connector joints cannot easily be used for timbers with a characteristic density of more than about 500 kg/m^3 (Trada, 1996), similar issues can be expected for punch metal plate fasteners used in laminated bamboo.
Laminated bamboo is a material that will be used not only for its strength properties but also for aesthetical reasons. Therefore eye pleasing connections are of great importance. It is assumed that truss nodes with slotted-in steel plates are considered more aesthetically attractive than punched metal plate fasteners or metal stirrups. In light of this, dowel-type connections with use of slotted-in steel plates seem to be more versatile and sooner used in laminated bamboo connections. Hence, the main concern of this research will be to test the strength properties of laminated MOSO bamboo concerning slotted-in steel plates.

Figure 1 – Truss node with slotted-in steel plates **(Kobel, 2011)**

Figure 2 - Roof truss with punched metal plate fasteners **(Hansson, 2001)**

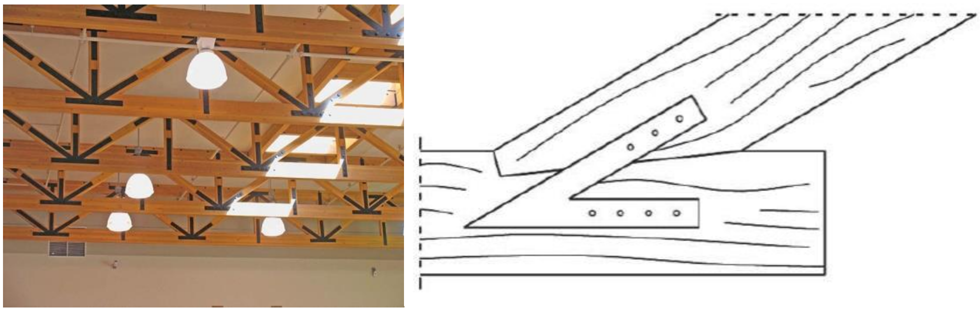


Figure 3 - Truss connection with metal stirrups **(Branco, 2009)**

From the results of tests done by the Lignum Test Centre and the University of Cambridge (Schickhofer, 2015) the expected strength of laminated bamboo is relatively high. This will make the use of multiple slotted-in steel plates interesting when designing a full strength connection. Eurocode 5 gives design rules for determining the strength of a connection using only one slotted-in steel plate in timber. For such a double shear connection a lot of research has been done with use of normal strength steel, hss and vhss dowels (e.g. Groesen and Kranenburg, 2007, Langedijk, 2007, Van de Kuilen and De Vries, 2008, Islamaj, 2009, Van de Kuilen, 2009) (Sandhaas, 2012). The use of multiple slotted-in steel plates is not so often researched. For the determination of the strength of connections the Eurocode makes use of the European Yield Model (EYM) that was first published by Johansen (1949). In this model it is assumed that no premature brittle failure of the timber such as splitting, plug shear or tensile failure in the reduced cross section occurs before the fasteners reach their ultimate resistance (Mischler, 2016). By making use of adequate end and edge distances and spacing between dowels Johansen (1949) determined that splitting of the timber could be prevented. Therefore, as a first assumption based on the observations made by Sharma et al. (2015), the fastener spacings prescribed by Eurocode 5 will be applied when researching the capacity of the slotted-in steel plates in laminated bamboo. However, the use of large fastener spacings does not give absolute certainty that splitting of members will be avoided (Murty, B., Smith, I., Asiz, A., 2005). Connections with slotted-in steel plates will be tested by using the minimal required spacings from Eurocode 5 and the occurrence of a splitting failure shall be investigated. When splitting of the bamboo occurs during testing within this research, the spacings used in Eurocode 5 for timber may have to be adapted to fit the behaviour of laminated bamboo. For this more testing will then be needed, which falls outside the scope of this research.

If through the use of proper fastener spacings splitting failure modes can be avoided the strength of a connection in timber would be a function of the embedment strength of the timber material (N/mm²), the thickness of the timber member (mm) and the diameter (mm) and yield strength (N/mm²) of the used dowel (the moment resisting capacity). Herein it is assumed that the slotted-in plates have such strength (and stiffness) that they do not cause a connection failure. The determination of this required strength and stiffness (thickness of the plate) will be a part of the test preparation.

The determination of the strength of a connection according to Eurocode 5 and the European Yield Model is done by first determining the resistance per dowel per shear plane. Then by multiplying by the amount of shear planes and the (effective) number of dowels the resistance of the total connection is obtained. The determination of the effective number of dowels in a row parallel to the fiber in the Eurocode is done according to a formula derived for timber materials. The effective number of fasteners in laminated bamboo is not necessarily the same and research on this topic is still needed. This research falls outside the scope of this thesis and will be done by J. Hover for his master thesis. This thesis will therefore, if necessary, only consider the number of effective fasteners as it is prescribed by Eurocode 5 for timber materials. After its completion J. Hovers research will provide insight in the amount of effective fasteners in laminated bamboo. The amount of shear planes in a connection is dependent on the amount of slotted-in steel plates (two planes per slotted-in plate). Since the Eurocode and most researchers mainly focus on connections using one plate (double shear), this research will commence also with testing connections using only one slotted-in plate. After that, a comparison can be made with design rules from Eurocode 5. Then this research will consider connections with two slotted-in plates (quadruple shear) and observe the difference in behaviour for these connections and report on the added value of multiple slotted-in plates. During the literature study on testing methods and test piece design a calculation will be made in which the required size of the test pieces per slotted-in plate is determined. The configuration (size) of the test pieces will preferably be in such a way that the main failure modes such as plasticity of the dowel, embedment failure or even (unexpected) splitting modes can be studied independently. The strength and quality of the steel as well as the diameter of the dowels used to make the connections thus depends on the outcome of the literature study and the design of the test pieces.

The base of this research are connections that can be used in truss structures. Since these connections are predominantly loaded parallel to grain, for this thesis, no research will be done on properties related to other angles of loading. The connection that will be tested is illustrated in Figure 4 - **Laminated MOSO bamboo connection parallel to fiber using multiple slotted-in steel plates**.

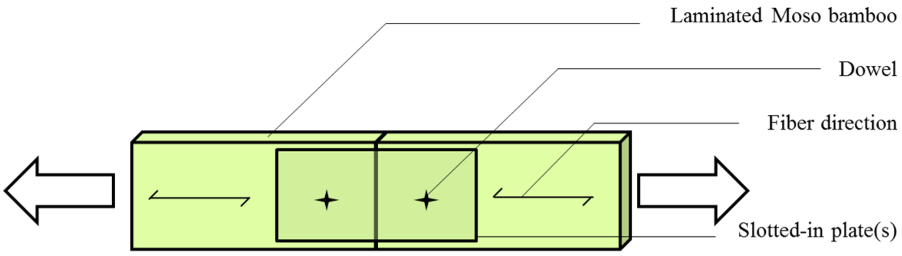


Figure 4 - Laminated MOSO bamboo connection parallel to fiber using multiple slotted-in steel plates

In order to predict the strength of a dowel type connection in bamboo engineered products, knowledge about the material is essential. This research will be confined to laminated bamboo made from MOSO bamboo. In order to acquire knowledge about the material itself, the already available documents on this topic will be studied. For the scope of this research no further investigation of the material is planned.

The laminated bamboo used for testing in this research is comprised of small bamboo strips that are glued together. A schematisation of the lay-up of a laminated beam is shown in Figure 5 - **Substructure of laminated bamboo and a joint in longitudinal direction** .

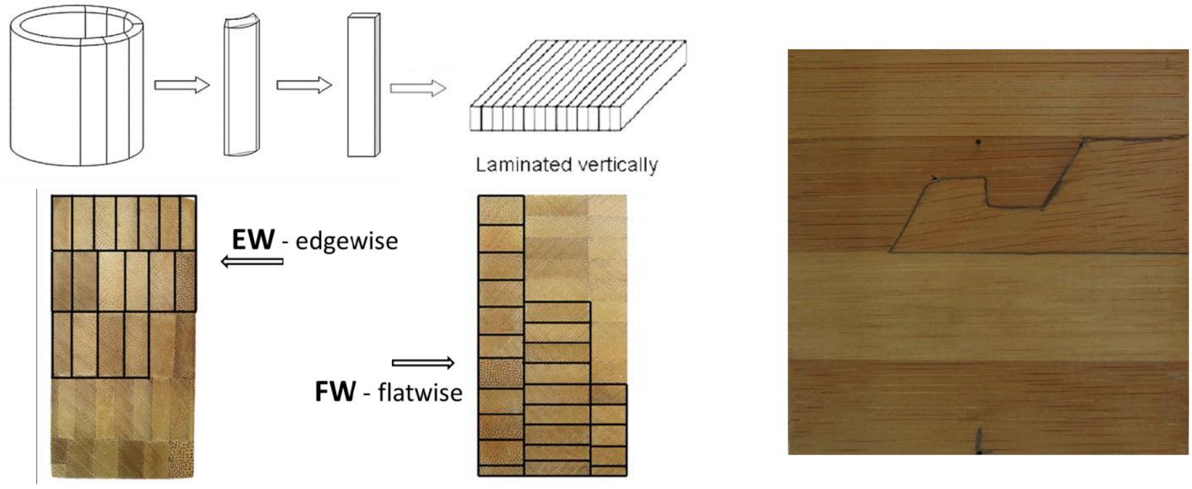


Figure 5 - Substructure of laminated bamboo and a joint in longitudinal direction **(Schickhofer, 2015)**

In this figure can be seen that a dowel can be either inserted in edgewise or flatwise direction. When a dowel is inserted edgewise the properties of the connection (e.g. the embedment strength) are expected to be more uniform. Since properties related to edge and flatwise direction (and the difference in these properties) will be investigated by TUGraz and this research concentrates more on a probable relation to design rules in the current codes (which assume more or less uniform material characteristics), connections in this research shall be tested edgewise.

Determination of the strength properties of dowel type connections will be done according to the European standard for timber. The norms used for this research are listed amongst the references.

Since this research focuses itself on connections in roofing structures using slotted-in steel plates, the connection properties will be tested using a dowel diameter which is likely to be used such connections. Since most of the material properties concerning connections are under investigation at TU Graz, only strength properties of MOSO laminated bamboo that are already tested by the Lignum Test Centre in 2015 can be used for this research. Other necessary, but missing, parameters will be determined using design formulas from Eurocode 5.

1.4 Plan of action

This research will consist of two phases. During the first phase knowledge about the bamboo engineered products, test set-up and testing procedure will be acquired. In the second phase the emphasis will be on testing and the analysation of test results.

1.4.1 Phase 1

The first stage of this thesis commences with a literature research. One of three objectives of this literature study is to create a better understanding of the material itself. Knowledge about the production process and the structure of the material should be acquired. Some strength properties of laminated bamboo are already tested by the Lignum Test Centre and the University of Cambridge (Schickhofer, 2015), these test results will be analysed. On the basis of these properties expectations can be made with respect to the performance of the material so possible strengths and/or shortcomings during testing and use can be anticipated and a proper design of the test pieces can be made. The literature study is also necessary to determine the testing procedures, the required test set-up and all needed materials. The test set-up will have to be such that the strength of a realistic connection can be determined. A

realistic connection is, in this research, taken as a connection using one and two slotted-in steel plates. An example of such a realistic connection design was shown in Figure 4 **- Laminated MOSO bamboo connection parallel to fiber using multiple slotted-in steel plates**.
This thesis will make use of the European testing norms for wood products (Eurocode). During the literature study the required size, moisture content and temperature of the test pieces will be determined. Also an extensive research into the background of the formulae of the Eurocode shall be performed during this phase. By investigating the origins of the design formulas a decision can be made with respect to the possible applicability of current design formulas on laminated bamboo. On the basis of that knowledge, the most appropriate design formulas can be adopted in the design of the test pieces.

1.4.2 Phase 2

Having obtained the required knowledge and having made an appropriate test piece design, the research can be continued with the second phase. For comparable test results the test pieces should, at the start of each testing, have a similar moisture content and temperature. The test pieces will be placed in a climate chamber until their moisture content has levelled and resembles that of the chamber. After this acclimatising period the test pieces will be assembled according to the in phase 1 consulted testing norms. After that the required tests can be executed. Since bamboo is a natural material a variance in test results between test pieces can be expected. For accurate test results it will be necessary to perform multiple tests per connection variant. From a comparison between results a natural variance and mean value can be deduced.
The obtained test results can be compared to the predictions made using the design formulas from Eurocode 5 and the literature study. By comparing these, comment can be made on the possibility to accurately predict the capacity of laminated bamboo connections using existing timber design formulas and principles.
Comparing the results of the tests to one another will give valuable information on the benefits and possible added value of using multiple slotted-in plates in a connection.

1.5 Reading guide

Part 1 of this report will start of by performing a literature research. In this part first a short introduction is given in 2 - **Introduction literature research** on the method which will be used for the literature research. The laminated bamboo itself is examined in 3 - **Laminated bamboo**. The applicable design formulas and their derivation and determining factors are given in 4 - **Applicable design formulas**. The selected testing method is briefly explained in 5 - **Testing methods**. Based on these formulas and testing methods the test piece design is made in 6 - **Design of test pieces**.
Part 2 of the report focusses on the testing of the test pieces and the analysation of the found results. This part will start off with a short introduction in 7 - **Introduction testing**. The fabrication of the test pieces and encountered anomalies in the material are discussed in 8 - **Fabrication of test pieces**. The test setup and any deviations in this from the, in part 1, made design are explained in 9 - **Testing process**. All individual found test results are described in 10 - **Test results**. The method for analysing the results of the conducted tests and their analysation is made in 11 - **Result analysis**. Lastly, part 3 of the report includes some final remarks in 12 - **Final comments** and based on these final comments and all encountered problems during the completion of this thesis, recommendations for future research are given in 13 - **Recommendations**.

Part 1:
Literature research

2 Introduction literature research

In order to answer the main question of this research, connections with slotted-in plates in laminated bamboo have to be made and (destructively) tested. To perform such kind of tests knowledge about the way of testing, the material and test piece design needs to be present. This knowledge can only be gathered by doing a literature research in which already available documents are consulted. The first part of this thesis thus consists of a literature research in which the material will be analysed, the testing method shall be established and the test pieces will be designed.

2.1 Goal

Part 1 of this research will give an answer to the following question:

<u>What testing procedure should be used for testing laminated bamboo connections and how should the test pieces be designed (or assembled)?</u>

Only by implementing the proper test method acceptable results can be obtained and used for structural design in practice. To perform tests correctly not only the testing method needs to be right, also the design of the test piece should be such that only the to be tested properties will be tested (i.e. the test piece should not fail in a way that does not yield useable information, such as testing the shear capacity of the dowel).

2.2 Plan of action

Apt results can only be obtained by implementing the right testing procedure and test piece design.
To determine the correct testing procedure knowledge about the material itself (and its expected properties) is essential. For this, a short study to the material laminated bamboo will be made. During this study the growth of bamboo and typical material properties and characteristics shall be named. Also the fabrication process of laminated bamboo shall be looked into. Information about the material shall be obtained by analysation of earlier researches. On top of the material growth and lamination process also some already researched strength properties of laminated bamboo will be analysed. For these strength properties use will be made of test results from Lignum Test Centre and University of Cambridge. Results of these tests have been made available for use in this research by MOSO International B.V.. Values given amongst these results will be used during this research whenever necessary.

Based on the found material characteristics of laminated bamboo similarities with other materials will be sought. Since no testing standard has, as of yet, been established for bamboo, the testing standard of a material similar to laminated bamboo (e.g. timber) will be used to perform tests during this research. Applicable testing standards for connections will be sought in the Eurocode and analysed during the literature research. The testing standard found most appropriate for laminated bamboo will be mentioned in this report and the, by this standard, prescribed testing procedure shall be explained.

After finding an appropriate testing standard for laminated bamboo connections the test pieces have to be designed. For correct test results it is important that the design of the test pieces fits the intended use. With this is meant that only the parameters to be tested should come up in the test results. A proper test piece design will thus have to make sure that only parameters related to laminated bamboo will be tested and other used materials for testing (e.g. dowels, slotted-in plates) remain intact or only show yielding in envisaged locations.
In order to appropriately design these test pieces the design norms of the same material the test procedure is based on (e.g. timber) will be used. For correct determination all strength values of a connection made in laminated bamboo, the design formulas from the applicable norms cannot just be applied without knowing their background. Since laminated bamboo is still a different material, the formulas used for designing the test pieces need to be analysed and the origin of all factors which they use needs to be checked. Only when the derivation of the used

design formulas is understood the applicability of these formulas on connections in laminated bamboo can be judged. After investigating the origin of the design formulas and determining the most applicable (form of) formulas the test pieces can be designed. Through use of strength parameters obtained from the formulas the pieces can be designed in such a way that only the intended failure mode (or place of failure) will occur. Also an expectation can be made with regard to the capacity of the designed connection in laminated bamboo. Based on this expected value testing equipment, like the slotted-in plates and connection to the testing apparatus, can be calculated so that no failure or yielding in these parts shall occur during testing.

2.3 Reading guide

Part 1 of this thesis commence with a material study. The findings of this study are summarized in 3 **- Laminated bamboo**. Next the design formulas for timber will be analysed and their origin will be studied. This is done in 4 - **Applicable design formulas**. Based on the found characteristics of laminated bamboo a testing method was sought. The selected testing method is given in 5 - **Testing methods**. Lastly the test piece design and all considerations done for the calculation are explained in 6 - **Design of test pieces**.

3 Laminated bamboo

In this chapter more information will be given on the material. First the growth process of the bamboo species will be explained and some properties following from the growth process will be highlighted. After that, the production process of Moso Laminated Bamboo shall be discussed.

3.1 Bamboo

In the following the properties and growth of round bamboo culms will be discussed.

3.1.1 Growth

Bamboo belongs to the Gramineae family and is essentially a grass (Trujillo, 2009). It forms a unique group of giant arborescent grasses and usually flowers only once, namely at the end of its lifespan of about 20 to 40 years. It grows naturally on all continents except Europe, and is mainly distributed in countries with a tropical to subtropical climate. Some species are known to be able to tolerate temperatures up to 50 degrees Celsius whereas others can withstand severe frost (Liese, 1987), such as the species that live on the Himalaya Mountains. Giant bamboo species, which have the most potential for industrial processing and economic development, mainly derive from (sub) tropical areas, usually developing countries or emerging economies (Van der Lugt, 2008). In China and India the largest stocks of the worldwide 20 million hectares of bamboo forest can be found.
Bamboo grows in two distinctly different forms, either single stemmed (leptomorph) or densely clumped (pachymorph). Compared to wood species that are currently used for structural timber, bamboo has a remarkably fast growth rate, it can reach its full height of 15-35m within a period of 2 to 4 months by diurnal growth rates of about 20cm up to 100cm. However, when having reached its full height it cannot yet be used as a suitable building material. When the culm has stopped growing and the culm sheets have dropped, the typical colour appears dull and the culm is called "immature". Later on, it becomes greenish and often yellowish as signs of ageing and maturity. During this ageing process the culms also gain in strength (Liese, 1987).

3.1.2 Anatomy

The chemical composition of bamboo is almost identical to wood, the difference in anatomical composition however is significant (Van der Lugt, 2008). Bamboo has no rays or knots and the stem is hollow. Compared to a solid stem for trees. In the cross section of the bamboo three main components can be identified. They are cellulose fibers (40%), vascular bundles (10%) and an in-between parenchyma tissue (Van der Lugt, 2008). See also Figure 6 – **Microscopic three dimensional representation of bamboo tissue consisting of parenchyma cells and vascular bundles (black) circled by fibers (light and solid)** .

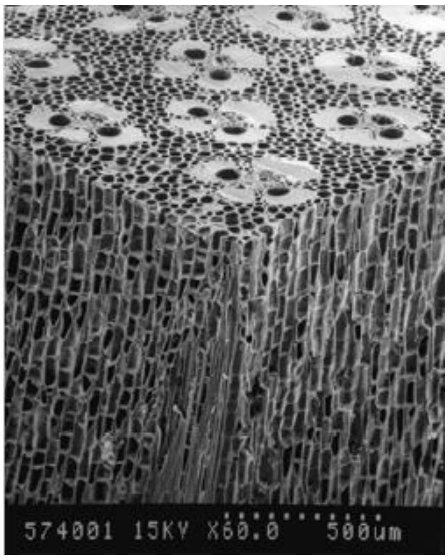


Figure 6 – Microscopic three dimensional representation of bamboo tissue consisting of parenchyma cells and vascular bundles (black) circled by fibers (light and solid) **(Van der Lugt, 2008)**

The fibers and parenchyma cells together work as a composite material. The cellulose fibers in a matrix of thin-walled parenchyma cells have a function similar to steel in reinforced concrete. The fibers run in longitudinal direction around the vascular bundles. The outer layer of the stem consists of a thin 0.25mm silica layer that provides protection of the stem. The outer and inner walls of the stem are also covered by a thin waxy layer.

The culm of a bamboo plant has a hollow cylindrical shape with nodes that are a fairly constantly distributed over the length. The density of vascular bundles (and with that also the fibers) increases from the inner side to the outer side of the stem (Qisheng, Z., Shenzue, J., Yougyu, T. , 2002). This results on cross-sectional properties that are good for taking up bending moments. Toward the upper part of the culm the percentage of fibers is distinctly higher than in the lower parts. Both these characteristics contribute to its superior slenderness (Liese, 1987). The fibers in the inner layer of the culm are round and tend to be oval towards the outer side of the culm (Kanzawa, E., Aoyagi, S., Nakano, T., 2011).

Unlike the dicots, the structural systems in bamboo for the conduction of water in the xylem and for the carbohydrates in the phloem cannot be replaced by new tissue but have to function throughout the entire lifetime of the culm. Dicotyledonous trees may deposit residues of their metabolism in central parts of their stem or in the bark, but due to its hollow shape and the arrangement of its fibers bamboo does not possess such repositories and has to make do with vertical transport only. This results in a large amount of long, and parallel to each other, vertical vessels that run all the way up the bamboo plant.

3.1.3 Strength properties of round bamboo culms

As described above, bamboo culms consist mainly of strong vascular bundles parallel to the longitudinal axis. Only at the nodes some of these bundles branch in a relatively random manner to form a diaphragm acting as a stiffener. In 2004 D. Trujillo and R. Murphy examined Guadua bamboo and found that bamboo species have high tensile (>35 N/mm^2) and compressive (38 N/mm^2) strength parallel-to-grain, and if the strength-to-weight ratio is considered, bamboo's tensile strength is astonishingly high (Trujillo, 2009). Similar results were obtained on the physical and mechanical properties by (Yu, H.Q., Jiang, Z.H., Hse, C.Y., Shupe, T.F., 2008) who tested Moso bamboo. They found a mean tensile modulus of elasticity (MOE) ranging from 9.0 GPa to 27.4 GPa and a tensile strength ranging from 115.3 MPa to 309.3 MPa with the highest strength in the outer layer of the culm.

From tests D. Trujillo and R. Murphy also established a characteristic embedment strength of 54 N/mm^2 for a 6.35 mm bolt. If expression 8.16 from (NEN-EN 1995-1-1+C1+A1:2011) was used with the mean density of Moso

Laminated bamboo of 666 kg/m² (Schickhofer, 2015) used for this research, the characteristic embedment strength of timber with comparable density would be about 50 N/mm² (for a 6.35mm dowel). From this point of view bamboo would have similar mechanical properties to timber. Their test results also confirm that the 12*d edge distance recommendation set out in table 8.2 in (NEN-EN 1995-1-1+C1+A1:2011) for nails is appropriate for bamboo and their results seem to indicate that bamboo connection design might not be that different from that of timber. In other tests D. Trujillo and R. Murphy found that bamboo's weak parenchyma matrix and parallel longitudinal fibers result in low tensile strength perpendicular-to-grain (0,22 N/mm²) and shear values (2,3 N/mm²). Due to this the compression strength perpendicular-to-grain of a whole round culm is mostly governed by tension perpendicular-to-grain, resulting in crushing of the section (Trujillo, 2009).
Unfortunately the weaker mechanical properties will govern bamboo culms use in design. Sections subject to bending will be governed by crushing at the supports, shear failure or even tension perpendicular-to-grain. This might make bamboo's tensile strength difficult to exploit when applying round culms in the design. And with the help of modern technology the traditional use of raw bamboo culms is not the only nor the most effective application (Xiao, Y., Shan, B., Yang, R.Z., Li, Z., Chen, J., 2014).

3.2 Production process

As already stated by (Xiao, Y., Shan, B., Yang, R.Z., Li, Z., Chen, J., 2014), the use of round bamboo culms in structural design is not the most effective application of the material. Therefore, many engineered bamboo products are already available like SWB (Strand Woven Bamboo) or laminated bamboo. This research focusses on properties of laminated bamboo as it is supplied by Moso International B.V.. This paragraph gives all, for this research, known information about the production process of MOSO Laminated Bamboo.

The general production process consists of a number of steps. All steps of the process will be using the board from Figure 7 – **3-layer bleached Plybamboo board** as an example.

Figure 7 – 3-layer bleached Plybamboo board **(Van der Lugt, 2008)**

The steps in the production process of this board are the following (Van der Lugt, 2008):

1. Harvesting of bamboo on sustainably managed plantations
2. Transport from plantation to strip manufacturing facility
3. Strip making
4. Transport from strip manufacturing facility to factory
5. Rough planing
6. Strip selection
7. Preservation and colouring: bleaching
8. Drying
9. Fine planing
10. Strip selection
11. Glue application

12. Pressing strips into and 1-layer board
13. Sanding the 1-layer board
14. Glue application
15. Pressing three layers to one board
16. Sawing
17. Sanding 3-layer board
18. Dust absorption (during all steps)
19. Transport from factory to harbour (CH)
20. Transport from harbour (CH) to harbour (NL)
21. Transport from harbour (NL) to warehouse

The first step of the production process is the harvesting of the bamboo culms. When the bamboo stems are 4 to 5 years old they are harvested for production (MOSO International BV, 2016). During this step the culms are cut into lengths of 8 meters and loaded onto a truck for transport to the strip manufacturing facility. See Figure 8 – **Harvesting and transportation of bamboo culms** .

Figure 8 – Harvesting and transportation of bamboo culms **(Van der Lugt, 2008)**

After transportation the bamboo culms are loaded off the trucks and gathered at the strip manufacturing facility. The task of this facility is to cut the bamboo culms lengthwise into strips. See Figure 9 – **From stem to strip**.

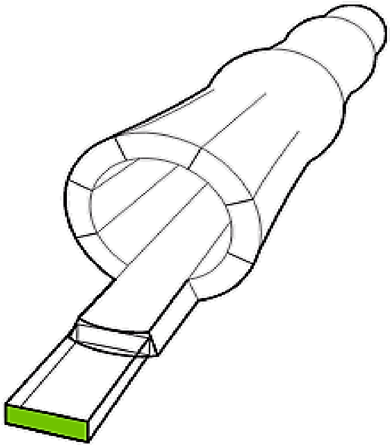


Figure 9 – From stem to strip **(MOSO International BV, 2016)**

At this point the strips are loaded back onto trucks and transported to another factory where the strips will receive a rough planing. In this rough planning process the outer layers of the strips are removed. See Figure 10 – **Rough planing of bamboo strips** .

Figure 10 – Rough planing of bamboo strips **(Van der Lugt, 2008)**

After the rough planing process a selection process follows. During the selection the trips that do not meet the quality standards are removed. The removed strips will be used for biofuel. Approximately 6% of the strips are removed during this selection (Van der Lugt, 2008).
The strips that do meet the quality requirements undergo a preservation process. The preservation can either be done by bleaching or carbonization. From the natural growth (and ageing) process the strips have a light yellow colour. The colour of the end product is largely dependent on the method chosen during this step. These treatments not only provide a durable end product but also contribute to the aesthetical diversity.

During the bleaching process the strips are 'cooked' for 4 hours in a H_2O_2 solution at 70-80°C. With one pool of this solution a total of two rounds of strips can be cooked. After that the solution cannot be used again and is settled through chemical treatment. See Figure 11 – **Bleaching of bamboo strips** . After bleaching the strips are dried in a drying chamber. Here the bleached strips are be placed with a maximum of 30 000 at a time for a period of 72 hours.

Figure 11 – Bleaching of bamboo strips **(Van der Lugt, 2008)**

During the carbonization process the natural sugars in the bamboo are caramelized. This is done through the use of steam at a temperature of 120-130°C and a high pressure of 0.21-0.25MPa. As a result of this preservation process, the bamboo strips acquire a darker (caramelized) colour than strips that undergo a bleaching process. The carbonization process is shown in Figure 12 - **Carbonization process** .

Figure 12 - Carbonization process **(Van der Lugt, 2008)**

To fully preserve the strips two rounds of carbonization are necessary. Each round takes 150-170 minutes (depending on the preferred level of darkness for the material). The strips can be either steamed to acquire a light brown colour (similar to caramel) or, alternatively, they can be thermally treated to acquire a dark brown colour (similar to chocolate) (MOSO International BV, 2016). In the first round 4000 strips per day can be processed and in the second round 6000 strips per day. After carbonization the strips have to be dried. This is done in a drying chamber and is done after each round. The drying times for carbonized strips differ from those for bleached strips. Carbonized strips require a 168 hour drying cycle after the first round and a 72 hour cycle after the second round. The drying chamber is able to dry 30 000 strips at once (Van der Lugt, 2008).

After the preservation and drying processes the strips are fine planed. This planing process can handle up to 38-40 meters of strips per minute per fine planer (20 kW). At a strip length of 2.63 meters this corresponds to 15 strips per minute (or 900 strips per hour).
When the strips have been fine planed another selection process takes place. Also during this selection process the strips that do not meet the quality standards are discarded and used for bio fuel. The amount of discarded strips in this step is again about 6% (Van der Lugt, 2008). The total amount of discarded strips in the process will thus be about 12% (rounded up from 11.64%).

The next step will be to glue the strips together into 1-layer boards. The assembly can be done in various ways. The individual strips are attached to each other by use of a phenol formaldehyde (PF) resin, and, when it's meant for outdoor use, receive a biocide treatment (Sharma, B., Ramage, M., 2015). The used glue for the assembly of the strips can also be urea formaldehyde (UF) (Van der Lugt, 2008).
The orientation of the strips within a beam can be either Plain Pressed, Side pressed or High Density (MOSO International BV, 2016). Another variation is offered in which the strips are glued using a flexible latex or fabric backing, but since this research focusses on structural connections the flexible material is only mentioned here for completeness.

The plain pressed version is shown in Figure 13 – **Plain pressed**. In this version the bamboo strips are positioned horizontally and glued together. In doing so, the natural line pattern and the characteristic nodes of the bamboo are clearly visible. The glue consumption for making 1-layer plain pressed bamboo boards is, in case of urea formaldehyde, 50 grams per m² in wet conditions.

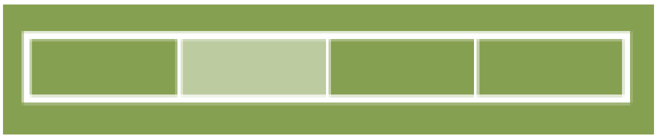


Figure 13 – Plain pressed (PP) **(MOSO International BV, 2016)**

The Side Pressed version is shown in Figure 14 – **Side Pressed (SP)**. In this version the bamboo strips are positioned vertically and glued together. This variant gives a more subtle visualization of the natural line pattern and the nodes of the bamboo. The glue consumption for the side pressed variants is also 50 grams of urea formaldehyde per m² of glued surface.

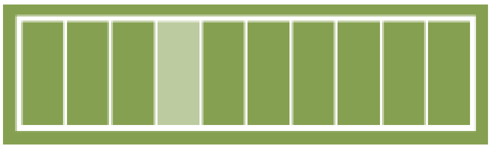


Figure 14 – Side Pressed (SP) **(MOSO International BV, 2016)**

The High Density version is shown in Figure 15 - **High Density (HD)**. In this variant the individual strips are crushed and then glued under extremely high pressure. This compression method increases the density of the final product to values ranging from 700kg/m³ to 1000kg/m³. The result is a much denser and harder product than normal laminated bamboo and is only mentioned for completeness. The look of laminated bamboo is unique: it largely resembles wood with the typical 'flame' pattern and the bamboo nodes are only slightly visible.

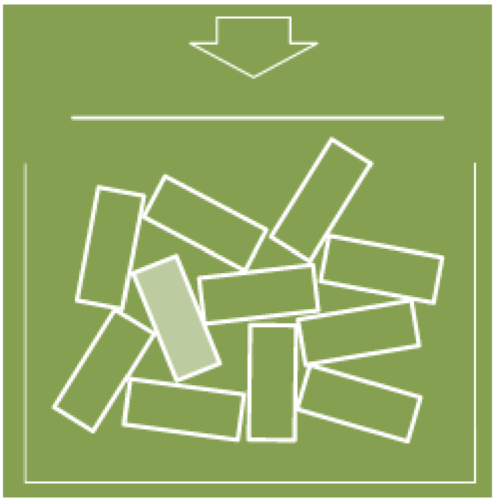


Figure 15 - High Density (HD) **(MOSO International BV, 2016)**

To increase the fabrication lengths of laminated bamboo, the strips are provided with a hook joint (see Figure 18 - **Substructure of laminated bamboo and the longitudinal joint**) that allows for longer beams to be laminated.
After glue application the strips are processed into 1-layer boards using hot presses (see Figure 16 – **Hot pressing of 1-layer bamboo boards**). Per day (8 hours) an area of 350m² boards can be processed. This corresponds to 43.75m² per hour.

Figure 16 – Hot pressing of 1-layer bamboo boards **(Van der Lugt, 2008)**

Now that the 1-layer boards have been fabricated they need to be sanded. A total of 400m² of 1-layer board can be processed per hour per sanding machine of 55-90kW. The 3-layer board from the examples consists of 3 layers and thus requires three 1-layer boards for the final product. Another glue process is thus required. For this glue process an additional 150-180 grams of glue per m² of glued surface are required (average 165g/m²). Since two planes need to be glued to make the 3-layer board about 330 grams of glue are required per m² of board. After the glue application the, now 3-layer, boards are pressed using a multi-layer cold press of 5.5kW seen in Figure 17 – **Multi-layer cold press** .

Figure 17 – Multi-layer cold press **(Van der Lugt, 2008)**

Via this cold pressing process around 80m² of 3-layer board can be processed per day. This equals about 10m² per hour. When the pressing process is done the boards can be cut into pieces of exact dimensions. The sawing machines of 5.5kW can process up to 450m² of boards per day (56.25m² per hour).

The sawn pieces will then be sanded to remove any sharp or rough edges. The dust produced by all sawing and sanding processes is collected by a dust absorption system acting in the entire board-producing factory. After completion of this last sanding and dust absorption process the final product is ready to be shipped. The product is transported to the harbour where it will be put inside a container and shipped off by a trans-oceanic freight ship to its destination (e.g. to Rotterdam from where it's transported by truck to the warehouse in Zwaag). A standard size 20-foot container has dimensions of 5.90x2.35x2.39 meters (33.2m³) and a maximum load of about 30 tons (including 2.3 tons of self-weight of the container).

3.3 Quality control

MOSO International BV is a supplier of a large variety of bamboo products. The MOSO Laminated Bamboo that is used for this research is fabricated in China and imported for use in Europe and other parts of the world. To oversee the production process, MOSO International B.V. has a unit that is permanently located at the production plant in China. This ensures a continual control of the fabrication procedure and a constant quality of the supplied end products. Production of the material takes place in ISO 9001 and ISO 14001 certified facilities.

3.4 Researched material properties

In 2015 MOSO International B.V. commissioned the Lignum Test Centre and the University of Cambridge to test the physical and mechanical properties of MOSO Outdoor Laminated Bamboo according to ÖNORM EN 408:2012. Tests were done on test specimens which were laid-up in edgewise or flatwise direction. The direction of loading in these lay-ups is given in Figure 18 - **Substructure of laminated bamboo and the longitudinal joint**.

