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Innovations in using bamboo as a structural load bearing element: Experimental performance evaluation

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Abstract: Bamboo has been used in housing since time immemorial but its use has been restricted as a load distributor in roofs. Limitations like the variability in the properties of bamboo with topography and environment have been a deterrent to standardisation of bamboo based technologies for housing. Moreover, the absence of the cost effective test set-up for ascertaining the structural safety aspects of bamboo structures, at decentralised locations, have prohibited the massive use of bamboo in building construction. Addressing these limitations and various research gaps in using bamboo as the main load bearing material in building construction, the present experimental study evaluates the load carrying capacity of the innovative bamboo based structural beam elements Split Bamboo Infill Concrete Arch, which were tested in full sizes in a specifically designed test set-up. The highly encouraging results as obtained from the load deflection analysis of the beam elements put across a strong possibility of using bamboo as a structural load bearing element for building construction. The simplicity and ease in the installation of the test set-up makes it possible for envisaging large-scale housing projects using bamboo. The massive application of bamboo in construction will not only solve the problem of affordable housing but will also address the environmental concerns.

Keywords: Bamboo, green buildings, affordable housing, environmental concerns.

INTRODUCTION

Growing concern over the impact of increasing Green House Emissions on the environment have prompted innovations in construction technology that would substantially reduce the carbon footprint of the building construction and building maintenance. These building integrated climate mitigation strategies have prompted the researchers to explore the various natural materials and composites which satisfy the structural requirements for construction and are less polluting.

Bamboo has been used in building construction since times immemorial but its potential has not been fully utilized. Inspite of the various inherent advantages of bamboo, its

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functional usage has been restricted as a load distributor in roofs (Hidalgo, 2003). Bamboo is a fast, naturally growing, renewable material, having the unique property of producing harvestable culms throughout the year for several decades. Moreover, unlike long gestation period for trees, bamboo culms require regular harvesting from the time the culms become 3-4 years-old, to keep the bush healthy, thus assuring the continuous availability of bamboo. However, it should be noted that bamboo is an intelligent functionally graded material and its properties vary with the topography and climate (Gnananharan, 1991; Nogota and Takahshi, 1995; Hidalgo, 2003). Moreover, bending test with short span (in the order of 700mm) does not reflect the actual potential of bamboo because in short span testing the specimens invariably fail due to crushing or shear even at lower loads (Gnanaharan and Janssen, 1995). As pointed out by Gnanaharan and Jansen, 1995 the importance of testing bamboo in full sizes has been emphasized by Meyer and Eukelund, who commented as early as 1924, that 'bamboo must be accepted as it is naturally, should be tested in full sizes and in the same way as it is used in structures'.

In the background of the above remarks and extending the studies of Sudhakar, 2006 and Sudhakar *et al.*, 2007, Chugh *et al.*, 2009 documented the preliminary scientific experimental findings on 'twin vertically separated half split bamboo parabolic tied arches with cement concrete infill' as a structural load bearing element. A photograph of such an arch is shown in Figure 1. The initial success in using cost effective test setup (as shown in Fig. 2) for testing the entire arch specimen was very encoraging. Hence, using this test set-up and employing the load deflection criteria under various loading conditions, detailed test methodology for testing and evaluation of the arch specimen was drawn upon. The present study gives details of the innovative test set-up used for the structural performance evaluation of the bamboo-based structural beam element Split Bamboo Infill Concrete Arch (SBICA) as above. The results of the load deflection analysis of two arch specimens which were tested in full sizes in the specifically designed test set-up under uniformly distributed loading condition have been used for evaluating the structures.

