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Translated Paper

Pier Luigi Nervi's design process of hangars

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Abstract

The objectives of this paper are to report the construction process of hangars in Orvieto and Orbetello by the construction company of Nervi and Bartoli, and to analyze the formation process of the design philosophy proposed by Nervi through a model experiment conducted on both hangars. Nervi initially attempted to design a hangar with pin joints. This indicates that although Nervi was initially uncertain of the structural safety of a vault roof with rigid joints, he eventually understood its structural safety through experiments. In conclusion, Nervi arrived at a hyperstatic structure of the diagonal rib vault which consisted of crossing each arch in the design process of the hangar in three phases. Furthermore, the joint between the roof composed of them and the pillar is ultimately rigidly joined instead of pin junctions after sketching the relevant plans. Nervi's design philosophy is to connect each member with a rigid joint, a solid monolithic structure, that is, to constitute a hyperstatic structure, which was seen in the design process of the airplane hangar.

Keywords
pier luigi nervi, hangar, reinforced concrete, model experiment, diagonal rib vault

1. Introduction

1.1 Research background

In Italy, steel frames were introduced in the 19th century, and a new material called reinforced concrete (RC) was introduced in the 20th century. Pier Luigi Nervi (1891-1979) is said to have contributed to the development of structural forms of expression through RC construction.[Note 1]

This research attempts to position the construction activities of Nervi in terms of the expression of structural forms and the development of structural mechanics, while also discussing the trend of improvements in RC construction technology in Italy. Taking a cue from it for the present times, the focus of this study is on the construction activities of airplane vaults that were conducted from the interwar period to the war by Nervi e Bartoli (Società per costruzioni Ing. Nervi e Bartoli; N & B), which was established in 1932.[Note 2]

Other than hangars, the main achievements during the interwar period were a bridge and a salt warehouse with a vaulted roof in which pointed arches were lined up in parallel,[Note 3] and a water tank formed by a wall surface, which was sprayed with a cement gun on a metal mesh that was formed and so on.[Note 4] After gaining such construction experiences, Nervi was appointed as the dome investigator of the Santa Maria del Fiore in Florence in January 1934,[Note 5] and the results were recorded in a report published in 1939.[Note 6] We analyzed how these experiences contributed to subsequent hangar designs.

Some of the masterpieces of hangars designed by Nervi (Aviorimessa) were built in the cities of Orvieto and Orbetello. There were five initial plans that led to the implementation plan, which can be specified in the ascending order based on the period when they were proposed. The first was the plan draft designed in the early 1930s.[Note 7] The second was the patent for the movable floor of the vault that was accepted in January 1932. The third was the plan that was exhibited at the Triennale di Milano in 1933. The fourth was a plan for the Italian Air Force platoon. The last was a plan for the Ciampino Airport, which was submitted in the competition that was held in 1935.

At the request of the Italian Air Force, Nervi built an airplane hangar in Orvieto in 1939 and Orbetello in 1942. In the final plan of the hangar for Ciampino Airport, a diagonal lattice rib vault roof was conceived. While considering the implementation design of the Orvieto hangar, structural experiments were conducted on the overall model of that form. Furthermore, during the construction of the Orbetello hangar, a precast method, which was rare in Italy at that time, was adopted, and the construction was industrialized. Later, Nervi described the design and construction of a series of hangars as, "From a technical point of view, this design was one of the most difficult tasks in my life".[Note 8] Thus, there is no doubt that this plan is important while examining the process of forming the design philosophy of Nervi during the interwar period.

1.2 Research subject and purpose

This paper focuses on hangar plans, including the airplane hangars at Orvieto and Orbetello, for which Nervi was in charge of the design, structural design, and construction. Furthermore, from the perspective of clarifying the design philosophy of Nervi during the interwar period,[Note 9] this paper presents an analysis of the transition of the structural form in each plan and attempts to clarify the intention behind the change. In the theater in Naples that was mentioned in a previous article, the ribs are connected to each other in a ring to form the roof. Furthermore, at Berta Stadium, cantilever beams are lined in parallel to construct spectator seats.[Note 10] In the hangar implementation plan, multiple arches are crossed diagonally at 45° to a rectangular plane that is arranged horizontally to form a diagonal rib vault ceiling. However, the researchers plan to analyze the background and implementation plan and clarify the design philosophy of Nervi.

1.3 Previous research

The major previous studies focusing on the architectural works during the N & B period of Nervi (1932-1945) were presented by C. Greco and A. Bologna et al.[Note 11]-[Note 12] The paper written by the former author is a standard for research pertaining to Nervi during the interwar period and discusses works other than airplane hangars. Furthermore, it discusses construction techniques such as the model experiment and precast method introduced while designing the hangar, which is the culmination of construction techniques in the interwar period and shows various supporting materials.

Conversely, the work of Bologna et al. deals with the historical background of the construction of hangars. The self-sufficiency policy (Autarky) of the late 1930s, which is discussed in detail, resulted in changes in the design in the Orbetello and Orvieto hangar implementations, which were built with restricted use of rebar and formwork timber. Furthermore, G. Neri conducted a detailed investigation into the model experiments conducted by Nervi.[Note 13] The model experiments were also introduced in the hangar at Orviate, which is discussed in this paper. Although Neri mentioned the model experiments conducted at the laboratory in Milan, he did not specify the detailed design proposal changes after the experiments. There is also individual studies by P. Pachetti and F. Presenti on the hangars of Orvieto and Orbetello. The study presents the historical background of the construction site but does not describe the design process leading up to the implementation plan. Pachetti showed a detailed drawing and an axon diagram of the proposal for the Orvieto hangar; however, these analyses were limited to the implementation plan.[Note 14] As a background to the hangar construction at Orbetello, Presenti discussed shell-structured buildings completed in Germany and Milan during the same period and analyzed the Italian hangars, including the proposal by Nervi.[Note 15]

In previous research, attention was primarily focused on the implementation plan of the hangars at Orvieto and Orbetello and the new construction method introduced at that time. In short, no studies on the design process have been conducted. This paper can be regarded as a study that elaborately analyzes the transition in these structural forms.

1.4 Research method and chapter structure

This paper analyzes the plans leading up to the final implementation plan of the hangar at Orbetello, which was designed by Nervi. By comparing them with the historical background in consideration, this paper uses a method to clarify the process leading to the selected structural and roof frame forms. Chapters 2-4 analyze the works, including unimplemented hangar plans. The design change process is clarified by referencing the original drawings and the drawings published in the previous research of Greco. The original drawings were obtained from the Parma Research Center and Museum (Centro Studi e Archivio della Comunicazione (CSAC))[Note 16] and the collection of the National Archives of the State (Archivio Centrale dello Stato di Roma (ACSR)) in Rome.[Note 17] In the drawing analysis, the researchers discuss the 2D plan, roof, and cross-sectional composition, extract the structural types examined by Nervi, and compare them with each plan. In Chapter 5, based on the analysis of the previous chapter, this paper presents the reasons for changing the structural form. Furthermore, this paper clarifies the design philosophy of Nervi, which focuses on the transition of the structural form and joining type of the airplane hangar.

2. Design plan of cantilever-type airplane hangar

The involvement of Nervi in the earliest hangar design was around 1930. The hangars constructed at that time used a circular plan and cantilever beams.[Note 18] There were two plans among those mentioned above: one where the roof member was changed from RC to a steel structure in 1932 and the other is described in the application as a patent for the movable floor in the same year. There were a total of five proposals. Two proposals were exhibited at the 1933 Milan Triennale.

2.1 Circular hangar in reinforced concrete (1930)

The RC circular hangar proposal in 1930 was included in a collection of works and was designed as a voluntary proposal (Figure 1).[Note 19] It can be noted from the drawing that the plane shape of the hangar is circular, and the internal dimension of the radius is 35.4 m. The breakdown in the dimensions is 7.0 m for the warehouse, 2.5 m for the ground contact width between the V-shaped pillar and the ground, and 25.9 m for the storage space. Fourteen V-shaped pillars support the roof, and each pillar is connected to the capital to form a ring. The height of the space in the center of the hangar is approximately 5 m, and the maximum height of the entire hangar is 10.3 m. The beams that constitute the roof extend radially from the center of the circular plane and branch into three at the capital of the outer circumference of the V-shaped column. At a part of the tip of each beam, 18 trapezoidal columns with short upper sides are erected, and a brick wall is inserted between them to form an outer wall. On the other side, there are two entrances and exits for airplanes with a width of approximately 47.0 m, and metal sliding doors are to be installed at the entrances and exits.

From the cross-sectional view (Figure 1), it is assumed that one small- and one medium-sized airplane could be accommodated on the left and one large airplane could be accommodated on the right. The floor is a movable floor, and the plane could be easily moved to the doorway. Then, the apex of the V-shaped column, start and end points where the cantilever beam constituting the roof branches in three directions, and tip

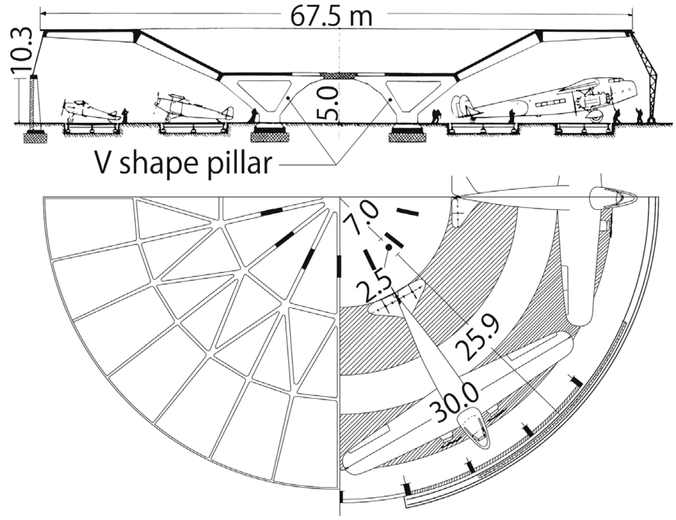

Figure 1. Section and plan of a circular hangar in reinforced concrete (RC)

of the beam at the upper part of the doorway are connected in an annular shape by a connecting beam. Based on this, it can be observed that an integral structure was intended.

