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To cite this article: M C Acuña-Prada *et al* 2021 *J. Phys.: Conf. Ser.* **2102** 012003

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Physics in architecture projects, a perfect match on Alamillo's bridge by Santiago Calatrava

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Abstract. The Alamillo's bridge by Santiago Calatrava was studied, who develops projects and structures with morphological, sculptural, and conceptual aspects associated with physics and contemporary architecture, through experimentation with forms of nature, the movement of the human body and, materials such as steel and reinforced concrete. The methodological framework corresponded to a documentary study that determined the importance of the bridge from its historical context as part of the infrastructure of the 1992 Universal Exposition in Seville, as well as the analysis of the physical concepts used in its design and construction; and, a quantitative-descriptive study applied to the seventh semester students of the Architecture program of the Universidad Francisco de Paula Santander, Colombia, which determined their level of recognition of the physical concepts of this project. As a finding, it is highlighted that this bridge applied physical concepts such as: aerodynamics, torsion, compression, tension, traction, and gravitation, in compliance with its formal-aesthetic design criteria, and those students recognize the physical concepts, design and technical characteristics -formal, typical of the project. Likewise, it was determined that this urban landmark represents a comprehensive solution that solves the structure and form through solutions associated with the field of engineering, architecture, and physics.

1. Introduction

The industrial revolution brought with it innumerable advances from technique, technology, and material, and therefore, one of the great challenges that it posed corresponded to the joint work between architects and engineers, bringing consequently new associated challenges over the years to the form, function, and structure of projects that call attention to the successful integration of knowledge [1]. A clear representation of this is evidenced in the work developed by Santiago Calatrava, who from his profile of architect, engineer, and artist has managed to develop works of high visual, morphological, conceptual, and structural impact, which combine function, order, and the symbol of the modernity of cities [2].

The 1992 Universal Exhibition of Seville, Spain under the slogan "The era of discoveries" on the V centenary of the discovery of America, configured an important challenge for Seville, as a host city, from which, the city faced an urban transformation associated with the adaptation and construction of infrastructure [3]. As part of the urban planning proposed by the Junta de Andalucía.

As mentioned above, the present investigation determined as research questions: Can the application of physics in architecture favor the structural and material composition and the design of architectural projects? And what is the level of perception and knowledge manifested by the students of the seventh semester of the architecture program of the Universidad Francisco de Paula Santander, Colombia, with



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respect to the basic concepts of physics applied to the Alamillo's bridge? The development of this research allowed to reaffirm that physics is present in the design and construction of architectural projects; and therefore, it is necessary for architects in training to include the application of physical concepts in the development of their projects. Likewise, this research allowed us to recognize that from the use of physical concepts it is possible to strengthen the formal and aesthetic aspects in architectural projects; achieving, as in the case of the Alamillo bridge, to balance a composition centered on design (form), physics (structure), and art (concept).

2. Method

This research was framed within the particularities of the quantitative approach at the descriptive level [4] since it characterized the perceptions and knowledge of basic physics that students of the seventh semester of the Architecture program of the Universidad Francisco de Paula Santander, Colombia. The survey [5] was used as an instrument for data collection, once the document review stage [6] and the background were completed, in order to strengthen the researchers' knowledge regarding the structure of the Alamillo bridge. and the physical concepts that accompany it.

Non-probability sampling was applied using the intentional sampling technique [7]. The population of this research corresponded to the active students of the Architecture program of the Universidad Francisco de Paula Santander, Colombia, and the sample was 50 students in the seventh semester, considering that these students are completing the cycle of deepening their curricular proposal. The survey consisted of five items with closed response options, questions 3, 4 and 5 relate descriptive paragraphs that relate aspects about the technique and design of the Alamillo's bridge, accompanied by graphics that illustrate the basic concepts of applied physics in the object of study, for students to identify the types of effort. From the data collected, the SPSS v25 software was used as a support tool for their processing and the generation of information that has been synthesized.

3. Results

Santiago Calatrava designed and built the Alamillo's bridge between 1987-1992 over the old channel of the Guadalquivir river [8], as can be seen in Figure 1 this impressive structure is the perfect combination between architecture and physics, it contains a 142-meter-high pylon with a 58-degree inclination, which counteracts the weight of the deck and, therefore, avoids the implementation of handrails, achieving that all of its loads can be supported by thirteen pairs of cables, in addition its columns work as buttresses that allow their thinning at the top or crown [9]. In order to determine the tension of a cable, in some cases linear models are used in which the natural frequency, the length, the mass per unit length of the cable and the tension are related [10].

