Lightweight Bamboo Double Layer Grid System

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Abstract:

The paper presents the structural and environmentally sustainable aspects of bamboo as a valid construction material. A special PVC joint designed for bamboo double layer grids (DLG) is presented and implemented in a 2.3x2.3x0.9m DLG module. Experimental results obtained from evaluating two bamboo species, proof loading of the proposed PVC joint and loading of the DLG module are presented and compared to numerical predictions. The results indicate that the proposed DLG system can be used in practice for constructing lightweight medium-span bamboo structures with excellent structural, aesthetic and environmental attributes.

Keywords: Bamboo, PVC joint system, Double-layer grid, lightweight structures

1- Introduction:

Bamboo is characterized as a renewable, biodegradable and energy efficient natural resource with a great potential as an environmentally sustainable building material. The rapid depletion of natural forests makes bamboo a viable alternative to timber. Bamboo grows around 15-18 cm/day and reaches its full height in 4-6 months. It can be harvested within 3-5 years of growth compared to 20-40 years for timber. It has excellent strength to weight ratio compared to conventional materials such as timber, steel and concrete. Table 1 gives a comparison of the structural attributes of bamboo vis-à-vis other conventional materials [1]. It is clear that bamboo is comparable to steel in terms of strength and stiffness efficiency while the production energy required for bamboo (per m^3) is only 0.1% of that required for steel. On average bamboo culms can reach 8-15m length, 5-12cm diameter with wall thickness 5-10mm, a tensile strength around 100MPa and compressive strength about one third the tensile. There are over 1000 species of bamboo and for certain species a tensile strength of 370MPa was reported [2]. Mechanical properties of bamboo are influenced by the bamboo's moisture content.

Traditionally bamboo has been used in rural housing and scaffolding in South-East Asia and South America. Conventional lashing techniques are usually used for joining bamboo. The use of bamboo in construction has been hindered by the lack of practical and reliable engineered joint systems. In recent years some research work has been carried out on developing new joint systems for bamboo such as plywood inserts, wooden plugs, steel clamps and aluminium plates [3,4]. The establishment of the International Network for Bamboo and Rattan (INBAR) in 1997 contributed to the renewed interest in research on bamboo [5].

2- Assessment of the Structural Characteristics of Two Bamboo Species:

Two locally available bamboo species were sourced to evaluate their compression, bending and buckling capacities. The two species are Phyllostachy Bambusoides (PB) and Phyllostachy Pubescens (PP) commonly known as Mao Jue. The culms used were 3-

6 years old, 50-65mm external diameter and over 1.5m length. A total of 28 specimens were prepared, 14 specimens of each type (PB and PP). For each type of bamboo, 8 compressive (stub), 3 bending (beam) and 3 buckling (column) tests were conducted. No attempt was made to determine the moister content of these culms but rather an estimate was made based on the bamboo's skin colour. The PB has greener appearance than the PP which has a yellow-brown colour. Based on this it is assumed that the moisture content for PB is 15-30% while for PP is 5-20%. For each sample, three measurements of the external and internal diameters were made at each end and the cross-section area and moment of inertia were determined by averaging over the two ends of the sample. For the compression tests, a sample length of twice the external diameter of the culm and no less than a minimum of 75mm was used. For the bending test, a three point setup is used with a sample length of 1.2m with a 1m simply supported span. For the hinge-hinge column buckling test a slenderness ration of around 70 was used for all the samples. Figure 1 shows a schematic view of the three test setups. From these tests, average compression strength σ_c, bending elastic modulus, E_b, and buckling stress σ_b were obtained and listed in Table 2. Both types of bamboo have a similar E_b while PP (Mao Jue) offers higher compression and buckling capacities. Figures 2 and 3 show the different tests conducted on both bamboo types. It is worth noting that under bending test the PB samples failed by splitting along the entire span starting from mid span while the PP samples failed by local crushing under the applied load as shown in Figure 2. Table 3 lists the results obtained recently by Chung et al in Hong Kong using Mao Jue (PP) bamboo [6]. Given the inherent imperfections in bamboo as a natural material, the results obtained from the

current testing (Table 2) are in good agreement with Chung et al results (5-30% moisture content, Table 3).

3- A Special PVC Joint for Bamboo:

The main obstacle to the use of bamboo in construction is the lack of engineered joint system suitable for bamboo. Joints always been the least predictable part of the structure and for bamboo rudimentary jointing techniques, such as lashing, has been widely used. Jointing techniques that are based on drilling through the bamboo culm for sake of fastening reduce the bamboo's carrying capacity through cleavage failure. Techniques utilising timber plugs inserted or slotted into the bamboo culm suffer from culm splitting.

A special joint system suitable for the construction of bamboo double layer grid is proposed in this work. To maintain the lightweight nature of a bamboo structure, PVC (Polyvinyl Chloride) was selected as a suitable material for the joint. Another possibility is to use Fibre Reinforced Polymer (FRP) composite for the joint. The joint design is based on preserving the good tensile and compression strength of bamboo culms without adversely affecting them through cleavage or splitting failure. To allow some flexibility in the configuration of the double layer grid assembly, keeping in mind the inherent imperfection in the bamboo culms, a joint design as shown in Figure 4 is proposed. The joint can accommodate up to 8 members, is composed of a joint hub and up to 8 cylindrical connectors. The joint hub itself is composed of two identical parts that are connected together by 20mm diameter bolt. This allows the joint to be used for different configurations and can accommodate the expected imperfections in the assembly. The ends of the bamboo culms are encased inside the cylindrical connector with a megapoxy grouting material filling the gap between the bamboo and the PVC wall.

