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THE ITALIAN EXPERIENCE IN PRECAST CONSTRUCTION IN THE SECOND HALF OF THE 20TH CENTURY: SYSTEMS FOR INDUSTRIAL BUILDINGS

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Abstract

The developments in concrete prefabrication techniques from the second half of the 20th century, particularly in Italy, have established these methods as a dominant force in the construction of industrial buildings. This period offers a valuable opportunity to explore the industrialisation of the construction sector. The roots of this transformation can be traced back to the 1920s, when a highly rational approach to building design and production processes began to take hold in industrial construction. This rationality persisted into the post-World War II era, where technological advancements in materials enabled the creation of innovative and daring structures for industrial purposes. The industrial boom further fueled the demand for new buildings to be constructed rapidly, ensuring swift production capabilities. This article aims to provide an overview of the key precast reinforced concrete construction systems that formed the backbone of industrial construction in the post-war period. During this time, industrial construction fostered experimentation and the development of cutting-edge techniques, achieving significant results across various fields of application. The article offers a taxonomy of the main systems used during the period under review, with a particular focus on structural systems, ranging from those partially cast in situ to fully industrialised systems, as well as on building envelope elements. The goal is to provide a comprehensive understanding of the critical role of precast systems in Italy's industrialisation.

Keywords

Architectural engineering, Italian precast construction, industrial buildings, History of 20th-century construction, Reinforced concrete buildings.

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1. INTRODUCTION

The ontological singularity of industrial construction is its relatively short history, which detaches it from the value and semantic categories proper to residence. On the other hand, the matured environmental sensitivity is relevant regarding land consumption and its high impact on the quality of anthropised space [1]. Beginning with the building types generated by the Second Industrial Revolution and the striking examples that characterised the phenomenon of Universal Expositions, industrial construction also found its modernity in the period between the two world wars, especially in the 1930s immediately following the development of the 1929 economic crisis [2].

The fact that the functional characteristics of the industrial building require internal clear spans of 10-15 m makes the roof the technically and formally characterising element of the specific typology [3]. Here too, reinforced concrete, which has been proposed by Hennebique as early as 1894 in the sheds of the Saint-Ouen refineries and "poetised" by Maillart at the beginning of the 20th century, tends to replace the classic metal solutions of the tie rod and rafter (Polonceau and triangular trusses), the three-hinged arch and portal frame that characterised industrial construction in the second half of the 19th century, projecting on this typological category design features of absolute methodological clarity [4].

In the 1940s and 1950s, new solutions were inspired by what was developed in the 1920s and 1930s about thin curved slabs and, more generally, double-curved surfaces. The general analytical treatment for the membrane analysis of rotating and translating surfaces is due, between 1928 and 1933, to Dischinger and Finsterwalder, who propose some covers that have become paradigmatic. Furthermore, in 1933, the magazine *Construction et Travaux Publics* published an article by Freyssinet dedicated to prestressed reinforced concrete. Synthesising all this wealth of ideas was Edoardo Torroja Miret, who, by expressing a design that legitimised technology as a source of inspiration, gave rise to a veritable School to which numerous structural engineers would refer, the most famous of whom were Ildefonso Sánchez del Río Pisón, Lucio Costa, Félix Candela, Eladio Dieste and, already mentioned, the Italian Pier Luigi Nervi. The latter also tackled industrialising the construction process, as it was evident that these structures' limitations resulted from the considerable cost of building on-site using essentially traditional construction techniques [5].

The return to Italy of Franco Levi, an expatriate following the promulgation of the 1938 racial laws and already Colonnetti's assistant, gave new impetus in Italy in the 1950s to studying prestressed structures [6]. The degree of maturity achieved in this field can be seen in the linear beams used for the monorail operating in the *Italia '61* event in Turin (Figs. 1a and 1b). The first precast roof element in the shape of a hyperbolic paraboloid, intended for spans of 18-20 m, is another example of the degree of maturity; it had been developed in the late 1940s, patented in Germany in the early 1950s by Wilhelm Silberkuhl and is still in production today (Figs. 1c and 1d) [7].

In Italy, however, the precasting of industrial roofing in the 1950s was heavily influenced by models developed in the pre-war period, as demonstrated by the activities of Rizzi, Donelli, and Breviglieri (R.D.B.). The R.D.B. company, which has been producing bricks since 1908, had already proposed early forms of precasting in the 1930s, such as reinforced beams made from hollow blocks, as well as SAP (*Solaio ad Alta Portata* – High Capacity Floor) and STIMIP (*Solaio in Travetti in Materiale Isolante e Pignatte* – Precast Hollow Core Slab with Insulating Material) slabs. It is no coincidence that the products currently on the market for industrial roofing utilise structural brick technology, in which the company has significant expertise. R.D.B. products, supported by the magazine *Il Laterizio* and technical manuals published by the company, became a general reference model for new producers of precast elements [8].

Similar to what happened in Italy, the situation throughout Europe is a result of the new social order complicated by the substantial blockage of activities due to the war events; in this shared context, construction responds with major public interventions characterised by formal simplification, unification of building types, compaction of housing blocks, and the meeting of art and industry. Interest in and attention to the issues of seismic safety and building energy behaviour will only arise from the 1970s onward. Since the Second World War, reinforced concrete has become the construction technique of reference for social housing and is no longer the object of patents and company specialisations.

