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Self-supporting thin Shells in Italy. Space and Structure of the Industrial Buildings (1930-1970)

Bóvedas delgadas autoportantes en Italia. Espacio y estructura de los edificios industriales (1930-1970)

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ABSTRACT

In the Twentieth Century, the industrial buildings featured a broad experimentation on the load-bearing structures suited to the production spaces. Among the structural elements explicitly designed for factories were reinforced concrete thin shells. In Italy, where reinforced concrete was the predominant construction technique for the entire century, the evolution of the thin shells for industrial buildings traced a significant story: starting from the introduction of foreign systems and patents in the 1920s, the design and construction of the thin shells gradually stacked to national productive and technological specificities. This paper presents a historical investigation of the application of thin shells in Italy between 1930 and 1970, remarking, thus, the local contribution of Italian contractors and designers in the evolution of both the design solutions and production process. Furthermore, the study presents a systematic historical and technical framework related to thin shells to support the actions of knowledge and safeguard the industrial building heritage.

Keywords: *industrial buildings heritage; thin shells; reinforced concrete; precast concrete; Twentieth Century.*

RESUMEN

En el siglo XX, los edificios industriales presentaron una amplia experimentación sobre las estructuras de carga adecuadas para los espacios de producción. Entre los elementos estructurales diseñados explícitamente para las fábricas se encontraban las bóvedas delgadas de hormigón armado. En Italia, donde el hormigón armado fue la técnica de construcción predominante durante todo el siglo, la evolución de las bóvedas delgadas para edificios industriales trazó un hito histórico significativo: a partir de la introducción de sistemas y patentes extranjeras en la década de 1920, el diseño y la construcción de las bóvedas delgadas se aplicaron gradualmente a las especificidades productivas y tecnológicas nacionales. Este artículo presenta una investigación histórica de la aplicación de las bóvedas delgadas en Italia entre 1930 y 1970, destacando, por lo tanto, la contribución local de los contratistas y diseñadores italianos en la evolución de las soluciones de diseño y el proceso de producción. Además, el estudio presenta un marco histórico y técnico sistemático relacionado con las bóvedas delgadas para apoyar las acciones de conocimiento y salvaguardia del patrimonio de la construcción industrial.

Palabras clave: *patrimonio de la construcción industrial; bóvedas delgadas; hormigón armado; hormigón prefabricado; siglo XX.*

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1. INTRODUCTION

Reinforced concrete thin shells, in the punctual sense of thin self-supporting shells, found significant application in the industrial buildings of the 20th Century: the self-supporting shells - modular and structurally efficient for roofing intermediate spans in the industrial load-bearing structure - are, in fact, particularly suitable for roofing production spaces, characterized by large rooms free of intermediate supports and illuminated with natural light.

In Italy, and in other countries where reinforced concrete constitutes the benchmark technological horizon (1-3), the design and construction evolution of thin self-supporting shells for industrial buildings is a compelling chapter in the history of construction.

Starting from the valuable studies already present in the literature, relating to authors, single works and restricted chronological areas (4-7), by interlacing heterogeneous data - patents, case studies, authorial research - deduced from new investigations in the field, interrogating the bibliography of the time and archival sources, this essay presents a first reconstruction of the technological and building evolution of thin self-supporting shells used for the construction of industrial buildings, in the fifty years of their maximum diffusion in Italy (1930-1970).

Circumscribing the study of a specific component to only one building sector, such as the industrial one, is consistent with the feeling of the technicians of the time for whom in construction technique structural proposals were distinguished precisely according to their general uses, civil and industrial. Mario Baroni recalls that industrial ones are «buildings in which technical criteria and requirements must prevail almost absolutely over purely aesthetic or artistic ones [...] the only objective must be to find the best technical solution for the industry, for which they are intended» (8). This basic premise explicates the abundance of construction solutions for industrial buildings. Therefore, the study has the dual purpose of providing an overview of the evolution of a specific structural element, in the Italian technological and productive context, and of offering an operational tool for the most current actions of knowledge and valorization of the industrial construction heritage of our country (9).

In this regard, the study constitutes, in the authors' intentions, the outset for a series of insights into the design and construction history of the most significant structural and building elements that characterized the typological and spatial evolution of industrial buildings in Italy in the 20th century.

2. THE "ITALIANIZATION" OF THE SELF-SUPPORTING SHELLS

The introduction of thin vault in Italy is due to the international activity of the German company Dyckerhoff & Widmann AG (D&W). Thanks to inspired experimental and entrepreneurial policies, the meeting-clash of two brilliant engineers - Franz Dischinger and Ulrich Finsterwalder (10) - and a first successful patent for thin reinforced concrete domes (11, 12), developed in collaboration with Carl Zeiss Company and Walther Bauersfeld, at the end of the 1920s D&W was ready to promote and spread its findings beyond national borders (13).

The system for domes construction showed limited possibilities of application. Conversely, the patent for self-supporting cylindrical shells (14) revealed immediately its potential, especially for industrial buildings: the peculiar structural behavior of this kind of vault makes the system particularly promising for projects that require large spans without intermediate supports. The D&W cylindrical shells have a beam-like behavior: particularly reinforced, in the longitudinal and transversal directions and along the isostatic curves, they have transversal stiffening members, to counteract the bending moment and transfer the loads on the columns, and longitudinal beams on the edges.

2.1. The introduction of foreign systems in Italy and their diffusion at the turn of the 1930s

In Italy, the construction company of the Italian-German engineer Rodolfo Stoelcker - specialized in reinforced concrete - became the local dealer of the D&W patent for cylindrical shells (15).

Two garages built in Rome between the end of the 1920s and the early 1930s demonstrated the efficiency of the roofing system: the first for the Società Trasposti Automobilistici (STA), built between 1929 and 1938 (Figure 1a), the other for the Azienda delle Tramvie e Autobus del Governatorato (ATAG), completed between 1930 and 1932 (Figure 1b).

For both applications, the structural calculations and the executive projects were drawn up by the D&W central office in Biebrich in compliance with the characteristics of the patent: the two projects present similar construction solutions and spatial layouts tailored to the specific requests of clients.