The spatial aspects of the joint were determined based on geometric requirements and finite element analysis using PVC material properties. Three coupon tests were conducted on the PVC material which gave tensile yield strength of 45 MPa and Elasticity modulus of 3000 MPa. Figure 5 shows Von Mises stress contour plot of the joint under one of the loading conditions, a 12 kN compression load case, used in the design. As can be seen from this figure, the stress in most of the joint is maintained at an acceptable level below the 45MPa capacity of the PVC material used. Figure 6 shows a prototype of the joint system. At this stage of research the joint was fabricated by machining using CAM and usual structural steel bolts were used. It is envisaged that for practical applications the joint can be produced economically using mould injection and a special PVC bolts can be used instead of the steel ones.

Proof testing of the prototype joint was also conducted. Six joint hub samples were tested under compression, tension and bending (two tests each) as shown in Figure 7. The joint hub component failed under 24 kN load in compression, 9 kN load in tension and 3 kN load in bending with failure pattern as shown in Fig 7. Figure 8 shows a typical load-displacement response of the joint hub obtained from the compression test together with the prediction from linear finite element analysis.

Similarly a pull-out test was conducted on the cylindrical connector as shown in Figure 9. Two techniques were used here, the first was that the bamboo member is inserted into the cylindrical connector and grouted. In the second technique, the two ends of the bamboo member were roughened using sandpaper and three grooves were made at each end before inserting into the cylindrical connector and grouting. Each groove is 5mm wide and 3mm deep, the grooves were made at 20mm apart and starting at 20mm from each end of the bamboo member. As shown in Fig 9, the test sample without grooves failed by slippage between the bamboo and the PVC connector. This took place at 13 kN. The test sample with grooves failed at the bolt hole of the PVC connector without any noticeable slippage. The failure load was 19 kN. It is clear that the insertion of grooves at the two ends of the bamboo member results in higher strength (about 150% increases) and stiffness (170% increases). This approach was adopted in the fabrication of the double layer grid described in the following section.

4- Prototype Double Layer Grid (DLG) Module

The PVC joint described in the previous section is used to assemble an offset square-on-square module of bamboo DLG. Mao Jue (PP) bamboo described in section 2 is used. The module is 2.6x2.6m in plane and 0.9m deep as shown in Figures 10 and 11. The module is composed of 32 bamboo members with an average length of 1.15m each and 13 PVC joints. Each joint has a number of connectors that vary from 3 to 8 connectors depending on the location of the joint in the grid. Each member was inserted into the connectors and grouted first. The grout was allowed to cure for 24 hours. Following that the grid was assembled. The assembly was carried out by one person and it took only 30 minutes to complete with all bolts being snug tight. The total weight of the assembled DLG is about 100kg only.

Following the assembly, the grid was supported at four corner supports shown as A, B, C and D in Fig 10. At support A, all degrees of freedom were restrained while supports B, C and D allow free in-plane translation and free rotation about the vertical axis. Thirteen members were instrumented with strain gauges, two gauges were used for each member and placed on opposite sides and located at the member's mid-length. These members are labelled X1 to X13 in Fig 10. Two members were selected in the top layer (X12 and X13), five web members (X5-X7, X9 and X11) and six members in the bottom layer (X1-X4, X8 and X10). The displacements were monitored at four nodes, these nodes are shown in Fig 10 as N5, N11, N13 and D. N5 is the central node in the bottom layer, N11 and N13 are corner nodes in the top layer and node D is corner support at the bottom layer. A rigid frame was placed inside the grid and used as a base for the LVDT displacement measurements, similarly a rigid cross frame was placed on the top layer to transfer the applied load to the top four nodes as shown in Fig 11.

A uniform load was incrementally applied on the top layer of the grid. The loading was applied using a timber pallet loaded with concrete mix bags with a total weight of 10 kN (equivalent to 5.92 kPa applied on the top layer of the grid). The load was applied in six increments, following each load increment, the average strain in each of the thirteen members and the displacements at the four instrumented nodes were recorded. The loading of the grid from zero loads to 10 kN was completed in about 15 minutes, the load was kept on the grid for 3 minutes then was removed. No visible damage or excessive deformation was observed. Figure 12 shows the loading process of the grid.

Table 4 gives the measured axial forces in each of the thirteen members indicated in Figure 10 when the total applied load on the grid is 10 kN. The highest compression is close to 3.5kN in member X-7 (web member) and the highest tension force is close to 1.8 kN in member X-2 (bottom layer). Elastic geometric nonlinear analysis of the grid was also conducted and the predicted results were compared to the ones obtained from the experiment [7]. This comparison is shown in Table 4. For the bamboo members, the properties shown in Table 5 were used in the analysis. These properties are based on the average properties obtained for the 32 members used in the grid. Due to the inherent imperfections in the bamboo, a 3% member geometric imperfection was found to give the best agreement between the nonlinear analysis and experimental results. Figure 13 shows the load-deflection response of the DLG, the vertical deflection at node N5 (central node at the bottom layer) is shown in this figure. The nonlinear analysis prediction is in good agreement with the experimental response. The grid response is quite stiff with a total deflection of only 2.5mm under the 10kN applied load.

Using the member forces obtained form the nonlinear analysis under 10kN applied load, finite element analysis of different joints in the DLG was carried out to assess the stresses within the PVC joints [8]. Figure 14 shows Von Mises stress contour plot for support node D at the total applied load. It is clear from this figure that the stress within the joint is kept within acceptable limit within 50% of the PVC material capacity (45MPa).