The focus of research on building industrialisation often overlooks the use of precast reinforced concrete solutions, particularly in non-residential sectors such as industrial construction. This paper addresses this gap by highlighting the key precast building systems employed in industrial construction. Specifically, the study aims to emphasise the role of the precast industry in Italy, particularly in the construction of production facilities, whose development has frequently mirrored the country's economic growth phases. This paper provides an overview of the principal systems utilised in industrial construction during the 20th century, offering a technical perspective. Through an analysis of bibliographic sources, including contemporary volumes on the subject and

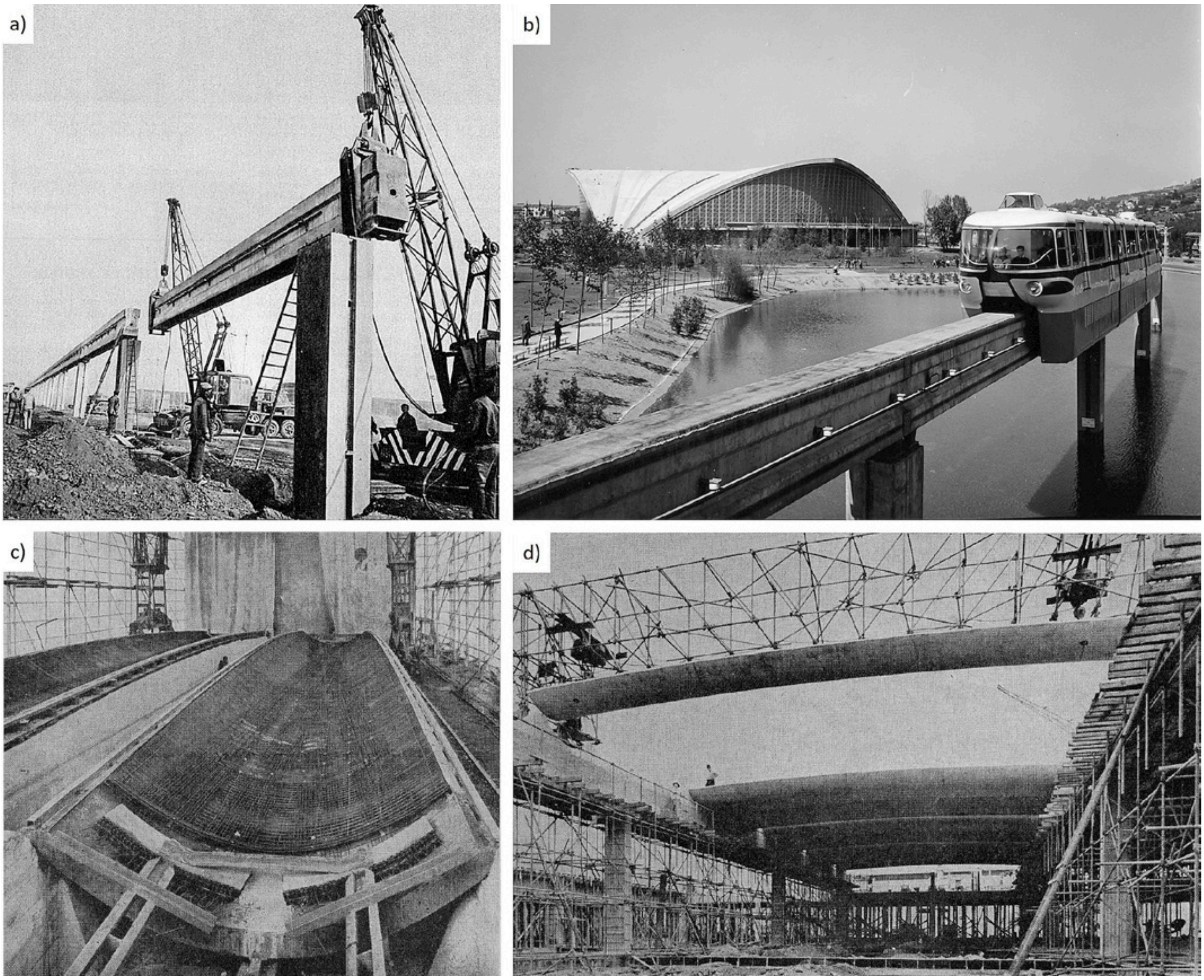

Fig. 1. *(a) Advances in precast reinforced concrete technology: assembly of the beam for the monorail built for the International Labour Exhibition, Turin 1961. Source: www.italia61.org; (b) the system in operation with the Palavela in the background. Source: Wikimedia Commons; (c) Silberkuhl production with special slab reinforcement. Source: [7]; (d) assembly of the Silberkuhl shell elements. Source: [7].*

period-specific catalogues, the paper presents the main solutions developed in Italy between 1950 and 2000. The evolution of each system is traced, showcasing the predominant types that became widespread from the mid-20th century onwards and establishing an evolutionary path among different types. In particular, the analysis focuses on structural systems, demonstrating how roof system design led to fully precast structures. The paper also outlines the significant developments in building envelopes, illustrating how the initial emphasis on lightness and installation speed has gradually shifted towards energy efficiency, reflecting the adoption of sustainable construction practices. The presented overview aims to serve as a tool for fully understanding the main technologies employed in industrial construction during the post-war period, with a view towards their future conversion and valorisation.