The construction solution applied to the STA garage meets both company needs and the Italian regulations of the time. The roofing system is composed of eight thin shells - 8 cm thick, 15 m span, and 2.5 rise - set on two large spans. Three longitudinal beams, placed on the extrados, complete the system and transfer loads to three rows of columns. The roof has smooth reinforced concrete intrados without visible beams and tie rods, as requested by fire brigade regulations, and a double free span of 25 m (16). The result is a homogeneous and minimal interior space, highly adaptable and easily rearranged according to the needs of the parked vehicles. Even in the case of the ATAG garage in the Trastevere district, the D&W project prevails on the solution for the preliminary project, allowing to avoid the tie rods at the intrados usually used to contrast the outward thrust of the shells (solution already applied for example in the Littorio garage in 1928, in the San Paolo district). The solution proposed by Stoelcker consists of four thin shells geometrically similar to those of the STA - 8 cm thick, 14 m span, and 2.5 m rise - set on two spans of 20 m. In this case, the solution differs for the introduction of the skylight, as already proposed by D&W in the projects for the hangars in Bug (Rugen, in 1937-1938), in Hamburg, and in Gasolei Halle in Düsseldorf (1927).

The system was also applied in Turin in 1931 for the hangars of the S.A. Italian Air Force (Figure 1c). The roof is composed of 14 lowered-11.50 m, and a longitudinal extension without

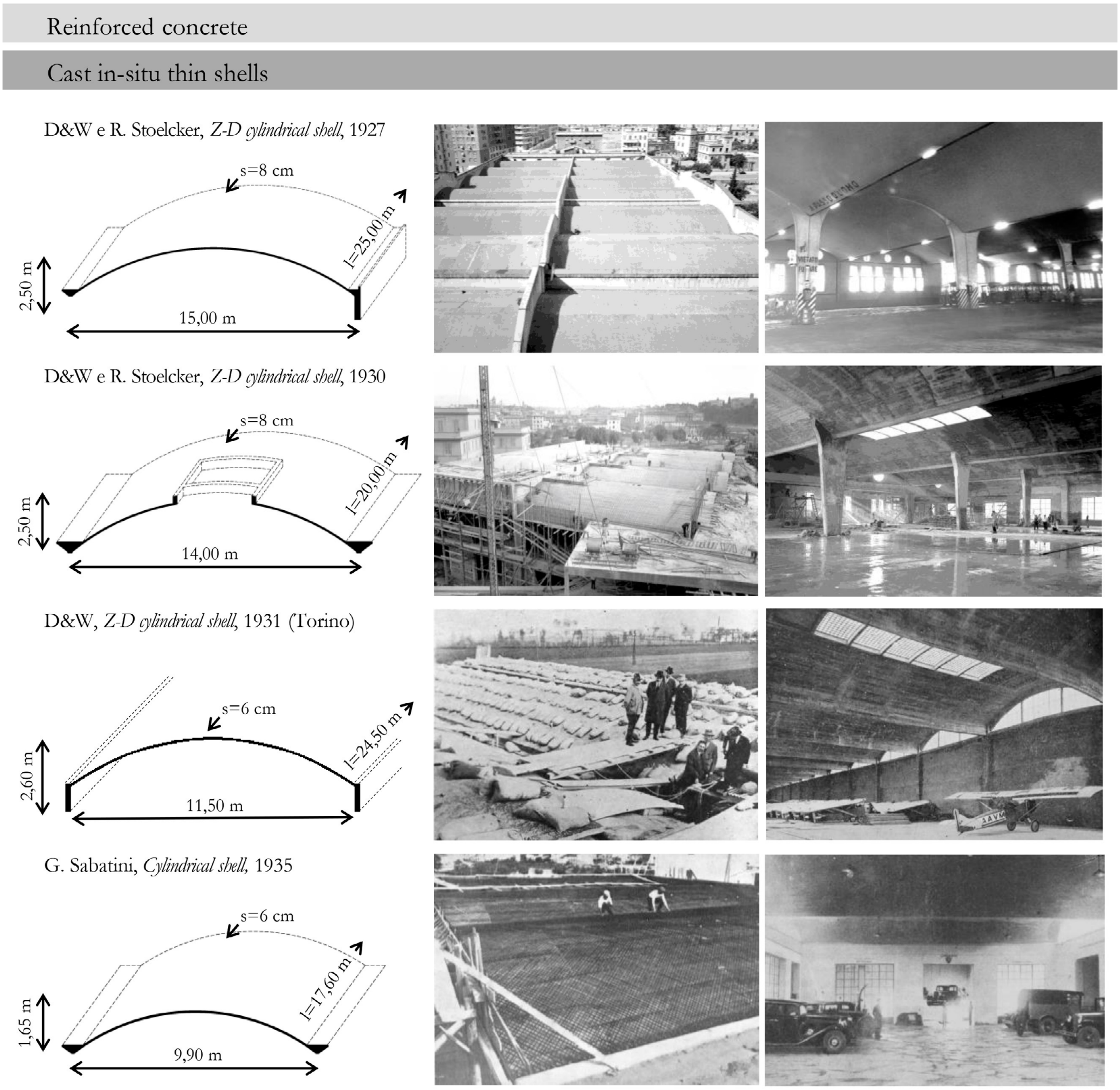

Figure 1. Cast in-place reinforced concrete thin shells. From top to bottom: a) garage of the Società Trasposti Automobilistici (STA) in Rome, b) Azienda del le Tramvie e Autobus del Governatorato (ATAG) in Rome, c) hangar for the S.A. Italian Air Force in Turin, d) central hall of the Ardito Sellari Company in Grosseto