5- Conclusions:

The structural evaluation of two bamboo species was conducted and results were compared with other conventional building materials. The structural characteristics of bamboo together with its excellent environmental attributes highlight the potential of bamboo as a construction material. A special PVC joint was proposed in this paper and experimental results obtained from testing of this new joint system were presented. The joint was implemented in a bamboo double-layer grid module that was tested and the obtained results were reported. Results obtained indicate that the new PVC joint system can be used in practice for constructing lightweight medium-span bamboo DLG structures with excellent structural and aesthetic aspects.

6- Acknowledgement:

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7- References:

1. Janssen, J.J.A., “Bamboo in Building Structures”, PhD Thesis, Eindhoven University of Technology, Holland, 1981.
2. Ghavami, K., “Bamboo as Reinforcement in Structural Concrete Elements”, Cement & Concrete Composite, 27, 637- 649, 2005.
3. Jayanetti, D.L., Follett, P.R., “Bamboo in Construction: An Introduction”, INBAR Technical Report No. 16, TRADA, UK, 1999.
4. Ghavami, K. and Moreira, L.E., “Development of A New Joint for Bamboo Space Structures”, Mobile and Rapidly Assembled Structures, Computational Mechanics Publications, Southampton, UK, 201-210, 1996.
5. Janssen J.J.A., “designing and building with bamboo”, INBAR Technical report 20, 2000, (www.inbar.int).
6. Chung, K.F., Chan, S.L. and Yu, W.K., “Mechanical Properties and Engineering Data of Structural Bamboo”, Bamboo Scaffolds In Building Construction. Joint Publication, the Hong Kong Polytechnic University and International Network for Bamboo and Rattan, 1-23, 2002.
7. NIDA, Nonlinear Integrated Design and Analysis of steel frames, Department of Civil and Structural Engineering, Hong Kong Polytechnic University, Hong Kong.
8. Strand7 finite element software, G+D Computing, www.strand.aust.com

Table 1 Structural attributes of bamboo against conventional materials

Building Material	Modulus of Elasticity (MPa)	Working stress (MPa))	Density (kg/m3)	Efficiency for stiffness	Efficiency for strength	Energy of production (MJ/kg)	Energy of production (MJ/m3)	Energy per unit stress
	A	B	C	D = A / C	E = B / C	F	G = F * C	H = G /B
Steel	210,000	160	7800	27	0.02	30	234000	1500
Concrete	25,000	8	2400	10	0.003	0.8	1920	240
Timber	11,000	7.5	600	18	0.013	1	600	80
Bamboo	20,000	10	600	33	0.017	0.5	300	30

Table 2 Compression, Buckling and bending Test Results

Bamboo type	σ_c MPa	σ_b MPa	E_b MPa
PB	41.8	26.1	10052
PP	49.5	35.8	10173

Table 3: Test Results from Chung et al [6]

Bamboo Species	Moisture Content (%)	Compressive Strength (Mpa)			Buckling Capacity (Mpa)			Elasticity Modulus Eb (GPa)		
		Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Phyllostachys Pubescens (Mao Jue)	< 5%	122	152	134	-	-	-	10.3	19.7	13.2
	5% - 30%	48	114	75	12.6	42	27 (S=67.6)	7.1	18.2	11.4
	> 30%	37	81	57	10.2	41	25.6 (S=72.5)	5.4	16.4	9.6

S= slenderness ratio

Table 4: Comparison of member axial forces obtained from experiment and nonlinear analysis (Negative is compression)

Total Applied Load =10 kN			
Member	Axial Force (kN)		
	Analysis (1)	Experiment (2)	(1)/(2)
X-1	1.75	1.62	1.08
X-2	1.63	1.77	0.92
X-3	1.75	1.53	1.14
X-4	1.63	1.62	1.01
X-5	-3.46	-3.23	1.07
X-6	-3.46	-3.39	1.02
X-7	-3.46	-3.48	0.99
X-8	0.015	0.019	0.79
X-9	-0.011	-0.068	0.16
X-10	-0.0059	-0.009	0.66
X-11	-0.14	-0.105	1.33
X-12	-1.68	-1.27	1.32
X-13	-1.68	-1.35	1.24

Table 5: Average properties of the bamboo members used in the double layer grid

Structural Properties of Phyllostachy Pubescen (Mao Jue)		
External Diameter	61.18	mm
Thickness	6.09	mm
Cross sectional Area	1.054×10^3	mm^2
Second Moment of Area About y-y Axis	4.052×10^5	mm^4
Second Moment of Area About z-z Axis	4.052×10^5	mm^4
Section Modulus About y-y Axis	1.325×10^4	mm^3
Section Modulus About z-z Axis	1.325×10^4	mm^3
Modulus of Elasticity	7.411	GPa
Yield Strength	49.5	MPa

