Process of Design and Materialization of an Emergency Structure as Part of a Methodological Proposal

Pedro J. Villanueva [1], Alfredo Flores [2] Iván A. Ramírez [3], Diemel Hernández [4], Armando A. Suarez [5] and Elda N. Mendoza. [6]

[1] Universidad Autónoma Metropolitana, Xochimilco, pvilla@correo.xoc.uam.mx
[2] Universidad Autónoma Metropolitana, Xochimilco, afloresp@correo.xoc.uam.mx
[3] Universidad Autónoma Metropolitana, Xochimilco, iramirez@correo.xoc.uam.mx
[4] Universidad Autónoma Metropolitana, Xochimilco, dhernandez@correo.xoc.uam.mx
[5] Universidad Autónoma Metropolitana, Xochimilco, arca@correo.xoc.uam.mx
[6] Cube.arch58, arqfismen@yahoo.com.mx

Abstract. This document presents one of the most outstanding prototypes that have been developed in the Virtual Laboratory of Infographic Simulation and Materialization of Design (LAVSIMAD, for its acronym in Spanish), which consisted of a modular triangular lattice structure whose final shape was obtained from the geometric polymorphism of the transformation of a geodesic dome, frequency 2. This prototype was based on a method proposed for teaching Design in general and in the Architecture Bachelor in particular, known as CONINPRE, which considers the factors of concurrence, interdisciplinary, parallelism, and recursion in an integral way in the design process.

Keywords: Modular triangular lattice structure. Digital model and physical prototype. Infographic simulation. CONINPRE Method.
DOI: https://doi.org/10.14733/cadaps.2024.119-130

1 INTRODUCTION

Since the end of the last century, new digital technologies have evolved substantially, to such an extent that they have changed the way of conceiving design in general and architecture, in particular [1]. Three aspects are becoming increasingly decisive in the design processes related to digital technology: parametric design, digital simulation (computer graphics) and digital fabrication (CAD/CAM). These aspects, considered in an integral way, are worked in the Virtual Laboratory of Computer Infographics Simulation and Materialization for Design (LAVSIMAD) for its acronym in Spanish) that has contemplated the form finding process, this is integrated to the proposed methodology, which has been called CONINPRE, which integrates the following concepts:

concurrent, interdisciplinary, parallel and recursive, hence its acronym and the name given to the methodology.

Digital technologies have allowed synthesizing complex mathematical processes in visual simulations that allow organizing and understanding in a better way the design prefiguration process. The manufacturing process has also been optimized [2][3]. As an example, the LAVSIMAD laboratory team found an opportunity to make use of the tools offered by digital technology in this research and provide a social benefit from the materialization of modular structures that served as emergency housing using the CONINPRE methodology, parametric design and digital fabrication. This would allow experimenting, introducing variables of various types, with multiple possibilities to obtain different shapes and sizes of structures with the same modulation.

The synergy of this knowledge, allowed the development of the proposal presented here, based on a geodesic dome of frequency 2, the premise was to obtain a modular structure designed and built with the support of the visual programming language ©Grasshopper, it was required that such modulation was regular, without losing the properties of easy transportation and assembly, as well as structural stability, since they would serve as temporary structures to support the victims of earthquakes occurred in September 2017. The following is a summary description of this proposal, from the methodology used to the final fabrication.

2 DEVELOPMENT OF MODULAR STRUCTURE THROUGH THE CONINPRE METHOD

2.1 CONINPRE Method

This methodological proposal arises from the combination of concepts previously proposed by various authors who approach the design process in a more dynamic way, such as the design process proposed by M. Mutlu, Potapova, S. Silverstein, J. Sundberg, M. Watabe [4], who propose a collective collaborative work of non-linear interdisciplinary architectural design. Another design process is that Marios C. Phocas [5] proposed in which he proposes an open-loop methodology of interdisciplinary physical and digital investigations from conceptual development, through refinement and detailing, to detailed physical prototyping, all based on concurrent engineering.

So, the proposed method CONINPRE, consists of considering the disciplines involved in the design of an object, from the beginning of the prefiguration to the final stage, in a concurrent, interdisciplinary, parallel, and recursive way (hence the acronym of the method). For this, it is necessary to establish strategies and technical and technological resources that allow the objectives of the method to be met. Of these strategies and resources, digital models are used to generate the conceptual idea, to experiment with its space-form-function-environment-technology relationship. The physical prototype is used to evaluate the digital model and detect possible problems of design, and assembly and propose improvements that can then be implemented in the original model, defining an iterative and symbiotic optimization process in which the digital and physical tools improve and complement each other. The bridge between these two stages is the digital simulation that allows the representation of real situations already studied and tested previously, through artificially created models, aiming to forecast and verify future stages.

