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PRELIMINARY APPROACH FOR A PROTOTYPE OF SUSTAINABLE ANTISEISMIC DWELLING IN NEPAL BASED ON THE HISTORIC VERNACULAR TRADITION

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Abstract. *The effects of the 2015 Gorkha earthquake in Nepal revealed deficiencies in the most recent vernacular architecture, which no longer uses wooden reinforcements due to national anti-deforestation laws. It also highlighted the shortcomings found in reinforced concrete architecture, which is generally scanty and poorly reinforced due to the high import cost of construction steel. The geography of Nepal has led to the development of a wide variety of vernacular architecture using local materials such as stone, brick or earth in the form of rammed earth and adobe walls [1]. Moreover, although its tradition in the construction of vaults is not as prominent as in neighbouring regions of India, Nepal has developed its own tradition in the construction of vaults and domes, which are generally self-supporting and made of brick or adobe with lime mortar. The design of a prototype of seismic house in Nepal aims to use a modular housing unit with rammed earth walls and/or walls made of materials recycled from previous earthquakes, as well as tile vaults with bamboo sleepers, and possibly vegetable fibre grids. These avoid the use of imported materials, favouring km0 and sustainable materials while following local tradition. Several potential housing units have undergone linear seismic analysis on finite element models, with variations in planimetric layout and the types of tile vault, from the simpler barrel vault to the sail vault. Both are analysed searching for the best shape in terms of seismic efficiency, evaluating stress and strain state. The results obtained from this preliminary study clearly show that, under seismic actions, the response from the construction system using depressed sail vaults and rammed earth walls with bamboo reinforcements is more efficient and homogeneous in terms of tension and deformation. This is due to the geometric symmetry which determines the same response in several directions, unlike vaults with a characteristically strong directionality (barrel vault). The seismic response of the prototype described is examined by assessing the influence in terms of thrust and deformation of bamboo reinforcements inside the walls. For this, laboratory tests are used to identify the mechanical characteristics of bamboo to be employed in the finite element modelling and calculation, as the values found in the literature vary depending on the physical and chemical characteristics of the material. This study therefore proposes a more sustainable architectural model with greater antiseismic resistance, always in keeping with local constructive tradition.*

1 INTRODUCTION

The project of an antiseismic dwelling in Nepal aims to merge the characteristics and needs of an antiseismic structure with the architectural tradition of Nepal. The damage caused by the earthquake has steered design towards a modernization of the vernacular architecture, reproducing Western architecture and using reinforced concrete structures. However, these are unsustainable both in environmental and economic terms, given high construction costs. The design of a housing unit prototype is proposed in order to return to the language of vernacular architecture using local materials, but avoiding wood which has become considerably more expensive following the implementation of anti-deforestation legislation. Therefore, a prototype of a dwelling with rammed-earth walls and bamboo reinforcements has been studied. The rammed earth technique, which compacts the soil in formwork using a rammer, is a highly sustainable practice already widespread in Nepal. This technique has been largely researched in the last two decades due to its properties, including good hygrothermal behaviour and low embodied energy. Numerous studies have been carried out on its mechanical characteristics [2-9], seismic assessment [10-12] and energy efficiency [13,14]. The use of structural elements in bamboo (*Bambusa Balcooa*), plentiful in the region, was decided in order to overcome the shortage of wood. Different studies have also been carried out on the physical and mechanical properties of bamboo [16-23] and its application in rammed earth structures [24,25]. The slabs are to be made of tile vaults, which are increasingly gaining international recognition for their durability, economy and ease of construction, as they require no centring [17-19]. Finite element models were created and analysed before the prototype was built in order to identify the type of vaulted dwelling with no fibre grid reinforcement in the type of vault most resistant to seismic stress. This paper reflects this first study. In a second step, this project will focus on the potential improvement of this vault with the insertion of a fibre grid reinforcement, in a departure from previous experiences in the field [30,31].