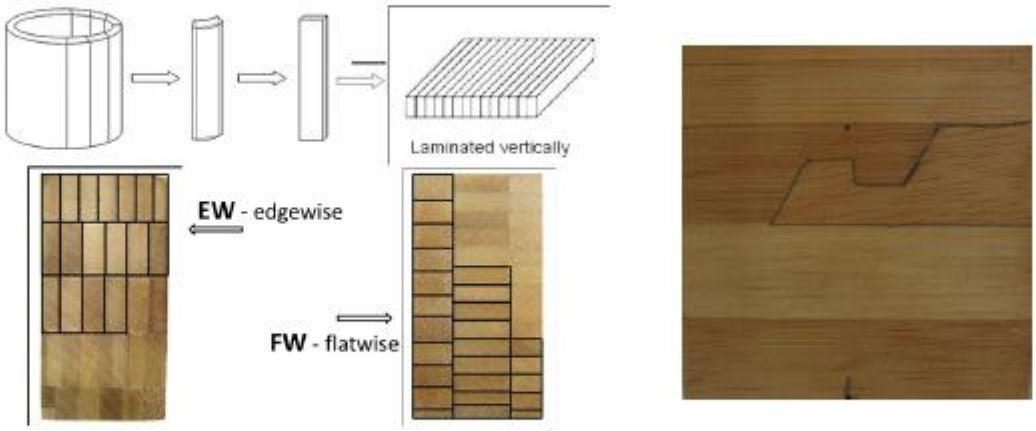
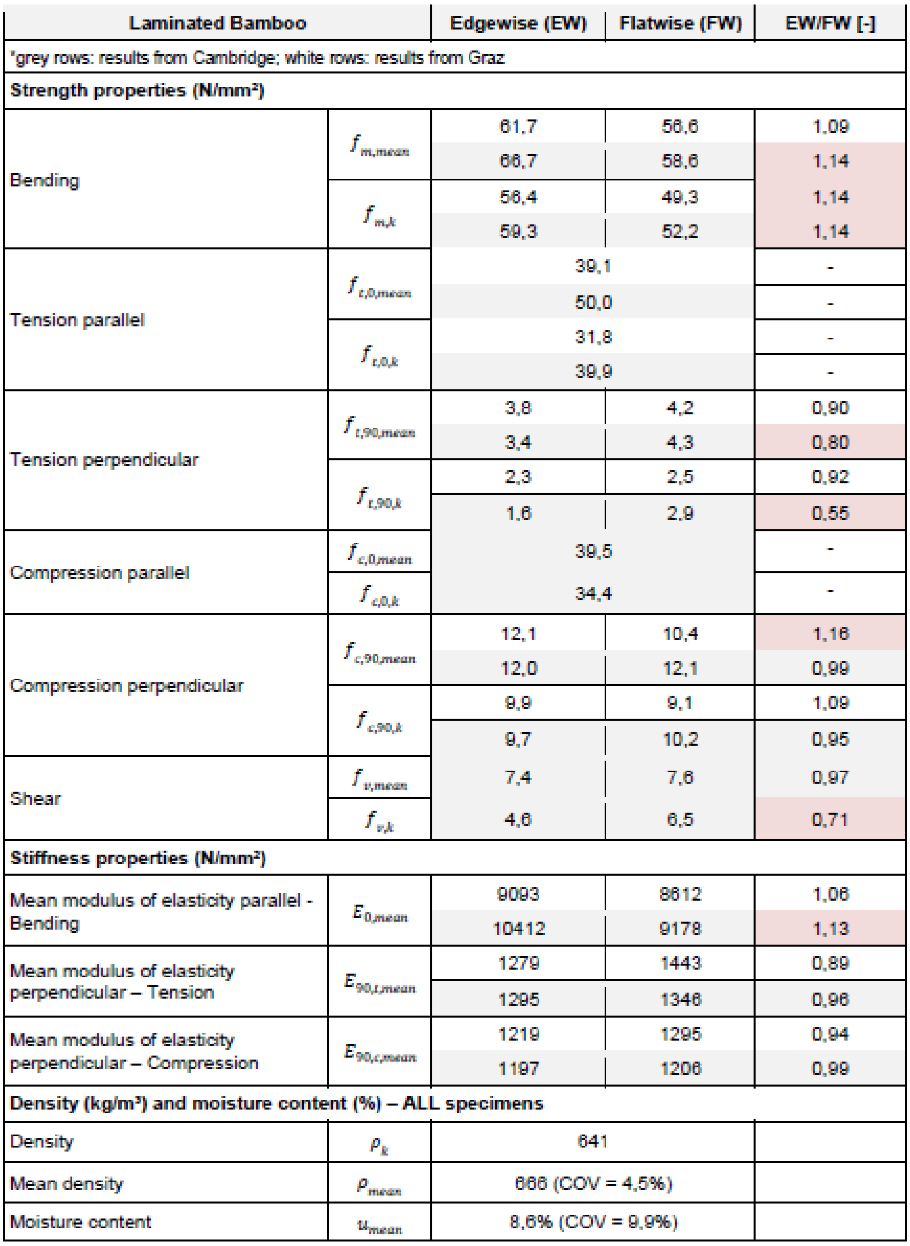


Figure 18 - Substructure of laminated bamboo and the longitudinal joint **(Schickhofer, 2015)**

The scope of testing comprised tests in bending, tension and compression parallel and perpendicular to the grain and shear tests with flatwise and edgewise arranged bamboo strips (Schickhofer, 2015). A summary of the test report has been made accessible for this research and test results, like the measured mean density, will be used to predict the capacity of the connections that shall be tested and design the test pieces accordingly. On the basis of their test results a comparison was made between the strength and stiffness values of edgewise and flatwise laminated bamboo test specimens (Schickhofer, 2015). The results of this comparison have been included in this report in Figure 19 - **Comparison of flatwise and edgewise laminated bamboo** . In this figure the white coloured rows are the results from Graz and the grey coloured rows are the resulting strength and stiffness properties from Cambridge.



Laminated Bamboo		Edgewise (EW)	Flatwise (FW)	EW/FW [-]
'grey rows: results from Cambridge; white rows: results from Graz				
Strength properties (N/mm²)				
Bending	$f_{m,mean}$	61,7	56,6	1,09
		66,7	58,6	1,14
	$f_{m,k}$	56,4	49,3	1,14
		59,3	52,2	1,14
Tension parallel	$f_{t,0,mean}$	39,1		-
		50,0		-
	$f_{t,0,k}$	31,8		-
		39,9		-
Tension perpendicular	$f_{t,90,mean}$	3,8	4,2	0,90
		3,4	4,3	0,80
	$f_{t,90,k}$	2,3	2,5	0,92
		1,6	2,9	0,55
Compression parallel	$f_{c,0,mean}$	39,5		-
	$f_{c,0,k}$	34,4		-
Compression perpendicular	$f_{c,90,mean}$	12,1	10,4	1,16
		12,0	12,1	0,99
	$f_{c,90,k}$	9,9	9,1	1,09
		9,7	10,2	0,95
Shear	$f_{v,mean}$	7,4	7,6	0,97
	$f_{v,k}$	4,6	6,5	0,71
Stiffness properties (N/mm²)				
Mean modulus of elasticity parallel - Bending	$E_{0,mean}$	9093	8612	1,06
		10412	9178	1,13
Mean modulus of elasticity perpendicular – Tension	$E_{90,t,mean}$	1279	1443	0,89
		1295	1346	0,96
Mean modulus of elasticity perpendicular – Compression	$E_{90,c,mean}$	1219	1295	0,94
		1197	1206	0,99
Density (kg/m³) and moisture content (%) – ALL specimens				
Density	ρ_k	641		
Mean density	ρ_{mean}	666 (COV = 4,5%)		
Moisture content	u_{mean}	8,6% (COV = 9,9%)		

Figure 19 - Comparison of flatwise and edgewise laminated bamboo **(Schickhofer, 2015)**

4 Applicable design formulas

In the previous chapter a literature study has been done to acquire knowledge of the material and its production process. To assess the applicability of laminated bamboo in structures and to test the strength properties of connections that can be made between different elements of bamboo, first the design formulas have to be analysed. By studying design formulas, and more importantly their theoretical background, from Eurocode 5 for timber, insight can be obtained in ways to calculate laminated bamboo joints and possible applicability of Eurocode 5 formulas in such joints.

In practice a timber joint with slotted-in plates consists of multiple dowels. However, in the context of this research the behaviour of only one dowel in a joint is investigated.

This chapter will review all formulas from Eurocode 5 that would be necessary to determine the strength of a connection with slotted-in steel plates using one dowel.

4.1 Objective

This chapter will answer the following question:

What is the theoretical background of the formulas from Eurocode 5 for the determination of the strength of a dowel type connection with slotted-in steel plates using one dowel?

The Eurocode 5 gives design rules for calculating the load-carrying capacity of joints with slotted-in steel plates in timber. There are also guidelines that describe the required edge and end distances. The thickness of the timber member can also be determined in order to cause a certain failure mode to take place. These design rules are based upon a theory first developed by Johansen (1949), a Danish professor for concrete and steel structures, who, during the second world war, tested timber connections as a result of a lack of concrete and steel for experiments (Jorissen, A., Leijten, A.). He developed a model to predict the capacity of a timber connection which was were later on extended by Meyer (1957) (Hieralal, 2006). This calculation model has been accepted in Europe and America and is known in Europe as the Johansen model (Jorissen, A., Leijten, A.).

4.1.1 Plan of action

To answer the question design formulas from will be studied. This chapter will focus itself on the design formulas for joints with mechanical fasteners for a material that is expected to show the most resemblance with laminated bamboo.

The material that is anticipated to have a similar behaviour in connection properties is hardwood. Therefore, the design formulas for dowel type connections in hardwood will be examined. The formulas that are used in the Netherlands are included in the Eurocode.

In Eurocode 5 (NEN-EN 1995-1-1+C1+A1:2011) the design formulas for dowel type connections are given in chapter 8. By use of these formulas the maximum capacity “$F_{v,Rk}$” of a connection with dowel type fasteners can be determined. Dependent on the parameters one uses when applying these formulas the capacity of the connection can be calculated in every direction (i.e. parallel and perpendicular to fiber or a direction in-between these angles). Since this report focusses itself solely on properties parallel to fiber, only formulas and parameters that are used for this angle will be studied. To apply or judge the applicability of these formulas on laminated bamboo connections the background of these formulas needs to be known. With this the derivation of the formulas and the parameters needs to be understood. The design formulas will be studied in the upcoming paragraphs. After that the capacity of a connection in laminated bamboo can be estimated and the actual behaviour and capacity can be verified by lab testing.

4.1.2 Reading guide

After this short introduction in 4.1 - **Objective** the main modes in which a timber connection can fail will be explained in 4.2 - **Failure modes**. Next 4.3 - **Design formulas from Eurocode 5 for slotted-in steel plates** will show the design formulas Eurocode 5 gives for failure modes that are relevant for this research. The lay-up and the derivation of these formulas will be explained in 4.4 - **Derivation of the design formulas**. All of these formulas depend on material and system properties. The determination and background of these individual properties shall be given in 4.5 - **Origin of factors**.

4.2 Failure modes

A connection between timber elements or steel to timber connections can fail in different manners. The different failure mechanisms that are included in Eurocode 5 can roughly be divided in three main failure modes (Jorissen, A., Leijten, A.). An understanding of these main failure modes is the basis of connection design in all timber or timber-related materials. In this paragraph the main modes of failure will be explained.

4.2.1 Mode 1

It's possible that solely one of the timber members in a connection will fail. The fasteners will, in this case, remain intact. This failure mechanism appears when a timber plate is connected to another timber member (or a steel plate) which, in relation to the thin plate, is much stronger. This in combination with a strong and stiff (i.e. large diameter) fastener will lead to an embedment failure in the thin timber plate. In other words failure mechanism 1 occurs when a timber member is not able to ensure a plastic hinge in the fastener.

Johansen (1949) states that by the use of proper end, edge and spacing distances between the fasteners and the edge of the connected members premature splitting of the wood can be avoided (Jorissen, A., Leijten, A.). The maximum capacity in this case is dependent on the embedment strength of the timber (N/mm²), the thickness of the timber members (mm) and the diameter of the dowel (mm).

The embedment strength in this case is defined as the maximal stress that can be exerted by the timber onto a dowel that has been placed in a fitting, predrilled hole. The embedment stress is assumed to be uniformly distributed over the projected area of the dowel (De Vries, P.A., Van de Kuilen, J.W., 2012).

An image of this mechanism is shown in Figure 20 – **Failure mode 1**. In this figure a thick steel plate is shown in which the dowel is clamped (a single shear connection). It has to be noted that this mechanism can also occur in a double shear connection with thin steel plates.

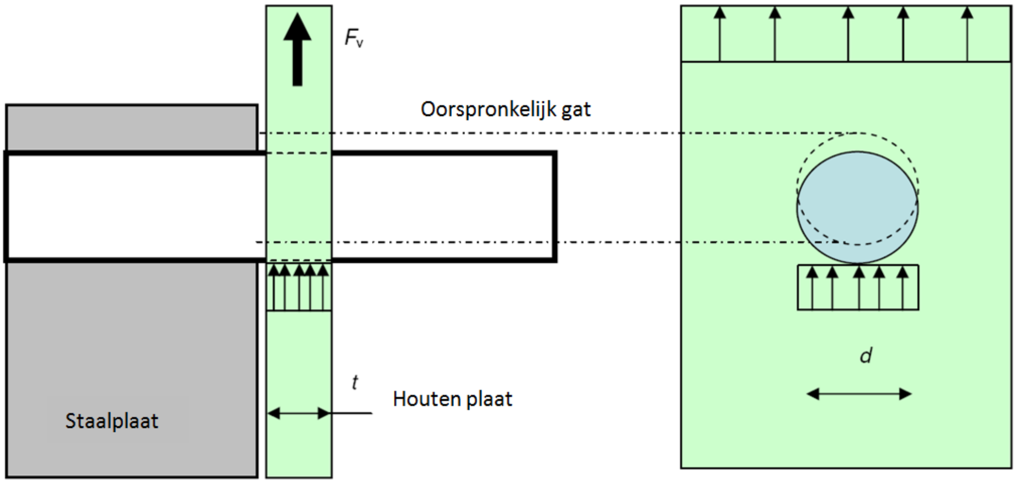


Figure 20 – Failure mode 1 **(Jorissen, A., Leijten, A.)**

4.2.2 Mode 2

While in failure mode 1 solely the timber material suffers from an embedment failure, in failure mode 2 also the dowel will show signs of deformation (or failure).

By the use of a thick steel plate (or a double shear connection) the dowel can be considered clamped at one side. If the thickness of the timber member from mode 1 than increases also the bending moment in the dowel will increase. At a certain thickness of the timber plate the bending moment in the dowel will be so large that the moment capacity of the dowel will be reached. This leads to the formation of a plastic hinge. At which point the connection may be considered as failed. A schematisation of failure mode 2 is given in Figure 21 – **Failure mode 2**.

The capacity of the connection is dependent on the diameter of the dowel (mm), the bending moment capacity of the dowel (Nmm), the embendment strength of the timber (N/mm²) and the thickness of the timber (mm).

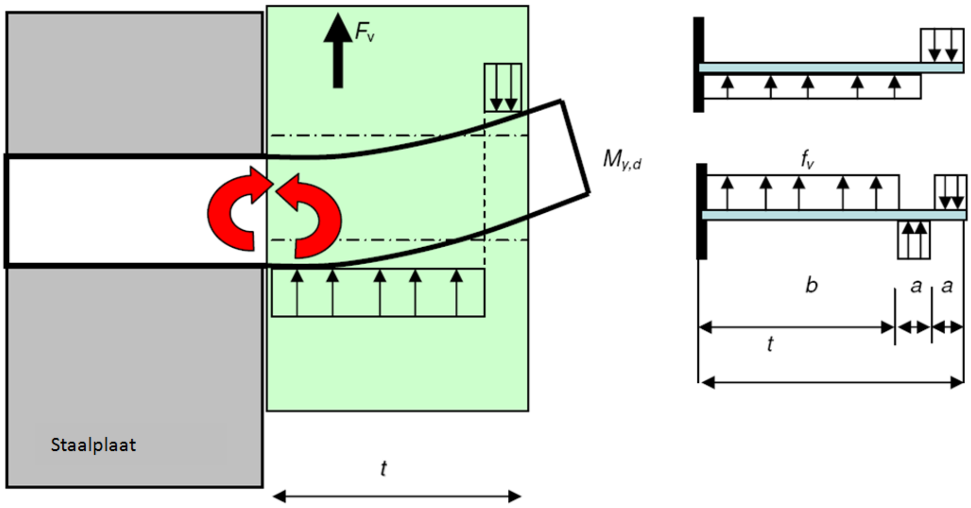


Figure 21 – Failure mode 2 **(Jorissen, A., Leijten, A.)**

As a consequence of the deformation of the dowel in this failure mode, the timber member will start to exert a loading on the dowel in the opposite direction of the force F_v. This opposite loading provides a small bending moment in the dowel. If then the plate thckness again increases this moment will become bigger and a second plastic hinge will form. This behaviour falls under failure mode 3.

4.2.3 Mode 3

For failure mode 3 the thickness of the member from failure mode 2 further increases. Because of this increase in thickness the use of longer dowels will, of course, be necessary. The force exerted by the woodfibers furthest away from the shear plane causes the dowel to bend. At a certain thickness of the timber member the bending moment in the dowel becomes so large that the end of the dowel will not rotate but stay in place (relative to the timber). As the connection then deforms the bending moment in the dowel will become so large that a second plastic hinge can be formed. When this phenomenon occurs the maximum (useful) width of the connection has been reached. A further increase in member thickness will then yield no further increase in the capacity of the connection (Aune, P., Patton-Malory, M., 1986).

The maximum capacity of the connection in this failure mode is dependent on the diameter of the dowel (mm), the bending moment capacity of the dowel (Nmm) and the embendment strength of the timber (N/mm²). Figure 22 – **Failure mode 3** gives a schematic representation of failure mode 3.

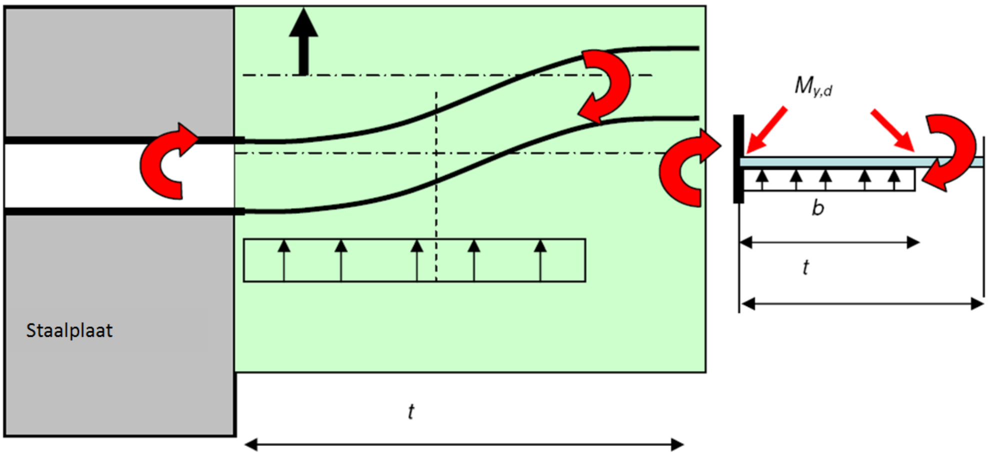


Figure 22 – Failure mode 3 **(Jorissen, A., Leijten, A.)**

4.3 Design formulas from Eurocode 5 for slotted-in steel plates

For the calculation of the strength of a timber connection section 8 from Eurocode 5 (NEN-EN 1995-1-1+C1+A1:2011) is usually used. Since this research focusses on connections using slotted-in steel plates only the design formulas and failure modes concerning this type of connection will be highlighted and explained.

A steel to timber connection usually consists of multiple fasteners that traverse one or more steel or timber elements. This section will show the method by which the Eurocode 5 calculates such a connection. In North America this method is often referred to as the European Yield Method (Murty, B., Smith, I., Asiz, A., 2005).
In all possible failure mechanisms for steel to timber connections Johansen (1949) and Meyer (1957) assume that the steel plates used to form the connection are of such strength and stiffness that they will not contribute to (i.e. lower) the capacity of the connection for a specific failure mechanism nor that they will introduce new failure mechanisms.

Connections that make use of slotted-in steel plates always have two timber members adjacent to one steel member. This makes that per slotted-in plate there are two shear planes. So connections with slotted-in plates are always, at the very least, double shear connections, depending on the amount of slotted-in plates. In such a double shear connection with a steel plate between two timber members the Eurocode distinguishes three different failure mechanisms. These failure modes are given in Figure 23 – **Failure mechanisms for slotted-in plates in Eurocode 5** (NEN-EN 1995-1-1+C1+A1:2011). The failure modes in this figure use the same principle as described in the previous section and consider an embedment failure of one (or both) of the timber elements or the formation of one or more plastic hinges in the fastener. The amount of plastic hinges depends on a combination of factors (moment capacity of the dowel, embedment strength of the timber and the thickness of the timber).

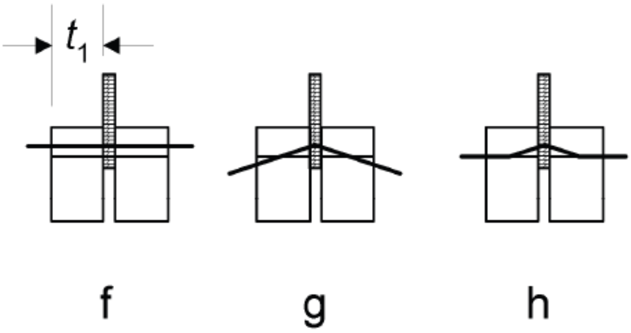


Figure 23 – Failure mechanisms for slotted-in plates in Eurocode 5 **(NEN-EN 1995-1-1+C1+A1:2011)**

Failure mechanism f

In failure mechanism f the embedment strength of the timber is exceeded. This failure mechanism complies with failure mode 1 in which the timber fails and the fastener remains intact.

Failure mechanism g

Failure mechanism g is a mechanism that falls under failure mode 2. Here the bending moment resistance of the fastener is exceeded and a plastic hinge is formed. Locally the embedment strength of the timber will be reached.

Failure mechanism h

This mechanism considers a situation in which multiple plastic hinges will be formed in the fastener. The bending moment capacity will of the fastener will be reached in all timber members and at the location of the steel plate. Locally the embedment strength will be reached. This mechanism falls under failure mode 3.

Which failure mechanism will occur is dependent on the embedment strength of the timber members, the thicknesses of the timber members, the diameter of the dowel and the steel grade.
For double shear connections with a slotted-in steel plate (independent of the thickness of this slotted plate) the Eurocode gives the following design formulas (shown in Figure 24 – **Design formulas for the capacity of connections with slotted-in plates in Eurocode 5** and taken from chapter 8.11 of (NEN-EN 1995-1-1+C1+A1:2011)).

$$F_{v,Rk} = \min \begin{cases} \text{f.} & f_{h,1,k} * t_1 * d \\ \text{g.} & f_{h,1,k} * t_1 * d\left[\sqrt{2 + \frac{4 * M_{y,Rk}}{f_{h,1,k} * d * t_1{}^2}} - 1\right] + \frac{F_{ax,Rk}}{4} \\ \text{h.} & 2{,}3\sqrt{M_{y,Rk} * f_{h,1,k} * d} + \frac{F_{ax,Rk}}{4} \end{cases}$$

Figure 24 – Design formulas for the capacity of connections with slotted-in plates in Eurocode 5 **(NEN-EN 1995-1-1+C1+A1:2011)**

The following explanation is given for each of the parameters:

$F_{v,Rk}$	The characteristic value of the capacity of the connection per fastener per shear plane
$f_{h,1,k}$	The characteristic value of the embedment strength of the timber elements
d	The diameter of the dowel
t_1	The thicknesses of the timber members
$M_{y,Rk}$	The characteristic value of the plastic bending moment resistance of the dowel

In these formulas the first part is the capacity of the connection as it was determined by Johansen (1949). The second part of the formulas ($\frac{F_{ax,Rk}}{4}$) is the so called chord-effect.
For failure modes 'g' and 'h' it is of no concern whether the connection makes use of either thin or thick slotted-in plates, since the capacity of the connection is based on the capacity per dowel per shear plane and the amount of plastic hinges in the dowel per shear plane will be the same when applying a tin or a thick steel plate.
The maximum capacity of the connection is determined by taking the maximum capacity of each dowel per shear plane ($F_{v,Rk}$) and multiplying this by the amount of (effective) dowels and the amount of shear planes in the connection.

4.4 Derivation of the design formulas

In this section the build-up and the derivation of the design formulas from Eurocode 5 will be given. As mentioned before the design formulas consist of two parts. The first part is the resistance as determined by Johansen (1949) and the second part consists of the chord-effect.

To further analyse these two parts, this section commences with further explaining the global structure of the formulas. Here the function of the two parts will become clear and two different theories about the origin of the factors in the formulas shall be discussed. Since both theories yield the same (correct) formulas but the origin of the factors matters in order to correctly assess the applicability on laminated bamboo, a discussion will be made on with whichever theory this research will agree. After this the Johansen part and the chord-effect will be analysed.

4.4.1 Global structure of the formulas (Porteous, J., Kermani, A., 2007)

In a connection using dowel type fasteners two different types of frictional forces are to be distinguished (Porteous, J., Kermani, A., 2007).

The first type of frictional force is a consequence of friction between the elements after fabrication of the connection. These frictional forces will (e.g. due to shrinkage of the timber because of weather conditions) decrease in time or even fully disappear. Because of the complexity of determining the actual magnitude of these frictional forces and their (usually) relatively short lifespan, if even existent at all (Aune, P., Patton-Malory, M., 1986), frictional forces of this type are, in the formulas established by Johansen (1949) and Meyer (1957), neglected (Hilson).

The second type of frictional force arises from a situation in which the dowel deforms and starts pulling the timber members closer together. This form of friction appears in failure mechanisms where the dowel shows plastic deformation (plastic hinges). This type of friction is taken into account by the Eurocode (Pedersen, M.U., Clorius, C.O., Damkilde, L., Hoffmeyer, P., Esklidsen, L., 1999).

To make a better visualisation of the frictional forces taken into account by the Eurocode a connection between a plywood plate and a timber member is considered. In this connection one single dowel is used. The connection is visualised in Figure 25 – **Example of a connection using a dowel type fastener**.

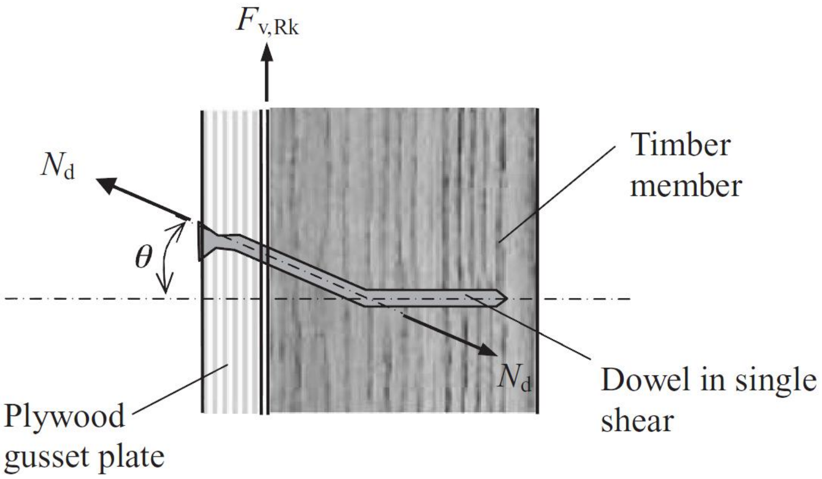


Figure 25 – Example of a connection using a dowel type fastener **(Porteous, J., Kermani, A., 2007)**

In the considered connection the dowel will, as a consequence of shearing forces in the connection, form two plastic hinges. One of these hinges will be in the gusset plate and one of the hinges will be in the timber member. As a result of the formation of the plastic hinges the fastener will rotate over an angle θ. Both ends of the fastener are kept in place by frictional forces between the fastener and the wood material. Due to this, after the rotation, an axial force N_d will arise in the fastener. This force will place the fastener under tension. As a result of the rotation over θ the force N_d acts in a direction at an angle to the direction of loading and will thus have a vertical component ($N_d*\sin(\theta)$)

and a horizontal component (N_d*cos(θ)). The horizontal component of N_d will pull the timber members closer together and ultimately create extra frictional forces between the timber members. This will have an increasing effect on the capacity of the connection. The magnitude of this increase in capacity depends highly on the frictional coefficient μ of the timber members. The extra capacity can be calculated as μ*N_d*cos(θ).
The total capacity of the connection will then be a summation of the vertical component of N_d, the frictional force between the timber elements and the force that results from the formulas of Johansen (1949).

$$F_{v,Rk} = N_d * \sin(\theta) + \mu * N_d * \cos(\theta) + Johansen\ yield\ load \tag{1}$$

At the moment of failure of the connection Eurocode 5 (NEN-EN 1995-1-1+C1+A1:2011) defines the vertical component (N_d*sin(θ)) as $F_{ax,Rk}$/4, where $F_{ax,Rk}$ is the fasteners characteristic withdrawal capacity (Porteous, J., Kermani, A., 2007). This is what's called the chord effect.
The frictional forces that are a consequence of the horizontal component of N_d (μ*N_d*cos(θ)) are in Eurocode 5 equated to a percentage of $F_{y,Rk}$, the Johansen yield load. By making these substitutions in the calculation of the capacity of the connection the Eurocode 5 formulas are written in the following format.

$$F_{v,Rk} = frictional\ factor * Johansen\ yield\ load + \frac{F_{ax,Rk}}{4} \tag{2}$$

The value used for the frictional factor in case the fasteners fully yields is 15% (Porteous, J., Kermani, A., 2007). The numerical coefficient belonging to this value is 1.15. This factor can be found in formula 'h' of Figure 24 – **Design formulas for the capacity of connections with slotted-in plates in Eurocode 5** where 1.15 is multiplied by a factor 2 that originates from the Johansen yield load.

4.4.2 Global structure of the formulas by ratio of partial factors

Another, explanation of the global structure of the formulas is to determine the capacity of the connection by only taking the Johansen yield load and the withdrawal resistance into account. The factor of 1.15 is in this case a ratio between the partial safety factors of steel and timber, not a result of frictional forces as assumed by (Porteous, J., Kermani, A., 2007). This theory is explained during the course CT4110 at TUDelft. Within this theory the frictional forces between members are assumed to be negligible and the factors that take into account the difference in partial factors between timber and steel are calculated mathematically. The derivation, and explanation, of the factor 1.15 as it is explained during this course is given below.

Usually for the calculation of the load carrying capacity of a structure design values are used. The formulas given in Eurocode 5 yield a value for $F_{v,Rk}$, a characteristic value. In order to get a design value, in timber design, one has to multiply the characteristic value by $\frac{k_{mod}}{\gamma_M}$. However, since these factors do not account for the partial factors of steel in the equation a constant C has to be added to the equation of $F_{v,Rk}$ such that after multiplication by $\frac{k_{mod}}{\gamma_M}$ the right design value is obtained.

$$F_{v,Rd} = \frac{k_{mod}}{\gamma_M} * C * F_{v,Rk} \tag{3}$$

To find the value of this constant C, a look is taken to a, maybe more straightforward, way of determining $F_{v,Rd}$. A formula will now be given in which $F_{v,Rd}$ is calculated simply by taking design values for the parameters in the formula of failure mechanism h.

$$F_{v,Rd} = \sqrt{4 * M_{y,d} * f_{h,k} * d}$$
$$F_{v,Rd} = \sqrt{4 * M_{y,k} * \frac{k_{mod}}{\gamma_M} * \frac{f_{h,d}}{\gamma_s} * d}$$

$$F_{v,Rd} = \sqrt{4 * M_{y,k} * f_{h,k} * d} * \sqrt{\frac{k_{mod}}{\gamma_M * \gamma_s}} \tag{4}$$

Now two different formulas for the determination of the design value $F_{v,Rd}$ have been established. It will be clear that both formulas have to yield the same value for the capacity of the connection. Based on this requirement a value for constant C can be determined.

$$\frac{k_{mod}}{\gamma_M} * C * F_{v,Rk} = \sqrt{4 * M_{y,k} * f_{h,k} * d} * \sqrt{\frac{k_{mod}}{\gamma_M * \gamma_s}}$$

$$\frac{k_{mod}}{\gamma_M} * C = \sqrt{\frac{k_{mod}}{\gamma_M * \gamma_s}}$$

$$C = \sqrt{\frac{\gamma_M}{k_{mod} * \gamma_s}} \tag{5}$$

The partial factors are given in the Eurocode. By taking γ_M= 1.3 for sawn timber and k_{mod}= 0.9 for short term loading (NEN-EN 1995-1-1+C1+A1:2011) combined with γ_s=1.1 (although γ_s=1.0 according to 6.1 of (NEN-EN 1993-1-1+C2, 2011) and 3.13.2 of (NEN-EN 1993-1-8+C2)) gives the following value for C.

$$C = \sqrt{\frac{1.3}{0.9 * 1.1}} = 1.14592 \xrightarrow{yields} 1.15$$

By implementing this factor into the design formulas of the Eurocode, the calculation of the design value for the capacity of a connection requires less work and can be done quicker. However, to obtain a realistic value for the characteristic strength of the connection one will have to remember to leave out the additional constant. As for the absence of a similar factor for failure mechanism g the reason remains somewhat unclear.

4.4.3 Global structure adopted for this research

Both of the explained theories are used in literature and result in similar values for the additional factor to the Johansen yield load. Although in this research the second theory, by the course CT4110, is deemed more likely than the first theory by e.g. (Porteous, J., Kermani, A., 2007) and (Pedersen, M.U., Clorius, C.O., Damkilde, L., Hoffmeyer, P., Esklidsen, L., 1999), which theory holds the most ground will, for the design of test pieces in this research, not be of such importance.

Since this research will be doing tests for which only the characteristic strength is of importance, the constants that make up for the differences in partial factors do not need to be taken into account. Also through the use of dowels axial forces occurring in the fastener will be limited and frictional forces resulting from these shall be negligible. Therefore the design of test pieces will make use of the formulas given by (Murty, B., Smith, I., Asiz, A., 2005), in which the additional factors are not incorporated. The formulas are shown in Figure 26 – **Formulas for the characteristic capacity** .

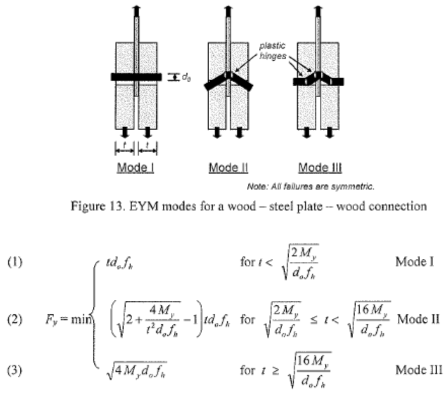


Figure 13. EYM modes for a wood – steel plate – wood connection

$$F_y = \min \begin{cases} t d_o f_h & \text{for } t < \sqrt{\frac{2M_y}{d_o f_h}} & \text{Mode I} \quad (1) \\ \left(\sqrt{2 + \frac{4M_y}{t^2 d_o f_h}} - 1\right) t d_o f_h & \text{for } \sqrt{\frac{2M_y}{d_o f_h}} \le t < \sqrt{\frac{16M_y}{d_o f_h}} & \text{Mode II} \quad (2) \\ \sqrt{4 M_y d_o f_h} & \text{for } t \ge \sqrt{\frac{16M_y}{d_o f_h}} & \text{Mode III} \quad (3) \end{cases}$$

Figure 26 – Formulas for the characteristic capacity (Murty, B., Smith, I., Asiz, A., 2005)

4.4.4 Johansen yield load

The formulas for determining the capacity of connections with dowel type fasteners loaded in shear are, as they are represented in Eurocode 5, mainly based on work done by Johansen in 1949. During World War Two the Danish professor K.W. Johansen performed, due to a lack of building materials as steel and concrete, a series of tests on timber connections (Jorissen, A., Leijten, A.). On the basis of his test results, Johansen managed in 1949 to compose equilibrium equations with which he could describe the capacity of dowel type connections with one shear plane or two shear planes (Schoenmakers, 2010). When deriving these equations he assumed that all loads, which are acting in the connection, are uniformly distributed and that the timber elements were of the same quality (made from the same wood species). Also the timber elements in a double shear connection (with the timber as the outer parts) were assumed to be of the same thickness. The steel in the connection was assumed to be elastic. Later an extension to the formulas of Johansen was made by Meyer (1957) with which also the plastic deformation of the steel could be taken into account. Perfect plasticity is assumed for both the steel dowels and the timber (Sjödin, 2008). The loads are still assumed to be uniformly distributed, but differences in the embedment strength of the individual timber parts is now also considered. All formulas are established for determining the capacity of connections parallel to the fiber but can also be applied on connections that are loaded perpendicular to the fiber (Schoenmakers, 2010).

The mathematical elaboration of the Johansen yield load, as it is presented in Eurocode 5, will, as to not negatively influence the readability of the report, be included in **Annex A –** Mathematical elaboration of the Johansen yield load.

