Work in Progress – Pushover Test of Bamboo Portal Frame Structure

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Abstract – Structural applications of indigenous materials such as bamboo are an integral part of sustainable development. The use of natural materials for construction, however, is often limited to cultural-based traditions with little or no standardization. To develop sustainable construction materials, in both an engineering and cultural sense, one must evaluate the traditional building techniques in terms of engineering standards and develop equivalent design methodologies to assess and improve structural performance. In May 2008, a team from the University of Pittsburgh traveled to the Darjeeling region of northeast India to survey indigenous forms and methods of constructing bamboo structures. This paper focuses on the bamboo structures and connections that were observed at the St. Joseph's School in Mungpoo, India. The objective of the present work is to define an engineering basis for non- or marginally-engineered connections appropriate for indigenous vernacular construction. A preliminary test program of a prototype portal frame is presented and the results described in terms of how they point to the need for additional experimental and analytical research.

Index Terms – Bamboo, frame construction, pushover, sustainability.

INTRODUCTION

In May 2008, a team from the University of Pittsburgh traveled to the Darjeeling region of northeast India to survey indigenous forms and methods of constructing bamboo structures [1]. This paper focuses on the bamboo structures and connections that were observed during this field survey at the St. Joseph's School in Mungpoo. These structures may be considered to be marginally-engineered and provide representative details for the prototype structure discussed herein. The prototype structure is a single story four-classroom building (Figure 1a and b) consisting of a reinforced concrete grade-beam foundation with rubble infill (Figure 1c) supporting reinforced concrete plinths with multiple (two or four) bamboo culms forming single columns (Figure 1c). The culms are connected to the footing using a grouted reinforcing bar connection. Bolted connections are used to connect primary roof framing (Figure 1d) and infill panels to the columns. The resulting structure consists of five two-dimensional portal frames in the 'short direction' and two multi-bay frames in the long

A) FRONT ELEVATION

B) END ELEVATION

C) CONCRETE GRADE-BEAM FOUNDATION WITH RUBBLE INFILL.

D) BOLTED CONNECTIONS USED TO CONNECT PRIMARY FRAMING.

FIGURE 1
PROTOTYPE STRUCTURE – SINGLE STORY FOUR-CLASSROOM BUILDING.

direction. The infill wall panels consist of framed sections with fish mouth or saddle joints and woven bamboo infills.

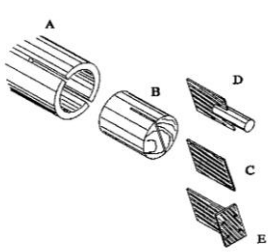
BAMBOO CONNECTION DETAILS

Bamboo structures utilize a variety of connection details. Traditional details vary from lashing to dowel connections while more contemporary non-engineered structures use simple mechanical connectors, such as steel bolts and wire. Engineered bamboo structures have typically employed a variety of proprietary mechanical connections which usually take the form of a connection 'node', such as those examples shown in Figure 2.

The use of nodal connections for bamboo is intended to enforce a 'truss-like' structural behavior: ensuring that only tension and compression forces are carried by the bamboo members. Connection details affect the failure mechanisms associated with the joints. Splitting of bamboo is often a critical limit state; thus a connection that limits the flexure that may be imparted into the connected culm helps to mitigate shear-flow (i.e.: VQ/It) induced splitting. Nonetheless splitting, 'block shear' and local crushing failures resulting from the manner by which the culm is connected to the node may also occur [2]. Examples of splitting failures from the St. Joseph's School structures are shown in Figure 3.

A) BAMBU-TEC CONNECTION

B) PAN FRAME-WORKS CONNECTION



C) WOOD-CORE CONNECTIONS

D) SHOEI YOH CONNECTION

FIGURE 2
COMMERCIALLY AVAILABLE ENGINEERED BAMBOO CONNECTIONS [3].

