Numerical simulation of the optimization in the design of a hybrid steel-bamboo rigid floor in a self-supporting structure

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Numerical simulation of the optimization in the design of a hybrid steel-bamboo rigid floor in a self-supporting structure

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Resumen

Partiendo de una estructura autoportante, se pretende mostrar las consideraciones y modificaciones de diseño llevadas a cabo para desarrollar la optimización de un suelo rígido acero-bambú para dicha estructura. Se justifica la elección de los materiales a través de sus propiedades mecánicas y coste, mostrando las ventajas del empleo del bambú como material de construcción. Con el propósito de lograr el mejor resultado en la optimización del modelo, se emplea como metodología de trabajo la simulación numérica por medio de elementos finitos utilizando el software comercial Abaqus. Se llevan a cabo distintas configuraciones dentro de la estructura autoportante (empleando elementos de refuerzo) y en la propia configuración geométrica de los paneles de bambú y de su soporte de acero,

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generando tres modelos diferentes (A, B y C), de tal forma que sea posible, en las tres opciones, elaborar un análisis que relacione tanto los esfuerzos generados como el desplazamiento y la deformación que sufre la base sometida a estudio. Finalmente se realiza una comparación de los resultados obtenidos por medio de las simulaciones, para concluir cuál de ellos consigue la optimización más adecuada del modelo, observándose cambios significativos en la flecha y ciertas variaciones en los esfuerzos internos.

Palabras clave: simulación numérica, elementos finitos, optimización, suelo de bambú, comportamiento estructural.

Abstract

Considering a self-supporting structure, it is intended to show the considerations and modifications in the design which have been carried out to develop the optimization of a hybrid steel-bamboo rigid floor for the structure. The materials applied in the design of the floor, steel and bamboo, are chosen because of their mechanical properties and their cost. it is shown the benefits of using bamboo as building material. Due to reach the best result in the optimization of the model, it is used, as methodology, numerical simulations by finite elements using Abaqus software to obtain the structural behavior of the different elements. Several configurations are carried out in the self-supporting structure (using reinforced elements) and also it has been varied the geometric configuration of the bamboo panels and their steel support. According to those changes, three different models have been created (A, B and C) making possible, in every option, the analysis of the different generated stresses, the displacement and deformation suffered by the case study floor. Then, it has been carried out a comparison between all the results obtained by the numerical simulations according to changes in deflection and certain variations in stresses. Finally it has been concluded which model (A, B or C) reaches the most efficient optimization.

Keywords: numerical simulation, finite elements, optimization, bamboo floor, structural behavior.

1. Introducción

At the beginning of 2014, there were 51,000,000 of internally displaced persons[2] because of natural disasters or armed conflicts; 46,300,000 of concern to UNHCR.

Moreover, in developing countries, the necessity of housing is highly increasing. Attending to this demand becomes complicated, especially because of the existing poverty in wide sectors of the population [1].

However, it is also important to build healthy environmental houses [2-3]. It is commonly known that there are several studies and practice related to the construction of ecological houses, in which technological and design techniques have been developed (Zhenyu and Wei, 2013; Nayoon and KyungSook, 2010; La Roche and Berardi, 2014; Quaglia et al., 2014).

In this context, bamboo should be considered as a possible construction material. It could be used as substitution of timber or even steel construction. Its use should be considered in emergency houses, especially in seismic areas, because of its cost and structural behavior.

Nowadays, bamboo is considered as an ecological material and its use in the construction sector is increasing. This occurs because of its economic competitiveness. Comparing bamboo with wood, it has been verified that, because of its hollowness, bamboo's effectiveness as a beam is 1.9 better than a wooden beam and, considering that bamboo price would be US$ 105 per cubic meter, for wood to be economically as competitive as bamboo, it should not cost more than US$ 55, result reached dividing 105(US$) by 1.9, per cubic meter [4]. Nevertheless, wood used as building material has a higher prize, emphasizing the competitiveness of bamboo in the construction sector.

[2]www.unhcr.org.

The manufacture of bamboo-construction, offers employment to a large number of people. Only in India, bamboo generates jobs for a total of 60-72 million workdays before primary processing and 120 million workdays for weaving works [5].

Bamboo guadua is considered a sustainable material, optimum for building use because of its growth rates. Under normal conditions and in periods of greatest development, they add eight to ten centimeters in twenty-four hours. Bamboo takes usually between three to six years from plantation to harvesting [6] and the culms attain their maximum diameter, to twenty centimeters, soon after initiating growth and reach their full height in eighty to one hundred days [7].

Nowadays, more than a billion people already live in bamboo structures. The innovation lies in developing ways to exploit bamboo's resilience. Easily prefabricated, fire resistant and far lighter than steel, bamboo-based structures could be assembled in three weeks and last 50 years. At five dollars a square foot, they would cost roughly half as much as brick-and-block construction [8].

Bamboo grows in a wider range of climate all around the world, as high as 4000m, although those regions are mostly confined to tropical and sub-tropical regions. It grows in most of African and Asian countries, where there is a need for cheap building materials for housing, because of current housing problems.

Moreover, according to several studies (van der Lugt et al., 2003, 2006; Rittironk and Elnieiri, 2007), it is important to note that the mechanical properties of bamboo are mainly similar, in some cases even superior, to the ones of structural timber [5, 9]. This is why timber can be substituted by bamboo, not only because of its structural behavior, but because of its cost. It can suppose an alternative to the ever-shrinking natural forests in several countries.

Additional programs have been developed to study the mechanical properties of bamboo (Arce-Villalobos, 1993; Lo et al., 2004, 2008; Guzman and Morel, 2005; Murali Mohan Rao and Mohana Rao, 2007). Structural applications of bamboo have been established such as: connection for bamboo frames and design considerations, the influence of fiber density on strength capacity of bamboo showing the optimum structural behavior of the material or the possibility to use bamboo fibers as reinforcement for composites.

Further researches have focused their attention on natural aspects related to bamboo, showing that suitable species of bamboo for construction are available all the countries where it grows naturally [10]. There are 65 species of bamboo which are used as building materials [11-13]. Guadua angustifolia is one of the common species used in the construction field. It grows normally in Latin America countries. Similarly, Bambusa nutans, Dendrocalamus strictu or Dendrocalamus hamiltonii are widely used in Asian countries. Bambusa arundinaceae and Bambusa vulagris are found in Africa [14].

2. Prototype analyzed

Guadua angustifolia is the material used in the floor of the prototype presented in this paper to numerically simulate its structural behavior. This structural behavior has been analyzed in an emergency house prototype developed by REbirth INhabit research group, within VEM project (Reference Oracle MEADSAIR), sponsored by Airbus Defence and Space. This is a patent prototype with the reference ES2488790A1 *Modular Adaptable Housing Architecture, with the international* extension WIPO/PTC WO 2014/114836 A1.

The VEM project consists of the development of an innovative project which relates emergency aid with the industrial applicability. It gives a rapid response to shelter necessity in case of disaster (figure 1).

Figure 1. Emergency house prototype[3]

Source: by the author.