DESCRIPTION OF THE BAMBOO BASED ARCH SPECIMENS

The two arch specimens, referred in the present study as arch B1 and arch B2, were constructed of span length (L) 2.84 m and 2.79m with effective rise of 0.39 m and 0.40 m respectively. The bamboo used in the arch segment of the specimen is *Bambusa*

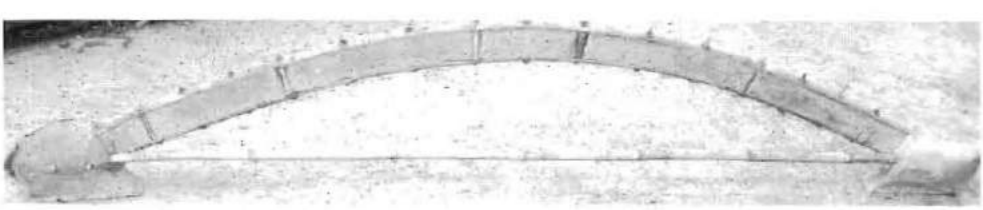

Figure 1. Photograph of the Arch Specimen

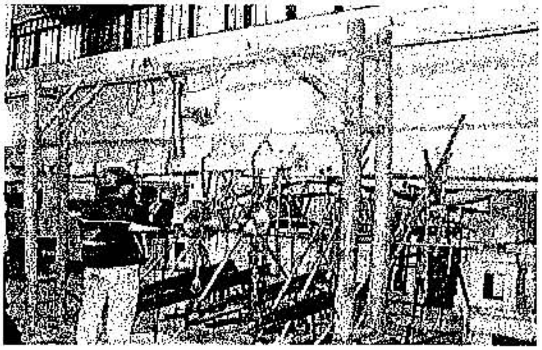

Figure 2. Instrumental setup for testing the structural strength of the arch specimen (Chugh *et.* al, 2009).

pallida and that used in tie element is *Dendrocalamus strictus*. Young's Modulus of both the types of bamboos has been taken as 1.5×10^7 kN/m². The outer diameter of tie is 25 mm for arch B1 and 34 mm for arch B2 while the average thickness of bamboo is 7 mm and. The average outer radius of the upper bamboo of the infill arch segment is 16 mm for B1 and 18 mm for B2 while the outer radius of lower bamboo of the infill arch segment is 17 mm for B1 and 19 mm for B2. The Young's modulus of concrete infill is 3.6×10^7 kN/m² since its f_{ck} arrived at is 52.8N/mm². The depth of the rectangular concrete section in the infill is 92 mm for the arch specimen B1 and 94 mm for the arch specimen B2, with breadth 4 cm.

LOAD DEFLECTION TESTING METHODOLOGY

Figure 2 shows the test setup for evaluating the structural performance of the arch specimen in full sizes, under in plane loading conditions (Chugh *et.* al, 2009). Figure 3(a) shows the schematic sketch of the test setup while Figure 3(b) shows the force transfer mechanism in the test set-up. To test the structural performance of the arch specimens, a comprehensive test procedure was evolved, in which the arch specimens

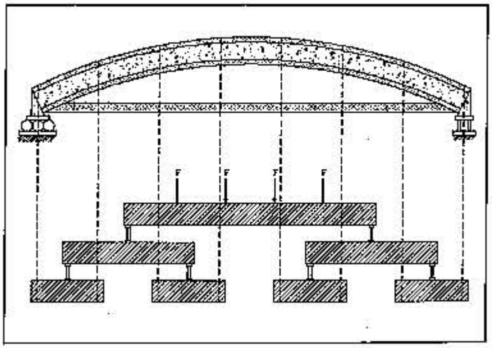

Figure 3(a). Schematic sketch of the test set up showing the testing of the structural properties of the full size arch specimen

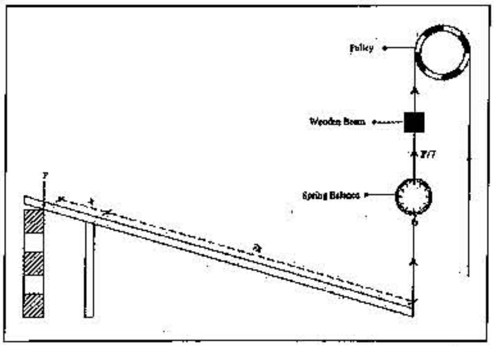

Figure 3(b). Force Transfer Mechanism used in the test setup were subjected to five forms of loading *i.e.* uniformly distributed loading - for the full span, left half span, for the right half span, for the centre half span and the crown point loading. However, in the present study, the results of the load deflection analysis of the two arch specimens subjected to in-plane uniformly distributed loading condition are reported.

