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DOWEL TYPE CONNECTIONS IN LAMINATED BAMBOO WITH MULTIPLE SLOTTED-IN STEEL PLATES

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ABSTRACT: Laminated bamboo can be produced in sizes that are similar to glued laminated timber. As a result, large connections with multiple dowels and slotted-in steel plates are similarly possible with bamboo. MOSO bamboo was used in this study, with a density of around 660 kg/m^3, potentially creating connections having higher load carrying capacity than softwood. A large experimental campaign was set-up in order to determine the mechanical properties of connections with various ratios of dowel diameter to bamboo thicknesses and with single and double steel plates. Furthermore, influences of the density of the material, related to the embedding strength for fasteners, as well as the splitting sensitivity with multiple fasteners in a row are playing crucial roles with respect to the load carrying capacity. Therefore, multiple test series on large bamboo connections have been performed in order to study various possible failure modes, as dependent on embedding strength, steel grade, number of fasteners in a row, and the influence of multiple steel plates. The various failure modes have been analysed analytically with the Johansen equations, similar to the design equations proposed for the upcoming version of Eurocode 5 for multiple steel plate connections, confirming their applicability to bamboo and its similarity with wood.

KEYWORDS: bamboo, connections, failure modes, slotted-in steel plates, multiple fasteners, CT-Scanning.

1 – INTRODUCTION

Laminated bamboo can be produced in sizes which are similar to glued laminated timber. Moso is the Chinese word for the bamboo species "Phyllostachys edulis" and growths widely in East-Asia. Together with the species Guadua, it has considerable potential as structural material for building applications. However, it has to be processed from the original round and hollow bamboo sections, into a rectangular product for efficient glulam type structures. For that, the bamboo culms are splitted, flattened, lengthwise connected via hook joints, and consequently flatwise and edgewise glued into a full size beam, see Figure 1. The full size beams allow for large connections with steel dowels and slotted-in steel plates.

Bamboo has many similarities with wood and as such, is highly anisotropic. However, as it lacks radial growth it may be more vulnerable to splitting, so possibly not all design rules that are valid for wood can be used for bamboo without modification. As the fibre structure in bamboo is generally more straight, and no rays are present that may reinforce wood in the perpendicular direction, it could be more vulnerable to splitting as well. While the material itself has been widely studied, heavy structural connections with multiple fasteners in a row, or with multiple parallel steel plates have not been analysed yet in great detail as far is known to the authors, possibly also because design rules for large bamboo connections are partly lacking in design codes and applications in

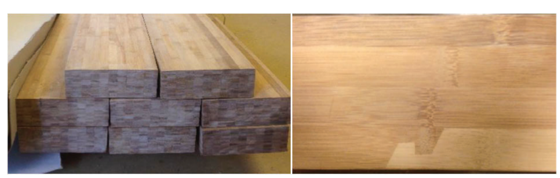

Figure 1. Cross section of laminated bamboo beam (left) and face showing a bamboo strip with hook joint (right).

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large quantities are not yet sought after. Therefore, a large experimental programme was set-up to determine the properties of bamboo connections made from large laminated bamboo cross sections, of which the end grain with the identifiably bamboo strips and the face with a longitudinal hook joint in one of the strips are shown in figure 1.

The research was divided into two major parts. One part focused on the effect of multiple dowels in a row, in order to determine the effective number of fasteners n_{eff}, whereas the second part focussed on the load carrying capacity of connection with one or two slotted in steel plates [1],[2]. Consequently, in this work, two main research questions have been formulated:

1) What is the effective number of fasteners in a row a bamboo connection with a slotted in steel plate and 12 mm steel dowels, and is this similar to timber?

2) What are the failure modes that may develope in a connection with multiple slotted in steel plates, with various ratios for the middle and side member thickness respectively?

Regarding the first research question, bamboo may behave differently compared to wood. In fastener loading parallel to the grain, splitting may occur prematurely when compared to wood, and consequently the load carrying capacity of single dowels in bamboo could be lower compared to wood for the same density and geometry conditions. Similarly, for multiple fasteners in a row, the effective number of fasteners n_{eff} in bamboo could possibly be lower than that of wood. At the same time, bamboo has its own inhomogeneities that may cause volume effects when the strips of bamboo are processed and glued into a the final laminated bamboo product.

