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Improving stability of an ecological 3D-printed house - a case study in Italy

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ABSTRACT

Purpose: The structure WASP'S GAIA house printed without beams and columns; therefore, it's not safe enough against earthquake or wind. Moreover, the structure printed layer by layer doesn't present a good stability for build other floor in seismic zones. The aim of this work is to study stability of this house and give new technique to improve stability of the ecological house printed in 3D.

Design/methodology/approach: For resolving this problem we considered the structure printed in 3D is simulated with rammed earth characterized by a horizontaly striped and the basic principles of seismic justification are similar to unreinforced mansory, we use spectral analysis method in order to find a maximum displacement induced by a seismic excitation and robot structural analysis software to analyze the mechanical resistance of the studied structure.

Findings: The center of gravity approaches the twist center, presented in the results, which prove a good stability of the structure when we use circular beams and columns fabricate with wood material. We carried out three analyses: A modal analysis with 4 vibration mode when the cumulative mass reaches 99.98%. A seismic analysis according to the moroccanearthquake construction regulations (RPS 2011). Use natural beams and culumns to improve the stability of a structure with one wall and two walls, in the case of with or without reinforcement can prove a good stability. Compromising between ecology, safety and technology. Increase the mechanical characteristics to increase safety and prevents collapse in the seismic zones. The possibility of exploiting our cultural heritage with the development of other complex design in the field of construction.

Research limitations/implications: The possibility of exploiting our cultural heritage with the development of other complex design in the field of construction. Development the diameter of crane wasp 3D printer.

Practical implications: Exploiting this technology in the case of a natural catastrophic (seism, inundation, pandemic) to build safe and ecological building in the seismic zones. Build safe schools in the poor area for children.

Originality/value: Development the design of GAIA WASP printed in 3D with two walls and other zones to improve the stability of house. Add natural beams and columns made by wood or bamboo inside the house printed with one wall, and two walls. Study the stability of house to obtain the twist centre approaches to centre of gravity. We carried out three analyses: A modal analysis with 4 vibration mode when the cumulative mass reaches 99.98 %, a seismic analysis, and a spectral analysis of the maximum acceleration.

Keywords: Printing, Construction, Improve the stability, Seismic zone, Earth building

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ANALYSIS AND MODELLING

1. Introduction

According to ASTM, additive manufacturing is an assembly process of material printed layer by layer to make objects from 3D model [1], the building in 3D printed started to make evolution with many start-ups and other companies [2-13]. WASP – World's Advanced Saving Project – is a company founded in 2012 in Massa Lombarda, Italy, inspired by the "mason wasp", which builds its own nest with materials collected from the surrounding environment, the company designs and produces 3D printers, GAIA is the first 3D printed ecological house in 2018, and TECLA is the new eco-habitat project created with recyclable and biodegradable materials [8]. The study of stability for a 3D printed structure presents a great challenge because the structure is printed without columns and beams. This article presents a new technique which helps improve stability and print other floors. On the other hand, Crane WASP is a collaborative 3D printing system capable of printing ecological houses with natural materials for the purpose of decreasing greenhouse gas emissions. The WASP'S house printed with a BigDelta printer, a huge printer with 12 m of height implemented with solar energy with no impact on the environment. Despite there are many standards regulating earth construction, these are not enough [14-16] to cover all methods that should be used to build earth houses. These standards have been applied within earth construction techniques, namely, adobe, earth bricks and rammed earth. This article focuses on studying stability on earth construction printed by additive manufacturing technique. Moreover, this study gives much attention to earth building structure design development [17-19], Thus improving mechanical safety of earth building and developing designing models by the use of new 3D printing technology can urge people to adopt this process and promote to sustainable development. Therefore, it can be a way to achieve success known as ETP, that is, Environment, Time and Price. The Moroccan seismic regulation RPC2011 [20] defines some earth construction requirements in adobe, rammed earth, cob or rubber stone with earth mortar. The Crane WASP house is simulated with rammed earth characterized by a horizontally striped and compacted layer by layer [21], and the basic principles of seismic justification are similar to unreinforced mansory. According to many scholars, There are many techniques to improve the strength of Unreinforced Mansory (URM) like Wire Ropes and Carbon Fiber Reinforced Polymer strips (CFRP) [22,23]. In our study After defining the characteristics values of geotechnical parameters for the material, Robot Structural Analysis Software is used to analyze the Mechanical resistance of the studied structures and Response spectrum analysis which measures the Maximum acceleration influenced by the different frequency and damping coefficient is put to test, we propose also a new design in terms of positioning natural columns and beams inside the earthen wall with a test of seismic stability for each one of them in order to demonstrate that adding circular wall can improve the stability of the building.