2.2 Form Finding

In this part of the process, a first proposal was based on considering a rectangular base structure that added up to approximately the area of two geodesic domes with a decagonal base. However, this first approach presented the problem that the central part that joined the two ends of the geodesic had pieces of different dimensions and angles making it unaffordable due to the complexity of the production of a greater number of pieces as well as a more elaborate construction process that would impact the final cost. On the other hand, the aim was to maintain the modulation of the geodesic dome from which it had started and, by increasing the longitudinal dimensions of the covered area, not to increase the height. That is, to maintain a height of 2.50 meters.

For this, using the graphic programming language ©Grasshopper in ©Rhinoceros, the geometric base of the decagon of a frequency two geodesic dome was modified to a square with chamfered corners that allowed obtaining both the rectangular base and other regular shapes such as the hexagon and the octagon, resulting in the design of a modular corner that allows the configuration of various types of frequency two lattice structure.

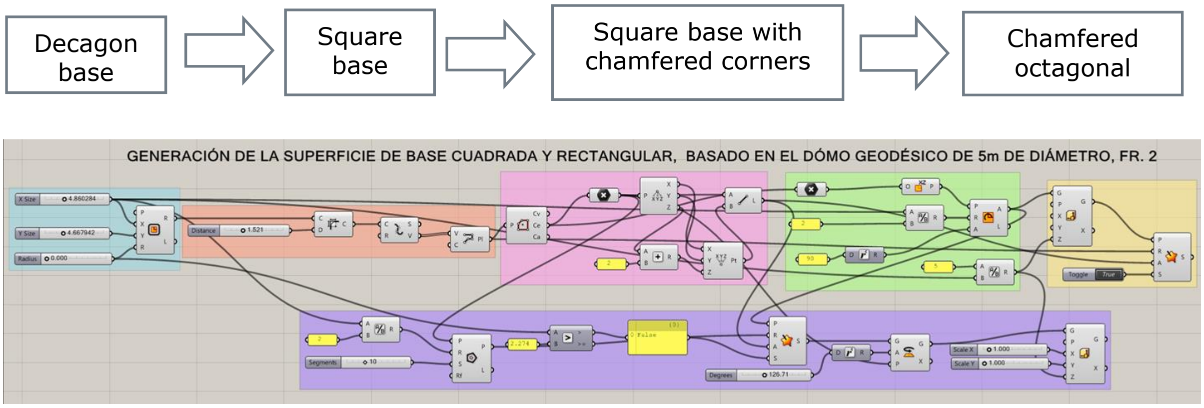


Figure 1: Grasshopper script for the generation of the rectangular-based lattice structure.

From the new square shape and the modular design of the prototype in the chamfered corner, with the same script, it was possible to obtain both the rectangular base and other regular shapes such as the hexagon and octagon, resulting in the design of a modular corner that allows, from this, to configure various types of reticular structure of frequency 2. In this case, the CONINPRE methodological process was carried out for a reticular structure with a square base.

