4
Theoretical and experimental analysis of full scale two-way concrete slab reinforced with bamboo strips

4.1. Introduction

Conventional reinforced concrete, which is one of the most widely used construction materials worldwide, is a composite material of steel bars embedded in a hardened concrete matrix. The physical properties of concrete are such that it has a high strength in compression but a low tensile strength. On average the tensile strength of concrete is about 10% of the compressive strength. The addition of steel reinforcement bars to concrete is therefore used to enhance the tensile load carrying capacity of the concrete member when subjected to typical internal forces such as axial forces, shear forces, torsion moments and bending moments. The high ecological cost of reinforced concrete coupled with a bid to protect the environment from non-biodegradable wastes such as metals and concrete debris has led to worldwide research into the use of plants in construction.

This chapter presents the results of a theoretical and experimental research, investigating the strength and serviceability of a full scale two-way spanning concrete slab reinforced with bamboo strips (without any shear reinforcement). The concrete slab was reinforced in two directions using approximately 22 mm width and 8 mm thick bamboo (*Phyllostachys Pubescens)* strips. The surfaces of the bamboo strips were treated with epoxy resin and 2 mm aggregate to improve bonding with the concrete (identified as the best surface treatment, analysed and presented in chapter 4). The slab was simply supported along its four sides and subjected to a central concentrated load (see layout in Figure 4.1). A finite element model was created (Figure 4.5) using SAP2000 to analyse and design the bamboo reinforcement (using DELCAR) for a 3000 mm square (2800 mm effective span) and 130 mm thick slab (110 mm effective depth). The theoretical model predictions were then compared against experimental test results from a slab containing 3.3 percent bamboo reinforcement, which was subjected to nine load cycles prior to failure. The span-to-effective depth ratio of the slab was 25.45. The first cracking load of the reinforced concrete slab averaged at 42% of the failure load predicted through FE for the un-reinforced concrete section. Experimental failure load was found to be approximately 148.39 % and 110.91 % of the theoretically predicted values by FEM and by ultimate punching shear load following BS 8110 [36] respectability. The slabs exhibited high stiffness against deformation prior to collapse by punching shear load.

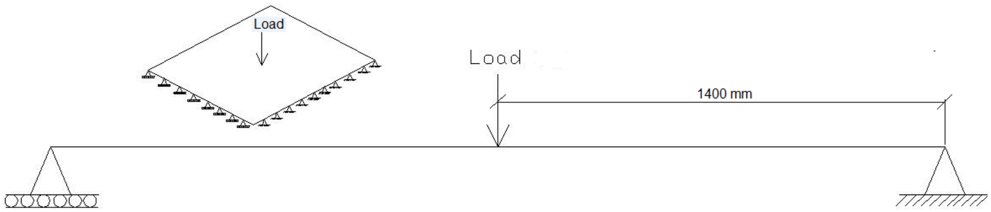


Figure 4.1- Simply supported slab and central concentrated load test (layout)

4.2. Experimental programme

4.2.1. Materials

As shown in Figure 4.2, a bamboo splitter machine was created to make the bamboo strips from three to four year old Chinese *Phyllostachys Pubescens*, which had previously been gas fumigated against insect pests. The force needed to split the bamboo culms was registered. The average maximum force to split the bamboo culms was 4.21 KN (required on the bamboo nodes) as show in the Figure 4.2d.

Figure 4.2- (a) Metallic blades to split the bamboo culm section (b) blades positioned on a steel beam (c-d) split force registration (e-f) bamboo splitter procedure

The bamboo surface treatment applied on the strips was prepared in the laboratory by first cleaning the bamboo surface using a metallic brush connected to an electric drill, and then painting the surface with epoxy resin (0.5mm-1mm in thickness) to immediately embedding in 2 mm aggregate pieces as shown in Figure 4.3. After around five hours the resin was completely dry and the treated bamboo strips were then ready to prepare the bamboo mesh. The concrete mix is given in Table 3.2 (chapter 3). The mean concrete compressive strength was 32.8 MPa, determined by testing five 100 mm cubes.

Figure 4.3- (a) Cleaning bamboo strips (b) painting surface with epoxy resin (c) coating bamboo strip with 2 mm aggregate (d) Dry treated bamboo strips

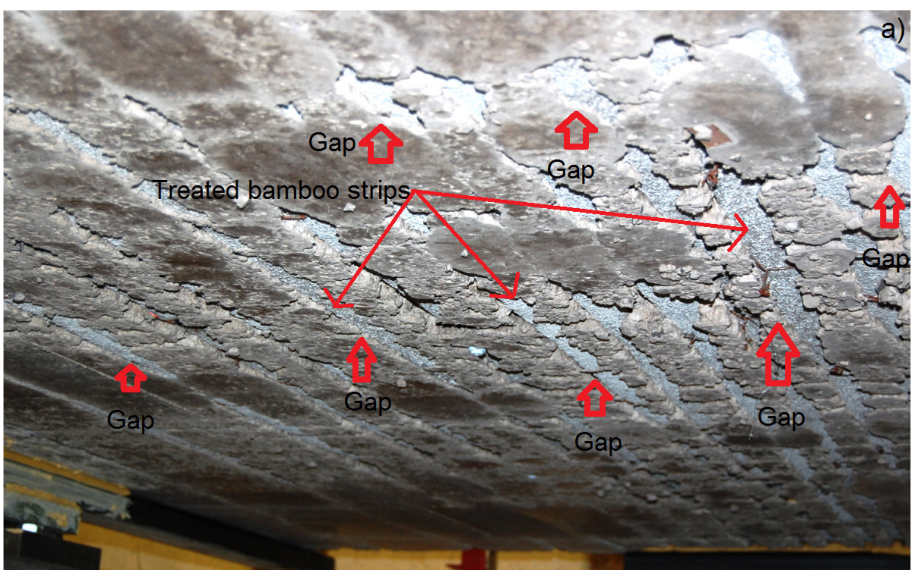
4.2.2. Specimen details

A two-way square concrete slab reinforced with bamboo strips from *Phyllostachys Pubescens* bamboo measuring 3000 mm by 3000 mm and 130 mm thickness was prepared in the laboratory. The average cross section of bamboo strips used in the bamboo mesh concrete reinforcement was 22 mm by 8 mm. Considering 98 KN as a ultimate load and changing parameters of DELCAR (software used to design steel concrete reinforcement) the bamboo mesh concrete reinforcement was designed using the results of a final element model created by four nodes Thin Shell elements of SAP2000 software (Figure

4.5). The bamboo reinforcement required (result of DELCAR, Figure 4.6a) was simplified for construction reasons as presented in Figure 4.6b.

The geometrical characteristic of the bamboo mesh and the bamboo mesh before casting are presented in Figure 4.7 (where it can be observed that the distances between strips are variable for regions). The slab was reinforced in both directions with a clear concrete cover of 20 mm. The percentage of total reinforcement was 3.33 (bamboo maximum tensile strength 177.97 MPa).

It is important to highlight that the two-way square concrete slab reinforced with bamboo strips prototype had approximately 25% of its bottom face with gaps concentrated at the central region (Figure 4.4a). this was mainly driven by four reasons: The concrete slump required (120mm) was not used (using approximately 80mm); The spaces between the bamboo strips at the slab´s central region was too small for this type of concrete reinforcement; The approximately rectangular cross section of the bamboo strips interfered negatively with the concrete coating around the bamboo strips during the casting (as show schematically in Figure 4.4b) and the small concrete cover (20mm) for this type of reinforcement.



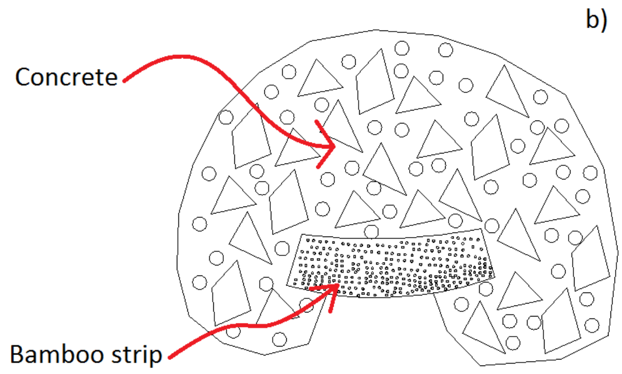
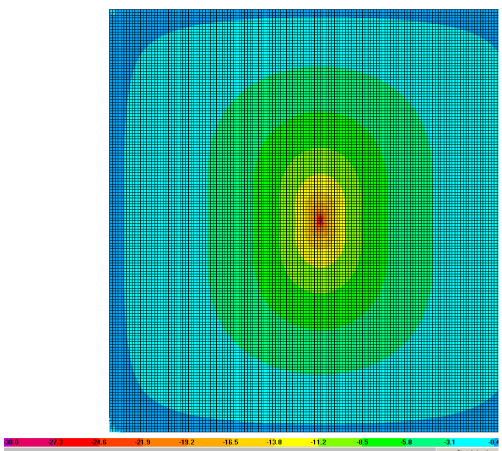


Figure 4.4- (a) Slab´s bottom face before testing (b) Scheme of the Influence of the bamboo strip cross section in casting



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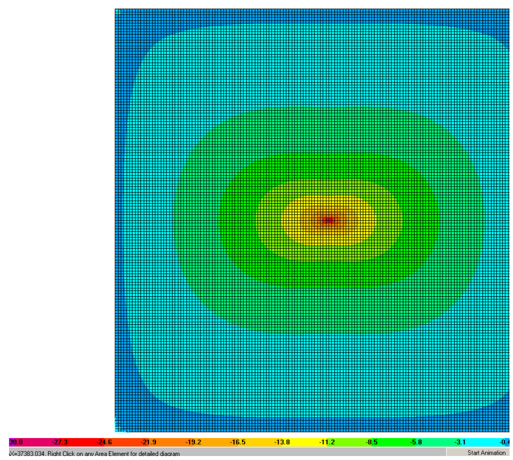

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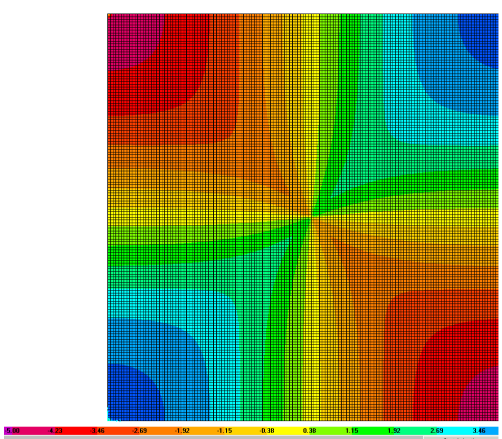