One of the main innovations of this prototype is that its different components are designed in order to achieve simple assembly. It can be constructed by two persons in two hours without specific machinery. DfMA-design is developed in the prototype (Design for manufacturing and assembly) in order to control its manufacture, assembly, transport and packaging. Thus, the design of every piece becomes important as is it intended to reduce weight, cost, and dimension.

Two 3mx3m modules are attached in order to achieve an interior living space of 18m2. It has a resistant structure (figure 2), which base its structural behavior on self-tensioning, with tubular bars assembled using fasteners by rotational mechanical joint

Figure 2. Freestanding structure of the prototype[4]

Source: by the author.

This paper aims to analyze which configuration (A, B or C) is the best one for the bamboo floor in the prototype (figure 3). Taking into account which one best fits in the main structure and which one has the best behavior. At the same time, the steel frame of bamboo floor is optimized by simulating the prototype and by changing the width of the steel frame around bamboo (3mm, 2.5mm, 2mm and 1.5mm), thus 12 different models have been studied (four per option A, B and C).

Figure 3. Bamboo floor panel[5]

Source: by the author.

[3]REbirth INhabit research group. December 2014.

[4]REbirth INhabit research group. September 2014.

3. Methodology

By using numerical simulations, the structural behavior has been changed according to the floor configuration elements and the width of the perimeter metallic sheet around bamboo panels. Then, a higher security factor can be obtained in the freestanding structure design when it is under permanent loads and wind loads. This will suppose an improvement in its functionality, security and habitability.

The security factor is determined by the next expression:

$$\eta M = \sigma VM / \sigma Y$$

Where,

ηM is the security coefficient which is applied to the materials properties in the static loads combinations for the different materials.

σVM is the value obtained from the stress occurred because of the applied loads (Von Mises stress in this case).

σY is the value calculation of the properties of the materials.

It is commonly known that Von Mises criterion is based on that the material will collapse when the maximum distortion energy is presented in ductile materials which are capable to absorb a certain energy quantity before collapsing.

According to this criterion, a structural element collapses when, in any of its points, the distortion energy per unit volume increases a certain threshold.

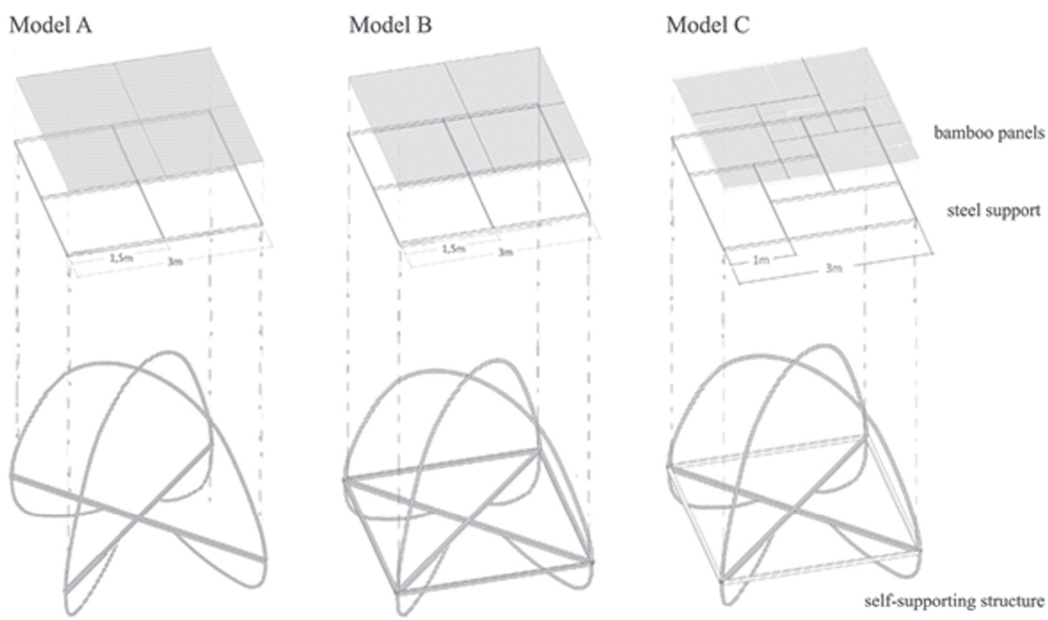
$$e_{dist} \geq \frac{\sigma_Y^2}{2E}$$

Three different prototypes have been created to conclude which one supposes the best configuration of bamboo floor. At the same time, in every model, the steel sheet in the perimeter of each of the bamboo panels is simulated with 3mm width, 2.5mm width, 2mm width and 1.5mm width. The models have been created in Autocad 3D and then imported to Abaqus, where the mechanical properties of every material used have been defined, links between different elements have been created, loads and boundary conditions have been applied and the mesh of the prototypes has been defined to obtain appropriate results of the structural behavior.

The three case study models to simulate are the following ones:

[5]REbirth INhabit research group. November 2014.

Figure 4. Three case study models



Source: by the author.

• **Model A is made up by:**

• Self-supporting structure with lower steel crossing and upper aluminum crossing

• Steel sheet, in the perimeter of every bamboo panel, above the lower steel crossing of the self-supporting structure

• 4 bamboo panels. Each of them has three 15cm width bamboo layers; thus, every panel is 45cm width.

• **Model B has the same elements than model A but a perimeter steel frame in the self-supporting structure.**

• **Model C has the same elements than model B a new geometric disposition of bamboo floor:**

• Four 1m x 2m bamboo panels

• One 1mx1m central bamboo panel

• Steel sheet in the perimeter of every bamboo panel.

Numerical simulations are carried out, in every case study model, by making a variation in the thickness of the steel sheet which goes all along the bamboo panels. It is considered four different widths: 3mm, 2.5mm, 2mm and 1.5mm for all of the three models. Thus, results are obtained four times per model, according to the variation of steel width (3mm, 2.5mm, 2mm and 1.5mm) in the perimeter of bamboo panels.

Once the models are defined, the properties of the materials are assigned in the different elements of the analyzed prototypes. It is also needed to define their cross section and, if it is necessary, their location in the space.

In table 1 it is shown the mechanical properties, of every material, considered for the numerical simulations.

Table 1. Mechanical properties of steel, aluminum and bamboo

	Steel	Aluminum	Aluminum
Poisson number	0.3	0.33	0.4
Young module (GPa)	202	70	11.7
Density (Kg/m^3)	7850	2700	400
Yield strength (MPa)	300	150	142
Elongation	0.2	0.08	0.1
Strength (MPa)	500	180	265

Source: by the author.

Bamboo is not an isotropic material, but an anisotropic one. Because of that, the way bamboo behavior is simulated by finite elements should be studied. Three choices to simulate bamboo, which have been the ones put into consideration for this paper, are shown below [15]:

-Modelling of bamboo attending to its morphology and the physical properties of bamboo's microstructure.

-The material could be laminated as a composite with several unidirectional continuum layers each with different mechanical properties. This gives good results for bending behavior.

-2 Layers composite. Bamboo elements are divided into two layers with different mechanical properties where the outer layer in much stronger than the inner one.

According to the characteristic of every modelling option, previously described, 2 layers composite is the one that has been chosen to perform the numerical analysis by finite elements. Additionally, it is the choice which provides better computational efficiency as the model has been simplified; thus, the numerical analysis would be faster.