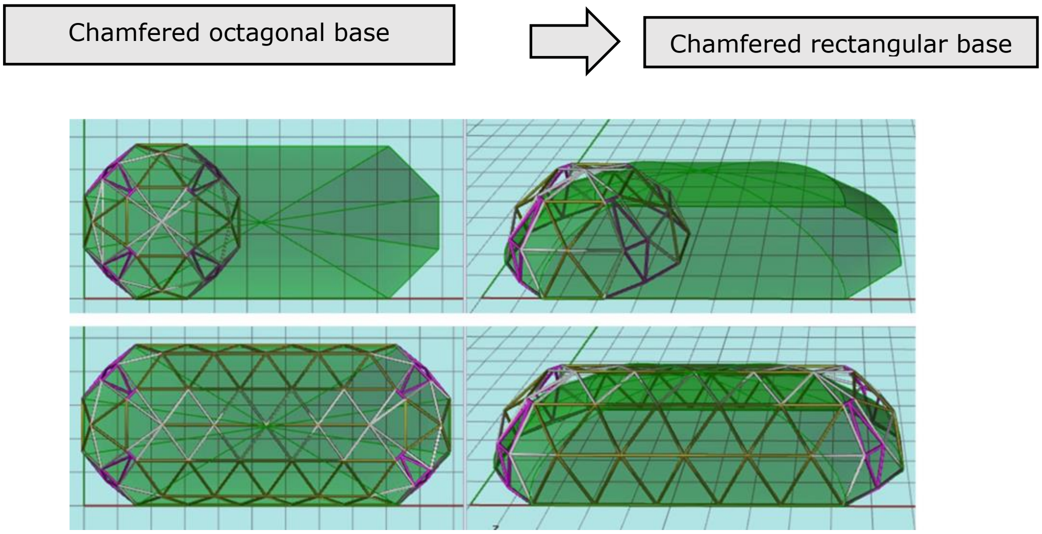


Figure 2: Generation of chamfered rectangular base surfaces from the Grasshopper script.

With this possibility of dynamic geometric configuration of the base, it was possible to design a module (prototype) for the 4 chamfered corners that would be modular in size and height and that, together with the rest of the structure, would behave structurally adequate within the tolerances established by the regulations for a temporary structure.
The design of the modular corner of this prototype was key to the development of more low weight, modular, economical, temporary and structurally adequate structures with different dimensions that, in the experimentation of this research, generated covered spaces of more than 100 m2 following the parametric and modular principles of this prototype.

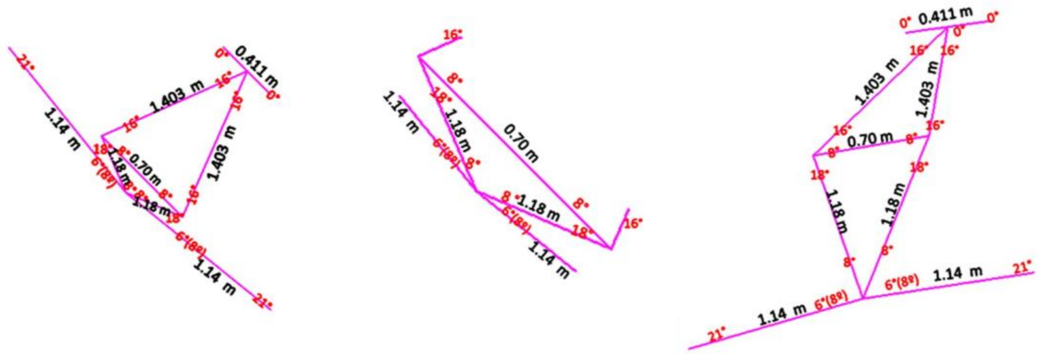


Figure 3: Final design of the prototype Lattice corner from geodesic dome transformation, frequency 2.

No. tubes	***Length (m)***	***Bending angle***	
2	1.18	8°	18°
2	1.403	**16°**	16°
1	0.411 (flattened at the centre and ends)	No bending (0°)	
2	1.14	8°	18°
Total: 8 tubes. Length Development = 8.56 m x 4 modules = 32 tubes = 32.24 m			

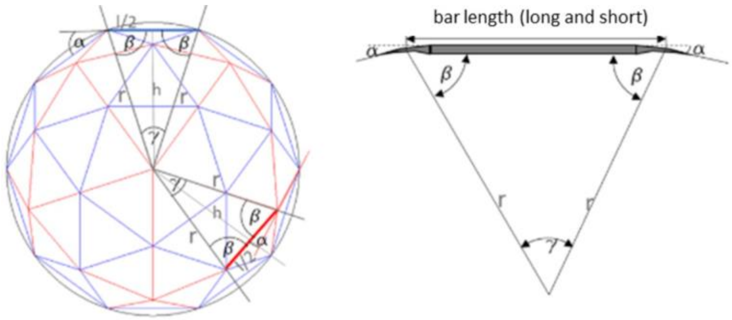
Table 1. Prototype of 4 modular corners of 8 tubes. Connecting elements to generate the octagonal, square, and rectangular base structures.