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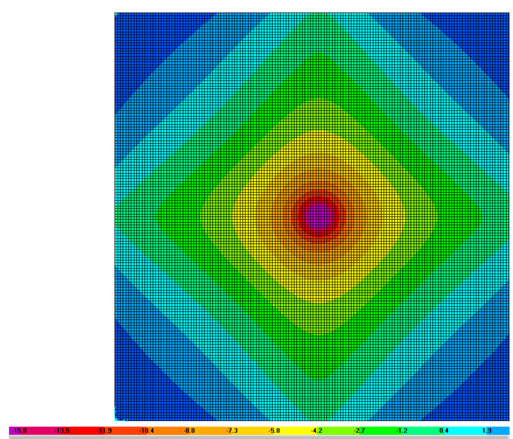
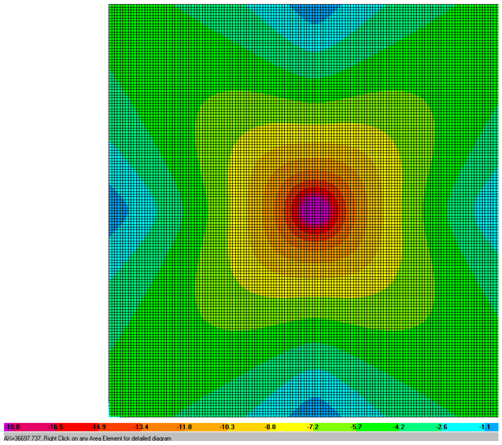
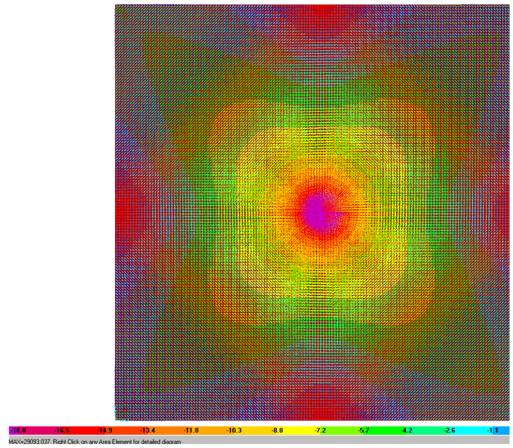


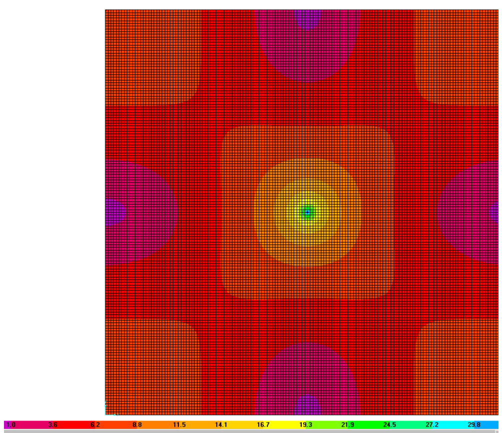
SMAX



SMin



SMax and SMin Arrows



SVM

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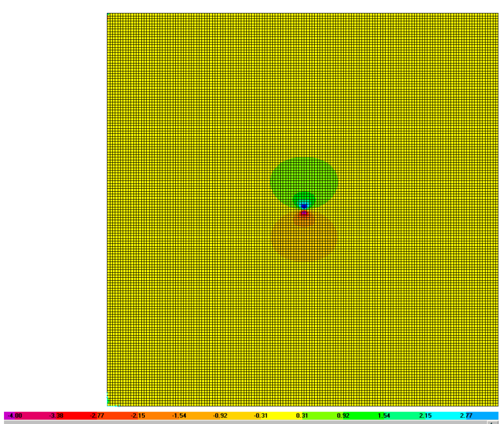

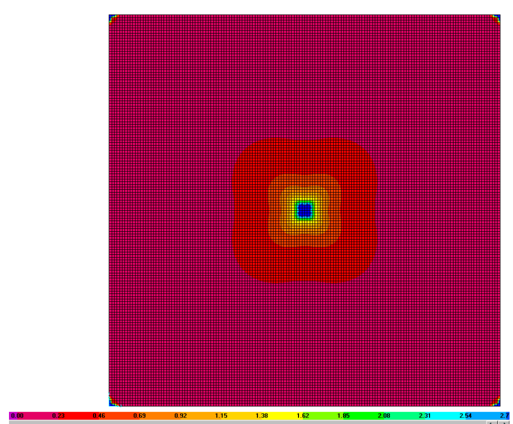

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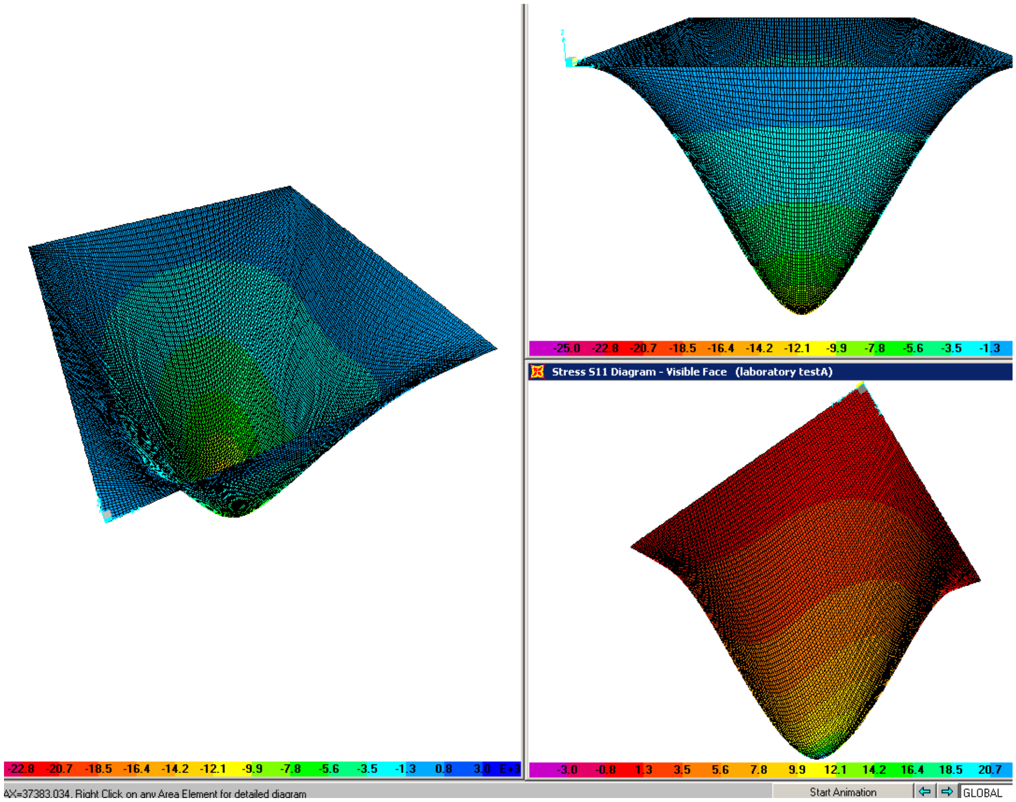
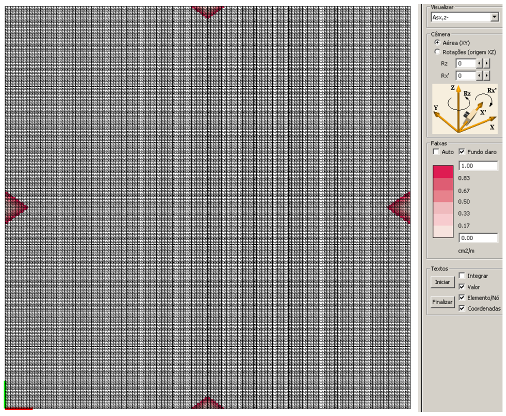


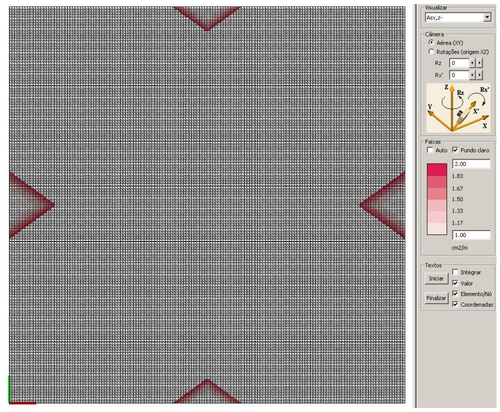
S11

Figure 4.5- SAP2000’s tension analysis for design bamboo reinforcement considering 98 KN centred load (KN,m)

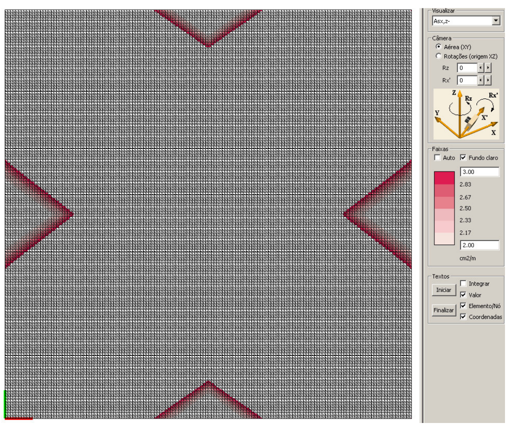
(a)