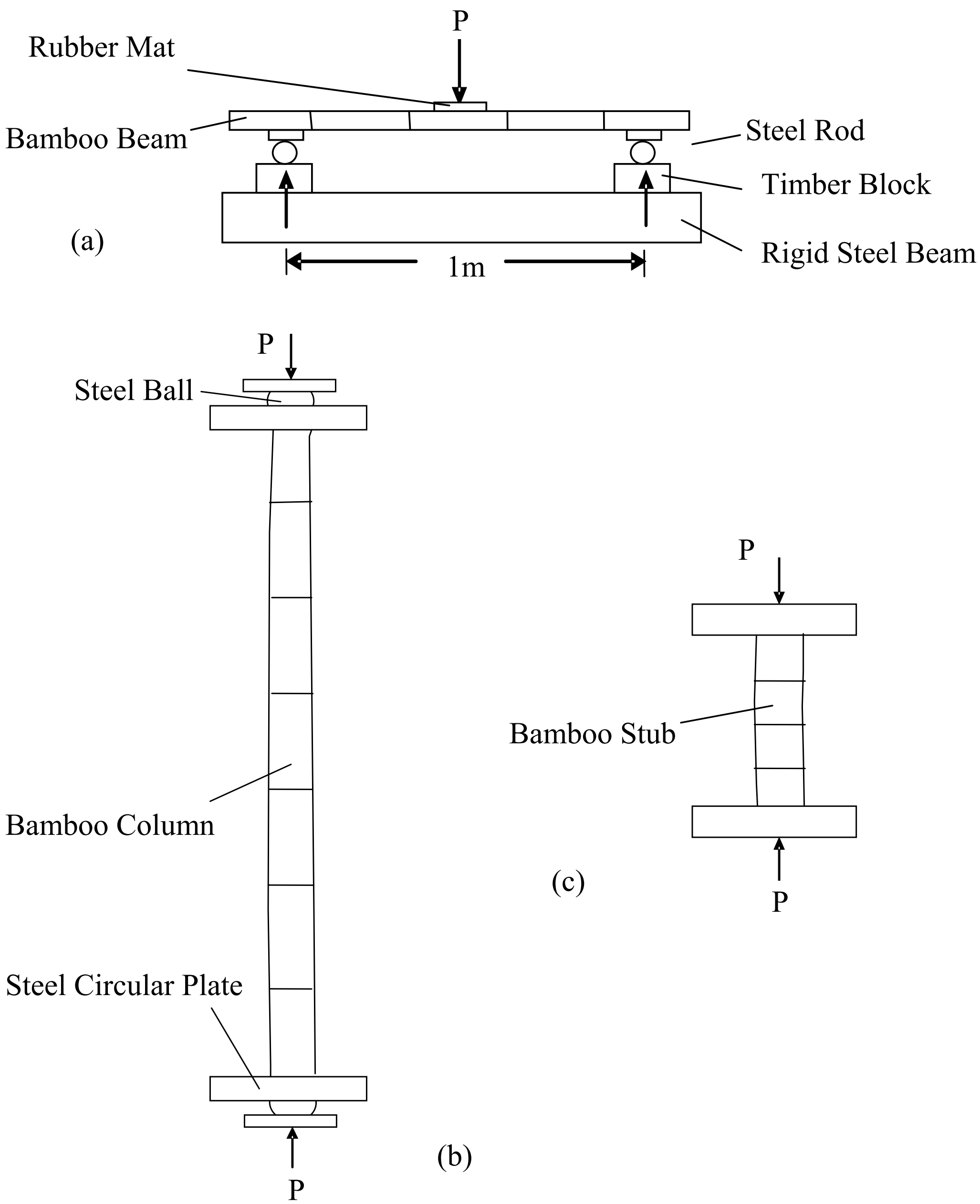


Figure 1: a) Bending, b) Buckling, c) Compression tests of bamboo

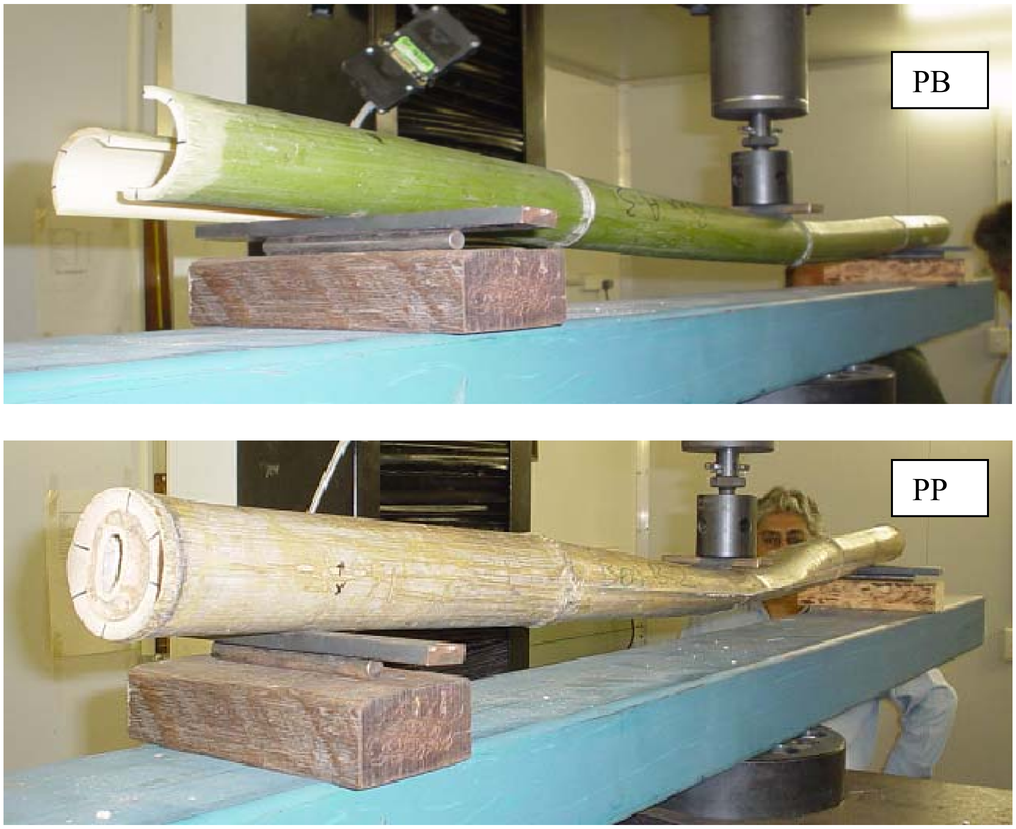


Figure 2: Bending Test

PB PP PB PP

Figure 3: Compression and Buckling Tests

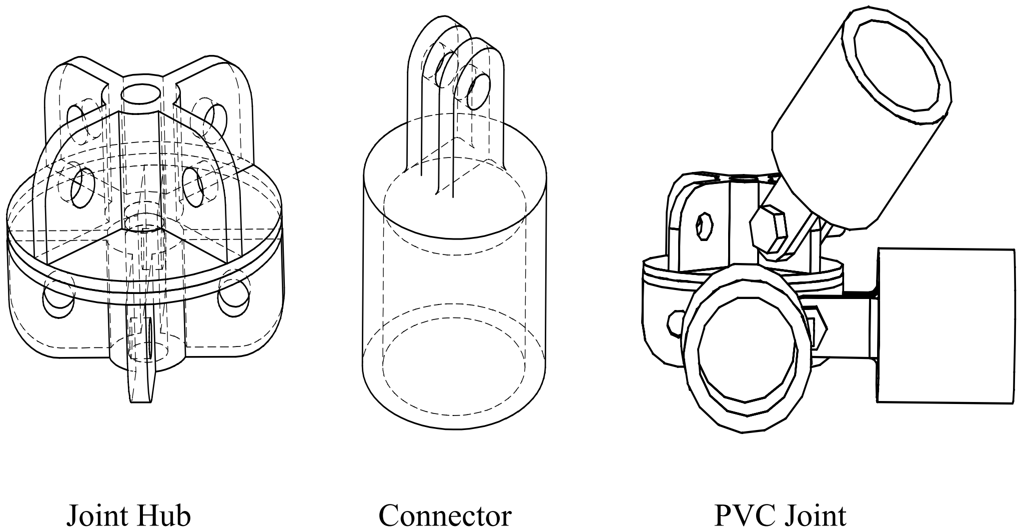


Figure 4: Proposed new PVC Joint System for bamboo