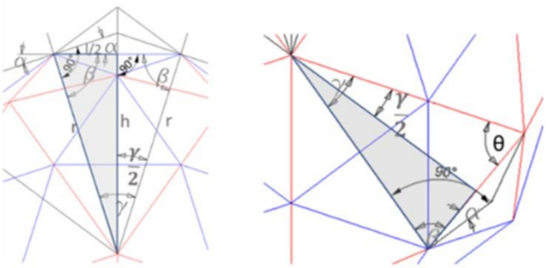
2.2.1 Obtaining the bending angles of the ends of the structure's tubes

In addition, the modular prototype design was also able to reduce the bending angles of the tube ends to 3 (the original 2 angles of the frequency 2, geodesic dome of 16° and 18°, an angle of 8°, as well as having tubes with no bending, i.e., an angle of 0°).

2.2.2 Frequency geodesic geometry constant factors 2

The length constants of each of the corresponding axial angle bars are obtained by dividing the length of the edge by the length of the radius of the sphere in which the geodesic is inscribed. In the same way, the internal angles are obtained through the equations of the law of cosines. This information is summarised in the following table and image.





α= Bending angle of the bar
b= angle between radius and edge (bar)
θ= axial angle between edges (bars)
γ = angle at the centre point of the geodesic dome
r= geodesic dome radius
h= length of the mean ordinate (median)

Figure 4. Bending angles of the ends of the tubes in the two end sections of the rectangular structure (geodesic dome).

Geodesic dome, frequency 2 of 5 m diameter (2.5 m radius) and 2.5 m Height							
Bar type	Bar colour	Factor	Length	Average length (h)	Axial angle (β)	Dome pc angle (γ)	Bending angle (α)
Long	Blue	0.61803	1.545 m	2.377 m	72°	36°	18°
Short	Red	0.54653	1.366 m	2.405 m	74.143°	31.717° => 32°	15.85° => 16°

Table 2. Linear and angular dimensions of the geodesic dome giving origin to the rectangular-based lattice structure.

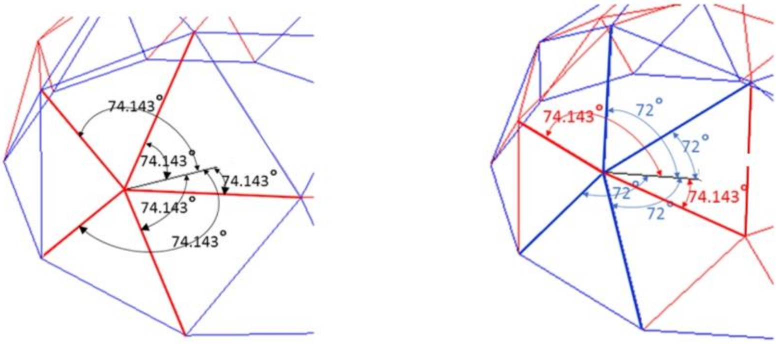


Figure 5. Angular dimensions of the geodesic dome part.

Bar	*Angulo Axial*	*Constante*
Long	60°	0.61803
Short	67°30′	0.54653

Table 3. Constant values of the bars used in the geodesic dome.

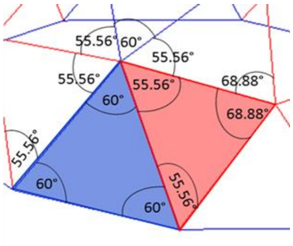


Figure 6. Angular dimensions of the geodesic dome module.

Applying again the law of cosines

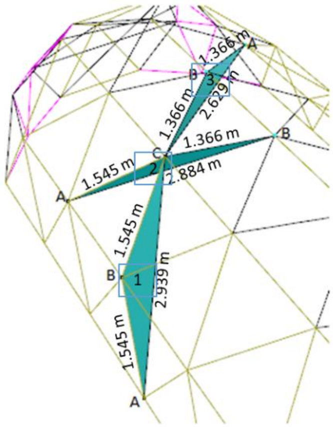


Figure 7. Angular dimensions of the geodesic dome part

Triangle A= Triangle B = Triangle C = Law of Cosines

$$C = \cos^{-1}\left(\frac{a^2 + b^2 - c^2}{2ba}\right) \quad (1)$$

a=long bar (m)	**b= distance between vertexes (m)**		**c= short bar (m)**
	A and C	B and C	
1.545	2.939	2.884	1.366

Table 4. Angular dimensions of the geodesic dome part

2.2.3 Generation of the rectangular base structure of 47.40 m2 footprint using 4 modular corners.

The following is an exploded view of the rectangular-based structure that was later donated to a family of disaster victims in San Luis Tlaxialtemalco, in the municipality of Xochimilco, south of Mexico City.