2.2 Circular hangar in steel (1932)

The second plan, a circular hangar plan in steel,[Note 20] was a voluntary proposal by Nervi, which was similar to the RC plan (Figure 2). Based on the drawing, it can be noted that the planned shape of the hangar is circular, similar to the RC plan; however, the exact values are unknown because there is no description of the dimensions. Therefore, assuming the same radius (35.4 m) as the RC plan, the radius of the central cylindrical structure is smaller, which implies that the storage space for the airplane was expanded. In the RC plan, only two small airplanes could be accommodated; however, based on this plan, it would have been possible to store three airplanes and a large airplane with a margin. This was achieved by reducing the cylindrical structural wall that supports the roof to a radius of approximately 3 m.

The members that constitute the roof were planned to be constructed using steel, and it can be observed that 32 cantilever beams in two upper and lower stages are arranged radially. The connecting beams are hung at intervals of approximately 3.5 m, forming a total of eight rows in the form of rings. At the tip of the cantilever, a metallic truss is assembled between each to connect with a circular ring (door frame) that supports the movable door of the outer wall. Furthermore, a movable door is provided on the entire outer circumference, and an airplane can enter and exit from any position, eliminating the need for a movable floor.

The S-structured cantilever truss beam described in the cross-sectional view (Figure 2) is tilted upward toward the outer circumference. As for the truss beam structure, a box shape is formed by a two-stage cantilever beam and bundle member, and an oblique member is provided in the direction in which the entire cantilever truss beam would be pulled up. In addition, the effect of pulling up the tip of the beam was achieved by connecting the truss beams made of steel with the connecting beams on the concentric circles. Measures were considered to prevent the tip of the cantilever from hanging by connecting the cantilever in an annular shape in both the RC and steel plans mentioned above. At Berta Stadium, which is described subsequently, the cantilever beams are lined up in a row with each cantilever beam connected to another beam.

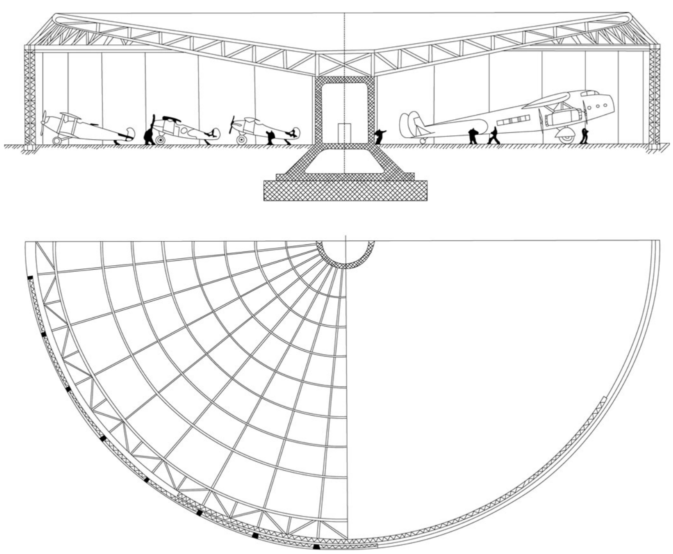

Figure 2. Section and plan of a circular hangar in steel

2.3 Hangar in reinforced concrete shell (patent plan) (1932)

Nervi applied for a patent on the rotating floor of the hangar, which was accepted on January 8, 1932. The patent name (Figure 3) was "Circular hangar with a rotating ring floor for airplanes and vehicles",[Note 21] and the material was obtained from ACSR.[Note 22] The plane shape was also circular, but the dimensions were not described as in the S-structured circular hangar plan, and the exact numerical value is unknown. Assuming that the dimensions of the airplane were similar to those described in the RC plan (width 30 m/depth 20 m), the size of the hangar was approximately 62 m in diameter.

The central warehouse space had a radius of approximately 5 m, and the size of each of the six pillars that constitute the structural core of this hangar was approximately a square of 1 m length. Connecting beams connected the tops of the pillar, and a shell (cantilever slab) overhanging of approximately 26 m covered the storage space. A part of the tip of the slab was connected to a fixed wall on the outer circumference, and one entrance and exit were arranged. Therefore, a movable floor was planned, and the stored airplanes could rotate and move inside the hangar. The application for a patent for this rotating floor initially stated that the problem with the design of an airplane hangar was that the size of the doorway makes it impossible to move the aircraft in and out.[Note 23] In response to this, three solutions were presented: a circular or polygonal shape that is similar to a circle, a central structure

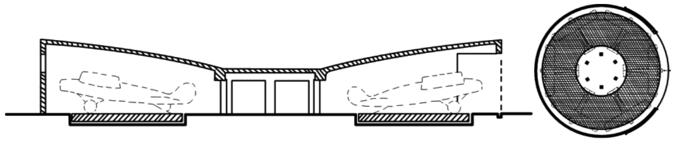

Figure 3. Section and plan of a hangar in RC shell (Patent) (1932)

that eliminates the requirement for columns around the circle, and a rotating floor.

2.4 Milan Triennale exhibition plan (1933)

The next time the plan was announced can be identified by the proposal to exhibit at the 5th Milan Triennale held in 1933. Looking at the exhibition catalog, it can be observed that Nervi exhibited two plans for airplane hangars along with the architect Cesare Valle (1902-2000), who was active in Rome.[Note 24] One was a civilian hangar for tourism (Figures 4 and 5), and the other was a military hangar for three platoons (Figure 6).[Note 25] Other than the panels exhibited at the exhibition, these plans were also published in a special issue of the Italian architectural magazine "Architecture" (Architettura).[Note 26]

2.4.1 Private hangar for tourism business (unbuilt)

This facility consisted of a semicircular hangar and a rectangular office building (Figure 4). In addition, the dimensions were not described in the plan view published in "Architettura." However, while introspecting (Figure 7), it can be noted that one airplane was listed, which is considered to be approximately the same size as the RC airplane hangar plan (1930).

Looking at the cross-sectional view in the parallel direction (Figure 8) and considering the office, it can be observed that there are two RC V-shaped columns in the center. A cantilever extends from the pillar to the side of the outer wall; moreover, the outer wall is not required to bear the bearing capacity and is used as a curtain wall. There is an annular connecting beam on the outermost circumference, which also serves as a hanger rail for the sliding door. While looking at the cross section in the direction perpendicular to the office building, it can be observed that the storage space is also covered with cantilever beams supported by V-shaped pillars. The V-shaped pillars are also planned between the storage space and the aisle.

2.4.2 Military hangar for three platoons (unbuilt)

The planned shape of the RC hangar of the Italian Air Force was square (Figure 6), and its size was approximately 120 × 120 m. At the center of the hangar, there was a 40 × 60 m warehouse (Figure 9), from which the cantilever beams extended horizontally by 40 m in each direction, and the hangar was under the roof in three directions.