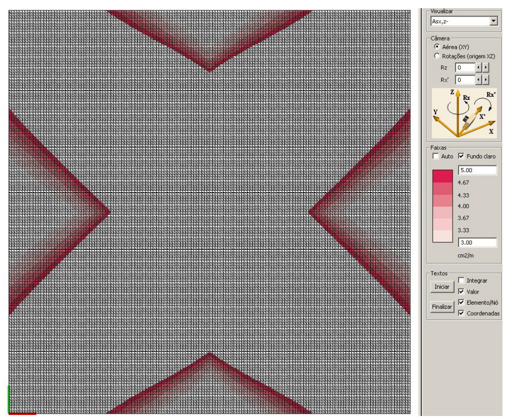
0 to 1 cm^2/m



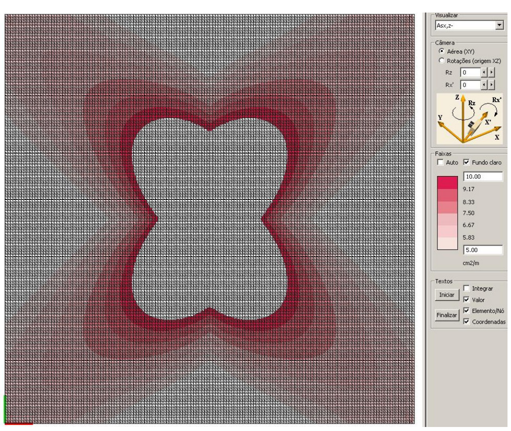
1 to 2 cm^2/m



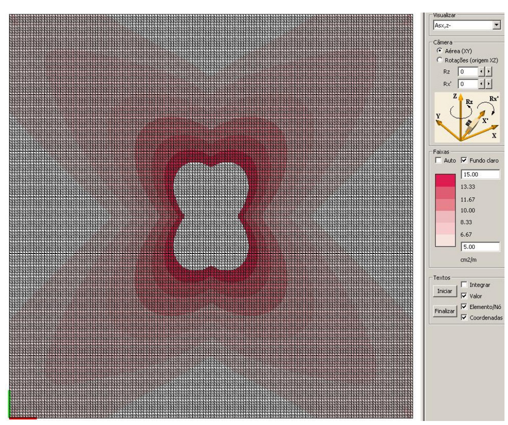
2 to 3 cm^2/m



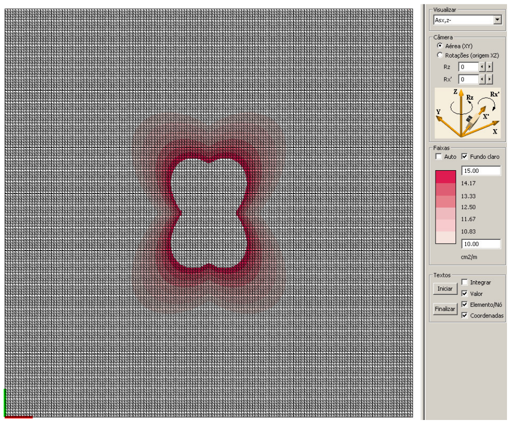
3 to 5 cm^2/m



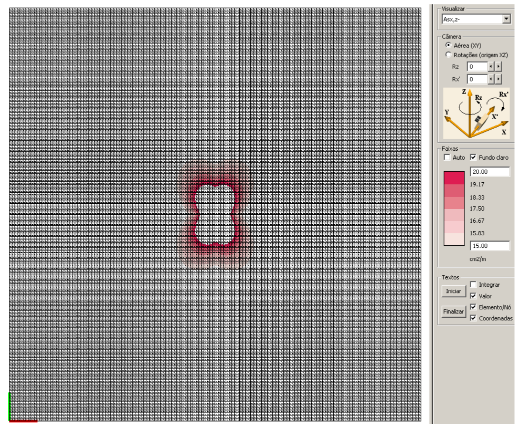
5 to 10 cm^2/m



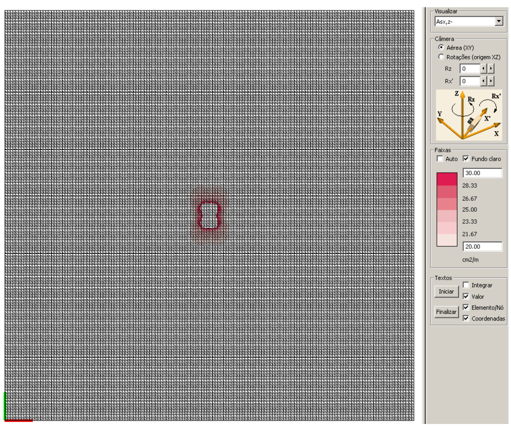
5 to 15 cm^2/m



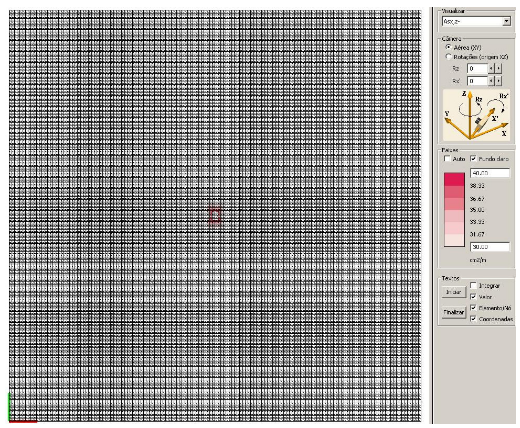
10 to 15 cm^2/m



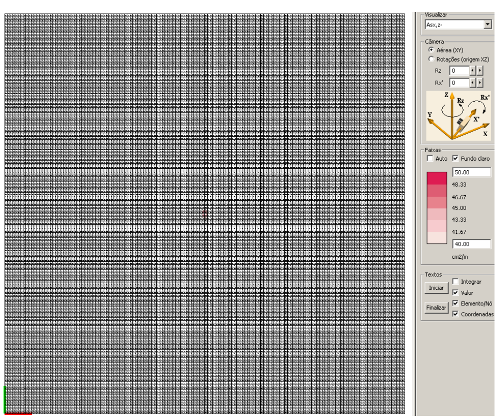
15 to 20 cm^2/m



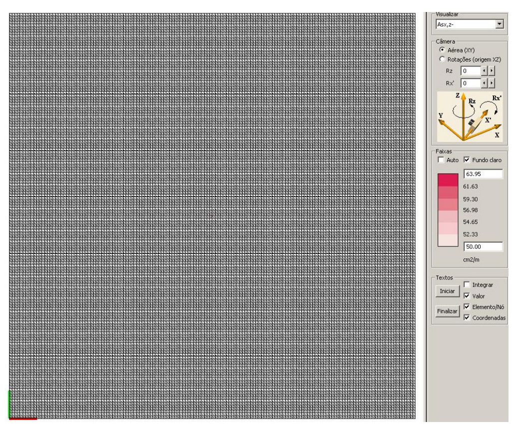
20 to 30 cm^2/m



30 to 40 cm^2/m



40 to 50 cm^2/m



50 to 63 cm^2/m

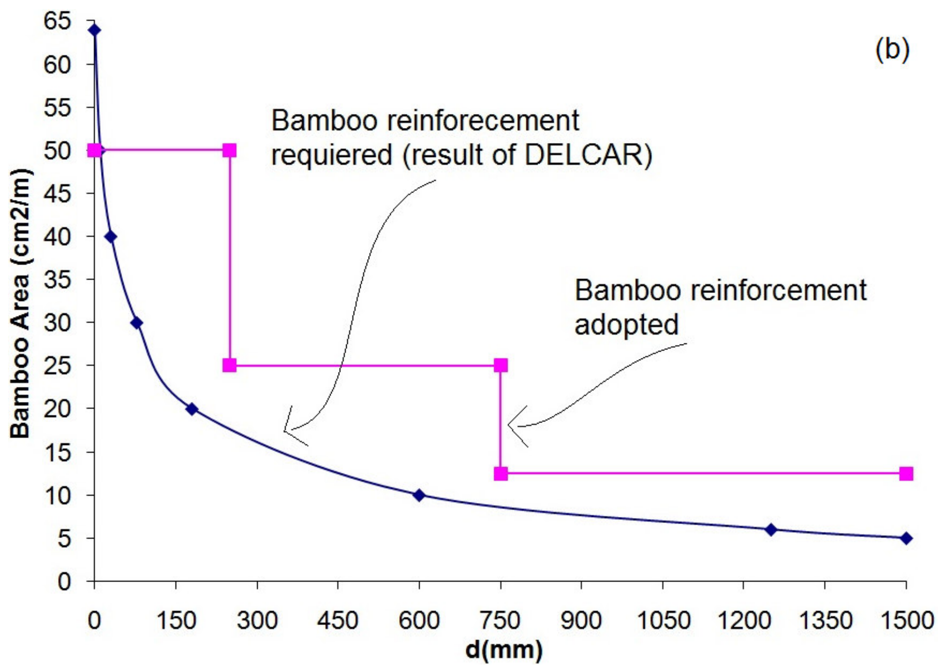


Figure 4.6- (a) DELCAR’s results for bamboo reinforcement (b) Bamboo reinforcement adopted

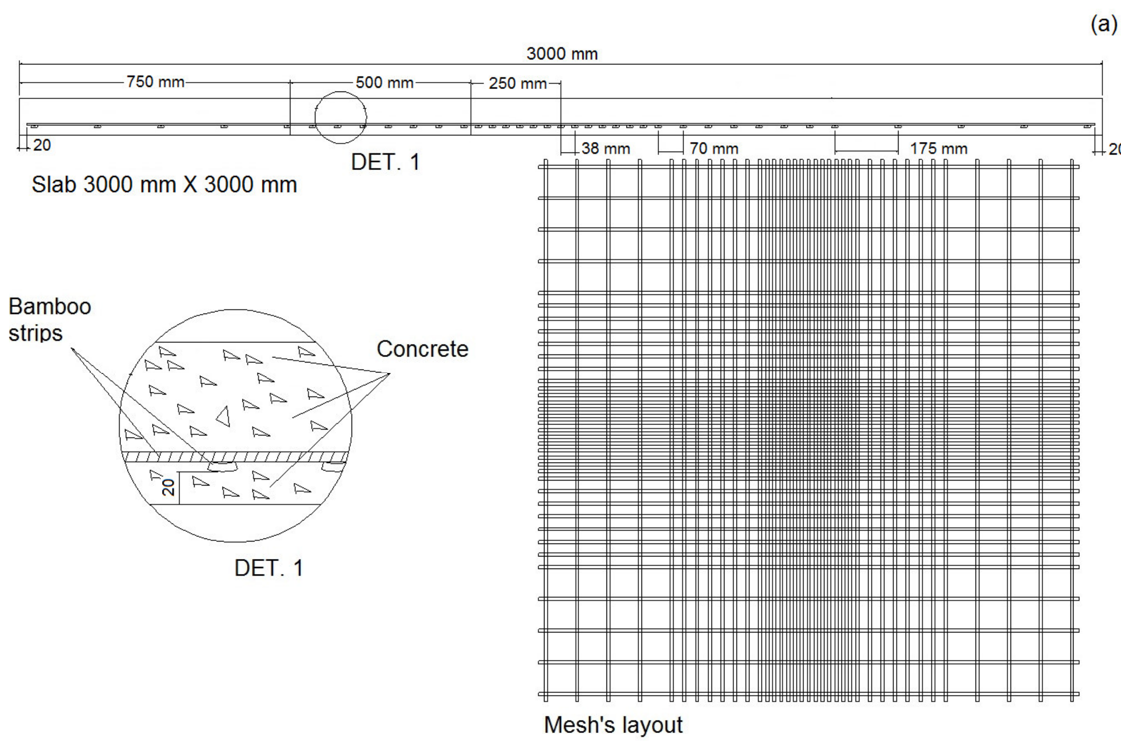
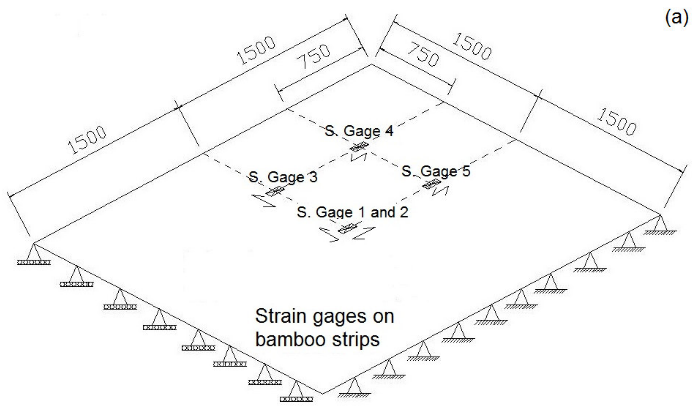