No.	**Length (m)**	**Quantity**	**Height**	**Area (m^2)**	
			Structure	**Footprint**	**Envelope**

1	1.545	84	2.5 in the crowns	47.40	83.52
2	1.366	48			
3	1.141	8			
4	1.18	8			
5	1.403	8			
6	0.70	4			
7	0411	4			
	total	164	bars (total length: 229.6 m)		

Table 5. Measuring the 2 bars (galvanised steel tubes) and the bars comprising the prototype (4 corners) used to generate the rectangular-based lattice structure.

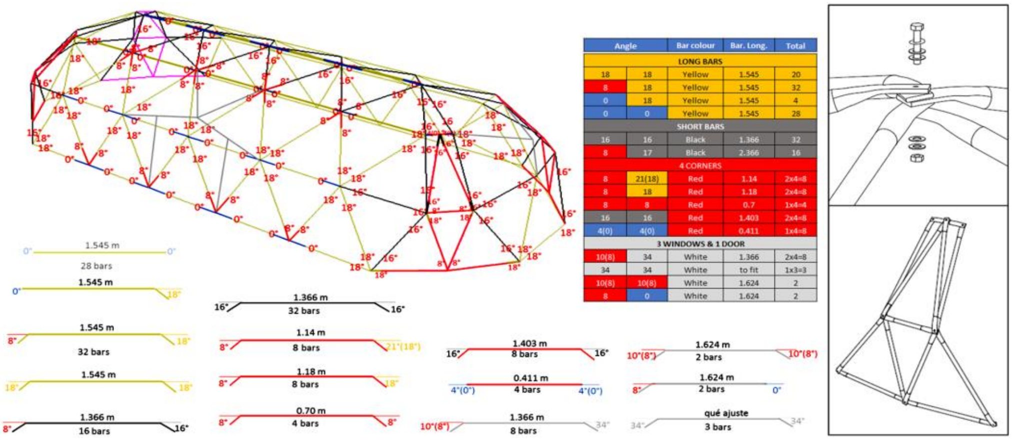


Figure 8. Breakdown of the rectangular-based lattice structure.

3 STRUCTURAL SAFETY ASPECTS

3.1 Physical Model and Digital Structural Simulation

After the geometric design, a physical model of the rectangular-based structure was built to corroborate the digital design, specifically the shape of the structure, the dimensions and quantity of the bars, both prototype of the corner module and of the rest of the structure, as well as the connection angles of the bars and the bending angles of the ends of the bars. A 3D printer was used for this purpose. Once the physical model had been assembled and some small flaws in the original design had been corrected, a digital simulation of the structural behavior was carried out. For this, using the SAP 2000© software, the boundary conditions (materials, lengths) were established.

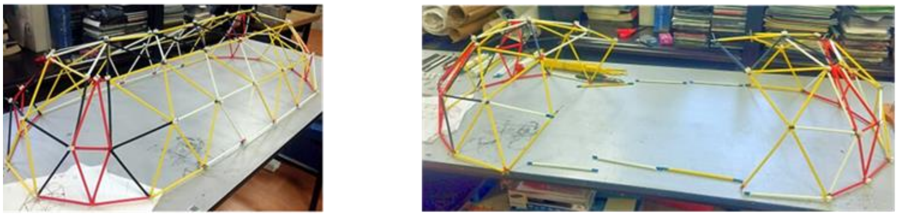


Figure 9. Physical model (obtained by 3D printer) of the rectangular-based structure.

3.2 Structural Simulation Results

The designed structure is based on the structural principle of triangular lattice structures (triangular shapes that are inherently more stable) in which loads flow through a system of linear elements (bars) which are subjected to axial forces, tension/compression, which depend on the number of bars that concur in each of the connections (nodes) of the structure and the angles that form them. In this context, for a formal spherical configuration, the linear elements with angles less than 45° (almost horizontal) will work in traction, while those linear elements greater than 45° will work in compression. On the other hand, in triangular grids whose formal envelope is based on a continuous barrel vault, the horizontal linear elements work mainly as a long beam where there is minimal bending, so there will also be traction, also in a reduced way, being compression the one that prevails to a greater extent. Linear elements larger than 45° will behave similarly to a sphere, i.e., in compression.