supports of 24.50 m. Unlike the solutions designed for the garages in Rome, in this case, the edge beams are realized, at one end, by thrust-eliminated arches, on the other end, by an extradosed beam 3 m high. The final testing was carried out by the eminent Giuseppe Albenga and was fully favorable, encouraging the diffusion of the system (17). Also, the thin shells used in the central hall of the Ardito Sellari Company garage, designed in Grosseto (Figure 1d) by the engineer Giulio Sabatini (1935), are self-supporting and have a cylindrical geometry (18). Sabatini was involved once construction had begun due to the impossibility of using the metal trusses proposed in the original project. He designed a solution similar to the D&W shells used by Stoelcker but without its signature. The hall's roof comprises 3 thin self-supporting shells, 6 cm thick and 17.60 m long - with a span of 9,90 and a rise of 1,65- completed by transverse beams and stiffened by reinforced edges. Sabatini designed and verified the shells with Culmann's graphic method, using his own original calculations, and paid particular attention to arranging the reinforcements required to properly guide the internal forces in the shells (18). In this case too, the project prevails over alternative solutions due to economic convenience, the overall lightness of the system, and the aesthetic impact of the interiors. Furthermore, the Italian contribution to these systems extends to theory. Belluzzi's research on the instability of the elastic equilibrium of inflected beams with particularly deformable sections - such as the case of D&W cylindrical shells - provides an evaluation of the critical bending moment after which the moment of inertia of the section is significantly reduced (19).

2.2. Cast in place autarchic shells (1930s-1940s)

Following the success of the first applications, the use of self-supporting thin shells applied to industrial buildings further spread in the second half of the 1930s, in the most critical phase of the regime's autarkic policy.

An interesting autarchic application of self-supporting shells for production spaces was developed by the engineer Dante Fornasir in Panzano (Monfalcone) for the machinery warehouse and workshop of the Cantieri Riuniti dell'Adriatico (CRDA). Involved yet in 1920 in the design of the vast industrial complex (20), Fornasir experimented with the application of self-supporting shells in two buildings between 1937 and 1939, demonstrating their convenience compared to flat slabs of similar span in terms of iron savings.

Fornasir modified the traditional shape-resistant geometry of the cylindrical vault using elliptical sections with vertical tangents along the edges - already identified by Dischinger as the most suitable shape to obtain a self-supporting behavior - in order to obtain a general reduction of the reinforcing steel. The geometry of the shape-resistant section was sized and verified thanks to a scale model (1:3) that showed a global proper behavior and nearly zero elastic deformations: in the first building - built in 1937 as an expansion of the iron manufacturing department - the elliptical shells are designed with a thickness of 5 cm, a span of 18 m (Figure 2a), and a length of 10 m (21) in the second (Figure 2b) - realized in 1939 - with a thickness of 8 cm, a span of 12 m, and a length of 20 m (22).

In addition to the significant iron savings - calculated by Fornasir between 50% and 75% for 20 m span shells compared to flat slabs - the elliptical shape facilitates the correct natural lighting of the production spaces; optimizing the angle of incidence of the sun's rays.

During the 1930s, two engineers stood out for their experimental contribution to industrial roofing: Giulio Krall and Giorgio Baroni. The work of Giulio Krall with self-supporting thin shells is part of his long career as director of the Ferrobeton company (23). After studying with Arturo Danusso - an eminent Italian engineer and academic in the field of mechanics and constructions -, Krall started his theoretical research with polygonal cross-section shells before exploring the cylindrical ones. The projects where Krall applied his studies (24-26) for self-supporting shells are numerous and include - with specific solutions - also tanks and silos.

Among those are two projects, realized between the end of the 1930s and the beginning of the 1940s, at the Ansaldo shipyards in Genoa: the tower assembly workshop and the tracing building (25, 26). In the first case, Krall designed shells similar to those tested by Fornasir in Panzano. The roofing system comprises a self-supporting shells sequence with an elliptical section of 9 cm thick, 10 m span, and 22.90 m long. In the second - more complex - case, he proposed a notable constructive solution (Figure 2c). The structures of the three-stories tracing building is supported by a system of frames extradosed from the building envelope. The sawtooth roofing is composed of a thin circular shells sequence, 10 m wide, featured by the presence of reinforced concrete tie rods that, together with an upper transverse allows to eliminate intermediate supports. In this building, the intermediate floor slab is also designed with a self-supporting vaulted structure with an elliptical section. The solution, tested for the first time in this building, was widely applied by Krall in the following years.

Krall design also vaulted solutions of larger span for industrial plants of Carbonia (Serbariu, Sardinia) and Montecatini (San Giuseppe di Cairo, Liguria): the 35 m span of the "bath" hall in Carbonia is covered with a thin vault supported by a sequence of stiffening ribs, arranged every 20 m; the Montecatini's sulfate warehouse has a self-supporting vault of 25 m span and 7 cm thickness (25, 26).

Giorgio Baroni can be considered the Italian interpreter of international research on the double curvature thin shells. Son of the influential Milanese structural engineer Mario Baroni (27, 28), in those years he found in industrial buildings the most suitable opportunity to apply its systems on the national territory, as well as his father did before him (29).

Baroni filed two patents for thin reinforced concrete shells (30, 31). Using his first patent (30), between 1936 and 1938, he signed the projects for the Vanzetti Foundry after-work theater and the iron warehouse of the Alfa Romeo at Portello, in Milan. In both cases, he exploited the advantages of the hyperbolic paraboloid (HP) double curvature: by assembling in a gabled configuration four three cm-thick HP sections, Baroni obtains a quadrilateral module suitable for covering spans between 18 and 26 m and for realizing roofs with a sequential construction, reducing the use of reinforcing steel and optimizing the construction processes (Figure 2d).

The second patent (31) was registered after the Second World War (1949) but had already been experimentally applied in 1940 in Tresigallo (Ferrara) for the construction of a storage hemp warehouse (Figure 2e). Compared to the early applications, Baroni changed the aggregative configuration of the HP sections. The structure consists of 18 umbrellas, each with four HP sections supported by a central column. The HP sections should have been precast in-situ and then positioned and assembled, but the limited technical skills of the local workers compelled Baroni to use traditional construction techniques. The unfavorable conditions of the construction market influenced by the autarchic policy did not foster the application of these patents in further projects, even though Baroni has claimed a limited use of reinforcing steel.