2. Materials and methods

2.1. The construction of houses by the additive manufacturing technique

Geotechnical characteristic of material

<u>Granulometry</u>

The crane wasp house printed with natural components consisting of two walls, one interior load-bearing and the other exterior. An air gap separates the two walls in which thermoacoustic insulation (rice) is interposed as shown in Figure 1 and Figure 2.

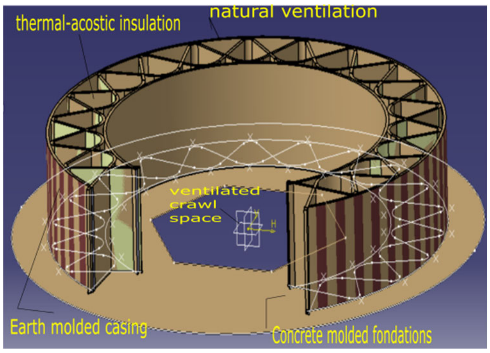

Fig. 1. GAIA Wasp model house in 3D printed

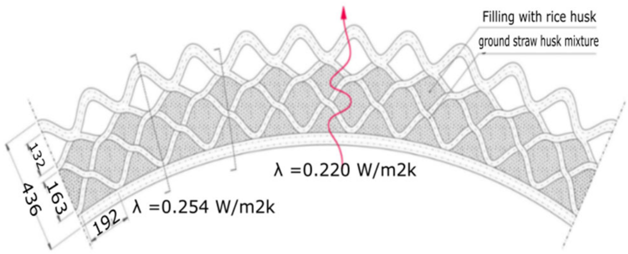

Fig. 2. Description of the earthen wall with rice insulation [8]

Construction material:

- 25% of earth taken from the site,
- 30% of clay,
- 40% of limon,
- 30% of sand,
- 40% of straw chopped rice,
- 25% of rice husk,
- 10% hydraulic lime.

These elements maintain a confortable temperature inside in winter and summer, and acheive the following perforformance as shown in Table 1.

The lime, sand and clay components with rice have been broadly used by the Chinese dynasty as shown in (Fig. 3) to improve the mechanical strength and durability.

Table 1.
Geotechnical characteristic of material

Plasticity			Compatibility		Active clay
Plasticity index	Liquidity limit	Plasticity limit	W_{op}	D_{max}	VB
8	40	12	8	2	12

W_{op}: optimum water content determined by the proctor test
D_{max}: maximum dry density
VB: the volume of mythelene blue absorbed by the clay particles

Fig. 3. a) Tonguan city wall (413CE), b) HAKKA earth building complex (-1555) [24]

Foundation

The foundation of the earthen wall of the GAIA house was built by cyclopean concrete with a filling sole whose width to the thickness of the wall estimated at 40 cm in case of one level and 1.5*40 cm in case of two levels.