The second research question relates to the fact that failure modes for connections with multiple steel plates are not often studied. Even though symmetry assumptions may lead to theoretical derivations, experimental validation is complex and quite expensive as the required specimens and test set-up become quite large. The second test series was therefore set-up to test the boundaries between plastic and brittle failure modes for a number of configurations, either on the side members or in between the steel plates. This would also lead to more generic knowledge also for similar shaped timber joints as many research questions have still not been sufficiently addressed or clarified.

2 – MATERIALS AND CONNECTION DESIGN

2.1 MATERIALS

Bamboo was provided by MOSO Bamboo BV, Zwaag, the Netherlands. The density of the bamboo was determined after conditioning at 20±2°C and 65±5% relative humidity and attaining constant mass in accordance with ISO 3131 [17]. The mean density was determined at 681 kg/m^3 with a COV of 3.3%, so very homogeneous. The characteristic density was determined at 638 kg/m^3, assuming a standard normal distribution.

2.2 BAMBOO CONNECTIONS

The connections with the slotted-in steel plates have been designed using the minimum required spacings for timber joints with steel dowels from Eurocode 5 [13}. This was done primarily to obtain comparable load-displacement curves for bamboo and obtain relevant information about the possible risk of splitting and whether this risk could be higher than that of timber, at similar steel fastener material as well as spacings. Should splitting of bamboo occur prematurely during testing, spacings used in Eurocode 5 for timber might have to be adapted to better fit the behaviour of laminated bamboo.

All connections were manufactured in the wood shop of Delft University, and tested with smooth 12 mm steel dowels, steel grade S235 as ordered. As the strength of the steel dowels is important for the development of plastic hinges in the cross section, the steel tensile strength was measured in a tensile test and was found to be 537 MPa, which was further used during the design and analysis.For the analysis of the effective number of fasteners in a row, the test scheme as shown in figure 2 was developed. Member thicknesses were varied between 15 and 90 mm with 1, 2 and 3 fasteners in a row for the single steel plate connections. The sizes were chosen with the focus on failure modes with straight dowels in thin bamboo, as well as the two failure modes where plastic hinges in the dowels could develop.

For the second series the goal was to obtain various failure modes in connections with two parallel steel plates. Depending on the distance in between the steel plates, the bamboo in the center part may fail brittle by plug failure. On the other hand, when the plates are sufficiently far apart, the dowel may deform plastically in the center part by developing one or two plastic hinges. Similarly, on the outside of the steel plates, brittle bamboo failure may occur when those parts are thin, or plastic hinges in the dowel may occur when sufficient bamboo thickness is available.

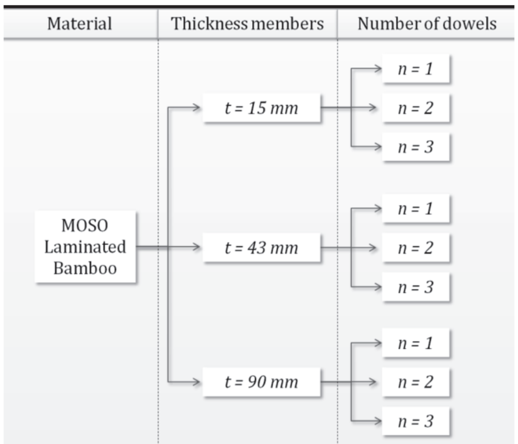

Figure 2. Test scheme for determination of the effective number of fasteners in a row for a single steel plate.

For a dowel diameter of 12 mm, end spacing becomes $7d = 84mm$, fastener spacing along the grain becomes $5d = 60mm$, while minimum edges are $3d = 36mm$. The 3 thicknesses given in Figure 2 should then trigger the 3 possible failure modes of the fastener with 0, 1 or 3 plastic hinges. Slenderness ratios t/d of the dowels varied consequently between 1.25 for the stocky dowels, 3.6 for the medium dowels and 7.5 for the slender dowels.

For the double steel plate specimens, failure modes were derived focusing particularly on the middle part. When the middle part is thin, only embedding will take place, without plastic hinges developing. However, when the centre part is wide, it should be possible for the dowel to develop plastic hinges also there. The thickness of the steel plates was 8 mm, designed in accordance with EN 1993 [4]. In Figure 3, the general lay-out of such a connection is given. The various possible failure modes are presented in figure 4, depending on the ratio between side members and middle member, and the spacing between the steel plates. Only single dowels in multiple shear passing through the complete cross section were tested for the double steel plates variants.