The experimental test set-up

The arch specimen was made to rest on a hinge support on one side and on a roller support on the other. The in-plane loading is ensured, by holding the arch vertical with the help of suitable lateral supports. For the application of the load on the arch specimens which are to be tested in full sizes, lever arm method was used. The load was applied through the effort arm. As the fulcrum was hinged, the load arm generated the required load as shown in Figure 3(b). The arms ratio for loading was kept as 1:7. The base for mounting the hinge for the fulcrum was made with a bamboo column, which in turn was locked to the strong floor. The lever arm was made up with steel section ISMB 100, as per the design to resist the required bending moments. Four such force arms of four levers equispaced were connected through the spring balance to a common wooden beam as shown in Figure 3(a) and Figure 3(b). The wooden beam was pulled using the chain block pulley arrangement. This chain block pulley was put up on a bamboo frame.

The uniformly distributed loading was applied on the arch specimen using a 'wiffle tree' network as shown in the Figure 3(a). All the members of the wiffle tree were made up of wooden beams. The load 'F' was applied at the four equispaced centre symmetric points on the top beam using the lever arms. The chains were suspended from the arch to act as supports to the wiffle tree network. The tension generated in the suspended chains due to application of load on the wiffle tree network pulls the arch in a uniform manner generating the required uniformly distributed loading condition. To ensure further distribution of load, an inverted angle is put on the point where the chain rests on the arch.

The load was applied on the arch specimen by pulling the chain of the pulley, as shown in Figure 3(b), for generating 0.5 mm vertical deflection at the crown point. After achieving the required deflection, the loads were recorded in the four spring balances. Vertical deflection at the left quarter, right quarter and horizontal deflection of the roller support were also recorded using dial guages.

Quantifying the structural performance of the arch specimens

The structural performance of the arch specimens B1 and B2 was evaluated in the specifically designed test set-up, as described above, for the various forms of loading conditions, however, in the present study, only the load deflection analysis of uniformly distributed load throughout the span length is discussed. The arch specimens were subjected to a cycle of 'loading, unloading and reloading' for gradually varying uniformly distributed loading. Figure 4 shows the behaviour of the arch specimen under the gradually varying loads for the cycles of loading, unloading and reloading. From the response of the arch specimen to the cycle of loading, unloading and reloading, it was seen that the arch specimen B1 got stabilized at the 15th cycle of loading *i.e.*, during the load interval 318-333. Thus, for the quantification of the structural performance of the arch B1, the deflection behaviour of the arch during the 15th cycle of gradually varying loading condition was considered. Similarly the behaviour of arch B2 got stabilized in the 14th cycle of loading during load interval 246-275. Arch B1 was loaded upto 10.18 kN in the 15th cycle while arch B2 was loaded upto 8.47 kN in the 14th cycle. Figure 5 shows the deflection behaviour at various points on the arch B1 *viz.* crown, left quarter span(L/4), right quarter span(L/4) for the gradually varying loads at the 15th cycle of loading. Figure 6 shows the out-of-plane failure of the arch specimen B1 after it was subjected to several cycles at varying load conditions upto a load of around 10 kN.

RESULTS AND DISCUSSION

The results of the load deflection analysis of the arch specimens are very encouraging. The total load carried by arch B1 was 10.18 kN and that carried by arch B2 was 8.47 kN. This load consists of two parts *i.e.* the load required for the settling of the arch and the remaining which causes the deflection. For arch B1, the load required for the setting was 2.46 kN while that required for the arch B2 was 1.13 kN. For the load-deflection analysis, the deflection values are considered only after the arch has settled down. The maximum vertical crown deflection observed in the specified cycles in

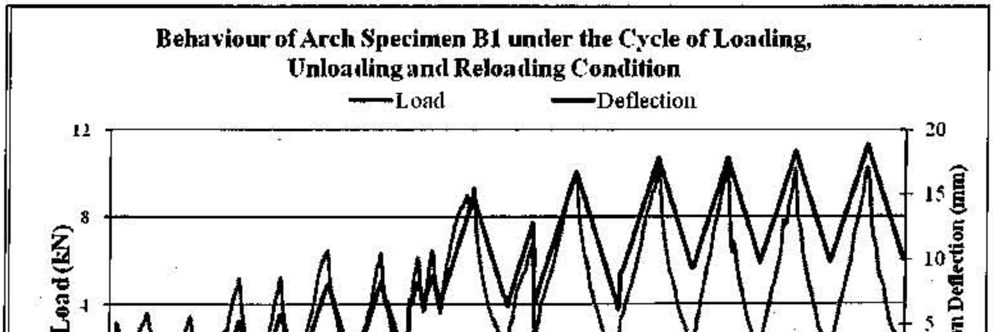

Figure 4. Behaviour of the B1 Arch under the gradually varying loads for Cyclic Loading, Unloading and Reloading conditions