Once the analysis method has been chosen, the loads applied to the models are defined:

•In the upper crossing of the self-supporting structure:

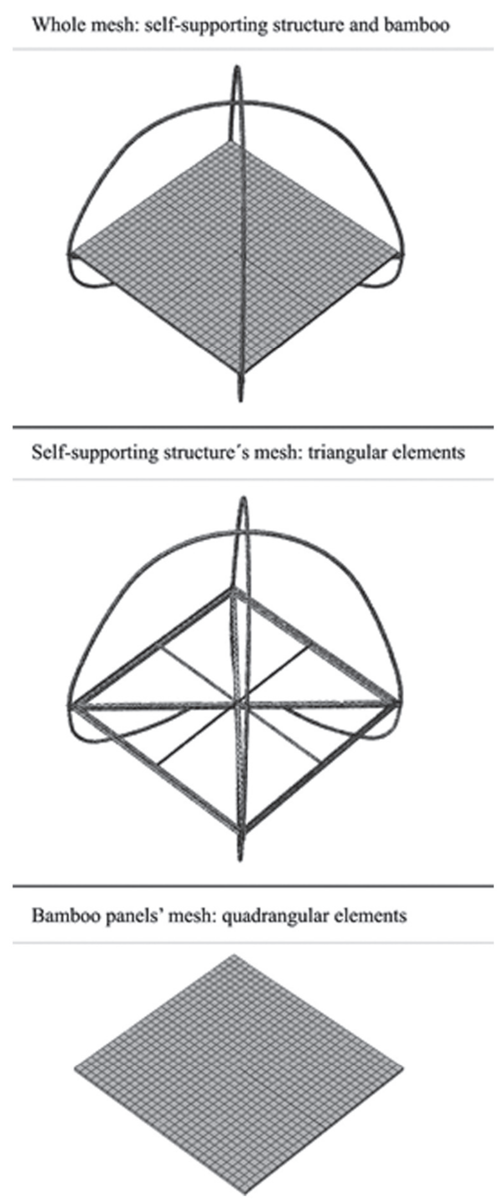
- Snow: 20Kp/m2
- Roof: 3Kp/m2
- Windward: 66Kp/m2
- Leeward: -30Kp/m2
- In the lower crossing of the self-supporting structure:
- Coriolis: 15Kp/m2
- Ballast: 1800Kp/m2
- In the bamboo panels:
- Use: 200Kp/m2

Encastre in every support (in their lower surface) is considered as boundary condition.

The loads have not been considered instantaneous. A step of 5 seconds has been established (in minimum intervals of 0.05 seconds of time) with a proportional increment of the loads to the time. Before the step finishes, the loads reach the maximum value until the end of the step. This methodology has been followed in order to ease the convergence and to obtain in a precise way the behavior of the structure in quasistatic conditions.

In every model, the same type of mesh is applied (figure 5). All the elements are meshed with C3D8R element types. The models were discretized from a meshed structure by hexahedral linear elements with 8 nodes of C3D8R type (reduced integration). These elements give precise results with lower computational cost.

Figure 5. Mesh used for the numerical simulations



Source: by the author.

In each of the case study models several elements and nodes are generated according to the mesh type applied (table 2). The higher the number of elements and nodes, the greater the time the computer lasts in simulating.

Table 2. Mesh for every model according to the variation of the steel sheet (3mm, 2.5mm, 2mm, 1.5mm). Characteristics

Model A				
	3mm	2.5mm	2mm	1.5mm
Nº elements	26281	38562	26213	26309
Nº nodes	53458	78936	53364	53499
Model B				
	3mm	2.5mm	2mm	1.5mm
Nº elements	28954	38567	28969	28937
Nº nodes	59520	79189	59619	59509
Model C				
	3mm	2.5mm	2mm	1.5mm
Nº elements	35492	33996	34032	35120
Nº nodes	75651	70482	70529	70604

Source: by the author.

Once introduced the materials, the loads, and meshed the models, the structural behavior of every prototype can be obtained.

Thus, the results got with the numerical simulations by finite elements are shown next.

The outcomes obtained for the whole structure are organized in three different figures (figure 6, figure 7 and figure 8) where, by changing the steel sheet width (3mm, 2.5mm, 2mm and 1.5mm), several modifications are shown according to Von Mises strength, displacement and deformation.

In the first of the three figures (figure 6), which refers to model A, it can be seen, in the bamboo floor, several areas where the maximum stresses occur in areas connected to the self-supporting structure and those stresses decrease in areas next to the center of the structure. Maximum displacements are located in the upper crossing and also in the middle points of the outside edges of the bamboo base; those displacements decrease when getting closer to the lower crossing and they do not exist in the connection between bamboo and the lower crossing.

According to Von Mises Strength, it can be seen (in figure 6) that maximum strengths are about 300 MPa, the values vary according to the width of the steel sheet located in the perimeter of the bamboo panels:

- 3mm steel sheet width: 300.8MPa
- 2.5mm steel sheet width: 306.6MPa
- 2mm steel sheet width: 298.5MPa
- 1.5mm steel sheet width: 302MPa

Hence, it is recommended the use of appropriate steel with 400MPa yield strength, higher than 300 MPa, to guarantee an optimum security factor (up to 1.30) in the lower crossing of the self-supporting structure.

In the next figure (figure 7), which refers to model B, it can be seen the same structural behavior than model A, where maximum stresses occur in areas connected to the self-supporting structure and higher displacements are located in the upper crossing and also in the middle points of the outside edges of the bamboo base.

According to Von Mises Strength, it can be seen (in figure 7) that maximum strengths in the whole structure vary from model A in 50MPa, they are about 250 MPa. They suffer little deviations by modifying the width of the steel sheet located in the perimeter of the bamboo panels:

- 3mm steel sheet width: 248.8 MPa
- 2.5mm steel sheet width: 257.5 MPa
- 2mm steel sheet width: 249.1 MPa
- 1.5mm steel sheet width: 247.2 MPa

Therefore, the use of steel with 300 MPa yield strength is appropriate in this case study model.

Finally, in figure 8, which refers to model C, the structural behavior is the same than model A and B taking into account the areas where maximum stresses occur and the displacement of the whole structure.