The sizes t_s - t_c - t_s for the bamboo were the following for thin central member: 12-24-12, 36-24-36 and 72-24-72 mm, whereas for the thick central member the sizes were 12-144-12, 36-144-36 and 72-144-72mm respectively. With the dowel diameter set at 12 mm, it was anticipated that both brittle and plastic failure modes could be obtained.

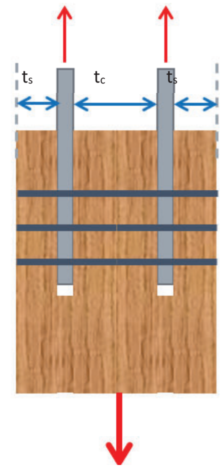

Figure 3. Principle of test specimen to determine possible failure modes with various steel plate spacings t_{side} and t_{centre} and effective number of fasteners in a row (1, 3 or 5).

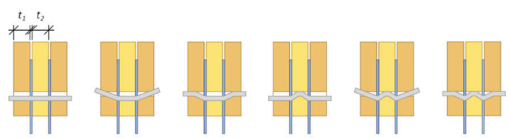

Figure 4. Possible failure modes in joints with two parallel slotted-in steel plates (single dowel)..

2.3 EMBEDDING STRENGTH

For the theoretical approach of the expected load carrying capacities of the various types of connections, values from Eurocode 5 and background knowledge were used for the embedding strength. Eurocode 5 presents an Eq. (1) for the calculation of the characteristic embedding strength, where the embedding strength depends on the diameter of the dowel and the characteristic density of the timber.

$$f_{h,0,k} = 0.082(1-0.01d)\rho_k \quad (1)$$

Here, considering that test results should yield values around the mean value of the embedment strength, equation (2) is used, based on an analysis of Ehlbeck and Werner [5], as well as Van de Kuilen and De Vries [6] and Sandhaas et al. [7-10]. The equation is the result of a regression analysis of embedment test results on various wood species with densities from 300 to 1100 kg/m^3 as well as 12 and 24 mm diameter and reads:

$$f_{h,0} = 0.102(1-0.01d)\rho_{mean} \quad (2)$$

It was assumed that a calculation with the average density, using (2) would give a reliable result for the embedment strength of bamboo.

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A similar approach was taken for the load carrying capacity of the bamboo connections. After performing tests with a range of soft- and hardwoods, various steel grades and geometries [6-10], it was decided to assume also the European yield model for the preliminary design of the bamboo specimens. Similarly for the connections with 2 slotted in steel plates, Fig. 3 and 4. However, for the multiple slotted in steel plates, only single dowelled tests were performed as the main goal was to verify whether the expected failure modes of the dowels would actually occur in bamboo and how the splitting and failure behaviour could differ from wood.

3 – TEST SET-UP AND PROTOCOL

All tests were performed in the Stevin 1 laboratory of the Faculty of Civil Engineering at TU Delft. The laboratory is climatized at the reference temperature of about 20°C and 65% relative humidity. The test set-up is shown in Figure 5, with a connection having a single steel plate. All connections were tested in accordance with the procedure of EN 26891 (ISO 6891) based on [3]. The values for the maximum load F_{max} were estimated on the basis of mean material property values using the equations of EN 1995-1-1.

4 – RESULTS AND DISCUSSION

4.1 EMBEDDING STRENGTH

The embedment strength is estimated to be 64 N/mm^2 by calculating the embedment stress from test series 1 where two laminated bamboo members with a thickness of 15 mm each and a central 2 mm thick steel plate were applied while no dowel bending was observed. This is an estimation as no dedicated embedment test according to EN 383 [11] were performed in this case. The plastic branch in the load slip diagram of this test series makes it assumable that this is an acceptable prediction of the embedment strength. Based on this finding it seems that the equation for calculating the embedment strength given by Eurocode 5 only slightly underestimates the embedment strength of laminated bamboo. On the basis of Eq. (1) a value of 61.1 MPa is obtained which is just 4.7% lower. Considering the non-standard test in comparison to EN 383, this is considered a negligible difference. It is also in the range of scatter that is found in tests in wood over a range of densities [9].