The factors that are included in the Johansen part of the formulas for the determination of the capacity of timber joints with dowel type connections in single or in double shear are: the embedment strength of all timber parts, the relation between these embedment strengths (β) and the yield moment of the used fastener (which depends on the diameter of the fastener and the steel grade). The origin of these factors will be treated in '4.5 - **Origin of factors**'. In order to judge the applicability of the design codes from Eurocode 5 on connection design in laminated bamboo, it has to be checked whether or not it is possible to determine every factor, which would influence on the capacity of a connection in timber, for laminated bamboo. The validity of the mentioned design formulas on connections in laminated bamboo can thereafter be verified by lab testing.

4.4.5 Chord-effect

For the determination of the capacity of a dowel type connection, next to the formulas by Johansen (1949) and Meyer (1957), also the so-called chord-effect is taken into account by Eurocode 5. As previously discussed, The Eurocode 5 design rules are written in such a format that the first part of these formulas is the Johansen yield load (with an extra frictional or partial factor if necessary) and the second part is the chord-effect ($F_{ax,Rk}/4$).

In a loaded connection, in which a plastic hinge forms in the fastener, the fastener will be loaded with an axial force (tension). Because the fastener is, in most cases, able to give resistance to these axial forces (e.g. by friction between fastener and timber, because of a nail head or because of a nut that prevents the fastener from moving), the fastener can, in such a state, give an increase in the capacity of the connection. This effect is called the chord-effect. For a visual display of the chord-effect one can refer to Figure 27 - **Visual display of the chord-effect** . The actual magnitude of this increasing effect on the capacity is, of course, dependent on the withdrawal capacity of the fastener. The Eurocode 5 however does make a restriction with regard to the percentage of the withdrawal resistance that can be added to the capacity of the connection. The maximum amount is restricted to 25% of the withdrawal resistance (thus: $F_{ax,Rk}/4$) (Jorissen, A., Leijten, A.).

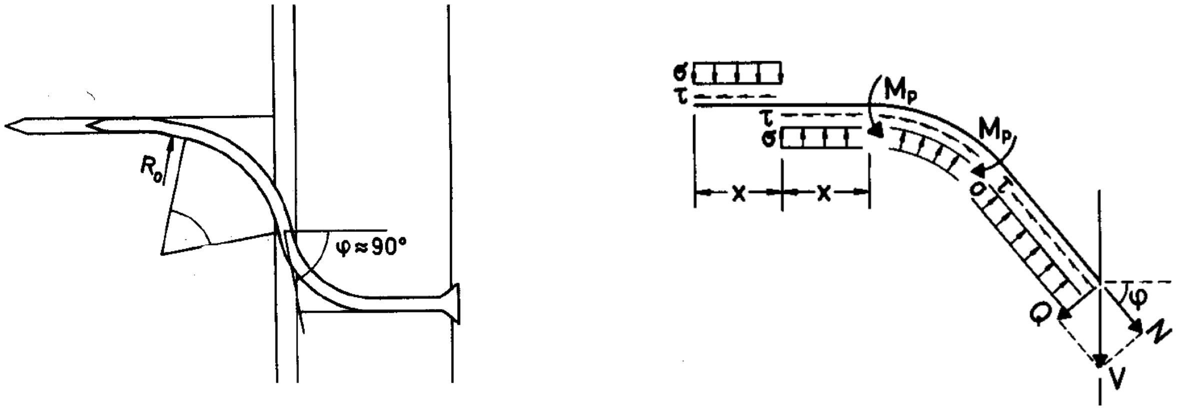


Figure 27 - Visual display of the chord-effect **(Jorissen, A., Leijten, A.)**

It may be clear that the characteristic withdrawal capacity ($F_{ax,Rk}$) of the fastener is highly dependent on the type of fastener. A wood screw or a lag screw will, after all, have a higher withdrawal resistance than a smooth nail. To account for differences in maximum withdrawal capacity between variants of the same type of fastener (e.g. a smooth round nail or a profiled round nail), in Eurocode 5 a limit was set to the maximum value of $F_{ax,Rk}/4$ (as a percentage of the Johansen yield load) that can be added to the capacity as it is determined by only the Johansen yield load. These maximum percentages are as follows:

- Square nails:	15%
- Other nails:	50%
- Wood screws:	100%
- Lag screws:	100%
- Bolts:	25%
- Dowels:	0%

From these given percentages it can be seen that the additional capacity gained by the chord-effect in the case of dowels is 0%. Since this research focusses on connections using smooth dowels, the connections that will be tested are not expected to gain any additional capacity as a result of the withdrawal resistance of the fastener.

4.5 Origin of factors

In this section the theoretical background and the origin of the factors, which are needed to apply the formulas of Johansen (1949) as they are presented in Eurocode 5 (NEN-EN 1995-1-1+C1+A1:2011), will be examined. In '4.4.5 - **Chord-effect**' has already been determined that, for this research, due to the use of smooth dowels, the withdrawal resistance of the fasteners will not make a contribution to the capacity of the connection. The factors needed to determine the withdrawal capacity thus fall outside of the scope of this research. The remaining factors to be studied are the embedment strength and the yield moment of the fastener. First the embedment strength will be explained. After that the yield moment will be addressed.

In a connection using multiple fasteners also the effective number of fasteners plays a role in determining the capacity of the connection. Since this property, for laminated bamboo, is being studied in another research, this report will focus on properties of connections using only one dowel.

4.5.1 Embedment strength

Together with the yield moment capacity of the fastener, the embedment strength of the timber is one of the primary determining factors in the capacity of a dowel type connection. The embedment strength is dependent on the timber species, the type of fastener, the shape of the connection (e.g. the end and edge distances and the thicknesses of the timber members) and the size of the pre-drilled holes. In other words the embedment strength is not so much a material property as it is a system property (De Vries, P.A., Van de Kuilen, J.W., 2012).

4.5.1.1 Testing the embedment strength

The embedment strength is defined as the maximum pressure the timber can exert on the fastener in case the fastener is pressed into the timber. In a standard test for embedment strength according to (NEN-EN 383:2007), a fastener will be pressed into a timber member by the use of steel plates. A visualisation of the test set-up can be seen in Figure 28 – **Embedment strength test set-up** .

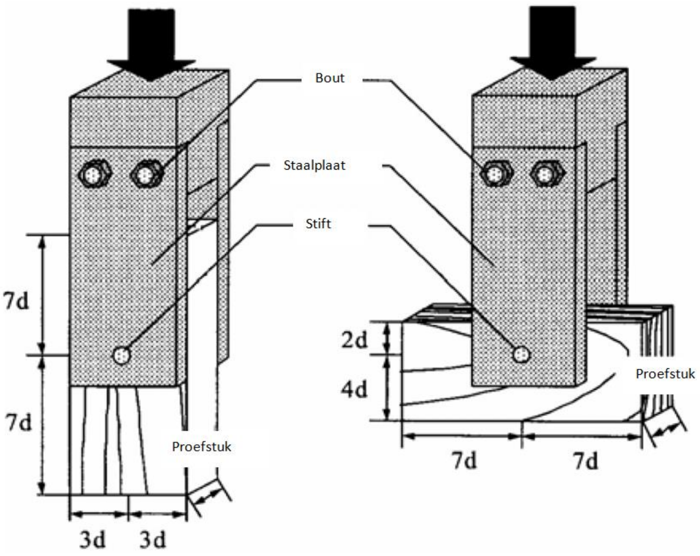


Figure 28 – Embedment strength test set-up **(Sawata, K., Yasumara, M., 2002)**

In this test set-up the dimensions of the timber are chosen such that only the timber will deform. The embedment stress is then determined by dividing the applied load on the test piece by the product of the dowel diameter and the thickness of the timber (Jumaat, Z., Bakar, A., Razali, F.M., Rahim, A.H.A., Othman, J.). In formula:

$$\sigma = \frac{F}{A} = \frac{F}{t * d} \tag{6}$$

By performing tests, values of the embedment strength can be graphed as a function of the measured deformation. In Figure 29 – **Relation between embedment strength and measured deformation** a graph is shown that was obtained by (Sawata, K., Yasumara, M., 2002) by testing different dowel diameters. On the left a graph is shown that represents the embedment strength as a function of displacement parallel to grain. The right side shows the same but perpendicular to grain.

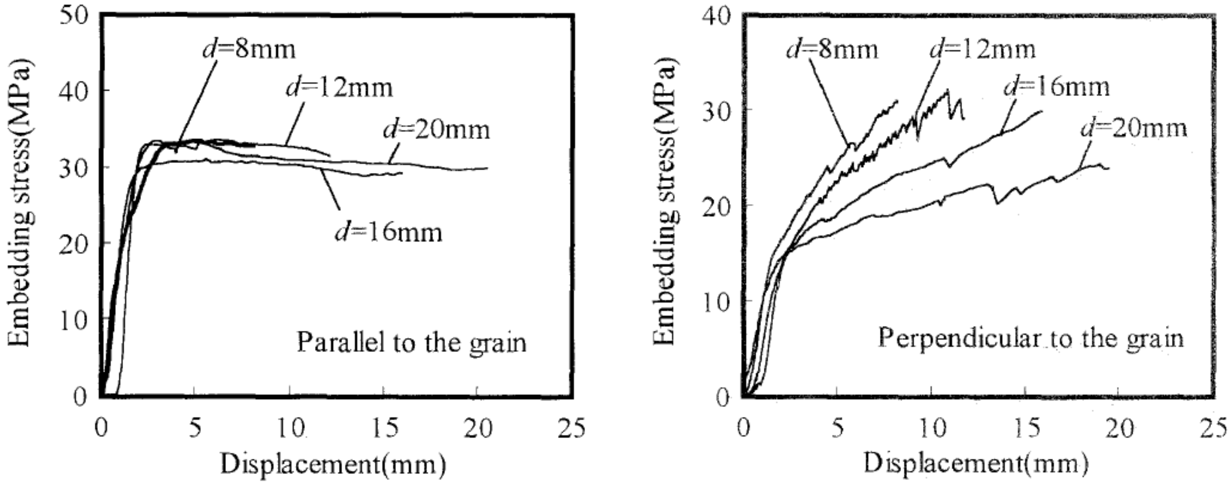


Figure 29 – Relation between embedment strength and measured deformation **(Sawata, K., Yasumara, M., 2002)**

To obtain these graphs about 1000 tests were done on different timber species and using dowel diameters 8mm, 12mm, 16mm and 20mm. the tests were done according to (NEN-EN 383:2007). With the results of these tests stress-strain diagrams were made. On the basis of these diagrams formulas were established with which the embedment strength of timber can be predicted.

Parallel to the fiber it can be seen that the timber relatively behaves linear-elastically. Here it can be noted that the largest embedment stress is reached with use of the smallest dowel diameter. Perpendicular to fiber the linear-elastic part of the curve is somewhat shorter, after that the embedment stress increases slower than the increasing deformations. Ultimately the embedment stress parallel to fiber lies within the same range as it would have been perpendicular to fiber. The standard embedment strength in Europe is defined at a displacement of 5mm of the dowel into the timber, regardless of the type of timber, the diameter of the dowel and the angle to the grain (Jorissen, A., Leijten, A.). It will be clear that the embedment strength perpendicular to the fiber is not fully utilised at that point.

4.5.1.2 The embedment strength in Eurocode 5

The design formulas Eurocode 5 gives for the determination of the embedment strength are given in chapter 8 of (NEN-EN 1995-1-1+C1+A1:2011). These formulas are also displayed in Figure 30 - **Design formulas embedment strength Eurocode 5** .

$$f_{\mathrm{h},\alpha,\mathrm{k}} = \frac{f_{\mathrm{h},0,\mathrm{k}}}{k_{90}\sin^2\alpha + \cos^2\alpha} \tag{8.31}$$

$$f_{\mathrm{h},0,\mathrm{k}} = 0{,}082(1 - 0{,}01d)\rho_{\mathrm{k}} \tag{8.32}$$

waarin:

$$k_{90} = \begin{cases} 1{,}35 + 0{,}015d & \text{voor naaldhout} \\ 1{,}30 + 0{,}015d & \text{voor LVL} \\ 0{,}90 + 0{,}015d & \text{voor loofhout} \end{cases} \tag{8.33}$$

Figure 30 - Design formulas embedment strength Eurocode 5 **(NEN-EN 1995-1-1+C1+A1:2011)**

4.5.1.3 The determination of a design formula for embedment strength

The determination of the factors that make up the formula for the embedment strength will be explained in the following.

The formula for the determination of $f_{h,0,k}$ is empirically determined. To obtain the formula many tests have been done (e.g. by (Sawata, K., Yasumara, M., 2002)). Sawata and Yasumara have, in 2002, done many tests and used the results of their tests to draft graphs in which the embedment stress is represented as a function of the displacement of the dowel. One of such graphs is show in Figure 31 – **5%-offset method** . The graph shown represents the measured embedding stress of one single test piece. In order to design a connection however, one has to have a graph that is representative for all test pieces and of which one knows it, by hook or by crook, meets, but not exceeds, the embedding strength given by this graph. For this, the characteristic strength of the material has to be determined. The characteristic value of the strength is defined as that value that is exceeds all but 5% of the material. In other words: the characteristic strength value is a value that is exceeded by 95% of the material. The characteristic value is also called the 5-percentile value.

To determine the 5-percentile value several methods can be applied. The most important methods are the (American) '5%-offset method' and the method as it is prescribed by EN 383 (Sawata, K., Yasumara, M., 2002). For more information on the EN 383 method a reference is made to (NEN-EN 383:2007). The American method bill be briefly explained below. For this, Figure 31 – **5%-offset method** will be used.

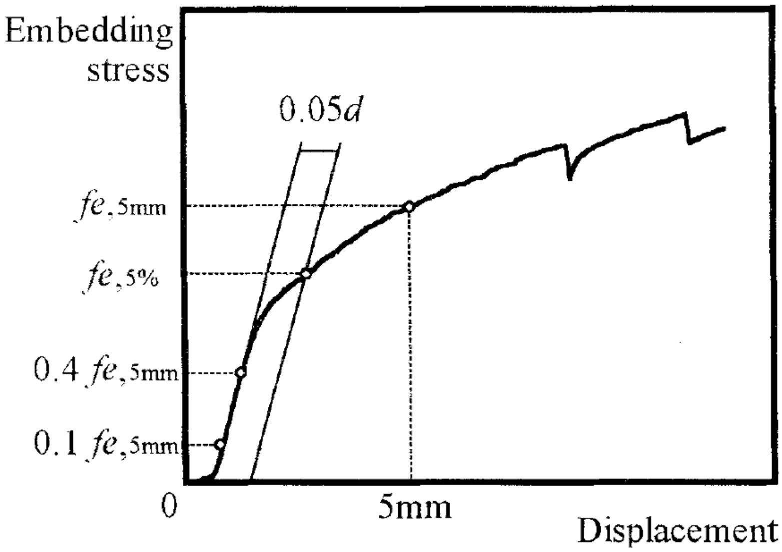


Figure 31 – 5%-offset method **(Sawata, K., Yasumara, M., 2002)**

In this figure an embedding stress-displacement diagram is shown. Here the embedment stress is shown in a force per area (e.g. N/mm²) on the vertical axis and the displacement is shown in mm on the horizontal axis. The diagram shows a linear elastic behaviour at a stress level in between 10% and 40% of f_e. In this case f_e is the embedment stress at 5mm displacement (this is also the embedment stress that is prescribed by Eurocode 5). To find the characteristic value of the embedding stress, the 5%-offset method makes use of a tangent line at the linear part of the graph (between $0.1*f_e$ and $0.4*f_e$). This tangent line will then be moved to the right over a distance of 5% of the dowel diameter. The intersection point of this offset line with the embedding stress-displacement diagram is defined as the characteristic (or 5-percentile) value (Sawata, K., Yasumara, M., 2002).

During their research Sawata and Yasumara also looked into the differences (and resemblances) between the American 5%-offset method and the EN 383 method. They found that for a loading parallel to the fiber direction of the timber the 5-percentile values given by the two methods are similar. For loadings perpendicular to the fiber

direction they found that the 5%-offset method is much less sensible to changes in dowel diameter than the EN 383 method (Leijten, A., Köhler, J.).
A design formula for the embedding strength is then obtained by determining the 5-percentile values for all test pieces according to one of the described methods. These 5-percentile values are then charted based on the dowel diameter and the density of the timber. This results in a range of points which can be described by a graph that relates the embedding strength to the density of the timber and the diameter of the dowel.

In Figure 32 – **Embedding strength in relation to the density of the timber** an example of such a chart is shown. The figure, made by (Hübner, H., Bogensperger, T., Schikhofer, G.), gives data of the embedment strength in relation to the density of the timber taken from research done by Ehlbeck & Werner (1992), van Whale, Smith & Hilson (1986) and from Hübner, Bogensperger & Schikhofer (2008).

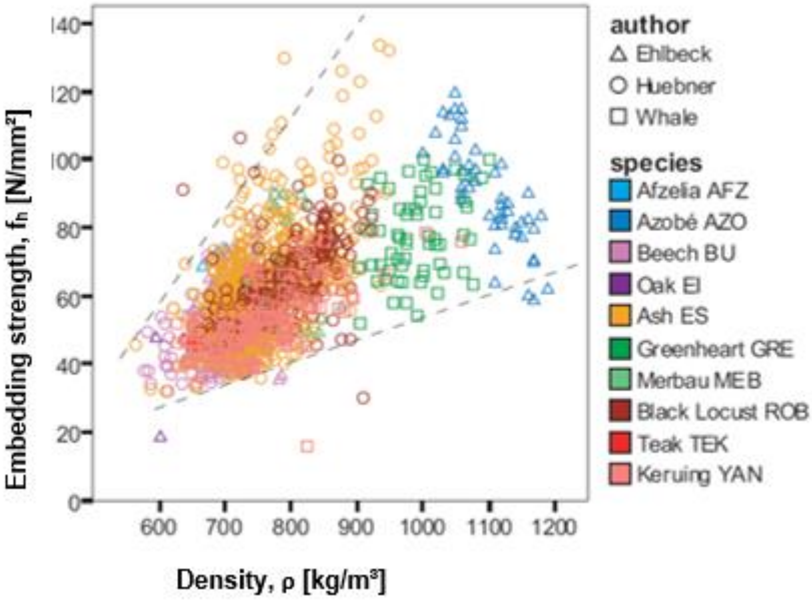


Figure 32 – Embedding strength in relation to the density of the timber **(Hübner, H., Bogensperger, T., Schikhofer, G.)**

On the basis of values given in such charts formulas can be composed with which $f_{h,0,k}$ can be predicted. The formulas for $f_{h,0,k}$ that were established by Ehlbeck and Werner in 2011 have been adapted in Eurocode 5 and are shown in Figure 30 - **Design formulas embedment strength Eurocode 5** of this report.
To calculate the embedment strength under an angle with the fiber the ratio between $f_{h,0,k}$ and $f_{h,90,k}$ is used. To better understand this ratio the Hankinson (1929) formula is used. This formula is as follows.

$$f_{h,\alpha,k} = \frac{f_{h,0,k} * f_{h,90,k}}{f_{h,0,k} * \sin^2 \alpha + f_{h,90,k} * \cos^2 \alpha} \qquad (7)$$

By means of testing, Ehlbeck and Werner (2011) have found that a formula can be established that describes the relation between $f_{h,0,k}$ and $f_{h,90,k}$. This relation is given by the factor k_{90} and is dependent on the timber species, the density of the timber and the dowel diameter. Ehlbeck and Werner (2011) give the following definition for the ratio k_{90}.

$$k_{90} = \frac{f_{h,0,k}}{f_{h,90,k}} \text{ or } f_{h,0,k} = k_{90} * f_{h,90,k} \qquad (8)$$

Substituting this factor in the Hankinson equation gives the following relation:

$$f_{h,\alpha,k} = \frac{f_{h,0,k} * f_{h,90,k}}{f_{h,0,k} * \sin^2\alpha + f_{h,90,k} * \cos^2\alpha}$$
$$f_{h,\alpha,k} = \frac{f_{h,0,k} * f_{h,90,k}}{k_{90} * f_{h,90,k} * \sin^2\alpha + f_{h,90,k} * \cos^2\alpha}$$
$$f_{h,\alpha,k} = \frac{f_{h,0,k}}{k_{90} * \sin^2\alpha + \cos^2\alpha} \tag{9}$$

4.5.1.4 Expected embedment strength of laminated bamboo

In the previous the method for the determination of the embedment strength of a timber material was briefly explained. Since the embedment strength of laminated bamboo is, at the time of this research, still under investigation and thus not yet known, an assumption has to be made with regard to the expected value of the embedment strength in order to design the test pieces.

The Eurocode 5 uses design formulas determined by Ehlbeck and Werner (2011) on the basis of characteristic values. Since the formulas are meant to ensure a safe design, the values obtained from them will give lower results for the embedment strength than one would find during testing. For test piece design, it will be clear that the embedment strength of the laminated bamboo has to be estimated at a more realistic value. It is for this reason that, for the design of the test pieces, also a formula established by Ehlbeck and Werner in 1992 will be taken into account. In 1992 Ehlbeck and Werner established a formula for the determination of the embedment strength specifically for hardwood species (Islamaj, 2009) (Sandhaas, 2012). Another advantage of this formula is that the average density of the timber is used instead of the characteristic density like in the Eurocode 5 design rules. Considering the average density of laminated bamboo (666 kg/m³ as determined by (Schickhofer, 2015)) the 1992 formulas may be more applicable in the design of test pieces. The considered formula is as follows.

$$f_{h,0} = 0.102(1 - 0.01 * d) * \rho_{average} \tag{10}$$

4.5.2 Yield moment of the fastener

The yield capacity of the used fastener strongly determines the total capacity of the connection. In this section the determination of the yield moment of a fastener will be explained.

4.5.2.1 Theoretical yield capacity

For the calculation of the yield capacity a full plastic behaviour is assumed. In this case, the yield capacity of the used dowel will be equal to a multiplication of the area of the tensile (or compressive) zone and the internal lever arm of the cross section with the yield stress of the steel. A visualisation of this is given in Figure 33 - **Plastic bending moment resistance of a circular cross section**.

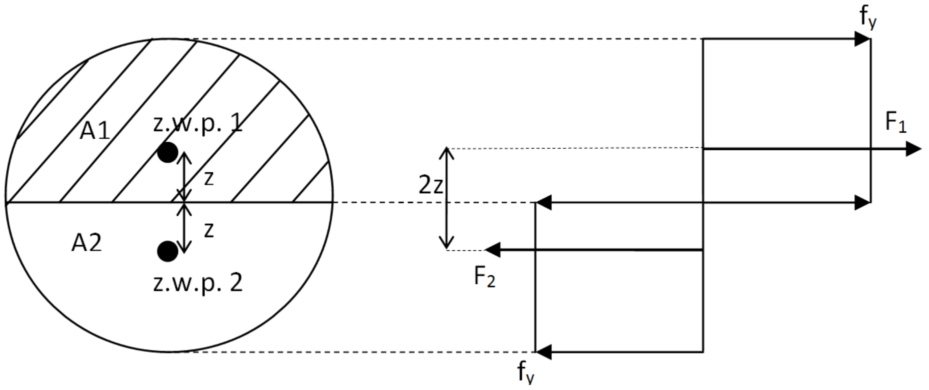


Figure 33 - Plastic bending moment resistance of a circular cross section

The formula for the theoretical bending moment resistance:

$$M_{y,Rk} = A_n * 2z * f_y \tag{11}$$

In which:

$M_{y,Rk}$	The characteristic value for the yield moment [Nmm]
A_n	The area of half of the cross section of a round dowel [mm^2]
z	The distance from the centre of the cross section to the centre of gravity (z.w.p.) of the halved cross section of the dowel. Or: half of the internal lever arm (i.e. the centroidal distance of a halve circle) [mm]
f_y	The yield stress [N/mm^2]

The centroidal distance of a halve circle is determined by use of the following formula (with the diameter of the dowel 'D' in mm):

$$z = \frac{2*d}{3*\pi}$$

The area of half of the cross section of a round dowel can be determined by:

$$A_n = \frac{1}{2} * \frac{1}{4} * \pi * d^2$$

$$A_n = \frac{1}{8} * \pi * d^2$$

Substituting these formulas, the theoretical yield moment of a round dowel is defined as the following:

$$M_{y,Rk} = A_x * 2z * f_y$$

$$M_{y,Rk} = \frac{1}{8} * \pi * d^2 * 2\frac{2*d}{3*\pi} * f_y$$

$$M_{y,Rk} = \frac{1}{6} * f_y * d^3 \tag{12}$$

4.5.2.2 Eurocode 5 (1993)

In the previous f_y was used to determine the yield moment of a fastener. Eurocode 5 however makes use of the ultimate tensile stress $f_{u,k}$ instead of the yield tress f_y. The stress $f_{u,k}$ is obtained via tensile tests on a tensile bar of the same steel grade (and quality) as the dowel to be used. In Figure 34 – **tensile rod** such a tensile bar is shown. In this figure the force acting on the tensile rod is depicted as F. As a consequence of this, the rod, with diameter d, will constrict and start yielding at the weakest spot (usually where the diameter is smallest). This is indicated with d'.

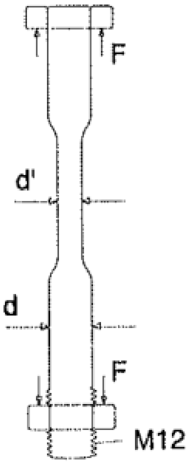


Figure 34 – tensile rod **(Jorissen, A., Blaß, H., 1998)**

On the basis of test results stress-strain diagrams can be made. An example of such a stress-strain diagram is given in Figure 35 - **Stress-strain diagram** .

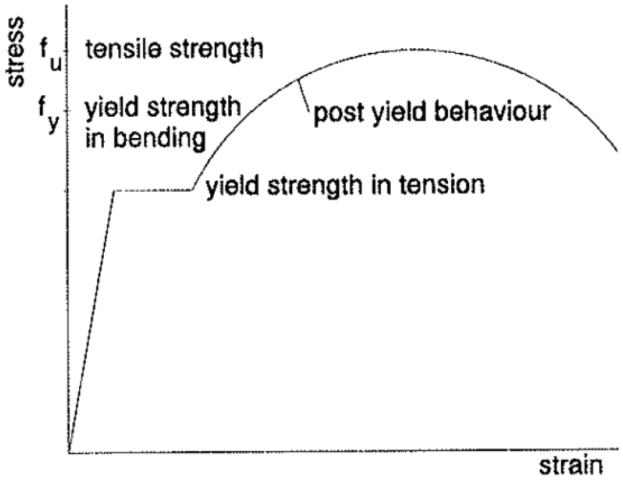


Figure 35 - Stress-strain diagram **(Jorissen, A., Blaß, H., 1998)**

The ultimate tensile strength can then be determined by:

$$f_{u,k} = \frac{F_{max}}{\frac{1}{4} * \pi * d'^2} \tag{13}$$

In this formula F_{max} is the force exerted by the pulling device at the moment of failure of the rod. This force is divided by the (initial) area of the dowel. This ultimate tensile stress is called f_u in the figure.

It has to be noted, to determine the moment capacity, the tensile strength of the dowel in bending is needed (in the figure named 'yield strength in bending'). The yield stress f_y in bending is equal to the ultimate tensile stress obtained in tensile tests in case the fastener is bended over an angle of 45 degrees.
In case a dowel has a diameter larger than 8,0mm failure will occur at an angle lower than 45°. The assumption of a full plastic cross section will not be valid anymore and material at the edge of the cross section will already start yielding while the heart of the cross section has only barely deformed. Therefore the tensile strength of the fastener in bending will be approximated by:

$f_y = 0{,}8 * f_{u,k}$ (Jorissen, A., Blaß, H., 1998)

The value f_y is in the Eurocode assumed at 80% of the ultimate tensile stress. It is found that this factor of 0.8 gives a good approximation of the real yield stress f_y (Jorissen, A., Blaß, H., 1998). This factor can be applied to both small and large diameter dowels (Jorissen, A., Blaß, H., 1998).
The formula for the calculation of the yield capacity of dowel-type fasteners as it is depicted in ENV 1995-1-1:1993 (Eurocode 5) is the following.

$$M_{y,Rk} = \frac{1}{6} * 0{,}8 * f_{u,k} * d^3 \tag{14}$$

4.5.2.3 Eurocode 5 (2011)

By (Jorissen, A., Blaß, H., 1998) and (Rouger, 1998) was shown that the yield moment capacity of dowels as calculated by the formula from ENV 1995-1-1:1993 (Eurocode 5, 1993) and the yield moment found by the method described in EN409 does not fully resemble the exact yield moment (Larsen, H., Munch-Andersen, J., 2011). In the present Eurocode 5 (NEN-EN 1995-1-1+C1+A1:2011) the following, empirically determined, formula is given to determine the yield moment of dowel-type fasteners.

$$M_{y,Rk} = 0{,}3 * f_{u,k} * d^{2{,}6} \tag{15}$$

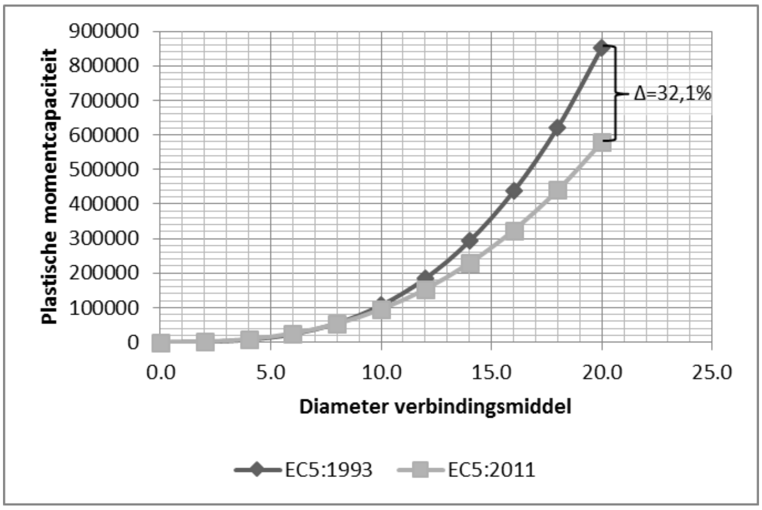
During the execution of the tests, on which this formula is based, account is taken of the fact that large diameter fasteners are not able to reach bending angles of 45°. A bending angle of 10° to 20° would be more suitable for these types of dowels (Larsen, H., Munch-Andersen, J., 2011).
A condition for the application of this formula is that the ultimate tensile strength of the steel has to be larger than 600 N/mm² (Jorissen, A., Leijten, A.). An upper boundary for the tensile strength in the application of this formula is set at 800 N/mm². By the use of these steel grades the requirements for the minimal strain at rupture will also be fulfilled (De Vries, P.A., Van de Kuilen, J.W., 2012).

By (Jorissen, A., Leijten, A.) is stated that the given formula in (NEN-EN 1995-1-1+C1+A1:2011) also takes into account splitting of the timber. Herein lies also the reason for the exponent of the formula to be 2.6 instead of 3 as prescribed by Eurocode 5, 1993. Especially when applying large diameter dowels the timber will have failed due to splitting prior to reaching the yield moment of the dowel (Jorissen, A., Leijten, A.).
The effect the diameter of the fastener has on splitting of the timber increases with increasing diameter.
Through testing it appears that the design formula from Eurocode 5, 2011 always gives lower values than the exact yield moment (Jorissen, A., Leijten, A., 2005). The formula can thus be used to get safe values for any dowel diameter (Larsen, H., Munch-Andersen, J., 2011). In CIB paper 38-7-5 it is argued that the Eurocode 5 design rules need to be kept simple and easy to use and a proposal was made by (Jorissen, A., Leijten, A., 2005) to also apply the adapted formula for small diameter dowels. This led to an adaption to the design formula of Eurocode 5, 1993 in which the formula from 4.5.2.2 - **Eurocode 5 (1993)** was changed to the formula depicted above.

4.5.2.4 Comparison EC5 from 1993 and 2011

Here a comparison will be made between the formulas from Eurocode 5 from 1993 and 2011. In Figure 36 - **Differences between the yield moment for dowels between EC5:1993 and EC5:2011** a graph is shown in which the formulas have been graphed and differences become visible.

Ø [mm]	**EC5:1993** [Nmm]	**EC5:2011** [Nmm]
0.0	0	0
2.0	853	1455
4.0	6827	8822
6.0	23040	25317
8.0	54613	53487
10.0	106667	95546
12.0	184320	153491
14.0	292693	229163
16.0	436907	324282
18.0	622080	440473
20.0	853333	579281



Ø [mm]	**EC5:1993** [Nmm]	**EC5:2011** [Nmm]
0.0	0	0
2.0	853	1455
4.0	6827	8822
6.0	23040	25317
8.0	54613	53487
10.0	106667	95546
12.0	184320	153491
14.0	292693	229163
16.0	436907	324282
18.0	622080	440473
20.0	853333	579281

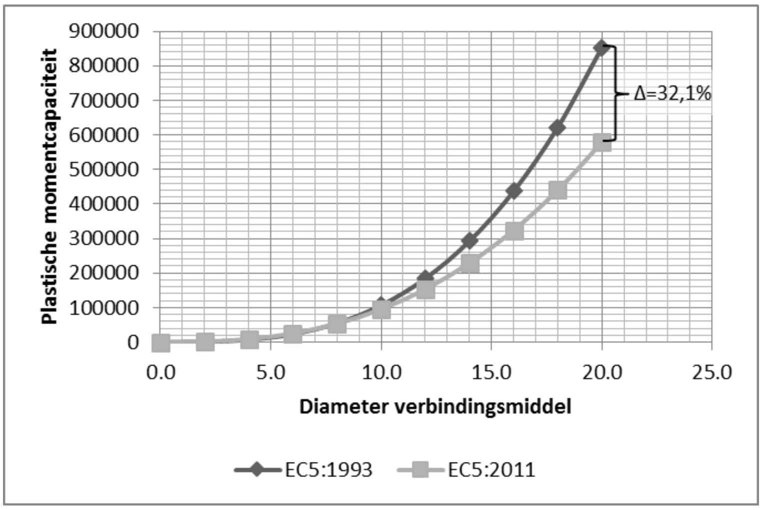


Figure 36 - Differences between the yield moment for dowels between EC5:1993 and EC5:2011

In this graph can be seen that for dowel diameters 6mm to 10mm the differences are fairly small but from diameters 12mm and up the difference in these formulas becomes quite large.

In this research testing will be done at dowel diameters most likely used for slotted-in plate connections for roofing structures. A smaller diameter dowel will be applied in the test pieces. For these small diameters the formulas are more or less equivalent. However, due to the lack of modification factors for large dowel diameters the formula from Eurocode 5:1993 is preferred. Also, since for testing dowels can be ordered based on the yield strength, the proposal by (Jorissen, A., Blaß, H., 1998) to approach the yield stress in bending strength by taking 80% of the ultimate stress can be omitted. The formula by which the yield moment capacity of the fastener used in the test pieces will be determined shall thus be the theoretical yield moment as determined in 4.5.2.1 - **Theoretical yield capacity**. The formulas is given here:

$$M_{y,Rk} = \frac{1}{6} * f_y * d^3$$

5 Testing methods

In the previous chapter the design formulas that are normally used to calculate the capacity of a connection have been analysed. In this analysation all necessary formulas to determine the strength of a connection with slotted-in steel plates have been sought and the theoretical background of these formulas has been looked into. In doing so knowledge has been obtained about the various parameters and factors that have an influence on the strength of such a connection. With this knowledge a testing method can now be sought through which the strength of a connection with slotted-in steel plates in laminated bamboo can be tested.

5.1 Objective

Only when the right testing method is implemented the actual resistance of a test piece can be determined. In order to determine the right testing method research is needed. For this the following question will be raised.

Which testing method is necessary to determine the strength of a dowel type connection with slotted-in steel plates in laminated bamboo?

5.2 Plan of action

By means of testing, the strength of a connection with slotted-in plates in laminated bamboo has to be determined. Before testing can commence knowledge about the way of testing has to be gathered. To ascertain this knowledge a literature study is needed. During this study the applicable standards shall be sought and analysed. In doing so the requirements which the tests have to meet will become clear and a suitable testing procedure can be established. The testing norms that will be consulted in this literature study are included within the Eurocode. The consulted norms give requirements and procedures for doing tests on timber materials. Since timber is the material that is closely related to bamboo, the norms for testing in timber shall be used for testing on laminated bamboo during this research.

When a suitable testing procedure has been established the test pieces can be designed to meet the required sizes and specifications. In doing so the resistance of the test pieces for various modes of failure can be determined and a comparison can be made between the expected resistance of a test piece, as determined according to Eurocode 5 (NEN-EN 1995-1-1+C1+A1:2011), and the actual failure load resulting from experiments.

The literature study and the resulting requirements and testing methods are given in **Annex B –** Testing procedure.