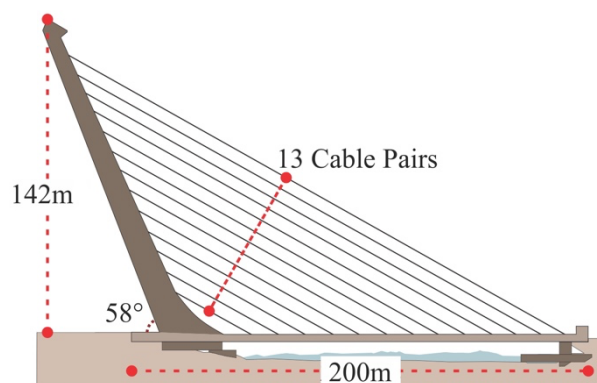


Figure 1. Alamillo's bridge by Santiago Calatrava.

The fundamental equation that describes the vibration of a cable with wave equation for $y(x, t)$ and a mass per unit length m subject to a tension T , corresponds to Equation (1), from which when performing the modal analysis to determine the frequency of the n -th harmonic f_n it is defined from the

Equation (2) where L corresponds to the length of the vibrating part. Therefore, the tension as a function of the first vibrating mode f_1 is determined by Equation (3). In some cases, it is not possible to identify the first mode f_1 , so it is determined using the frequencies of higher modes of vibration, as mentioned in Equation (4).

$$\frac{\delta^2 y}{\delta x^2} - \frac{m}{T} \frac{\delta^2 y}{\delta t^2} = 0, \quad (1)$$

$$f_n = \frac{n}{2L} \sqrt{\frac{T}{m}}, \quad (2)$$

$$T = m(2Lf_1)^2, \quad (3)$$

$$f_1 = \frac{\sum_{i=2}^n f_i}{\sum_{i=2}^n i}. \quad (4)$$

The Alamillo's bridge, considered a symbol of modern Seville, represents within its structural composition, materiality and design the versatility of Calatrava, based on the harmonious union of concepts derived from architecture, calculation, physics and art; through which he implemented the concept of movement within his works; Part of his research and initial experimentation for this project was based on the elaboration of a sketch of the human body and the sculpture called Running torso, where elements associated with stretching and physical tension are appreciated; by means of the implementation of inclined and correctly balanced marble cubes through a tensioned cable [11]. For Santiago Calatrava, the static properties of the bridge are fundamental due to the achievement of balance, integrality, and the functioning of each of its parts [12].

In Figure 2, it is observed that Calatrava manages to determine the movement and organic expression of his bridges from the inclusion of three primary components from design (form), physics (structure), and art (concept) (Figure 2(a)); through which elements such as arches gain relevance from the distribution of symmetric and asymmetric forces (Figure 2(b)), the implementation of tension and compression forces and the distribution of loads to the ground, through of the use of support columns (Figure 2(c)) and finally, a result of artistic composition achieved through stretching and physical tension (Figure 2(d)). The Alamillo's bridge is recognized as the first bridge supported by cables, where the platform is in balance thanks to the use of an inclined mast, which replaces the arch and supports forces under tension and compression [13].

Figure 3 shows how the Alamillo's bridge condenses basic concepts of physics applied to architecture such as the traction force, represented in the cables subjected to an elongation or stretching effort towards the deck and the mast (Figure 3(a)), the compression force; evidenced in the reduction or shortening of the volume, this being in accordance with Newton's third Law "Principle of Action-Reaction" that in the Alamillo's bridge is developed from the compression reaction of the deck and the neck under the purpose of avoid the deformation of the structure (Figure 3(b)), and, the gravitational force or mutual attraction, represented in the bridge in the transmission of the weight directed towards the center of the earth, which causes a direct reaction in its pillars (Figure 3(c)). This may be represented in what was established by Newton in his fourth Law called "Law of universal gravitation" [14,15].

Consequently, within this research the relationship understanding and use of physics in architecture was recognized by identifying the level of perception and knowledge manifested by students of the seventh semester of the architecture program with respect to the basic concepts of physics. Applied to architecture. It is noteworthy that the work of Santiago Calatrava "Alamillo's bridge" was taken as an object of study within the framework of projects associated with science, technology, art, and mathematics considering that its design and structure complies with the combination of concepts associated with physics and architecture and their development was in response to a historical moment of relevance for Seville.