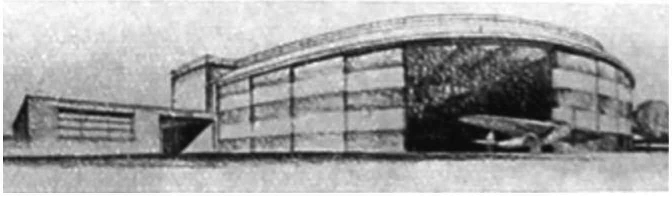

Figure 5. Design of a hangar for a civil air company

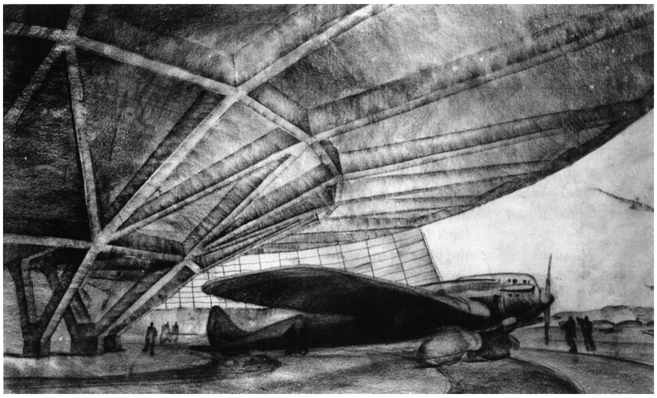

Figure 6. Square plan of the hangar

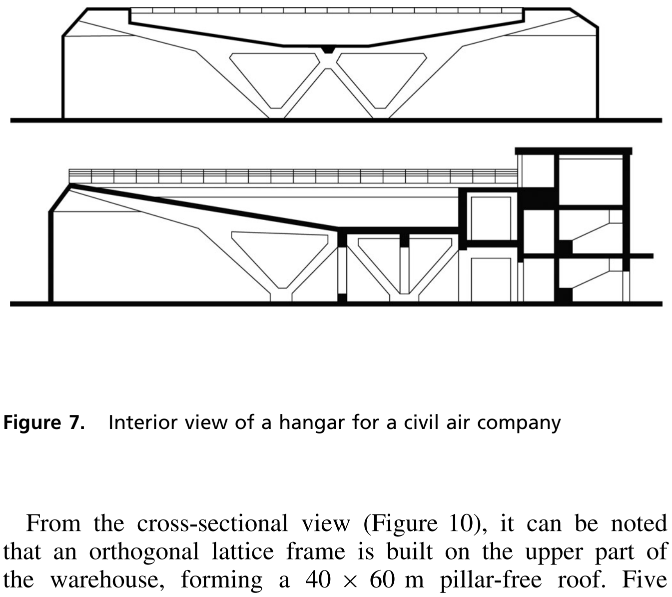

Figure 7. Interior view of a hangar for a civil air company

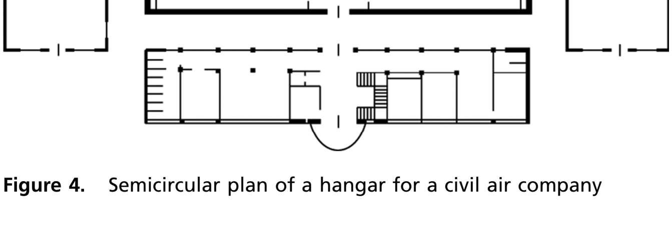

Figure 4. Semicircular plan of a hangar for a civil air company

From the cross-sectional view (Figure 10), it can be noted that an orthogonal lattice frame is built on the upper part of the warehouse, forming a 40 × 60 m pillar-free roof. Five beams of the same shape, approximately 60 m long, are hung across a 40-m-long Feelendale truss beam over the upper part of the warehouse. A haunch is provided at the joint between the beam and the column, which is the same as that provided at the warehouse and side of the hangar. The roof at the top of the hangar is composed of loosely curved slabs, and two tensioning materials prevent the slabs from hanging down.

Furthermore, the storage spaces of Hangar 1 and Hangar 3 are symmetrical to each other, and the attractive force applied to the pulling material of the cantilever slab could be offset. However, there were measures to deal with structural imbalances, such as the asymmetry between Hangar 2 and the laboratories and workshops, and the need to install pillars in the laboratories and workshops.

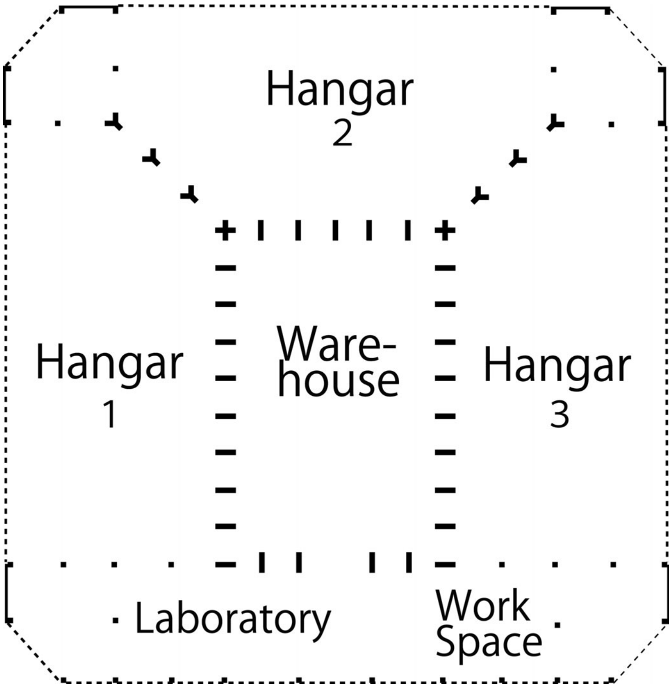

Figure 8. Structural cross sections (parallel and vertical directions)

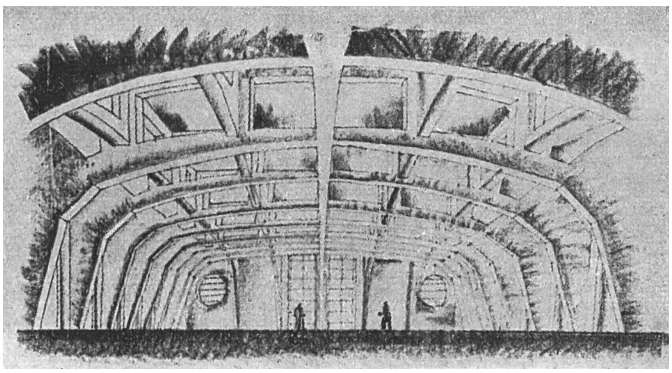

Figure 9. Drawing of the warehouse

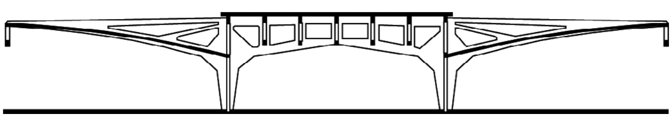

Figure 10. Section of a square plan of a military hangar for three platoons

In the same plan, to avoid installing pillars on the entrance/exit side of the hangar, a form was adopted in which the colonnades around the warehouse were used as the core of the structure, and cantilever beams of approximately 40 m were used on the outside. However, the hangar space was divided into three parts, and problems such as the space not being a single large area and the asymmetrical aspect of the structure remained.

3. Transition to the parallel arrangement of arches and truss beams

It is unclear how the hangar of the Italian Air Force platoon was designed as it had a different planar shape than previous designs. Nervi reached his limit in terms of the cantilever design in the military airport hangar plan (RC square plan) for three platoons, which was exhibited at the Milan Triennale in 1933. To overcome this, Nervi considered an arched roof in the hangar of the platoon. In addition, while designing a hangar for Ciampino Airport, there was a design competition in 1935, and he applied with a draft plan.[Note 27]

3.1 Hangar plan for the Italian air force platoon

As this plan has not been implemented till now, most of the remaining drawings and sketches are available at CSAC.[Note 28] The planned time is unknown, but the drawing number is 1445. The drawing number of the hangar plan for the Ciampino Airport, which is discussed in the next section, is 1487. Therefore, it is possible that this plan for the military platoon was planned earlier.[Note 29]

It can be observed that the entire building, including the hangar (Figure 11), consists of a shallow vault spanned between two RC-built two-story buildings (Figure 12). The overall size is 36 × 54 m, and the size of the storage space is 36 × 40 m. Its maximum height is approximately 16 m, and the arch rise is approximately 7 m. Offices of 7 × 36 m are planned on both sides of the storage space, which corresponds to the thrust transmitted to both ends of the roof. The doorway is only on one side of the long side. The distance between the 10 arches in RC that make up the roof is 3.6 m, and bricks are filled between them.[Note 30]

It can be observed that RC hinges are planned for the top of the roof, and the same style was applied to both ends of the roof, and a vaulted roof with a parallel arrangement of three-hinge arches is planned. The brick slabs installed between the arches are stretched diagonally (Figure 13). The left side from the center of the roof is stretched to the upper end of the arch, and the right side is stretched to the lower end of the arch (Figure 12). Even between the left and right arches (Figures 14 and 15), the roofing positions are alternately installed up and down.[Note 31] By doing this, an effect similar to the flange effect of the steel frame is assumed in the roof of the hangar made of RC and brick, and it was speculated that the strength of the roof as a surface was increased.

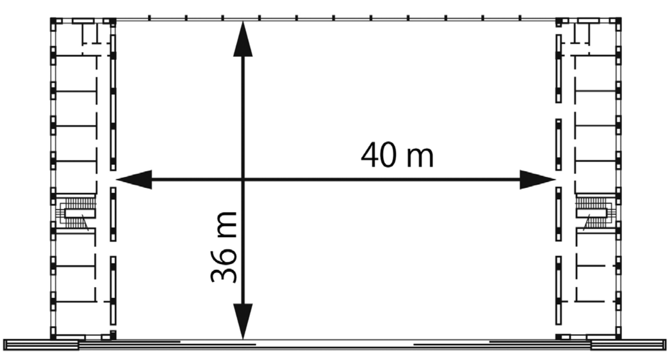

Figure 11. Plan of a hangar for an Italian Air Force platoon

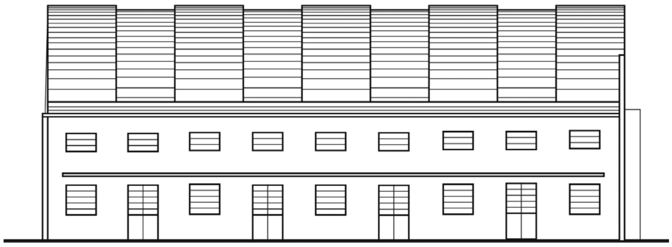

Figure 12. Cross section (Longer side)

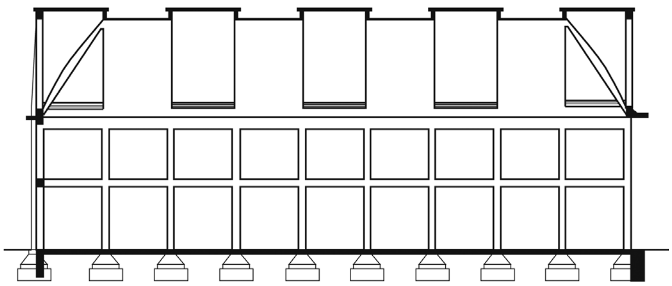

Figure 13. Two arches with a brick roof

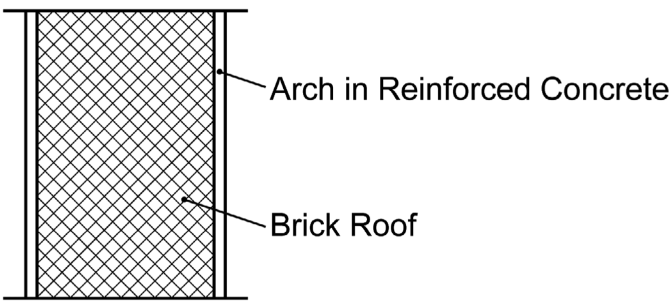

Figure 14. Elevation

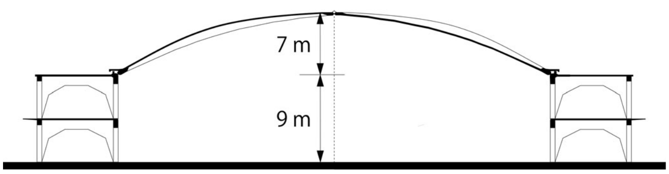

Figure 15. Cross section (Shorter side)

As mentioned above, in the hangar plan for the Italian Air Force platoon, the conversion from the cantilever-type roof to a type of roof using arches is observed. Consequently, there is a requirement for thrust treatment; however, in the plan, offices are placed on both sides of the arch to deal with this. The arches of this plan are provided with hinges at the top and ends, and a three-hinge arch was being attempted in the plan. In addition, the general type of roof construction of that time was adopted, in which multiple arches were arranged in parallel and bricks were laid between them to form a vault. Moreover, it can be pointed out that the diagonal brickwork is an idea that resulted in a diagonal grid rib vault in the hangars of Orvieto and Orbetello.