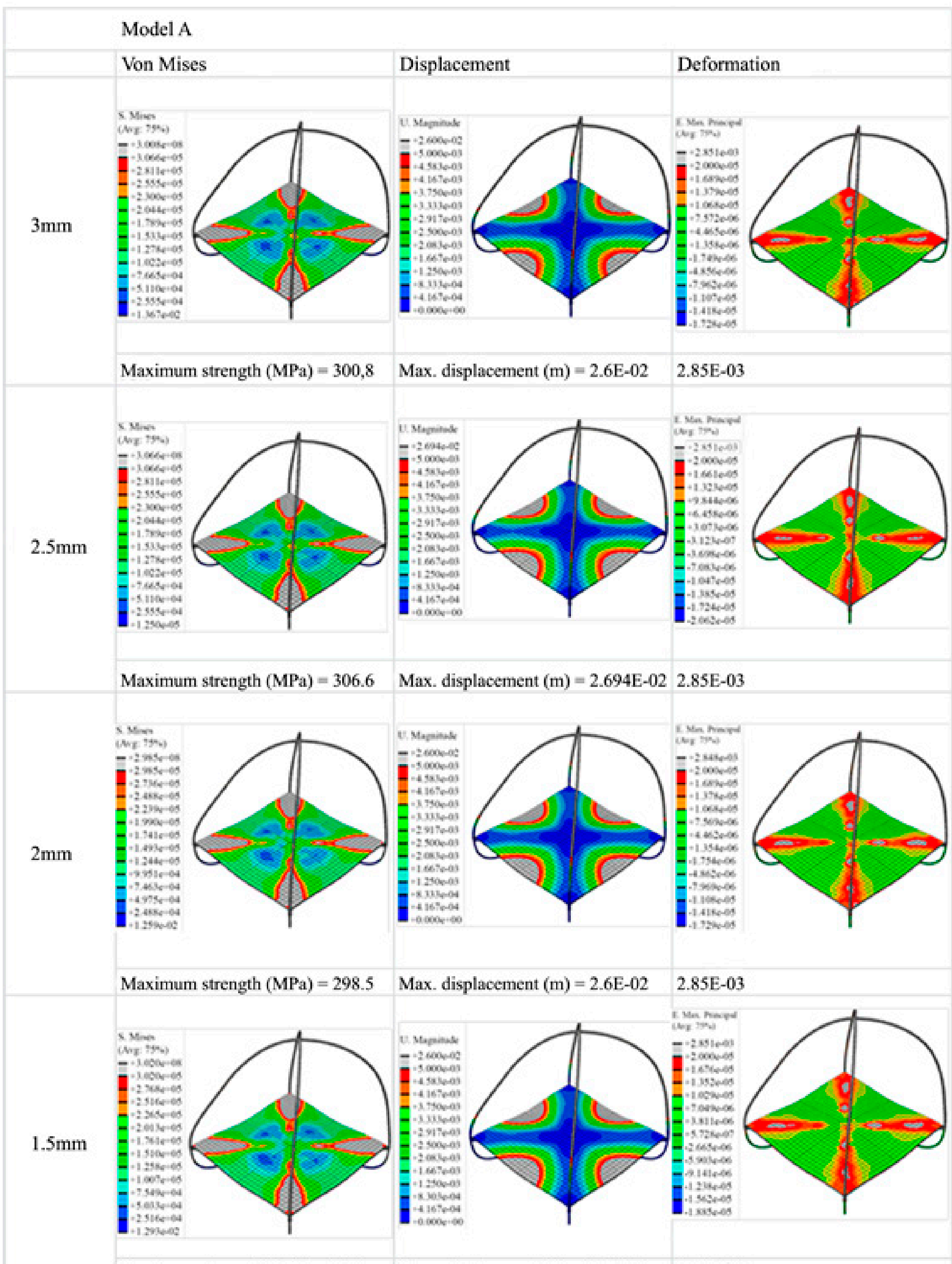
If Von Mises Stress is analyzed, it can be seen (in figure 8) that maximum strengths in the whole structure vary from model B and they get closer to model A. They are about 300 MPa. As it happens with model A and B, the values vary according to the width of the steel sheet located in the perimeter of the bamboo panels:

- 3mm steel sheet width: 288.5 MPa
- 2.5mm steel sheet width: 302.4 MPa
- 2mm steel sheet width: 311.8 MPa
- 1.5mm steel sheet width: 308.1 MPa

The steel used as building material should be the same as in model A, steel with 400MPa yield strength, to guarantee a security factor up to 1.30.

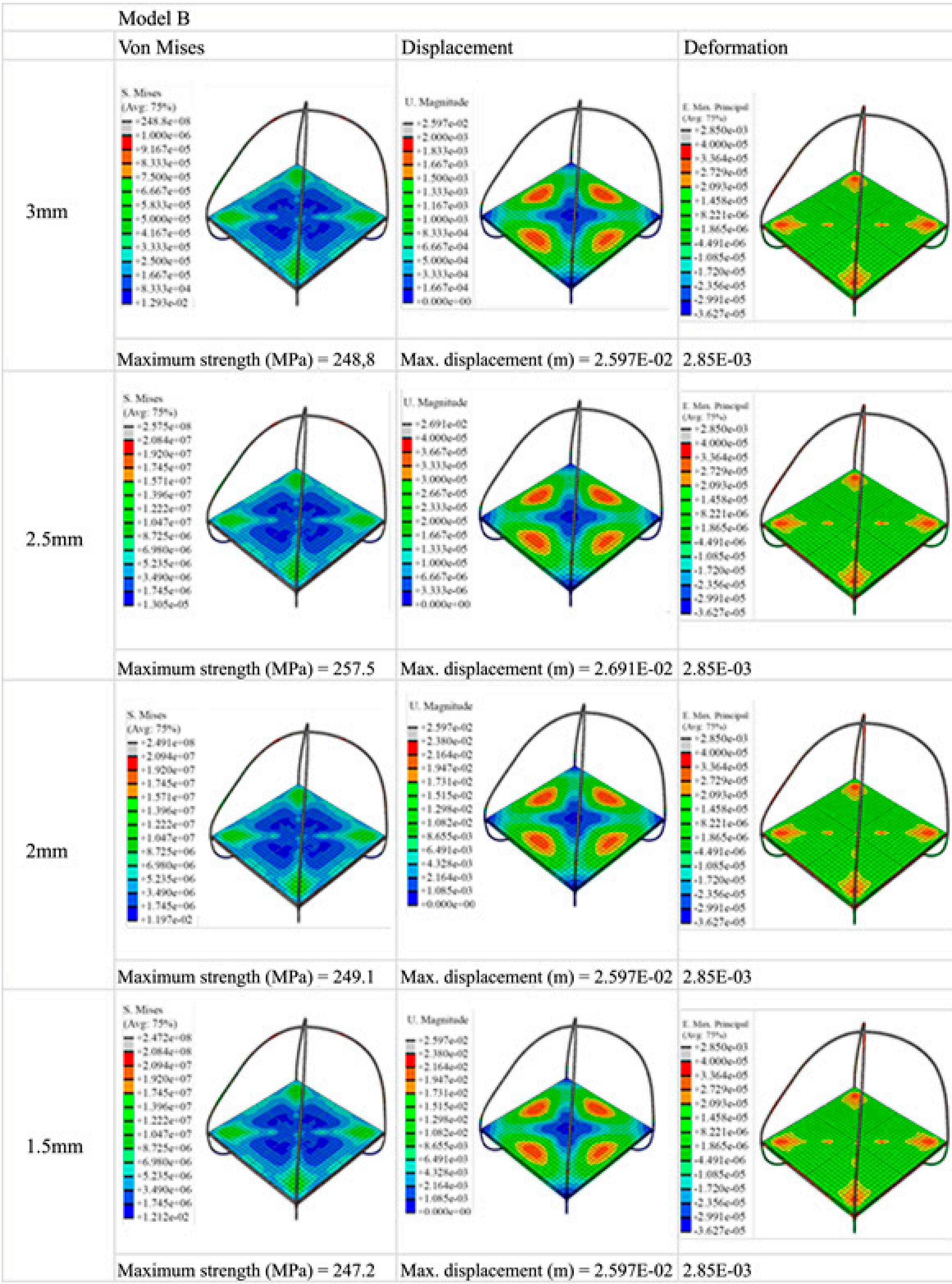
The variations between the different results of each model, apart from the modification in the steel width, can be also due to the mesh applied to the model. The higher the number of elements in the mesh, the more reliable the results.