2. STRUCTURAL SYSTEMS

This chapter outlines the main precast structural systems, beginning with the earliest precast construction methods, where only roofing elements were precast while structural components such as beams and columns were cast in situ. These systems include no-thrust systems (older systems) and shell structures. The former comprises trusses and barrel vaults with metal tie rods, tensioners, and conoids; the latter includes ribbed and hyperbolic paraboloid vaults. Domes, the only non-precast structures, are not utilised in industrial buildings. The inclination of the components and the specialisation of the vertical supporting structures with sawtooth shapes introduces the shed variant, a concept originating in the 19th century when natural solid lighting was required. The chapter then details how the evolution of roofing systems has led to the development of lightweight precast roofs and slabs. Finally, it concludes with a description of fully precast structural systems and specialised roofing elements developed at the end of the 20th century.

2.1. ELIMINATED THRUST SYSTEMS

Eliminated thrust systems include truss variants (Fig. 2), with continuous pitches on ridge support and barrel vaults (Fig. 3). Both systems utilise off-site precast components [8]. These systems require edge beams cast in place and oriented according to the roofing direction. A more straightforward precast method is seen in the SAP© trusses (Fig. 2a), which consist of inclined SAP© slabs formed from precast beams placed side by side, with additional reinforcement extending into the sealing ribs, which are then saturated with concrete castings [8]. Another system is the BISAP© trusses (Fig. 2b), comprising precast panel elements 0.80 m wide, with additional reinforcement for negative bending moments at the supports and roof ridge, incorporated into the sealing ribs and saturated with concrete castings. Finally, the CELERSAP© trusses (Fig. 2c) represent a system with the lowest level of precasting. These trusses are composed of prestressed concrete joists and intermediate brick blocks bonded with concrete casting, with additional reinforcement for negative bending moments. These solutions can span from 7 m to 14 m, with thicknesses ranging from 0.08 m to 0.20 m.

Additional systems include barrel vaults. The SAP© vault (Fig. 3a) consists of reinforced brick beams (approximately 5.00 m long) that form the elements of individual arches, placed side by side and bonded with concrete casting. The heads are constrained by longitudinal reinforced concrete ribs (0.30 m to 0.50 m wide). With circular shapes ranging from 0.08 m to 0.20 m thick, these vaults can cover 8 m to 30 m [9]. Subsequent productivity demands led to the development of the BISAP© vault (Fig. 3b), a system consisting of BISAP© panels (0.80 m or 1.20 m wide) shaped with a curved profile to form the vault segments. In-situ casting is limited to the sealing ribs between the panels, which are reinforced along with the spring connections. With thicknesses between 0.12 m and 0.24 m, these vaults can span between 8 m and 30 m and achieve a productivity rate of 1000 m²/day per crane.

Further advancements in precast are represented by the PANSAP© vault (Fig. 3c), which consists of 1.20 m wide BISAP© panels spanning the entire width. These vaults are finished with plaster on the intrados and range in thickness from 0.13 m to 0.25 m, covering spans from 8 m to 30 m. The ST'AR© vault (Fig. 3d) completes the range of roof structural systems, characterised by a system not based on precast elements but rather on the industrialisation of the mobile ribbing system. The essential components include special hollow bricks joined together at the top and supported by joists at the bottom. This system is designed for day-to-day work, allowing for the stripping and sliding of the rib. An interesting variant, the "conoid", creates a surface formed from a straight line with a slope of no more than 35%, moving along parallel arcs with different arrows. The scaffolding for this variant consists of fixed ribs with varying curvatures, spaced 2.00 m apart and connected with wooden joists spaced approximately 1.00 m apart. This variant, with north-facing skylights, achieves unilateral and dif-

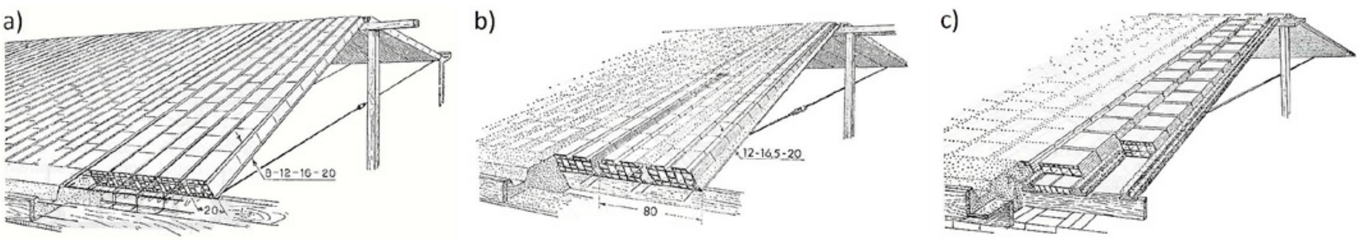

Fig. 2. *Eliminated thrust truss system: (a) SAP© trusses; (b) BISAP© trusses and (c) CELERSAP© trusses. Source: [8].*