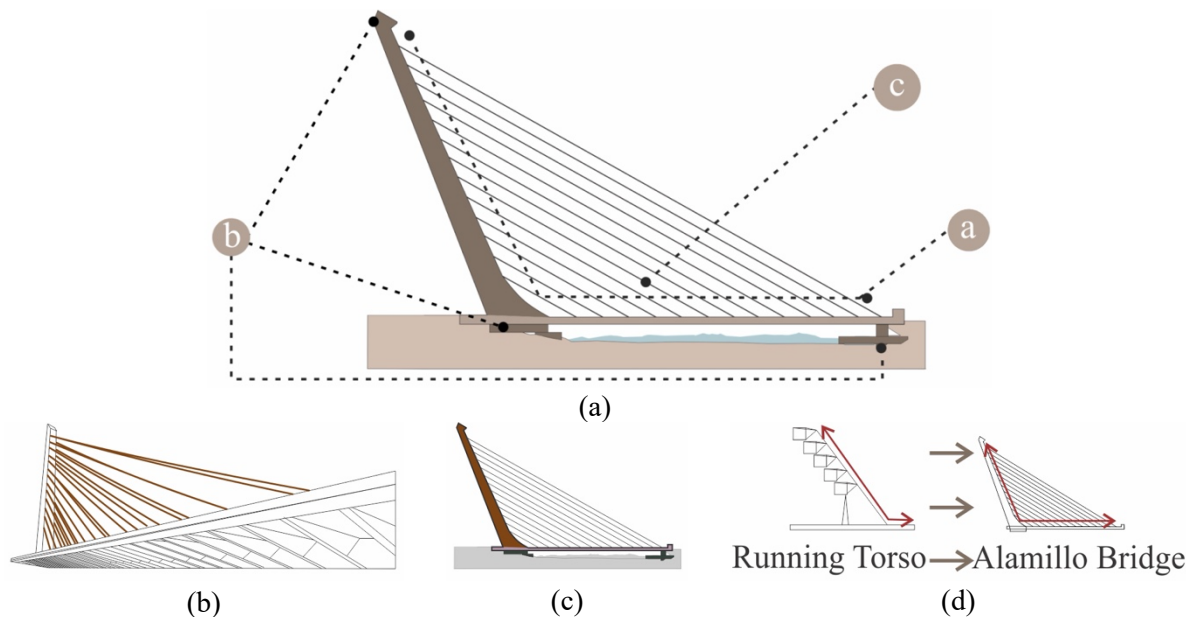


Figure 2. Main design elements in the Santiago Calatrava bridges: (a) form, structure, and concept in the Alamillo's bridge, (b) form as the basis of architectural design, (c) physics in structural calculation, (d) art as a design concept and generator of movement.

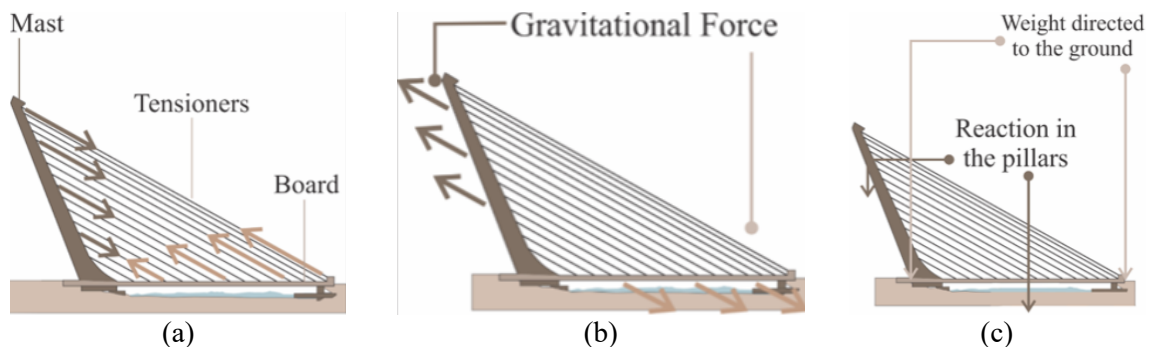


Figure 3. Basic concepts of physics applied to the Alamillo's bridge: (a) traction force from elongation or stretching efforts, (b) compression force associated with Newton's third law "action-reaction", (c) gravitational force transmission of weight towards the center of the earth.