2.2. Mechanical characteristic of the earth wall

There are many studies on mechanical properties of earth building techniques: adobe, rammed earth and compression brick earth. In this study, the technique used to make an earth building is the 3D printing. The compressive strength depends on the material vacuum index, its water content and the time setting of 3D printer. The test is performed with the use of at least 6 cylindrical tubes whose size is 16*32 cm or 25*50 cm in order to define the characteristic minimum resistance f_c=0.5 N/mm^2 [20], the Young's modulus suggested by New Zeland standard E_{cb}=300 f_{cb} [17] and the poisson's ratio estimated at m_{cb}=0.1 [21]. For variety of materials, the Poisson's ratio should be estimated between 0.1 and 0.2 [21,25]. Earthen blocks, when tested, must have an average strength of 20 kgf/cm^2 for class 20, and 30 kgf/cm^2 for class 30 [26-34]. These results are obtained after preparing the soil and applying the Brazilian mechanical tensile testing [28] as shown in the results below.

Compressive strength

$$R_C = 10.\frac{F}{S} MPa \quad (1)$$

R_c: Compressive strength of the blocs in MPa
R_c=2.45 MPa
F=20 kgf/cm^2 For the maximum load supported by the two half blocks .
S=40 cm^2 Average surface

Tensile strength

$$R_t = 0.9102 \frac{F}{\pi le} \quad (2)$$

or

$$R_t = 18.\frac{F}{\pi le} \quad (3)$$

The tensile strenght test depends on vacuum index and the thixotropy of material.

Therefore:

R_t=0.553MPa

in which:

R_t: The tensile strength of blocks
F: equal of 20 kgf/cm^2 for class 20, and 30 kgf/cm^2 for class 30

l=290 mm:block width
e=70 mm: block thickness

For several authors, the determination of Young's Modulus and the Poisson's ratio remain insufficient to know the mechanical properties of an earthen material.

Shear strength

Shear strength is considered f_{ec}=0.08 MPa [20]

These tests allow the determination of elastic deformation modulus.

2.3. The 3D printing process

The printed layers have a thickness of about 45 cm. To ensure adherence between layers, the water content and properties of material plays an important role in the rising of capillarity of wall and damp phenomena [35]. On the other hand, the time setting between the printing of layers and the compaction energy of the nozzle had an influence on the maximum dry density and thus on the material resistance. The maximum height of load-bearing earth wall is an average of 4 m for a single story construction and 6.5 m for two-story construction. The earth wall shown in Figure 4 printed with "BigDelta", a huge printer with 12 m of height implemented with solar energy as shown in Figure 5. It works with 60 volt and 220 volt. The motors used in the extruder are 400 watt to reduce the vibrations of the printer. The quantity of material carried is 40 kg-60 kg. The velocity of printer is 400 mm/s based on the quantity of material inside extruder [8].

a) b)

Fig. 4. (a) Earth wall design and (b) BigDelta Wasp 3D printer [8]

The 3D printing of the earthen structure involves a software part and a hardware part as summarized in the Figure 5, the software part includes:

- modelization,
- slicing,
- conversion to the G-code format which represent the machine.

The second hardward part including The extrusion technique as shown in (Fig. 4a) is based on:

- data preparation of material
- material preparation.