6 Design of test pieces

In the previous chapters the applicable design codes have been investigated. The calculation rules for timber connections with slotted-in steel plates were studied and, on the basis of this knowledge, now expectations can be made regarding the, most likely, behaviour of connections with slotted-in steel plates in laminated bamboo. Preparatory to testing, a provisional assumption regarding the behaviour of laminated bamboo connections was made. The expected behaviour of laminated bamboo is taken to be similar to timber and so, testing methods designed originally for timber connections will, in this research, be adopted for testing laminated bamboo. The testing norms have been studied in 5 - **Testing methods** and a testing procedure has been established. In this chapter the design of the test pieces, which will be tested according to the established procedure, will be treated.

6.1 Goal

In order to get adequate test results, the test piece design has to fit the intended testing procedure. This raises the following question:

What is the design of the test pieces and which materials are needed to form them?

6.2 Plan of action

In the previous chapter the testing procedure was determined according to (NEN-EN 1380:2009). At the end of the procedure the ultimate strength of the test piece will be determined. Tests will thus be done in a destructive manner. In order to perform destructive tests, expectations need to be made with regard to the magnitude of the ultimate load. On the basis of this expected load test pieces have to be designed. Only by properly designing the test pieces can be assured that the test pieces will break at the intended locations (e.g. at the connection rather than in the steel used to attach the test piece to the equipment). Also the design of test pieces has to account for different failure modes to be tested. In 4 - **Applicable design formulas** was determined that, based on a number of parameters, various failure modes can be observed when a connection is loaded. To observe the behaviour of the connection in a certain failure mode the tests piece design has to fit all parameters necessary for that specific failure mode to occur. Especially since certain failure modes can be unwanted in practice (e.g. brittle/sudden failure) the maximum capacity of all individual failure modes and its potential compliance with Eurocode 5 has to be looked into.

For comparable test results, and to only test connection parameters related to laminated bamboo, the testing equipment and the steel used (dowels, slotted-in plates) will, for every test variant, be kept at the same size, thickness and strength. The necessary size and strength of the steel will follow from the test variant that will be most demanding of the steel.

Test piece design will commence with calculating the capacity of the connection on the basis of different failure modes. In this calculation it is kept in mind that the connections to be tested have to represent connections one would find in an actual structure. A lamination width of 18mm is be taken into account (since, in practice, the width of the applied beam is generally determined by the amount of lamellas that are glued together and, thus, will always be a multiplication of the width of a single lamella, although exceptions on this could be made if specifically asked for). With this lamination width in mind a dowel diameter and grade will be sought which can be kept constant over all variants of test pieces. Then, by making adaptions in member thicknesses between different variants, the behaviour of the failure modes can be studied for connections using one and two slotted-in plates.

6.3 Reading guide

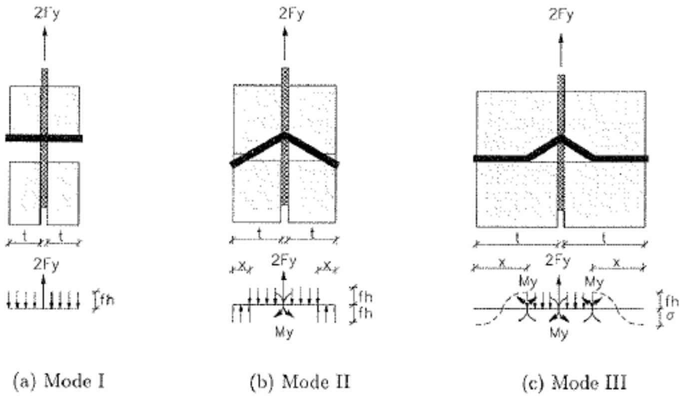
In **Annex C** – Design of test pieces the calculations made for the design of the test pieces and the necessary steel to attach the test piece to the equipment is given. The following chapters will elaborate on the equations made in the annex and provide information about the assumptions made during the calculation. For clarity, paragraph 6.4 - **Used design formulas** will give a summation of the design formulas used to calculate the test pieces. The fastener spacings will be given in 6.5 - **Fastener spacing**. Based on these fastener spacings dowel 1 will be designed in 6.6 - **Design of dowel 1**. With the dowel diameter known several test piece variants can be formed in 6.7 - **Test piece variants**. After that, 6.8 - **Attaching the test piece to the testing machine** will discuss the way in which all of these variants are going to be connected onto the testing apparatus. The strength verification of all connecting means will be done in 6.9 - **Design verifications**. Now that all necessary materials have been determined and their strength has been verified 6.10 - **Materials needed** will give a summation of all materials that will be used to form the test pieces.

6.4 Used design formulas

In 4 - **Applicable design formulas** was, during the study on the background of the design formulas, already stated which formulas would presumably be most applicable for the design of the test pieces. For the sake of clarity the used formulas for the design will be summarized in the following subparagraphs.

6.4.1 The capacity of the connection

In the design formulas of Eurocode 5 (NEN-EN 1995-1-1+C1+A1:2011) design formulas are given with which the capacity of a connection per dowel per shear plane can be determined. As stated by (Pedersen, M.U., Clorius, C.O., Damkilde, L., Hoffmeyer, P., Esklidsen, L., 1999) and mentioned in 4.4.1 - **Global structure of the formulas**, these formulas take frictional forces and axial forces in the fastener into account. Since for this research connections are tested using only smooth round dowels, the axial forces in the fastener are assumed to be negligible and will not contribute to the capacity of the connection. Therefore, test piece design will be based on the Johansen yield load only. The used formulas for the determination of the yield load per failure mode are given in Figure 37 – **Capacity per shear plane per dowel** . The formulas given in this figure are similar to those given in Eurocode 5 (CEN 1995, eq. 6.2.2e-f) (Pedersen, M.U., Clorius, C.O., Damkilde, L., Hoffmeyer, P., Esklidsen, L., 1999).



(a) Mode I (b) Mode II (c) Mode III

$$F_y = min \begin{cases} t\,d\,f_h & \text{for} \quad t < \sqrt{\frac{2M_y}{d\,f_h}} & \text{Mode I} \\ \left(\sqrt{2 + 4\frac{M_y}{t^2\,d\,f_h}} - 1\right) t\,d\,f_h & \text{for} \quad \sqrt{\frac{2M_y}{d\,f_h}} \le t < \sqrt{\frac{16M_y}{d\,f_h}} & \text{Mode II} \\ \sqrt{4M_y\,d\,f_h} & \text{for} \quad t \ge \sqrt{\frac{16M_y}{d\,f_h}} & \text{Mode III} \end{cases}$$

Figure 37 – Capacity per shear plane per dowel **(Pedersen, M.U., Clorius, C.O., Damkilde, L., Hoffmeyer, P., Esklidsen, L., 1999)**

6.4.2 Determining factors in the capacity

The embedment strength of laminated bamboo will be determined using the formula derived by Ehlbeck and Werner in 1992. In consideration of the density of laminated bamboo (666 kg/m³ (Schickhofer, 2015)) this formula for hardwood species (Sandhaas, 2012) is expected to be more applicable for this research. The formula is as follows:

$$f_{h,0} = 0.102(1 - 0.01 * d) * \rho_{average}$$

The moment resistance of the dowels will be calculated based on the assumption of full plasticity of the dowel. The derivation of the formula was made in 4.5.2.1 - **Theoretical yield capacity**. This formula was also adopted by Meyer (Jorissen, A., Leijten, A., 2005) and is as follows.

$$M_{y,Rk} = \frac{1}{6} * f_y * d^3$$

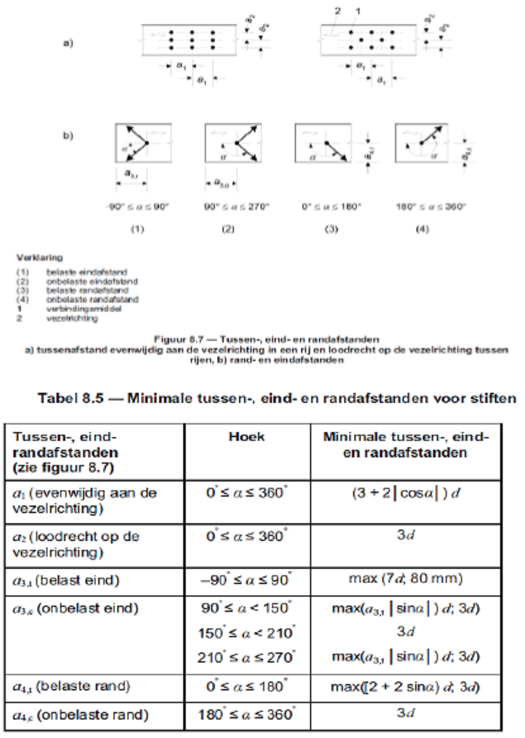
During testing by (Sandhaas, 2012) the strength of the steel that was supplied appeared to be higher than what was ordered. Therefore, for test piece design, also account will be taken of a potentially higher yield strength of the steel. This will be done by adding 20% to the ultimate tensile strength of the steel and making use of the relation between ultimate tensile strength and yield strength in bending given by (Jorissen, A., Blaß, H., 1998). This relation is given below and can be substituted in the formula for $M_{y,Rk}$ given above.

$$f_y = 0{,}8 * f_{u,k}$$

Assuming a 20% higher ultimate strength and approximating the yield strength as 80% of the ultimate strength results in a calculation in which the yield strength of the ordered steel is taken almost equal to the initially estimated ultimate strength.

6.5 Fastener spacing

For fastener spacings the minimum requirements given by Eurocode 5 will be used. By setting minimum end, edge and spacing distances, Johansen (1949) stated premature splitting of the timber can be avoided (Jorissen, A., Leijten, A.). But the use of large fastener spacings will not give absolute certainty that splitting of the members can be avoided (Murty, B., Smith, I., Asiz, A., 2005). By making use of the minimum requirements given in Eurocode 5, potential differences in the required minimum spacing between timber species and laminated bamboo could thus be investigated. The minimum fastener spacing from Eurocode 5 are given in Figure 38 – **Minimum fastener spacings from Eurocode 5** .



Verklaring

(1) belaste eindafstand
(2) onbelaste eindafstand
(3) belaste randafstand
(4) onbelaste randafstand
1 verbindingsmiddel
2 vezelrichting

Figuur 8.7 — Tussen-, eind- en randafstanden
a) tussenafstand evenwijdig aan de vezelrichting in een rij en loodrecht op de vezelrichting tussen rijen, b) rand- en eindafstanden

Tabel 8.5 — Minimale tussen-, eind- en randafstanden voor stiften

Tussen-, eind- randafstanden (zie figuur 8.7)	Hoek	Minimale tussen-, eind- en randafstanden
a_1 (evenwijdig aan de vezelrichting)	0° ≤ α ≤ 360°	$(3 + 2\lvert\cos\alpha\rvert)\,d$
a_2 (loodrecht op de vezelrichting)	0° ≤ α ≤ 360°	$3d$
$a_{3,t}$ (belast eind)	–90° ≤ α ≤ 90°	max ($7d$; 80 mm)
$a_{3,c}$ (onbelast eind)	90° ≤ α < 150° 150° ≤ α < 210° 210° ≤ α ≤ 270°	$\max(a_{3,t}\lvert\sin\alpha\rvert)\,d; 3d)$ $3d$ $\max(a_{3,t}\lvert\sin\alpha\rvert)\,d; 3d)$
$a_{4,t}$ (belaste rand)	0° ≤ α ≤ 180°	$\max([2 + 2\sin\alpha)\,d; 3d)$
$a_{4,c}$ (onbelaste rand)	180° ≤ α ≤ 360°	$3d$

Figure 38 – Minimum fastener spacings from Eurocode 5 **(NEN-EN 1995-1-1+C1+A1:2011)**

6.6 Design of dowel 1

In the test pieces for this research two different dowels are used. Dowel 1 is used in the connection with laminated bamboo and dowel 2 is used to connect the test piece to the testing device. For the connections with laminated bamboo a smooth round dowel is used.

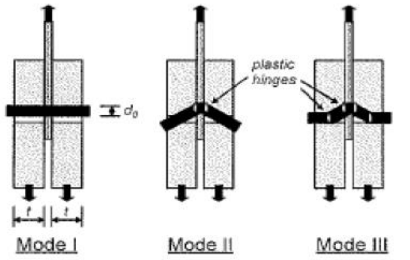
The yield strength of the used dowel will be 355N/mm². The ultimate strength corresponding to this yield strength is taken to be 510N/mm² (NEN-EN 1993-1-1+C2, 2011).

Usually a dowel diameter would be assumed and the thickness of the bamboo beam would depend on the failure mode we want to observe (Murty, B., Smith, I., Asiz, A., 2005). However, since the connections in this research will be made using a set lamination width, the dowel diameter will be the variable that has to be calculated. When a dowel is inserted in the laminated beam the bolt hole can be either through a glue line or entirely through a single lamella. Since in practice presumably no differentiation will be made with regard to these two situations and it is hard to predict on beforehand which of the situations will create a weaker connection, this research will not take the placement of the dowel, with respect to a potential glue line, into account. This way both the strong variants and the weak variants shall be tested.

Since the edge distances for doweled connections prescribe a distance of three times the dowel diameter a practical width of the test piece is 72mm. The width of 72mm is a multitude of the lamination width and, when applying a dowel of 12mm in diameter, is also equal to six times the dowel diameter (3*d at each side of the dowel).

Now that the dowel diameter is determined the thicknesses that will be tested have to be calculated.

For this calculation the formulas given by (Murty, B., Smith, I., Asiz, A., 2005) will be used. Note: these formulas are identical to those used by (Pedersen, M.U., Clorius, C.O., Damkilde, L., Hoffmeyer, P., Esklidsen, L., 1999). The formulas are given in Figure 39 – **Formulas for determining the dowel diameter** .



Note: All failures are symmetric.

Figure 13. EYM modes for a wood – steel plate – wood connection

$$F_y=\min\begin{cases} t d_o f_h & \text{for } t<\sqrt{\dfrac{2M_y}{d_o f_h}} & \text{Mode I} \quad (1)\\ \left(\sqrt{2+\dfrac{4M_y}{t^2 d_o f_h}}-1\right) t d_o f_h & \text{for } \sqrt{\dfrac{2M_y}{d_o f_h}} \le t < \sqrt{\dfrac{16M_y}{d_o f_h}} & \text{Mode II} \quad (2)\\ \sqrt{4M_y d_o f_h} & \text{for } t \ge \sqrt{\dfrac{16M_y}{d_o f_h}} & \text{Mode III} \quad (3) \end{cases}$$

Figure 39 – Formulas for determining the dowel diameter **(Murty, B., Smith, I., Asiz, A., 2005)**

By inserting the determined dowel diameter in these formulas (and with it also M_y and f_h, since these are dependent on d), member thicknesses can be determined that mark the transition point between different failure modes. When these transition thicknesses are determined, thicknesses in between these will be chosen for testing the capacity of the connections.

6.7 Test piece variants

The aim is to determine whether the properties of laminated bamboo resemble those of timber (i.e. hardwood) enough so the design formulas of Eurocode 5, and all assumptions made for these formulas, can also be applied to laminated bamboo connections. In order to test this, a series of tests is necessary that gives results in all failure modes. The timber dimensions need to be chosen such that there will be a variant for failure mode 1, 2 and 3. Since in connection design some failure modes are more beneficial than others (e.g. for ductility and redundancy in the overall structure), the material thickness that marks the transition between failure modes has to be predicted. Only then can be ensured that variants will be made that give results for every failure mode (instead of a scenario in which two variants give an outcome in the same failure mode resulting in one failure mode still to be studied).
The transition thicknesses will follow from the formulas given in Figure 39 – **Formulas for determining the dowel diameter** . To ensure that a test piece gives results in one specific failure mode it is of importance that the tested member thickness does not resemble any of these transition thicknesses. The calculation of the transition thicknesses is done in **Annex C** – Design of test pieces and takes into account different scenario's depending on variations in embedment strength (Eurocode 5 or Ehlbeck and Werner, 1992) and the actual yield stress of dowel 1 (355N/mm² as ordered or an assumption of 20% higher yield stress). These different scenarios result in a range of member thicknesses in which the transition between failure modes could take place. The tested member thicknesses have been chosen outside of this range (18-20mm and 47-56mm). By only testing the member thicknesses certain to display one single failure mode impurities due to some intermediate failure behaviour will be excluded from the test results as much as possible.

In case of one slotted-in plate this results in a total of 3 different variants (one variant for each of the failure modes). The first variant (12mm thickness) is expected to display only failure mode 1. Also, since failure mode 1 is primarily dependent upon the embedment strength of the material an expectation can be made based on the test results of this variant on whether the embedment strength of the laminated bamboo is in line with the calculation rules from Eurocode 5. Although this is not an embedment test it can still prove some insight in the correctness of the calculated embedment strength with which the test pieces were designed. The second variant shall have a member thickness of 36mm and is, as it lies in between the two transition thicknesses, expected to show failure behaviour corresponding only to failure mode 2. The third variant will be made with a member thickness of 72mm and will, as this is well above the maximum predicted transition thickness of 56mm, display failure mode 3.
To take account of natural variance of the material, each variant will be tested five times using a connection at the top and bottom of the test piece (this goes for the variants with one slotted-in plate as well as for the variants with two slotted-in plates). In this way per test two results are measured. One of the connections will break and gives a measurement for the ultimate strength, the other connection will, at least, have a higher failure load than the first. A drawing of the test piece design is included in Figure 40 – **Test piece design**.

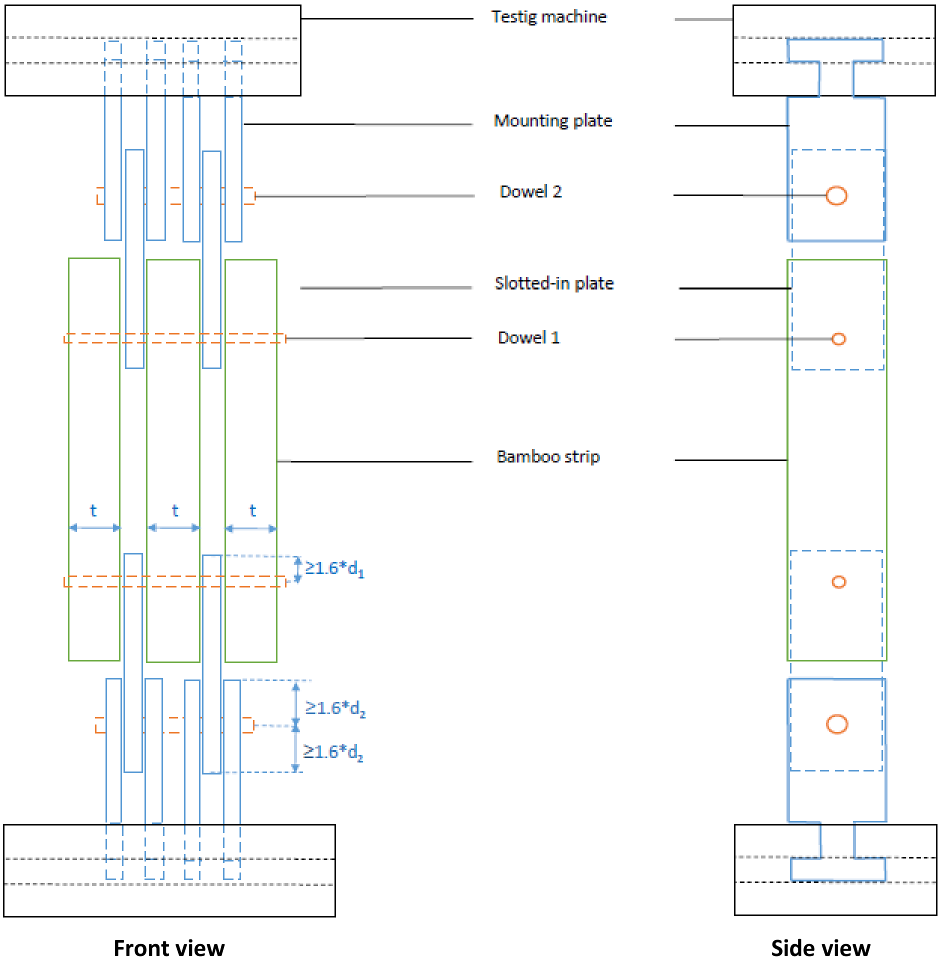


Figure 40 – Test piece design

In this figure it can be seen that the test piece is comprised of individual laminated bamboo strips. The use of individual members is specified by (NEN-EN 1380:2009) and is discussed in **Annex B** – Testing procedure. Furthermore, the figure shows the test setup as it will be used for the two slotted-in plate variants. It will be obvious that the variants consisting of only one slotted-in plate will be tested using the same setup making use of only two bamboo members instead of three.

The member thicknesses of the two slotted-in plate variants were determined by looking at the expected ways of failure for these connections. Since to achieve failure mode 2 in the middle member only one plastic hinge in the dowel may occur per shear plane, this failure mode is not likely to occur in the middle member. Therefore, the expected ways of failure of the middle member were sketched and the corresponding member thicknesses were sought. This resulted in two ways of failure for the middle member (failure mode 1 at a thickness smaller than two times the transition thickness of 18mm and failure mode 3 at a thickness bigger than two times the transition thickness of 56mm). The tested thicknesses of the middle member thus were 24mm (two times 12mm) and 144mm (two times 72mm). Combining these two different thicknesses for the middle member with 3 different failure modes to occur in the outer members, a total of 6 variants can be tested when making use of two slotted-in plates. The considered modes of failure for two slotted-in plates are shown in **Annex C** – Design of test pieces and in Figure 41 - **Expected failure behaviour of connections with two slotted-in steel plates**.

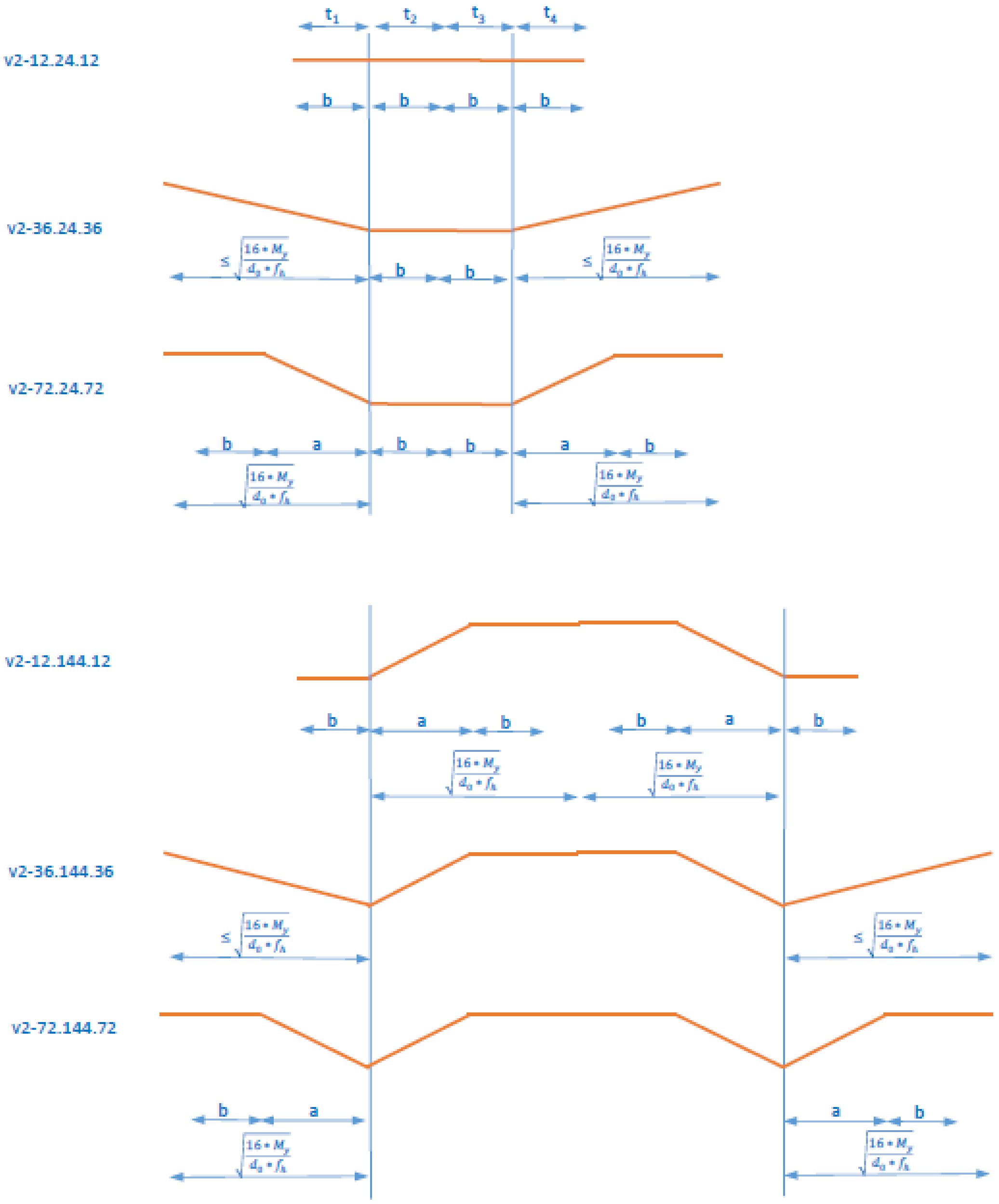


Figure 41 - Expected failure behaviour of connections with two slotted-in steel plates

In this figure the slotted-in plates are indicated by two vertical blue lines. The dowel is described by the red line. The different variants have also been given a name. The explanation of the variant name (i.e. code) is the following:

$$Variant\ \#_{slotted-in\ plates} - t_{side\ member\ 1}.t_{middle\ member}.t_{side\ member\ 2}$$

6.8 Attaching the test piece to the testing machine

To properly conduct the tests all test pieces need to be firmly attached to the testing device. For this, a way of connecting the test pieces had to be drafted, calculated and made. The main requirement of this connection was that all slotted-in plates (two or four) had to be attached to the device in such a way that they were loaded by only an axial force, not by a bending moment. Also a connection that would be easily (de)constructed and maybe used multiple times was preferred.

For connecting test pieces to the testing device three grooves are available in the device. In Figure 42 - **Connection plate of the testing device** these three grooves are shown.

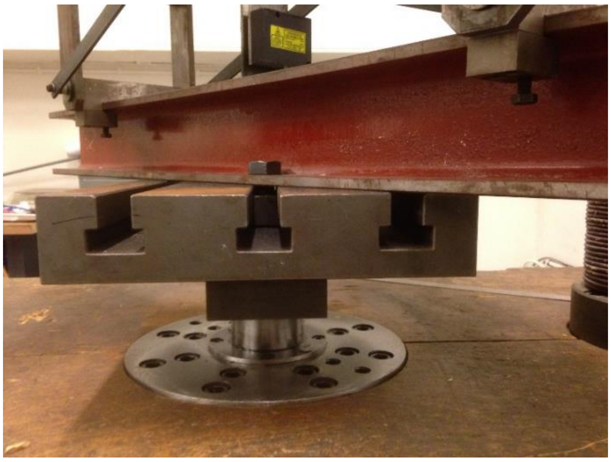


Figure 42 - Connection plate of the testing device

In this figure it can be seen that usually a beam would be attached by a bolt and a steel cap that slides into the grooves. Some pictures of this steel cap can be seen in Figure 43 - **Steel cap for the grooves in the connection plate**.

Figure 43 - Steel cap for the grooves in the connection plate

By making use of these caps, a test piece can easily be mounted (and demounted) in the testing apparatus. The same principle can be used to attach the slotted-in plates. For this, auxiliary plates were designed which, at one end, fit into the grooves of the testing machine and, at the other end, were given a bolt hole to attach the slotted-in plates. These plates can be seen in Figure 40 – **Test piece design** and will be called ‘mounting plates’. The dimensions of the head of the mounting plate (which slides into the grooves) will be kept the same as the caps from Figure 43 - **Steel cap for the grooves in the connection plate**. The required thickness (strength) of the mounting plates and the required dowel to attach the slotted-in plates are calculated in **Annex C** – Design of test pieces.

6.9 Design verifications

This paragraph will give the formulas used in **Annex C** – Design of test pieces to assess the strength of the steel plates and dowels used for the connections.

6.9.1 Calculating the expected capacity of the connection

Firstly, the expected capacity of the connection is determined. For this, the assumed diameter of dowel 1 and the determined thicknesses of the bamboo members were inserted in the formulas by (Murty, B., Smith, I., Asiz, A., 2005). This was done for every variant and every failure mode. The failure mode that results in the lowest failure load for a certain variant determines the capacity of the connection (for that individual variant). The variant for which the highest expected failure load is calculated determines the load for which the slotted-in plates, dowel 2 and the mounting plates have to be designed.

6.9.2 Dowel verifications

As stated before, two different types of dowels will be used for the construction of the test pieces. Dowel 1 will be used for connecting the slotted-in plates to the laminated bamboo (this is the dowel in the connection to be tested). Dowel 2 will be used to attach the slotted-in plates to the mounting plates. For dowel 1 a steel grade of 355N/mm² is used and its diameter is 12mm, this is also given in **Annex C** – Design of test pieces. For dowel 2 a bolt of steel grade 10.9 is taken with a diameter of 16mm. To verify the strength of these fasteners the design rules from the Eurocode are used. Calculation rules for the strength properties of such dowels are given in Eurocode 3 (NEN-EN 1993-1-8+C2). In table 3.10 of this code formulas are given by which the shear resistance and embedment strength of a dowel in a steel plate can be determined.

$$F_{v,Rd} = 0.6 * A * \frac{f_{up}}{\gamma_{M2}} \text{ (Shear)} \tag{16}$$

$$F_{d,Rd} = 1.5 * t * d * \frac{f_y}{\gamma_{M0}} \text{ (Embedment)} \tag{17}$$

In paragraph 6.1 of (NEN-EN 1993-1-1+C2, 2011) the following values are given.

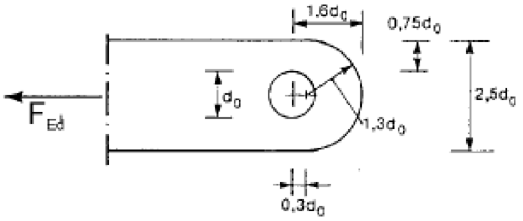
$$\gamma_{M0} = 1.0 \qquad \gamma_{M1} = 1.0 \qquad \gamma_{M2} = 1.25$$

The used verification for shear and embedment of the dowels is the following (with F being the total capacity of the connection).

$$\frac{F}{\#_{shear\ planes}} < F_{v,Rd} \text{ and } F_{d,Rd} \tag{18}$$

6.9.3 Slotted-in plate verifications

The minimum width of the slotted-in plates is taken to be equal to the width of the laminated bamboo (determined by (NEN-EN 1995-1-1+C1+A1:2011)) or equal to the limits set by the minimum requirements for steel dowel type connections given in Eurocode 3 (NEN-EN 1993-1-8+C2). In table 3.9 of Eurocode 3 requirements are given to the size and dimensions of dowel-type connections. In Figure 44 – **Requirements for dowel-type connections** these requirements are shown. In this figure d_0 is the size of the bolt hole. For test piece design this size will be taken 2mm larger than the dowel diameter.



$$t \geq 0{,}7\sqrt{\frac{F_{Ed}\gamma_{M0}}{f_y}} \;:\; d_0 \leq 2{,}5\,t$$

Figure 44 – Requirements for dowel-type connections **(NEN-EN 1993-1-1+C2, 2011)**

The minimum width of the plate is thus determined by design codes. The applied width of the plate however is determined by manufacturing considerations. Since the slotted-in plates are easiest and most economically manufactured by taking a standard size strip width and cutting this strip up to a desired length, the minimum determined width is rounded up to the nearest standard size. This also ensures that the plates will be wider than the bamboo members, which allows for practical instalment of the displacement meters.

With the width of the slotted-in plates decided, the strength of the slotted-in plates is determined primarily by the thickness of the plates. When determining this required thickness a few verifications need to be made. These verifications include a tensile failure of the gross or net section (at dowel 2, since this dowel is larger) and the requirements set by table 3.10 of (NEN-EN 1993-1-8+C2).

$$t_{slotted\ plate,min}\begin{cases}\dfrac{F_{v,Rk}}{\#_{slotted\ plates}*f_y*w_{plate}} & \text{Gross section} \qquad (19)\\[2ex] \dfrac{F_{v,Rk}}{\#_{slotted\ plates}*f_u*(w_{plate}-\emptyset_{dowel,2})} & \text{Net section} \qquad (20)\\[2ex] 0.7*\sqrt{\dfrac{F_{v,Rk}*\gamma_{M0}}{\#_{plates}*f_y}} & \text{Table 3.10 (NEN-EN 1993-1-8+C2)} \qquad (21)\\[2ex] \dfrac{\emptyset_{dowel,1}+1}{2.5} & \text{Table 3.10 (NEN-EN 1993-1-8+C2)} \qquad (22)\\[2ex] \dfrac{\emptyset_{dowel,2}+1}{2.5} & \text{Table 3.10 (NEN-EN 1993-1-8+C2)} \qquad (23)\end{cases}$$

The thickness of the plate will then by rounded off to an even number, since plate thicknesses come standard in 8, 10, 12, 14… millimetres. The calculation and exact measurements of the slotted-in plates can be found in **Annex C** – Design of test pieces. In this calculation the yield strength of the steel used for the slotted-in plates is 355N/mm². The ultimate strength is taken as 510N/mm² (NEN-EN 1993-1-1+C2, 2011).

6.9.4 Mounting plate verifications

The mounting plates are used to establish a connection between the slotted-in plates and the testing device. Since the mounting plates are used to attach all specimens to the apparatus they are not allowed to yield. To ensure this, the thickness of the mounting plates is, at least, taken to be equal to the thickness of the slotted-in plates. By taking this minimum width the capacity at the gross section, the net section at dowel 2 and the requirements from Eurocode 3 are automatically satisfied. At the head of the mounting plates the net section and shear capacity of the head still need to be calculated. The measurements of the head are the same as the caps from Figure 43 - **Steel cap for the grooves in the connection plate** and are given in **Annex C** – Design of test pieces. For clarity, a sketch of a mounting plate is also shown in Figure 45 – **Mounting plate**.

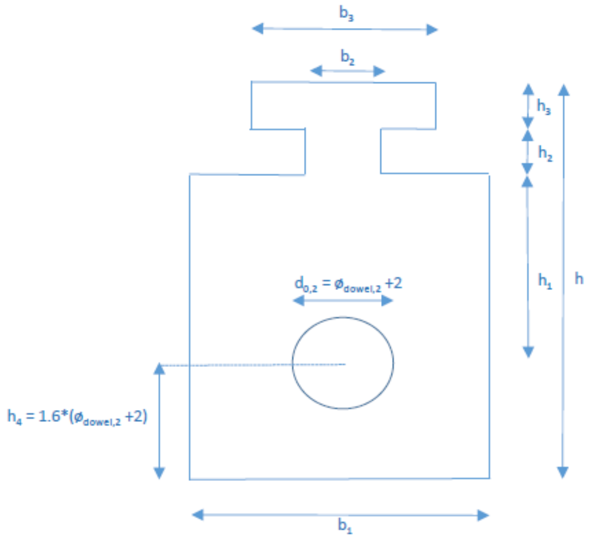


Figure 45 – Mounting plate

The minimum thickness of the plate will then be the maximum of either the thickness of a slotted-in plate (which accounts for gross and net section of the dowel and embedment and shear failure according to Eurocode 3), the required net section b_2 at the groove or the shear area h_3 at the groove.

$$t_{mountingplate,min} \begin{cases} t_{slottedplate,min} & & (24) \\ \dfrac{F_{v,Rk}}{\#slottedplates * \dfrac{\#mountingplates}{slotted\ plate} * f_y * b_2} & \text{Net section at groove} & (25) \\ \dfrac{F_{v,Rk}}{\#slottedplates * \dfrac{\#mountingplates}{slottedplate} * \dfrac{f_y}{\sqrt{3}} * 2 * h_3} & \text{Shear at groove} & (26) \end{cases}$$

As with the slotted-in plates, also here the diameter of the bolt hole is taken to be 2mm larger than the diameter of the bolt itself. Afterwards the required thickness was rounded off (upwards) to an even number to account for standard sizes. However, an extra requirement is needed for the mounting plates. Since the plates will be used to conduct all tests, they need to fit between the slotted-in plates of all variants. The minimum thickness of a middle member that will be tested is 24mm. For 2 mounting plates to fit between the slotted-in plates, the maximum thickness of a mounting plate may only be 12mm. In case the mounting plate thickness has to be more than 12mm, the plate thickness has to be taken as 24mm. This, to correctly support the bolt from 2 adjacent slotted-in plates.