The results of the axial stress simulation (compression-traction) under combined dead and live gravity loads show a maximum deformation of 1.4 cm at the apex of the structure, which is sufficient to absorb the combined load considered.

In this context, for the structural analysis based on computer simulation (digital) with SAP 2000, v 20, trial software, the structure was considered as a spatial mesh (truss) considering bending.

For the gravity load analysis, a live load of 150 kg (1,471 Newtons) and a self-weight according to the material used were considered. A combination of both loads was considered in a 1-to-1 ratio (1 CM + 1 CV).

Wind loads were also considered. For this, the average maximum wind speed in Mexico City of 22 m/s (80 km/h) and the generic equation F = A x Pz x Cd were considered to calculate the wind force acting on the structure. For this, the calculation was made for both the 10.86 m2 surface for the canyon and the 4 m2 surface for the geodesic. The higher value between the 2 calculations is the one considered for the simulation. The Cd (wind drag coefficient) for the case of this structure is considered to be 0.8

The design wind pressure Pz (30.2016 Kg/m2 [296.177 Pas]) as obtained using the Complementary Technical Standards (NTC for its acronym in Spanish) expression for wind design.

$$P_z = 0.048 \times C_p \times V_D^2 \tag{2}$$

$$V_D = F_{TR} \times F_a \times V_R \tag{3}$$

Pz= wind design pressure in kg/m2
Cp= pressure coefficient. It is obtained according to the type and shape of the structure. For the design of truss-type reticular structures, a pressure coefficient equal to 1.3 will be used, when the elements are of a circular cross-section.
VD = Design wind speed in m/s.
FTR = Corrective factor for topography and roughness. This factor is taken from table 3.3 of the NTC on wind design. For this case, a value equal to 1 was used (T3=Terrain practically flat, open field, absence of important topographic changes, with slopes less than 5%).
Fα = This factor establishes the variation of wind speed with respect to height (z). For this case, as the height z of the structure is less than 10 m, Fα is taken with a value of 1.0.
VR= Wind speed in m/s, depending on the region. For Mexico City (Zone 5), according to the NTC on wind design, the VR= 22 m/s.

Boundary conditions	***Values***
Dead Weight (Pp). According to material:	Galvanised steel 500, grade B (round)

Live load acting on nodes	1,471 N (150 kg)
Wind speed – Wind pressure Pz	22 m/s - 30.2016 Kg/m2 [296.177 Pas]
Total wind load in each node	514.85 N (52.48 kg ≈ 52.5 kg)
Combination of loads: Gravity	1.0 (Pp + CV)
Combination of loads: Wind	1.1 (Pp + CV + C wind)
Supports	Simples
Connections (nodes)	Semi-articulated, fixed with bolts
Section shape	Tube
Dimensions: diameter – gauge	1.5 "(3.81 cm) - 20 (0.1 cm)
Area	1.279 x 10^{-8} m^2
Moment of inertia (I_x, I_y)	2.189 x 10^{-8} m^4 (2.19 cm^4)
Section modulus (S_x y S_y)	1.15 x 10^{-6} m^3 (1.15 cm^3)

Table 6. Boundary conditions for non-linear structural analysis.

Mechanical properties	***Values***
Material	Galvanised steel 500, grade B (round)
Volumetric weight	78499,977 N/m^3 (8,004.77 kg/m^3)
Elastic Modulus (Young's modulus)	199,951.34 MPa (2'038,935.8 kg/cm^2)
Poisson's Coefficient (U)	0.3
Yield Strength of Steel (Fy)	289.59 MPa (2,953 kg/cm^2)
Shear Modulus (G)	76,904.36 MPa (784206.1 kg/cm^2)

Table 7. Mechanical properties of galvanised pipe bars.

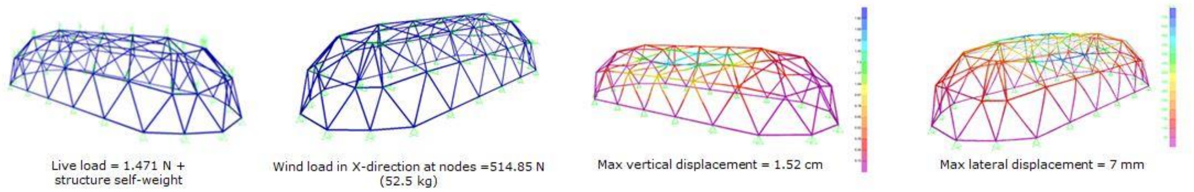


Figure 10. Non-linear structural simulation: Left. considering a live load of 1,471 N + the self-weight and wind load of the structure. Right. Results of the max vertical and lateral displacement, in cm.