Baroni's experimentations with form-resistant structures were not limited to the HP shape. In the same years, he explored the potential of the conoid shells (Figure 2f) that were thus used for the linen and hemp factory MALICA (Tresigallo, Ferrara) and the ATAG Central Workshops along Prenestina Street in Rome. In both cases, the construction phase exploited timely planning of the realization sequence of the shells, obtaining a considering reduction of construction times and costs (32). Unfortunately, after WW2, Baroni emigrated to the United States and did not participate in the intense post-war reconstruction and extensive development of industrial plants. After the last application of the second patent for market shelters at Mercati Generali in Rome - dating back to 1950 - the use of the two patents in Italy was interrupted (29).

Thin conoidal shells have also been studied by Aldo Pio Favini. In 1946, thanks to the research undertaken at the Polytechnic of Lausanne during his exile in Switzerland, he pub-

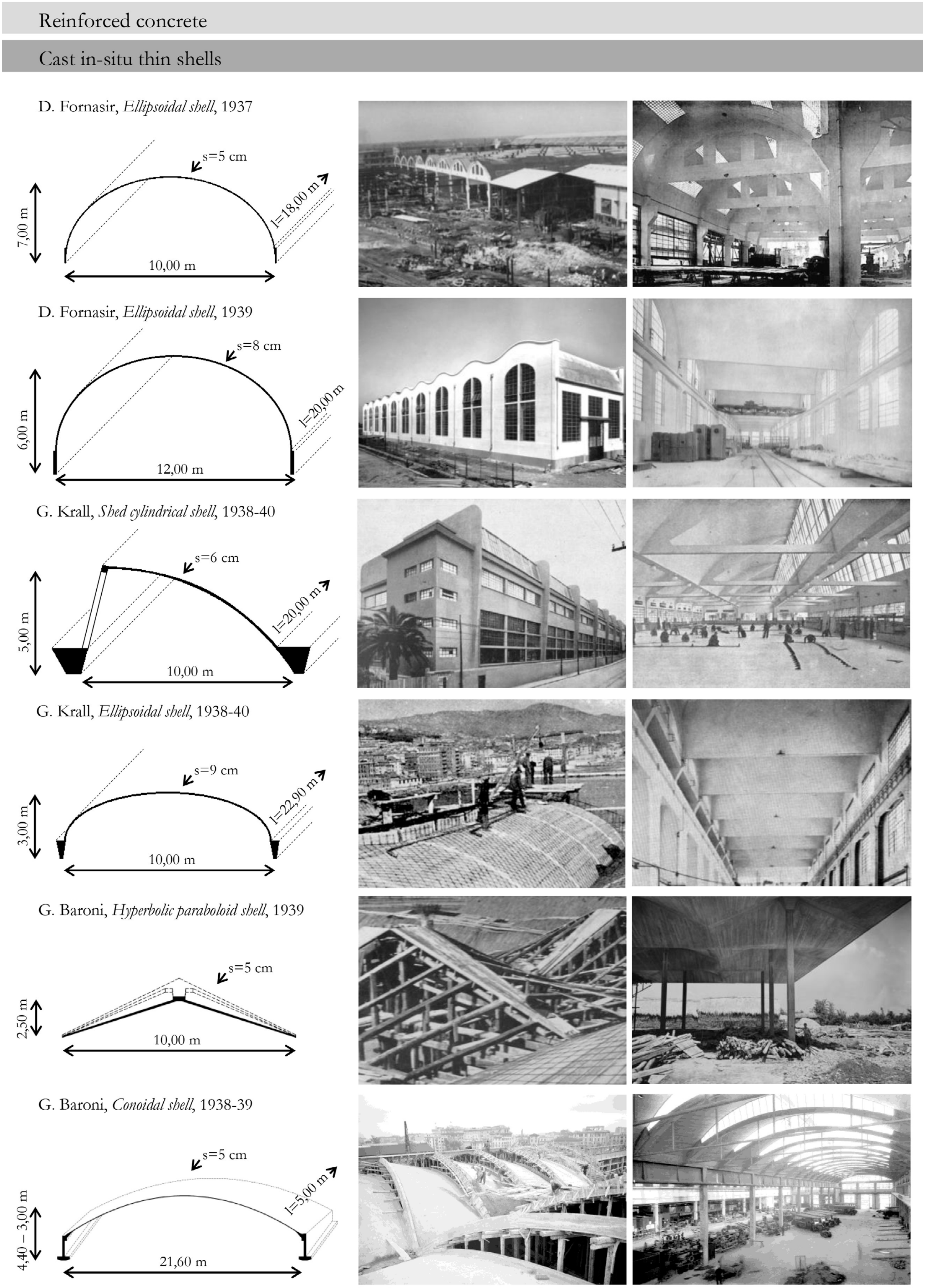

Figure 2. Cast in-place reinforced concrete thin shells: a) iron manufacturing department of the Cantieri Riuniti dell'Adriatico (CRDA) in Panzano (Monfalcone), b) warehouse of CRDA in Panzano, c) tracing building for the Ansaldo shipyards in Genoa, d) tower assembly workshop for the Ansaldo shipyards in Genoa, e) warehouse for the hemp in Tresigallo (Ferrara), f) ATAG Central Workshops in Rome

lished some considerations on the calculation of these kind of shells (33). In the following years, he extensively experimented with thin vaulted solutions. Among them, the L'Aquila fuel station stands out for the elegance of the roofing solution. Built in 1949 by the Ing. Tamburini company - with whom he has collaborated since 1945 -, the roofing is composed of a continuous wavy vault in reinforced concrete with a thickness of 5 cm, supported transversally on a span of 8.5 m and cantilevered by 6.5 m (34).

2.3. The reinforced brick shells (1930s-40s)

Since the 1930s, designers and construction firms have extended the study of vaulted roofing for industrial buildings beyond the cast-in-situ reinforced concrete technology. In this regard, several construction firms tested and developed the brick systems; between them, noteworthy was the contribution of the "F.lli Rizzi & C. - RDB" construction firm.

The RDB opened in 1908 for brick production; in the early 1920s, the Pontenure industrial complex was chosen as a pilot plant to enhance the experimental approach. In those years, the production studies were led by engineer Mario Cascione, focusing on optimizing the production of quality hollow bricks and the production of load-bearing structures in which brick played an active role in structural strength (35). In these years, the company patented the first prefabricated S.A.P. beams in reinforced brick and tested lightweight slabs and large-span vault systems (36).