3.2 Hangar plan for Ciampino airport

This plan was presented in the 1935 hangar design competition that was organized for obtaining possible plans for a hangar at Ciampino Airport; however, it was not selected for the first prize and was not implemented. Each drawing and sketch of this plan are available at CSAC.[Note 32]

It is difficult to identify the timeline of existing drawings related to this plan. However, in this paper, by classifying the plans created for the design competition into four plans, A to D, it is hypothesized that the plans proceeded in the order of A to D.[Note 33] This was based on a statement given by Nervi in a lecture presented at Harvard University in 1965. That is, he said that the type of roof of the hangar was changed from several types of solutions according to the "conventional plan" to a vault-type integrated structure.[Note 34] In this paper, the conventional plans in which multiple truss beams and arches are arranged in parallel are referred to as plans A to C, and the plan of the oblique lattice vault, which is a more integrated structure, is called plan D.

3.2.1 Plan A

In plan A, a box beam is hung parallel to the longitudinal direction of the plane, and 13 truss beams are hung on it to form a roof (Figure 16). The total size of the hangar is 36 × 80 m, and there is only one entrance and exit for the plane on one side of 80 m. A box beam (large girder) of 80 m along the long side is placed approximately 10 m away from the entrance/exit side, and one pillar is provided at the center of the large girder.

There is a sliding door at the tip of the eaves on the doorway side. The truss beams that constitute the roof and the columns on the opposite side of the entrance that support them are connected by rigid joints. A structure is examined in which one large girder and 13 L-shaped columns and beams are supported by one column in the center of the large girder.

Subsequently, we discuss the examinations conducted by Nervi pertaining to the beams and columns, which resulted in the final cross section of plan A (Figure 17) from the sketch. Initially, while examining the beam, the beam was small (Figure 18). However, the range of the truss increased (Figure 19), and it can be observed that it is composed of truss beams from the tip of the overhanging eaves to the pillar on the opposite side (Figure 20). Furthermore, the examination of the pillars arranged on the doorway side revealed that the initial design included two pillars, but eventually, it was changed to one (Figures 18–20). Furthermore, the cases where there are two box beams (Figure 18), one box beam (Figure 20), and no large girder were also considered (Figure 19). After these studies, a form (Figure 17) in which 13 small beams are hung on the box beam was completed.

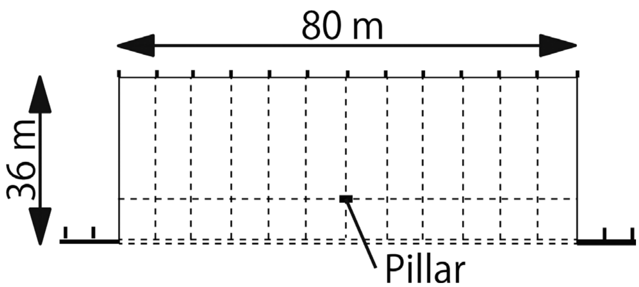

Figure 16. Plan for Ciampino Airport (Type A)

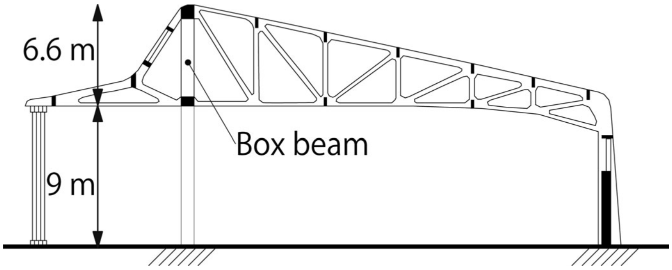

Figure 17. Cross section (Shorter side)

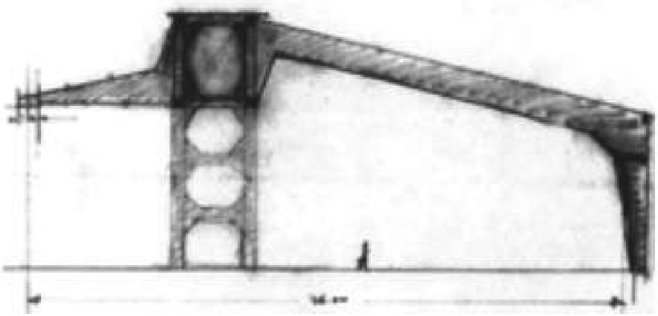

Figure 18. Sketch (1)

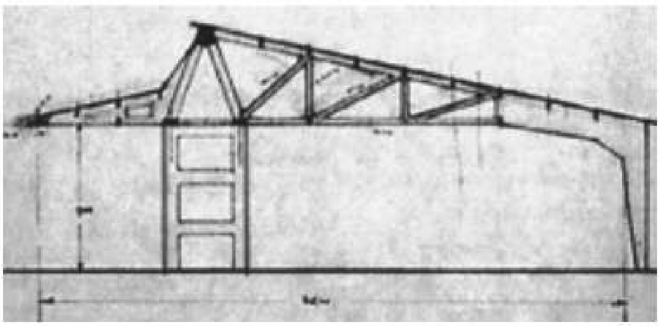

Figure 19. Sketch (2)

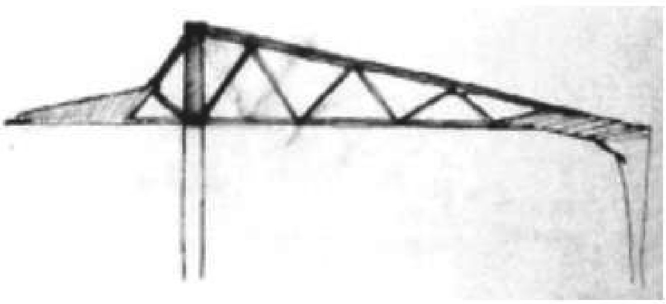

Figure 20. Sketch (3) of the beam

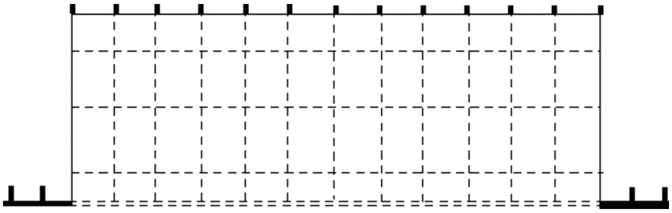

Figure 21. Plan (Type B)

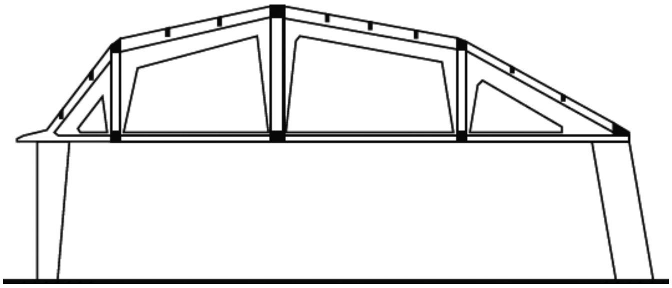

Figure 22. Cross section of hangar for Ciampino Airport (Type B)

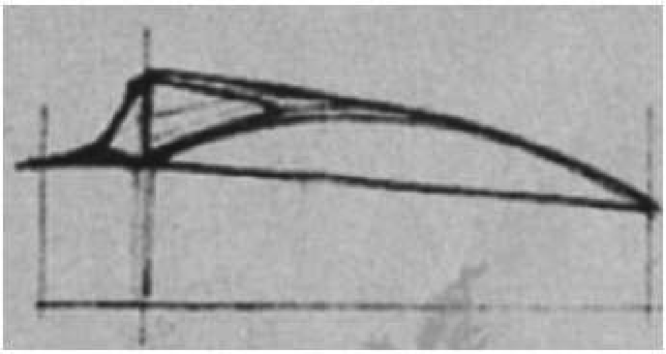

Figure 23. Sketch (4)

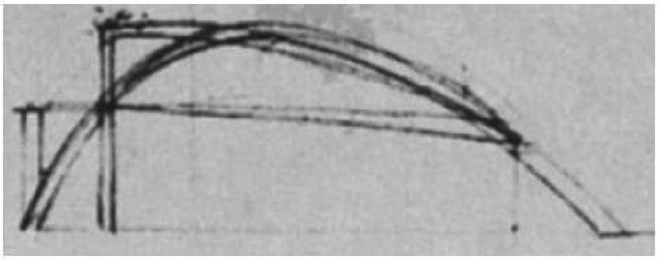

Figure 24. Sketch (5)

