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UDC 624.83

Pokrovskaya A.V. The Pivot Bridge by Leonardo da Vinci

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Abstract. *This study is dedicated to the investigation and analysis of the pivot bridge designed by Leonardo da Vinci. The paper explores Leonardo da Vinci's contribution to the development of engineering structures, examines the types of loads acting on bridge constructions, and provides a detailed analysis of the pivot bridge conceived by the renowned inventor. Particular attention is given to the unique structural feature that enables the bridge to rotate rapidly around its axis, allowing for the swift establishment or removal of a crossing.*

The practical section includes calculations of permissible loads, taking into account the weight of individuals and snow accumulation, as well as the identification of structural and material requirements necessary for the implementation of the project under near-real conditions. The study concludes with an assessment of the practical applicability of the proposed design and outlines the key elements that ensure its stability and reliability.

This research holds significance both in a historical-scientific context and as an educational example of engineering design.

Keywords: *Leonardo da Vinci's pivot bridge; load calculation for pivot bridges; Leonardo da Vinci's inventions; structural analysis of the pivot bridge; Leonardo da Vinci's contribution to science; model of da Vinci's bridge; structural elements of the pivot bridge; practical application of the pivot bridge; construction of da Vinci's bridge; pivot bridge project; research project; bridge stability and safety; da Vinci's bridge in modern conditions; how to build da Vinci's bridge; da Vinci; Leonardo da Vinci; Leonardo da Vinci's engineering designs.*

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Relevance of the Study: The relevance of this research lies in the growing interest in historical engineering solutions and their potential application in contemporary contexts. The constructions designed by Leonardo da Vinci—such as the pivot bridge—represent a unique synthesis of art and science, showcasing an innovative approach to problem-solving during the Renaissance period [1]. The study of these projects not only deepens our understanding of the history of technology but also reveals principles that remain relevant for modern engineering systems [2].

Research Hypothesis: The hypothesis of this study is that Leonardo da Vinci's pivot bridge, due to its self-supporting structure and efficient load distribution, can be adapted for modern use, provided that current requirements for stability and safety are taken into account.

Research Objective: The objective of this work is to analyze the structural design of Leonardo da Vinci's pivot bridge, assess its technical characteristics, and evaluate the feasibility of its practical implementation.

Research Tasks:

1. To examine Leonardo da Vinci's contribution to the development of engineering structures, with particular attention to his inventions in the field of bridge construction [4].
2. To analyze the types of loads acting on bridge structures and the conditions required for their equilibrium [5].
3. To perform strength calculations for materials and determine the required foundation depth to ensure structural stability [8].
4. To construct a functional model of the pivot bridge that demonstrates its operational viability.

Object of the Study: Leonardo da Vinci's pivot bridge.

Subject of the Study: The investigation of the structural features, engineering principles, and practical applicability of Leonardo da Vinci's pivot bridge, including the construction of a working model.

Research Methods:

1. **Historical-analytical method:** Examination of Leonardo da Vinci's contributions to science and engineering, with analysis of his inventions, including self-supporting and pivot bridge designs.
2. **Theoretical analysis:** Study of the types of loads acting on bridge structures, conditions for structural equilibrium, and specific features of the pivot bridge design.
3. **Engineering and calculation method:** Structural calculations of material strength, foundation depth, bridge length, permissible loads (such as human weight, snow, etc.), distribution of force moments, and other parameters to ensure structural stability, as well as determination of construction and material science requirements.
4. **Experimental method:** Construction and testing of a model of the pivot bridge to confirm its functionality and structural stability.
5. **Modeling and design:** Analysis of key structural elements that ensure the bridge's stability and reliability.

Final Product: A model of the pivot bridge constructed from wooden beams with a pulley system, demonstrating the ability to withstand combined loads (human weight, snow, wind) and to rotate around its axis.

The research is based on the works of contemporary authors [1, 4] as well as fundamental studies in the field of mechanics [5, 8].