One optional requirement to the mounting plates was also set by this research. For practicality reasons it would be beneficial to design the mounting plates so that their capacity exceeds that of the testing device. Since the mounting plates will be made part of the auxiliary equipment of the testing device after this research it's of interest to make the plates as widely adaptable as possible. The capacity of the testing device is 250kN. By taking the required spacings from Eurocode 3 the necessary thickness to achieve this capacity was calculated and divided by 4 (since four mounting plates will be used at each side of the apparatus). The resulting required thickness was, coincidentally, 12mm. Note: to make the mounting plates also applicable for another research at TU Delft some adaptions were made with regard to the dimensions of the mounting plates. Most notable was to make h_1 from Figure 45 – **Mounting plate** 60mm. Also the required end distance h_4 for bolts was applied (1.2*d_0 for bolts instead of 1.6*d_0 for dowels). A drawing of the final design is included in **Annex C** – Design of test pieces and shown in Figure 46 – **Adapted design of the mounting plates**.

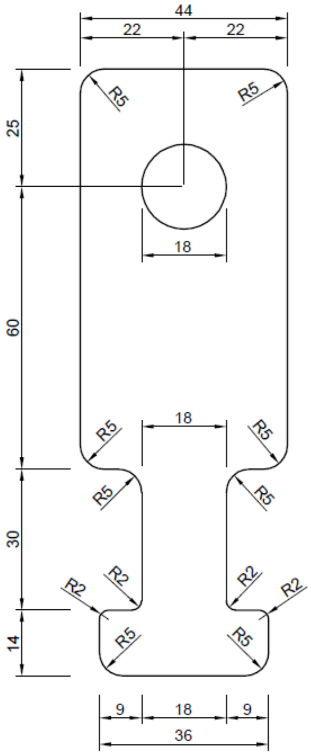


Figure 46 – Adapted design of the mounting plates

6.10 Materials needed

The materials needed for testing comprise strips of laminated bamboo, two times dowels 1 and 2 per test piece, a maximum of 4 slotted-in steel plates per test piece and 2 mounting plates per slotted-in plate for attaching the test pieces. The various materials needed will be discussed further in the following subparagraphs.

6.10.1 Laminated bamboo

For testing strips of laminated bamboo are needed. The thickness of these strips was calculated so that one clear failure mode can be expected during a test. The width of these strips is equal to the minimal required width according to the fastener spacings set by Eurocode 5. These spacings depend on the diameter of dowel 1 which is given in the calculation in **Annex C** – Design of test pieces. After determination of the width, the necessary length of the strips can be determined. Since per test piece two connections will be made the length of the strips has to be able to fit the required fastener spacings for both connections and provide for a sufficient distance between the connections. For connections loaded parallel to grain this necessary 'free length' is specified to be 50mm in 6.4.1 of (NEN-EN 1380:2009). Since two connections will be made with one single test piece a free length of 100mm between the connections will be adopted. The length of the strips that has to be met is visualised in Figure 47 – **Requirements for the length of the bamboo strips**.

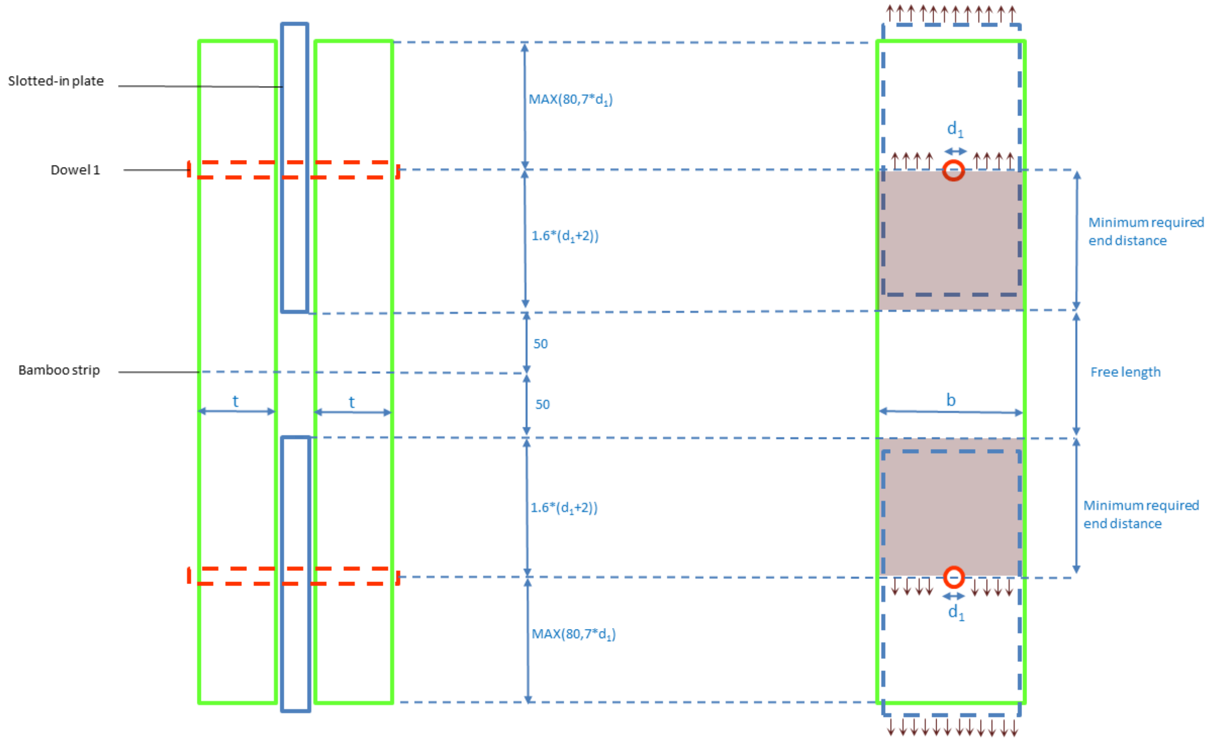


Figure 47 – Requirements for the length of the bamboo strips

The values for these measurements follow from calculation in **Annex C** – Design of test pieces. The formula used for determining the total length of the laminated strips is given below.

$$l_{strip} = 2 * max(80,7 * d_1) + 2 * 1.6 * (d_1 + 2) + 2 * 50$$

6.10.2 Dowel 1

Dowel 1 is used to connect the bamboo strips to the slotted-in plates. For this dowel a steel grade S355 is used with an expected ultimate tensile strength of 510 N/mm². As a result of insecurities in the actual yield and ultimate strength of the ordered and delivered dowel observed by (Sandhaas, 2012), the calculation in **Annex C** – Design of test pieces also takes into account a scenario in which the dowel has 20% higher strength values than originally intended. The diameter of the dowel is determined to be 12mm. The necessary length of the dowel is determined by a summation of the thickness of the bamboo strips in a test piece and the thicknesses of the used slotted-in plates. The applied length of the dowel will be rounded off to a practical length. Since every test piece will be tested at two sides, dowel 1 will be necessary two times per test piece.

6.10.3 Slotted-in plates

The slotted-in plates are connected by means of dowel 1 to the bamboo strips. The connection to the mounting plate is made by means of dowel 2. Both dowels will have a different diameter with a hole-clearance of 2mm. The thickness of the slotted-in plates is such that the plate will not yield during testing of the connection. By designing the plate strong enough so that no deformation occurs, the plates can be used for multiple tests. For practicality and as a safety measure in case one or more plate fail for unexpected reasons, twice the necessary amount of slotted-in plates will be ordered. In case of a variant with two slotted-in plates this results in a total number of 8 slotted-in plates to be made. The measurements of the slotted-in plates are determined by the most demanding failure mechanism and the same plates will be used for all variants. The determination of the width and thickness was already discussed in 6.9.3 - **Slotted-in plate verifications**. The length of the plate is determined according to the specified fastener spacings from Eurocode 3. Here also account will be taken of the spacings from Eurocode 5 with an additional 10mm so the end distances of the bamboo strips can easily fit between the bolt holes of the plates. The used formula for the length of the slotted-in plates is the following:

$$l_{slotted-in\ plates} = max(7 * d, 80) + 10 + 1.6 * (d_1 + 2) + 1.6 * (d_2 + 2)$$

The calculated dimensions and strength of the slotted-in plates are given in **Annex C** – Design of test pieces.

6.10.4 Dowel 2

Dowel 2 is used to provide the connection between the slotted-in plates and the mounting plates. As is the case for the slotted-in and mounting plates, dowel 2 will be used in all tests. Since the test pieces have the same connection at both sides of the testing apparatus only 2 specimens of dowel 2 are necessary. Dowel 2 will be made from a bolt of grade 10.9 with a shaft diameter of 16mm. The length of the bolt is determined by the width of the largest test specimen. The minimum required length of the shaft will be (for a specimen with 2 slotted-in plates) a summation the middle bamboo member thickness, 2 times the slotted-in plate thickness and 2 times the mounting plate thickness.

$$l_{shaft,dowel\ 2} = t_{bamboo\ strip} + 2 * t_{slotted-in\ plate} + 2 * t_{mounting\ plate}$$

6.10.5 Mounting plates

The mounting plates are used to connect the test pieces to the testing apparatus. The head of the plates is designed to slide into the grooves of the connection plate of the apparatus. Via the mounting plates (which are connected by dowel 2 to the slotted-in plates) the slotted-in plates and the rest of the test piece can be loaded. To obtain accurate test results it is paramount that the mounting plates do not yield under the applied load. For this, the minimum required capacity of the plates has to be calculated. The strength verification of the plates was discussed in 6.9.4 - **Mounting plate verifications**. There the determination of the dimensions of the plate was addressed. The final dimensions of the plate were largely determined by the (optional) requirement to make the plates as strong as the testing equipment. However, due to adaptions made to the design of the plates so that they could also be used in another current research, the ordered plates are no longer fit to be used for dowels. The end distance of the plates only allows for the use of bolts. The number of plates ordered is two mounting plates per slotted-in plate. This amounts to a total of 8 mounting plates.

The calculation of the minimum required strength of the mounting plates, the resulting dimensions and actual capacity is given in **Annex C** – Design of test pieces.

Part 2:

Testing and result analysis

7 Introduction testing

In part 1 of this report the design of the test pieces was the main topic. To establish this design first the material itself was shortly researched and the fabrication process was explained. After concluding that bamboo could best be researched as a wood-like product the design codes for wood (Eurocode 5) were studied. During this study all necessary formulas to determine the capacity of a timber connection were found and decisions were made as to which existing formulas are expected to be most applicable to connections in laminated bamboo. These formulas where then adopted in the design of the test pieces.

Now that the test pieces have been designed and all necessary dimensions are known, this part of the report will treat the fabrication of the test pieces, the testing process and the results acquired.

7.1 Goal

During this stage of the research the main goal is to perform testing on the laminated bamboo connections that were designed during the first phase. The testing procedure that was established during the first phase (based on (NEN-EN 1380:2009)) will be used to conduct these tests. The question to be answered during this stage is the following:

What is the strength capacity of a MOSO laminated bamboo connection loaded parallel to fiber using one dowel and one or two slotted-in steel plates and what are the benefits of using multiple slotted-in plates?

7.2 Plan of action

On the basis of the test piece design of phase 1 the test pieces need to be fabricated. For this, all necessary materials need to be ordered. The laminated bamboo will be ordered at MOSO International BV and the steel materials will be ordered at Van Nobelen Delft B.V..
After the acquisition of all needed materials, the ordered laminated bamboo beams shall be sawn to test piece dimensions at the wood workshop at TU Delft. Following the sawing process, but prior to making the pre-drilled holes for the dowels, the bamboo members will be placed in a climate chamber where they attain the required moisture content for testing. Following this acclimatising process the holes for the dowels can be made and the test pieces can be assembled.

Testing of the connections will be done in the Stevin lab at TU Delft. Here the connections will be tested (destructively) according to the testing procedure described in **Annex B** – Testing procedure.
First the connections using only one slotted-in plate will be tested. On the basis of these tests already a verification can be made on whether or not the actual capacity of the test piece is in line with the expected capacity and the correctness of the test piece design. Also, as another verification to the test piece design, extra dowels will be ordered of which the actual yield moment resistance will be tested to verify that the calculation, on which the test pieces are based, was made using the correct values for the resistance parameters of the dowel. Next the connections using two slotted-in plates will be tested.

During testing, the test pieces shall be equipped with deformation meters. These devices will measure the slip between the slotted-in plates and the laminated bamboo at the level of dowel 1. Based on the measured deformation and the force exerted on the connection by the testing apparatus, force-displacement graphs will be drawn for every test piece. After testing, with the results of all test pieces of a connection variant, distribution graphs will be drawn to show the average resistance of a testing variant and the found variance in results. Based on these results and distribution graphs a comparison with the expected capacity from timber design principles can be made to assess the possibility for calculating laminated bamboo connections by use of design formulas from EC5 and a comparison can be made amongst the different testing variants to assess the benefits of using multiple slotted-in steel plates.

7.3 Reading guide

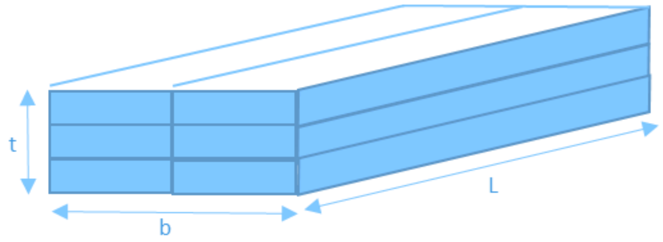
Based on the design of the test pieces, the test pieces can be fabricated from the ordered materials. The fabrication process is given in 8 - **Fabrication of test pieces.** This includes the acclimatising process, the method for determining the density and the assembly of the test pieces. The used testing protocol is given in 9 - **Testing process**. In that chapter also the tensile tests of the ordered dowels and the revised expectations of the connection capacities are given. The test results and information on how to interpret them are given in 10 - **Test results**. The analysis of the test results and an answer to the main topic of this thesis is covered by 11 - **Result analysis**.

8 Fabrication of test pieces

In this chapter the fabrication and assembly of the test pieces will be discussed. The sawing of bamboo, the acclimatising process, the drilling of the dowel holes and the final assembly of the test pieces are explained in the following paragraphs.

8.1 Sawing of bamboo

The desired test piece dimensions, as determined during the test piece design, are given in Figure 48 - **Desired laminated bamboo members**.



#	t [mm]	b [mm]	L [mm]
30	12	72	318
15	24	72	318
30	36	72	318
30	72	72	318
15	144	72	318

Figure 48 - Desired laminated bamboo members

Since these dimensions are not standard dimensions, in order to fabricate such laminated bamboo members a special order would have to be made, which would have a long delivery period. To hasten the fabrication of test pieces a decision was made to make use of beams that were readily available and had dimensions 90*200*5300mm (t*b*L). A picture of these beams is shown in Figure 49 - **Laminated bamboo beams**. It can now be seen that the thickness of the used beams (90mm) did not allow for the desired thickness of 144mm to be sawn. To make the variant with middle member thickness of 144mm two separate members of 72mm thickness were used.

Figure 49 - Laminated bamboo beams

A close-up of the cross section of the beam showing the individual lamellas and a longitudinal hook joint is displayed in Figure 50 - **Cross section of the beam and longitudinal hook joint**.

Figure 50 - Cross section of the beam and longitudinal hook joint

During the sawing process several pieces displayed cracks right along the glue lines between the lamellas. Since all of these pieces came from the same beam and no other abnormities were observed the crack is most likely the result of a production error. The observed cracks can be seen in Figure 51 - **Observed cracks in the glue lines**.

Figure 51 - Observed cracks in the glue lines

Nonetheless, in practice this beam would have been applied as a structural element (for the crack was not visible at the outside of the beam) and thus pieces sawn from this beam will be used for the formation of the test pieces. This will give realistic results of the capacity of the connections and any effects of these cracks (and potential hidden cracks) will influence the variance of the material. An AutoCAD drawing of all the cutting measurements is included in **Annex D** – cutting measurements.

8.2 Acclimatising

After the sawing process all individual bamboo strips were placed in a climate chamber (room S2 0.27). The conditions in this chamber are kept at a constant level of (20 ± 2)°C and (65 ± 5)% relative humidity. For comparable test results it is mandatory that all test pieces should be of equal moisture content prior to testing. By placing the test pieces in this climate chamber the moisture content of the test pieces was altered and equalised. The acclimatising process was considered complete when the mass of a test piece, resulting from weightings at intervals of 6h, did not differ by more than 0.1%. This is in accordance with (NEN-EN 1380:2009). A picture of the stacked up bamboo strips can be seen in Figure 52 - **Acclimatising of the test pieces**.

Figure 52 - Acclimatising of the test pieces

In this picture it can be seen that all test pieces have been placed in such a way that air is able to circulate around all individual test pieces. By making sure there is sufficient spacing in between the bamboo strips the acclimatising process can be done efficiently and the acclimatising time will be shorter.

After about four weeks of acclimatising the biggest piece of laminated bamboo a sample was taken as a sample from the stack to verify that the acclimatising process was complete. The measurements taken from that test piece are shown in Figure 53 - **Acclimatisation check 23-05-2016**.

23-05-2016	Mass at 10.30h [g]	Mass at 17.00h [g]	Difference [%]	Acclimatised
72.72 (1) i	1086.7	1086.6	0.0092	Yes
72.72 (1) ii	1090.0	1089.9	0.0092	Yes

Figure 53 - Acclimatisation check 23-05-2016

The test pieces of which this sample consisted were not randomly chosen. To be sure that every piece was acclimatised and that the sample measurements applied to all of the acclimatised test pieces, two of the biggest test pieces were chosen to be weighed. In the table can be seen that the difference in mass between two measurements 6.5 hours apart was no more than 0.01%. Since the requirement for acclimatisation was only 0.1% difference in mass, the test pieces were considered acclimatised.

8.3 Determining the density

Before assembly of the test pieces the density of the members had to be determined. Since the main goal of this research is to determine the possibility to calculate the capacity of laminated bamboo connections with design formulas from Eurocode 5, for an apt comparison to be made, the actual density of the test piece material needs to be known. After determining the actual density the expected capacity according to Eurocode 5 can be calculated. The density of the bamboo members will be determined according to (NEN-EN 323:1993). This norm specifies a method by which the density of wood-based panels can be determined. For this method the test pieces first have to be acclimatised. After that, the test piece shall be weighed to an accuracy of 0.01 grams and measured to an accuracy of 0.1 mm (for the thickness this is 0.05 mm). The locations of the measuring points are shown in Figure 54 - **Points of measurement.**

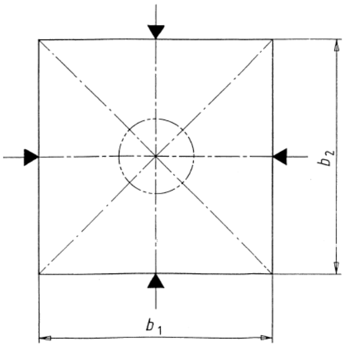


Figure 54 - Points of measurement

The lengths b_1 and b_2 (in mm) have to be measured at two locations along the member, the average of these two locations is taken as b_1 and b_2. The density of the test piece (in kg/m³) is calculated from the following formula.

$$\rho = \frac{m}{b_1 * b_2 * t} * 10^6 \tag{27}$$

For the determination of the density two small pieces were taken from the acclimatising chamber. This was done after making sure the bamboo was fully acclimatised (the acclimatising check was described in 8.2 - **Acclimatising**). The measurements taken to determine the density are given in Figure 55 - **Determination of the density 23-05-2016.**

23-05-2016	b_1	b_2	t	ρ
	[mm]	[mm]	[mm]	[kg/m³]
Piece 10	72.0	50.1	14.8	712.0
Piece 13	88.2	71.3	15.3	704.7

Figure 55 - Determination of the density 23-05-2016

From the above table can deduced that the average density of the test pieces is 708.3kg/m³. This found density is somewhat higher than the density of 666kg/m³ that was found by (Schickhofer, 2015). Since the test piece design was based on this lower density value of 666kg/m³ the expected capacity of the test pieces needs to be adjusted. The found capacity during testing then needs to be compared to the capacity found with the actual average density of 708.3kg/m³.

8.4 Assembling the test pieces

For the assembly of the test pieces first holes were drilled at the required locations to fit the dowel into the test piece. To ensure a fitting dowel hole this pre-drilling step took place after acclimatising of the material and just before performing the actual test. By doing this, possible shrinkage (or swelling) effects due to acclimatising were avoided as much as possible. To eliminate any effects due to difference in length between the individual members (as a result of imperfections from the sawing process) the locations of the drilling holes were all measured from one end of every member. This ensured that the distance between the boltholes of all members was exactly the same. Knowing that this distance would be the same for all members, a tight and fitting bolthole with little hole clearance could be manufactured. A visual display of the direction of measurement during this drilling process is given in Figure 56 - **Measurements to ensure an identical hole spacing.**

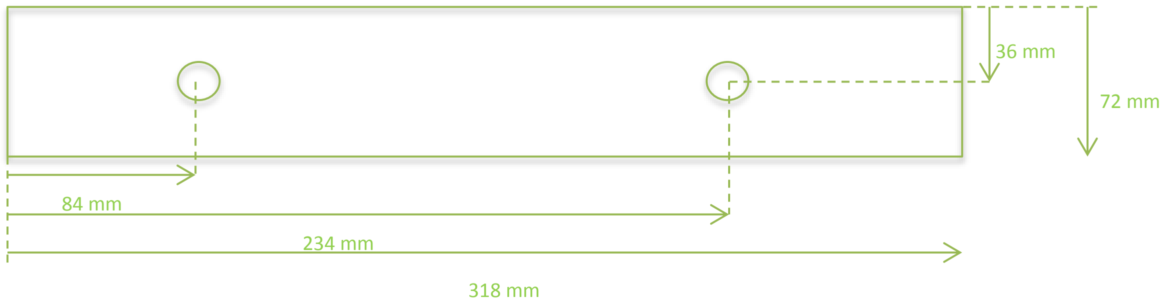


Figure 56 - Measurements to ensure an identical hole spacing

Next the test pieces were assembled and the hole clearance and spacing of the dowels were verified. The assembled test pieces are shown in Figure 57 - **Assembled test pieces.**

Figure 57 - Assembled test pieces

In the picture it can be seen that not all members of the test pieces are of the same length. This again shows the necessity of the ways of measurement from Figure 56 - **Measurements to ensure an identical hole spacing.**

9 Testing process

In this chapter the testing process will be discussed. First off, the yield moment capacity of the dowel will be checked and the expected yield capacity will be adjusted. After that testing of connections with one and two slotted-in plates can commence. At the end of each test the moisture content and the density of the test pieces will be determined.

9.1 The actual yield capacity of the dowel

To verify the calculation made in **Annex C** – Design of test pieces, the actual yield moment capacity of dowel 1 needs to be determined. In the design calculation dowel 1 was determined to be a dowel of 12mm in diameter and steel grade S355. During the calculation was anticipated that the actual yield capacity of the dowel would, in fact, be much higher than ordered. Therefore, the design calculation used not only a yield strength of 355N/mm² but also approximated the yield strength to be 0.8*f_u as suggested by (Jorissen, A., Blaß, H., 1998). In this approximation f_u was increased with 20%. The result was a range in which the moment capacity could lie and, based on that range, bamboo member thicknesses were chosen such that the desired failure modes could be tested.
Now that the ordered dowels are present the actual moment capacity needs to be tested and its position in the initially estimated range needs to be verified. The yield moment of the dowel will be determined by performing tensile tests in which a dowel is loaded to failure. The execution of these tensile tests is elaborated in **Annex E** – Dowel tensile tests. The resulting yield stress of the dowels was 537N/mm² and was within the boundaries made during the design phase.

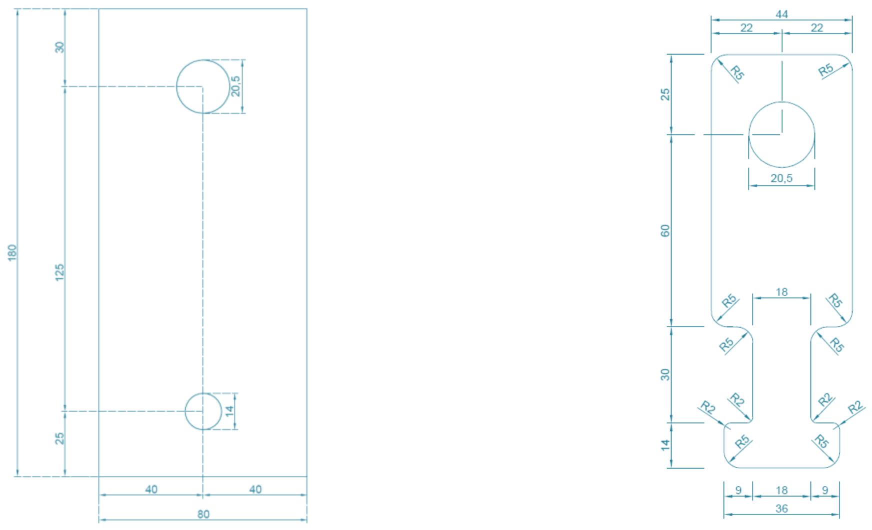
9.2 Testing protocol and setup

In the design of the test pieces (described in **Annex C** – Design of test pieces) mounting plates were envisaged and calculated to function as a means of connecting the test pieces to the testing equipment. These mounting plates were designed such that they could be slid into the grooves of the pulling bench. However, due to unforeseen circumstances during the design phase a discontinuity in the grooves went unnoticed. Due to this discontinuity the mounting plates could not be used in the way they were initially designed. To mount the test pieces onto the pulling bench, new and continuous grooves were made by bolting several thick steel plates onto the plateaus of the pulling bench. These thick plates and a mounted test piece can be seen in Figure 58 - **Mounted test piece**.

Figure 58 - Mounted test piece

The thick plates used to make a continuous groove for the mounting plates were calculated to be able to bear the resulting bending moments during testing. Unfortunately, due to the use of these plates (amongst others), the

measured displacement by the pulling bench can, of course, expected to be slightly higher than the displacement measured by the displacement meters mounted on the test piece itself.
Another issue with the initial design of the test pieces was the availability of the requested dimensions for dowel 2 (this is the dowel with which the slotted-in plates are connected to the mounting plates). The initial design required a large dowel length for some specific test pieces. The problem here was that a dowel of the requested diameter and length was not available. Since this dowel was only necessary to make the connection between the steel plates and thus does not affect the capacity of the connection (like dowel 1) it was, under advisement of the lab personnel and professors, decided to make use of a steel rod and larger diameter dowels. To make sure the used dowel or rods had enough load bearing capacity a diameter of 20mm was chosen and the holes for dowel 2 in the mounting plates and slotted-in plates were enlarged to 20.5mm. This is shown in Figure 59 - **Slotted-in and mounting plates with enlarged 20.5mm holes**.



Slotted-in plate

Mounting plate

Figure 59 - Slotted-in and mounting plates with enlarged 20.5mm holes

In '5 - **Testing methods**' the testing protocol and all necessary standards have already been discussed. The test protocol is again shown in Figure 60 - **Test protocol** .

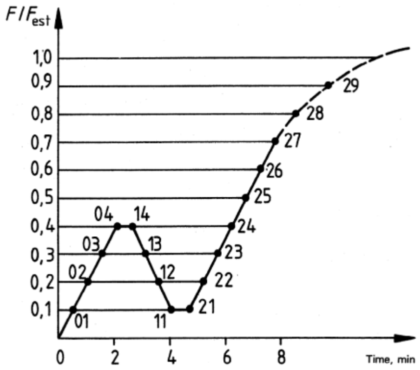
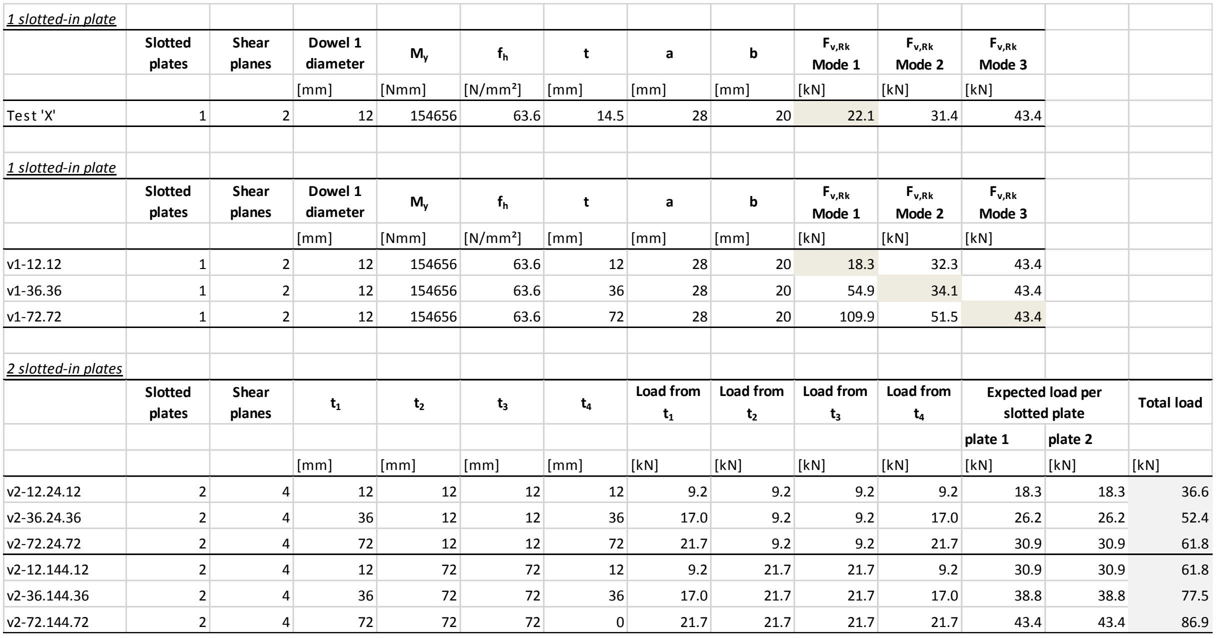


Figure 60 - Test protocol **(NEN-ISO 6891, 1991)**

The estimated load carrying capacity F_{est} cannot be determined unambiguously. Therefore, usually a first test is needed to confirm the calculated estimate. The resulting F_{max} from this first specimen of each testing variant will thus serve as an exploratory test to adjust the estimate of F_{max} for the following specimens if necessary.
An estimate of the yield capacity of all variants was already made during the design of the test pieces in **Annex C –** Design of test pieces. However, for the actual testing the expected yield capacity will have to be adjusted on the basis of the measured density of the test pieces, the measured embedment strength of the material and the tensile strength of the provided dowels. The measured average density of the acclimatised test pieces was discussed in 8.3 - **Determining the density** and was found to be 708.3 kg/m³. For the determination of the embedment strength of the material use will be made of exploratory tests. These exploratory tests serve both as a means of confirming (or invalidating) the expected embedment strength and as a means to get acquainted with the testing equipment. The results from these exploratory tests are given in **Annex G –** Exploratory tests. In this annex is concluded that the expected value of 63.6N/mm² for the embedment strength corresponds well to the obtained test results. One should keep in mind that these exploratory tests are not actual embedment tests and that all test pieces failed by plug shear. A phenomenon that is prevented in a standard embedment test. As a consequence, the obtained embedment strength is most likely underestimated.

9.3 Expected yield capacity

Based on the information gained from the exploratory tests, the density measurements and the dowel tensile tests the expected yield capacity for each test variant was recalculated. The adjusted yield capacities are given in Figure 61 - **Expected yield capacity**.



1 slotted-in plate

	Slotted plates	Shear planes	Dowel 1 diameter	M_y	f_h	t	a	b	$F_{v,Rk}$ Mode 1	$F_{v,Rk}$ Mode 2	$F_{v,Rk}$ Mode 3
			[mm]	[Nmm]	[N/mm²]	[mm]	[mm]	[mm]	[kN]	[kN]	[kN]
Test 'X'	1	2	12	154656	63.6	14.5	28	20	22.1	31.4	43.4

1 slotted-in plate

	Slotted plates	Shear planes	Dowel 1 diameter	M_y	f_h	t	a	b	$F_{v,Rk}$ Mode 1	$F_{v,Rk}$ Mode 2	$F_{v,Rk}$ Mode 3
			[mm]	[Nmm]	[N/mm²]	[mm]	[mm]	[mm]	[kN]	[kN]	[kN]
v1-12.12	1	2	12	154656	63.6	12	28	20	18.3	32.3	43.4
v1-36.36	1	2	12	154656	63.6	36	28	20	54.9	34.1	43.4
v1-72.72	1	2	12	154656	63.6	72	28	20	109.9	51.5	43.4

2 slotted-in plates

	Slotted plates	Shear planes	t_1	t_2	t_3	t_4	Load from t_1	Load from t_2	Load from t_3	Load from t_4	Expected load per slotted plate		Total load
											plate 1	plate 2	
			[mm]	[mm]	[mm]	[mm]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]
v2-12.24.12	2	4	12	12	12	12	9.2	9.2	9.2	9.2	18.3	18.3	36.6
v2-36.24.36	2	4	36	12	12	36	17.0	9.2	9.2	17.0	26.2	26.2	52.4
v2-72.24.72	2	4	72	12	12	72	21.7	9.2	9.2	21.7	30.9	30.9	61.8
v2-12.144.12	2	4	12	72	72	12	9.2	21.7	21.7	9.2	30.9	30.9	61.8
v2-36.144.36	2	4	36	72	72	36	17.0	21.7	21.7	17.0	38.8	38.8	77.5
v2-72.144.72	2	4	72	72	72	0	21.7	21.7	21.7	21.7	43.4	43.4	86.9

Figure 61 - Expected yield capacity

In the figure above the specimen 'Test 'X'' indicates the specimens used for the exploratory tests.

10 Test results

In this chapter the test results are given. First all individual test results will be given. These individual test results comprise of the measured capacities and deformations of all individual test pieces. After that the determination of the moisture content will take place. On the basis of the given test results and a few short remarks on abnormities during testing in this chapter, the following chapter will further analyse the test results and compare the results from the different testing variants with both the results of the theoretical calculation and the results from other similar testing variants

10.1 Individual test results

The results of all the individual tests are given in Annex H – Test results. In this annex, a chapter is dedicated to every testing variant. Per chapter first a few notes are made about the expected results for each testing variant. Thereafter a page size overview is given per individual test piece with the findings, measurements and pictures in failed condition. Next all individual findings per variant are combined and the average measured capacity of each variant is calculated and remarks are given on the behaviour of the connection variant during testing. At the end of every chapter a normal distribution is determined per variant. In this normal distribution two values for the capacity can be seen. The first value is the actual measured capacity during testing. The second value is the adjusted capacity. The adjusted capacity value is necessary for the analysation of the test results and more information on this is given in **Annex F** – Analysis of result distribution. This annex is also described in 11.1 - **Analysis of result distribution**.

Several noteworthy occurrences took place during testing. The first and most important was that during testing of variant 36.36 the first specimens started warping due to uneven failing of the connections. This warping is shown in Figure 62 - **Warping of test specimen 36.36 (1)**.

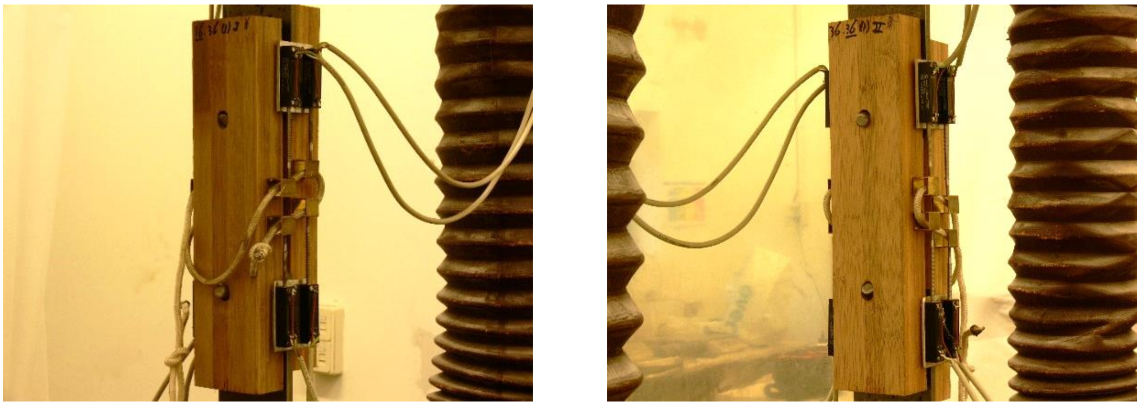


Figure 62 - Warping of test specimen 36.36 (1)

Due to this warping the deformation of the specimens started to increase without a significant increase in load bearing capacity. Since this is not a realistic failure behaviour for connections using slotted-in steel plates and this was not anticipated in the design the tests were stopped to prevent the displacement meters from breaking. The last few test pieces of this series and all following tests were equipped with a glued-in piece of laminated bamboo that would prevent such warping behaviour. For the gluing process a PVAc wood glue was used. Some pictures of the gluing process are shown in Figure 63 - **Gluing process using a PVAc wood glue**.