OBJECTIVE

The objective of the present work is to define an engineering basis for non- or marginally-engineered connections appropriate for indigenous vernacular construction. Use of indigenous materials and vernacular non-engineered building methods constitute a large portion of housing in the world. It is not believed that engineered nodal connections (such as those shown in Figure 2) represent practical alternatives for widespread indigenous adoption. Therefore, the experimental program focuses on the bamboo connection details used at the St. Joseph's School in Mungpoo (Figure 1). The purpose of this experimental study is to establish the physical behavior of a selected prototype structure. The results will be used to validate future modeling efforts. Additionally, the test method/protocol and infrastructure to conduct similar pushover tests is established.

PORTAL FRAME

The prototype structural system to be investigated is a portal frame having four-culm column base connections, which are affected by doweled and grouted connections to a concrete plinth (see Figure 1c). The column-to-roof joist connections are comprised of multiple single bolt connections shown in Figure 1d and schematically on Figure 4. Individually, each connection is a pin; however, the multi-culm geometry results in a moment resisting connection as a couple is generated between bolts and culms comprising the transverse framing (Figures 4d and e). The pinned nature of the individual culm connections limits the introduction of flexure into the culms. The 'staggered' bolt pattern limits the high local shear and flexure that would occur between adjacent bolts in a single culm.

The result is a three dimensional connection, with the header beams (long direction of building) connecting out-of plane and constraining the in-plane geometry of the connection. The experimental program, however, is limited to two-dimensional portal frame behavior in the short direction of the building. Nonetheless, the out-of-plane headers are included to both enforce the geometry of the connection and to affect the correct in-plane behavior. It is anticipated that as the joint deforms, the out-of-plane culms provide resistance to shear distortion of the connection (racking) that enhances the in-plane moment behavior.

The prototype frame was constructed in the Laborátorio de Estruturas e Materiais (LEM-DEC) at Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio). The structural system investigated is a portal frame, constructed of water treated *Phyllostachys aurea*. The experimental program is limited to the two-dimensional portal frame behavior with the out-of-plane movement braced. A cyclic pseudo-static pushover test was conducted to capture the behavior of the overall frame and local behavior of the connections. The initial results of the experimental study of the prototype frame are presented.

Preparation of the prototype frame and test set-up was conducted by the lead author with the assistance of both PUC-Rio students and NSF-supported undergraduate students from the University of Pittsburgh. As such, this test program has developed specific test infrastructure at PUC-Rio and served as research training for US and Brazilian undergraduate students.

(A) COLUMN SPLITTING NEAR SAWN END

(B) BEAM SPLITTING NEAR SAWN END AT DOWELLED AND LASHED JOINT

(C) SEVERE SPLITTING AT SAWN ENDS OF ROOF RAFTERS

(D) SEVERE SPLITTING INITIATED BY PRESENCE OF BOLTED CONNECTION

(E) INITIATION OF SPLITTING AT BOLTED CONNECTION

FIGURE 3.
EXAMPLES OF ST. JOSEPH'S SCHOOL STRUCTURES' TENDENCY OF BAMBOO TO SPLIT AT BOLTS AND JOINTS [4].

EXPERIMENTAL SET-UP

The prototype frame was braced to prevent out-of-plane movement, as shown in Figure 5. The horizontal members were braced using two steel channels that were cantilevered from an existing reaction frame. The channels served as a guide for the lateral members of the frame. Four steel angles were placed at four points along the length of the lateral members to center them within the guide.

The frame was instrumented using linear variable displacement transducers (LVDTs), placed at the top of both columns below the lateral members, at the peak of the roof truss and at mid-height of both columns. Also, dial gages were used to monitor the displacement of the columns bases. The lateral load was applied using a tension cable and the load was recorded using a 50 kN tension load cell.

