Journal of Physics: Conference Series

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To cite this article: J D González-Almeyda *et al* 2021 *J. Phys.: Conf. Ser.* **2118** 012021

Analysis of the application of physics in the design and construction of architectural projects. The Eiffel Tower

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Abstract. This article studied the impact and application of physical concepts in the design and construction of the Eiffel Tower in Paris, an architectural reference that implemented physical concepts in its structural design. A documentary methodological framework was used to establish the importance of the Eiffel Tower in the universal exposition of Paris in 1989 and, to carry out the structural analysis of the work; a quantitative-descriptive approach was used for the recognition of the basic concepts of physics from architecture according to gender, through a survey as a research instrument developed under non-probability and convenience sampling, which was applied to students of Architecture of the Universidad Francisco de Paula Santander, Colombia, in order to determine the knowledge of basic physics by students. The results of this research showed that the Eiffel Tower represents a milestone in architecture where physical concepts such as tension, compression, traction, aerodynamics, and torque were applied. Finally, it was evidenced that the students who participated in this study recognize the importance of applying the basic concepts of physics in architecture; fact by which it is recommended to encourage the study of physics, to strengthen the technological component of Architecture.

1. Introduction

The industrial revolution in Europe in the 19th century brought as a consequence great change of social, economic, political and cultural order that generated transformations in the cities. The implementation of new materials such as iron consolidated a dynamization of the economy that generated an acceleration in its production and use, impacting multiple scenarios in society [1]. Consequently, towards the middle of the 19th century, with the objective of making visible the technical, technological and scientific advances of the nations, the universal exhibitions were consolidated [2], which were characterized by presenting specific large-scale architectural landmarks, which were intended to host the exhibitions and, to demonstrate the grandeur and national supremacy from the technical and the technological, The first universal exhibition corresponded to London in 1851 with the Crystal Palace [3].

Between May 6 and October 31, 1889, the universal exhibition that commemorated the centenary of the French revolution was held in Paris, this exhibition was characterized by presenting the Eiffel Tower as a landmark or main symbol, a structure through which they were evidenced the advances in the design and construction of Paris and, which was established as a manifesto of faith in the commitment to technical progress [4] evidencing the importance of the application of physical concepts in architecture. The Eiffel Tower project was initially planned under the temporary duration of the universal exhibition, however, its construction system, its technological advance, hierarchy, and the successful implementation process next to the Seine River and the Champs de Mars made this project it will last in time and become a landmark, an urban heritage of humanity [5].

In this sense, this research posed as research questions: what is the application of physics in the design and construction of architectural projects? Can the application of physical concepts favor the structural and morphological design of architectural projects? And is it important that architects in training (students) recognize the basic concepts of physics and its application in architecture? The development of this research made it possible to demonstrate the importance of implementing physics within the design and construction processes of Architecture, highlighting that the relationship between physics and architecture acquired greater relevance and meaning from the industrial revolution. For this reason, its study, analysis, understanding, and application are essential elements within the teaching-learning processes of architecture.

2. Method

The methodological framework of this research work was developed from a documentary study [6] that established the importance and relevance of the Eiffel Tower for the universal exposition of Paris in 1989 and the technical aspects derived from the physical concepts applied to its design and construction. Likewise, a descriptive quantitative approach [7] was used that allowed the recognition of perception and knowledge of the basic concepts of physics implemented in architecture by gender differentiation, under the application of the survey as a research instrument and data collection from its primary source [8], its population focused on third-semester students of the Architecture of the Universidad Francisco de Paula Santander, Colombia, and the sample corresponded to 40 students.

For the selection of the informants, a non-probabilistic convenience sampling [9], was used through which the physical and architectural concepts of the Eiffel Tower were investigated among the students who were enrolled as students by the first semester of 2021 active, and that according to the curriculum of the architecture program they were finishing the basic cycle of academic training. The survey instrument was designed ad hoc by the researchers, it was composed of five questions posed under the scheme of the Saber Pro tests; that is, contextualized questions with a multiple-choice option with a single answer. The instrument incorporated supporting images about the Eiffel Tower into the sentences in order to provide visual support for reasoning and the subsequent selection of the correct answer.