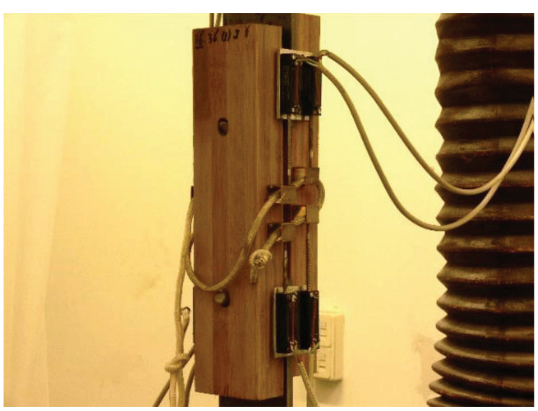

Figure 5. Bamboo joint with centre steel plate in the test set-up.

4.2 FAILURE MODES AND BEHAVIOUR FOR SINGLE SLOTTED-IN STEEL PLATES

Single slotted in steel plate joints gave good agreement between theory and experiment. Failure modes varied from shear plug under the dowel for the stocky dowels to dowel yielding with two plastic hinges for the slender ones. Examples of dowel deformation after the test are shown in Figure 6 for medium and slender dowels, confirming the expected failure modes.

The effect of a number of fasteners in a row becomes visible especially at the level of the stocky dowels, resulting in an increased risk of brittle failure. Stocky dowels will generate shear plug type failures between the fasteners (provided side distances and end distance are large enough). The first question is if there is a reduction in load carrying capacity per fastener if there are more fasteners in a row. For failure mode 1, the mean load carrying capacity increases from 23 kN to 48kN and 58kN for 1, 2 and 3 fasteners in a row respectively, indicating 2.53 effective fasteners when n = 3. For failure mode 2, these values are 44 kN, 71 kN and 108 kN respectively, and for failure mode III 55 kN, 89 kN and 139 kN respectively. In both cases the n_{eff} related is again about 2.5, indicating that an increase of n_{eff} because of a increased plastic capacity of the individual fasteners is not present in this case. The influence of the number of fasteners in a row is also noticeable from the maximum deformation reached at F_{max} for the three failure modes. As expected, for failure mode 1, the maximum slip is

Figure 6. Mode 2 and 3 failure of the dowel, confirming the expected failure mode for connections with a single slotted in steel-plate..

related to brittle failure and reaches values between 1.6 and 3.3 mm for a single fastener connection, which decreases to 1.5 to 2.3 mm for both 2 and 3 fasteners in a row. For failure mode 2, single fasteners reach maximum displacements between 7 and 15 mm, while for mode 3 this range is between 10 to 15 mm. In both these cases, the plastic behaviour reduces drastically when 2 or 3 fasteners in a row are present, with failure mode 2 being more affected than failure mode 3. Failure mode 3 probably has more internal redistribution capacity than failure mode 2, and consequently the scatter in u_{max} values reduces. The values of u_{max} for failure mode 3 with 3 fasteners in a row are reduced to 3 – 6 mm, so considerably smaller than for the single fastener connection. The behaviour with respect to the number of fasteners in a row shows a great resemblance to that of timber [6],[7]. It means that consequences and considerations for the treatment of data regarding modelling of load-slip curves and connections in general that go beyond the scope of this paper, could probably be done in a similar manner as done normally for wood, see p.e.[15],[16].

4.3 FAILURE MODES FOR DOUBLE SLOTTED-IN STEEL PLATES

The obtained failure modes followed primarily the expactations from the yield model approach. As an example, the results of the 2 larger sample sizes are presented, with a centre member of 144mm and side members of 36mm and 72mm respectively. The expected