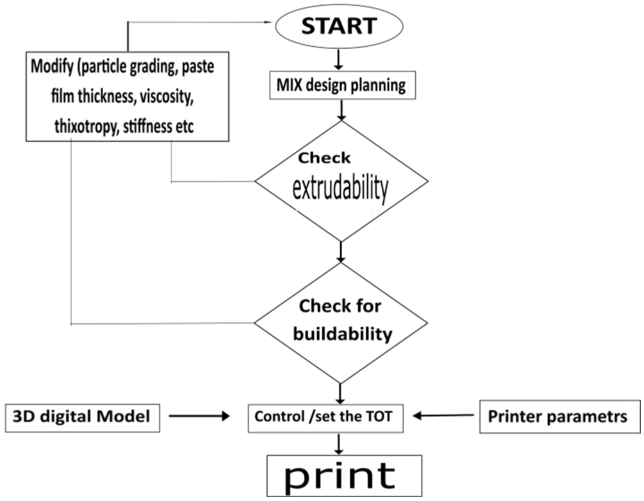

Fig. 5. 3D Printing process of a earthen house

2.4. Stability study of earth house

As regard to the stability, we can use natural columns and beams like wood or bamboo in the case of GAIA house, The stability of columns was subjected to compressive load based on their geometry in a time where the structure does not Undergo any change of shape and all its reactions are deleted. At this moment, we say that the structure is stable internally [36]. Generally, the earth wall was subjected to the laterally centered vertical loads and the laterally eccentric loads. The ruptures appear as vertical cracks, and the load is transmitted from floor to the roof during the surface eccentricity t/3 (t is a wall thickness) due to the impact of load [20].

Eccentricity at the head and feet of the earth wall is given by

$$ei = \frac{M_i}{N_i} + e_{hi} + e_a \geq 0.05t \qquad (4)$$

e_{hi}: Eccentricity at the head or foot of the earth wall due to transverse loads (wind or earthquake);

e_a: Accidental eccentricity to take account of uncertainties and the non-straightness of the wall;

$e_a = \frac{heff}{450} \approx 0.0089$ in which hef f is the effective height of the earth wall;

and

The ultimate effort applied N_i.

$N_i \leq K \otimes N_u$

$N_u = f_c A_m$

f_c=0.5N/mm^2: Compressive strength of the earthen wall.
A_m =40 cm^2: Earth wall section
$\varnothing$=1 In seismic calculation.
k is a reduction factor which depends both on the slendereness and eccentricity. The wall is subjected to transverse actions by the wind or earthquake which the maximum ultimate horizontal bending moment caused by them. And the lateral resistance depends on the support conditions presented by the support reaction:

$$R_C = \left(1 - \frac{2}{3}C\right)\left(P + \frac{1}{2}W\right) \quad (5)$$

C: seismic coefficient.
W: self weight of structure.

The slenderness of an earthen wall is given by:

$$Sr = \frac{av.h}{t} \quad (6)$$

Therfore: Sr~18 in which:
av = 2 owing the wall taken in our study supported laterally and embedded at its base.
h: Height of the earth wall=4 m.
t: Thichness of the wall=45 cm.

3. Results and discussion

3.1. Structure without reinforcement

To improve the stability of the WASP's GAIA structure printed with one wall as shown in Figure 6 and Figure 7, we develop internally a house design with two walls as shown in Figure 8 and Figure 9. In order to support the load of multiple floors on which we can put columns connected with beams as shown in Figure 10, Figure 11 and Figure 12. The structure class is 3 for ordinary earthen construction with the importance coefficient of 1.2 according to the antiearthquake Moroccan regulation for earthen constructions 2011. We worked in the site of S2 its coefficient S=1.2 for thick soil of 40 m, and in the seismic zone 2 with seismic coefficient of 0.16.

The resulting lateral seismic force at the base of the earthen construction is:

$$V = S.I.C.W \quad (7)$$

S: Site coefficient,
I: Importance coefficient,
C: seismic coefficient,
W: The load bore in the weight of the structure is W=G+ΨQ, with Ψ=0.2 (the dynamic coefficient of the building),
G: exploitations loads,
Q: permanent loads.