Figure 4.7- (a) Geometrical distribution of bamboo strips on the mesh (b) bamboo mesh ready before casting

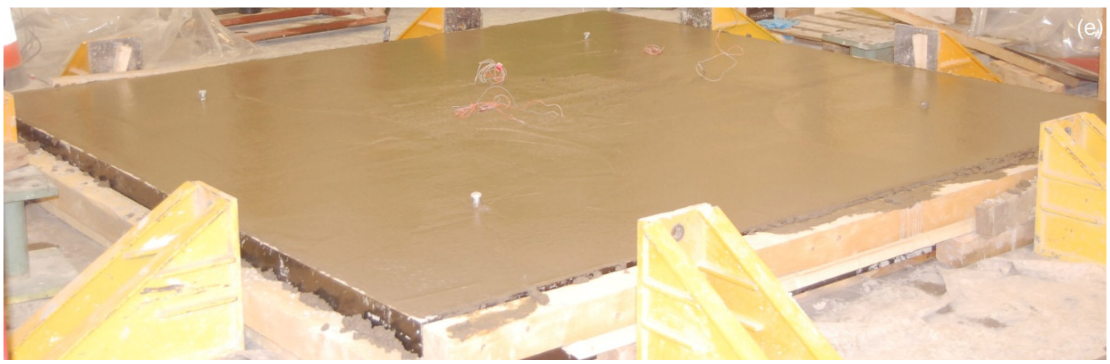
4.2.3. Instrumentation and casting

After cleaning small spaces of the gravel coating treatment, five strain gages were then positioned underneath of bamboo strips as presented in Figure 4.8 a-b. Using timber sheets, a formwork was prepared on the lab's floor level and then the bamboo mesh was positioned into it (Figure 4.8 c). The concrete used for casting consisted of a mix of 323 kg/m^{3}Cement (CEM II/B-V 32.5R), 877 kg/m^3 aggregate (100 mm), 874 kg/m^3 fine aggregate and 195 kg/m^3 of water (32.8 MPa compression strength at 28 days). 120 mm on the concrete Slump test was requested for casting. As shown in Figure 4.8 d-e, conventional procedures were adopted for casting. Finally, six LVDT (precision of 0.0001 mm) were distributed on the middle and quarter span as presented in Figure 4.8 f.


(a)
1500
750
1500
750
1500
1500
S. Gage 4
S. Gage 3
S. Gage 5
S. Gage 1 and 2
Strain gages on
bamboo strips


(b)
Instrumentation
using strain gage


(c)



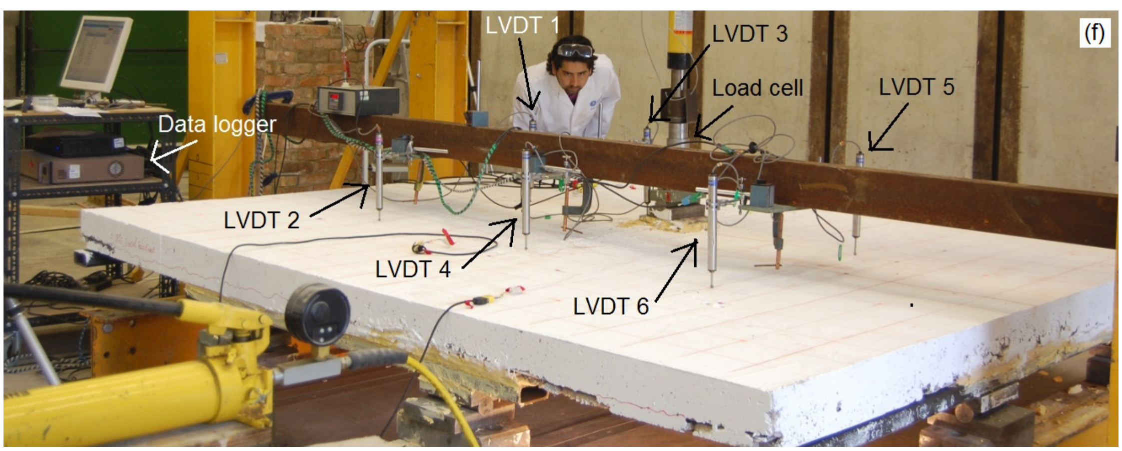


Figure 4.8- (a-b) Strain gages instrumentation (c-e) Casting of slab (f) LVDT instrumentation

4.2.4. Test procedure

The two-way slab was simply supported along its four edges by using steel beams. A central concentrated load was applied in 9 cyclic loading previous to failure as presented in Figure 4.9 whilst the deflections of the slab and strains on the bamboo strips were measured by the instrumentation (the test set-up is shown in Figure 4.8 f).

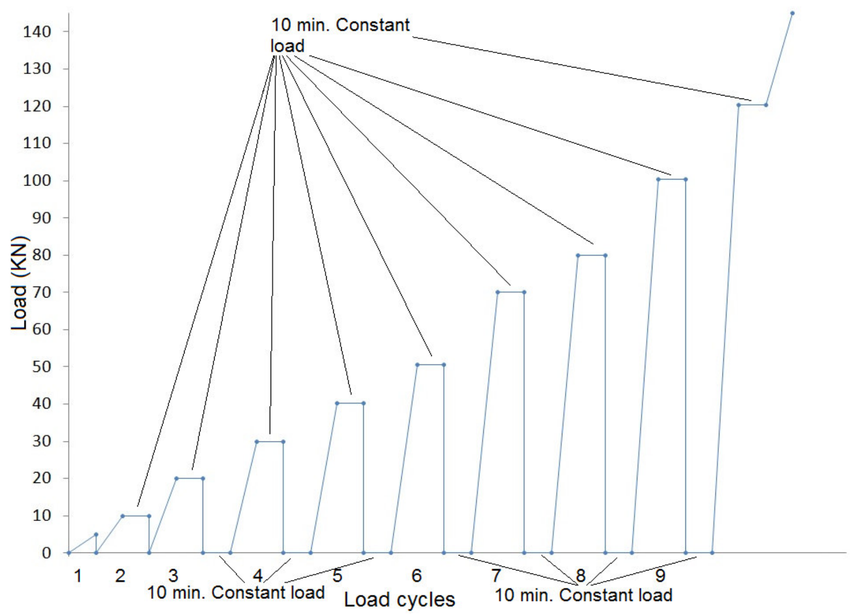


Figure 4.9- Test's loading procedure

4.3. Theory

4.3.1. Flexural theory

For a two-way slab simply supported along its four edges, and loaded concentrically, the ultimate moment of resistance based on the yield line method of analysis may result in one of two failure mechanisms, namely:

(a) Diagonal yield line pattern.
(b) Circular fan pattern.

The ultimate flexural load P_{ult} for the two failure mechanisms are, respectively,

$$P_{ult} = 8M_{ult} \tag{4.1}$$

$$P_{ult} = 2\pi M_{ult} \tag{4.2}$$

where M_{ult} denotes the ultimate moment per unit width of slab.

4.3.2. Punching shear strength

The theoretical punching shear strength as per the specifications of the British Code of Practice BS 8110 [36] is estimated to be made up of the following: (i) concrete section alone and (ii) both concrete section and tension reinforcement. The critical section was taken on a perimeter distant 1.5h from the boundary of the loaded area where **h** is the overall slab thickness. For a loading plate with a diameter of 200 mm, the average width of the ribs is b_v = (100+1.5h), therefore the effective area over which shear was critical is given by A= b_v x d, where **A** is the effective area and **d** is the effective depth of the slab.

4.4. Theoretical and experimental results

4.4.1. Material properties of slabs

The average compression strength result for five concrete cubes tested is 32.8 MPa with a modulus of elasticity equal to 35.1 GPa. The bamboo strips used in this study have an average tensile strength of 177.97 MPa and a modulus of elasticity of 16.54 GPa. The tensile strength of the bamboo was obtained from the specimens with and without nodes.

4.4.2. Behaviour of two-way slab

The cracking, theoretical and experimental failure loads of the two-way slab are presented in Table 4.1. Considering the ultimate tensile load of bamboo strips the bamboo mesh was designed with a theoretical failure load of 98 KN using the finite element method (using a numerical model created with SAP2000 software). Considering that the bamboo reinforcement adopted for construction reasons was 53.7% more than required, this method seems to be a highly appropriate method to use for concrete elements that are reinforced with bamboo (when bamboo strips are treated). The yield line method of analysis was used taking into account a diagonal yield line pattern in order to calculate the theoretical ultimate deflection load (this has approximately 51% difference with the experimental last load). To calculate the ultimate punching shear load using BS 8110 [36] the concrete section alone has been considered (it was the failure form presented experimentally). This last prediction of the ultimate punching shear load was shown to have approximately a 10% difference from the experimental result, therefore more appropriate for punching.