1.1. Leonardo da Vinci's contribution to science

History offers many examples of remarkable individuals—scientists, writers, and artists—each distinguished in their own field. Yet how many are known to have mastered multiple disciplines and achieved outstanding results in nearly everything they pursued? Undoubtedly, very few. This is precisely why the biography of Leonardo da Vinci is of particular interest. Humanity is well acquainted with his great masterpiece of painting, *Mona Lisa*, which is now housed in the Louvre and continues to attract thousands of visitors with its enigmatic allure.

Figure 1. Portrait of Madame Lisa del Giocondo

Leonardo began exploring the natural sciences in his youth while studying in Florence under the renowned painter and sculptor Andrea del Verrocchio. During this time, he sought advice from the mathematician and physician Paolo Toscanelli. Later, while residing in Milan, Leonardo engaged in dialogue with scholars from the University of Pavia and local Milanese scientists, studied scientific literature, and participated in discussions related to the scientific revolution and the re-evaluation of traditional Aristotelian views. Throughout his life, he actively investigated the natural world, conducted observations, made comparisons, and collected data, repeatedly returning to questions that captured his interest. As a scientist, da Vinci astonishes the intellect with the breadth of disciplines he engaged in—from medicine to celestial mechanics, his contributions are evident across a wide spectrum. The symmetry of the human body is elegantly depicted in his iconic work *Vitruvian Man*.

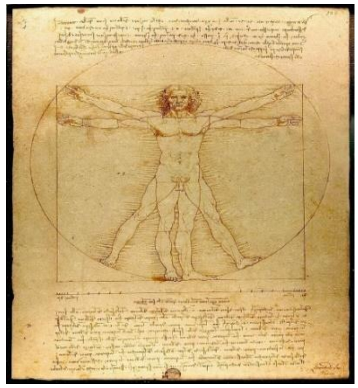


Figure 2. Vitruvian Man

In the field of biology, da Vinci was the first to describe several bones and nerves, and he proposed a then-novel concept of muscle antagonism. He also treated botany as an independent scientific discipline, which enabled him to be the first to describe many complex processes occurring in plants.

In physics, Leonardo also achieved significant results. He formulated the law of inertia—now more commonly known as Newton's First Law—which postulates the existence of inertial frames of reference. He studied free-falling bodies and the motion of objects thrown horizontally. As early as 1475, he hypothesized the impossibility of a perpetual motion machine. His knowledge of physics allowed him to develop numerous unique inventions, some of which have parallels in modern life. Among them:

- **Aerial screw:** This invention consisted of a metal frame covered with fabric—originally linen was suggested. A refined and enhanced version of this design is widely recognized today as the **helicopter**.
- **Parachute:** As early as the late 15th century, Leonardo proposed a device enabling safe descent from heights. The only major difference from modern parachutes was its **pyramidal shape**.
- **Self-propelled cart:** The mechanism at the core of this invention—a **spring-driven system** allowing movement without human input—is considered a forerunner of the **automobile**.
- **Bridge:** Unique in design for its time, the **self-supporting bridge** could be assembled and dismantled quickly, making it suitable for military operations during river crossings.