2 BAMBOO CHARACTERISTICS

In Nepal, bamboo is the natural material most widely used for different purposes, such as the production of tools or the manufacturing of construction elements. As a construction material, bamboo offers many advantages, as it is sustainable and easily renewable, with mechanical properties comparable to timber. One of the main advantages to bamboo is its rapid growth, which means it can also be widely used in areas where there is a shortage of wood for construction, as in Nepal, where the exploitation of forests has been restricted to prevent deforestation [24]. Furthermore, although bamboo is a type of woody grass and not a tree, bamboo forests display similar characteristics to tree forests in terms of their contribution to the carbon cycle, as bamboo retains carbon in its fibres and soil through photosynthesis [25]. Bamboo is part of the *Bambusoideae* grass family and its cellulose fibres, about 2 mm long with an average diameter of 20 μm, are immersed in a wooden matrix. The number of bundles of fibres and their scattering inside the bamboo culm affect the hardness of the bamboo [26]. In order to evaluate the potential use of bamboo ties in the prototype walls, the tensile strength of the bamboo (*Bambusa Balcooa*) samples taken in situ was assessed through laboratory tests.

Given the limited availability of specimens due to the distance from the site, these tests were conducted to compare the tensile strength of the specimens with the values found in literature [21-23], thus selecting proper values for the analysis.

Laboratory tests were carried out on three specimens from a bamboo culm from the *Bambusa Balcooa* species obtained in situ (Fig. 1). Three specimens of different widths and 9.5 mm thick were obtained eliminating the outer skin of the culm to obtain a smooth regular surface (Fig. 2). The first standard specimen [27] has a 20x9.5mm shaped section in the useful segment; the second has a rectangular section of 25x9.5mm, and the third a rectangular section of 50x9.5mm.

Figure 1. Bamboo culm.

Figure 2. Bamboo samples.

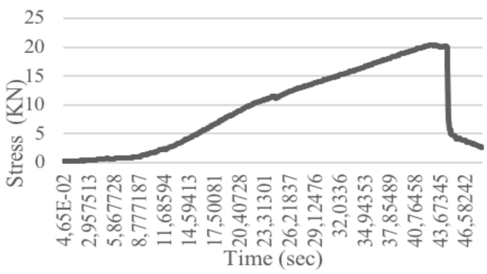
The first specimen, with a section shaped like a bowtie, was subjected to a direct tension test at a velocity of 0.5KN/sec (Fig. 3).

In the test the fibres slid and broke due to shear (Fig. 4). At breaking point a tension of 20.34 KN had been reached, with a tensile strength of 107.2 Mpa.

Figure 3. Traction equipment.

Figure 4. First specimen after the break.

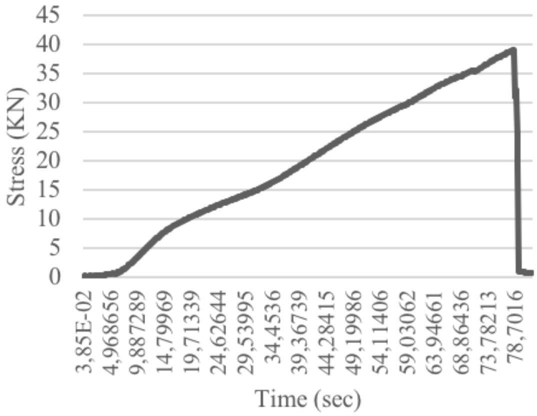
Table 1. Stress trend. First specimen



The second direct tension test was carried out on the specimen with a 50x9.5mm rectangular section. Under the same tensile velocity as that of the first test a break was also observed due to the compression of the ties at the end (Fig. 5). The tension recorded at breaking point was 39.10 KN and tensile strength was 82 Mpa.

Figure 5. Second specimen

Table 2. Stress trend. Second specimen



Finally, a bending test was carried out on the specimen with the 25x9.5mm rectangular section in order to indirectly obtain the tensile value which caused the inner fibres to break during the test. The specimen was subjected to continuous compression at a velocity of 4 mm/min, until the inner fibres broke due to tension (Fig. 6). Bending strength at breaking point was 118.9 MPa and, considering that the fibres under the neutral fibre reach breaking point due to tension when the section is subjected to bending, this value was considered equal to the tensile strength of the specimen.