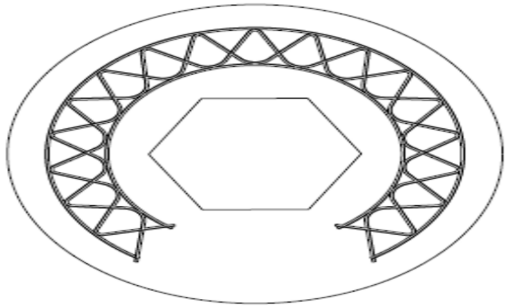

Fig. 6. The typical plan of the structure with one wall

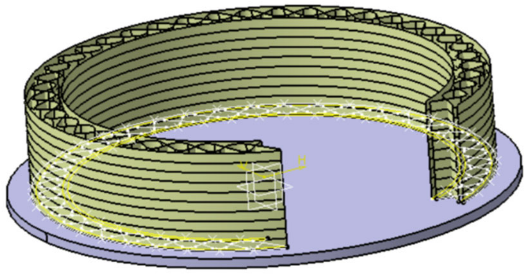

Fig.7. Structure with one wall printed in 3D

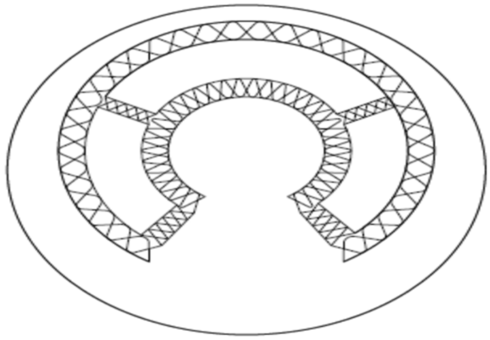

Fig.8 .The typical plan of the structure with two wall

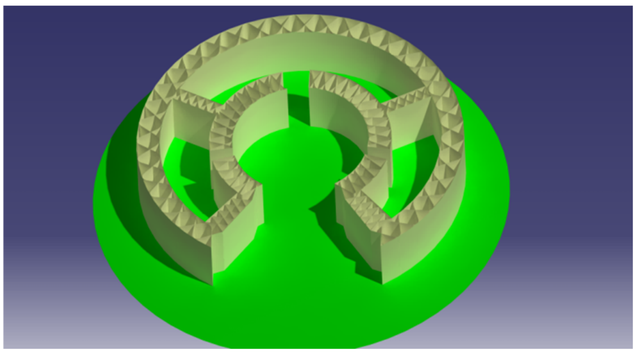

Fig 9. Structure with two walls printed in 3D

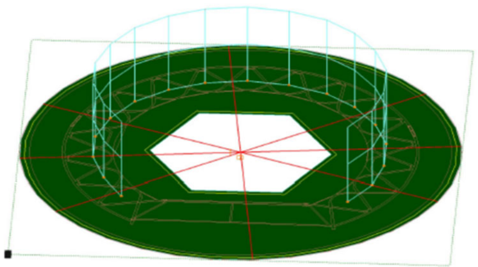

Fig. 10. Colums and beams position in a structure with one wall

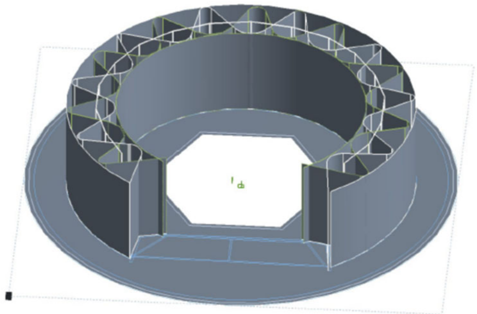

Fig. 11. 3D printed structure with reinforcement

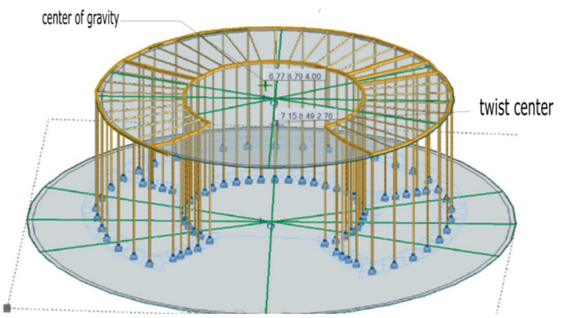

Fig. 12. Colums and beams position in a structure printed with two walls

3.2. Structure with reinforcement

As for the columns and beams used in the structure, we find a good stability in that the center of gravity approaches the twist center as shown in Figure13.