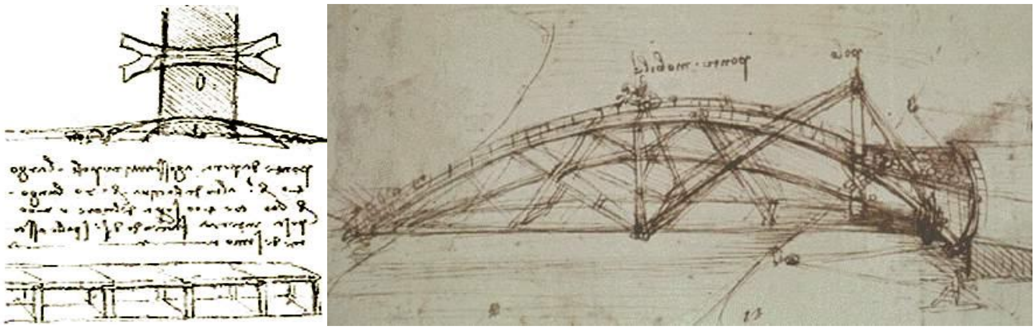


Figure 3. Leonardo da Vinci’s Bridge Sketches

A more detailed analysis of these inventions can be found in [2, 3, 4]. Among the inventions listed above, the **bridge** remains particularly relevant today, as modern designs differ little from da Vinci’s originals—unlike many of his other creations, which have been reinvented dozens, if not hundreds, of times.

Two known bridge designs were developed by Leonardo da Vinci. The first is a **self-supporting bridge**, a simple structure with enhanced load-bearing capacity achieved by incorporating several notched joints; an analysis of this design is presented in [1]. The second is a **pivot bridge**, a much larger and more complex structure intended for military purposes. This bridge continues to attract interest due to the uniqueness of its design.

Let us examine the pivot bridge in more detail. One end of the bridge was equipped with a massive **axle**, around which the remaining structure could rotate. This allowed the bridge to be deployed or retracted within minutes. For such a large structure to be feasible, several critical conditions had to be met:

- The **platform** housing the pivot axis needed to be exceptionally sturdy; if wood was the only available material, it had to be reinforced with metal inserts.
- To enable rotational movement, a **counterweight** was required, along with numerous **hinges, winches,** and **capstans**.
- The **rotating part** of the bridge had to withstand all loads during the transition between open and closed positions.

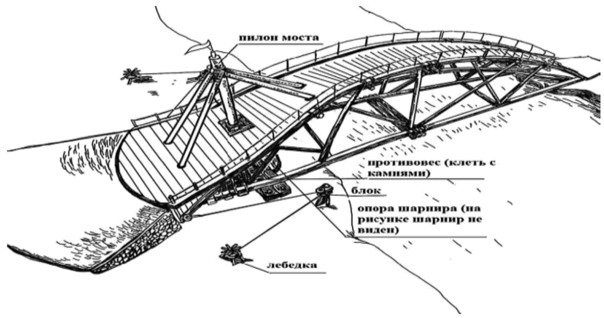


Figure 4. Pivot Bridge

Currently, the four most common types of bridges are beam, arch, cable-stayed, and suspension bridges. To which of these can the pivot bridge be classified? In order to answer this question accurately, let us first examine the key features of each type:

- **Beam bridge:** A simple and cost-effective design in terms of materials, ideal for short spans. Most small modern road bridges are beam bridges.
- **Arch bridge:** Highly durable and stable, often used for pedestrian routes in mountainous or riverine areas; known for its longevity.
- **Cable-stayed bridge:** Suited for long spans, such as those over straits. Lightweight and easier to construct than suspension bridges.
- **Suspension bridge:** The best option for the longest spans, typically used to cross large bodies of water or wide canyons. Though sensitive to wind, these bridges are very reliable.

Among these options, the **arch bridge** best aligns with the objectives pursued by Leonardo da Vinci in designing his pivot bridge. Its rigid structure makes it durable and resistant to the types of loads the bridge would be subjected to in use. A thorough understanding of the loads that occur under various conditions is key to successfully applying Leonardo's design in practice.

1.2. Types of Loads in Structures

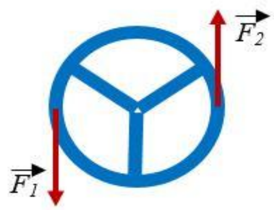
To design a bridge properly, one must accurately calculate the maximum load values the structure will experience. To perform such calculations, it is necessary to understand the conditions under which the structure will be in equilibrium. The first required condition is that the vector sum of all forces acting on the body must equal zero:

$$\sum_i F_i = 0. \tag{1}$$

Under such conditions, the center of mass of a body will remain at rest. However, if the body is not a material point, it is possible to apply forces whose vector sum equals zero in such a way that the center of mass remains stationary, while the body itself rotates around an axis passing through that center of mass. For such bodies, a second condition of equilibrium arises. To introduce this condition, we must define a physical quantity known as the **moment of force (torque)**, denoted as *M*:

$$M = F \cdot l,$$

where *l* is the shortest distance from the axis of rotation to the line of action of the force.