Figure 6. Whole model A. Structural behavior



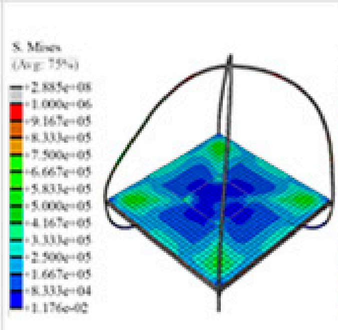
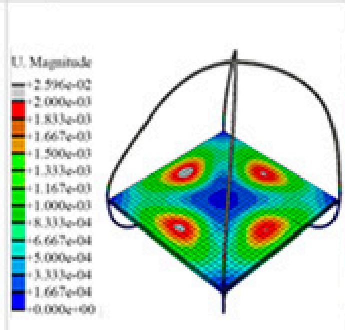
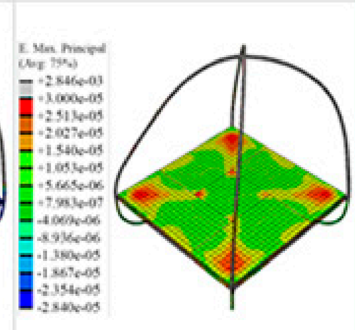
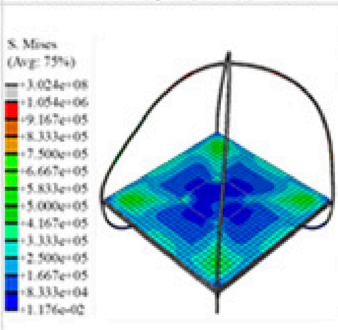
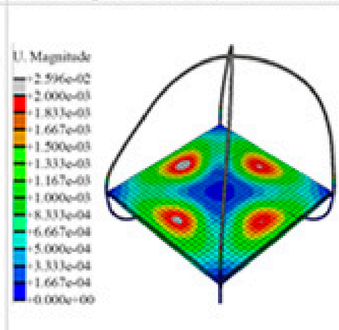
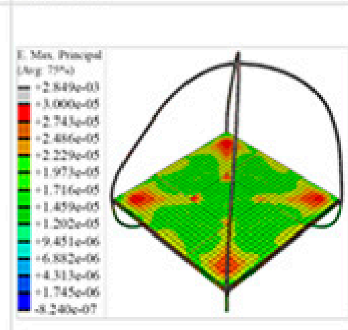
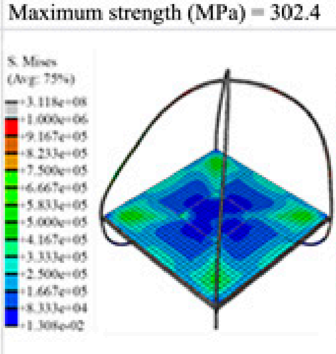
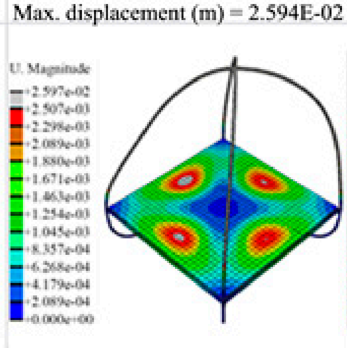
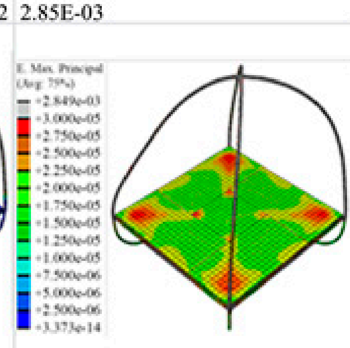
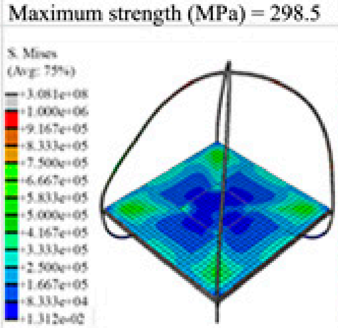
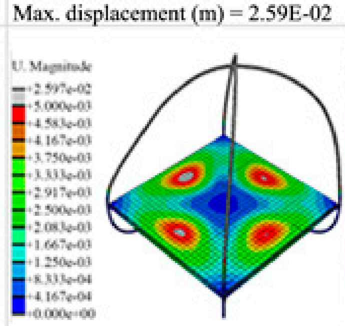
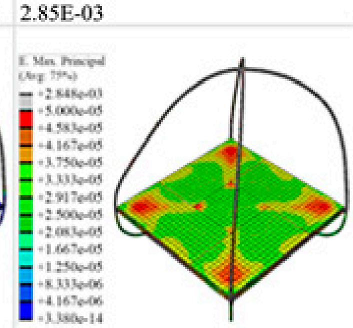
Source: by the author.