The demographic profile of the members of the sample, presented ages ranging between 19 and 21 years with an average of 20.7 years, the female gender is dominant with 60% of the cases, domiciled in the San José de Cucuta city and its Metropolitan area. In Table 1 it can be observed that 82% of the surveyed students considered that the concepts of tension and compression were the most influential in the structural design of the Alamillo's bridge, recognizing the compression force as a manifestation of the tension they experience. The elements of the structure of this bridge.

Table 1. Physical concepts associated with the structural design of the Alamillo bridge.

Parameter	Responses number	Percentage (%)
Rhythm, transmissibility	5	10.0
Tension, compression	41	82.0
Malleability, reciprocal quantities	4	8.0
Total	50	100.0

For Calatrava there are three aspects that can be molded in the design of a bridge, to achieve the organic concept: (a) symmetric and asymmetric forces in the arch of the bridge; (b) the work of tension and compression of the arches; (c) the work of the support columns and support for the arches in their function of distributing the weight to the subsoil. Based on this statement, the students were asked to identify the type of bracing characteristic of the Alamillo's bridge, 58% of the respondents were correct in their answer by ensuring that the asymmetric bracing with eccentric design was applied to this bridge (see Table 2); while the remaining percentage assured that a symmetrical bracing was applied to the bridge accompanied by straps in one case symmetrical and / or eccentric in another, this evidences a lack of knowledge of basic concepts of geometry (symmetry).

Table 2. Frequencies associated with the type of bracing applied in the structural design of the Alamillo bridge.

Parameter	Responses number	Percentage (%)
Symmetrical cable tie, equidistant straps	14	28.0
Symmetrical cable tie, eccentric design	7	14.0
Asymmetric cable tie, eccentric design	29	58.0
Total	50	100.0

To answer the third item of the survey, the following descriptive information was provided to the students: "The mast was manufactured with an envelope made of steel plates and reinforced inside with reinforced concrete. It has a height of 142 meters above the finished floor level and an inclination of 58° with respect to the horizontal, which allows it to receive the stresses of the tension of the cables that support the bridge, adopting in its design the shape of a arm and playing with the supporting tension and flexibility of the materials; from this information identify the predominant type of effort in the Alamillo's bridge". In Table 3, opinions are predominantly divided in 60% of cases in the selection of tensile stress, students recognize the tensile stress in the straps as the reaction they experience when they are placed on them. Applies a load, which in this case corresponds to the weight of the structure.

Table 3. Frequencies associated with the predominant type of stress in the structural design of the Alamillo's bridge.

Parameter	Responses number	Percentage (%)
Compression stress	8	16.0
Traction stress	12	24.0
Stress strain	30	60.0
Total	50	100.0

In the fourth item, the following information was provided in order to identify the name of the applied force: "The Alamillo's bridge presents a force resulting from the stresses or pressures that exist within a deformable solid or continuous medium, characterized in that it tends to a reduction in volume or a shortening in a certain direction. This force is contrary to the one mentioned above because it tries to compress an object in the sense of force". From Table 4, it can be determined that 62% of the students think that it corresponds to the traction force, while 36% suggest that it is the compression force. The predominant response shows that the concept of traction force is present in the students, understood as the interaction between two forces with the same direction, but with opposite directions, whose only intention is to produce the stretching of a body.

In this last question, the following information was presented in order to identify the force applied to the bridge under study: "It is related to Newton's fourth law, it corresponds to the force of mutual attraction that bodies experience due to the fact of having a determined mass, therefore; The Alamillo's bridge must support the weight, through the cables, making a tension which will correspond to be greater at the other end". In Table 5, it was possible to identify that the opinions are diverse, so it could be understood that there is no clarity in this concept. The correct and predominant response was the gravitational force in 60% of the cases, followed by the rotational and torsional force in 22%, the

gravitational force understood as that force experienced by two bodies that is proportional to the product of their masses and inversely proportional to the square of the distance that separates them.

Table 4. Frequencies associated with the type of predominant force in the deck and mast of the Alamillo's bridge.

Parameter	Responses number	Percentage (%)
Traction stress	31	62.0
Twisting force	1	2.0
Compression stress	18	36.0
Total	50	100.0

Table 5. Frequencies associated with the type of predominant force in the structural design of the Alamillo's bridge.