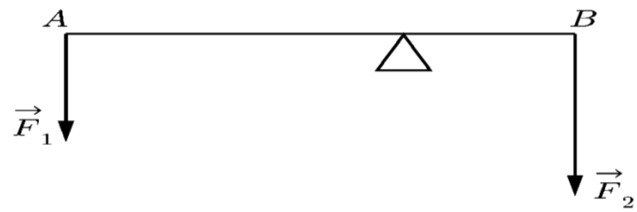


Figure 5. Example of Body Rotation

Figure 6. Example of Force Application in an Equilibrium Position

Now, having defined the concept of torque (moment of force), we can state the **second condition for the equilibrium of a body**:

$$\sum_i M_i = 0. \quad (2)$$

A more detailed explanation of these conditions can be found in [5, 6]. As is well known, according to the molecular-kinetic theory, every solid material contains significant internal interatomic forces. The presence of these forces determines a material's ability to withstand loads, characterizes its behavior under periodic or high-magnitude external forces, and defines its resistance to failure. These same forces govern the nature of deformation.

For small deformations, even a massive structure like a bridge can be considered elastic—that is, a body deformed under external forces will return to its original shape once those forces are removed. This elastic behavior is due to the internal properties of the material (in our case, wood). In bridge construction, the structure typically consists of rods that primarily function under bending loads. Such elements are referred to as beams.

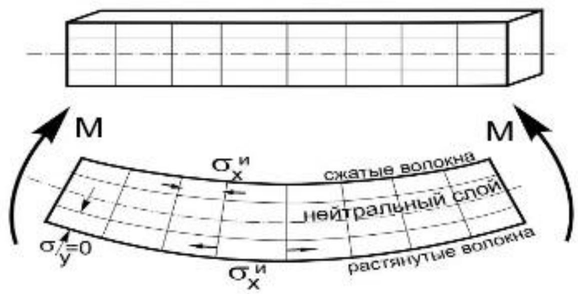


Figure 7. Beam Diagram in Unloaded and Loaded States

As is well known, in practice, loads are categorized into numerous subclasses. Below is a classification of the types of loads that may occur during the operation of a bridge:

I. By Mode of Application

a. **Concentrated Loads** – These loads are assumed to act at a single point. *Example:* The weight of heavy equipment placed on a beam.

b. **Distributed Loads** – These forces act along the length or over the surface of a structure and may be constant or variable. *Example:* The self-weight of a wall or water pressure on a dam surface.

c. **Surface Loads** – Spread across the surface of a structure. *Example:* Snow accumulation on a rooftop.

II. By Duration of Action

a. **Permanent Loads** – Constant in magnitude and continuously acting. These loads are critical in structural calculations during building design.

b. **Variable Loads** – Act for a certain period and may vary in intensity. *Example:* Pedestrians crossing a bridge.

c. **Short-term Loads** – Represent unusual or exceptional loads. *Example:* Transverse or longitudinal forces during an earthquake.

III. By Environmental Influence

a. **Wind Loads** – The aerodynamic shape of the structure plays a key role in the magnitude of wind-induced forces; streamlined shapes reduce these loads.

b. **Snow Loads** – Variable loads caused by snow accumulation, determined by the climatic conditions of the region.

c. **Hydrostatic and Hydrodynamic Loads** –

- *Hydrostatic:* Pressure from a static fluid on a wall or surface.
- *Hydrodynamic:* Impact of a moving fluid mass or wave action on the structure.

d. **Thermal Loads** – Characteristic of regions with fluctuating climates; account for the expansion or contraction of materials due to temperature changes.