Table 4.1- Experimental and theoretical result loads

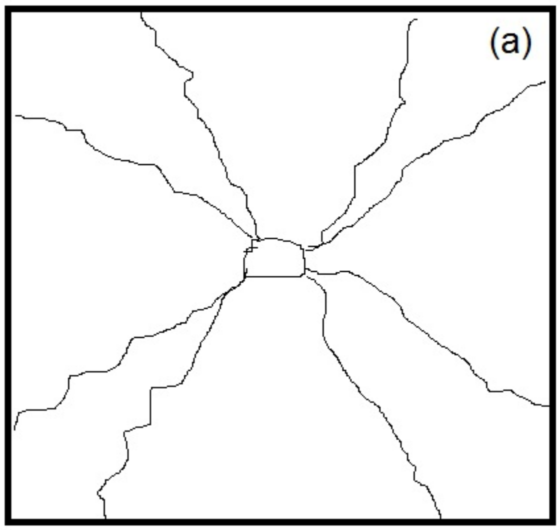
Experimental		Theoretical				Experimental/Theoretica		
First crack load P_{cr} (kN)	Failure load[a] P_{ul} (kN)	First crack load[b] P'_{cr} (kN)	Ultimate load deflection[c] (kN)	Ultimate load deflection[d] (kN)	Ultimate shear load[c] P'_{ul} (kN)	P_{cr}/P_{ul}	P_{cr}/P'_{cr}	P_{ul}/P'_{ul}
59.7	145.42	35.36	74.76	98	131.12	0.41	1.69	1.11

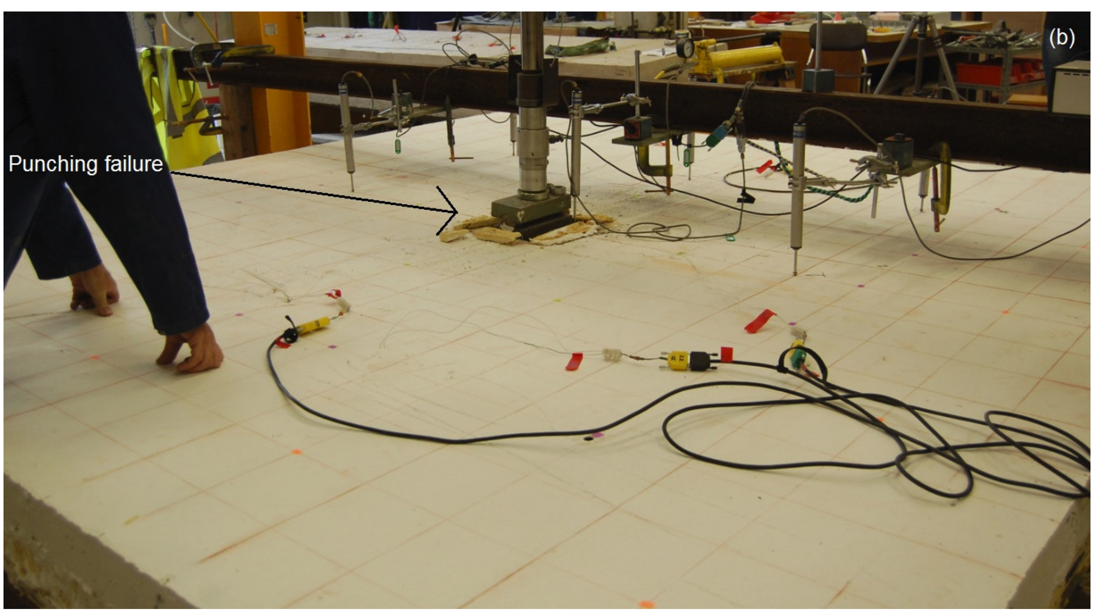
[a] Punching failure.
[b] Finite element method-Considering a concrete slab without reinforcement.
[c] British Code of Practice BS 8110 [36].
[d] Finite element method.

4.5. Discussion of test results

4.5.1. Mode of failure

For a two-way slab simply supported on all four sides and subjected to a central concentrated load, the central area undergoes maximum punching shear as well as maximum bending moment. Failures are generally due to a combination of the two failure modes with the least ultimate load governing the failure of the slab. Usually bending failure cracks are the first to develop underneath the slabs as applied loading is gradually increased and the concrete tensile strength is exceeded. This is because concrete is weak in tension. The crack pattern observed underneath the slab is illustrated in Figure 4.10a. From the figure it could be inferred that the yield line patterns did not conform to the mechanism of diagonal yield pattern used in deriving the ultimate theoretical flexural failure load (using BS 8110 [36]). Therefore the collapse occurred from punching shear. The final failure mode however depends on the amount of bamboo reinforcement, concrete strength and the effective depth of the slab. The punching shears failure (see Figure 4.10b-c) was initiated by a small section of flexural concrete crushing but the final failure mode was due to punching failure as can be closely predicted by theoretical analysis (see Table 4.1 above).





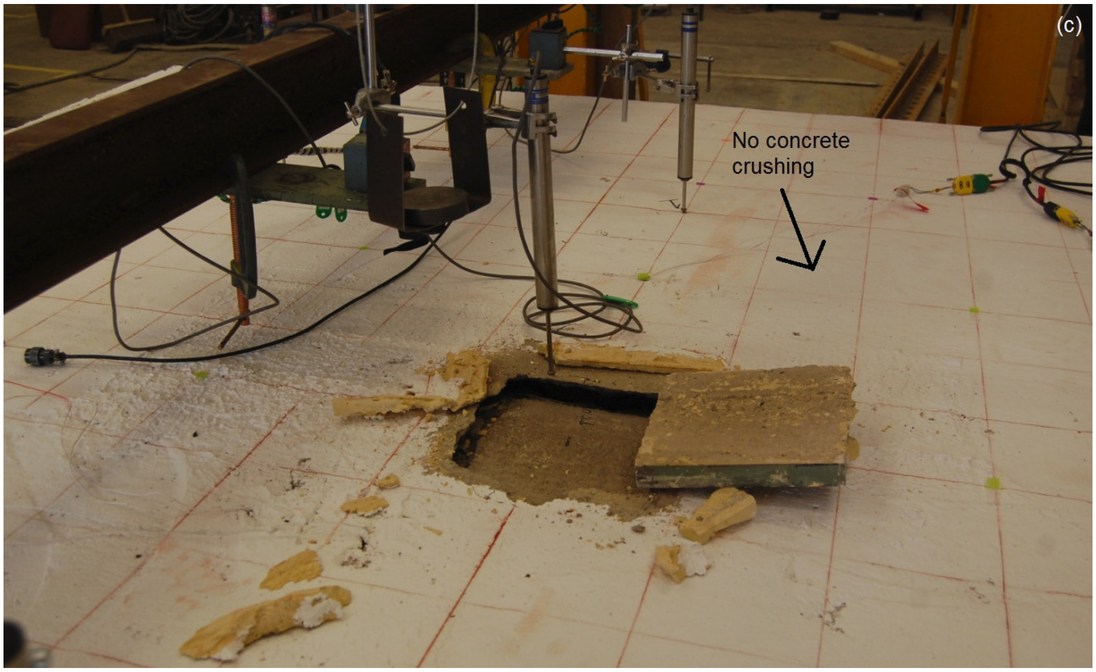


Figure 4.10- (a) Slab's crack pattern observed underneath (b) punching mode failure (c) no concrete crushing on failure

It was observed from the test that even though theoretical calculations had predicted concrete crushing and bamboo failure by tensile strength rather than punching shear failure, the opposite happened. This can be explained by the fact that the extra bamboo reinforcement adopted (53.7% more) instead of designed by DELCAR (for construction reasons due to not perfect straight strips for example) had a great influence, leading to a conclusion that the FEM analysis provides good precision in its application on treated bamboo strips reinforcing concrete. This means that the precision of method and the contribution of bamboo strips were under-estimated. The two-way slab also exhibited significant recovery of deflection on load reduction and removal. In addition the slab showed further resistance on re-loading. This may be explained by the fact that the bamboo strips were unfractured when punching failure occurred. After failure the slab was broken as shown in Figure 4.11 to verify the state of the bamboo surface treatment, which was in perfect condition without any gravel coating removed and also with perfect bonding between the strips/concrete. It can therefore be concluded that the gravel coating treatment on bamboo strips can be safely used and its role is achieve successfully.