Spending the 1930s between testing and verification, flanked by intensive popularization and promotional activities, S.A.P. systems gained academic (37) and political support (38) and commercial success (39).

Aided by the autarkic logic of the regime, RDB's systems won numerous orders in the late 1930s, finding a promising field of application in the industrial building sector.

The barrel brick shells, based on the S.A.P. system acted like traditional vaulted systems: experimented from 1937 onward, were thus used in 1939 for the large roofs of the S.A. Cementi plant in Monopoli (Bari) (40) (28.60 m in span and 40 m in length) (Figure 3a), and the Saponificio Ambrogio Silva in Seregno (Monza) (30 m in span and 80 m in length) (41) (Figure 3b). Subsequent applications of SAP barrel shells, pioneered in the 1930s, intensified and spread after World War II, experimenting even the large-span beam-like vaults.

3. EXTENSIVE APPLICATION AND OPTIMIZATION OF THE CONSTRUCTION PROCESS

In the 1950s, in the rapid development of industrial construction toward the so-called Italian economic miracle, thin self-supporting shells began to be enhanced by prestressing technique, improving their inner geometric structural capacity with significant material savings. At the same time, the execution processes, initially reduced to cast-in-place, were being updated by introducing heterogeneous prefabrication techniques, including on-site prefabrication and the use of mixed concrete and reinforced brick systems.

3.1. Thin shells in prestressed reinforced concrete

Thin prestressed shells applied to the roofs of industrial buildings in the early 1950s featured the traditional construction process of in-situ casting.

In 1954, the engineer Favini - who had already tested the design of thin shells with the use of prestressing techniques within his study with Professor Gustavo Colonetti during his exile in Switzerland (7, 42) - tested a novel system of prestressed thin shells for the roof of Officine Elettromeccaniche Ernesto Silvestri in Dormelletto.

The small pavilion of the Dormelletto plant - 750 square meters covered with five cylindrical shells arranged in a shed - had significant spans of 20 m and was the ideal building to set up a prototype to validate the extensive application of the thin vault system for the roofing of industries. The traditional beam operation of the shells - 20 m long, 7 m radius, 10 cm thick - was aided by the prestressing cables arranged longitudinally (43); a unique "miniature" anchoring device, patented in 1951, allows the six wires to be tensioned in the small thickness of the vault (44).

Within the design of the Dormelletto plant, Favini aimed to test the structural efficiency in terms of material savings and the possibility of optimizing the casting on-site process. The construction site was, therefore, an opportunity to experiment with the on-site prefabrication of temporary, modular, and reusable scaffoldings and ribs. Favini designed a unique assemblable wooden rib to support the vault cast: the rib was, thus, divided into parts - 1 m wide - assembled on site and reusable during the construction phase. In this way, the ribs' setup overlapped with the concrete's maturation times, allowing 5 shells to be built in 3 months, exploiting just two demountable ribs (45).

The system proposed in Dormelletto was then tested on a large scale by Favini in 1958 for the construction of the roofs of the Perugina factory in Perugia, designed by Carlo Rusconi Clerici (Figure 4a). The large building dedicated to the production featured seven sectors: for the roofing system, Favini used 210 thin shells arranged as shed elements; hollow beams functioned as ventilation devices and acted as supports. The construction site, entrusted to the Sogene company, presented a strict deadline of 14 months for the construction of the entire complex (47,700 m2). Two sets of construction works were, thus, conducted in parallel: the casting of the elevation structures started, and the temporary structures to support the cast of the shells. From this side, in just over a month, carpenters set up 252 pieces of wooden ribs to support the casting of 30 shells, corresponding to one of the seven sectors of the building. Once the casting of the shells of the first sector had started, carpenters started the second series of wooden ribs; by alternating the castings and reusing the ribs, in just two and a half months, three sectors of the building were completed, finishing all the roofing elements in five months (45).

In 1963, Favini's shells - optimized on-site - were applied even for larger spans. The occasion was the project of the Fimi factory in Rescaldina (Milan), where the Favini's shells reached 31 m in length and had a width of 7.20 m (Figure 4b). The shells were supported by beams, with C-shaped sections, forming the ventilation channels of the building. The roof of