Using all of the data described above, we proceed to analyze the structure of the pivot bridge.

1.3. Structural Analysis

To begin with, it is important to define the assumptions that will be used in the calculations. The density of the bridge material will be taken as a constant value, denoted by ρ. The structure will be considered symmetric with respect to a plane passing through the center of the bridge, parallel to the riverbanks and perpendicular to the water surface. The platform to which the pivot axis is attached will be assumed sufficiently strong to withstand the resulting rotational loads.

From the various types of loads described earlier, we will focus on those most likely to occur during the actual operation of the bridge. In terms of application, only those loads acting over more than a quarter of the bridge's length will be considered non-concentrated. Due to significant variability in average precipitation height, we will take 10 cm as a median value.

As previously mentioned, the bridge was most likely designed for military purposes. Therefore, we will consider the presence of 40 people on the bridge as a representative variable load, with the average mass of an adult male assumed to be 80 kg.

Climatic conditions also play a significant role. We will base our analysis on the climate typical of the regions where Leonardo da Vinci lived. Historically, da Vinci resided mainly in Italy and spent his final years in France, which correspond to subtropical and temperate climate zones, respectively. For the purposes of this study, we will assume an average winter temperature of –8°C and a summer temperature of +25°C.

The curvature of the bridge will be approximated with sufficient accuracy by a parabolic equation. The coefficient has been determined experimentally:

$$y=-0.02x^2$$

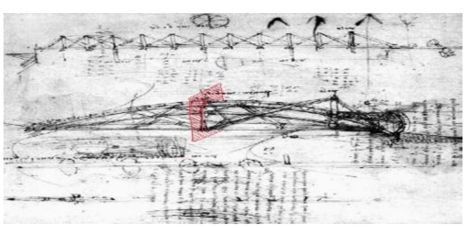


Figure 8. Plane of Symmetry of the Modeled Surface

Figure 9. Parabolic Approximation of the Bridge

In the formulation of our problem, due to the symmetry of the structure, the load can be considered as applied at the midpoint of the bridge, based on the property of the center of mass [7]. In this case, the moment generated by the bridge's own weight for a bridge of length *l* is calculated using the following formula:

$$M_{\text{м}} = \frac{\rho V g l}{2},$$

where ρ\rhoρ is the average density of the bridge material, V is the volume of the bridge structure, and g is the acceleration due to gravity.

When people move across the bridge, an additional load is generated, calculated as:

$F = n \cdot m \cdot g,$

here n is the number of people on the bridge and mmm is the average mass of one person.

We will also calculate the average force exerted by snow per unit area of the bridge surface:

$$\frac{F_{\text{с}}}{S} = \frac{\rho V_{\text{с}} g}{S},$$

where S is the surface area of the bridge span, and V is the volume of the snow. In the context of this approximation, the volume of snow accumulated on the bridge span can be calculated using the following formula: $V_{\text{с}} = h \cdot S,\ h = 10$ cm.

By definition, **pressure** P is the force divided by the area. Using this fact along with the expression for volume, we obtain:

$$P = \frac{\rho h \boxed{S} g}{\boxed{S}} = \rho g h.$$

Since snow is distributed across the entire surface of the bridge, the area terms cancel out. Thus, the **most critical loading scenario** for the bridge occurs when it is deployed across a river, with people standing at the midpoint and snow resting on its surface. The placement of people at the center is justified by the assumption that the bridge has a **second support** on the opposite riverbank. In such a configuration, the **maximum moment** acting on the main support—arising from a constant force—is achieved by maximizing the lever arm, which occurs when the load is concentrated at the midpoint.

Under these conditions, the bridge must withstand not only the total load but also the **bending moment** generated by that load, which must be compensated by the **foundation depth** of the supports embedded in the ground.