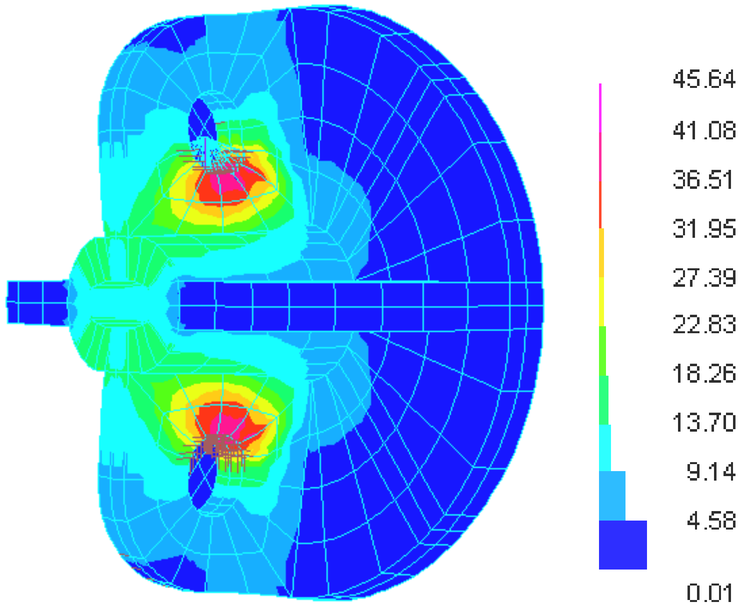
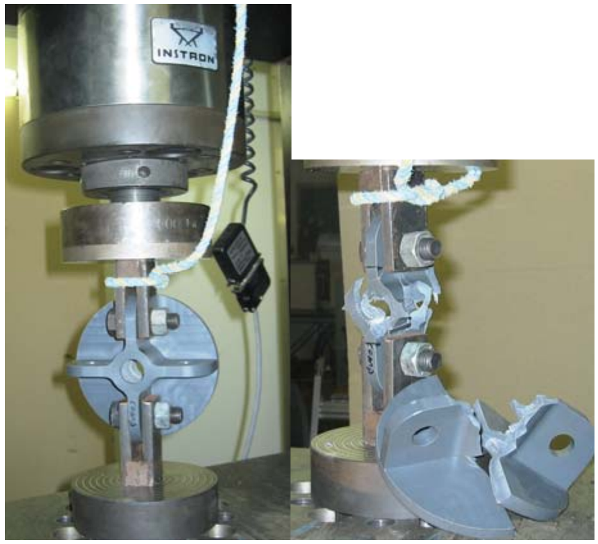


Figure 5: Von Mises stress contour (MPa) of one part of the hub under 12kN compression force


(a)


(b)

Figure 6: Prototype PVC Joint, (a) basic components, (b) assembled joint



(a)

(b)

(c)

Figure 7: Proof loading of the joint hub, (a) compression, (b) Tension, (c) Bending