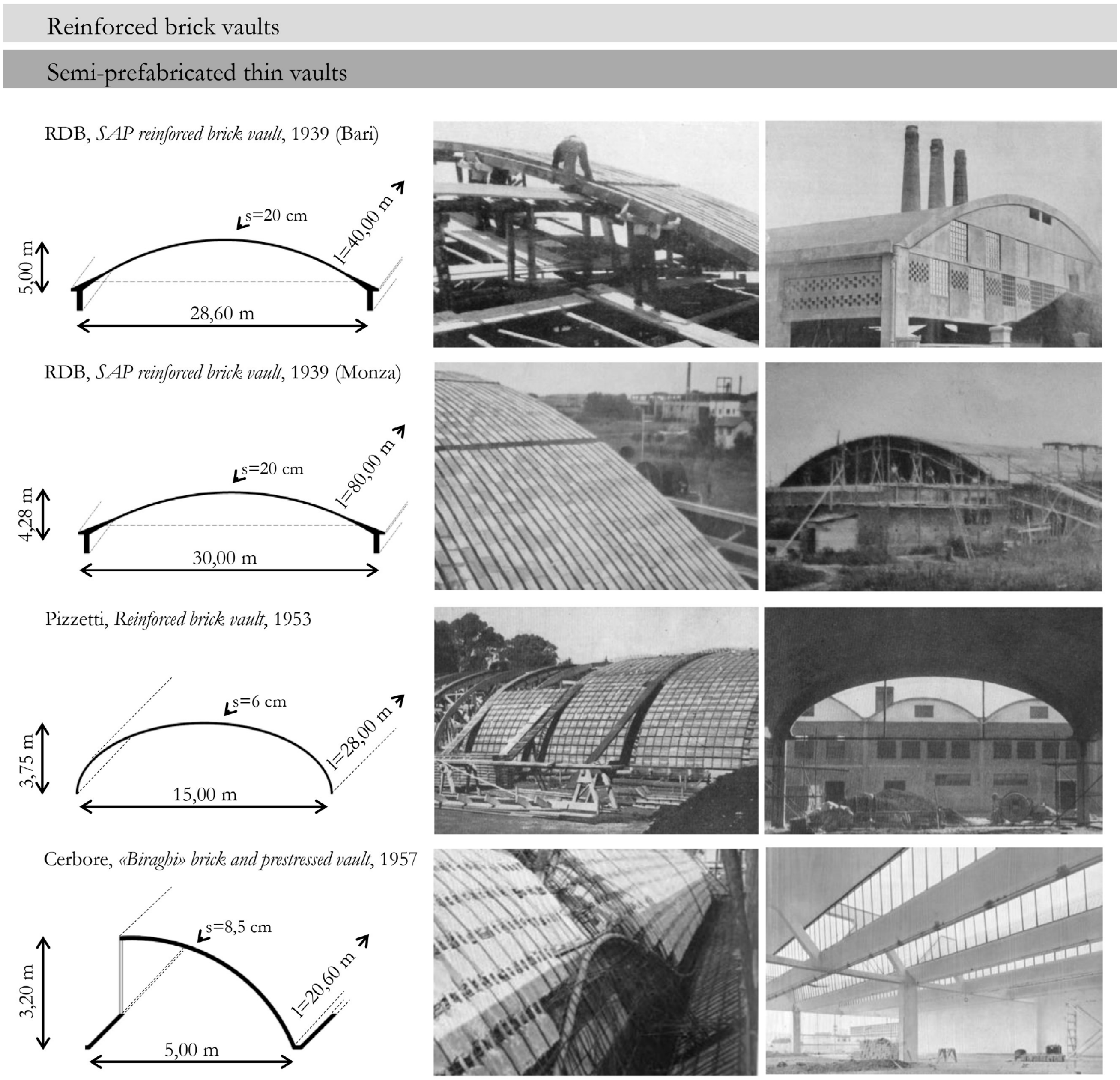

Figure 3. Semi-prefabricated thin vaults in reinforced brick: a) S.A. Cementi plant in Monopoli (Bari), b) ponificio Ambrogio Silva in Seregno (Monza), c) prototype of a thin vault in reinforced brick by Giulio Pizzetti, d) large hall of the Officine Biraghi mechanical workshop in Milan

the Fimi factory was included in the review of the most significant pre-stressed reinforced concrete structures built in Italy between 1962 and 1966: the ingenious construction process of the shells cast on-site, developed by Favini, is here defined as «laborious and time-consuming» in comparison to the adoption of prefabricated construction elements which characterizes the industrial buildings built in the same years (46).

3.2. Semi-prefabricated thin shells

The need to speed the vault construction process, cutting the costs of ribs and formwork, initially supported the experimentation of structures composed of brick and reinforced concrete that had already started before the war with the development of the S.A.P. system (47) and, subsequently, the application of prefabrication systems for prestressed reinforced concrete shells.

In 1953, the engineer Giulio Pizzetti developed a prototype of a «thin vault in reinforced brick»; specifically, the vault was conceived for the design of industrial buildings (48). The primary element of the vault was a brick with a square plan - 4 cm high - suitably perforated for the passage of the reinforcements, characterized by a significant inclination of the end faces (Figure 3c).

The 'basic prefabrication unit' of the beam was obtained by placing bricks side by side; the beams, placed in parallel, formed a brick skeleton featuring transversal and longitudinal channels to lay the reinforcements. The structure was, thus, completed by the execution of the cast. With straight beams exploiting the properties of the ruled surfaces, it was, thus, possible to obtain traditional cylindrical shells and more complex "skewed shells"; alternatively, arranging the bricks forming curved beams was possible. Once the joists have been fulfilled, the construction of the shells involves two