Let us examine these two problems:

1. Material Strength Limit

First, we determine the total force acting at the midpoint of the bridge. Let us assume that the bridge is sufficiently **wide and long** to accommodate **40 people** near its center, and that the longitudinal dimensions of each individual are **negligible** compared to the total length of the bridge.

($l_{\text{people}} \ll l_{\text{bridge}}$). We will consider "much smaller" to mean a **difference of one order of magnitude**, т.е. $\frac{l_{\text{people}}}{l_{\text{bridge}}} \leq 0.1$, Then, using reference data on average human body dimensions (0.3 m), and assuming that people are walking in a row of 8 individuals, we obtain the following value: $l_{\text{people}} = 0.3 \cdot 8 = 2.4$ (м), and, consequently, $l_{\text{bridge}} = 24$ (м). In this case, the **force exerted by the people on the bridge** is:

$$F_{\text{людей}} = 40 \cdot 80\ (\text{кг}) \cdot 9.8 \left(\frac{\text{м}}{\text{с}^2}\right) = 31360\ (\text{Н}).$$

Next, to calculate the **force exerted on the bridge by snow**, we determine the **transverse dimension** r of the bridge. Based on the assumption that the group consists of **8 people per row** and **40 people in total**, we conclude that there are **5 rows**. Referring again to tabulated data, the average **shoulder width** of a person is **87.5 cm**, so: $r = 0.875 \cdot 5 = 4.375$ м. The **force due to snow** acting at the center of the bridge in this case is:

$$F_{\text{с}} = P \cdot S^{'} = \rho \cdot g \cdot h \cdot l_{people} \cdot r == 100\ \left(\frac{\text{кг}}{\text{м}^3}\right) \cdot 9.8\ \left(\frac{\text{м}}{\text{с}^2}\right) \cdot 0.1\ (\text{м}) \cdot 2.4\ (\text{м}) \cdot 4.375\ (\text{м}) = 1029\ (\text{Н}),$$

where $S^{'}$ is the area of the analyzed section of the bridge.

From the force expressions, the **total force** is:: $F = F_{\text{people}} + F_{\text{с}} = 32389$ (Н). The **pressure** over the specified surface area is: $P = \frac{F}{S^{'}} \approx 3085$ (Pa). We use the formula for calculating the **flexural strength** under **three-point bending**, as described in [8]:

$$\sigma_f = \frac{3F_{\max}L}{2bh^2},$$

where: σ_f - is the flexural strength, $F_{\max}$ is the maximum load before specimen failure, L is the distance between supports, b is the width of the specimen, h is the thickness of the specimen. We apply this formula to an **oak beam** with a length of **4.5 m**, width **0.15 m**, and thickness **0.3 m**. For oak with a relative humidity of 15%, the following values are assumed:

$$F_{\max} = 220 \cdot 10^3\ \text{Н}, therefore\ \sigma_f = 110 \cdot 10^6\ \text{Pa}.$$

This value significantly exceeds the calculated applied stress, and therefore, **structural failure of the bridge can be confidently ruled out**.

2. Required Depth of Support Placement

To calculate the required depth of the support, we apply the following approximation: during the repositioning of the bridge, no people are present on the structure. The same geometric dimensions of the bridge, as previously used in the strength analysis, are applied here.

The distribution of the reaction force at the support, which contributes to the equilibrium of the structure, is assumed to be linear. Based on the constancy of forces, we introduce the approximation that the support is perfectly fixed—a condition that can be achieved through the regular replacement or maintenance of the bridge's pivot axis.

The material is assumed to be elastic and sufficiently strong to prevent the bridge from bending to a degree where its free end could no longer be retracted back to the shore. This assumption is valid due to the bridge's rigid arch-like structure.