3. Results

The Eiffel Tower challenges the physical concept of gravity from a false instability and a height corresponding to 300 meters, which classified it as the tallest element in the world for 41 years, after the inauguration of the Chrysler Building in New York that surpassed it by 19 meters and, later by the Empire State Building that surpassed it by 81 meters in height [10,11]. The structure of the Eiffel Tower is made up of four arched bases that make up a 275-meter-high column and three levels that act as dividing platforms.

The great structural challenge of the tower consisted in the very weight of the structure and the handling of the wind. Regarding the weight, the form of an intensive solid is adopted, this refers to the fact that each section of the solid is subjected to the same tension. As can be seen in Equation (1), it is verified that the pressure at any height of the tower is constant; next, by clearing the denominator of this expression, Equation (2) is obtained. This when solved as a differential equation by the method of separate variables, results in Equation (3), through which the statement is ratified, given that it is a function exponential.

$$k = \frac{V_x}{S_x} = \frac{\pi \int_x^{\alpha} [f(t)]^2 dt}{\pi [f(x)]^2}, \tag{1}$$

$$\int_x^{\alpha} [f(t)]^2 dt = k[f(x)]^2, \tag{2}$$

$$y = a * e^{-bx}. \tag{3}$$

Regarding the effect of the wind, the structure was designed in such a way that, for each elevation, the maximum moment generated by the wind is compensated by the moment of the weight of the tower (see Figure 1). To achieve this balance, the Eiffel Tower has curved legs, in such a way that its tangents, drawn at points at the same height, always intersect at the point through which the resulting wind effort passes, on the part that is above the analyzed points (equality of moments in Equation (4)).

$$F_v * h = W * b. \tag{4}$$

The structural design of the tower was largely elaborated from mathematical calculations applied to the arches, which formed the base, and from the implementation of the physical concept of aerodynamics [12], since the aerodynamic resistance is of vitally important to ensure structural integrity.

Figure 1 shows that the formal aspects that accompany the design of the Eiffel Tower were conceived from the configuration of an open and self-supporting structure [13], which implemented design concepts such as symmetry; understood in the project as a balanced structural, formal and visual arrangement [14], the rhythm; established from a prefabrication process but not standardization, because the variations in the sections of the pieces and the curvatures of the vertices, did not allow the unification or the interchange of pieces [15], a square pyramid shape with a base of 124.90 meters and a height of 324 meters that affected the balance and the distribution of live and dead loads due to their weight and height [16].

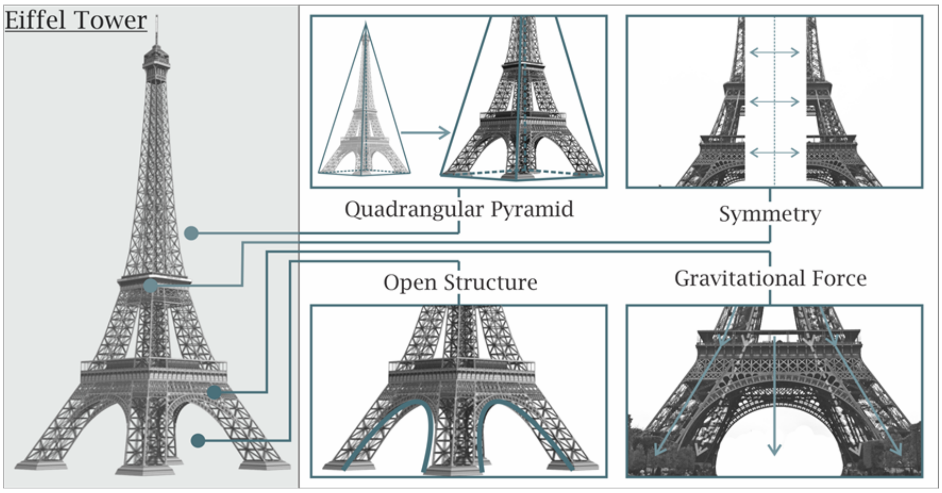

Figure 1. Physical and design concepts of the Eiffel Tower.

From the structural aspect, it should be mentioned that the tower presents wind and gravitational loads [17], as well as compression forces in the arches and compression-traction in the metallic triangular framework, in addition, a distribution of internal forces from the stress of torsion, represented in the internal rotation of the pillars that join the rest of the metallic structure [18,19]. In Figure 2 it can be seen that the tower implements the concept of aerodynamics, which allows the circulation of the wind through the structure [16], finally, it was established that the Eiffel Tower manifests a constant tension throughout its height, which it allows reducing the upper sections with respect to the lower ones and also, that from the beams tension can be generated in the upper part and compression in the lower part of the structure [20].