Figure 7. Whole model B. Structural behavior



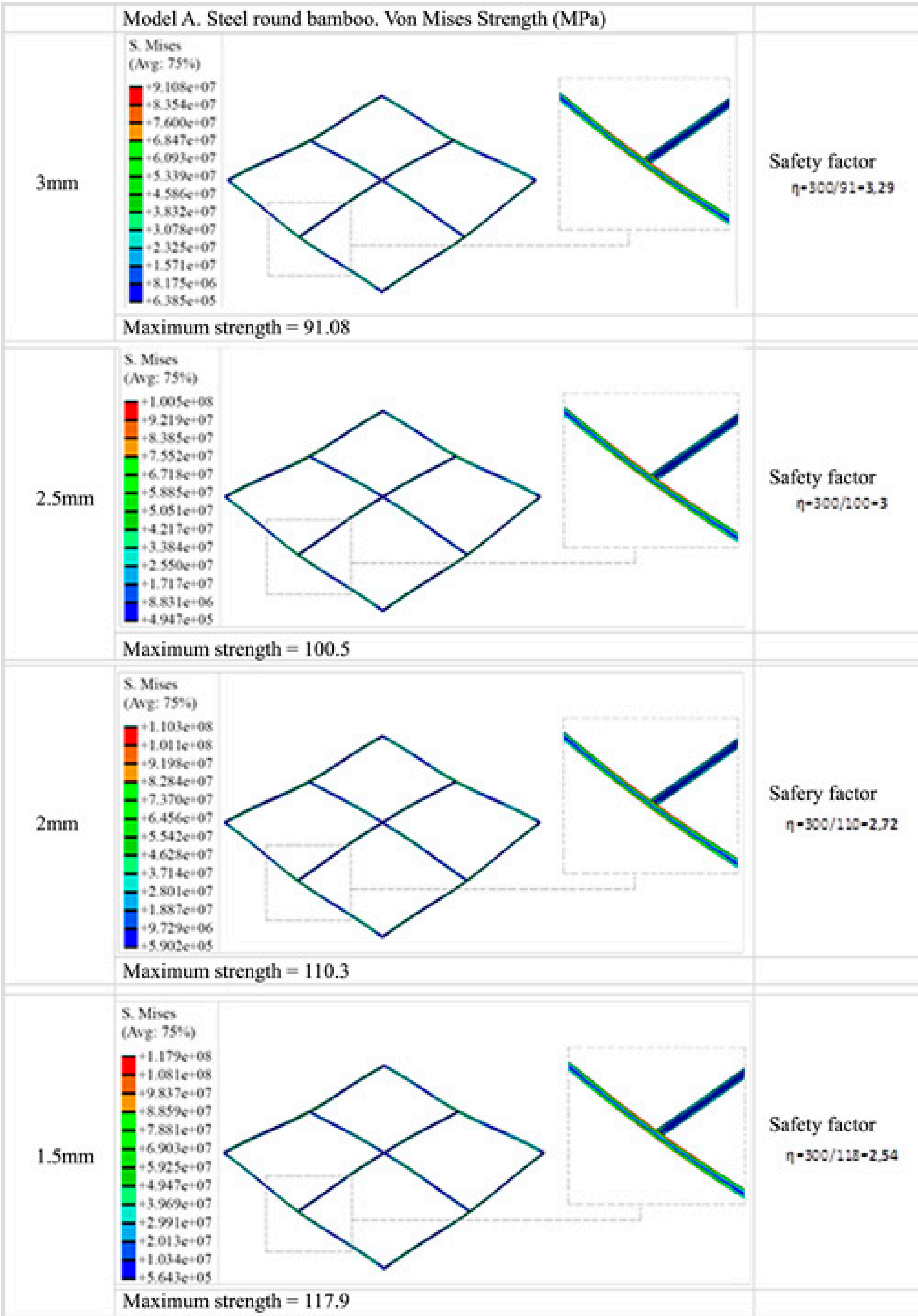
Source: by the author.

Figure 8. Whole model C. Structural behavior

	Model C		
	Von Mises	Displacement	Deformation
3mm			
	Maximum strength (MPa) = 288.5	Max. displacement (m) = 2.59E-02	2.85E-03
2.5mm			
	Maximum strength (MPa) = 302.4	Max. displacement (m) = 2.594E-02	2.85E-03
2mm			
	Maximum strength (MPa) = 298.5	Max. displacement (m) = 2.59E-02	2.85E-03
1.5mm			
	Maximum strength (MPa) = 308.1	Max. displacement (m) = 2.59E-02	2.85E-03

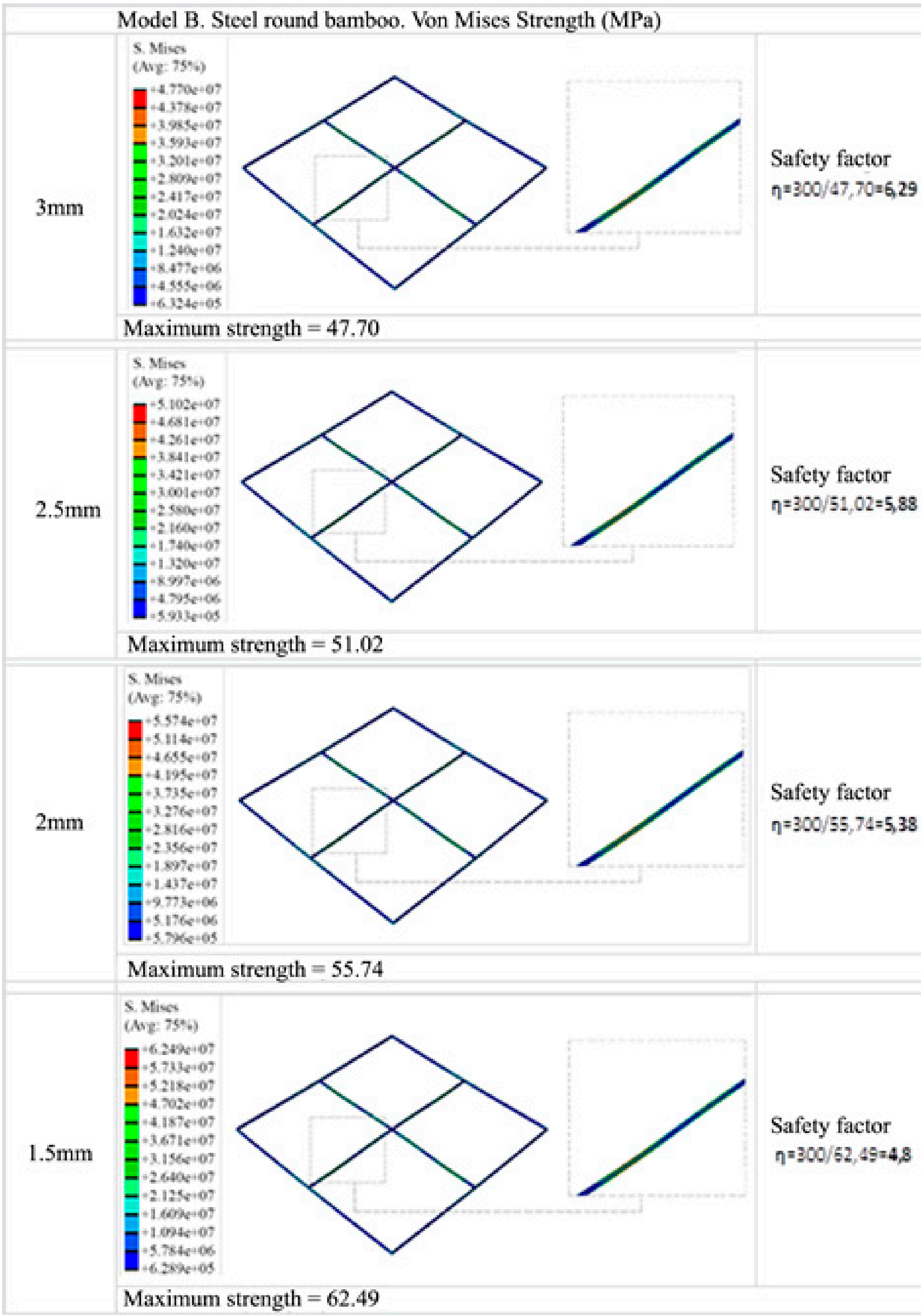
Source: by the author.