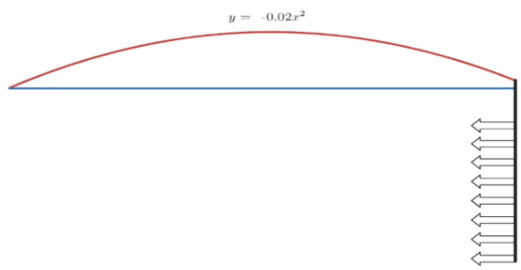


Figure 10. Computational Model for Determining Force Moments

The **average length of the force arm** resulting from the reaction at the bridge's axis is assumed to be $^{l_0}/_2$, where l_0 is the depth of the buried part of the axis. The **moment equilibrium equation** for this case can be written as:

$$\frac{m_{\text{bridge}} \cdot l_{\text{bridge}} \cdot g}{\boxed{2}} = \frac{N \cdot l_0}{\boxed{2}}.$$

The **mass of the bridge** is calculated based on the assumptions described above:

$$m_{\text{моста}} = \rho_{\text{bridge}} \cdot l_{\text{bridge}} \cdot r \cdot h = 700 \cdot 24 \cdot 4.375 \cdot 0.3 = 22050 \text{ (kg)}.$$

The **linear length** of the bridge is used here, since the deviation between a straight line and a parabola with a coefficient of 0.02 in the quadratic term is less than 1% (as calculated via WolframAlpha). The **density value** is taken from standard reference tables. The axis is assumed to be **cylindrical**, with a **radius** of 0.5 m. We now calculate the **critical force arm length**—that is, the value of l0l_0l0 at which the pressure resulting from the support reaction force reaches the material's strength limit:

$$P_N \cdot \pi \cdot r_N \cdot l_0 = \frac{m_{\text{bridge}} \cdot l_{\text{bridge}} \cdot g}{l_0} \qquad l_0^2 = \frac{m_{\text{bridge}} \cdot l_{\text{bridge}} \cdot g}{P_N \cdot r_N \cdot \pi}.$$

Since we are evaluating the case where the **material strength limit is reached**, we substitute $P_N = \sigma_f$

$$l_0^2 = \frac{m_{\text{bridge}} \cdot l_{\text{bridge}} \cdot g}{\sigma_f \cdot r_N \cdot \pi} = \frac{22050 \cdot 24 \cdot 9.8}{220 \cdot 10^3 \cdot 0.5 \cdot 3.14} \approx 15 \text{ (m}^2\text{)}.$$

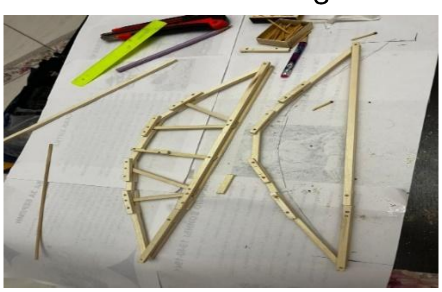
Thus, the final calculated value for the depth l0l_0l0 is **just under 4 meters**. Therefore, for a bridge of this design, the **minimum required depth of the pivot axis foundation is 4 meters**.

1.4. Main Structural Components

Based on the technical drawings, it can be concluded that the assembly of the bridge's main structure will require a significant number of **wooden beams** made from the same material, a **single wooden rod** to serve as the **pivot axis**, **ropes** to recreate the **bridge's railing**, and **metal blocks** to illustrate the **rotational mechanism**.

Construction begins with the **arches**, as these elements ensure the overall stability of the bridge and provide even load distribution throughout the structure. The method of securing the arches differs from medieval techniques due to the significant difference in scale between the prototype and the model, which limits the applicability of some structural properties in the model.

Once the load-distributing components are fabricated, they must be **rigidly connected** to one another in order to establish the initial outline of the complete bridge structure. At this stage, it becomes evident how crucial precise arch construction is for ensuring the smoothness of the future bridge surface.