arch specimen B1 and B2 was thus 8.3 mm and 6.94 mm respectively. Vertical deflection of a member is one of the lead criterions for deciding the safety of the structure. The limiting condition for vertical deflection is fixed in such a manner so that the deflection of a member shall not impair the strength or efficiency of the structure. The maximum allowable deflection on the member is given to be (span length) / 250 when there are no partitions (BIS-IS 456). Applying the above limiting condition for arch specimen B1 of 2840 mm span length and arch specimen B2 of span length 2790 mm, the maximum allowable deflection is 11.36 mm and 11.16 mm respectively. Thus the vertical deformations observed at the crown are within the permissible limits for both the arch specimen.

Structural analysis using equilibrium of moments and forces allows us to calculate the forces in the arch and the tie from the recorded values of deflection. The horizontal deflection at the roller end for arch B1 was 6.4mm and for arch B2 was 6.83 mm for the loads specified above. For these loads the axial force is maximum at the base and is 5.2 kN for arch B1 and 4.78 kN for the arch B2. The tensile force in the tie of arch B1 is 1.17 kN and in arch B2 is 2.22 kN. The stress in the arch section is 1.24 N/mm^2 for arch B1 and 1.05 N/mm^2 for arch B2. The maximum compressive stress levels for *D. strictus* is 35.9 N/mm^2 and that for *B. pallida* is 54.0 N/mm^2 (BIS-NBC, 2005). Using a factor of safety of 3.5, the allowable compressive stresses would be 10.26 N/mm^2 for *D. strictus* and 15.43 N/mm^2 for *B. pallida*. Therefore, the stresses generated in the arch segment of the specimen are well within the safe limits. Moreover, in the arch section, the compressive stress is primarily taken by concrete. The compressive strength of the concrete used (f_{ck}) was 52.8 N/mm^2. Since the compressive stresses are much lower than the actual capacity of concrete, it leads to a strong possibility of using other local materials easily available in the country side like dung, rammed earth and their combination, as infill materials. The tensile stress generated in the tie is 4.67 N/mm^2 for arch B1 and 6.5 N/mm^2 for arch B2. The tensile stress as per literature for bamboo is in the range of 12-53 N/mm^2 and is reported to be able to reach even 370 N/mm^2 (Ghavami 1995, 2005). Thus both the compressive and tensile stresses are well within the allowable limits.

The deformation pattern of the arch specimen B1 under uniformly distributed loading condition is symmetric, as shown in Figure 5. Bradford (2007) has indicated that the lowest value for in-plane symmetric buckling load q is governed by the equation $q=(8\delta^2 E I_x f) / L^4$, where E is the Young's modulus of the arch element, I_x is the moment of inertia around major principal axis of cross section of the arch, f is the effective rise and L is the span of the arch. The value of symmetric buckling load thus calculated is 181.5 kN for arch B1 and 234 kN for arch B2. The f_{ck} of concrete used is 52.8N/mm^2. Hence, the compressive forces which the arch can take are of the order of around 222 kN for arch B1 and 240 kN for arch B2. To generate forces of this order would require loading the arch B1 upto 75.86 kN and arch B2 upto 86.07 kN. Thus, the arch specimen is likely to undergo in-plane buckling failure before getting crushed.