Figure 9. Model A. Floor. Von Mises Strength in steel elements



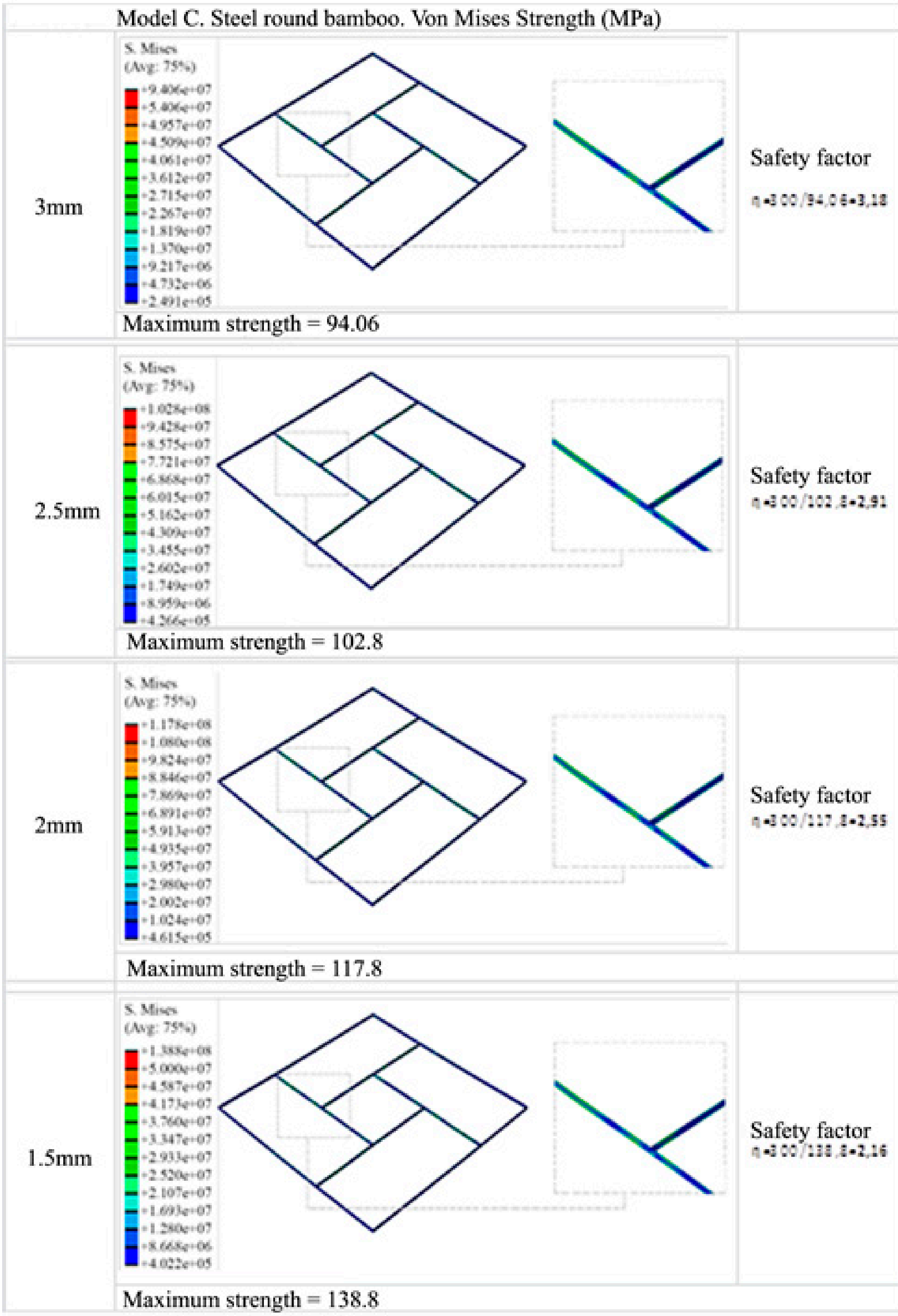
Source: by the author.

Figure 10. Model B. Floor. Von Mises Strength in steel elements



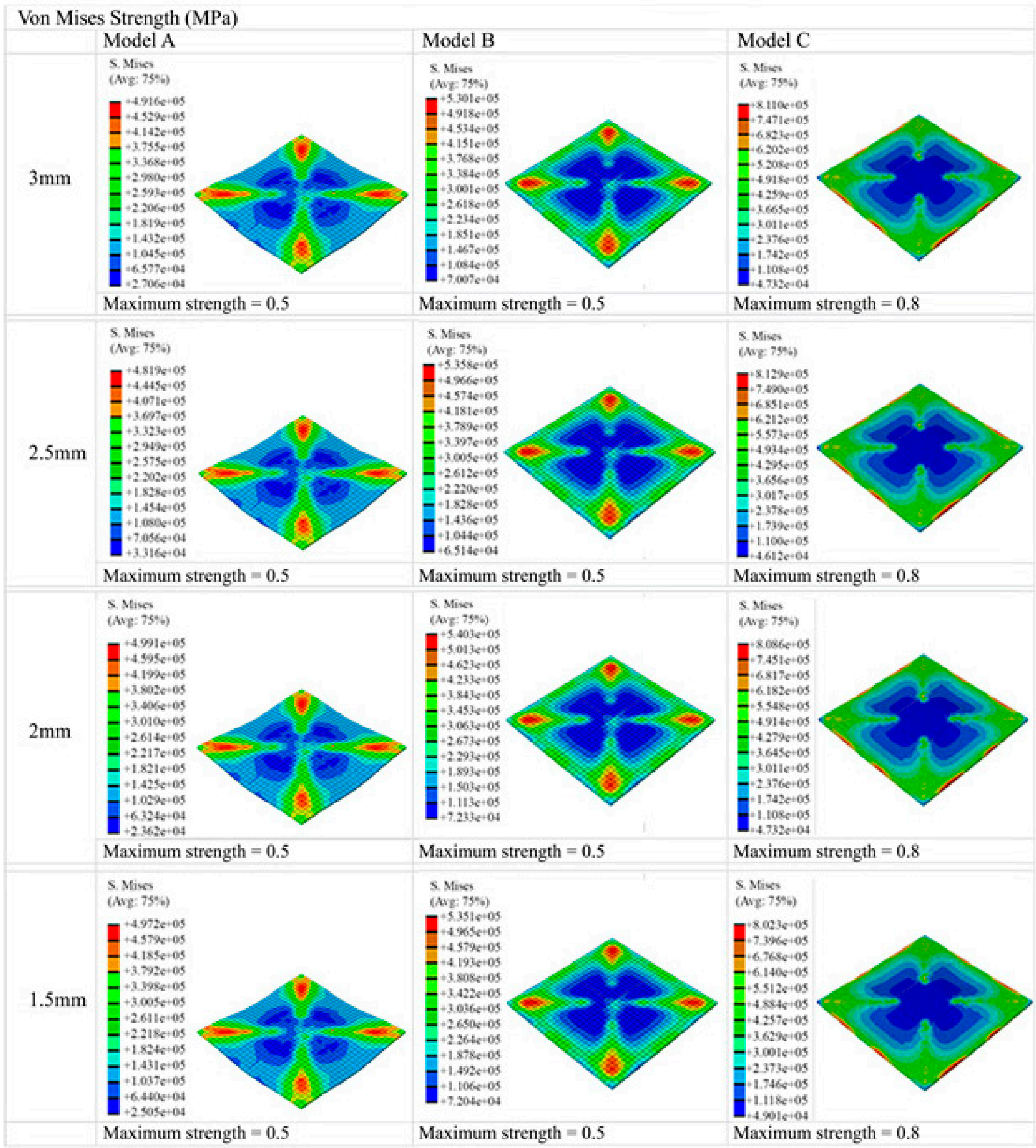
Source: by the author.