Mass center
X_m=6.77
Y_m=8.79

Twist center
X_T =7.15
Y_T =8.49

Twist eccentricity
e_x= | X_m-X_T |= 0.38
e_y=| Y_m-Y_T |= 0.3

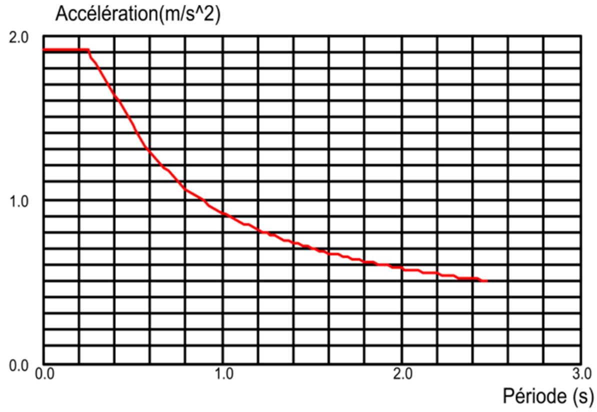

Fig. 13. Maximum acceleration in the direction X of excitation

In this study, we carried out three analysis: a modal analysis with 4 vibration mode in which the cumulative mass reaches 99.98 percent as shown in the (tab. 2), a seismic analysis according to the anti-earthquake construction regulations (RPS 2011), and a spectral analysis of the maximum acceleration as shown in Figure 13 obtained by the statictic forces shown in the modal analysis induced by a seismic zone, these analyses are based on spectrum analysis method (SAM) according to which it is likely to understand the contribution of different vibration modes to the seismic response of structure [37,38].

Table 2.
The cumulative mass in the modal analysis

Case mode	Peroiod, S	Cum. mass, UX, %	Cum. mass, UY, %	Cum. mass, UZ, %
1	8.90	72.29	0	0
2	8.44	72.39	0	0
3	7.50	99.98	0	0
4	0.09	99.98	0	0
1	8.90	72.29	0	0
2	8.44	72.39	0	0
3	7.50	99.98	0	0
4	0.09	99.98	0	0

However, the equivalent lateral concept is a set excitation, for each value of damping and frequency of the maximum accelerationon basis of the Duhamel's integral [39]:

$$h_j = \int_0^1 exp(-\xi_j W_j(t-\tau) \sin W_{dj} (t-\tau) d\tau \qquad (7)$$

It is a solution of the equation of an imposed movement of a seismic type representing the displacement of a single-degree-of-freedom(SDOF):

$$M\ddot{X} + C\dot{X} + KX = -M_r\ddot{x}_g \quad (8)$$

in which:
M,C and K are mass, damping and stifness Matrix X is a number of displacement relative to the basic one
r is unit vector
W_j Is an eigenvalue(represent frequency)
W_{dj}Is the modal damping such as egal 0.5 according the frenshreglement PS 92(NF P 06-013).
ξ_jDamping ratio

Since the earth is fragile this analysis cannot guarantee the safety of the structure. In additive manufacturing we must also check the adhesiveness between the layers. For this reasons we aimed at adding rice within material prapartion to increase the mechanical characteristics and use wooden beams, columns and roofing to increase safety and ensure that after certain stress there can be no collapse after cracking following certain pressure, based on the dynamic analysis we can know the behavior of the structure until getting fractured.

4. Conclusions

The aim of this work was to study the stability of a house built by 3D printing using natural local material. Seismic analysis of earth houses built under the GAYA program is performed. Many cases are tested, such as house structure built with one wall or two walls and with reinforcement or without reinforcement. Modal analysis with 4 vibration, seismic analysis and the spectral analysis shows that earthen houses are conform to antiearthquake regulations for earthen constructions. 3D printing technology can be safe and earthquake resistant. In perspective on this study, we intend to add rice within material preparation, use wooden beams, columns and roofing in order to increase the mechanical characteristics and to increase safety and prevents collapse of the buildings. Finally, this paper tries making a compromise between ecology, safety, technology development and the possibility of exploiting our cultural heritage with the development of other complex design in the field of construction.

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