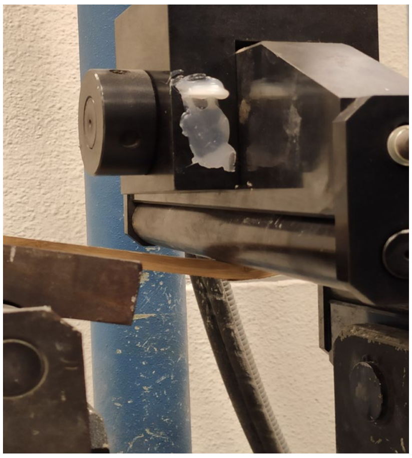


Figure 6. Rupture of the fibres of the third specimen.

Table 3: Stress-strain trend – Third specimen

The mean tensile strength value is 102.7 Mpa. This value should be considered a minimum tensile strength value as not all specimens broke due to the tension of fibres, but because of shear or the pressure of the ties.

Given the difficulties in accessing the location to obtain specimens the number of tests carried out may not be enough to obtain a population of values to define the characteristic tensile strength value. Thanks to the tests carried it was verified that the values obtained are within the range of values found in specialist literature [21-23]. Therefore, it was considered necessary to use the characteristic tensile strength values and other mechanical characteristics of bamboo as detailed by Kaminski et al. (2016), considered valid for all the species in the scheme design phase for buildings with smaller floor plans and elevations.

3 CONCEPTUAL DESIGN OF THE PROTOTYPE

Preliminary analysis with the finite element method was crucial to the definition of the type and shape of the vault to be used, given the extreme vulnerability of vaulted structures to drift. When executing a finite element analysis, the materials must be exactly defined. In this case, given the lack of experimental data, the mechanical properties considered for simple rammed earth are those found in the literature [4-9], reported in Table 4.

Table 4. Rammed earth mechanical properties in the literature

Author	Density [kg/m^3]	Compression [MPa]	Tensile [MPa]	Shear [MPa]	E [MPa]	G [MPa]	Poisson *ν*	Specimen [cm]
Lilley [6]	1870-2170	1.80-2.00	-	-	-	-	-	cube 15
Jaquin [7]	-	0.60-0.70	-	-	60	-	-	10x10x30
Novamooz [9]	2000	-	-	-	-	-	0.33	cylinder d=7 h=2
Bui [4]	2000	-	-	-	100-500	41-180	0.22-0.40	40x40x65
Gomes [5]	1900	0.67	0.13	0.08	200	74	0.35	NZ4297 [15]

The mechanical properties for rammed earth and bamboo used for FE analysis are shown in Table 5 and Table 6.

Table 5. Rammed earth mechanical properties used for the models.

E [MPa]	Compression [Mpa]	Tensile [Mpa]	Density [kg/m^3]
250	2.00	0.20	2000

ºTable 6. Bamboo mechanical properties used for the models.

Author	E [MPa]	Compression [Mpa]	Tensile [Mpa]	Flexure [Mpa]	Shear [Mpa]
Kaminski et al. [21]	17000	20	40	30	2

Linear seismic analysis on finite element models was carried out on several prototypes of housing units with different plans and tile vault types, from simple barrel vaults (Fig. 7) to pendentive domes or sail vaults (Fig. 8). This assumed different values for the height of the springer, rise and thickness, evaluating the tensile and deformative state, in order to establish the best overall shape in terms of seismic efficiency. Since this is a preliminary analysis, no non-linear analysis was carried out due to the highly variable data and computational difficulty.

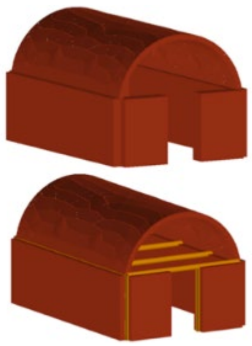


Figure 7. Models with barrel vault.

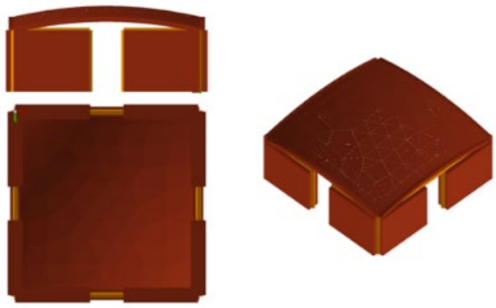


Figure 8. Model with pendentive dome.