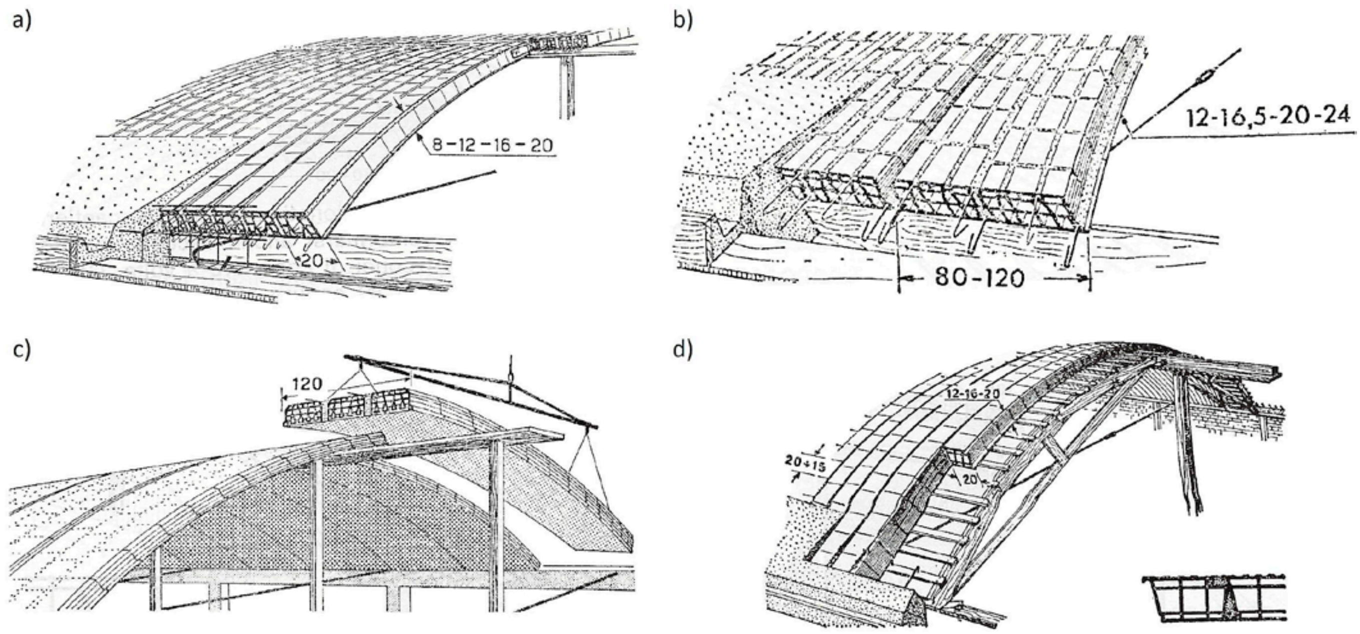

Fig. 3. *Barrel vault systems: (a) SAP© vault; (b) BISAP© vault; (c) PANSAP© vaults and (d) ST'AR© vault. Source: [8].*

fuse lighting. The ST'AR© vaults have thicknesses ranging from 0.12 m to 0.20 m and can span 8 to 26 m, while the conoid version covers spans from 8 to 20 m with similar thicknesses.

Membrane vaults represent a more complex category of structural elements in concrete. This category includes thin structures that lack flexural rigidity, do not resist shear forces perpendicular to the tangent plane, and remain undeformable under compressive and tensile stresses. It also includes hyperbolic paraboloid shells, corrugated vaults, double-curvature vaults, and beam vaults.

Hyperbolic paraboloids (Fig. 4a) are elements where the pitch is generated by the translation of a straight line that rests on two slanting directrices located in two parallel vertical planes. The generators are formed with precast reinforced brick joists spaced 0.20 m apart or with precast brick panels spaced 0.40 m to 0.80 m apart, featuring a slightly rotated straight axis. A collaborating slab, 0.03-0.04 m thick, is always provided. There are at least three construction solutions, depending on the configuration of the uprights. These structures have thicknesses ranging from 0.08 m to 0.16 m (excluding the slab) and a rectangular shape with maximum sides of 10 m to 40 m.

Another type is represented by corrugated vaults (Fig. 4b), constructed with precast joists or brick panels. The cross-section of these structural elements resembles a split unified by the reinforced upper collaborating slab. The long side of the vault varies from 30 m to 50 m with thicknesses of 0.12 m to 0.20 m, while the short side ranges from 2.50 m to 3.50 m. The main static behaviour is equivalent to a two-hinged arch with eliminated thrust.

The category of membrane vaults also includes double-curvature vaults (Fig. 4c). Geometrically, these are generated by an arc of a circle on a vertical plane that translates along another arc of a circle in a plane normal to the first. For aesthetic reasons and static simplification, the arrow of the long arch is set at 1/10 of the span, while the arrows of the side arches are equal. From a structural point of view, ST'AR© blocks on movable ribs or BISAP© panels are used. Perimeter Vierendeel arches replace the metal joints, with the lower flap acting as a tie rod, allowing support only on four pillars. Spans range from 10 m to 50 m with 0.12 to 0.16 m thicknesses.