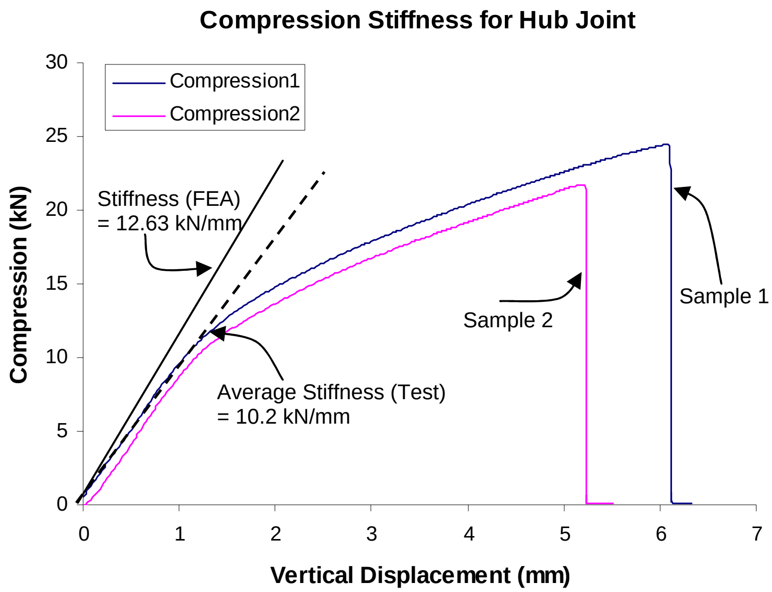


Figure 8: Compression test of the hub joint

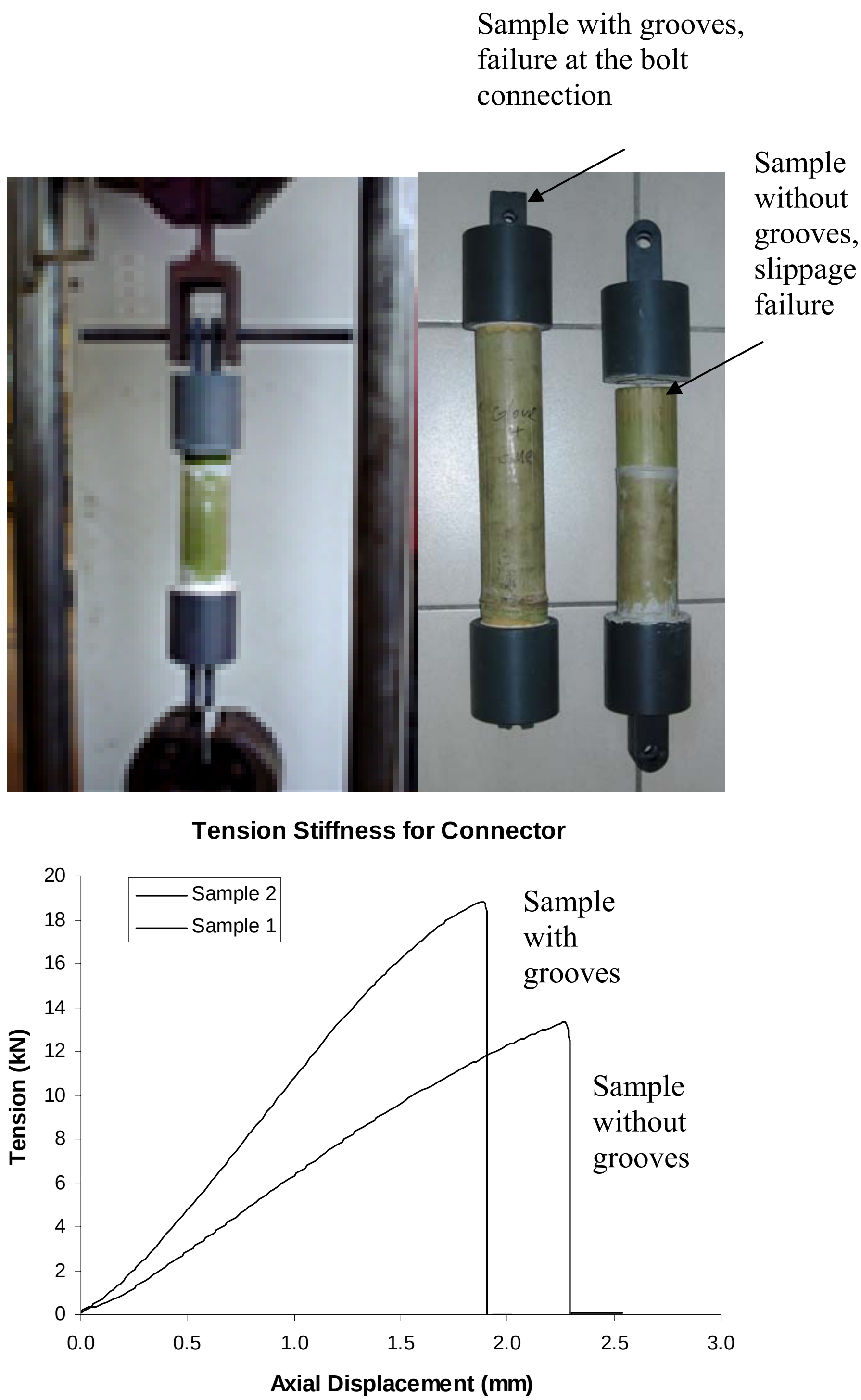


Figure 9: Pull-out test

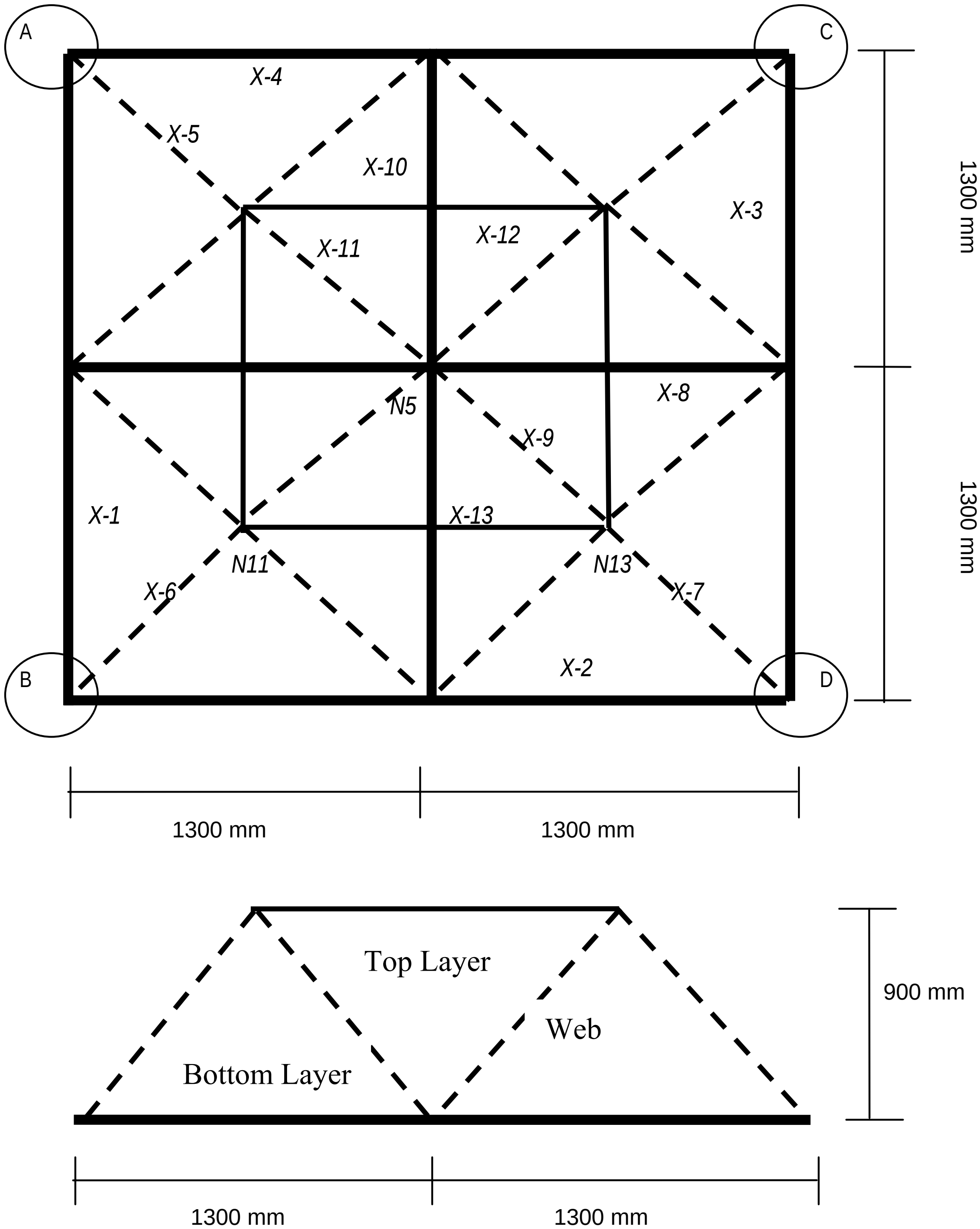