Rammed earth walls (45 cm thick) and the tile vault were modelled as shell elements defined by three and four nodes in space and five DOF (degrees of freedom) consisting of three components of translation and two components of rotation in the plane of the element.

In addition, bamboo elements were modelled as beam elements defined by six DOF consisting of three translation components and three rotation components, with a hollow section with a 7.5 cm external radius and 6 cm internal radius.

The analyses were carried out by varying the thickness of the tile vault, from a minimum of 7.5 cm to a maximum of 10 cm. Based on the incidence of bamboo reinforcements assessed for the individual models it can be stated that, regardless of the shape considered, the value of displacements significantly decreased when ties were used, improving seismic response (Fig. 10).

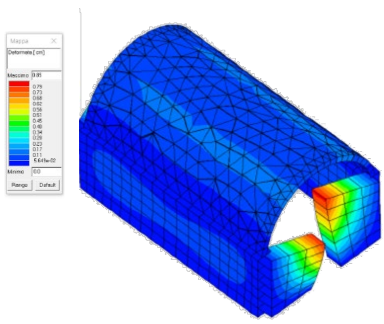


Figure 9. Deformation. Fifth mode. Unreinforced model.

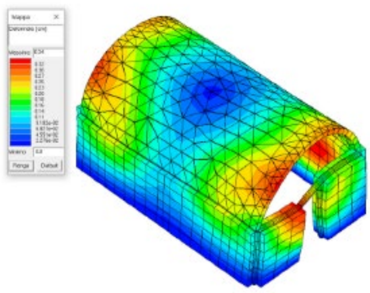
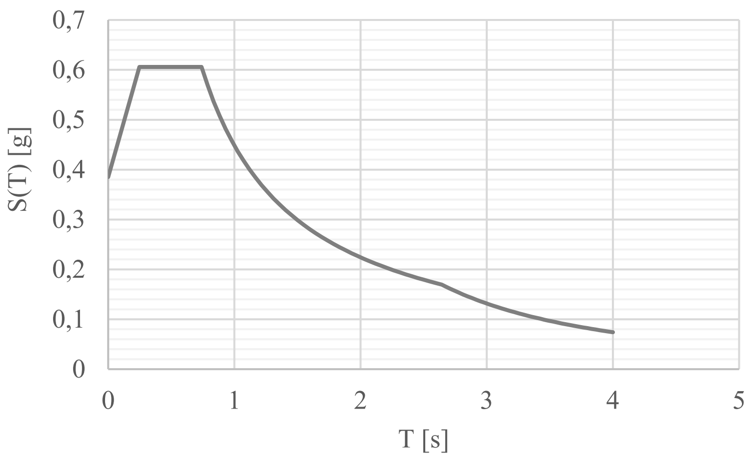


Figure 10. Deformation. Fifth mode. Reinforced model.

The 2015 Gorkha earthquake had a magnitude Mw of 7.8, 15 km deep, the recorded maximum PGA was ~ 0.25 *g*. The design PGA recommended by the Nepal building codes is 0.36 *g* (NBC-105, 1994). Based on the previous data, the acceleration response spectrum shown in Table 7 was considered.

Table 7. Design acceleration response spectrum



Tables 8 and 9 show the period and frequency values corresponding to the first 10 modes of vibration.

Table 8. Modal analysis results-barrel vault model

Modes	Frequency	Period
1	6.81	0.15
2	15.63	0.06
3	15.98	0.06
4	16.42	0.06
5	20.02	0.05
6	21.22	0.05
7	21.66	0.05
8	25.58	0.04
9	25.70	0.04
10	28.36	0.04

Table 9. Modal analysis results-pendentive dome model

Modes	Frequency	Period
1	7.32	0.14
2	8.77	0.11
3	8.77	0.11
4	9.02	0.11
5	9.43	0.11
6	9.91	0.10
7	11.14	0.09
8	11.16	0.09
9	14.02	0.07
10	14.10	0.07