3.2.2 Plan B

In plan B, a roof of the same size as plan A (Figure 21) is composed of 13 convex chord beams that are arranged in parallel, three girders and bundles extending along the long side, and tie bar-like members in RC along the short side (Figure 22). While examining the beam shape, a method of removing one column inside the hangar was being studied (Figures 23–25). The sketch shows that the truss is changed to an arch shape (Figure 23), and the arches that constitute the roof are connected to the ground on both sides (Figure 24). Furthermore, studies were being conducted to bring the columns of one span to both ends and to install a reverse beam that lifts the arch above the arch that constitutes the roof

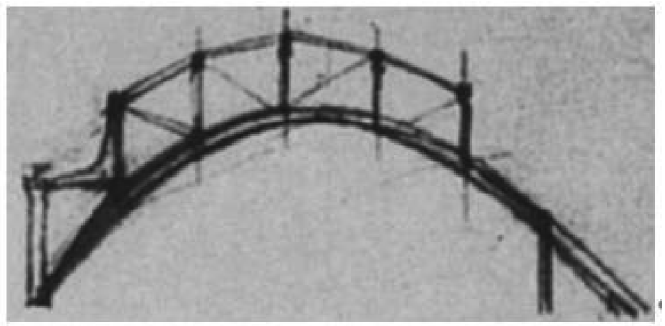

Figure 25. Sketch (6)

(Figure 25). Eventually, Nervi proposed the idea of a pillar-free space (in the absence of columns between the 36 m spans) with a tie bar connecting the columns on both sides in the direction of the short side, with an arched beam on top of it. (Figures 21 and 22). In plan A, there is only one large girder of 80 m in the longitudinal direction; however, in plan B, there are three. When compared to plan A, the roof shape is closer to the arch shape of the final plan, and improvements were achieved based on the fact that the pillars are not in the storage space.

3.2.3 Type C

Plan C was also planned for the same design competition. The tie bar and three girders are removed, similar to plan B, and three-hinge arches with hinges at both ends and the top are lined up in parallel. A roof covering a plane size of 44.8 × 80 m is constructed (Figure 26). During the study leading up to this proposal, Nervi considered tilting the pillars on both sides instead of perpendicular to the ground, thereby expanding the pillar-free space to 44.8 m. By considering half the section (Figure 27), we understand that Nervi planned to install pin joints at the top of the roof and a connection point between the roof and the inverted V-shaped pillars. Furthermore, six connecting beams are arranged for the half arches that constitute the roof, and the integration of 21 arches was considered.

3.2.4 Type D

Plan D is believed to have been submitted as the final plan for the design competition. The plane shape is the same as that in plan C, but a diagonal grid rib vault is adopted in this plan (Figure 28). The joints at both ends of the roof and stanchions are the hinges (Figure 29). In the process leading up to plan D, Nervi studied how to hang beams using a ceiling plan (Figure 30). In this study, a plan to hang two arches between three pillars was considered, and two types of beams were primarily hung on both sides of the pillar that was erected in the center of the entrance and exit side of the hangar.

First, on the left of the central column, finer diagonal ribs were considered for the beams hung parallel to the short side. Triangles and rhombuses that are surrounded by ribs can be observed. On the right side of the central pillar, it can be observed that the beams are evenly suspended along the long side. Three studies in which a diagonal line was drawn inside a rectangle that was divided into 10 equal parts were considered. A parabola is drawn, and one of the 10 equal parts is further divided into eight equal parts. In this way, the roof of the diagonal lattice rib vault (Figure 29) was completed after examining the intersecting ribs (Figure 30). Furthermore,

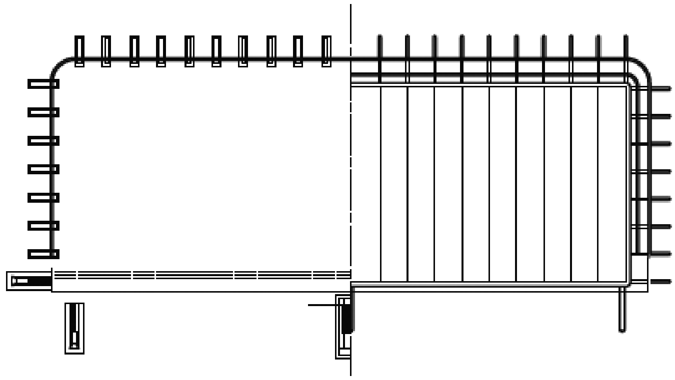

Figure 26. Plan (Plan C)

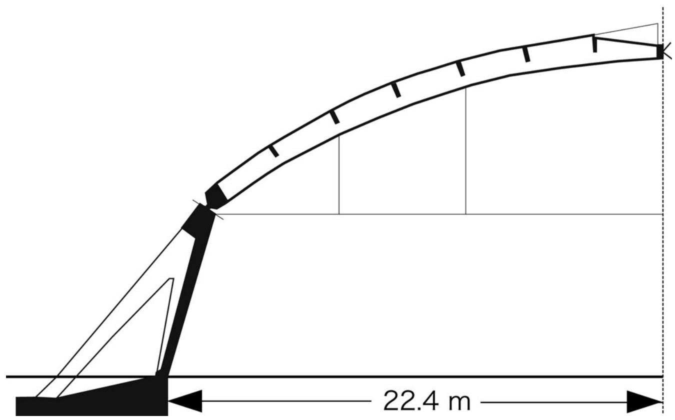

Figure 27. Cross section of hangar for Ciampino Airport (Plan C)

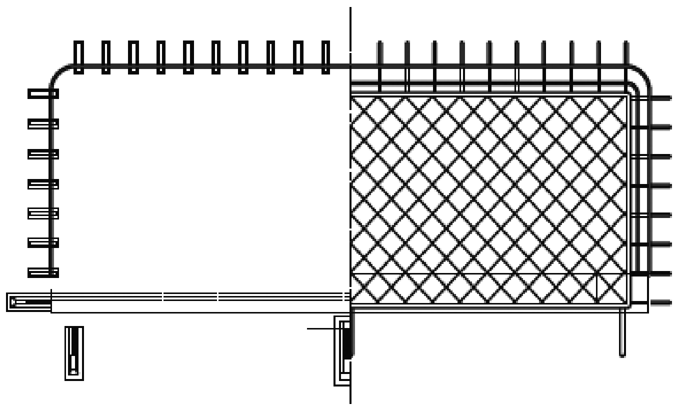

Figure 28. Plan of the hangar for Ciampino Airport (Plan D)

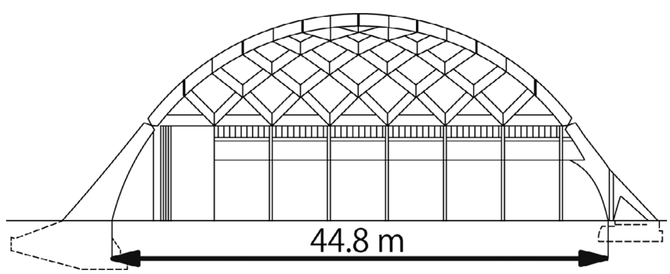

Figure 29. Cross section

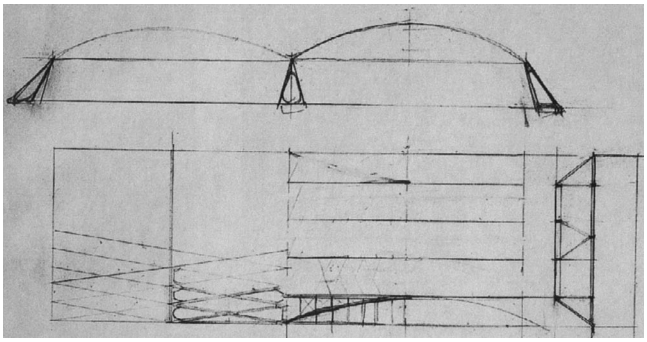

Figure 30. Sketch of the ceiling

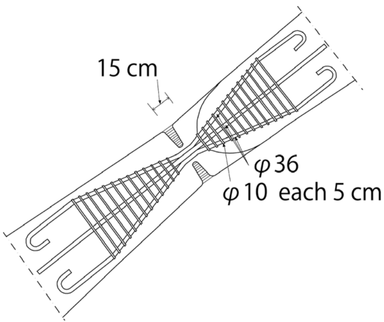

Figure 31. Bar arrangement of the arch

hinges were considered based on the joint between the roof and the columns. A detailed view of the joint is shown to illustrate the method of arranging the hinges (Figure 31). Asphalt insertion was planned to absorb the deformation of the entire roof at the joints.[Note 35]

4. Airplane hangar with diagonal lattice vault

The rib shape of the ceiling shown in the implementation plan of the Orvieto hangar is identical to plan D of the hangar for Ciampino Airport;[Note 36] however, the joint between the roof and the pillar was changed to a rigid joint. Finally, in the hangar at Orbetello, the ribs were in the form of trusses, and a reduction in the weight of the ribs was being considered.