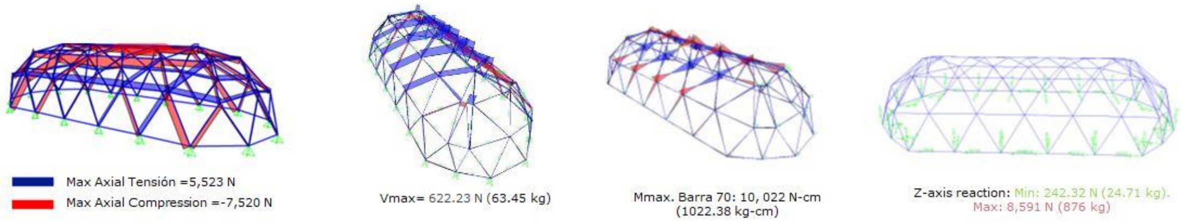


Figure 11. Result of the non-linear structural simulation: Left: max axial tension and compression forces as well as maximum Shear force. Right: maximum bending moment as well as reactions in the z-axis direction (vertical).

4 ARCHITECTURAL ANALYSIS TO DETERMINE THE USE CONFIGURATIONS OF THE PROTOTYPE

As part of the various analyses that were carried out, a spatial study was developed with various functional possibilities of the rectangular-based grid structure. Several aspects were considered, such as linear dimensions, envelope, and footprint area, as well as the conditions of temporary habitability and interior comfort.

Below is a series of images of the functional proposals that were considered most suitable considering what the emergency scenario required at that moment, such as Temporary Shelter, Temporary Primary Care Clinic, Emergency Housing and Temporary Classroom.

The results are presented in perspective views, showing the proposed main and secondary furniture layouts. There is also an area marked in green on the floor indicating the space that is recommended to be left free, as the shape of the structure makes this area curve up to the highest part making it difficult to carry out any activity, except perhaps its use as a storage space. This distribution was proposed after a meticulous ergonomic and anthropometric analysis that would ensure the comfortable and functional habitability of the proposed use.

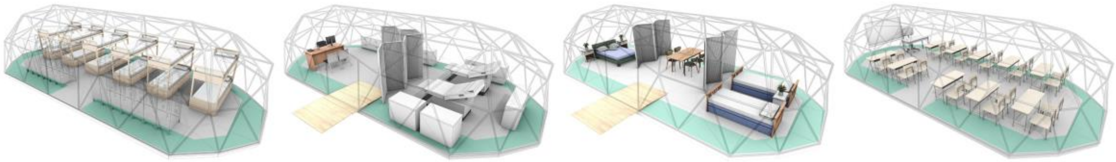


Figure 12. Prototype Functional Proposals: Temporary Shelter, Temporary Primary Care Clinic, Emergency Housing, Temporary Classroom.

5 FULL-SCALE MATERIALISATION OF TWO STRUCTURES BASED ON THE CHAMFERED CORNER PROTOTYPE

As a final design stage, the full-scale assembly of the rectangular base structures was executed. The purpose of this stage was to corroborate that both the digital design and the analysis in the physical model and structural analysis were as expected. In addition to assembling the rectangular-based structure, a square-based structure was assembled with the same tubes as the geodesic, frequency 2. Although the disassembly and assembly of the square-based structure presented some problems in the transition from one process to another, it was possible to verify that different typologies can be assembled with the same tubes based on the modular prototype of the chamfered corner.

Also at this stage, as part of the research, teaching strategy, and as an experimental workshop, students from the architecture and industrial design courses were involved in the construction of this structure under the supervision of the LAVSIMAD members.

Figure 13. Assembly of the temporary structure with a rectangular base.

6 ENVIRONMENTAL COMFORT

For the design of the access and ventilation shafts, a design based primarily on achieving cross ventilation regardless of the orientation of the structure was considered to achieve an adequate temperature inside the structure.