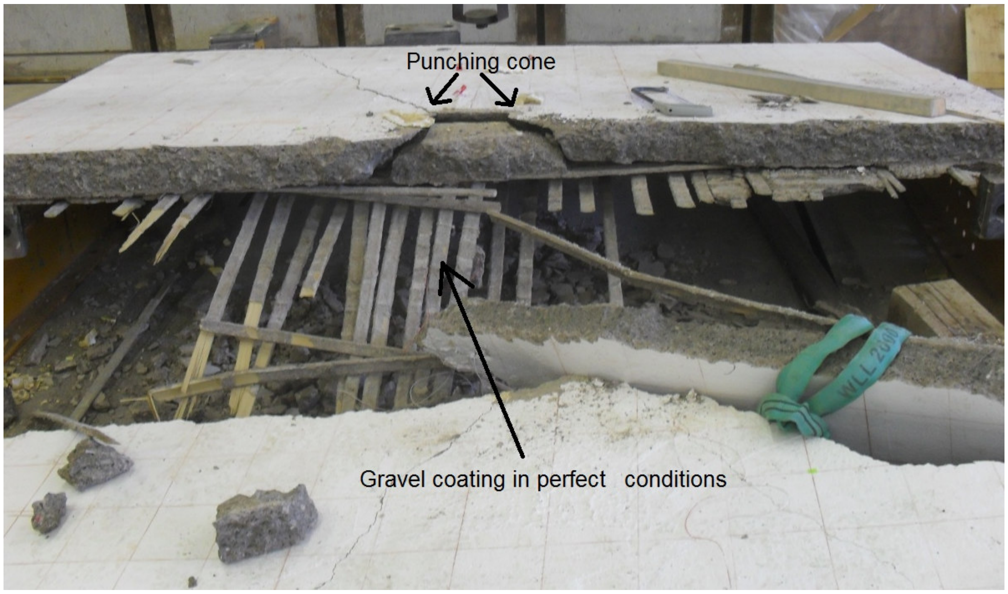
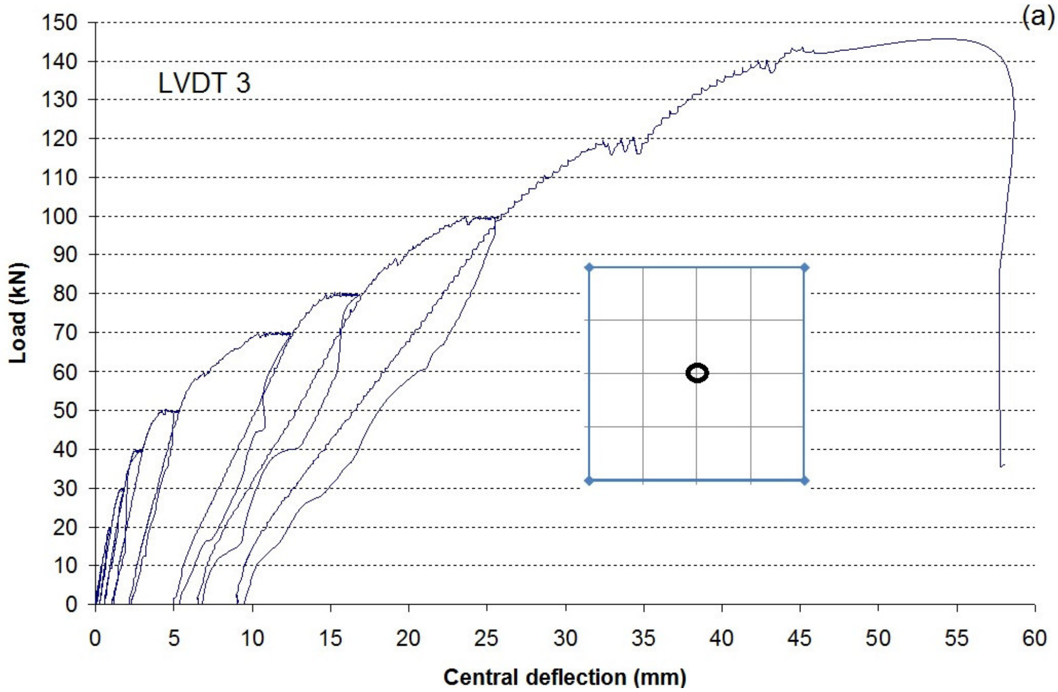
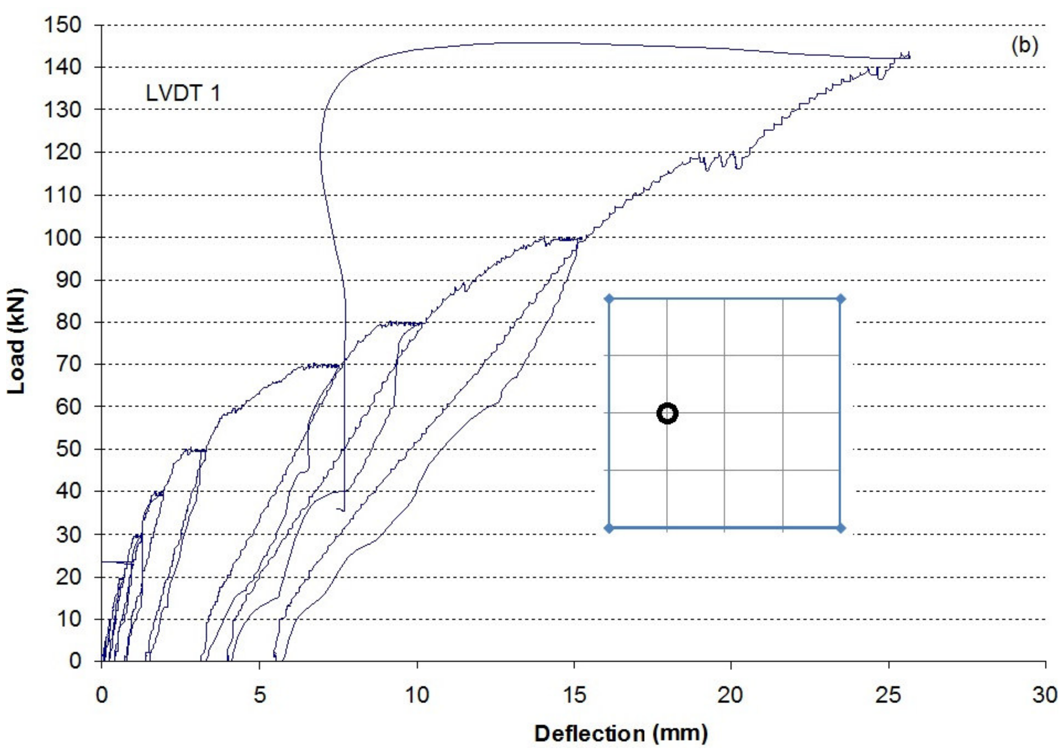


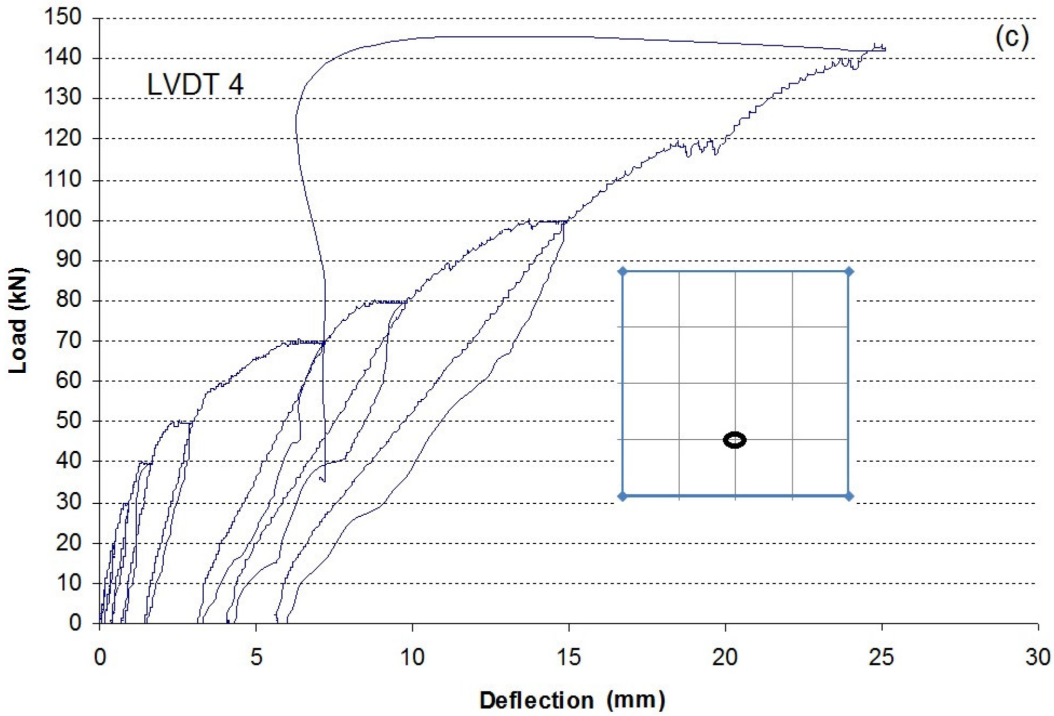
Figure 4.11- Analysis of bamboo strips surface treatment (gravel coating) after test