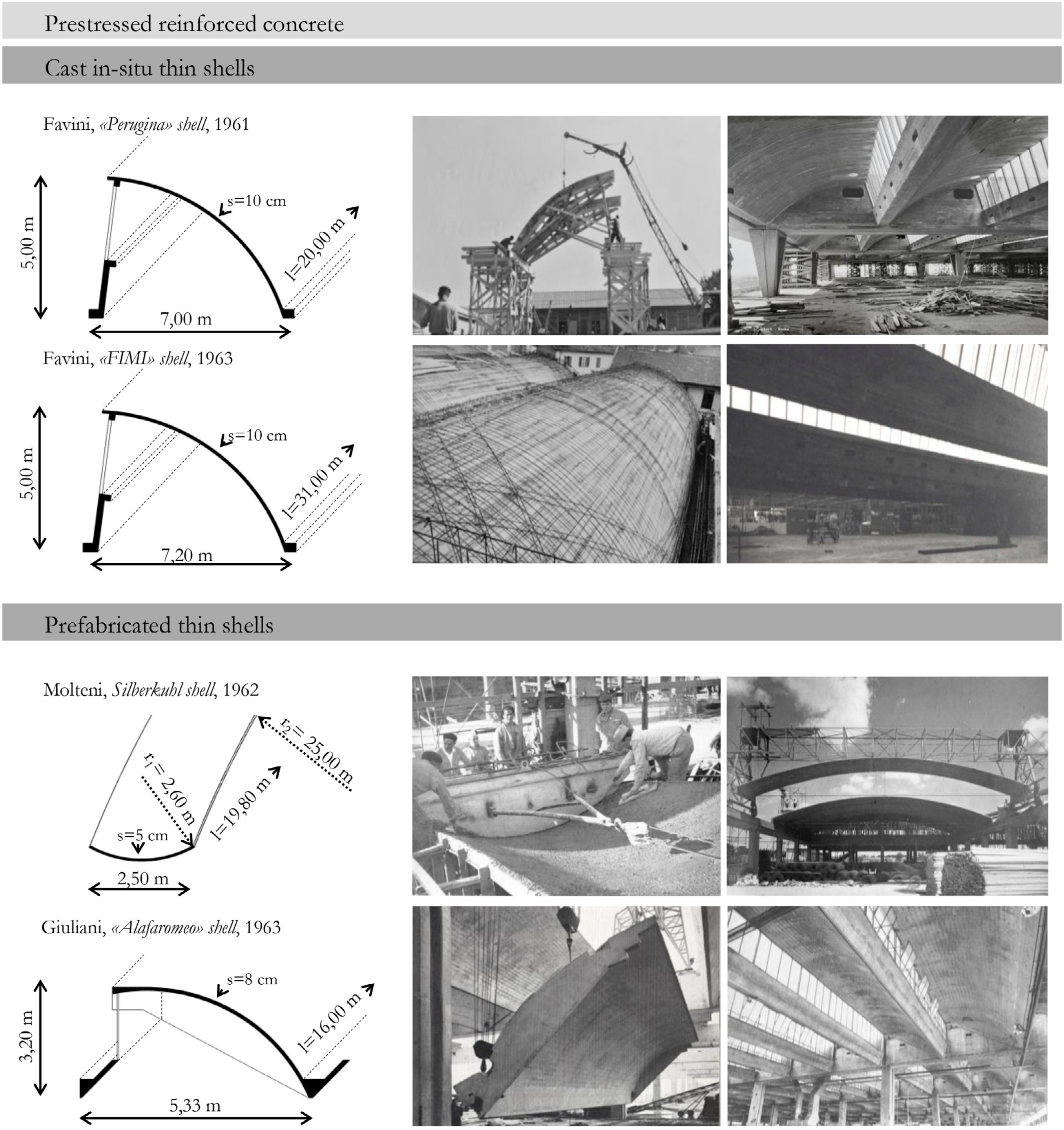

Figure 4. Cast in place and prefabricated thin shells in prestressed reinforced concrete: a) the Perugina factory in Perugia, b) the Fimi factory in Rescaldina (Milan), c) warehouse for the Rinascente in Rome, d) Alfa Romeo factory in Arese (Milan)

alternative methods: the production of the structures entirely on-site, then installed as monolithic structures after the execution of the castings, or the preparation of the 'basic prefabrication unit' prefabricated on site, and the execution of the castings on site.

Brick and reinforced concrete shells found extensive applications in industrial buildings of the 1950s, also resorting to the prestressing technique. In 1957, the engineer Giovanni Cerbore designed six cylindrical shells in brick and prestressed reinforced concrete for the roof of the large hall of the Officine Biraghi mechanical workshop in Milan (49): the shells - 20.45 m long, 2.50 m wide, 8.5 cm thick - were composed of the so-called Virex-type bricks joist, reinforced by a steel net and precompression cables (Figure 3d). The construction took five months. The process concerned five phases: i) prefabrication of the reinforced brick beams on the ground; ii) setting them up on the ribs; iii) laying the prestressing cables and the mesh reinforcement steel net; iv) casting of the concrete; v) tensioning the prestressing cables.

In 1958, the engineer Egone Cegnar applied the system of brick and prestressed reinforced concrete shells to the roofing of the Municipal Garage of Ponichelli Street in Turin. The building was a significant application of this system for constructing asymmetrical shells with circular generators and rectilinear and parallel directions, arranged in sheds, with demanding spans of 28.30 m and wide of 9.20 m. (50).

3.3. Prefabricated thin shells

In the 1960s, fastening the construction process of the shells became a priority to allow their extensive application to new industrial complexes, guaranteeing economy and speed of construction: on the path of experimentation started in the 1950s on semi-prefabricated mixed systems, the vault in prestressed reinforced concrete was thus linked to industrial production processes.

The building of the Alfa Romeo factory in Arese, designed in 1963 by the engineer Gian Carlo Giuliani, was a significant example (Figure 4d). Seven hundred twenty self-supporting shells in prestressed reinforced concrete, arranged in a shed, composed the roof of the building. The shells with a span of 18 m - 6 cm in thick and 5.3 m wide - were supported, in this case too, on hollow beams, functioning as ventilation channels. The construction process featured an integer prefabrication process, lasting 24 hours: the procedure involved the use of metal formwork, steam curing of the castings, texturing of the prestressing cables, dismantling and lifting on site, with the aid of an electric overhead crane that exploits the support of the beams, already built on site (51). In this way, the production and setting up of the seven hundred twenty shells took just six months of work: the system - three times more efficient than the Favini method tested in Perugia - demonstrated the convenience of industrial production of this structural element.

Among the examples of integral prefabrication of the shells, a significant case was represented by the construction system of the roof of the Rinascente warehouse in Rome (Figure 4c), designed by the engineer Aldo Molteni, using the system patented by the German engineer Wilhelm J. Silberkuhl (52), and applied by the company Società Edile Lavori Pubblici Industriali (S.E.L.P.I.). The roof featured spans of 20.40 m: approximately 400 HP shells with double inverse curvature were used and carried out off-site, simply resting on a partially prefabricated reinforced concrete framework. The shells were only 5 cm thick, exploiting a double-curvature surface obtained through the translation of a circular arc with a radius of 2.60 m onto a circular arc of 25 m in radius. The Silberkuhl patented systems protected HP shells. For the shell of the Rinascente warehouse, casted on site, the parabolic curves were approximated to circles.

The structure was aided by the action of a steel tie rod- with adjustable tension - which connects the shutters, absorbing the horizontal thrust. The shells were produced on-site with the aid of a parquet formwork and a machine for vibrating the castings, which allowed, at the same time, to profile the extrados; after 24 hours, the single vault was ready to be installed, the subsequent dismantling finishing and transport operations take a total of just 30 minutes of work.

4. THE THIN SHELLS LEGACY

In the mid-1960s, the pre-compressed, semi-prefabricated, and prefabricated thin shells transformed into shape-resistant elements with different profiles.

This was the case of the roofing of the Nuova Cesenathe food industry, commissioned by the Arrigoni company to the Codelfa company with the consultancy of the engineer Tihamér Koncz - already well-known for his studies on building industrialization - and by Favini (53). The roof designed by Koncz - to be completed within a year to respect the time between two harvests - was composed of a sequence of thin elements in prestressed reinforced concrete, 18 meters in span, arranged in sheds: the geometry of the cylindrical vault self-supporting, transformed into a slender S-shaped section, only 8 cm in thick, reinforced with prestressing cables and a steel net. The shell section was produced by a continuous casting device composed of a mold and cast vibrator bracket.