Parameter	Responses number	Percentage (%)
Gravitational force	30	60.0
Rotational-torsional force	11	22.0
Friction force or friction	9	18.0
Total	50	100.0

4. Conclusions

According to the results obtained in this research in relation to the question of Can the application of physics in architecture favor the structural and material composition and the design of architectural projects? It was evidenced that Santiago Calatrava from his training as an architect, artist and engineer manages to balance in his works aspects associated with design, structure, and concept, also linking the notion of the organic and the movement in his bridges. The foregoing shows that physics and architecture can work together, achieving impact projects with an innovation approach that can favor the structural composition, material, scale, and design of architectural projects. In the Alamillo's bridge, the previous statement is relevant by showing that its structure combines basic physics with architecture, through the application of concepts associated with Newton's laws, as well as the distribution of forces and loads that accompany the structural design of the bridge.

Regarding the physical concepts present in the structural design of the bridge under study, the following stand out: tension and compression forces. About the bracing applied to the structural design of the Alamillo's bridge, the eccentric design with asymmetric cable-stayed type was evidenced, with respect to the predominant stress in the structural design of the bridge, the tensile stress, the predominant type of force in the deck, and the bridge mast corresponds to the traction force and finally, that the predominant type of force in the structural design of the bridge is gravitational. These elements are part of the physical concepts that configure the design and construction of the Alamillo bridge, recognized as the first bridge supported by tie rods with a balanced platform that supports tension and compression forces from the mast.

To the research question related to the perception and knowledge of the seventh semester students of the Architecture program of the Universidad Francisco de Paula Santander; Colombia, it is highlighted that the results obtained through the application of the survey evidenced a basic understanding of the associated concepts to the physics present in the Alamillo's bridge in Santiago Calatrava, considering that the affirmative responses were higher than the average in a range between 60% - 82%. This may be related to the level of competencies acquired for the academic semester taken and the approval of the basic and professionalization cycles. However, with the aim of strengthening the architectural and/or urban design processes, the academic program is recommended to promote strategies that allow the implementation, analysis, and recognition of physics within architecture to be strengthened. This will positively impact the skills acquired by the students and therefore the performance in proposing innovative projects in terms of morphology, structure, and conceptualization.

References

- [1] Chaves J 2004 Desarrollo tecnológico en la primera revolución industrial *Norba Revista de Historia* **17** 93
- [2] Hernández B 2004 La arquitectura del ingeniero. La materia, la técnica y la forma *Técnica Industrial* **253** 66
- [3] Fernández V 1993 Las grandes transformaciones urbanas de Sevilla durante los años previos a la exposición universal *Estudios Geográficos* **54(212)** 387
- [4] Hernández R, Fernández C, Baptista P 2014 *Metodología de la Investigación* (México: McGraw Hill)
- [5] Otzen T, Manterola C 2017 Tecnicas de muestreo sobre una población a estudio *International Journal of Morphology* **35(1)** 227
- [6] Peña T, Pirela J 2007 La complejidad del análisis documental *Información, Cultura y Sociedad* **(16)** 55
- [7] Argibay J C 2009 Muestra en investigación cuantitativa *Subjetividad y Procesos Cognitivos* **13(1)** 13
- [8] Serrera R M 2009 La huella de la historia: La Sevilla Americana *Nuclear España* **302** 29
- [9] Jodidio P 2007 *Santiago Calatrava 1951 Arquitecto, Ingeniero, Artista* (Germany: Taschen)
- [10] Carrión Viramontes F, Hernández Jimenez J, Terán Guillén J 2005 *Estudio Experimental de un Puente Atirantado. Evaluación de Cables, Publicación Técnica 265* (México: Instituto Mexicano del Transporte)
- [11] Casado A 2008 La ciudad y el cuerpo en la obra de Santiago Calatrava y Oscar Niemeyer *Revista de Filología Románica* **2** 59
- [12] Calatrava S, Lewis C, Pendleton J 2003 *Santiago Calatrava. Conversaciones con Estudiantes* (España: Gustavo Gili)
- [13] Alonso C, Atienza J R, Beng A 1992 Proyecto de Construcción del Puente del Alamillo. Sevilla (España) *Hormigón y Acero* **43(183)** 49
- [14] Orozco-Echeverri S 2016 Sobre el concepto de las leyes de la naturaleza en Isaac Newton *Revista Colombiana de la Filosofía de la Ciencia* **16(32)** 155
- [15] Sebastián J S 2013 Las Leyes de Newton de la mecánica: Una revisión histórica y sus implicaciones en los textos de enseñanza *Didáctica de las Ciencias Experimentales y Sociales* **27** 199