A final type of membrane vault is represented by beam-vaults (Fig. 4d). These cylindrical vaults do not use continuous support along the spring generators but rely on terminal and, if necessary, intermediate lines. Geometrically, the most commonly used type has a ratio between longitudinal and transverse dimensions greater than 1.5. The cross-section can take on different shapes, with loads transmitted to the edge beams by gables or rigid arches shaped according to the cross-section.

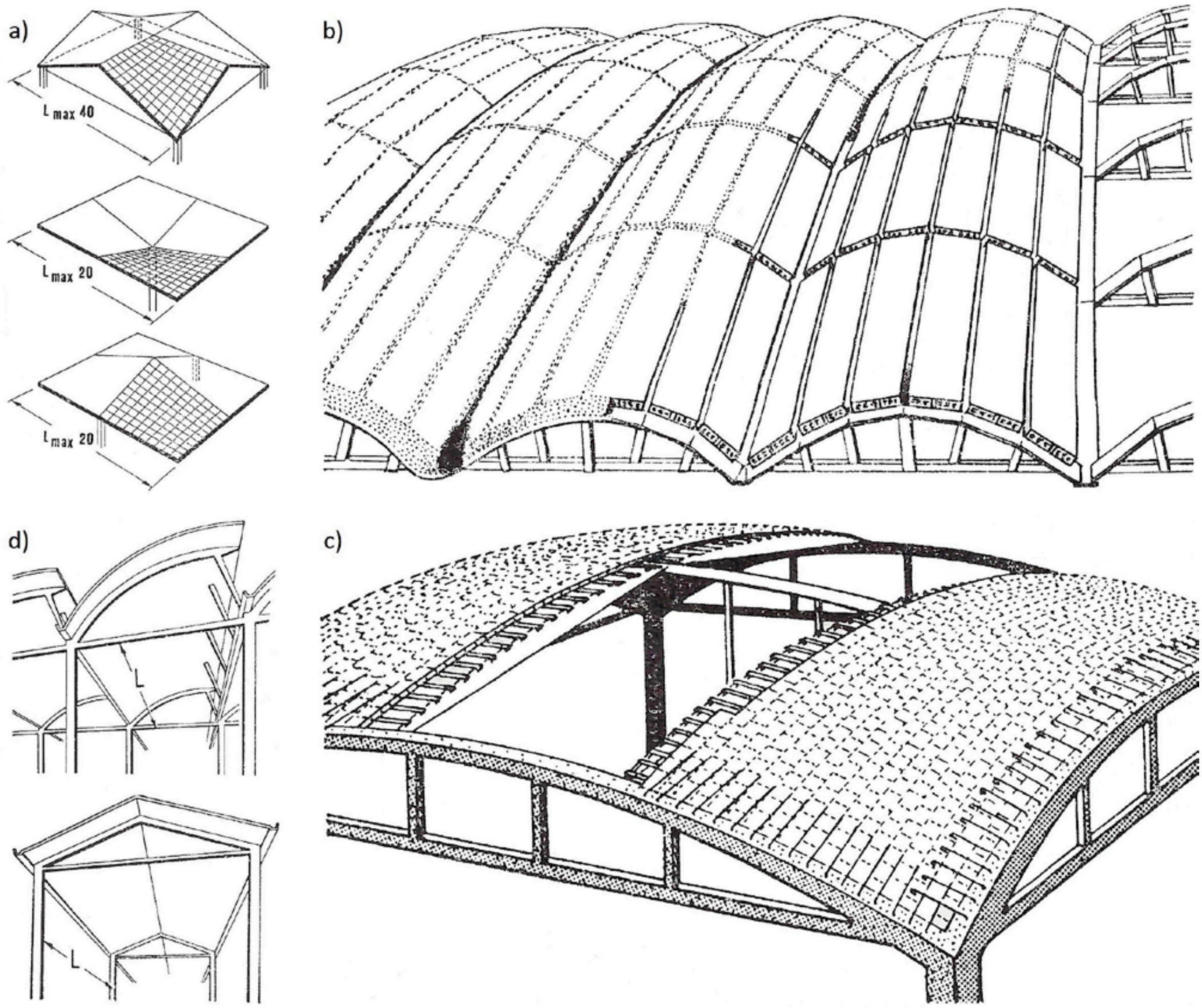

Fig. 4. *Curved surface shells: (a) hyperbolic paraboloids; (b) corrugated vaults; (c) double-curvature vaults; (d) beam-vaults. Source: [8].*

The previous systems were gradually abandoned starting in the early 1960s, as prestressed concrete technology reached a high reliability standard. Double-slope beams (usually with a 10-12% slope, also known as variable-height or delta beams) and double-T were produced based on existing German models [10].

The spread of precast construction during these years was also favoured by the significant development of the highway system, which substantially increased the production of factories located near major highways. The typical span of these beam systems ranged from 12 m to 24 m, with special series capable of spanning up to 30 m. The pitch of the beams was determined by the size of the roofing elements, which initially consisted of hollow brick slabs with spans between 6 m and 9 m or innovative prestressed components with an omega cross-section or pi-shaped profile. These double-ribbed panels, with widths of 1.20 m and 2.40 m, were optimised for road transport within the 2.40 m limit gauge. The structural grid dimensions were greatly expanded with these components, allowing spans from 12 m to 16 m. Omega slabs had a distinctive feature: they included reinforcement and supplementary castings, enabling them to be constrained in continuity with rectilinear beams, resulting in flat roofs where the slope (1-2%) was achieved by inclining the main beams. In contrast, the two-rib elements (Pi-shaped beams) were designed to form channels for collecting rainwater. These components were alternated with hollow areas covered with skylights to achieve natural zenithal lighting. These beams have a closed section, so they were secured with simple constraints, relying on weight and friction to resist horizontal forces [11].