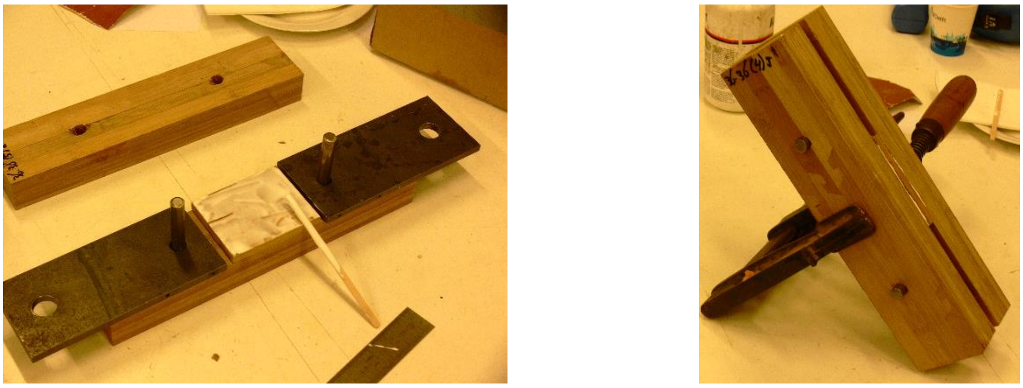


Figure 63 - Gluing process using a PVAc wood glue

Gluing the test pieces with the dowels in place ensured that the accuracy with which the dowel holes were drilled during the fabrication process was maintained. For all further test pieces the warping effect was prevented. About half way during testing the thickness of the glued-in piece had to be adjusted. This was due to some embedment deformation of the slotted-in plates. This embedment deformation caused the steel plates to thicken somewhat and required the glued-in pieces to thicken as well. The embedment deformation was caused by the more than anticipated capacity of the testing variants in mode 2 and 3. The capacity of these failure modes was ultimately almost equal to the calculated capacity of the steel plates. Pictures of this deformation are shown in Figure 64 - **Embedment deformation of the slotted-in steel plates**.

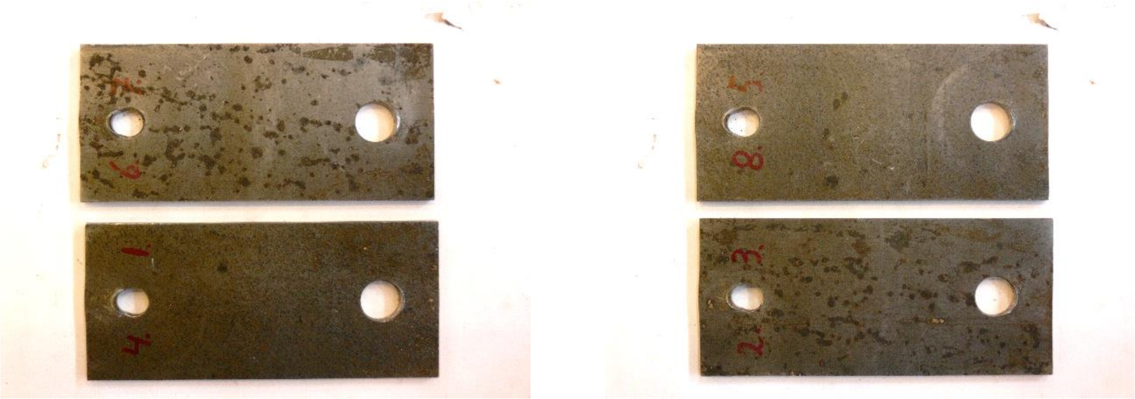


Figure 64 - Embedment deformation of the slotted-in steel plates

Most of the test specimens showed the failing behaviour that was anticipated during the design of the test pieces. There was one few exceptions however. One of the test specimens showed an asymmetrical bending of the dowel caused by a strength difference between the three members of the connection. A picture of this uneven bending pattern in the dowel is shown in Figure 65 - **Asymmetrical bending of the dowel**.

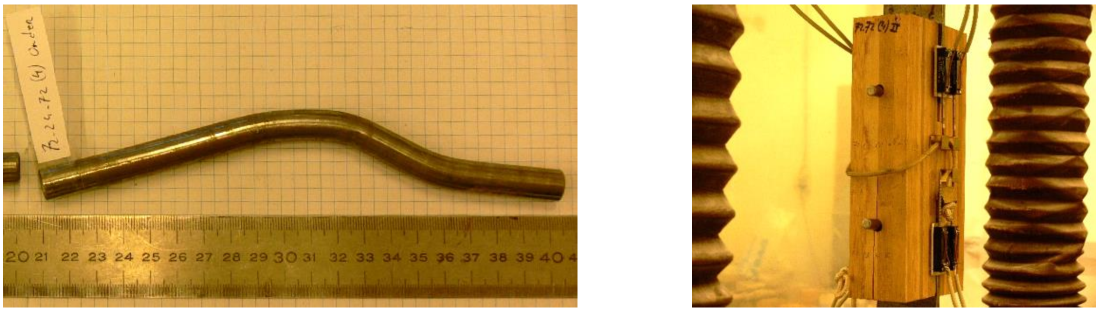


Figure 65 - Asymmetrical bending of the dowel

This picture is taken from test piece 72.24.72 (4). In the picture can be seen that one of the two lamellas failed before a proper plastic hinge in the dowel could be formed. This specific test piece was the only one to show such an asymmetrical behaviour and could therefore be seen as an anomaly that is not likely to occur. The asymmetrical behaviour also had very little effect on the total capacity of the connection. With its capacity of 59.13kN this specimen was the weakest of the entire variant but it was only slightly lower than the average of 62.09kN.

10.2 Determination of the moisture content and density measurement

The determination of the moisture content takes place after testing. A sample is taken from each test piece and dried in an oven according to (NEN-EN 322:1993). In this standard a method is described to determine the moisture content of wood based panels. In this method a sample of any shape is taken from the test piece and dried in an oven at 103 ± 2 °C until a constant mass has been reached. The moisture content H of the test piece is calculated as a percentage by mass in accordance with the following formula:

$$H = \frac{m_H - m_0}{m_0} * 100 \tag{28}$$

The measurements of size, mass and the resulting moisture content of all individual test pieces are given in Annex I – Moisture content measurements. Not only does this annex give the measured moisture content of the test pieces, it also displays the density of the members. For this, every sample was measured before placement in the drying oven. The measured dimensions and the mass before drying are given in the first few columns. Also the date at which the samples were placed in the oven is denoted. After a drying time varying from 1.5 months for the first sample to 1 month for the last sample, the samples were weighed at two different points in time with an interval of at least 6 hours. For practical reasons the interval used here was 96 hours, which gives a much stricter requirement. The test pieces were considered dry when the mass of both measurements did not differ by more than ±0.1%. In the Annex can be seen that some of these samples still differed more, but due to the low mass of the samples combined with the accuracy of the scale and the long weighing interval, these samples can be considered dry.

The average found density during testing was 666.81kg/m³. Note that this is equal to the value determined by (Schickhofer, 2015) and somewhat lower than the value gained from the samples used in 8.3 - **Determining the density**. The determined moisture content of the samples was 9.26% on average with a coefficient of variation of 0.07. The normal distributions of the measured density and moisture content are given in Figure 66 - **Normal and cumulative distribution of the test piece density** and Figure 67 - **Normal and cumulative distribution of the test piece moisture content** respectively. Indicated in these pictures are also the 5-percentile values for both the density and the moisture content. To calculate this value, a k_s factor of 1.76 was used. This corresponds to a sample size of 100 pieces.

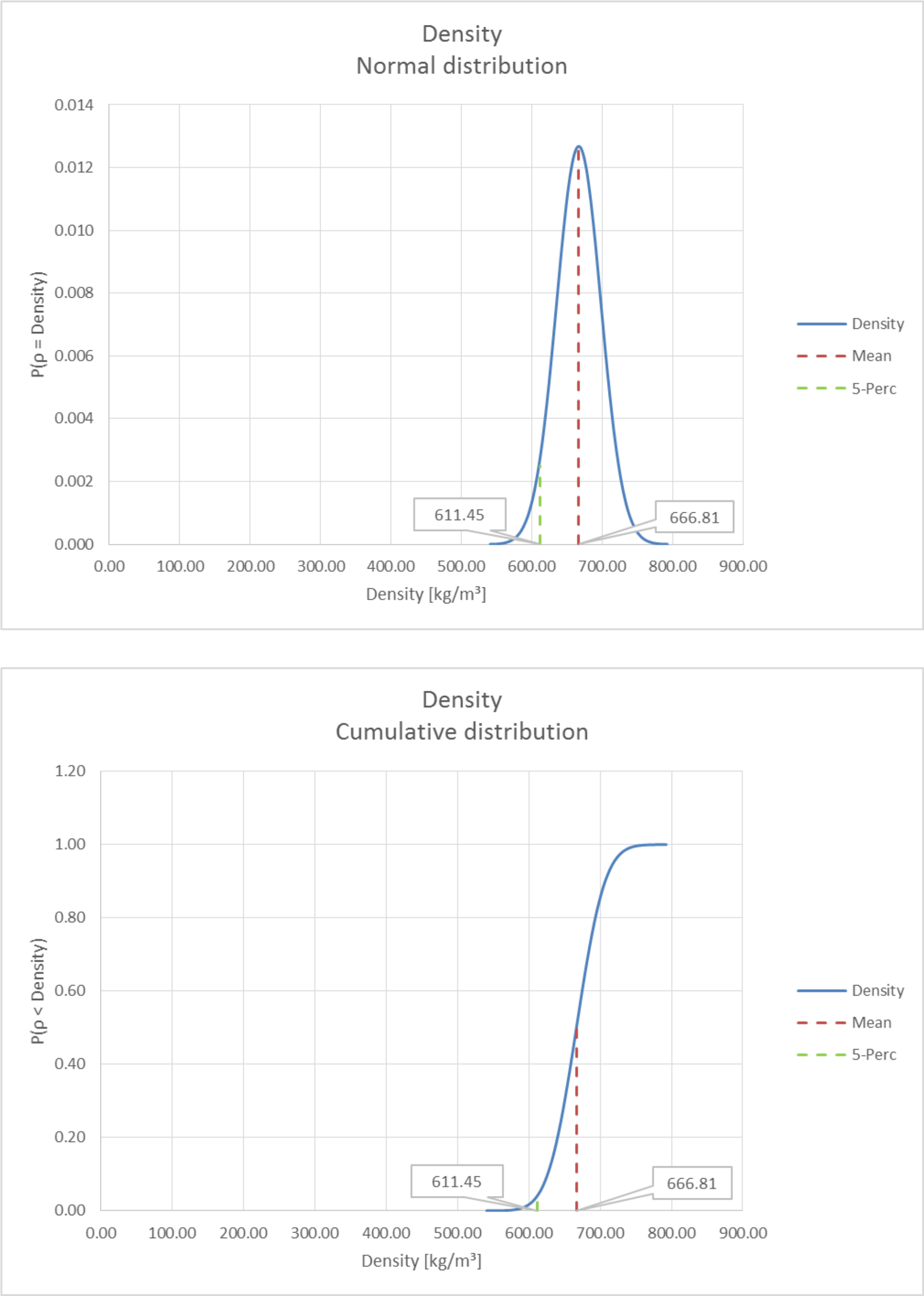
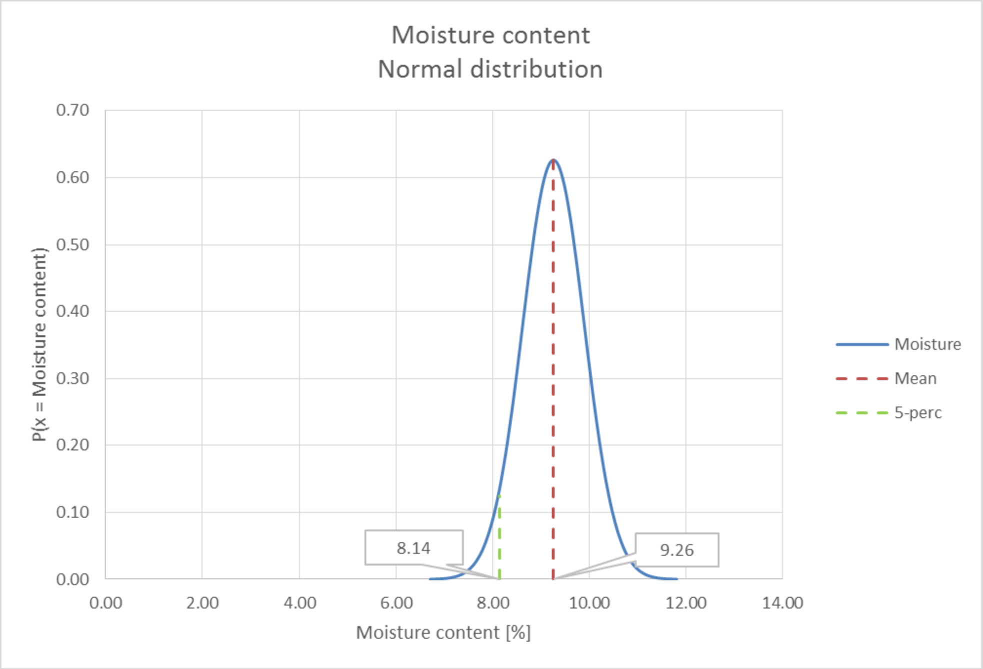


Figure 66 - Normal and cumulative distribution of the test piece density



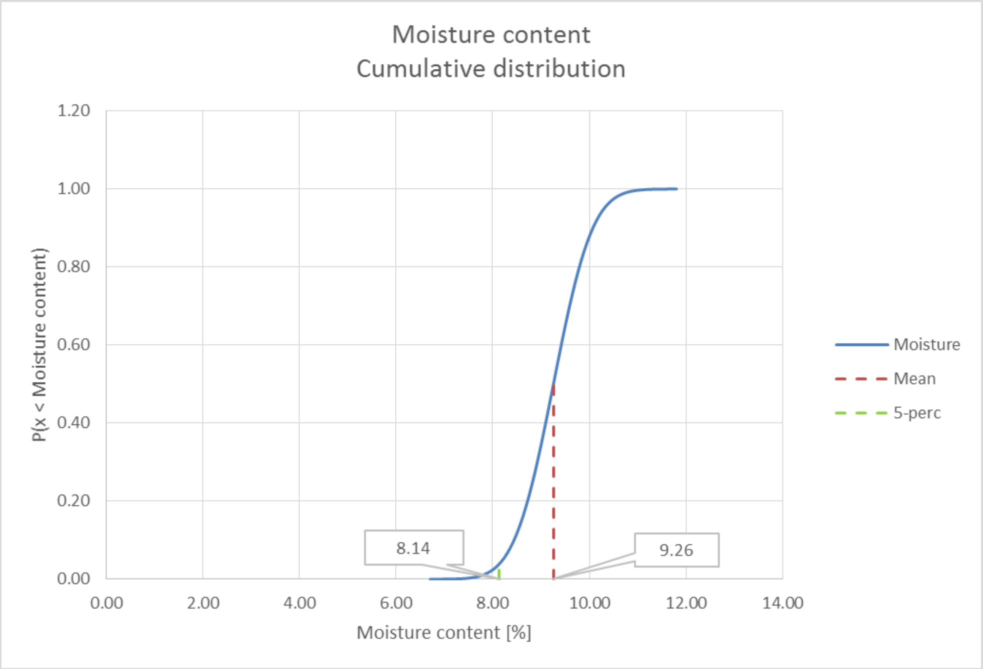


Figure 67 - Normal and cumulative distribution of the test piece moisture content

11 Result analysis

Now that the test results of all the individual tests have been shown and the moisture content and density measurements have taken place, this chapter will describe and comment on the observed behaviour of the various testing variants and explain any deviations with the expected behaviour and predicted capacity of the connection. This will be done for every connection variant individually. After that, the behaviour and capacity of the single slotted-in plates will be compared to that of the double slotted-in steel plates and some remarks will be made on the benefits and drawbacks of using multiple slotted-in steel plates.

11.1 Analysis of result distribution

For this research all test pieces were equipped with two connections. One connection at the top and one at the bottom. The test pieces were all loaded to failure and always one of the two connections would break. At the moment of breaking, the force exerted by the pulling bench is the capacity of the weaker of these two connections. The only data obtained from the stronger connection is that the capacity is higher than the force exerted by the pulling bench. So per test piece actually two results were obtained. One result is the capacity of a 'weaker' connection and the other result is the knowledge that the other connection is stronger.
From the data obtained from the weaker connections an average of the measured capacity for a certain type of connection variant can be determined. However, since half of all tested connections did not fail, the actual average capacity of that type of connection should really be somewhat higher than measured by the pulling bench. To take this effect into account, a study into probabilistic design was necessary and way had to be devised through which the measured average capacity of the weaker half of the tested connections could be used so that the actual average capacity of all connections could still be analysed.
During this literature study, first a formula was established with which the actual capacity of all connections could be estimated from the obtained test results. This formula however was based upon some assumptions which had the effect to overestimate the actual capacity of all connections. The established formula thus yields an upper bound value for the capacity.
To further analyse the problem several simulations were done using Excel. From these simulations was concluded that the obtained test data can be considered normally distributed and that the average measured capacity is very close to the actual capacity of all connections. The 5-percentile values (lower value) show even closer resemblance. The full description and commentation of the performed investigation is included in **Annex F** – Analysis of result distribution. Given that the obtained test data can be considered normally distributed, the measured average capacities and standard deviations can be adjusted so that the respective values for all connections are approximated. This adjustment will be done according to findings of Van Douwen et al. (1958) who state that, for symmetrically loaded test specimens, the following relations apply (Van de Kuilen, J.W.G., Blass, H.J, 2004):

$$x_1 = x_2 + c_1 * \sigma_2 \tag{29}$$
$$\sigma_1 = c_2 * \sigma_2 \tag{30}$$

The correction factors in these relations are $c_1 = 0.68$ and $c_2 = 1.21$. A more extensive explanation is given in the annex.

Through the use of the given relations all measured capacities were adjusted. The average of the measured and adjusted capacities are given per testing variant in Figure 68 - **Comparison of average measured and adjusted capacities**.

Comparison $F_{measured}$ and $F_{adjusted}$								
Testing variant	***Failure mode***	***$F_{measured}$***	***COV_{meas}***	***5-perc $_{meas}$***	***$F_{adjusted}$***	***COV_{adj}***	***5-perc $_{adj}$***	***5-perc $_{adj}$ /5-perc $_{meas}$***
		[kN]	*[-]*	*[-]*	*[kN]*	*[-]*	*[-]*	*[-]*
12.12	1	19.1	0.06	16.21	19.88	0.07	16.40	1.01
36.36	2	40.4	0.08	32.29	42.68	0.09	32.83	1.02
72.72	3	59.8	0.02	57.43	60.42	0.02	57.59	1.00
12.24.12	1,1	35.6	0.10	27.03	38.02	0.11	27.60	1.02
36.24.36	2,1	55.4	0.06	47.64	57.59	0.07	48.15	1.01
72.24.72	3,1	62.1	0.04	55.23	63.99	0.05	55.69	1.01
12.144.12	1,3	54.1	0.05	47.35	55.92	0.06	47.80	1.01
36.144.36	2,3	100.5	0.03	93.71	102.49	0.03	94.17	1.00
72.144.72	3,3	111.0	0.03	102.10	113.46	0.04	102.69	1.01
		Average:	0.05			0.06		1.01

Figure 68 - Comparison of average measured and adjusted capacities

In the above figure both the average measured capacities and the adjusted capacities are given as well as their corresponding 5-percentile values. Here can be seen that the values for the adjusted capacities are indeed somewhat higher than the measured capacities. But due to both an increase of the average values and a larger standard deviation for the adjusted capacities, the 5-percentile values of the measured and adjusted capacities are, with a difference of only 1% on average, nearly the same. This concludes that, for design purposes, a test set-up with equal connections at the top and bottom might be even better than a traditional set-up in which only one connection fails. This because symmetrically loaded specimens give almost the exact 5-percentile values and can achieve a lower standard deviation with the same amount of material. Only if the actual average capacity is required an adjustment needs to be made using the given relations.

11.2 Test results per variant and comparison with used design formulas

In the following subparagraphs the results of all different testing variants are commented upon by comparing the seen behaviour with the expected behaviour. A short overview of the test results is given in Figure 69 - **Overview of test results**.

Comparison $F_{calculated}$ and $F_{adjusted}$										
Testing variant	***Failure mode***	***F_{calc}***	***$F_{adjusted}$***	***5-perc $_{adj}$***	***F_{adj}/F_{calc}***	***Min. displacemen***	***Max. displacement***	***Max. dowel angle***	***Density***	***Mositure content***
		[kN]	*[kN]*	*[-]*	*[-]*	*[mm]*	*[mm]*	*[°]*	*[kg/m³]*	*[%]*
12.12	1	17.2	19.88	16.40	1.15	2.23	3.78	0	679.91	9.39
36.36	2	32.7	42.68	32.83	1.31	9.92	13.59	43	658.00	9.48
72.72	3	42.2	60.42	57.59	1.43	12.96	13.65	45	668.40	8.96
12.24.12	1,1	34.5	38.02	27.60	1.10	1.22	3.27	0	674.34	9.52
36.24.36	2,1	49.9	57.59	48.15	1.15	2.37	4.46	25	674.28	9.24
72.24.72	3,1	59.4	63.99	55.69	1.08	1.78	8.35	45	664.11	9.21
12.144.12	1,3	59.4	55.92	47.80	0.94	1.57	2.75	18	669.22	9.43
36.144.36	2,3	74.9	102.49	94.17	1.37	8.52	11.62	45	678.74	9.15
72.144.72	3,3	84.3	113.46	102.69	1.35	9.33	20.66	60	672.75	9.02
				Average:	1.21				666.81	9.26

Figure 69 - Overview of test results

In the figure above, the calculated capacity F_{calc} (based on a density of 666.81kg/m³) and the adjusted value of the maximum capacities $F_{adjusted}$ are shown. From the ratio between these two already can be seen that the used design formulas give a safe estimate of the actual capacity. Note that the calculated capacity shown here is different from that in the annex of the test results. The estimated capacity in the annex is the one used for the test protocol (based on a density of 708.3kg/m³).

11.2.1 Testing variant 12.12

A picture of one of the (failed) test pieces of this variant is shown in Figure 70 - **Test 12.12 (5)**.

Figure 70 - Test 12.12 (5)

For this testing variant two pieces of 12mm thickness were used. With this thickness, failure mode 1 was expected in both lamellas. The calculated capacity for failure mode 1 was 17.2kN. In the picture can be seen that the test specimen failed due to slitting of the material combined with a plug shear at the bottom connection. This is well in correspondence with failure behaviour belonging to failure mode 1. The force displacement graph of this testing variant is shown in Figure 71 - **Force-displacement graph of 12.12 (average)**. This graph shows the average force-displacement of all 5 test pieces of this variant. The individual graphs are given in **Annex H** – Test results.

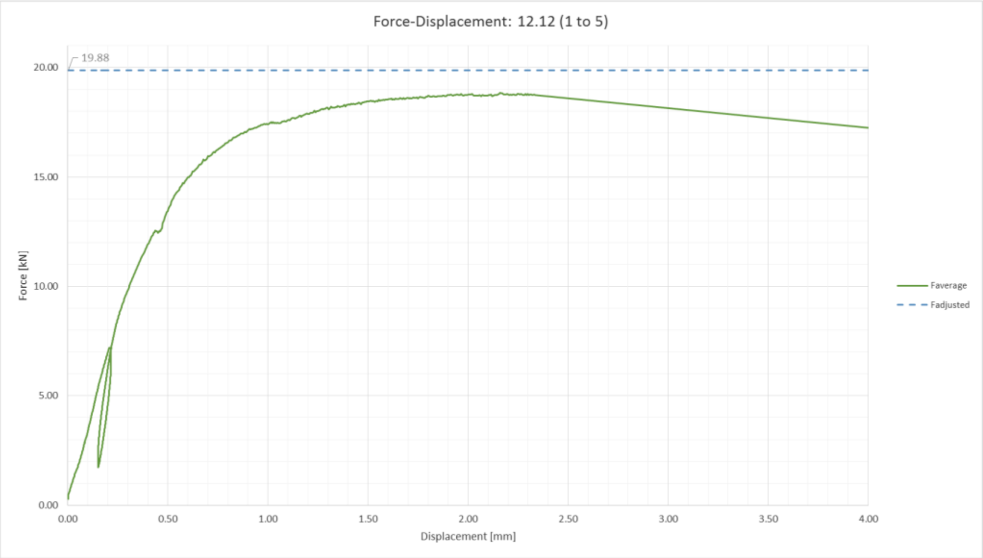


Figure 71 - Force-displacement graph of 12.12 (average)

In this graph can be seen that the $F_{average}$ lies below $F_{adjusted}$. This is partly because $F_{adjusted}$ was calculated from the test values and partly because of the way the graph of $F_{average}$ is determined. The average maximum force of the testing variant is determined by taking the maximum occurring force from every test piece and calculating the average. The maximum force of all these test pieces does not necessarily have to be at the same displacement or even at the same

testing time. So when the graph of $F_{average}$ is determined by taking the displacement and force value of the test pieces at a certain point in testing time the graph will not reach the value of $F_{max,average}$.
In the figure can also be seen that the average maximum capacity for this testing variant was 19.88kN. This is close to the estimate of 17.2kN. The test specimens however fail at a relatively low displacement of 2.5mm. Combined with the plug shear that was observed indicates that perhaps the end distance used here was a bit small. The end distance used was the minimum distance prescribed by Eurocode 5 (NEN-EN 1995-1-1+C1+A1:2011). To get more knowledge on possible benefits of increasing the end distance on the capacity of the connection, further research will be required. In such a research several variants will have to be made so that various end distances can be tested. Nonetheless, it is safe to say that the capacity of a connection of failure mode 1 with one slotted-in steel plate in laminated bamboo can be calculated using the already existing design formulas for timber.

11.2.2 Testing variant 36.36

A picture of one of the (failed) test pieces is given in Figure 72 - **Test 36.36 (1)**. This testing variant consisted of two pieces of 36mm thickness. Given this thickness, failure mode 2 was expected. The calculated capacity of such a connection was 32.7kN.

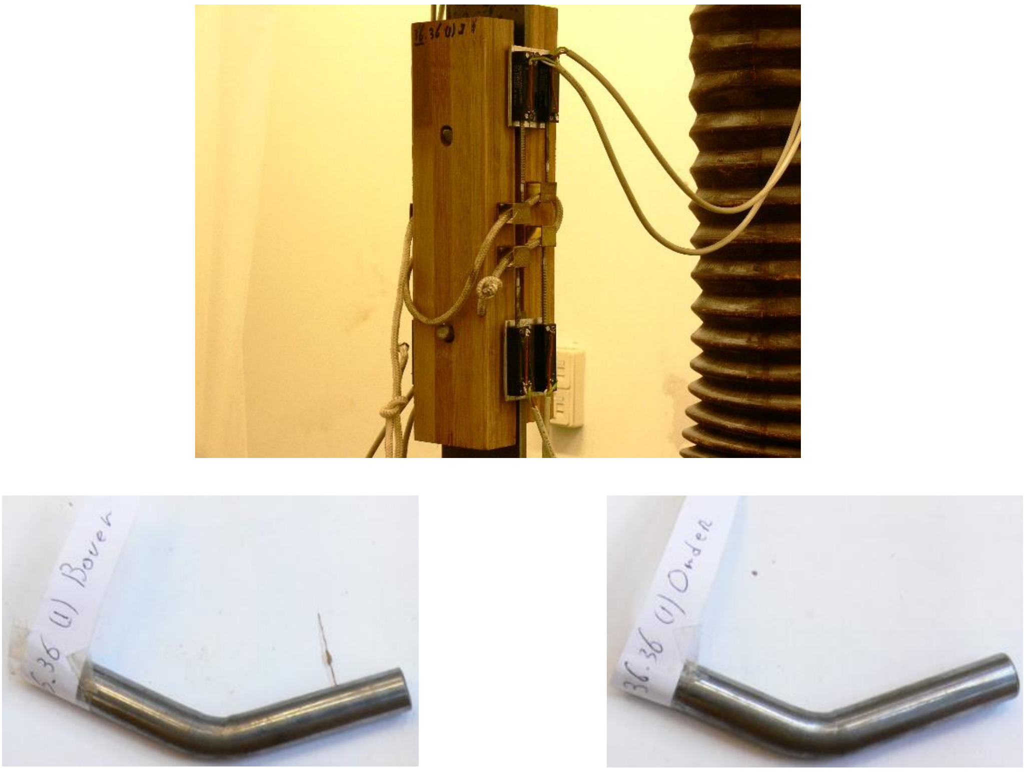


Figure 72 - Test 36.36 (1)

In the picture of the failed test piece can be seen that, during testing, the two individual members started to slide. A failure behaviour that, although beneficial for redundancy, is not likely to happen in practice, since in practice the steel plate will be placed in a slot made in a solid beam. In order to make the connection more realistic, the last three test pieces of the series were equipped with a glued-in piece of bamboo. The glued in piece had a thickness of 9mm. This ensured that the slotted-in plates of 8mm still fitted in-between the two bamboo members. A picture of one of the glued test specimens is shown in

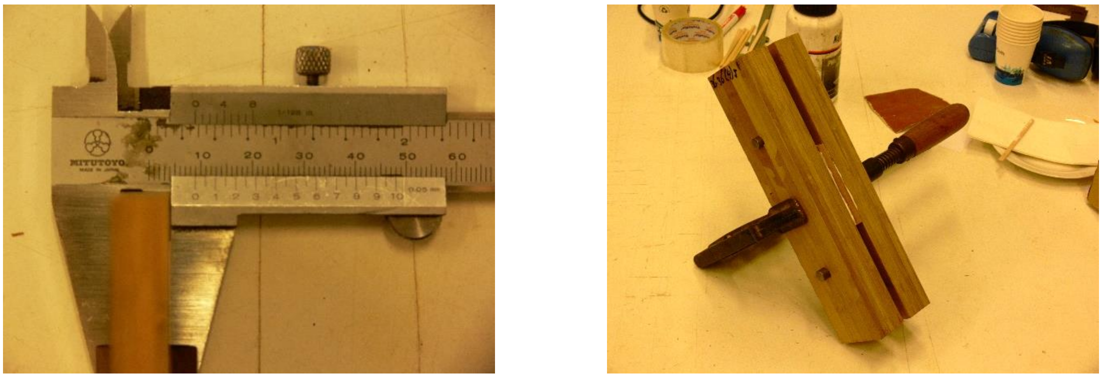


Figure 73 - Glued-in piece to prevent warping

During the gluing process the dowels were placed in the test pieces to make sure that the holes of the two lamellas were situated correctly and the test piece was correctly glued.

The glued test pieces all showed failure behaviour corresponding to failure mode 2. The average measured maximum capacity of this variant was 42.68kN. This is shown in Figure 74 - **Force-displacement graph of 36.36 (average)**.

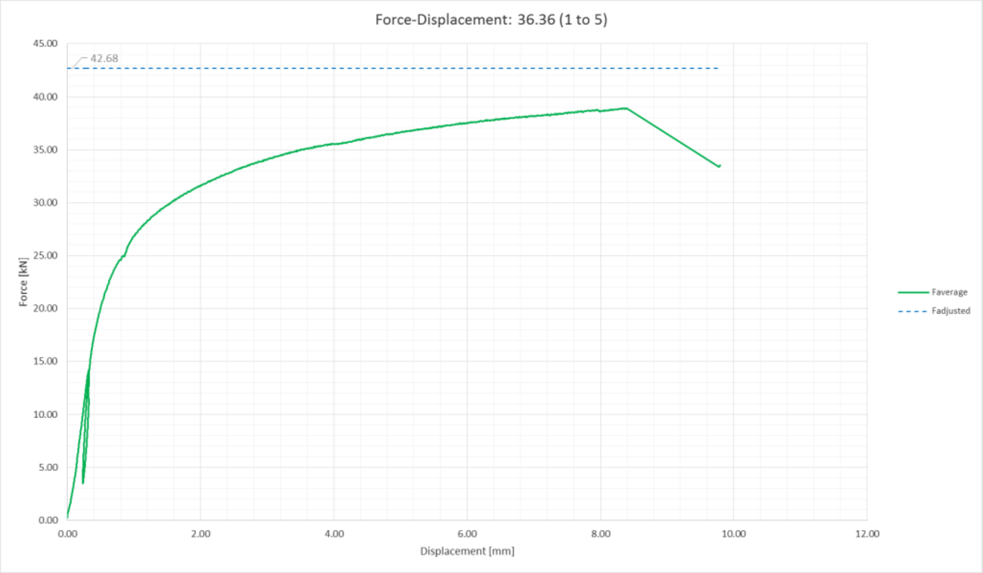


Figure 74 - Force-displacement graph of 36.36 (average)

The actual capacity of 42.68kN was somewhat larger than the expected 32.7kN. In the previous paragraph already was explained that the used end distance could be a little short. An increase of this end distance may have a beneficial effect on the connection capacity. Although further research is necessary to confirm this.

An explanation for the difference in capacity could be that the embedment strength used in the calculation is too low. This because the embedment strength used was derived from the capacity found during the preliminary tests. As already mentioned in 9.2 - **Testing protocol and setup**, the preliminary tests were not actual embedment tests and failed by splitting and plug shear. A phenomenon that is largely prevented in an embedment test because the test piece in an embedment test is fully supported in the direction of the force. Hence the embedment strength used here is most likely underestimated. In the figure this is also visible since the loading was still increasing somewhat when the test specimens failed.

11.2.3 Testing variant 72.72

A picture of one of the (failed) test specimens is presented in Figure 75 - **Test 72.72 (3)**.

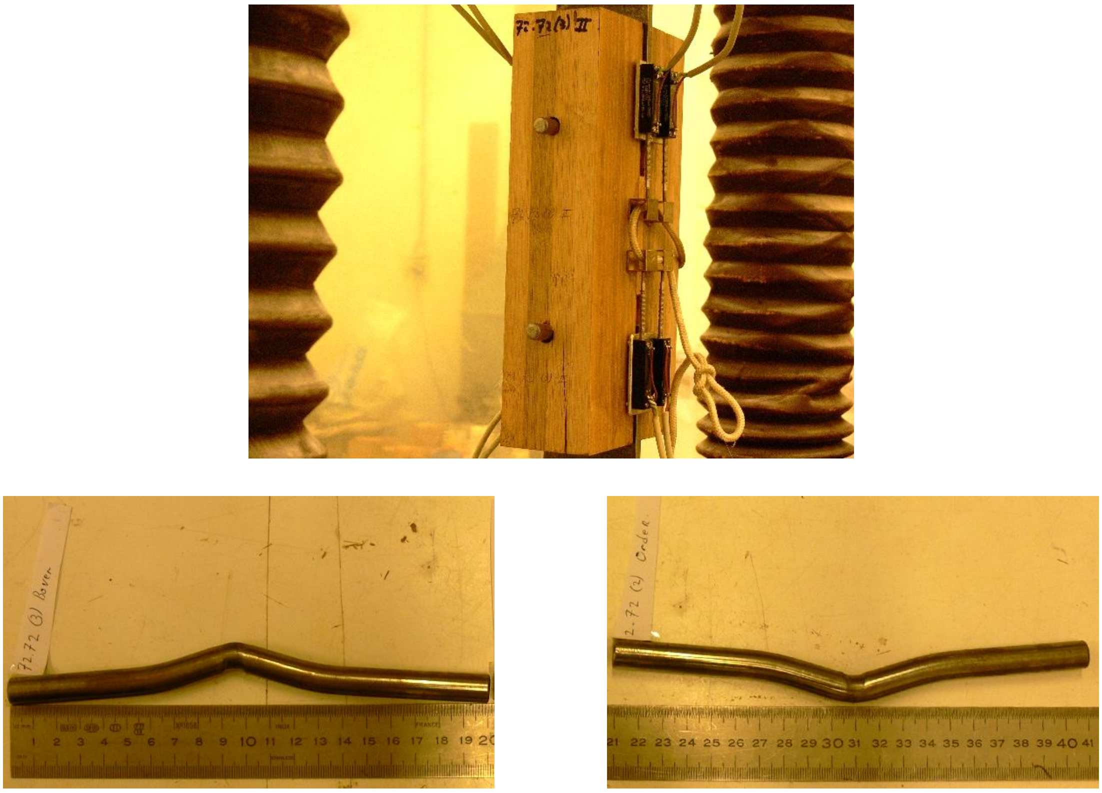


Figure 75 - Test 72.72 (3)

This variant makes use of one slotted-in plate and two pieces of bamboo of 72mm thickness. With this thickness failure mode 3 is expected to occur. The calculated capacity for this variant is 42.2kN.