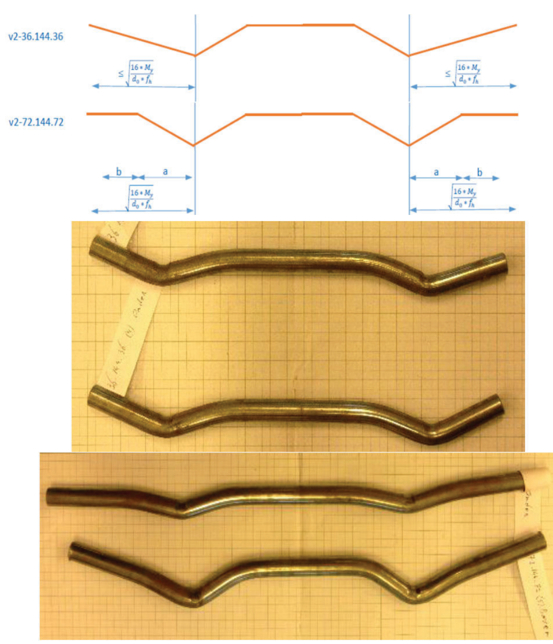

Figure 7. Predicted shape and experimental result of deformed fasteners in double slotted-in steel plate connections

failure modes would lead to side members of 36 not exhibiting a plastic hinge in the fastener, whereas the 72mm would have. The expected and realized failure modes are combined in figure 7. The upper red lines indicate the expected deformation shape for the connection with 36 mm side members, whereas the lower red line shows the expecetd deformation for 72 mm side member thickness.

The lower two steel dowels in Figure 8 were taken out after testing, and are a good example for the variation in maximum displacements that can be obtained. Both

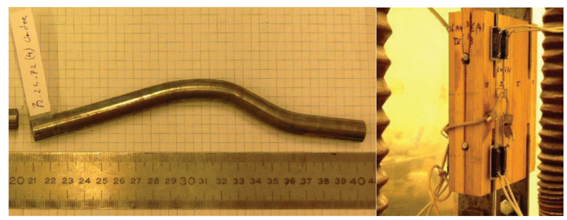

Figure 8. Non-symmetrically failed dowel from a double slotted-in steel plate connection.

fasteners show plastic hinges in the side members, even though they clearly have different angles. This angle difference is hoever caused by the rotation in the plastic hinges at the location of the steel plates, which in the lower dowel is far larger.

This picture is taken from a test piece with thick side members and a slender centre piece: 72.24.72. It can be seen that on one of the two sides failed before a proper plastic hinge in the dowel could be formed as would be expected from the theory. 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 59.1kN this specimen was the weakest of the series, but only marginally compared to the average of entire variant but it was only slightly lower than the average of 62.1kN. However, it shows that the case in which geometries and materials used in a connection in a way that the load carrying capacity is near or at the boundary between two failure modes, a small difference between the embedding strength of the bamboo on the two sides of the specimen may trigger a ´mixed´ failure mode.

4.4 DENSITY AND LOAD CARRYING CAPACITY

The density of the material was measured for all connection components, in order to see any relationship with the load carrying capacity. The results are combined

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in Figure 9 for all single slotted steel plate connections, relative to the mean of each series.

If a failure of a connection was caused by only one of the two bamboo components, only that density was used, if the failure of both members was observed, both values were plotted. The latter would have a similar effect as taking the average of those two components. No correlation could be found between density and load carrying capacity of the bamboo joints, confirming previous research on several wood species (i.e. spruce, beech and azobé) by Sandhaas [10] and Van de Kuilen [12].

4.5 CT-SCANNING

As the results of various tests gave rise to further study the influence of the density variations of the bamboo inside the single specimens, some of the tested specimens were analysed using a CT-Scanner. Bamboo itself has a considerable density gradient over the culm, which can vary between 500 and 800 kg/m^3. This might end up influencing the density variations inside the member components. At the same time, a densification process below the fastener will take place during a test. In Figure 10, a CT-Scan of the density variation is after a test is shown. Not only is the densification under the fastener clearly visible, also the density variation of the bamboo strips is clearly identifiable.

Figure 10). Density variation over a cross section around a deformed dowel. The densification on the lower left side and upper right side is where the dowel crushes the bamboo fibres.

Whether such a density variation actually influences the load carrying capacity remains to be seen, as the bamboo strips are small compared to the member sizes and it may be expected that the average density is actually representative for the global connection behaviour. In other words, it will be very hard to show statistically that such density variation can be attributed to a relevant connection property.