4.1 Airplane hangar in Orvieto

This hangar is a facility for the Italian Air Force (Figure 32). In 1936, the Italian Air Force conducted a design competition to obtain a reasonable estimate for two hangars and nominated several domestic construction companies for their construction. The Air Force stated that the best plans would be selected from the applicants in the design competition, and if all other conditions were the same, the construction company with the most economical quoted price will be selected; this would ensure that maximum economic efficiency is achieved.[Note 37]

In the plan, the shape of the hangar was 111.5 × 44.8 m, and the pillar-free space inside was larger than that in plan D plan of the hangar at Ciampino Airport. The door frame (girder) was supported by three pillars on only one side.[Note 38] There were several sliding doors with a width of 12.5 m and a height of 9.0 m. Hanger rails were to be installed on both sides of the doorway when it is open.[Note 39]

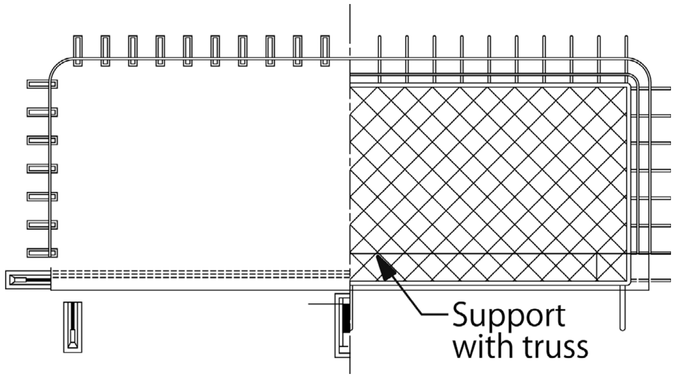

Figure 32. Plan of hangar at Orvieto

The ribs on the roof were unified at 990 mm, but the rib width varied from 120 to 200 mm, depending on the position. The ribs formed multiple squares with a side of approximately 4.6 m to form a roof.[Note 40] The height of the roof was approximately 10 m, and the total height was approximately 19 m. To integrate the roof, the surface was to be composed of reinforced bricks with holes on the upper surface of a structure made of ribs, and a corrugated asbestos slate was to be used for finishing.[Note 41]

In his 1965 lecture, Nervi recalled the structural form, not as a combination of trusses and beams, but as a structure that resists integrally. Consequently, the external force due to its weight, wind, and snow could be reasonably diffused. The support placed on the three sides and the pillars on the center of the opening side could transmit the stress to the ground.[Note 42] Nervi was concerned that the distribution of bending stress would be significantly disturbed owing to the asymmetry of the structure.[Note 43] However, he developed a truss-type structure assembled with multiple ribs and placed a large horizontal truss on the opening to reinforce it (Figures 32 and 33).[Note 44]

While considering the horizontal truss, Nervi stated that it absorbs the horizontal component force generated along the outer edge of the structure. As the design stage progressed, it became apparent that the accurate structural calculation of this design was too complicated to analyze. Perhaps today, it would be easy to analyze such a structure using a computer,[Note 45] and Nervi will explore other analysis methods that are different from calculations. The resulting plan was a structural experiment with a reduced model conducted with Arturo Danusso (1880-1986) of the Milan Institute of Technology.

Finally, the joint between the roof of the hangar and the columns must be noted. The top of the arch, the joint between the roof and the stanchions, was designed with rigid joints instead of pin joints, and the three hinges of the initial design were modified (Figure 33). The Italian Air Force platoon and plans C and D of the Ciampino Airport were designed with pin joints; however, they were changed to rigid joints during the implementation stage. This was implemented to make the roof integral, and although structural analysis is impossible, it can be speculated that Nervi was attempting to create a strong structure by increasing the statically indeterminate order. By changing the joints between the tops of the arches and the members that constitute the diagonal grid with ribs and those between the roof and the columns to rigid joints, it became a strong structure that directly transmits the load of the roof to the ground.

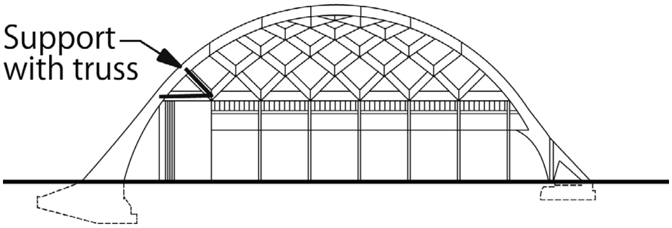

Figure 33. Cross section

4.2 Airplane hangar in Orbetello

The Italian Air Force sponsored the Orbetello airplane hangar design competition in 1939, a year after the completion of the Orvieto hangar. The demands of the Air Force included the incorporation of the Autarky policy, economization of time and money, and industrialization of the construction procedures as much as possible. It was also necessary to perform the construction with the maximum savings of iron materials and formwork wood. From the various applicants, N & B was selected for the construction of the Orvieto hangar, allowing the building of six similar hangars in Orbetello. An analysis of the drawings of the implementation plan is presented below.

The planar shape of the hangar (Figure 34) is 102.50 × 36.9 m, the height of the doorway was widened from 9 to 10.5 m, and the maximum height of the hangar is 22.5 m (Figure 35). The diagonal grid with a rib vault of parabolic arches is supported by six stanchions at the center of the two girders at the four corners and the long sides. Unlike the hangar at Orvieto, the structural system here is symmetrical, and the sizes of each of the six columns are the same. The joint between the roof and the columns is a rigid joint, similar to that at Orvieto (Figures 35 and 36).

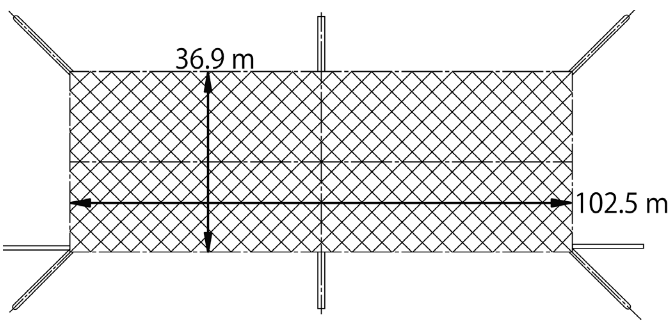

Figure 34. Plan of the hangar at Orbetello

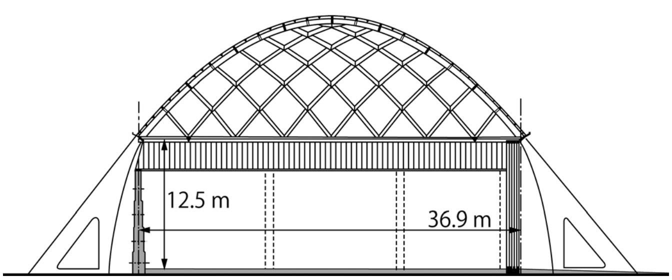

Figure 35. Cross section

To reduce the weight of the ribs that constitute the roof, the unnecessary parts are the truss beams (Figure 37), and Nervi referred to the resulting roof as a mesh structure of small precast concrete beams.[Note 46]

As for the roofing material, the reinforcement of the hollow bricks that had fallen off in the Orvieto hangar was stopped, and it was replaced with asbestos slates. By doing so, the load on the entire roof was reduced and the thermal stress was managed. Nervi also adopted the precast method in response to the request of the owner for the industrialization of the construction method and aimed to rationalize the construction of this hangar.[Note 47]

5. Consideration (reason for designing diagonal grid with rib vault)

By analyzing the structural forms of the hangars in the previous chapters, it can be observed that Nervi implemented a two-step structural form conversion (Figure 38). The first stage is a shift from a cantilevered roof configuration to a method of arranging multiple arches and truss beams in parallel to form a roof surface. The second step was not to arrange the arches in a parallel direction but to hang multiple arches diagonally at 45°, then shift to a mesh-like structure in which each arch was diagonally crossed.

5.1 Clue to the diagonal grid rib vault (reason for design change)

An important part of the process leading up to the design of the diagonal grid rib vault was the major shifts that had occurred between the series of cantilever-type proposals and the Italian Air Force platoon proposal, and between plans C and D of the Ciampino Airport proposals.

As shown in Chapter 3.1, Nervi changed the frame format to a method in which multiple arches were lined up in parallel and bricks were laid between them to form a roof surface. A method was being studied in which perforated bricks were laid diagonally between each of the 10 arches hung at an interval of 3.6 m to form an integrated roof surface. This method of constructing a roof with perforated bricks was a patent obtained by Danusso in 1911 and was a common construction method at that time. However, it appears that the original method of Nervi stretched it diagonally.

Conversely, laying bricks diagonally instead of laying bricks in a straight line was also observed in traditional Italian buildings. Nervi directly focused on such traditional construction methods at the dome of the Cathedral of Santa Maria del Fiore in Florence, which was constructed by Filippo Brunelleschi (1377-1446). Among them, herringbone stacking was used. Nervi learned from an example of diagonally stacked bricks in

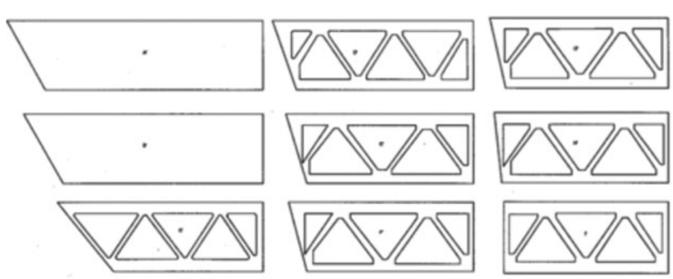

Figure 36. Rigid joint between the roof and the pillar

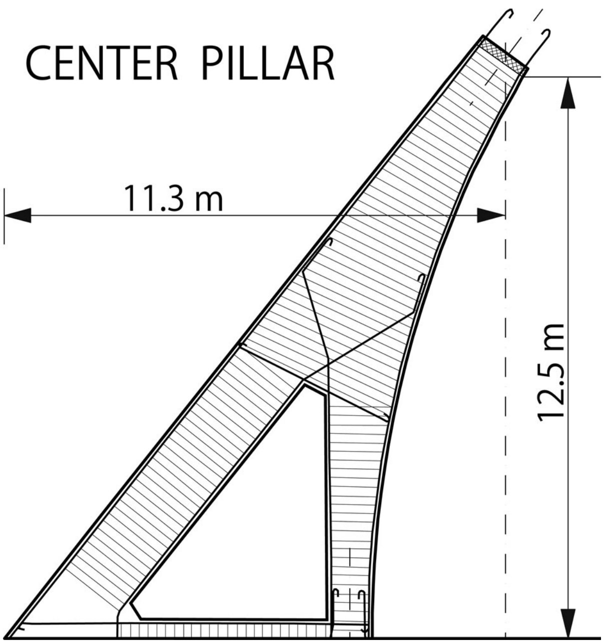

Figure 37. Precasted beams

a 1934 dome survey, which he considered when designing the hangar for the Italian Air Force platoon.