2.2. SHED

Another solution commonly used in industrial construction was based on shed roofing systems. This approach was implemented in four configurations: macrosheds, simple sheds, double sheds, and Z-shaped roofs.

Macrosheds (Fig. 5a) consisted of rectilinear Prestressed Reinforced Concrete (P.R.C.) beams placed at an incline on pillars with double support seats. These systems typically spanned 10 m to 16 m, with inclined elements made from hollow brick slabs, which limited the spacing of the portals to 6 m to 10 m.

Another category was the simple shed (Fig. 5b), characterised by 7.5 m spaced piers with forked heads supporting prestressed concrete beams. These beams had pockets spaced 4 m apart to receive knee-high reinforced concrete beams. The structural grid in these systems typically had dimensions of 7.50 m by multiples of 4 (typically 12 m).

An evolution of this configuration is the double shed (Fig. 5c), where the primary difference is an increased distance of 12 m between the main elements. The prestressed concrete beams in this system support trusses that create the double shed configuration.

The final category is represented by Z-shaped roofs (Fig. 5d). This system's pillars are spaced 6 m to 7 m apart and support rectilinear beams spanning 20 m. At 4 m intervals, these beams carry double-knee secondary beams on both the lower and upper wings. In all configurations, the pitches are constructed using hollow brick slabs with a 4 m span.

2.3. COMPLETE PRECAST SYSTEMS

The previous systems persisted throughout the 1970s until improvements in basic materials – primarily concrete and admixtures – refined industrial manufacturing processes, and the emergence of computer tools for calculation and design impeded new construction solutions.

By the late 1980s, the market had expanded significantly, with over 250 companies registered under Assobeton in the precast structures category, specialising solely in industrial buildings. These companies were primarily located in central and northern Italy, particularly in Lombardy, Emilia-Romagna, and Veneto – the regions with the highest levels of industrialisation. Production was typically organised into complete systems that included foundation elements, columns, beams, floors, and specialised roofing components [12].

What characterises production in the late 1980s and early 1990s is the emergence of specialised roofing components, such as winged slabs inspired by the original Silberkuhl and microsheds, which are noted for their reduced thicknesses, a return to partial membrane behaviour, and increased formal variety. This production was made possible by the high standards achieved in ordinary concretes, the development of self-compacting concretes that eliminate the need for vibration, and the use of superplasticizing additives and fibres – first metallic and later synthetic [7].

Self-supporting formwork increased the speed of production related to the curing of the mix, eliminating the need for rigid prestressing tracks and heating them with

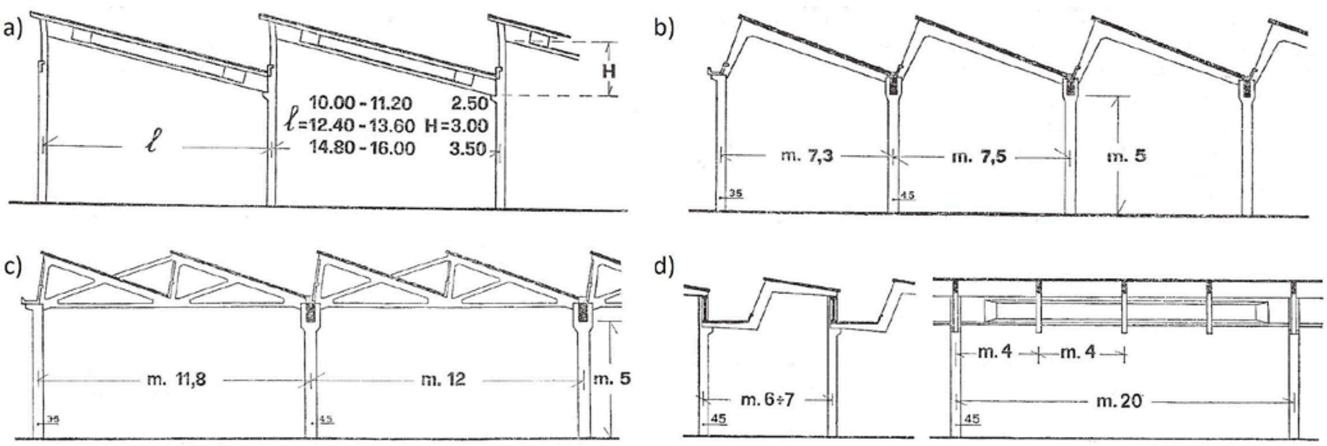

Fig. 5. *Shed system: (a) macroshed; (b) simple shed; (c) double shed; (d) zeta roofs. Source: [8].*