The Eiffel Tower is presented as a significant reference that allows making visible the importance of the use of physics in architecture, by considering that the implementation of physical concepts can strengthen the design, structure, and aspects derived from construction in architecture; for this reason, the present study considered it important to recognize the level of perception and understanding manifested by students of the third semester of the architecture program with respect to the basic concepts of physics applied to architecture.

In this sense, according to the demographic characteristics of the informants, it was possible to identify that 59.1% corresponded to the female gender with an average age of 19.6 years, and 40.9% to the male gender with an average age of 20.1 years. Regardless of gender, 71% come from stratum two and 29% from stratum three, residing in the San José de Cúcuta, Colombia, and its metropolitan area. This research was organized as a comparative study based on the gender of the informant that allowed to recognize the perception and knowledge of the basic concepts of physics with respect to the Eiffel Tower.

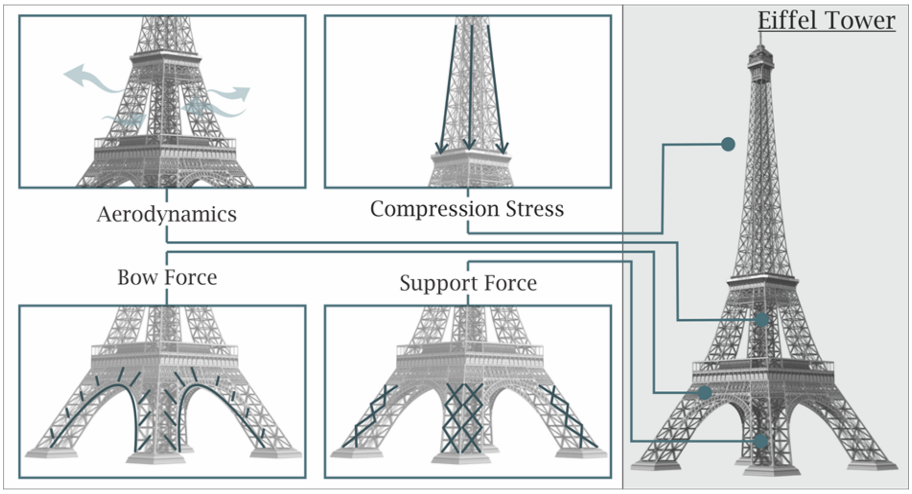

Figure 2. Physical concepts in the structural component.

Regarding the question, what physical concepts are present in the design of the structure of the Eiffel Tower? It was determined that 4.5% of the sample (equivalent to 7.7% of the women) assured that the structural design of the tower presents physical concepts such as: malleability, reciprocal quantities and the Avogadro principle, a situation that evidenced ignorance of the subject, since Avogadro's principle is associated with the ideal gas laws, the reciprocal quantities are recognized as scalars and whose product is the unit and, the malleability that corresponds to a property of metals to assume particular shapes, this could be associated with the structure but it differs, in the sense that beams of different sizes were incorporated into the Eiffel Tower.

Regarding the physical concepts associated with the structure, it was identified that 13.6% of the sample (with relative percentages of 15.4% women and 11.1% men, respectively), assured that the concepts of rhythm, transmissibility and capillarity, were the ones that influenced the structure of the Eiffel Tower, which shows a certain level of knowledge of physics, since the principle of Transmissibility is understood as a force applied to a rigid body, which could be replaced by another force with equal intensity, meaning and direction of the original force; but the concepts of rhythm and capillarity, are not located as physical concepts but design.

81.8% of the students in the sample recognized that the concepts of tension, aerodynamics and torsion were the most influential in the design of the object of study, understanding that a mechanical stress is exerted on the structure, and that its aerodynamic shape, it facilitates the flow of the wind throughout the structure, as well as that the torsion is present in the form that the structural elements take (see Figure 3).

The survey provided to the students the definition of the concepts of hierarchy and asymmetry in order to identify which of them is associated with the design of the Eiffel Tower. It was determined that 86.4% of the sample considered that the hierarchy is evident in the monumentality of its form. This response was provided by 92.3% of the total women, while the percentage of men was lower than this value by 14.5%. The remaining percentage chose to ensure that the concept associated with the design of the tower was asymmetry, showing that it was men who most favored this response option, surpassing women in more than 15% of cases.