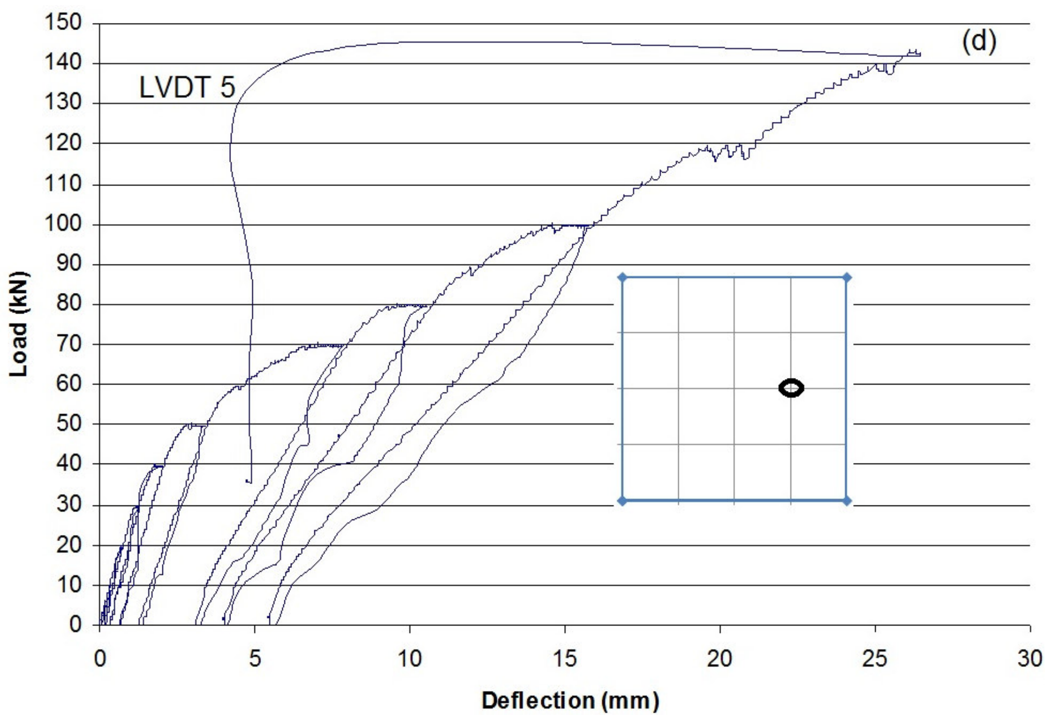
4.5.2. Load–deflection curves

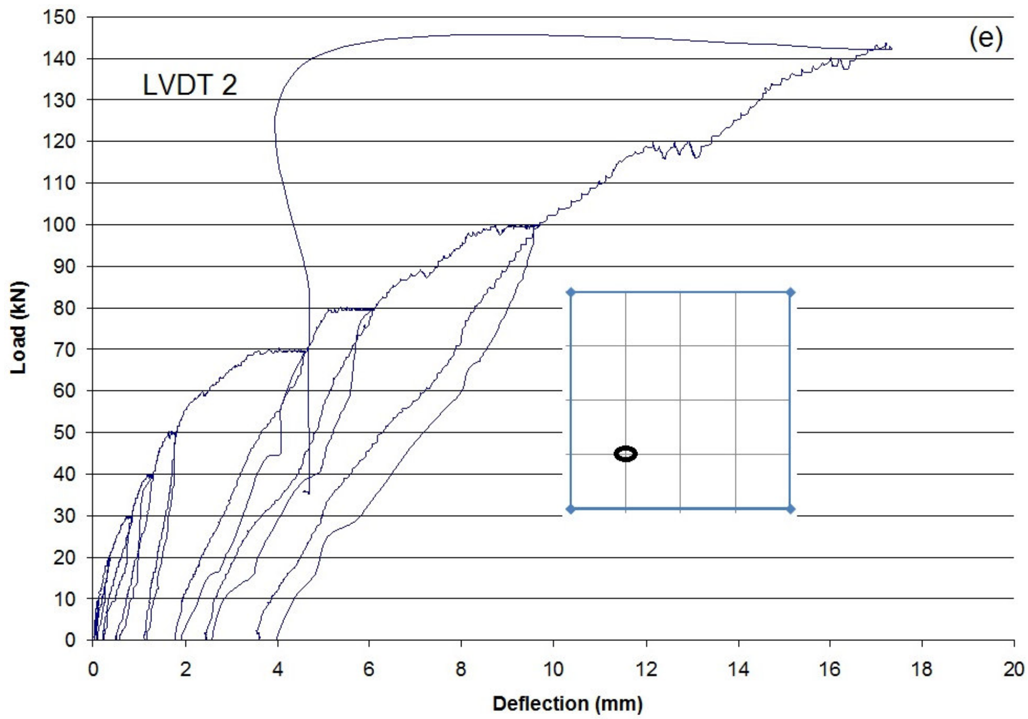
Typical load–deflection curves of the two-way slab that was subjected to cyclic loading are shown in Figure 4.12 (all measured points). The slab showed little reduction in stiffness when the loading regime changed from the pre-cracking to the post-cracking stage (load equal to 59.7kN) during cyclic loading. Considering the Brazilian standard code in practice NBR 6120 [63] the load–deflection curves of the slab exhibited linear elastic behaviour before the concentrate equivalent service load (5kN/m^2) was reached. The deflection at that equivalent service load was 3.12 mm. This was therefore 48% less than the limit deflection for use recommended for the NBR 6118 [64]. At state limit of use [64], the equivalent distributed load (6.34 kN/m^2) was 26.8% superior of the load service recommended for [64]. At ultimate load (144.99 kN) the maximum deflection was 58 mm representing the high stiffness of the slab and this showed that a perfect bonding existed between the bamboo strips and the concrete. It was observed that the deflection in the two-way slab in the post-cracking stage of loading was lower than those observed in bamboo concrete composite floor slabs tested by Acha [35]. This could be explained by the general increase in stiffness as a result of the two-way action of reinforcement. In Table 4.2 is presented the deflection of the slab at points of instrumentation (see Figure 4.11) when equivalent load service, limit state of use and ultimate load is considered. It can be observed through the results that the test was well executed due the symmetrical response of symmetrical instrumentation.






(c)
LVDT 4
Load (kN)
Deflection (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
0
5
10
15
20
25
30


(d)
LVDT 5
Load (kN)
Deflection (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
0
5
10
15
20
25
30



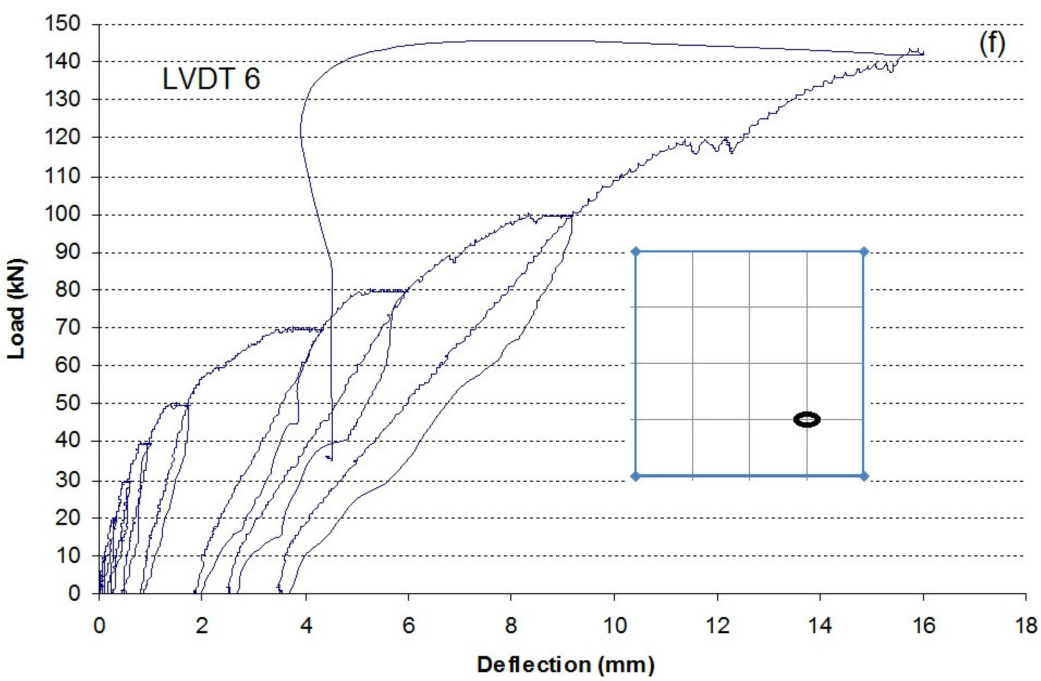
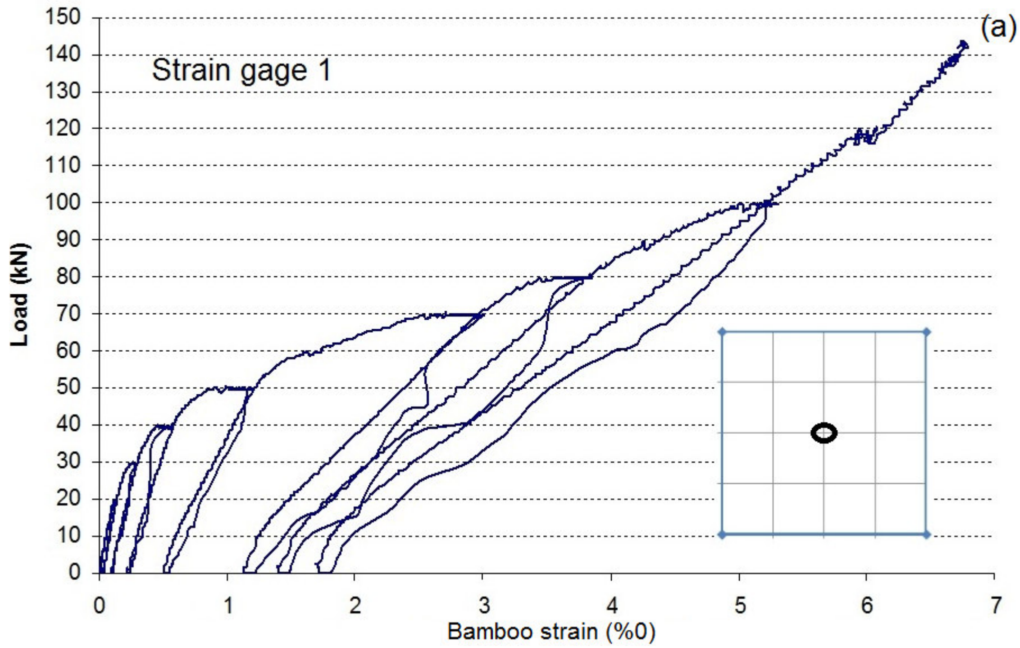