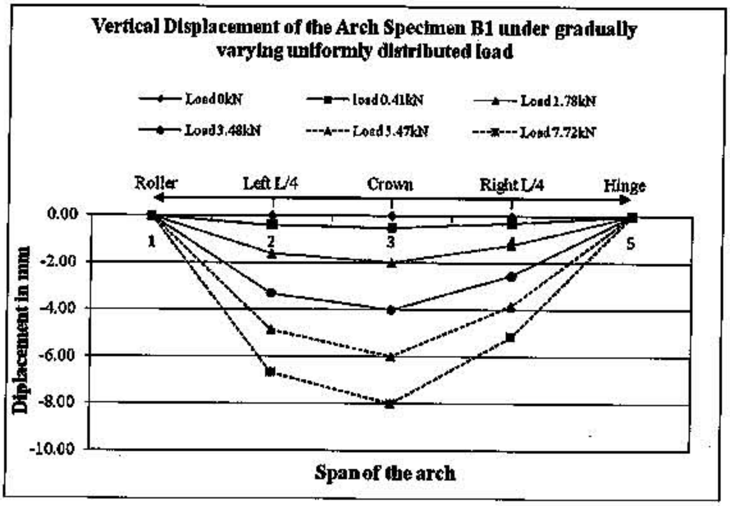

Figure 5. Deflection behaviour of the Arch Specimen B1 under gradually varying uniformly distributed load

The present test set-up is able to load the arch specimen up to 10 kN in a uniformly distributed loading condition before failure as shown in Figure 6. It is quite encouraging to note that upto this loading, in both arch specimens, neither the concrete surface at the tie joint nor the concrete in arch segment had developed any cracks and even the half split bamboo had not shown any forms of splitting or cracking at the bolted regions. It was observed that the failure of the arch specimen was due to lateral out-of-plane buckling. By judicious use of lateral supports (purlins and diagonal cross ties), the lateral out-of-plane buckling could be easily constrained and therefore these arch specimens could easily take higher loads than the present value of 10 kN. Thus, a roof structure for a room of dimension 3 m x 4 m which is required to carry an imposed load of 1.5 kN/m^2 and dead load of 1.0 kN/m^2 with a factor of safety 1.5 on design load as per BIS-NBC, 2005 specifications, can be designed using 4 arch specimens as shown in Figure7.

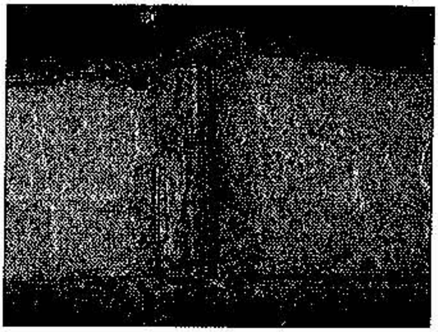

Figure 6. Out of plane failure of arch

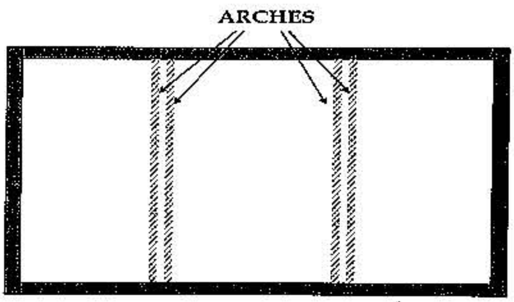

Figure 7. Twin Half Split vertically separated bamboo parabolic tied arches with concrete infill

The cost effective equipment would however need further refinement. In the present setup, the force arm is not always horizontal but makes an angle as it is pulled up or moved down through the pulley contraption. Thus the load which gets transmitted is to be multiplied by the cosine of the angle the force arm makes with the horizontal. This angle varies with each incremental application of load. So, an area of further research is to modify the present cost effective set-up to overcome this limitation. Also, further research is required to enable the set-up to provide higher loading.

CONCLUSIONS

The structural performance evaluation of the 'twin half split vertically separated bamboo parabolic tied arches with concrete infill' using the load deflection criteria suggests that the arch specimen so fabricated is able to satisfactorily function as a main load bearing element. It thus puts across that bamboo could be effectively used as a structural load bearing beam element for building construction. These arches are a 'green' and 'economical' solution for housing, especially in the rural areas. Though the properties of bamboo vary with location and climate yet, the 'cost effective' and 'easy to install' test setup enables the evaluation of the structural performance of the arch specimens at decentralised field locations where mass scale replication of the arch specimen is required. Moreover, it enables the evaluation of the structural performance of the arch specimens of full sizes giving further assurance of their safety.

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