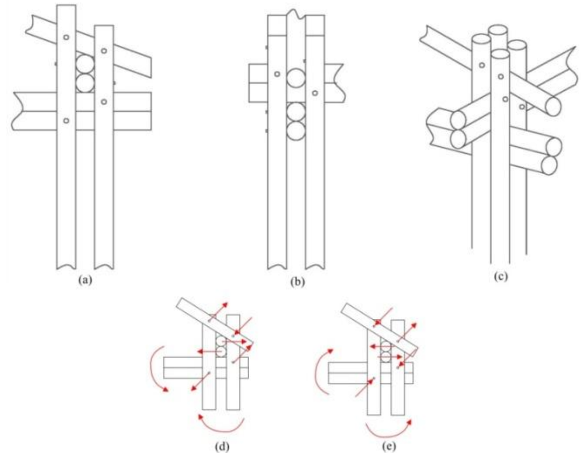


FIGURE 4
PROTOTYPE COLUMN – ROOF TRUSS JOINT
(A) LATERAL ELEVATION, (B) LONGITUDINAL ELEVATION,
(C) AXONOMETRIC DRAWING, (D) OPENING MOMENT AND RELATED FORCES,
AND (E) CLOSING MOMENT AND RELATED FORCES.

The lateral load was applied using a manual winch anchored to an external reaction frame. The test was conducted in 'load control' to the degree possible using a manual ratchet winch. At each load step, visual measurements and LVDT measurements were recorded and a photo was taken. The frame was loaded and unloaded to capture the hysteretic behavior of the frame and connections.

FIGURE 5
PROTOTYPE FRAME READY FOR TESTING.

RESULTS

The majority of the test data was collected manually or recorded with photographs. The LVDTs provided some initial data, however the deflection was greater than the instruments capability. The load-deflection response of the prototype frame shown in Figure 6 illustrates the behavior at the top of both columns under the load cycles that were applied. The maximum deflection recorded was 562 mm at a lateral load of 760 N. This displacement corresponds to a lateral drift ratio of 0.26. As seen in Figure 6, the stiffness of the frame at this deflection was negligible.

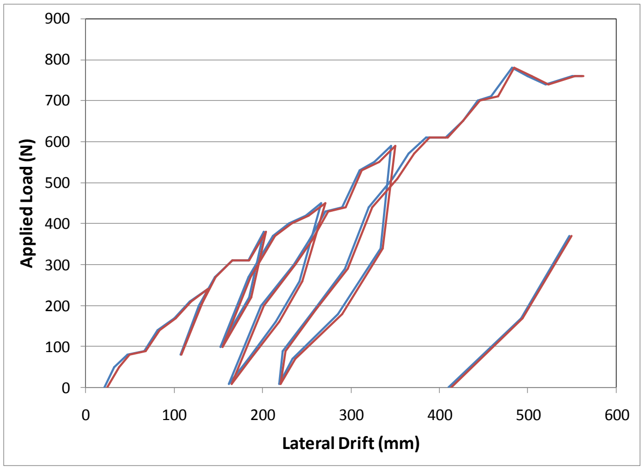


FIGURE 6
LATERAL LOAD – DISPLACEMENT RESPONSE OF PORTAL FRAME.

DISCUSSION

The anticipated portal frame behavior was relatively rigid column base behavior and moment resistance at the roof-column joint. Both connections exhibited less moment resistance than anticipated. The column bases exhibited a rigid body rotation behavior as the individual culms rocked about their bases. The roof-column connections exhibited greater racking than expected with the out of plane culms providing less constraint than anticipated (Figure 7).

A) PRE-FAILURE B) FAILURE C) POST-FAILURE

FIGURE 7
RIGHT COLUMN-ROOF JOINT EDGE BEARING FAILURE OF LOWER OUT-OF-PLANE MEMBER.

The joint racking shown in Figure 7 resulted largely from the edge bearing failure of the out-of-plane culms (seen in Figure 7c). This observed behavior has led to further study of edge bearing so that it may properly included in models of joint behavior. Further study on the rocking behavior of the column base is also being carried out to quantify this behavior.

SUMMARY

The prototype frame test provided useful information for the further study of the behavior of a bamboo portal frame construction. The pushover test further developed the test method/protocol and infrastructure necessary to conduct similar pushover tests. Future research is being conducted to explore the behavior of the column bases and joint regions.

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