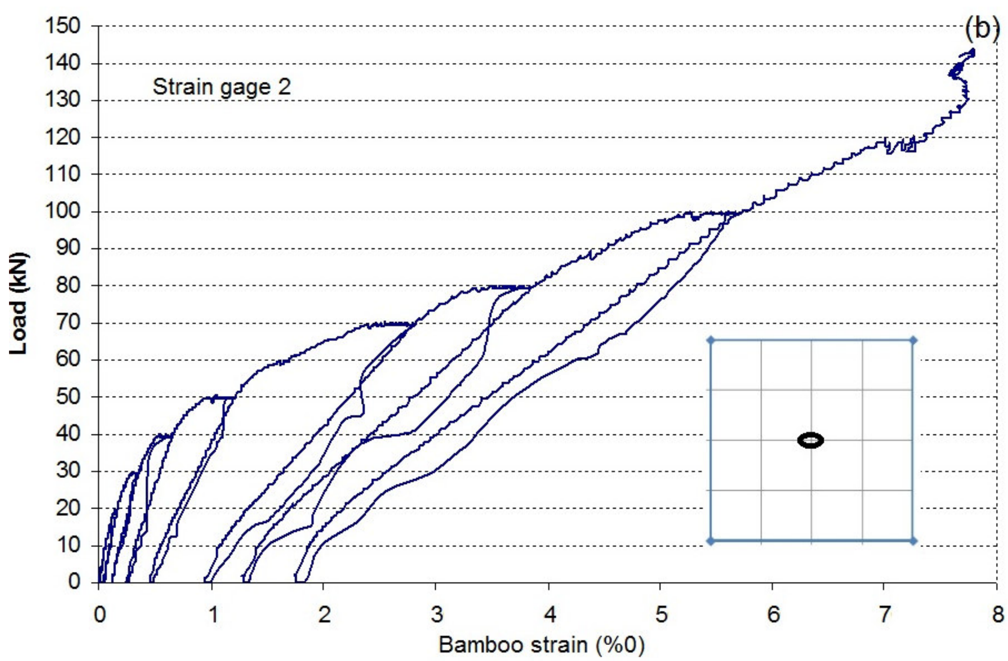
Figure 4.12- Load-deflection curves

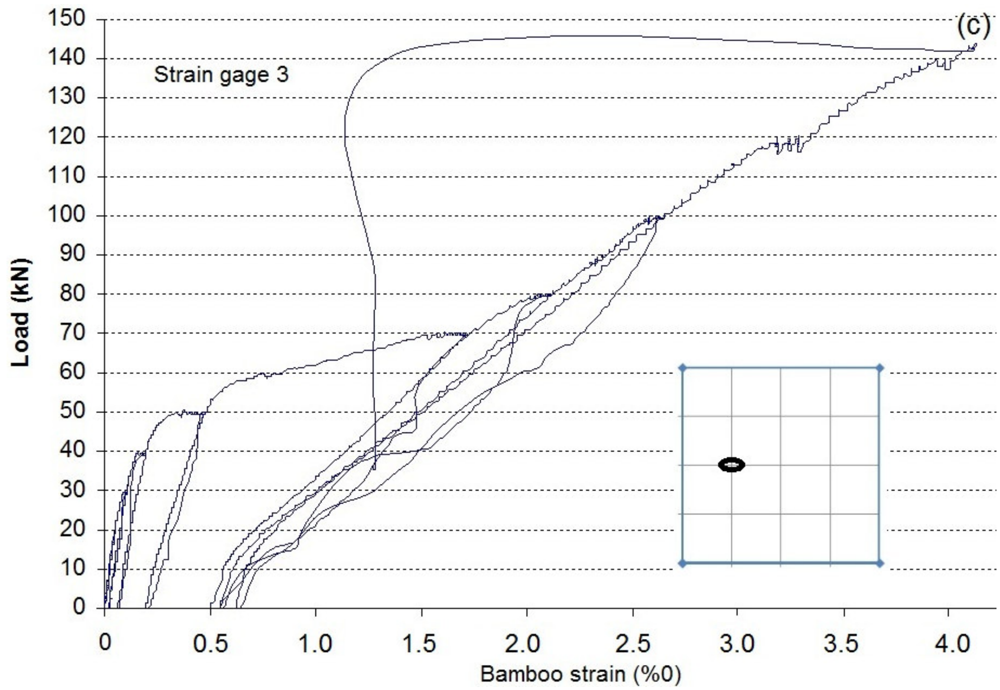
4.5.3. Load–bamboo strain curves

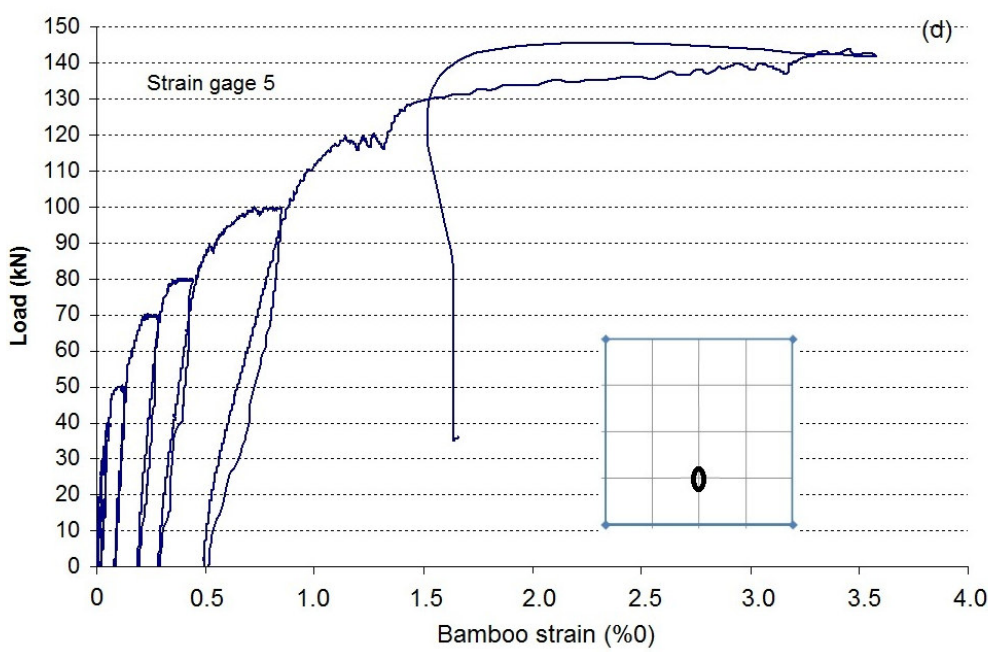
Typical load–strain curves of the two-way slab that was subjected to cyclic loading are shown in Figure 4.13 (all measured points). The stresses on the bamboo strips at instrumentations points (see Figure 4.8a above) were estimated for load service, state limit of use, and ultimate load using Hook's law ($\sigma = E\varepsilon$) as its constitutive diagram is linear (strains obtained through instrumentation). As shown in Table 4.2 the strain on the bamboo at state limits of use is 1.44 ‰ when the concentrate load is 57.03 kN which explains the first crack on the concrete at 59.7 kN since there is a short distance between the bamboo and concrete surface (maximum strain for concrete before cracking 2 ‰). The maximum tensile strength (128.84 MPa) on the bamboo strips at ultimate load (Table 4.2) presented at the middle span is 27.61% less than the maximum tensile strength of *Phyllostachys Pubescens* bamboo used, resulting at all states to be characterized as an over reinforced structural element.

The load-bamboo strain curves show that before the equivalent concentrate load service (45 kN) the bamboo strips do not present significant creep for constant loads. After ultimate state of use load (57.03 kN) and the first crack, creep phenomenon is accentuated initially, but then reach quick stability. Through these results it can be concluded that the FEM analysis for bamboo strips reinforcement design has good accuracy and more studies on creep of bamboo strips is required.


(a)
Strain gage 1
Load (kN)
Bamboo strain (%0)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7


(b)
Strain gage 2
Load (kN)
Bamboo strain (%0)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8


(c)
Strain gage 3
Load (kN)
Bamboo strain (%0)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


(d)
Strain gage 5
Load (kN)
Bamboo strain (%0)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

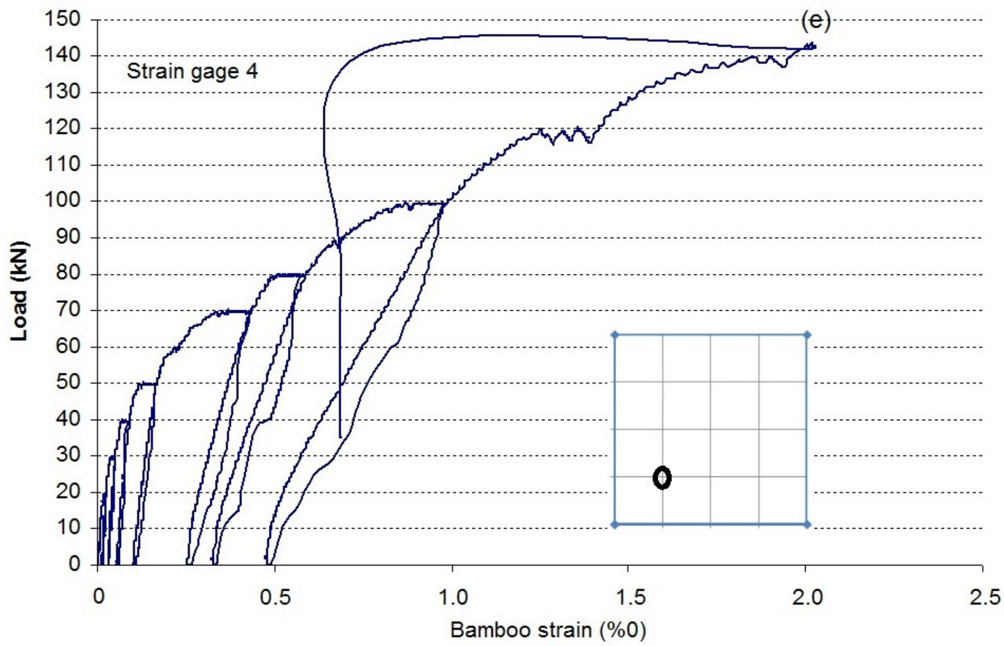


Figure 4.13- Load-bamboo strain curves

Table 4.2- Deflection of slab and strain on bamboo strips at service load, state limit of use and ultimate load

Instrument	Service load ($5KN/m^2$)			State limit of use (L/500)			Ultimate load			
	δ (mm)[a]	σ_b (MPa)[b]	ε_b (‰)[c]	q (kN/m^2)[d]	σ_b (MPa)[b]	ε_b (‰)[c]	q (kN/m^2)[d]	δ (mm)[a]	σ_b (MPa)[b]	ε_b (‰)[c]
LVDT 3	3.12							58.00		
S. gage 1		10.79	0.65		23.88	1.44			111.59	6.75
S. gage 2		12.15	0.73	6.34	23.88	1.44	16.11		128.84	7.79
LVDT 1	2.25							25.60		
S. gage 3		3.72	0.22		9.43	0.57			67.79	4.10
LVDT 2	1.40							17.30		
S. gage 4		1.45	0.09		2.98	0.18			33.43	2.02
LVDT 4	1.80							25.00		
S. gage 5		1.21	0.073		3.17	0.19			59.43	3.59
LVDT 5	2.25							26.74		
LVDT 6	1.12							16.04		

[a] Vertical displacement. [b] Bamboo stress.
[c] Bamboo strain. [d] Equivalent distributed load.

4.5.4. Effect of cyclic loading

A typical load–deflection curve for cyclic loading on slabs was obtained as illustrated in Figure 4.12. (hysteresis loops). 9 Loading–unloading cycles before slab's failure was applied. It was observed that the load–deflection curves (at all points where the LVDTs were positioned) after load cycling were able to re-trace their initial curve paths for the limited loading cycles used in the investigation. The ability of the slab to retrace their initial loading paths (all LVDTs) and as the gradients of the reloading curves were similar to those of the initial loading curves signify that there was little stiffness degradation. However, the reinforcing bamboo strips were not able to dissipate energy without small permanent deformations after service load (remaining 1.25 mm deflection).

4.6. Conclusions

Laboratory test was carried out on two-way concrete slab reinforced with bamboo strips from *Phyllostachys Pubescens* bamboo that was subjected to concentrated load. The experimental failure load under cyclic loading was approximately 148.39 % and 110.91 % of the theoretically predicted values by FEM and ultimate punching shear load following BS 8110 [36] respectability. Cracking of the concrete initiated at the central point of the slab and radiated towards and near to the centre of the edges. Collapse of the slab occurred through punching shear load. The results showed that even though theoretical calculations predicted concrete crushing and tensile failure of bamboo strips the slab failed through punching load. The implications of these findings show that FEM analysis and DELCAR have good precision in its application on treated bamboo strips for concrete reinforcement. Also it can be concluded that the gravel coating treatment on bamboo strips can be safely used and its role is achieve successfully.