Figure 10: Plan and side view of the double layer grid

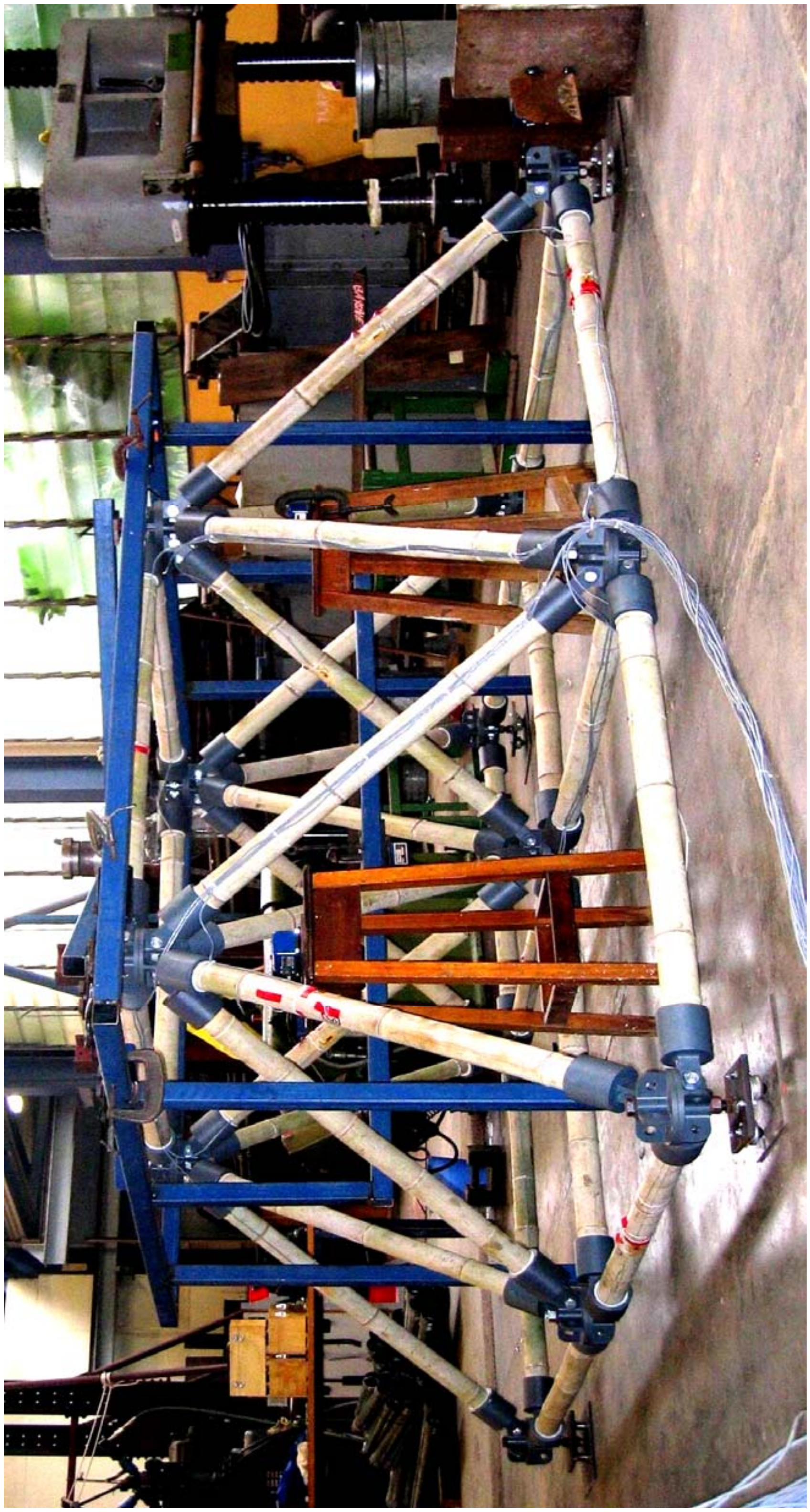


Figure 11: Experimental setup of the Double Layer Grid

Figure 12: The Loading of the Double Layer Grid

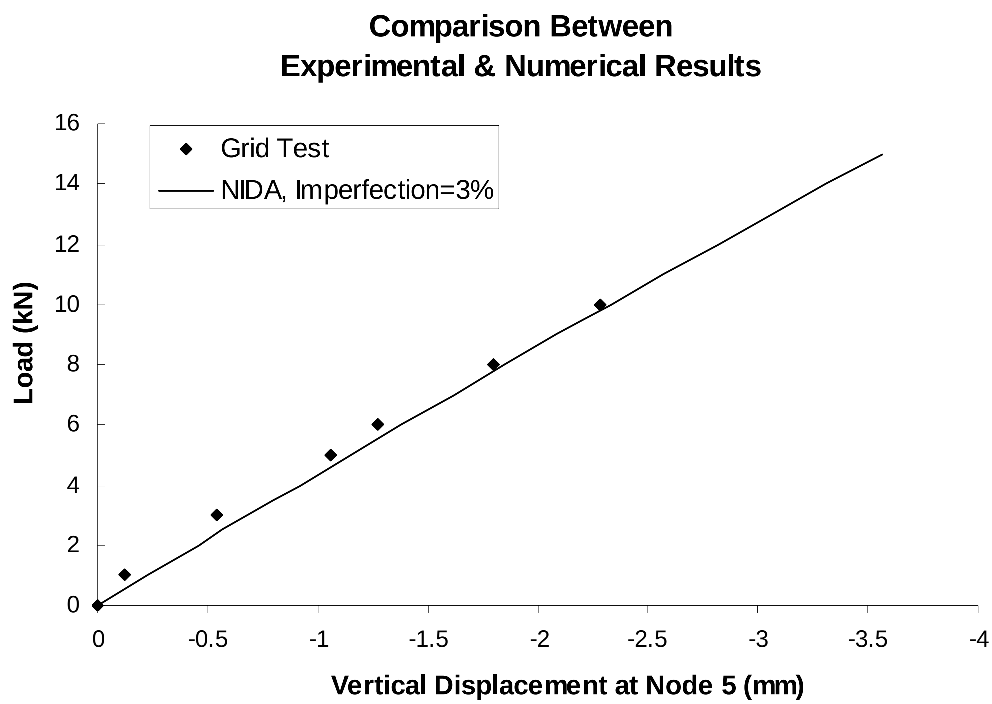