Furthermore, in the design process change from plan C to plan D of the hangar at Ciampino Airport, Nervi left a sketch of how to hang the ribs diagonally at the ceiling surface. Nervi came up with the idea of diagonal ribs in the design process while considering whether to hang the girder in the direction of the long side or short side. Eventually, the ceiling was designed as a diagonal lattice with arched ribs.

5.2 Encounter with theorist Danusso (about design philosophy)

Nervi conceived the oblique grid with a rib vault but was aware of its complexity and was unable to undertake the actual construction. In a dome survey conducted in 1934, he met Danusso and had the opportunity to discuss the complex structure of the hangar at Orvieto, which was designed by Nervi and consisted of arch ribs.[Note 48] Danusso was studying integral structures using rigid joints and had published two innovative proofs to support the safety of statically indeterminate structures. Their discussion may have helped to create the plan for the diagonal rib vault roof.

Nervi described the distress of the structural analysis of the hangar at Orvieto in his 1965 lecture.[Note 49] Danusso of the Milan Institute of Technology, who was the first to introduce a structural experiment using a strain measuring instrument as a scale model, solved this difficulty. Danusso wrote a paper in 1934 entitled Self-Stress Theory – Clues and Practical Applications.[Note 50] Its particular notes are the proof of the theoretical safety of the Risorgimento Bridge in Rome, which was completed in 1910 and involved the Hennebique Company and German theorists in a discussion. It theoretically proved the safety of a rigid joint bridge that was designed by the empirical rules proposed by Hennebique.

Nervi and Danusso, who have a good track record, verified the quantitative safety of the structure of the Orvieto hangar. Experiments using structural models were conducted from 1935 to 1936.[Note 51] In the subsequent remarks by Nervi, there is a reference to the property of redistribution of stress that is demonstrated by a structure integrated by the rigid joint of the RC structure, which was specified as follows:

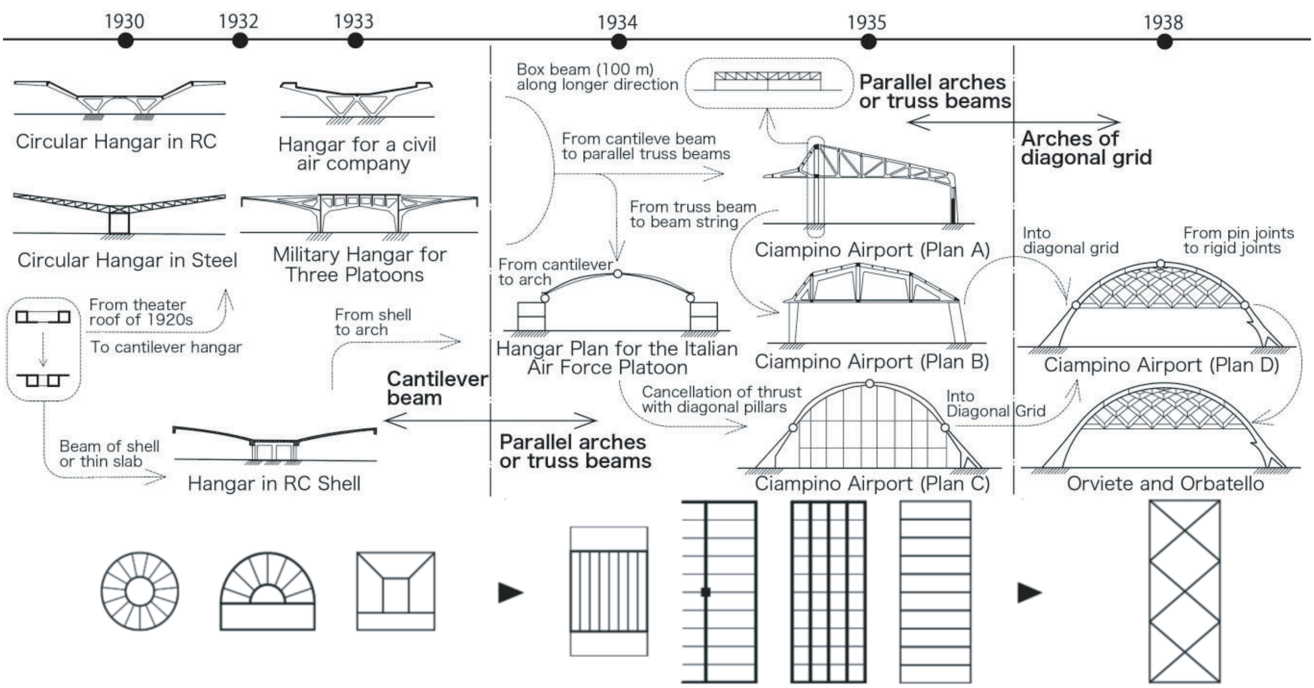

Figure 38. Flowchart of structural changes of each hangar

Integration maximizes these properties while resisting as many structural elements as possible, with great stability by statically indeterminate structure and functional complexity, resulting in a great deal of spread of internal stress. That leads to the logical question of whether it is rather inevitable.[Note 52]

Nervi finally adopted the proposals to use rigid joints instead of pin joints for the joints between the roof and each pillar at the hangars of Orvieto and Orbetello. The rationale for this decision could be the empirical verification in the model experiments. Nervi, who previously relied on craftsmanship to deal with unpredictable stresses generated in statically indeterminate structures, was aware of the stress redistributive nature of RC structures and used its nature for the design of hangars in Orvieto and Orbetello. Thus, after conducting model experiments, Nervi was convinced that an integrated roof could be constructed by making each joint of the RC diagonal lattice vault a rigid joint.

6. Conclusion

In conclusion, Nervi studied the arrangement of arches and truss beams in parallel, in variation to the formation of roofs using cantilever beams. He designed the oblique lattice rib vault by crossing each arch, resulting in a structure with a mesh-like network. The joint between the roof of the hangar and the columns was initially considered a pin joint, but eventually, it was changed to a rigid joint. Thus, Nervi showed an attitude of increasing the degree of unity of the structure as the design progressed.

While considering the design philosophy of Nervi, it can be said that Nervi was very determined to connect each member with a rigid joint to form an integral monolithic structure, that is, a statically indeterminate structure. In addition, the airplane hangar at Orbetello was a type of completed statically indeterminate structure that was designed and constructed by Nervi during the interwar period.

Figure Sources

Figs. 1-2) Created by the authors with reference to the drawings in Reference 2 (pp. 20-21).

Fig. 3) It was created by the authors with reference to the drawings described in the material of the Italian patent (No. 304282).

Figs. 4,6,8,10) Created by the authors with reference to Architettura (n. Speciale, p. 167, 1933).

Figs. 5,7,9) The drawings described in Architettura (n. Speciale, p. 167, 1933) are posted.

Figs. 11-13,15-17) Created by the authors with reference to the drawings presented in CSAC.

Figs. 14,18-20) The drawings obtained by the authors from CSAC are posted.

Fig. 21) Created by the authors with reference to Fig. 16.

Fig. 22) Created by the authors with reference to the drawings in Reference 1 (p. 166).

Figs. 23-25,30) Certain drawings obtained from CSAC are posted.

Figs. 26,28) The authors created a floor plan and ceiling plan with reference to Fig. 32.

Figs. 27,29,31) Created by the authors with reference to the drawings obtained from CSAC.

Figs. 32-33) Created by the authors with reference to the drawings in Reference 2 (p. 29).

Figs. 34-37) Created by the authors with reference to the drawings obtained from CSAC.

Fig. 38) Created by the authors.

Acknowledgments

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Conflict of Interest

There are no conflicts of interest other than CSAC. The authors have no conflicts of interest directly relevant to the content of this article.

Data Availability Statement

Moreover, the data that support the findings of this study are available from the corresponding author [Satoru Kimura], upon reasonable request.

Notes

Note 1) Reference [1], pp. 10-12. In previous studies, Greco cited the warehouse in Magliana, Rome, which was completed during the war, and the exhibition hall in Turin, which was completed in 1948. He praises the unique morphological expression of RC and the construction method.

Note 2) Olmo, Carlo. *Pier Luigi Nervi Architettura comes from sfida*. Chiorino, Cristian ed. Silvana Editoria; 2010:203-205. The base of the activities of Nervi should have been Rome, as during his tenure at N & B, the headquarters of the construction company was in Rome and his wife Irene also lived in Rome at that time. Bartoli is also a cousin of Nervi and an employee of N & B, and he appears to be an engineer. According to Ref. [1] (pp. 149-150), Bartoli was mainly in charge of clerical work, such as construction management and contracts. After hanging over the working of the construction company to Bartoli, Nervi was able to spend a lot of time developing technology.

Note 3) Nervi cited the Salginatobel Bridge (Switzerland, 1930) in Switzerland as a notable part of the construction of arch bridges in the 1930s, which was designed by Robert Maillart (1872-1940). This bridge was a three-hinge arch bridge, where pin joints were used at the joint between the top and the foundation. Nervi was interested in the construction of pin-joined bridges of RC, including the bridge mentioned in a magazine article. (Nervi P.L. Critica delle strutture. Cinque Ponti, *Casabella Continuità*. 1959;(224):54.)