To better understand the seismic behaviour of the models, it is useful to observe the major difference in behaviour between a simpler vault such as the barrel vault and the pendentive dome. The seismic response of the barrel vault model is poorer than that of the model with a pendentive dome. In fact, the deformation and the tensional state of a barrel vault are noticeably influenced in the direction of the earthquake, giving rise to greater deformation if orthogonal to the direction of the axis. In addition, tensile stresses appear in the entire structure which could lead to collapse. In Fig. 13 and Fig. 14, only tensions are highlighted, in order to reflect the peak reached when the seism is orthogonal to the axis, with a maximum value of 6.95 daN/cm^2. In contrast, the response of the model with a pendentive vault is not significantly affected by the direction of the earthquake, and the final deformation appears more homogeneous. Likewise, the tensional state of this model is less critical, considering the decrease of the tensile stresses, with a maximum of 2.12 daN/cm^2.

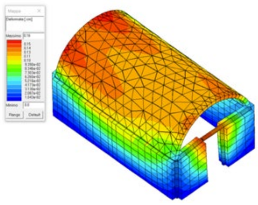


Figure 11. Barrel vault. Strain analysis. Seism: 30%X – 100%Y.

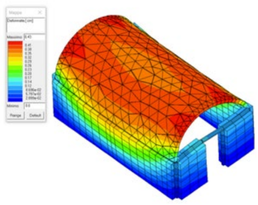


Figure 12. Barrel vault. Strain analysis. Seism: 100%X – 30%Y.

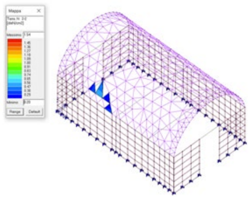


Figure 13. Barrel vault. Tension analysis. Seism: 30%X – 100%Y.

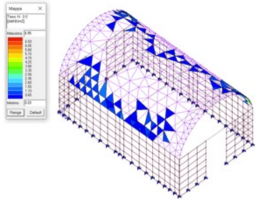


Figure 14. Barrel vault. Tension analysis. Seism: 100%X – 30%Y.

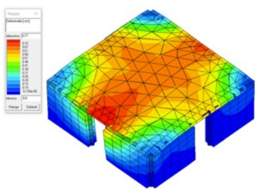


Figure 15. Pendentive vault. Strain analysis. Seism: 30%X -100%Y.

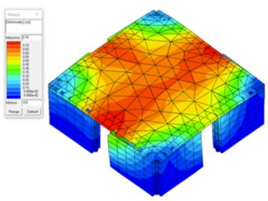


Figure 16. Pendentive vault. Strain analysis. Seism: 100%X – 30%Y.

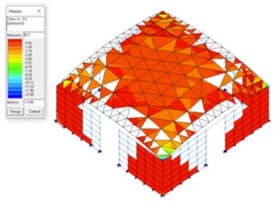


Figure 17. Pendentive vault. Compression. Seism: 30%X – 100%Y.

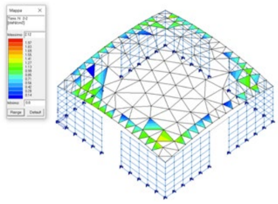


Figure 18. Pendentive vault. Tensile strength. Seism: 100%X – 30%Y.

4 CONCLUSIONS

Preliminary analysis of the models made it possible to identify the advantages and weaknesses of the recovered construction system, in order to move forward with a design which preserves traditional construction techniques while resisting seismic events, through the use of ties. Bamboo ties were inserted in order to ensure maximum sustainability for the project. It should be noted that tensile rupture of the test piece was not reached in any of the cases, and therefore the resistance values obtained should be considered to be minimum. Finally, the HouSe-Nepal project is imbued with the general spirit of the project of an antiseismic housing module born from the reinterpretation of vernacular architecture, better adapted to the environment both in terms of architecture and materials, and in terms of social and economic impact. The dwelling modules and the construction techniques presented in this paper are preliminary approaches to the design of a sustainable antiseismic dwelling in Nepal trying to provide an alternative for Nepalese dwellings which are currently being built with industrial materials such as cement blocks and metal sheets, which often generate unhealthy spaces.

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