The main access was in the center of one of the longest sides of the structure, with a ventilation shaft on the opposite side. A similar case was made with the ventilation openings located on the short sides of the structures. Despite the above, the fact of placing a plastic tarp as a cover caused the interior temperature to increase in summer, decreasing thermal comfort. This was translated in part of the recursiveness in the experimental process that demanded reconsidering the choice of materials for future covers.

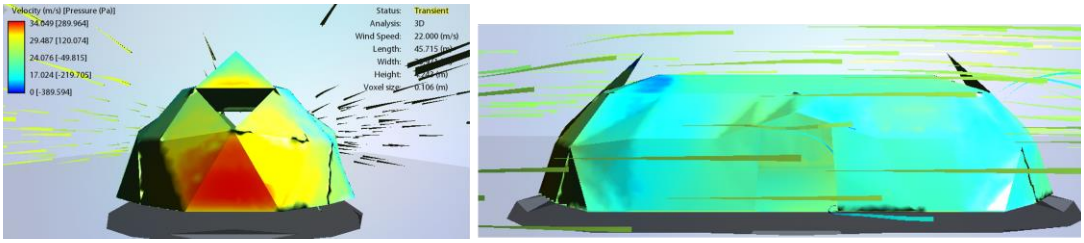


Figure 14. Simulation of cross ventilation with Flow Design© which, according to the maximum velocity of 34 m/s, generates maximum pressures of 290 pascals.

7 ECONOMIC FEASIBILITY

The final cost of the structure already assembled at the donation site was USD 1,169 for a floor area of 47.5 m2 and an envelope area of 83.5 m2 respectively. This translates to a floor area of USD 24.61/m2 and an envelope area of USD 14/m2.

8 CONCLUSIONS

The research proposed a design methodology that motivates teamwork involving several specialties to resolve a situation that requires very specific characteristics, which can also take advantage of computational analysis resources to constantly optimize and reorganize all the processes, such is the case of a modular emergency structure like the one that was built.

Although time was short, given the urgent need due to the emergency caused by a natural disaster, coordinated work was achieved thanks to the LAVSIMAD Laboratory. The concurrence of specialties was important from the beginning of the process, as well as interdisciplinary and parallel work, where work was coordinated between teachers and students from two careers: architecture and industrial design. It was also necessary to work recursively in order to adjust the structure according to the variables that emerged from the analysis of the computer graphics and physical models.

In this way, it was possible to combine the CONINPRE methodological work with LAVSIMAD and the use of parametric design to search for new three-dimensional geometric shapes known as geometric polymorphs, but adding factors that allow the analysis of different situations that must be considered for the prototypes to be developed in the most satisfactory way possible. Thus, a temporary triangular lattice structure with a rectangular base was achieved, giving rise to a corner prototype that has the possibility of generating new forms in the future, as well as complying with functionality, comfort, environmental aspects, economic viability, and structural safety, generating a positive social impact as a prototype. which was used as emergency housing for the victims of the 2017 earthquake, thus closing the cycle that comprises a design process, from pre-figuration to materialization and use.

Pedro J. Villanueva, https://orcid.org/0009-0002-6080-7108
Alfredo Flores, https://orcid.org/0009-0007-0368-5323
Iván A. Ramírez, https://orcid.org/0009-0005-0940-4882
Diemel Hernández, https://orcid.org/0009-0008-5034-5740
Armando A. Suarez, https://orcid.org/0009-0004-4345-5854
Elda N. Mendoza, https://orcid.org/0009-0005-0942-3397

REFERENCES

[1] Dunn, N.: Digital Fabrication in Architecture, Laurence King Publishing Limited, London, UK, 2012.

[2] Gardener, N.; Haeusler, M.; Zavoleas, Y.: Computational Design, From Promise to Practice, Avedition, Germany, 2020.

[3] Iwamoto, L.: Digital Fabrications, Architectural, and Material Techniques, Princeton Architectural Press, New York, NY, 2009.

[4] Mutlu, M.; Potapova, L.; Kara, H.; Georgouilias, A.: How the Architect Found the Engineer, Interdisciplinary Design: New Lessons from Architecture and Engineering, Actar Publisher, USA, 2012.

[5] Phocas, M.; Kontovourkis, O.; Ioannou, T.: Architectural Engineering Technology Journal, Volume 1, Issue 2. Interdisciplinary Research-based Design: The Case of a Kinetic Form-active Tensile Membrane, 2012. https://doi.org/10.4172/2168-9717.1000104