Note 4) There is a roof with RC arch-rib construction that was built by other engineers in the early 20th century, with a dome larger than the dome of the Pantheon in Rome and Santa Maria del Fiore in Florence. It is the Centennial Hall, designed by Max Berg (1870-1947), and built by Dyckerhoff & Widmann AG Company at Wroclaw in 1913. A wire rod constitutes the roof of the hall. Moreover, because the force flow is also expressed by each member and is clear, it is difficult to say that it is a structure that resists stress as a surface. The Centennial Hall is an important example of the earliest construction of an RC vault with arched ribs.

Note 5) Around 1436, 2 years before the 500th anniversary of the completion of the dome, an investigation committee was formed to conduct a careful investigation from the top of the cupola to the basement, focusing on the cracks.

Note 6) Nervi PL. Considerazioni sulle lesioni della Cupola di S. Maria del Fiore e sulle probabili cause di esse. In: Rilievi e studi sulla cupola del Brunelleschi, Tipografia Ettore Rinaldi; 1939; 44-49. The perspective of Nervi that the cracks in the Duomo's dome (cupola) in Florence did not lead to its collapse and the references to structural experiments for the cupola with Professor A. Danusso of the Politecnico di Milano are excluded in the report. Nervi and Danusso, who collaborated in the design of the hangar, which is described later, met at the time of the survey of the cupola in 1934.

Note 7) Reference [2], pp. 20-21.

Note 8) Reference [3], p. 23.

Note 9) The design philosophy in this paper is defined as "the way of thinking and direction regarding design and structure."

Note 10) Satoru K. The roof construction of a statically indeterminate structure by the company of Nervi & Nebbiosi and his consciousness of art. *J. Archit. Plann*. 2018; 83(750):1563-1570. In addition to the cantilevered roof, Nervi built a spiral staircase as an external staircase at Berta Stadium in Florence.

Note 11) Reference [1], pp. 158-175. In addition to the construction sites of Orviate and Orbetello, which were the subjects of the study, there was also a study on hangars constructed in "Torre del Lago." However, the city was not discussed in the previous research by C. Greco. In this paper, we focus on the hangars in the above two cities that were actually constructed and for which photographic materials are available.

Note 12) Gargian R., Bologna A. *The rhetoric of Pier Luigi Nervi. Concrete and ferrocement forms*. EPFL Press; 2016:69-93.

Note 13) Gabriele Neri. *Capolavori in miniature: Pier Luigi Nervi e la modellazione strutturale*. Mendrisio Academy Press, Silvana Editoriale; 2014:15-18.

Note 14) Pacetti, Pamela. Le Aviorimesse di Pier Luigi Nervi ad Orvieto. *La Caravella Editrice*. 2008;1-116.

Note 15) Presenti, Francesco. Quando Orbetello aveva le ali ed i capolavori Architettonici di Pier Luigi Nervi. *Aracne editrice*. 2013; S.r.l:1-255. Other previous studies include those by Ozawa and Siegel. Ozawa called the roof of the Orvieto hangar that was designed and constructed by Nervi as “a diagonal lattice Vault.” (Ozawa, Yuki. *Structural engineers in the 20th century*. Ohmsha; 2014:52-53). Siegel also described the Orbetello hangar as a structure similar to both cylindrical vaults and shells (Siegel K. *Structure and Expression of Contemporary Architecture (Strukturformen der Modernen Architektur)*. Kawaguchi M, ed. Shokokusha; 1961:154-157,192-193). The vault in this paper was a rib skeleton whose basic unit is an arch, or a curved surface and skeleton whose outside is covered with a curved plate. In contrast, the shell is a plate-like material composed only of curved surfaces, that is, a roof surface composed of a thin curved plate without ribs.

Note 16) The original map of this facility has not been converted into data. The author captured the original drawing using a digital camera and used the material for analysis.

Note 17) We purchased the patent data and used the text and drawing materials in it for analysis.

Note 18) Reference [2], pp. 20-21. In this study, the year of creation of the RC circular plane plan was specified as 1930.

Note 19) Ibid., p. 20. The title of this drawing is “Design for a circular hangar in reinforced concrete.”

Note 20) Ibid., p. 21. The title of this drawing is “Design for a circular hangar in steel.”

Note 21) Nervi PL. Capannone circolare per aero-plani o veicoli in genere con piattaforma anulare rontante, Brevetto (patent), n.304282, 8 gennaio 1932.

Note 22) There are twelve patent materials in total, six text materials with details related to the patent content, and one material Figure 3 with one cross-sectional view and one plan view. Other than that, the table of contents and cover of the materials necessary for applying for a patent are available.

Note 23) Ibid (patent)., pp. 1-6. There is a description of the number of pages in the patent document.

Note 24) Triennale di Milano (Pica, Agnoldomenico). Catalogo Ufficiale, Casa Editrice Ceschina, Milano, 1933:238-239.

Note 25) Ibid., pp. 238-239. The titles of this drawing are “Aeroporto civile per squadriglia da Turismo” and “Aeroporto militare per 3 squadriglie.” The panels on the display were identified at the military airports and stadiums for the three flight platoons. However, there are two plans that exhibit plans under the name of Nervi. The plan name was the roof of the pool (Piscina coperta) and a stadium for 50,000 people (Studio per 50.000 spettatori). The pool roof plan is a cylindrical vault with straight ribs.

Note 26) Nervi PL and Valle C. Aeroporto militare per 3 squadriglie, V Triennale di Milano. *Architettura*. numero speciale. 1933:167.

Note 27) Reference [1], pp. 163-169.

Note 28) There are two types of materials for this plan: one sandwiched between cardboards stating "Aviorimessa e Servizi per una Squadriglia" and the other stored with the same title and drawings wrapped around it. The project number is "1445" and there are nine drawings from 1445-1 to 1445-10, excluding the drawing numbered as 1445-2.

Note 29) Reference [1] introduces a hangar plan for Ciampino Airport after the hangar plan for the Italian platoon. In this paper, we followed the order of the plan.

Note 30) Reference [3], p. 163. The brick roof was constructed by passing the perforated bricks through reinforcing bars arranged diagonally to the ribs of the arch and filling them with mortar. Orthogonal brick roofs were developed by Danusso and were common in Italy at the time. However, the method of diagonally stretching the perforated brick is not described in the patent applied by Danusso, and it appears that it is a method invented by Nervi et al. (Danusso A. Capannone circolare per aero-plani o veicoli in genere con piattaforma anulare rontante, Brevetto (Patent), n.110064, 24 agosto 1911.)

Note 31) It has a type of folded plate structure. Consequently, the effect that increases the strength of the roof is expected.

Note 32) There are three types of materials related to this plan, which are clearly stated as follows: Aviorimessa per Aeroporto di Ciampino (Roll paper), Aviorimessa Ciampino, and Ciampino "C"- Calcoli. The number of the draft plan is "1487." There are 39 drawings, labeled 1487-1 to 1487-29, 1487-bis1 to 1487-bis6, and 1487-ter1 to 1487-ter4, whose drawing numbers could be identified. In addition, there are four sheets of structural calculations and 24 sketches without drawing numbers, and we obtained them.

Note 33) For sketches without a date, the author decided the order of each proposal based on the progress of the design.

Note 34) Reference [3], p. 25.

Note 35) Robert Maillart adjusted by inserting a piece of wood instead of asphalt.

Note 36) The date of the proposal of plan D of the Ciampino Airport is not known. However, as there is a drawing whose drawing number is "1487," which is a diagonal grid vault, the authors judge that the diagonal grid was considered in the final plan (plan D) of Ciampino Airport. Perhaps the final plan for the Ciampino Airport was diverted to the design for the hangar at Orvieto.

Note 37) Reference [3], p. 24.

Note 38) Reference [2], p. 29.

Note 39) Ibid., p. 32.

Note 40) Reference [3], p. 25.

Note 41) Reference [3], p. 25.

Note 42) Reference [3], p. 25.

Note 43) Reference [3], p. 25.

Note 44) Ibid., p. 25. In a lecture in 1965, Nervi showed the possibility that the shell roof could have solved the problem. However, it is unclear if he considered shell during the design process in 1938. At that time, he was considering how to construct a roof with ribs and arches instead of shells.

Note 45) Ibid., p. 25.

Note 46) Ibid., p. 96.

Note 47) Reference [1], pp. 182-187. The Italian military demanded the industrialization of the airplane hangar construction and also required restrictions on the use of wooden molds. Nervi introduced the precast method as a solution, but it was not a technique that he had previously used. After the war, Nervi developed a precast technology and developed a construction method called the Nervi system, which used both structural segmentation and ferrocement.

Note 48) The Duomo Cupola in Florence is not made of RC, but it is composed of arch ribs, which may have influenced the design of the hangar proposed by Nervi.

Note 49) Reference [3], p. 25.

Note 50) Danusso A. Le autotensioni. *Spunti teorici ed applicazioni pratiche*. 1934:242-243.

Note 51) In the book written by G. Neri, as listed in N13, the model experiments conducted by Nervi when designing the airplane hangar are discussed. The plan was to hang a weight equivalent to the actual load on a scale model of a celluloid hangar and measure the stress applied to the structure at that time. In the process of introducing model experiments, the theory of associating the stress relationship between the scale model and the actual building was established. Consequently, it is said that the accuracy of the results of the model experiments were improved. Experiments with scale models have proved that the Nervi hangar design is correct and that no changes in the draft are required.

Note 52) Nervi PL. Aviorimessa in cemento armato. *Casabella Costruzioni*, v.124, April 1938:4-9.

References

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.