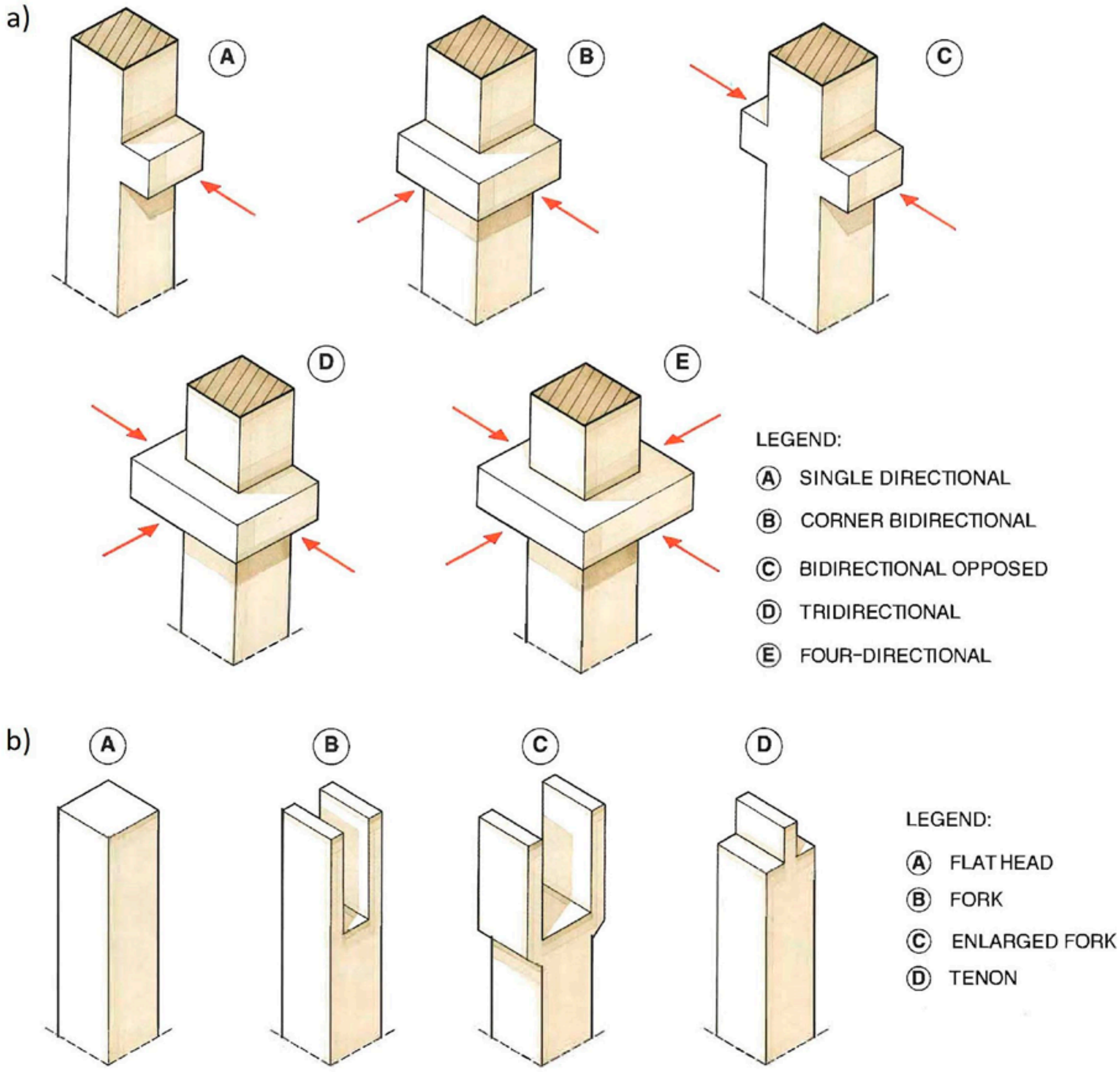

Fig. 6. *Morphology of (a) brackets and capitals, and (b) pillar heads. Source: [23].*

steam input [13]. Additionally, the finishing and accessorising of products at the plant were improved, effectively turning the construction site into a dry-assembly-only operation, significantly benefiting the overall construction process [10]. Seismic concerns were addressed by partially moving away from the trilithic system, using metal retaining inserts for horizontal components [14].

The foundation plinth receives the abutment in a socket, and subsequent grouting creates the only joint in the construction that can be likened, at least partially, to an interlock. The socket can be ribbed to counteract strong moments at the footing. If the sole size exceeds transport limits or to counteract excessive punching of the abutment, the sole socket may be precast and connected to a cast-in-place slab before casting [14].

Abutments, whose standard sections have minimum sides of 0.30 m with increments of 0.05 m, are not typologically classifiable but are designed according to the specific application. The typical pillar sections are square, while the H-section is used only when horizontal infill panels are planned to be inserted into the recess. This solution was widely practised until the 1970s but was gradually abandoned as the negative effects of thermal bridging caused by through-columns became apparent. At the intersection with horizontal structures, including bridge carriages, the abutment may have tapering, brackets, or capitals to allow for one to four beam connections (Fig. 6a). A notable feature is the head of the abutment, which may be flat, forked, or tenon-shaped to provide support and stability for the uppermost beams (Fig. 6b).