According to the Koncz design, the sheds had to be prefabricated in the factory with metal formwork and industrial pretensioning devices. The low technology of the Arrigoni construction site required a rethink of the construction process. A prefabrication workshop was, thus, set up in a disused warehouse of the Arrigoni complex; a brick mold was used instead of the metal formwork, and a 'profiling device' made of a steel sheet modeled the concrete cast from above (54). The construction system, allowing the production of four shed elements in only 18 hours, was considered very efficient in terms of time and cost. The production device was, thus, patented by Koncz in 1964 as part of a thin shell system in prestressed reinforced concrete for "folded roofs and self-supporting floors" spanning between 10 and 30 m (55).

The Arrigoni construction site remarked on the effectiveness of precast prestressed shells in designing modular roofs for industrial buildings. In 1966, for the roofing of the production plant in Varallo Pombia, Favini enhanced the design of precast sheds: he focused on a Z-shape shell with a wall of 7 cm thick, patented as a so-called "thin-wall prefabricated roofing element for industrial constructions". The production process of the Z-shape shell relied on metal formworks or required the joint of three precast plates, completed by a cast on site (56).

In the same year, the engineer Giuliani worked on the precast thin shell design for the ISI factory roof in Bellusco (57). The roof of this plant was composed of thin precast shells, spanning between 20 and 30 m, simply supported by pillars: the thin shells were entirely precast on-site, exploiting shotcrete.

In 1969, an elegant self-supporting prestressed vault was designed by engineers Giorgio Macchi and Gianluca Papini, in collaboration with the architect Piero Pallavicini, for the roofing of the Avon Cosmetic "shipping" building in Olgiate Comasco. The prestressed shells were only 12 cm thick and reached 69 m in span, exploiting the shape-resistant geometry of a double curvature surface obtained by translating a trochoid curve on an arch. The shells were strengthened by a series of transverse elements, placed at the extrados, simultaneously functioning as anchoring devices for the prestressing cables. The cast on-site of the shell was performed using a modular and mobile steel scaffolding in tube and coupler and metal lattice ribs (58).

5. CONCLUSIONS

This article traces the progression of thin self-supporting shells applied to industrial buildings constructed in Italy between the 1930s and the 1960s. Through the synthetic presentation of case studies, considered as exemplary, the text traces the main stages of the design and executive development of this fascinating structural element: the introduction in Italy of the Zeiss-Dywidag system produced by D&W and applied, under concession, by the Stoelker company; the gradual "Italianization" of the system during the most rigid years of the fascist autarkic policy, through the authorial contribution of the designers; the gradual enhancement of the structural capacities of thin shells, first through the study of new resistant geometries and more effective schemes for the distribution of reinforcements and, then, through the introduction of prestressing; the constant search for the optimization of construction site processes that, begun in the 1940s and conducted systematically in the 1950s and 1960s, led to the gradual metamorphosis of thin shells into new structural elements better suited to the general industrialization of the building site.

The diachronic reconstruction of the distinct phases of development of the thin self-supporting vault, during the fifty years of its maximum diffusion in Italy, allows, on the one hand, to retrace, through the history of a single structural element, the fundamental stages of the evolution of Italian building - from the autarkic experimentation on cast-in-place reinforced concrete, to the development of mixed systems of semi-prefabrication and on-site prefabrication, to the development of "unique" elements produced in workshops - on the other, to sketch the typological and spatial evolution of the production buildings, from the postwar years to those of the economic miracle. In this sense, the use of thin self-supporting shells made it possible to imagine and construct production spaces that, characterized by considerable heights and defined through the modulation of zenithal light, resulted in several original variations of the grid, dimensional and compositional, of the traditional industrial shed roof.

If, in fact, the strength conferred on thin shells by their shape allows for significant longitudinal development of the roofing elements, on the other hand, executive constraints suggest the adoption of very small chord sizes, thus introducing a new multiple span metric, based on the contraction of transverse spans between supports and the expansion of longitudinal ones. Ideal, for example, for Fordist-style assembly lines, or for housing machinery with significant longitudinal development, such as those in paper mills, or component batteries for the production of artificial fibers.

At the same time, studies on the optimization of the geometry over the strength of the shells - obtained by deforming their original cylindrical profile - has triggered a concurrent design research on the diffusion of zenithal light, for the purpose of a better functionality of production sheds, determining new forms of the shed vault, derived from the full integration of structural and lighting instances.

Finally, the necessary evolution of construction technologies, in order to ensure the economic sustainability - in terms of construction time and cost - of the extensive application of thin vault components for the roofing of postwar industrial complexes, substantiated a profound design reflection on the "industrial" identity of this structural element.

The vault, produced in components on the shop floor, became an iconic element of the integration of construction systems in the industrial process; in the specifics of the Italian construction site, the industrialization of construction processes came close to the coeval experiences in designing products -as evidenced by the numerous models patented in the 1960s- mediated by an obligatory design reflection on the integration of technique and form. As such, the experiences of the 1960s determine the definitive overcoming of the "standardization" of the structural and executive system, proposed in the patents of the 1920s, and the achievement of a complete technological and expressive maturity of this structural element, marking the way for subsequent hybridizations.

Rediscovering the history of thin self-supporting shells for industry, sketching their main synergies with the architectural evolution of the industrial building, allows to acquire fundamental knowledge for the current actions of conservation and enhancement of the heritage of existing industrial buildings, suggesting common lines of intervention - for example, considering "archetypes" corresponding to the different chronological phases of the typological and technological evolution of shells in accordance with the functional and architectural evolution of spaces for production - and cultural enhancement strategies according to a network, extendable beyond the boundaries of the national territory.

DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

AUTHORSHIP CONTRIBUTION STATEMENT

Edoardo Currà: Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

Ilaria Giannetti: Conceptualization, Methodology, Investigation, Visualization, Writing - original draft, Writing - review & editing.

Martina Russo: Conceptualization, Methodology, Investigation, Visualization, Writing - original draft, Writing - review & editing.

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