Regarding the concept of aerodynamics related to the shape and structure of the Eiffel Tower, it is highlighted that all the students surveyed defined that the design of the tower facilitates the movement of air in its interaction with the structure, allowing the circulation of the wind of the place and, in consideration of its height and weight.

In reference to the types of efforts present in the Eiffel Tower, 68.2% of the informants selected compression and traction, from the gender perspective, it was observed that 84.6% of the women chose this answer, compared to 44.4% of men, which made it possible to show that in this item women were more assertive than men. Finally, the type of effort present in the curved shape of the pillars of the tower was identified, for which 63.9% of the informants opted for torsion, with 76.9% of the women recognizing this option compared to 44.4% of men.

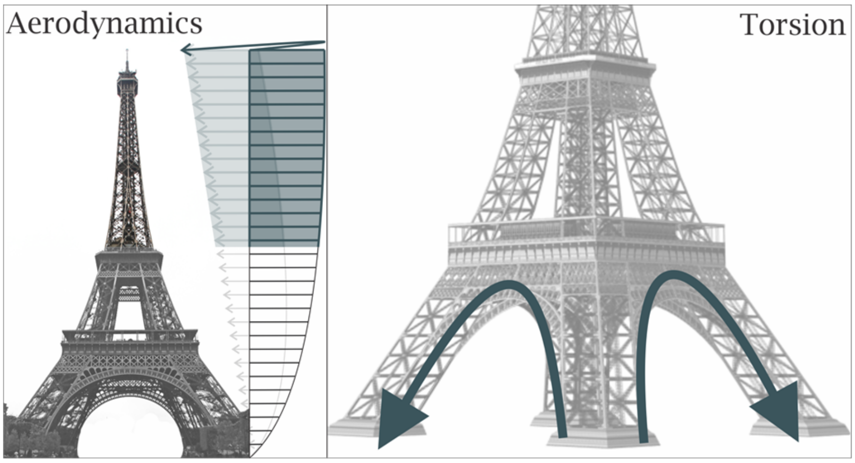

Figure 3. Influential physical concepts at the Eiffel Tower.

4. Conclusions

The research allowed from the documentary study to recognize the historical importance of the Eiffel Tower, as a representative and patrimonial element in the urban scale of Paris, which represented the advances in the design and construction of new structures that bet on the technical progress derived from the industrial revolution, which consequently managed to change the urban landscape of cities. Likewise, the documentary study determined the bases and the identification of the concepts associated with physics that were part of the analysis of the design and construction of the Eiffel Tower.

Regarding the research questions, what is the application of physics in the design and construction of architectural projects? and can the application of physical concepts favor the structural and morphological design of architectural projects? Through this research it was possible to establish that the Eiffel Tower as an object of study allowed to understand the application of physics in architecture from the implementation of the basic concepts derived from these branches of knowledge, through the understanding of the complexity of the structure of the Eiffel Tower and the handling of the winds. The above showed that the application of physics can favor the structural and morphological design of architectural projects, which in the case of the Eiffel Tower was evidenced in the application of ordering elements of design such as symmetry, hierarchy, and rhythm and, basic physics concepts such as aerodynamics, torsion, compression, traction, and tension; correctly balanced within the conception of the architectural design and the structure of the Eiffel Tower.

Regarding the research question, is it important that architects in training (students) recognize the basic concepts of physics and their application in architecture? It was confirmed that it is important for architecture students to recognize the usefulness of the application of physical concepts in architectural works; this when considering that its implementation can favor the formal, morphological, and structural aspect of architectural projects. Likewise, through the results obtained from the perception study applied to the third semester students of the Architecture program of the Universidad Francisco de Paula Santander, Colombia, it was possible to show that women present a greater recognition of the basic concepts of physics implemented in the architecture. The above when considering that the percentage of women who identified the correct answer was higher than that of men in four of the five items evaluated.

According to the results obtained within this research, it is recommended that the academic program review the curriculum with respect to the possibility of including a specific subject for the area of physics, as well as evaluate the topics addressed from the structures subjects (I and II), in order to potentiate the recognition, understanding and application of basic knowledge of physics in architecture in order to strengthen urban-architectural proposals from the technical, technological, material and formal components, as well as the competences of the sub area of technique present in the profile of the graduate architect.

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