Figure 11. Model C. Floor. Von Mises Strength in steel elements



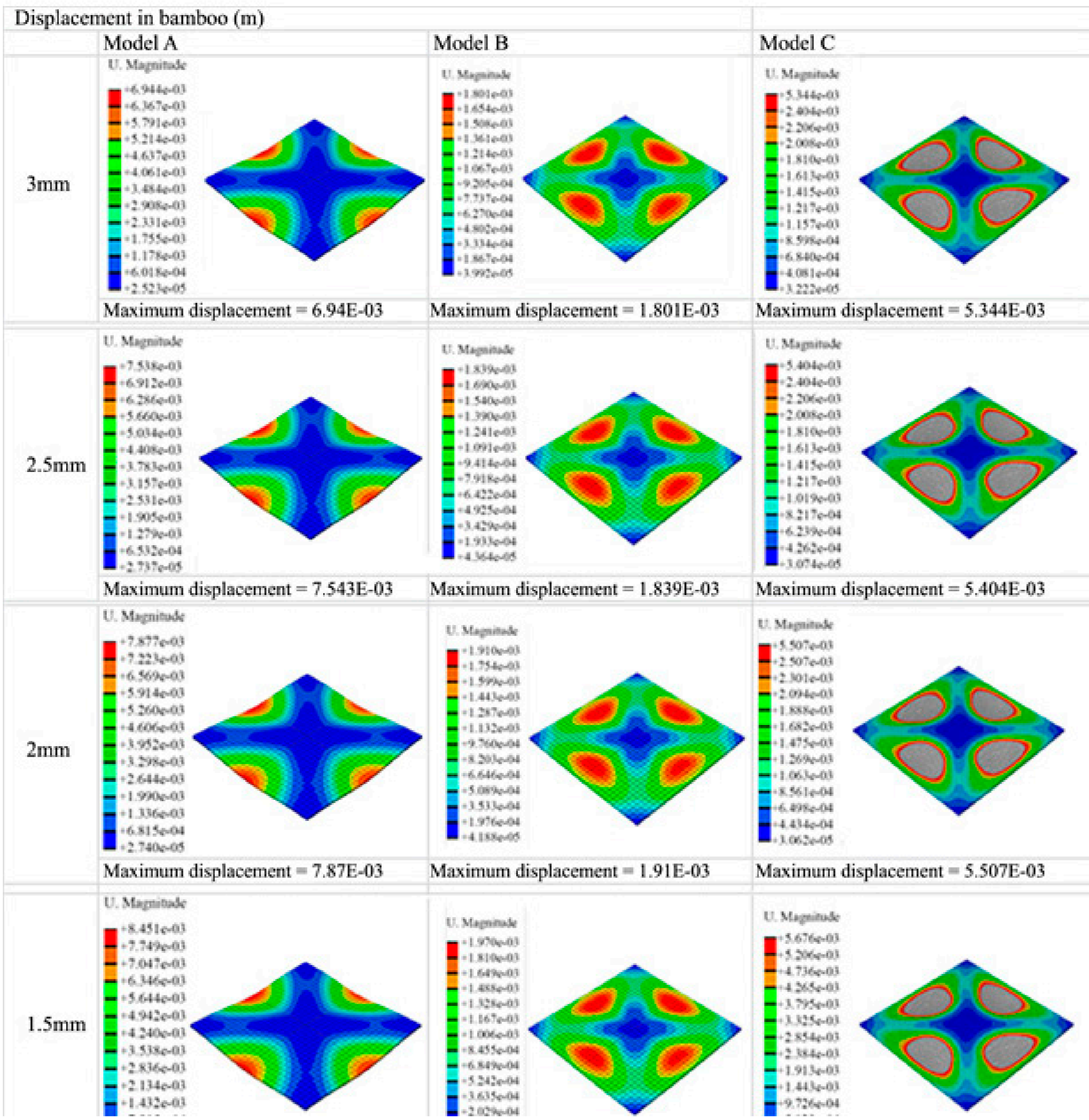
Source: by the author.

Figure 12. Von Mises Strength in bamboo panels



Source: by the author.

Figure 13. Displacement in bamboo panels



Source: by the author.

4. Results

The structural behavior of the whole prototype has been shown. Now, the res-ults obtained in bamboo floor are going to be indicated.

It is going to be analyzed in the following figures, per case study model (A, B and C) Von Mises Strength in the steel sheet and in the bamboo panels.

In the three models, maximum stresses are located in upper and lower fibre next to the external vertexes and in the middle of every edge in the external perimeter.

The safety factor in model A (figure 9) is close to 3 in every case, hence it is acceptable.

In model B (figure 10), safety factor increases a 50%; therefore, the structural behavior improves.

In model C (figure 11) the safety factor is close to 3 in every case. It is acceptable but is reduced by 50% compared to model B. In C, as there is more steel volume in the perimeter, the area for bamboo to be expanded is lower; therefore, stresses in the direction of its plane are higher, not only in bamboo panels but also in steel elements.

Stresses in bamboo panels remain constant in the four variations (3mm, 2.5mm, 2mm, 1.5mm) because the loads applied are the same in every case. In the next figure (figure 12) the results per model (A, B and C) are shown

Displacement in bamboo panels increases when the thickness of the steel sheet round them decreases, as it shown in figure 13, because the applied loads remain constant.

In model B, it can be seen a significant decrease compared to model A in bamboo displacement, due to the action of the frame which has been included.

In it shown, in model C, an increase in the displa cement compared to model B, because the ratio in the size of bamboo panels determines an increase in bamboo displacement in the direction perpendicular to its plane.

5. Conclusions

This paper aims to establish a comparative study between the three different models and, at the same time, an optimization of the steel sheet around bamboo. A minimum section of this steel element is obtained which supposes lower weight and lower cost.

It is concluded that the model which reaches the best optimization in model B because of the following reasons:

• The presence of the frame causes the decrease of maximum stresses in the lower structure by 16.67%.

• In the steel sheet around bamboo, stresses decrease by 50%, which leads to doubling the safety factor. When the steel sheet configuration is modified, the safety factor is halved in models A and C, compared to B (with frame and four bamboo panels).

• Bamboo displacement is reduced on case study model B by 76.4%, from 8.5mm to 2mm (from model A) in the case where the perimeter bamboo sheet has a thickness of 1.5mm. Deflection turns to be from the middle of the edges of the base of bamboo (model a) to the geometric center of the quadrant unsupported (model B). In model C, changing the configuration of the perimeter sheet, displacement increases by 71.2%.

• Internal stresses in bamboo panels are not affected by the presence of the frame, as it is shown in figure 13, maintaining a st¬ress to 0.5 MPa. In model C, these internal stresses increase by 60% due to increased volume of steel, reaching a value of 0.8 MPa, which minimizes the space for expansion in its plane, but considering that negligible increase.

As further research, it is important to take into consideration that bamboo culms are easily biodegradable and, therefore, need protection and treatment against insect/fungi even more than timber [16]. The technologies of applying bamboo treatments are different because of the anatomical composition of bamboo culms. As much as possible non-chemical protection should be applied, to avoid danger to mammals and environmental damages [17]. Hence, it should be studied which kind of treatment in bamboo vary its mechanical properties and, therefore, its structural behavior.

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