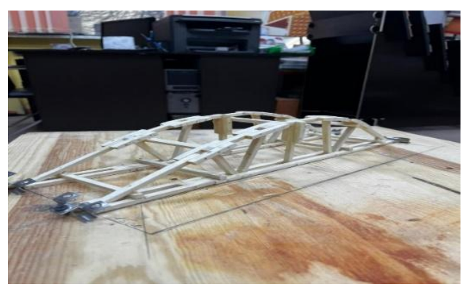


Figure 11. Fabrication of Bridge Arches
Figure 12. Bridge Load-Bearing Structure

1.5. Decking and Reinforcement

Now that the "skeleton" of the bridge is complete, it is time to install its main functional component: the **decking**. All beams used for this stage have identical **geometric dimensions**, are made from the **same material**, and were **sourced from a single location**, ensuring uniform relative humidity.

A **model of the mechanism** that reinforces the **rotating axis** is also attached at this point; visually, it resembles **half of a barrel** in the image.

To support the future installation of **railing posts**, we mark designated **reference points** on the deck using placeholders (in our case, **matchsticks**) to indicate where the **support posts** will be positioned.

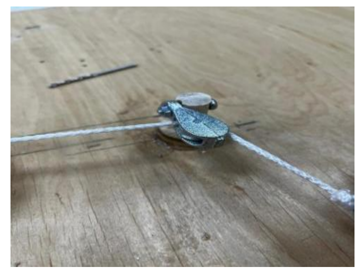


Figure 13. Assembled Bridge Span
Figure 14. Reinforcements of the Lower Bridge Structure
Figure 15. Component Representing the Pulley in the Model

Let us note that **without securely fastening the lower parts of the load-bearing structure**—namely, the elements of the arch parallel to the ground—internal looseness may develop within the bridge, significantly accelerating wear on the model. To prevent this, we **reinforced the weak points** by placing several beams parallel to one another, which makes the structure significantly more resistant to gaps and movement.

1.6. Core Conceptual Component

Now that the general structure of the bridge has been completed, we turn to the core conceptual feature that distinguishes this bridge from others—the rotating axis. To enable the rotational movement of such a heavy structure, an unconventional solution was required—especially considering the 16th-century context, where no modern machinery existed.

Here again, Leonardo da Vinci's extraordinary thinking becomes evident: he proposed the construction of a pulley-cable system near the bridge, through which a rope would pass over special fixtures at the top of the rotation axis. In this way, a horizontal pulling force applied by people on land could be effectively transmitted to the bridge—solving the problem of rotating the structure.

To finalize the model, we install railing posts into the pre-drilled holes along the deck.



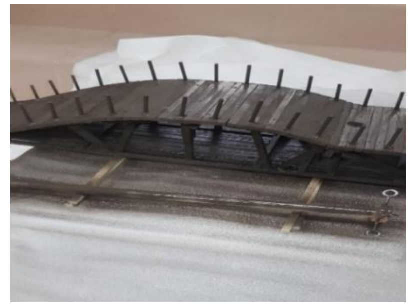


Figure 16. Complete Rotational System with Axis
Figure 17. Installation of Bridge Railings
Figure 18. Bridge Painting

The **final step** is to integrate the model into a **prepared landscape mock-up** and apply **finishing paint** to the structure.

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Figure 19. Final Bridge Model
Figure 20. Bridge in Rotated Position

Conclusion

This research paper has focused on the study of engineering aspects involved in the construction of structural models, using Leonardo da Vinci's pivot bridge as a case study. The theoretical section examined da Vinci's major contributions to science and engineering, including his inventions such as the self-supporting bridge and the pivot bridge. Special attention was given to the analysis of loads and equilibrium conditions, which made it possible to calculate the strength of the bridge and determine the required depth of its supports.

The practical section demonstrated the feasibility of implementing da Vinci's ideas under modern conditions. The pivot bridge model, built using wooden beams and a pulley system, confirmed the structural stability and functionality of the design. Calculations showed that, with a bridge length of 24 meters and the use of oak materials, the structure can withstand