In the picture of the failed specimen can be seen that with this variant, because of the glued in blocks, the warping of the test pieces was no longer a problem. The failure behaviour was consistent with failure mode 3 and two clearly visible plastic hinges developed in the dowel. The largest bending angle of the dowel was 45 degrees and indicates that full plasticity can be assumed here.

The averaged force-displacement graph is shown in Figure 76 - **Force-displacement graph of 72.72 (average)**.

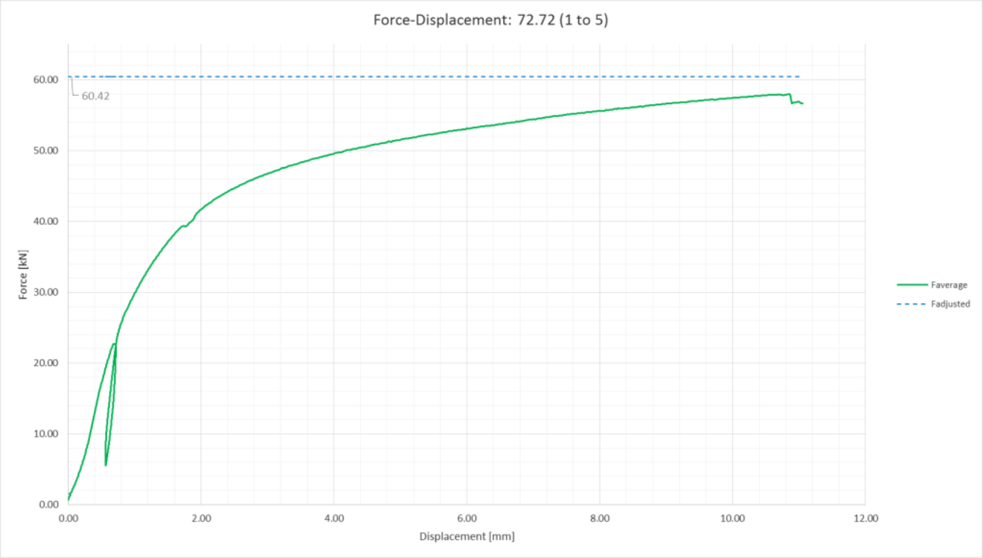


Figure 76 - Force-displacement graph of 72.72 (average)

The average maximum force measured was 60.42kN. This is well above the calculated capacity and, since the yield strength of the dowels has been tested in 9.2 - **Testing protocol and setup**, can only be declared by a difference in embedment strength. Same as for testing variant 36.36 additional embedment tests need to be executed in order to validate this. With the result of these embedment tests, the expected capacity can be recalculated and again be compared to the measured capacity.

Even though the calculated capacity does not exactly match the measured capacity, the design formulas used do give a safe estimate of the connection capacity and, if necessary, could be used to perform a design calculation when building a structure out of laminated bamboo.

11.2.4 Testing variant 12.24.12

A photograph of one of the failed test specimens is shown in Figure 77 - **Test 12.24.12 (1)**. This testing variant made use of two slotted-in steel plates and three laminated bamboo members. The outer members had a thickness of 12mm and the middle members had a thickness of 24mm. The expected failure mode was mode 1 in all three members. Since both slotted-in plates have to carry the load of two 12mm bamboo members, this testing variant can be seen as the two slotted-in plate variant of 12.12. Since variant 12.12 had two shear planes with both a failure mode 1 load of 8.6kN (17.2kN total), this variant, with four shear planes of failure mode 1, is expected to have a capacity of four times 8.6kN (34.5kN total). A more in-depth comparison between these two variants is made in 11.4 - **The benefits of multiple slotted-in plates**.

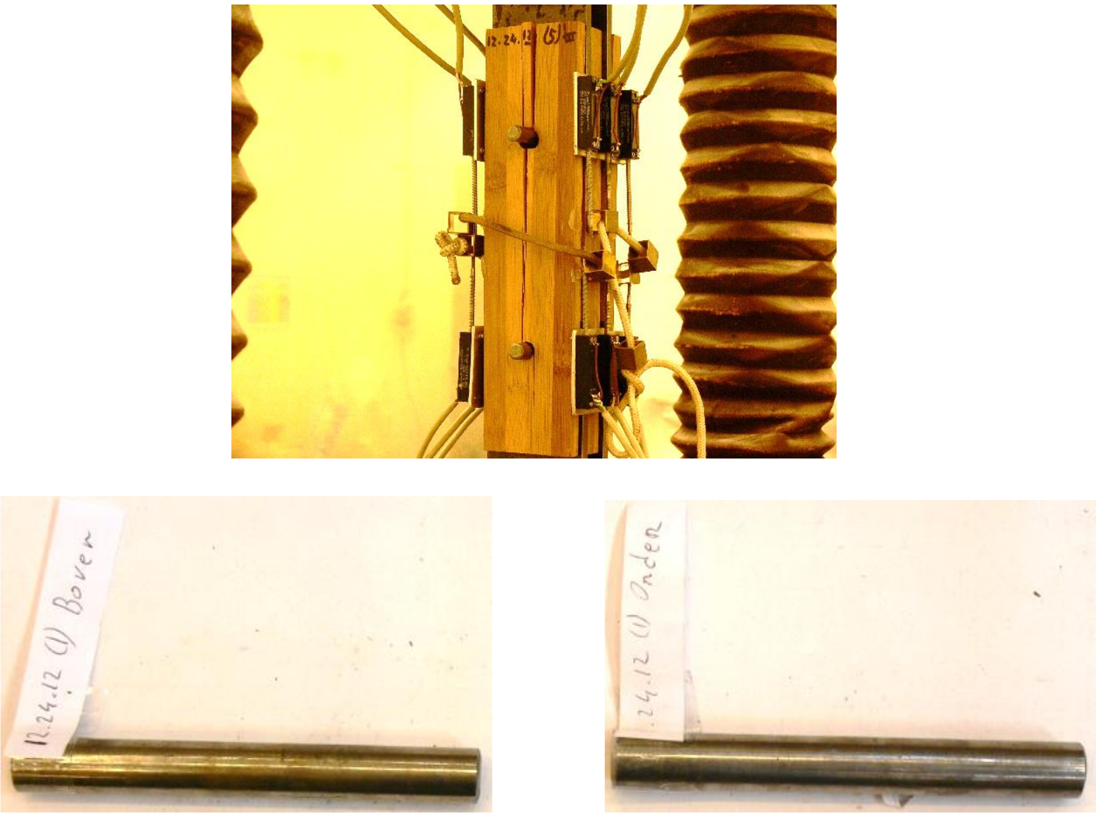


Figure 77 - Test 12.24.12 (1)

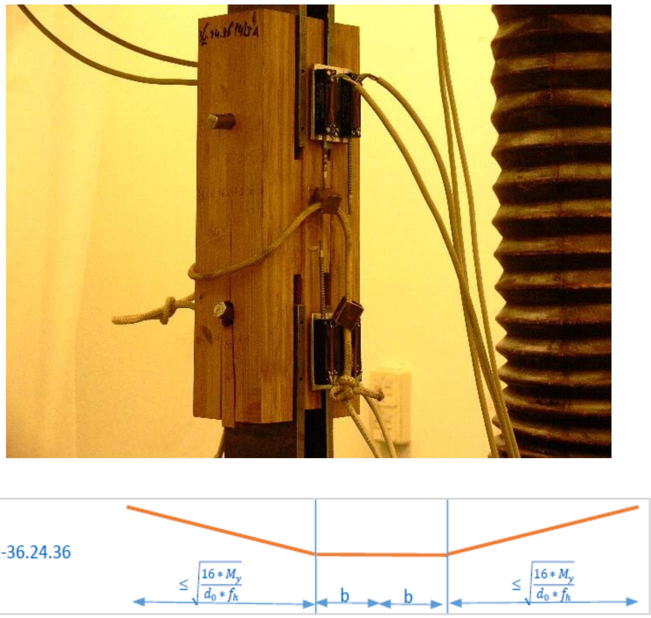
From the photograph can be seen that both splitting and plug shear occurred. Though this behaviour is consistent with failure mode 1, a larger end distance could be beneficial for the capacity of the test piece. As with other variants the employment of a larger end distance could mitigate or, at least, postpone the moment of splitting. Since splitting now occurred at a relatively low displacement the maximum embedment strength may not have been reached. A graph of the average force-displacement measured for this variant is given in Figure 78 - **Force-displacement graph of 12.24.12 (average)**.

Figure 78 - Force-displacement graph of 12.24.12 (average)

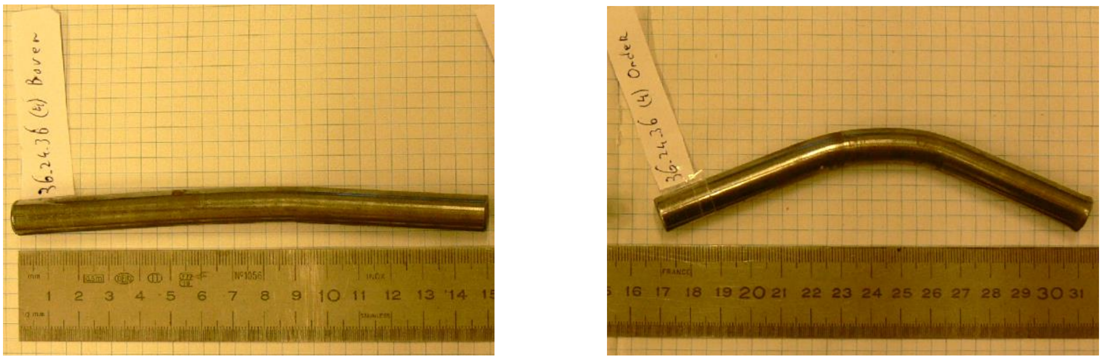
In the graph is shown the maximum capacity of this variant is reached at a displacement between 1 and 2.5 mm. This is consistent with failure mode 1 behaviour. The measured maximum capacity is about the same as calculated. Although this might also be a coincidence because of the embedment strength being most likely higher (which increases the capacity) and the end distance probably being a little low (which decreases the capacity). A follow-up research will have to shed more light on this.

11.2.5 Testing variant 36.24.36

One of the failed test specimens of this variant is depicted in Figure 79 - **Test 36.24.36 (1)**.



Expected behaviour from 'Annex C'



Observed behavour

Figure 79 - Test 36.24.36 (1)

This testing variant made use of two slotted-in plates and three laminated bamboo members. The thicknesses of these members were 36mm for the outer members (expected failure mode: 2) and 24mm for the middle member (expected failure mode: 1). The calculated capacity for this variant was one times failure mode 2 and one times failure mode 1 per slotted-in plate. This amounts to a total of 49.9kN for the entire test specimen. However, the calculated capacity should only give an upper bound estimate. This because of differences in deformation capacity between the two expected failure modes. Mode 1 will reach its maximum capacity at a much lower displacement than mode 2. This results that, at the moment the middle member (mode 1) fails the outer members (mode 2) should still have some capacity remaining. The first drop in the force-displacement graph should therefore be expected to happen somewhere below 49.9kN. The averaged force-displacement graph of this variant is shown in Figure 80 - **Force-displacement graph of 36.24.36 (average)**.

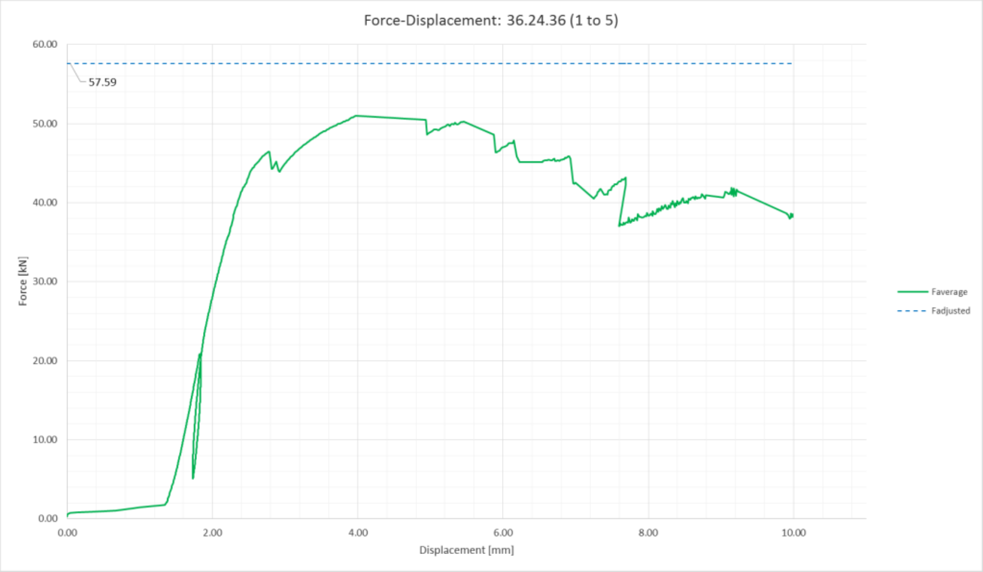
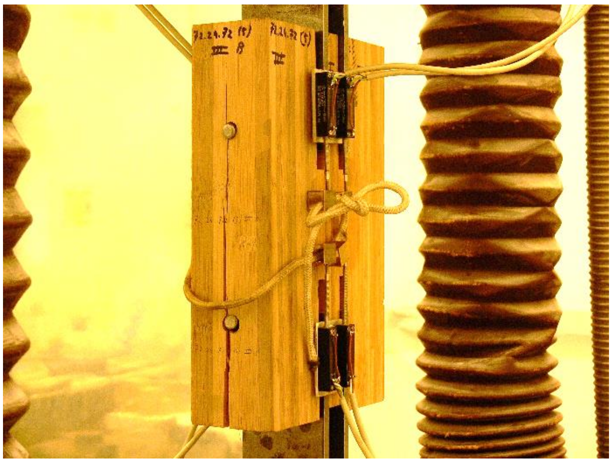


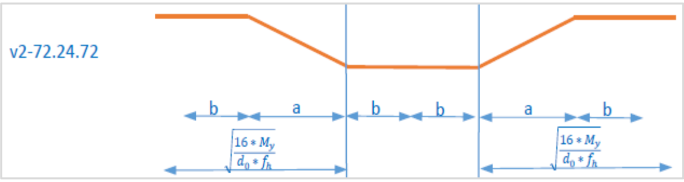
Figure 80 - Force-displacement graph of 36.24.36 (average)

The graph shows an instantaneous increase in displacement due to settlement of the test piece. When looked at the individual graphs for the test pieces in **Annex H** – Test results, the first peak is not lower than the calculated 49.9kN. This again probably due to a difference in calculated and actual embedment strength and is consistent with findings from other variants. After the first drop in capacity (failure mode 1 in the middle member) the displacement starts to increase until failure mode 2 occurs. Since the middle member has failed, at this stage it will not make a large contribution to the capacity of the test piece anymore. The capacity at this point should thus be equal (or a little bit more) to the capacity found with variant 36.36. This capacity was 40.43kN. The capacity found in this variant at the breaking point of mode 2 was 52kN. This should mean that the remaining capacity of the middle member was still 12kN.

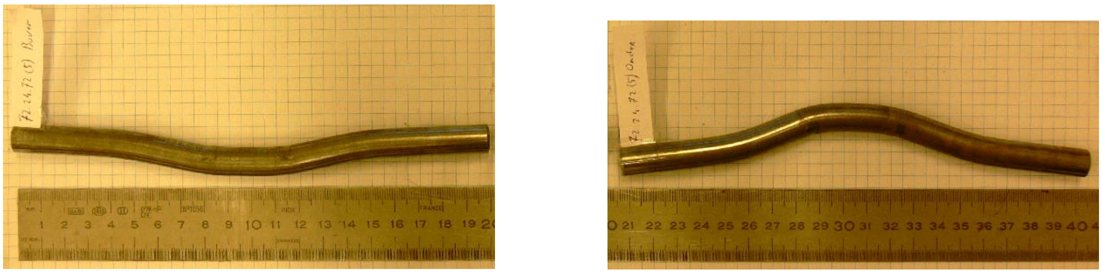
11.2.6 Testing variant 72.24.72

A picture of a failed specimen of this testing variant is shown in Figure 81 - **Test 72.24.72 (5)**.





Expected behaviour from 'Annex C'



Observed behaviour

Figure 81 - Test 72.24.72 (5)

For this testing variant two slotted-in plates and three bamboo members were used. The two outer members had a thickness of 72mm and expected failure mode 3. The middle member had a thickness of 24mm and expected failure mode 1. The calculated capacity of this connection was 59.4kN. But due to differences in deformation capacities between the two expected failure modes (as was the case with variant 36.24.36), the test piece is expected to break at a loading somewhat lower than the calculated value. After failure mode 1 has occurred, the middle member should have a little remaining strength and, at the moment failure mode 3 occurs, the loading should be equal to or slightly more than found in variant 72.72 (60.42kN). The averaged force-displacement diagram of this variant is given in Figure 82 - **Force-displacement graph of 72.24.72 (average)**.

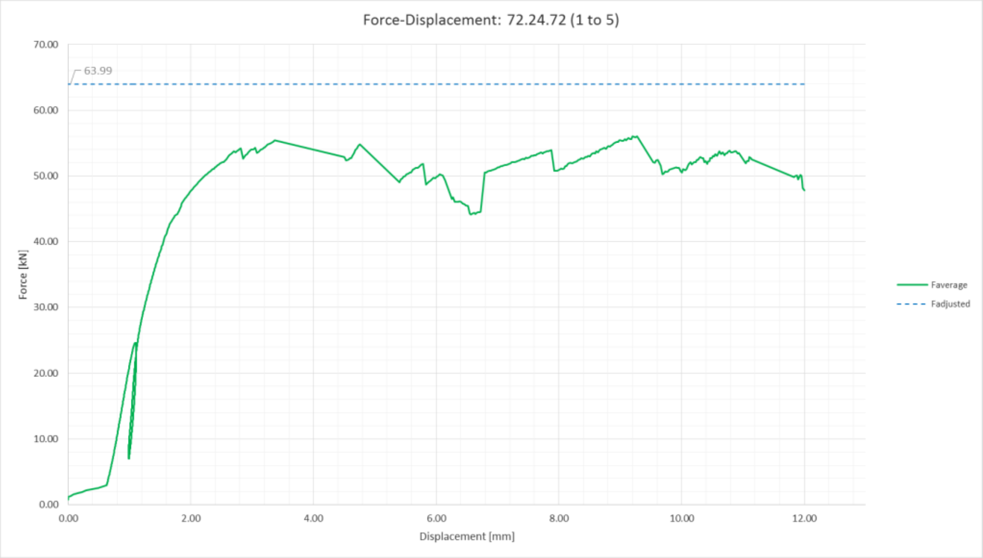
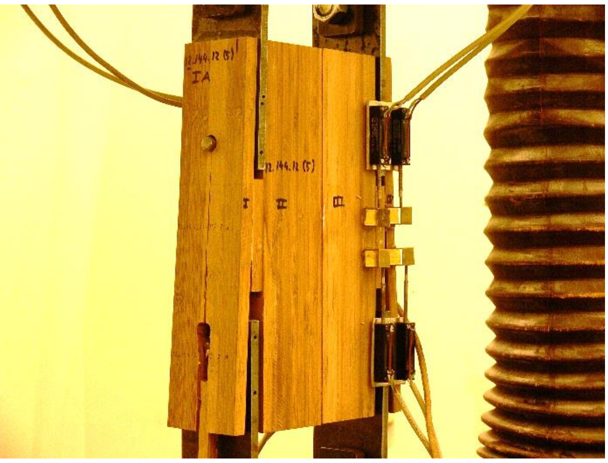


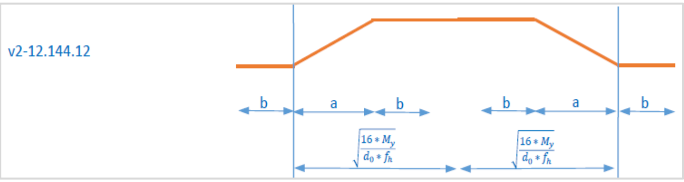
Figure 82 - Force-displacement graph of 72.24.72 (average)

In the given graph and the individual graphs of **Annex H** – Test results the first peak in the capacity is indeed slightly below the calculated 59.4kN. The average found maximum capacity of all specimens is 63.99kN. As expected, this value is somewhat higher than variant 72.72 (60.42kN) due to the middle member having some remaining capacity. However, when compared to the remaining middle member capacity of variant 36.24.36, the found 3.57kN here is much lower. A difference that might be caused by a variation in thickness of the glued-in piece which caused a larger clearance between the members of variant 72.24.72. The reason for the change in thickness is described in the annex.

11.2.7 Testing variant 12.144.12

One of the failed test specimens is displayed in Figure 83 - **Test 12.144.12 (5)**.





Expected behaviour from 'Annex C'

Observed behaviour

Figure 83 - Test 12.144.12 (5)

This variant consisted of two slotted-in plates and four bamboo members. The two outer members had a thickness of 12mm and expected failure mode 1. The two middle members had a thickness of 72mm each and were glued together to make one 144mm member with expected failure mode 3. Note that this variant is mirrored from variant 72.24.72. In this case mode 1 will happen at the outer members instead of the middle member and mode 3 happens in the middle member instead of the outer members. The expected capacity should therefore also be equal to that of variant 72.24.72, with the first peak just below 61.8kN and an average (adjusted) maximum capacity of about 63.99kN. The average force-displacement graph of this variant is shown in Figure 84 - **Force-displacement graph of 12.144.12 (average)**.

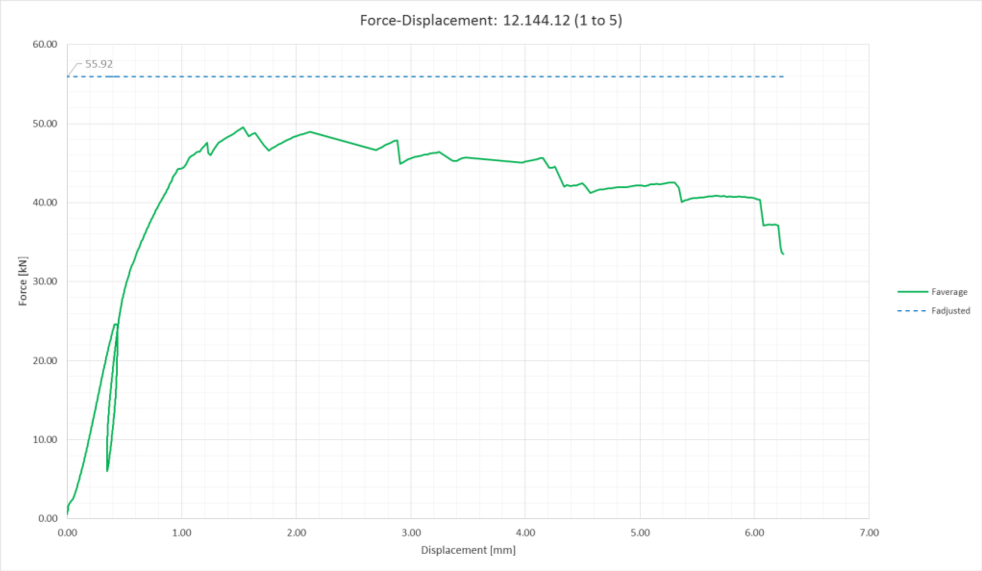


Figure 84 - Force-displacement graph of 12.144.12 (average)

In the graph the average capacity can be found at 55.92kN. This is below the expected capacity of 59.4kN. When looking at the failure behaviour of this testing variant, the difference between these two values is actually not that strange. Since the two failure modes have such a dissimilar deformation capacity, the outer members will fail long before the middle members reach their maximum capacity. In contrast to the behaviour of variant 72.24.72, where, after failure mode 1 has occurred in the middle member, the slotted-in plates were prevented from warping and further loading by the pulling bench was still in-plane of the slotted-in plates, in this variant the slotted-in plates were not anymore prevented from warping. In this case, the outer members failed first and now there was nothing that prevented the slotted-in plates from sliding over the dowel when it deformed on its way to failure mode 3. This effect is shown in Figure 85 - **Test 12.144.12 (1)**.

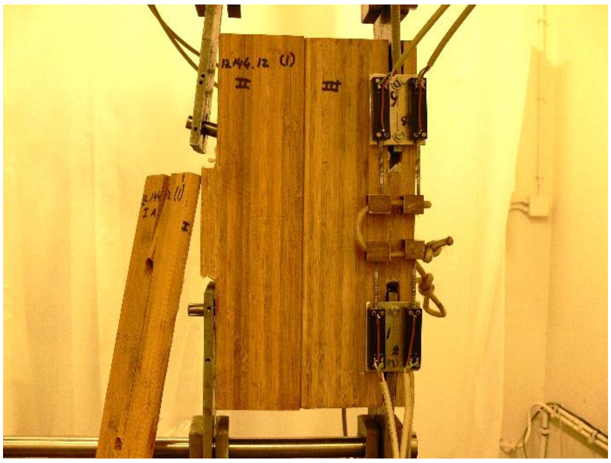


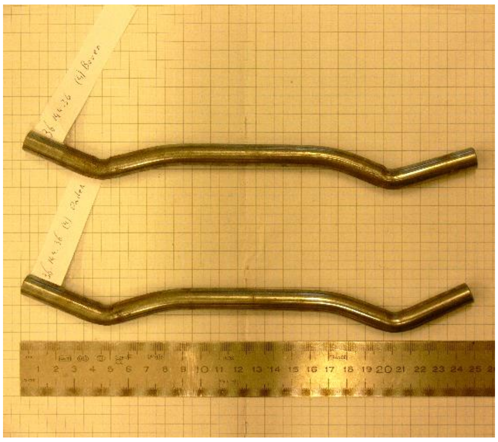
Figure 85 - Test 12.144.12 (1)

In this picture can be seen that the outer member was completely pushed away and that the slotted-in plate began to slide over the dowel. The slotted-in plate will now be loaded also in bending. A situation which was not anticipated in the design phase and for which the plates were not calculated. The test thus had to be stopped to prevent the plates from overloading. In the force-displacement diagram this effect can also be seen. After the first crack (failure mode 1) the displacement increases while the capacity decreases. This due to the sliding effect that not only directly causes extra deformation but also because of change of loading on the dowel. Since the location of this loading is now further away from the middle member, the dowel will also be loaded in bending and contribute to the increasing deformation of the test piece (compare the expected dowel behaviour to the observed dowel behaviour). From this can be learned that, when making a connection design in which different failure modes occur, the failure modes with the least deformation capacity should be placed such that, after failure, the steel plates are still loaded as intended. In this case that would mean to place failure mode 1 in the middle as in variant 72.24.72.

11.2.8 Testing variant 36.144.36

A failed specimen of this variant is shown in Figure 86 - **Test 36.144.36 (4)**.

Expected behaviour from 'Annex C'



Observed behaviour

Figure 86 - Test 36.144.36 (4)

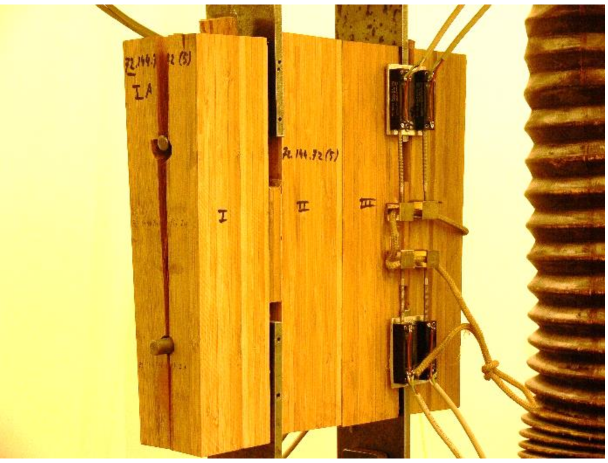
The specimens of this variant made use of two slotted-in steel plates and three bamboo members. The outer members had a thickness of 36mm and expected failure mode 2. The middle member had a thickness of 144mm (two 72mm pieces glued together) and expected failure mode 3. The expected failure load for this variant was calculated at 74.9kN. Again for this variant, due to the difference in deformation capacity between the two failure modes, the calculated value was not expected to be reached. Expected was that failure mode 2 would occur at a loading slightly lower than 74.9kN. Based on findings from the other mode 2 and 3 variants, this expected capacity should be a summation of the capacities found in variants 36.36 (42.68kN) and 72.72 (60.42kN). Which equals 103.10kN. The averaged load-displacement diagram for this variant is given in Figure 87 - **Force-displacement graph of 36.144.36 (average)**.

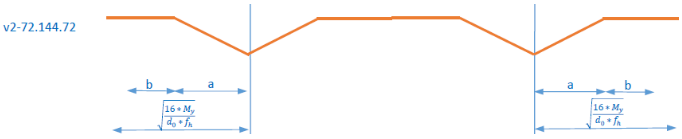
Figure 87 - Force-displacement graph of 36.144.36 (average)

In the figure an average found maximum capacity of 102.42kN is indicated. Although this is well above the calculated value, this capacity does resemble the expectancy based on variants 36.36 and 72.72. The difference in calculated capacity and measured capacity should also be due to a possible difference in embedment strength.

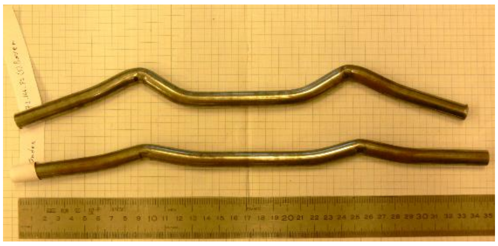
11.2.9 Testing variant 72.144.72

A picture of one of the failed specimens is shown in Figure 88 - **Test 72.144.72 (5)**.





Expected behaviour from 'Annex C'



Observed behaviour

Figure 88 - Test 72.144.72 (5)

This variant made use of two slotted-in plates with three bamboo members of thicknesses 72 and 144mm. All members had expected failure mode 3. The calculated capacity was 84.3kN (this is two times that of variant 72.72). From a comparison between the observed behaviour of the dowel and the expected behaviour can be seen that failure mode 3 occurred in all members. The dowel shows two plastic hinges at both sides of the slotted-in plates and the maximum bending angle of the dowel in this variant was 60 degrees. This clearly indicates that the bending moment capacity of the dowel was fully used in this variant and that any deviations between calculated and measured capacity should be within the (calculated) material properties of the laminated bamboo. The force-displacement diagram of this variant is given in Figure 89 - **Force-displacement graph of 72.144.72 (average)**.

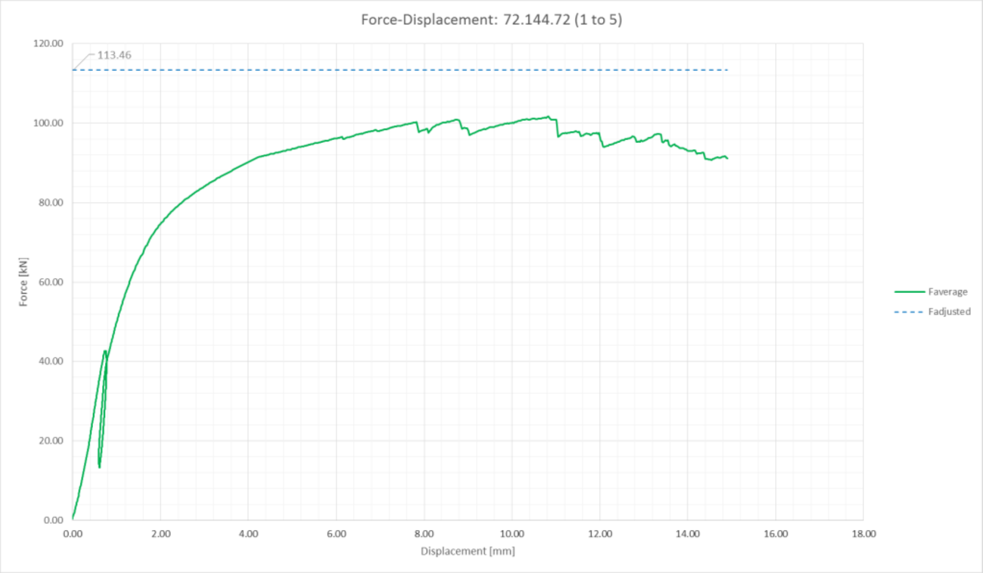


Figure 89 - Force-displacement graph of 72.144.72 (average)

In this diagram an average maximum capacity of 113.46kN is indicated. This is higher than the calculated value of 86.9kN, which is consistent with findings from other mode 3 variants (72.72 and 72.24.72). Also consistent with other mode 2 and 3 variants is the high remaining capacity after the first crack appears. The moment one of the members starts splitting is in many test specimens (not only this variant) also the moment of maximum capacity but, after that, the deformation can still increase a lot without much loss in strength.

11.3 Comparison with EC5

The previous paragraph made a comparison between the obtained results and behaviour of the test pieces and the formulas used for the design those test pieces. The used design formulas were chosen such that a realistic value of the strength capacity of a specimen could be calculated. The design formulas given in Eurocode 5 however do not necessarily give a realistic approximation of the capacity of a connection. This because of a number of safety factors incorporated into these formulas like the adaption of the bending moment capacity for dowels by taking '$d^{2.6}$' instead of 'd^3'. To evaluate a possibility to calculate laminated bamboo connections with use of formulas given in EC5 an additional comparison will thus have to be made. For this comparison the capacity of all testing variants is determined again by using the exact formulas from EC5. The formulas from EC5 are given in **Annex C** – Design of test pieces and are shortly summarized here:

$$F_{v,Rk} = min \begin{cases} f_{h,k} * t * d \\ f_{h,k} * t * d * \left(\sqrt{2 + \dfrac{4 * M_{y,Rk}}{f_{h,k} * d * t^2}} - 1 \right) \\ 2.3 \sqrt{M_{y,Rk} * f_{h,k} * d} \end{cases}$$

$$M_{y,Rk} = 0.3 * f_{u,k} * d^{2,6}$$

$$f_{h,k} = 0.082 * (1 - 0.01 * d) * \rho_k$$

The given formulas are taken from chapter 8.5 (bolts) of EC5 (NEN-EN 1995-1-1+C1+A1:2011). In the following table the capacity of the testing variants according to these formulas is given (see Figure 90 - **Test results for comparison with EC5**). For the calculation of this capacity the actual measured density of 666.81kg/m³ of the laminated bamboo and the tested ultimate tensile strength of 601N/mm² of the dowel are taken.

Comparison $F_{adjusted}$ and F_{EC5}

Testing variant	*Failure mode*	*F_{EC5}*	*$F_{adjusted}$*	*5-perc $_{adj}$*	*F_{adj} /F_{EC5}*	*5-perc $_{adj}$ /F_{EC5}*	*Min. displacement*	*Max. displacement*	*Max. dowel angle*	*Density*	*Mositure content*
		[kN]	*[kN]*	*[-]*	*[-]*	*[-]*	*[mm]*	*[mm]*	*[°]*	*[kg/m³]*	*[%]*
12.12	1	13.9	19.88	16.40	1.43	1.18	2.23	3.78	0	679.91	9.39
36.36	2	25.7	42.68	32.83	1.66	1.28	9.92	13.59	43	658.00	9.48
72.72	3	32.6	60.42	57.59	1.85	1.76	12.96	13.65	45	668.40	8.96
12.24.12	1,1	27.7	38.02	27.60	1.37	1.00	1.22	3.27	0	674.34	9.52
36.24.36	2,1	39.5	57.59	48.15	1.46	1.22	2.37	4.46	25	674.28	9.24
72.24.72	3,1	46.5	63.99	55.69	1.38	1.20	1.78	8.35	45	664.11	9.21
12.144.12	1,3	46.5	55.92	47.80	1.20	1.03	1.57	2.75	18	669.22	9.43
36.144.36	2,3	58.3	102.49	94.17	1.76	1.61	8.52	11.62	45	678.74	9.15
72.144.72	3,3	65.3	113.46	102.69	1.74	1.57	9.33	20.66	60	672.75	9.02
				Average:	1.54	1.32				666.81	9.26

Figure 90 - Test results for comparison with EC5

In the table a column named F_{EC5} is shown. This column gives the capacities according to EC5. These capacities are compared to the adjusted test results and the 5-percentile values of the adjusted test results. Through this comparison can be seen that the test specimens are on average 54% stronger then calculated on the basis of EC5. The found 5-percentile values are on average 32% higher. This shows that calculating a laminated bamboo connection with design formulas from EC5 gives a safe estimate of the strength capacity and arguably even an underestimation.