4.6 STIFFNESS OF THE CONNECTIONS

For the stiffness of the connections, a similar comparison regarding the design equation as given in Eurocode 5 was planned. In Eurocode 5, the stiffness k_{ser} is given as a function of material density and dowel diameter:

$$k_{ser} = \frac{\rho_m^{1.5} d}{23} \quad (3)$$

with density ρ in kg/m^3, diameter d in mm and k_{ser} in N/mm. As a number of specimen was prepared with the wrong sizes, an additional series could be tested with four fasteners in a row, so for this analysis, connections were available with up to 4 fasteners in row. On the one hand, the influence of density on the slip modulus was analysed, on the other hand the calculated or expected slip modulus ws compare with the measured slip modulus. The results of these two types of analysis are shown in figure 11 and 12 respectively.

From both figures a clear discrepancy between

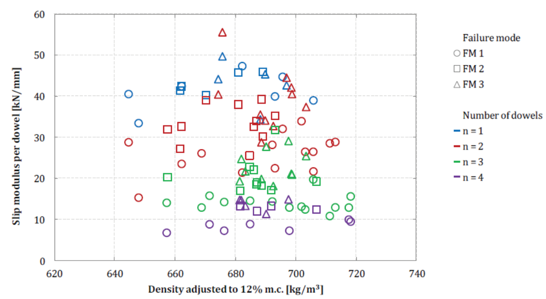

Figure 11. Influence of density on fastener slip modulus

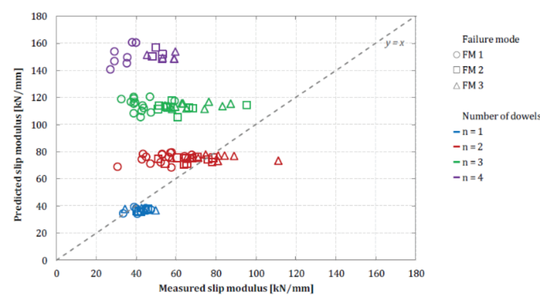

Figure 12. Measured slip modulus vs. Predicted slip modulus

experimental results and predicted results. There is no visible influence of the bamboo density on the slip modulus. For the measured slip modulus versus predicted slip modulus, there is a reasonable relationship for connections with one or two dowels, but no increase in slip modulus is found for three or four dowels. It might be that, as the slip is determined from relatively low load levels, within the specimens there is still room for displacement for some dowels, where other dowels are already fully employed, i.e. being tight with the circular hole, allowing considerable load transfer. Also in this

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case, observations made in [10], where dowelled connections with 1, 3 and 5 dowels in a row were studied with wood species covering a density range of 350 to 1200 kg/m^3, are basically confirmed.

5 – CONCLUSIONS AND RECOMMENDATIONS

From the results it may be concluded that proposed rules in Eurocode 5 for connections with multiple slotted in steel plates can equally be applied to large cross section joints made with bamboo. The effective number of fasteners in a row

The density is used for the calculation of the embedding strength and results in an accurate estimate as confirmed by tests which were similar to experimental tests according to EN 383. The load-carrying capacity of complete connections loaded in tension is, however, independent of the density of the bamboo, confirming similar findings in timber connection studies.

In addition to the load carrying capacity, it was confirmed that also an effect on the stiffness of the number of fasteners in a row is present, a conclusion that was also found for timber connections with high strength steel dowels in [10]. This effect should be incorporated in design codes to make the designs more accurate.

Regarding the combination of multiple slotted-in steel plates with multiple fasteners in a row, no experiments were performed. At the same time, the results of this paper indicate a great similarity in behaviour between bamboo and wood for the configurations studied here. However, other failure modes than those analysed could possibly occur, especially in very large connection with multiple steel plats and multpile fasteners in a row. In such cases, bamboo could reveal different behaviour compared to timber. Block shear failure could be such a case as both shear and tensile failure may occur in a brittle manner and crack formation can be local at first. Such complex and multiple stress states require careful consideration, not only in testing but also when the testing is supported by finite element simulations of the connections that integrate damage and failure modelling [18].

6 – ACKNOWLEDGEMENTS

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AUTHORS' CONTRIBUTIONS:

J.W.G. van de Kuilen: conceptualization, organization and management of research, funding, paper writing;
P.A. de Vries: conceptualization, design and engineering of the test set-up, laboratory management, data acquisition and quality control;
J.J.B. Debije: execution of research and writing, organisation;
J.H.P. Hover: execution of research and writing, organisation;
W.F. Gard: organization and management, funding, bamboo and CT-scanning;
G.J.P. Ravenshorst: conceptualization, design and engineering of the test set-up, management.

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