Figure 13: Comparison of the experimental and predicted results for deflection at node N5

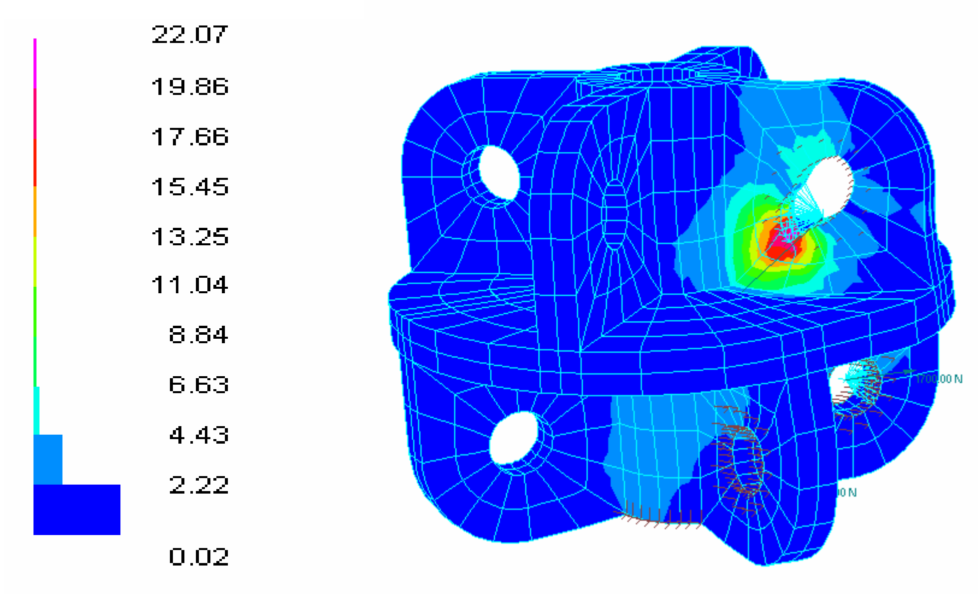


Figure 14: Von Mises stress contour (MPa) at node D under 10kN load on the grid