11.4 The benefits of multiple slotted-in plates

In this paragraph the effects of applying multiple slotted-in plates in a connection are discussed. The effect of multiple plates has been researched by either doubling a single slotted-in plate variant or mirroring an existing double slotted-in plate variant. Via a comparison in measured capacities and measured deformations the effects of multiple slotted-in plates can be analysed. Examples of doubling a single plated variant are 12.12 vs.12.24.12 in which all members show failure mode 1 and 72.72 vs 72.144.72 in which all members show failure mode 3. Mirroring of a variant was done with variant 72.24.72 to create variant 12.144.12. The effects of this mirroring have already been shortly mentioned in the analysis of variant 12.144.12.

Other effects of applying multiple slotted-in plates are a difference in capacity between variants of the same total connection thickness. Although this comparison was not initially taken into account in the design phase, comparing variants 36.36 (total 80mm) and 12.24.12 (total 64mm) can provide insight in the effects of applying more slotted-in plates in a connection. This can be particularly helpful when only limited space is available and still a strong connection is desired.

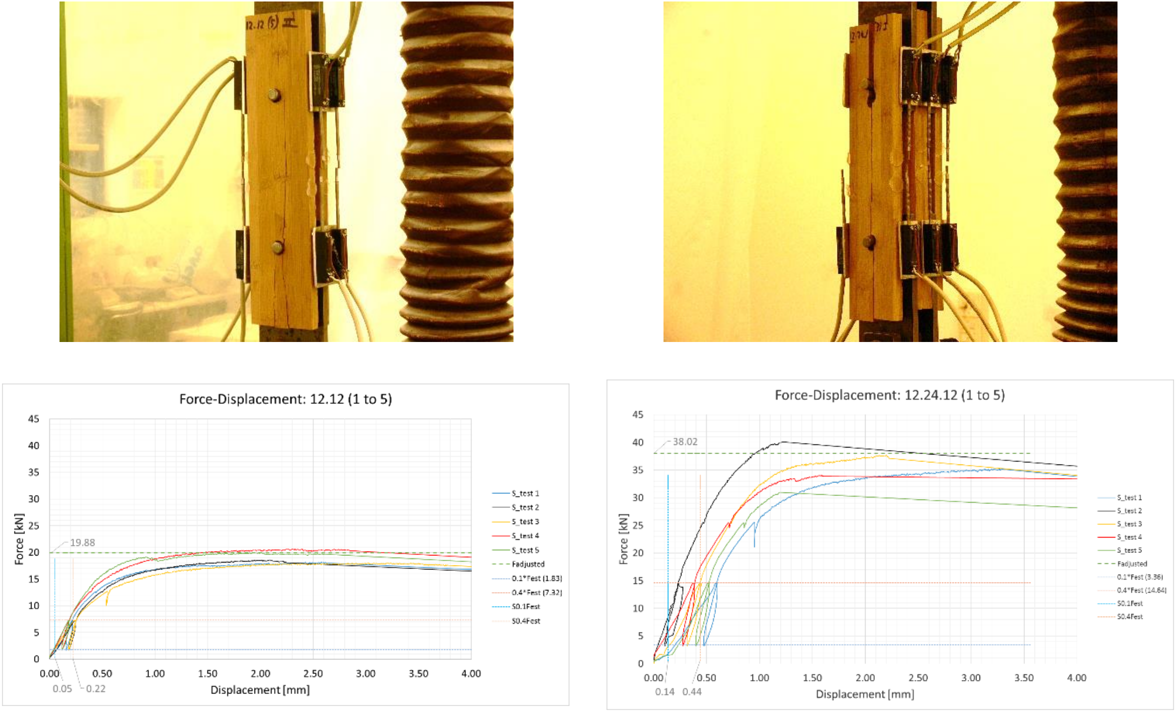
11.4.1 Capacity increase for multiple plates

This paragraph will discuss the effect of doubling a single slotted-in plate connection. The discussion will make use of a comparison between the behaviour of variants ’12.12 and 12.24.12’ (failure mode 1) and ’72.72 and 72.144.72’ (failure mode 3). For this comparison only the observed behaviour is taken into account. The difference between calculated and observed capacity has already been discussed in 11.2 - **Test results per variant and comparison with used design formulas.**

The observed behaviour and a picture of a test piece of the mode 1 variants are shown in Figure 91 - **One vs. two slotted-in plates for failure mode 1.**

Variant 12.12
(one slotted-in plate)

Variant 12.24.12
(two slotted-in plates)


Force-Displacement: 12.12 (1 to 5)

Force-Displacement: 12.24.12 (1 to 5)

Figure 91 - One vs. two slotted-in plates for failure mode 1

Both of the shown variants had two bamboo pieces of 12mm thickness for every slotted-in plate. For the two slotted-in plate variant this means that the middle member thickness equals 2*12 = 24mm. The occurring failure mode in these test pieces was mode 1. In the figure also the measured force-displacement is given for the individual test pieces. In these graphs the average of the measured maximum capacities is indicated for both test pieces. Variant 12.12 made use of one slotted-in plate and a maximum capacity of 19.88kN was found. Based on this measurement the maximum capacity for two slotted-in plates could be expected to equal two times this capacity. That should be 2*19.88 = 39.76kN. In the graph of variant 12.24.12 the maximum capacity for two slotted-in plates is shown to be 38.02kN. This is lower than expected on the basis of the single slotted-in plate capacity. The ratio between the two is given below.

$$Strength\ ratio\ mode\ 1\colon \frac{38.02}{19.88} = 1.912$$

From this ratio it is clear that the usage of two slotted-in plates in this variant does not give the connection double the capacity of one slotted-in plate. The connection here only gets a capacity increase of 91.2%.
From the slope of the shown graphs also the stiffness of the connections can be compared. Of course the connection with two slotted-in plates behaves stiffer over the whole measured deformation, but the force and displacement to determine the stiffness are on the linear part of the graphs at 0.1*F_{est} and 0.4*F_{est} (NEN-ISO 6891, 1991). For the single plated variant the resulting slip modulus is calculated below.

$$v_{12.12,mod} = \frac{4}{3}(v_{0.4F_{est}} - v_{0.1F_{est}})$$

$$k_{s,12.12} = \frac{0.4F_{est}}{v_{12.12,mod}} = \frac{7.32 * 10^3}{\frac{4}{3}(0.22 - 0.05)} = 32294\frac{N}{mm}$$

The slip modulus of the variant with two slotted-in plates is as follows:

$$v_{12.24.12,mod} = \frac{4}{3}(v_{0.4F_{est}} - v_{0.1F_{est}})$$

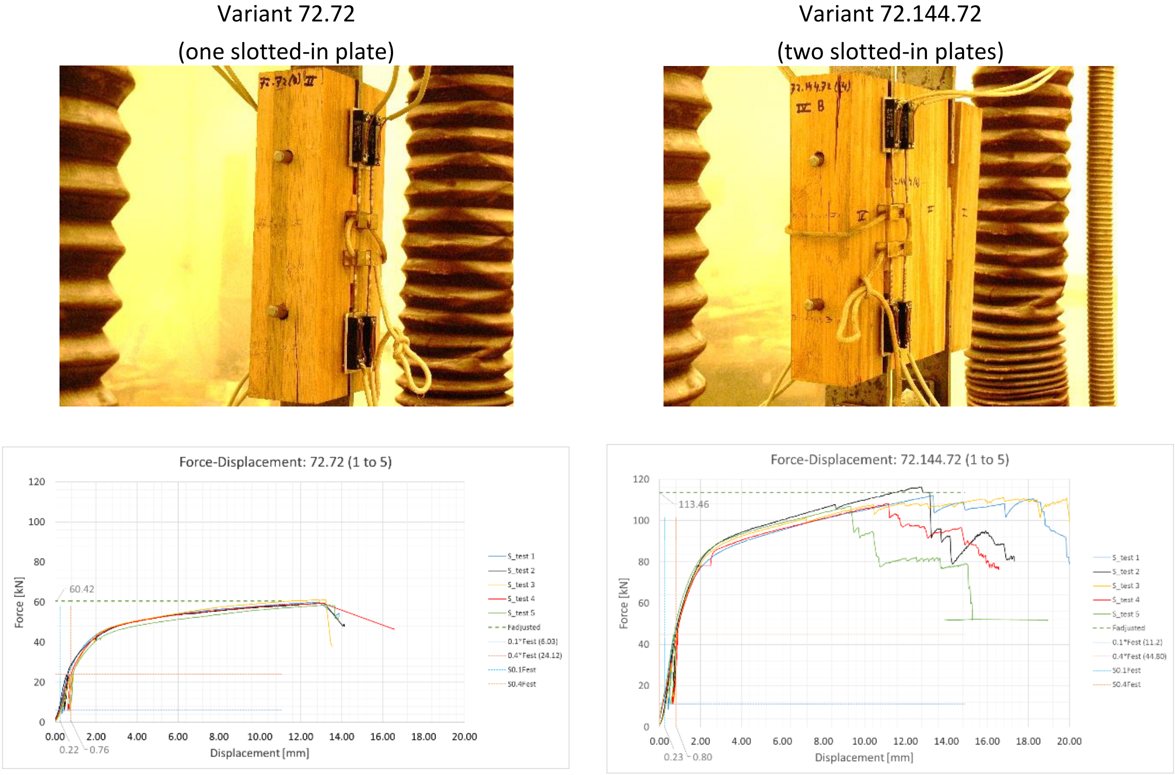
$$k_{s,12.24.12} = \frac{0.4F_{est}}{v_{12.12,mod}} = \frac{14.64 * 10^3}{\frac{4}{3}(0.44 - 0.14)} = 36600\frac{N}{mm}$$

Given these values the following ratio for the stiffness of the failure mode 1 variants can be calculated.

$$Stiffness\ ratio\ mode\ 1\colon \frac{36600}{32294} = 1.133$$

The ratio indicates that, like the strength, the measured stiffness of two slotted-in plates is somewhat higher than the stiffness when using a single slotted-in plate.

For the two failure mode 3 variants the observed behaviour and a picture of a test piece from both variants are shown in Figure 92 - **One vs. two slotted-in plates for failure mode 3**.



Variant 72.72

(one slotted-in plate)

Variant 72.144.72

(two slotted-in plates)

Figure 92 - One vs. two slotted-in plates for failure mode 3

The failure mode 3 variants had a bamboo piece of 72mm thickness on each side of the slotted-in plates. For the two slotted-in plate variant this means that the middle member has a thickness of 2*72 = 144mm. The force-displacement graphs of all individual test pieces are shown. In these graphs the average maximum capacity of the test pieces is indicated. For the single slotted-in plate variant this average capacity was 60.42kN. Based on this measurement the expected capacity for the two slotted-in plate variant should be about 2*60.48 = 120.96kN. The found capacity for two slotted-in plates was 113.46kN. This is somewhat lower than expected. The ratio between these two capacities is calculated below.

$$Strength\ ratio\ mode\ 3\text{:}\ \frac{113.46}{60.42} = 1.878$$

From this ratio can it will be clear that the application of the second slotted-in plate did not yield a doubling of the capacity. In fact, the capacity increase is now found to be only 87.8 %.

Also here the stiffness of the connections can be determined according to (NEN-ISO 6891, 1991). This is done below.

$$v_{72.72,mod} = \frac{4}{3}(v_{0.4F_{est}} - v_{0.1F_{est}})$$

$$k_{s,72.72} = \frac{0.4F_{est}}{v_{72.72,mod}} = \frac{24.12 * 10^3}{\frac{4}{3}(0.76 - 0.22)} = 33500\frac{N}{mm}$$

The stiffness of the variant with two slotted-in plates is as follows:

$$v_{72.144.72,mod} = \frac{4}{3}(v_{0.4F_{est}} - v_{0.1F_{est}})$$

$$k_{s,72.144.72} = \frac{0.4F_{est}}{v_{72.144.72,mod}} = \frac{44.80 * 10^3}{\frac{4}{3}(0.80 - 0.23)} = 58947.37\frac{N}{mm}$$

Given these values the following ratio for the stiffness of the failure mode 1 variants can be calculated.

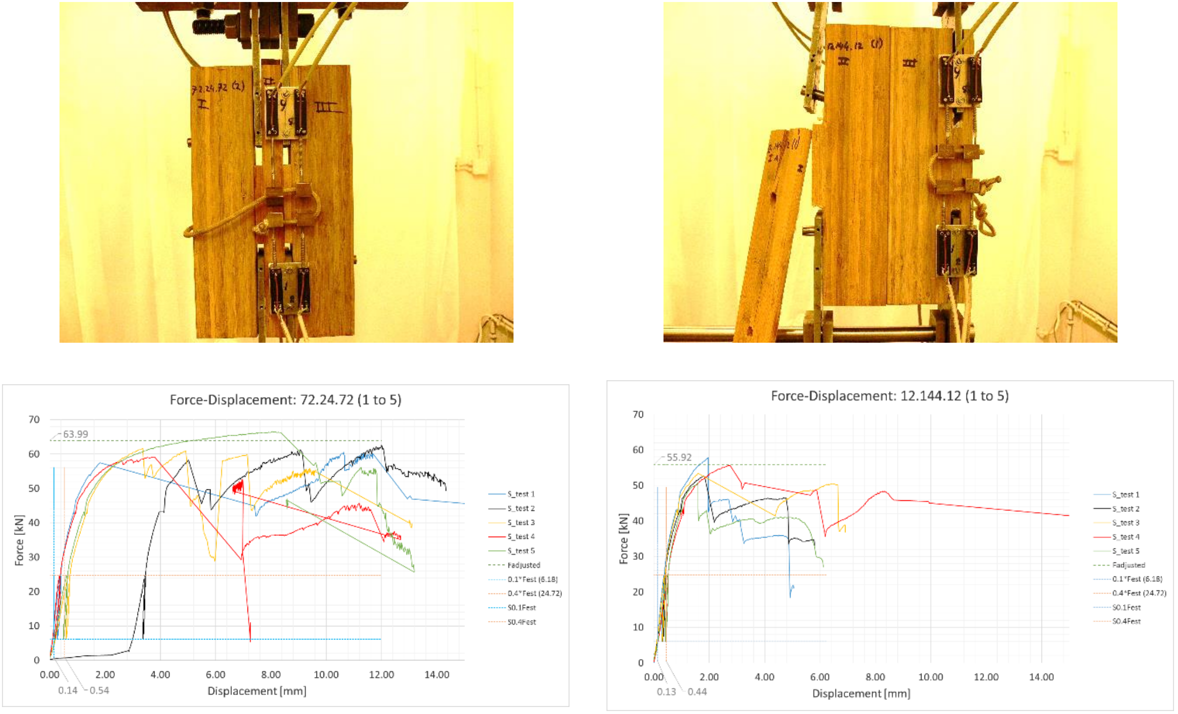
$$Stiffness\ ratio\ mode\ 3\text{:}\ \frac{58947.37}{33500} = 1.760$$

The variant with two slotted-in plates clearly has a higher stiffness than the variant with only one slotted-in plate. However, the stiffness is not twice as much, as one would expect. Just like the strength, the stiffness when using multiple slotted-in plates is not found to be just a multiplication of the amount of slotted-in plates.

An interesting observation is made by comparing the found strength ratios for failure modes 1 and 3. Although the ratios were not equal to 2, as was expected prior to testing, the found ratios are in fact very similar. This could mean that, like applying multiple dowels in a row, the placement of a second (or more) slotted-in plate could have an effect similar to the effective number of dowels. Based on these findings an effective number of plates is very likely. Considering that these numbers are based upon only 5 test specimens per variant, the similarity of these ratios could just be coincidental, although not probably. Further research will have to be conducted to confirm this theory.

11.4.2 The effects of plate placement

The placement of the slotted-in plates can have an effect on the capacity of the connection. By the placement of the plates is meant whether it is beneficial to place the plates more on the outer side or the inner side of a beam. The effects of plate placement can be analysed by a comparison of variants 72.24.72 and 12.144.12. A picture of a test piece from both variants as well as the force-displacement diagrams are shown in Figure 93 - **Plate placement effects**.



Variant 72.24.72
(thin middle member)

Variant 12.144.12
(thick middle member)

Figure 93 - Plate placement effects

Both of these variants had failure mode 1 and failure mode 3 at a side of the slotted-in plates. The side at which these failure modes occurred differed in both variants. In variant 72.24.72 mode 3 occurred in the thick outer members and mode 1 in the thin middle member. In variant 12.144.12 this was exactly the opposite, with mode 1 occurring in the thin outer members and mode 3 in the thick middle member. Since each slotted-in plate has both a loading from failure mode 1 and failure mode 3 in both variants, the expected capacity for both variants was equal. First variant 72.24.72 was tested. The resulting average capacity from these tests was 63.99kN. The stiffness of this variant is calculated below (note: for this calculation specimen 2 is not taken into account).

$$v_{72.24.72,mod} = \frac{4}{3}(v_{0.4F_{est}} - v_{0.1F_{est}})$$

$$k_{s,72.24.72} = \frac{0.4F_{est}}{v_{72.24.72,mod}} = \frac{24.72 * 10^3}{\frac{4}{3}(0.54 - 0.14)} = 46350 \frac{N}{mm}$$

For variant 12.144.12 similar values for the stiffness and capacity were expected. However, during testing of this variant a far lower capacity was found. This due to differences in deformation capacity of the two failure modes. Since failure mode 1 has a lower deformation capacity than failure mode 3 the thinner bamboo members will fail much quicker than the thicker members. During testing of variant 72.24.72 the failed thin member was in the middle and although failed, it was still a part of the connection. This prevented the slotted-in plate from sliding along the warped dowel and made it possible for the test to continue until failure mode 3 was reached. When testing variant 12.144.12 the thin members were on the outside of the connection. During these tests, when the thin members failed and the dowel started bending, the slotted-in plates started sliding over the dowel. The sliding of the plates caused a horizontal force on the outer members and eventually led to the outer plates braking off of the test piece. This can be seen in the figure. After that, there was nothing to keep the slotted-in plates in their position and the sliding could go on. This of course eventually leads to an out-of-plane loading of the plates, for which they are not designed. The capacity of variant 12.144.12 was found to be 55.92kN and its stiffness is calculated below.

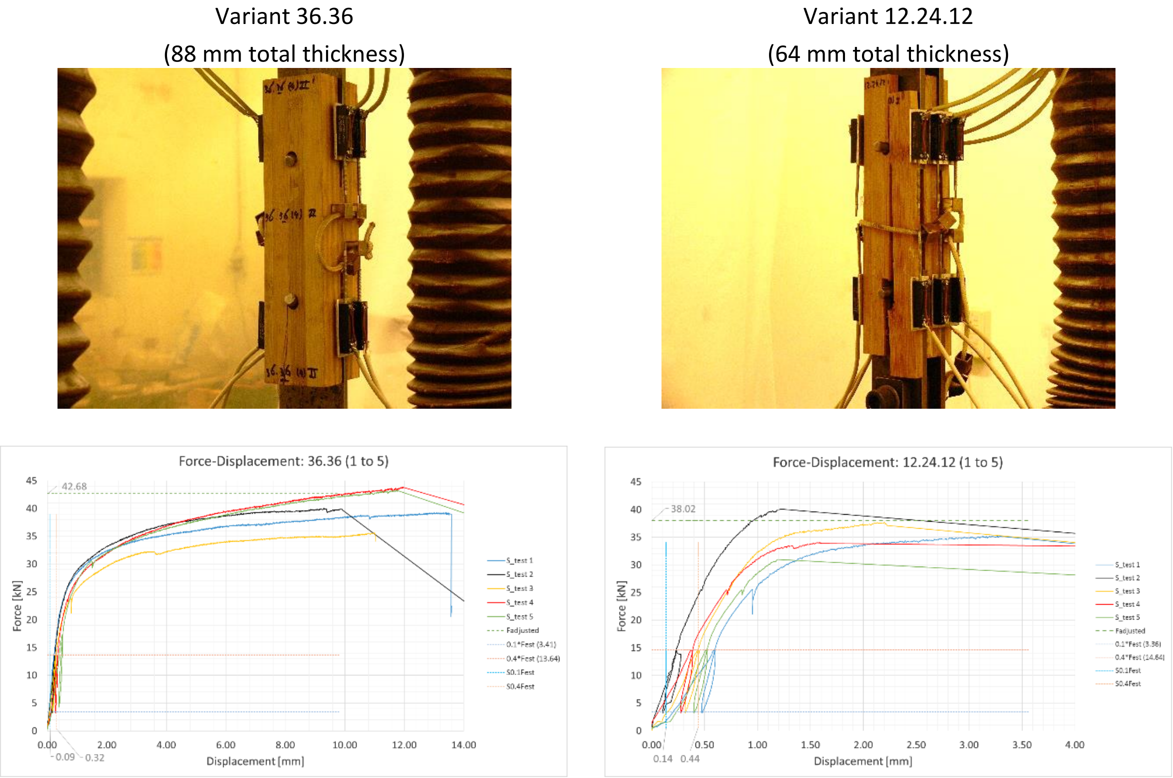
$$v_{12.144.12,mod} = \frac{4}{3}(v_{0.4F_{est}} - v_{0.1F_{est}})$$

$$k_{s,12.144.12} = \frac{0.4F_{est}}{v_{12.144.12,mod}} = \frac{24.72 * 10^3}{\frac{4}{3}(0.44 - 0.13)} = 61800 \frac{N}{mm}$$

Conclusively two can be said. The first being that, when placing multiple slotted-in plates in a connection, it is best to ensure every member will display the same failure load. The second being that, when making a connection consisting of different failure modes, keep the different deformation capacities in mind and place the plates such that, after failure, the slotted-in plates are still loaded in plane (in this case placing the thin members in the middle).

11.4.3 Multiple slotted-in plates with constant connection thickness

Sometimes when designing a connection only limited space is available to make the connection stronger. Increasing the amount of slotted-in plates within the same connection without changing the dimensions of the members that will be connected could be beneficial to the capacity of the connection. To illustrate this, a comparison between variants 36.36 and 12.24.12 is made on the basis of the pictures and force-displacement diagrams given in Figure 94 - **Multiple slotted-in plates in similar connection thickness**.


Variant 36.36
(88 mm total thickness)

Variant 12.24.12
(64 mm total thickness)

Figure 94 - Multiple slotted-in plates in similar connection thickness

In the above figure the two variants are shown that had the most similar total connection thickness. The measured capacity for variant 36.36 was 42.68kN and the stiffness is calculated below.

$$v_{36.36,mod} = \frac{4}{3}(v_{0.4F_{est}} - v_{0.1F_{est}})$$

$$k_{s,36.36} = \frac{0.4F_{est}}{v_{36.36,mod}} = \frac{13.64 * 10^3}{\frac{4}{3}(0.32 - 0.09)} = 44478\frac{N}{mm}$$

With its thickness of 64mm, variant 12.24.12 is 24mm smaller (27.3%). The capacity measured from this variant is 38.02kN. Which is only 12.3% lower. So, relative to the thickness of the connection, a variant with two slotted-in plates does have a higher capacity. This high relative capacity does however have a negative influence on the deformation capacity. Instead of having variant 36.36's failure mode 2 with an average of 11mm deformation before failure, variant 12.24.12 shows failure mode 1 with an average deformation capacity of 1.5mm. The choice to increase the capacity of a connection thus depends on the situation and the safety requirements of the structure. For future research it might be interesting to compare the effect of multiple slotted-in plates on the strength and deformation capacity using the exact same connection thicknesses.

Part 3:

Final comments and recommendations

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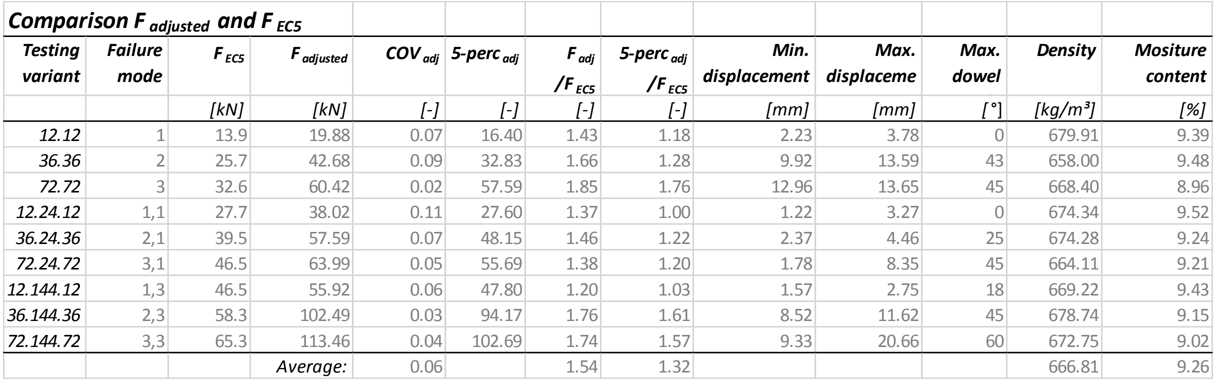
12 Final comments

This chapter will give a short overview of the observations and conclusions made during testing and the test result analysis.

12.1 Predicting the capacity of laminated bamboo connections using timber design principles from EC5.

After testing, samples of all test specimens were taken and dried in an oven to determine the moisture content. From measurements performed on the whole specimens and those samples, the density of the material was found to be 666.81kg/m³ and the moisture content 9.26% on average. With these values the expected capacity of the test specimens was recalculated using EC5 formulas and compared to the adjusted capacity of each testing variant. This is shown in Figure 95 - **Expected and measured capacities**.



Comparison $F_{adjusted}$ and F_{EC5}

Testing variant	*Failure mode*	*F_{EC5}*	*$F_{adjusted}$*	*COV_{adj}*	*5-perc $_{adj}$*	*F_{adj} /F_{EC5}*	*5-perc $_{adj}$ /F_{EC5}*	*Min. displacement*	*Max. displaceme*	*Max. dowel*	*Density*	*Mositure content*
		[kN]	*[kN]*	*[-]*	*[-]*	*[-]*	*[-]*	*[mm]*	*[mm]*	*[°]*	*[kg/m³]*	*[%]*
12.12	1	13.9	19.88	0.07	16.40	1.43	1.18	2.23	3.78	0	679.91	9.39
36.36	2	25.7	42.68	0.09	32.83	1.66	1.28	9.92	13.59	43	658.00	9.48
72.72	3	32.6	60.42	0.02	57.59	1.85	1.76	12.96	13.65	45	668.40	8.96
12.24.12	1,1	27.7	38.02	0.11	27.60	1.37	1.00	1.22	3.27	0	674.34	9.52
36.24.36	2,1	39.5	57.59	0.07	48.15	1.46	1.22	2.37	4.46	25	674.28	9.24
72.24.72	3,1	46.5	63.99	0.05	55.69	1.38	1.20	1.78	8.35	45	664.11	9.21
12.144.12	1,3	46.5	55.92	0.06	47.80	1.20	1.03	1.57	2.75	18	669.22	9.43
36.144.36	2,3	58.3	102.49	0.03	94.17	1.76	1.61	8.52	11.62	45	678.74	9.15
72.144.72	3,3	65.3	113.46	0.04	102.69	1.74	1.57	9.33	20.66	60	672.75	9.02
			Average:	0.06		1.54	1.32				666.81	9.26

Figure 95 - Expected and measured capacities

The design formulas and values used to determine F_{calc} are the following:

- Resistance per shear plane per dowel $F_{v,Rk}$ according to (NEN-EN 1995-1-1+C1+A1:2011).
- $M_{y,Rk} = 0.3 * f_{u,k} * d^{2,6}$ according to (NEN-EN 1995-1-1+C1+A1:2011).
- Dowel diameter 12mm with $f_y = 537N/mm^2$ and $f_{u,k} = 601N/mm^2$ obtained from dowel tensile tests.
- $f_{h,k} = 0.082 * (1 - 0.01 * d) * \rho_k$ as given in (NEN-EN 1995-1-1+C1+A1:2011).

The capacity of each variant was determined by taking the average of the maximum measured resistance of all 5 test specimens per testing variant. This average resistance was then adjusted to approximate a value that represents also the non-failed connections $F_{adjusted}$. The shown 5-percentile values are calculated using the adjusted test results.
In the figure the ratio $\frac{F_{adjusted}}{F_{EC5}}$ is given. From this ratio can be seen that the test specimens had a maximum capacity that was on average 54% higher than calculated using EC5 and an average COV of 6% in the test results. Looking at the ratio of the variants individually, every variant had a higher capacity than calculated using EC5. When comparing the ratio between EC5 and the test values between the variants, some variants were found to be a lot stronger relative to others. All of these strong variants had members displaying failure modes 2 and 3. This large deviation is could partly be caused by a larger than anticipated embedment strength of the material. As to why all failure mode 1 variants fail at a relatively lower capacity, the minimum end distances prescribed by EC5 could have caused the connections to prematurely split before the ultimate strength was reached. However, more research will be needed to fully understand the effect of increasing the end distance for connections in laminated bamboo.
The ratio of variant 12.144.12 stands out for being the lowest. Meaning that the test specimen was relatively weaker than all others. An anomaly caused by a less than optimal placement of the slotted-in plates.

12.2 Using multiple slotted-in plates

The effects of implementing multiple slotted-in plates have been investigated in three different ways.

12.2.1 Capacity increase for multiple slotted-in plates by widening a connection

The effect of making a connection bigger and applying more than one plate was investigated by comparison of variants 12.12 and 12.24.12 (failure mode 1) and 72.72 and 72.144.72 (failure mode 3).
Both variants with two slotted-in plates showed a large capacity increase relative to the variants with only one slotted-in plate. However, this capacity increase was not equal to double the capacity of one slotted-in plate. Two slotted-in plates were found to be weaker than two single slotted-in plates.
When comparing the strength ratios for one and two slotted-in plates a similarity was found. Even though only five test specimens per variant were tested, the strength ratio of two versus one slotted-in plates were found to be almost equal for both failure mode 1 as for failure mode 3.

$$\frac{R_{12.24.12}}{R_{12.12}} = \frac{R_{72.144.72}}{R_{72.72}} = \frac{R_{2\;slotted-in\;plates}}{R_{1\;slotted-in\;plate}} = 1.9$$

The similarity of these ratios means that most likely an effective number of slotted-in plates has to be considered when making a connection with more than one plate. The capacity increase for two slotted-in plates seems to be 90%. It would be beneficial to confirm this value by testing a larger amount of test specimens.

12.2.2 Plate placement

The effects of plate placement are of interest when different failure modes can be expected in a connection. When a different failure mode occurs at both sides of a slotted-in plate, the location of these failure modes has an effect on the capacity of the connection. During testing was found that when a failure mode of a lower deformation capacity was put on the outside of the connection, the load bearing capacity can be lower than anticipated. The lower deformation/strength capacity of a failure mode determines the sequence in which the various members will fail. If such a failure mode is put on the outside of the connection, the corresponding timber member loses a large amount of its resistance to keep the slotted-in plate in place. The slotted-in plate will then be free to move or slide over the dowel. This will cause a situation in which the slotted-in plates could be loaded out-of-plane, something for which they are usually not designed. The most likely scenario in this case is that the slotted-in plates will bend and the dowels will ultimately slide out of the plates resulting in a sudden failure of the connection.
To fully utilise the resistance of both the bamboo/timber members and the slotted-in plates the failure modes with the lowest capacity should be placed in-between two slotted-in plates. So that, when the first member fails, the slotted-in plates can still find horizontal support and the connection remains intact.

12.2.3 Increasing the amount of slotted-in plates within a connection

Through comparison of variants 36.36 and 12.24.12 was found that applying more than one slotted-in plate in a connection without changing the thickness of that connection, can have a beneficial effect on the maximum capacity of the connection. Variant 36.36 made use of one slotted-in plate and had a total connection thickness of 88mm (failure mode 2). Variant 12.24.12 made use of two slotted-in plates and had a total connection thickness of 64mm (failure mode 1). The two slotted-in plate variant was 27.3% smaller and had only 12.3% lower capacity. So, in relation to connection thickness, the use of multiple slotted-in plates in combination with smaller timber/bamboo members in between can be more efficient than a traditional single slotted-in plate. The increase in capacity can however have a negative impact on deformation capacity. In this case a mode 2 variant with an average deformation capacity of 11mm was transformed to a mode 1 variant of only 1.5mm deformation capacity. The application of multiple slotted-in plates to increase connection strength should thus only be done after consideration of this effect.

13 Recommendations

For future research and implementation of laminated bamboo in structures the following recommendations are made. The recommendations made here are based solely on findings and encounters made during the course of this research.

1) **Order dowel samples from different steel grades prior to making a test piece design.**
   When designing the test pieces a dowel of S355 was envisaged. During the literature study into the design formulas was found that the delivered dowel is most likely to be a lot stronger than the ordered dowel. On the basis of findings during previous researches at TU Delft, like (Sandhaas, 2012), (Islamaj, 2009) and (Hieralal, 2006), a deviation in dowel capacity was incorporated into the test piece design. After doing tensile tests, the ordered S355 dowels turned out to have a yield strength of 537N/mm². A deviation of 51.3%. Since the supplier of the dowels is only obligated to supply a dowel of a minimum yield strength (in this case 355N/mm²) a deviation like this can always be expected when ordering dowels and other steel products. To avoid unforeseen situations and to properly design test pieces of a certain expected capacity, it is recommended to order a series of samples of dowels from different steel grades prior to designing the test pieces. By performing tensile tests on the dowel samples, the correct dowels can be incorporated into the design.
2) **Connect the individual members of test pieces.**
   During testing of failure modes 2 and 3 some test pieces started warping. This was caused by the two connections failing in different members (e.g. upper connection in member 1 and lower connection in member 2). This warping of the test pieces caused a large increase in deformation without an increase in loading and was not a realistic failure mechanism. Since in reality a slotted-in plate is inserted in a slot made within a beam, the two members at each side of the plate are prevented from displacing relative to each other. When making a test piece that consists of individual members this prevention of relative displacement also needs to be incorporated. In this research this was done by gluing a piece of laminated bamboo in the middle of the test piece between the two individual bamboo members.
3) **Testing one connection per test piece.**
   In this research it was tempted to lower the amount of test pieces and needed materials by making two exact same connections per test piece. When the maximum capacity of one of these connections was reached the test piece would fail. The measured capacities therefore only consisted of the weak half of all connections. The actual values for the capacity and standard deviation were approximated by use of a found relation. This approximation method for symmetrically loaded test pieces only applies when shown that the test results can be considered normally distributed.
   To acquire the exact characteristic values of the tested material an intentional weak point has to be made so that only one test result per test piece is measured. To achieve this one connection in a test piece needs to be designed stronger than the other. If this is done correctly then also the observed warping of the test pieces can be prevented.
4) **Testing the embedment strength and necessary end distances of laminated bamboo.**
   Test specimens for failure mode 2 and 3 had higher capacities than expected on the basis of design formulas and failure mode 1 specimens did not. This could be caused by a larger embedment strength than calculated in combination with the minimum end distance from EC5 being too low. This results in failure mode 1 splitting and shearing out before reaching the embedment capacity of the material and failure modes 2 and 3 having larger than calculated capacities. To support this theory and to possibly improve the calculated capacities, embedment tests and end (and edge) distance tests should to be performed.
5) **Testing of multiple slotted-in plate connections and possible effective number of plates.**
   From the test results it appears that a connection using two slotted-in plates does not have double the capacity of a single slotted-in plate. The ratio of the capacity increase for two plates was found to be rather

constant. This could imply that, like multiple dowels in a row, using multiple slotted-in plates will not yield a simple multiplication of the capacity. An effective number of plates needs to be considered. This effect was found by comparing failure mode 1 variants 12.12 and 12.24.12 and failure mode 3 variants 72.72 and 72.144.72.

To further examine the effects of multiple slotted-in plates future research could be done on those same variants using more test specimens to reduce the variation in test results. An extension could be made by testing also three slotted-in plate variants as 12.24.24.12 and 72.144.144.72, different materials and a variation of dowel diameters. From those test results an exact effective number could be deduced.

6) **Multiple slotted-in plates with constant connection thickness.**

Instead of increasing the connection thickness by adding more bamboo members when increasing the amount of slotted-in plates, the connection thickness can also be kept constant. The extra capacity of adding another slotted-in plate without tempering with the connection thickness can provide a stronger connection while still preserving the structures' slenderness. To study the effects of multiple plates with constant total connection thickness the two variants were compared that had the most similar total connection thickness. The comparison showed that adding more slotted-in plates can increase the capacity of the connection but it can also change the occurring failure mode, which decreases the deformation capacity. To study these effects more closely, tests need to be conducted in which one constant total connection thickness (tested material + slotted-in plates) is tested with a variation in the amount of plates slotted into the test piece.

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