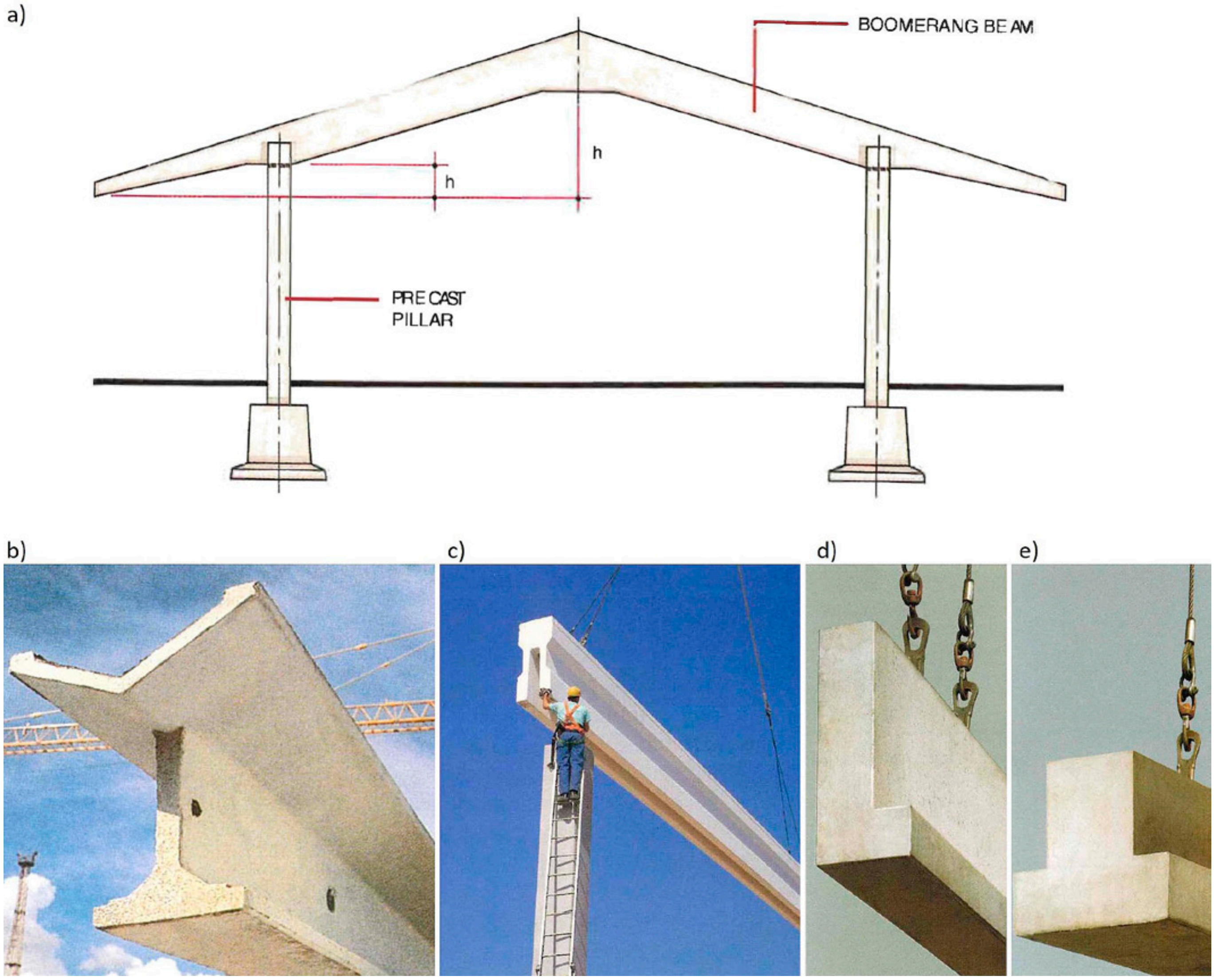

Fig. 7. *Types of beams: (a) boomerang beam; (b) Y beam; (c) H beam; (d) L beam, and (e) inverted T beam. Source: [23].*

Unlike plinths and piers, beams are not used indiscriminately; different types are employed to address specific structural requirements in conjunction with appropriate deck or roofing components. The production of double-sloped beams continues, including variants with lower slabs, although their usage has been gradually declining in favour of more versatile straight beams. In both double-slope and parallel flange variants, lattice girders have limited application due to the imperfect compatibility between the concrete material and the tensioned members, which sometimes necessitates prestressing [15].

An example of beam evolution is the "boomerang-shaped" beam utilised for open sheds (Fig. 7a). Other forms include Y beams and H-beams (Figs. 7b and 7c), prefinished with waterproofing layers and commonly referred to as channel beams due to their ability to collect and channel water to designated drainage lines or disposal points. Y-beams can be installed either side by side or spaced apart using thin curved slabs, while H-beams support winged slabs, whose mass production began in the late 1980s and continues to this day.

L and T beams are employed for intermediate flat floors or flat roofs (Figs. 7d and 7e). The L-shaped section addresses asymmetrical edge conditions, whereas the T-shaped section is designed for central bays supporting two adjoining floors of different thicknesses or at varying levels. Achieving continuous ceilings with increased usable height during operation is possible by partially precasting the beams or incorporating a dense metal bracket protruding from the top flange [16].

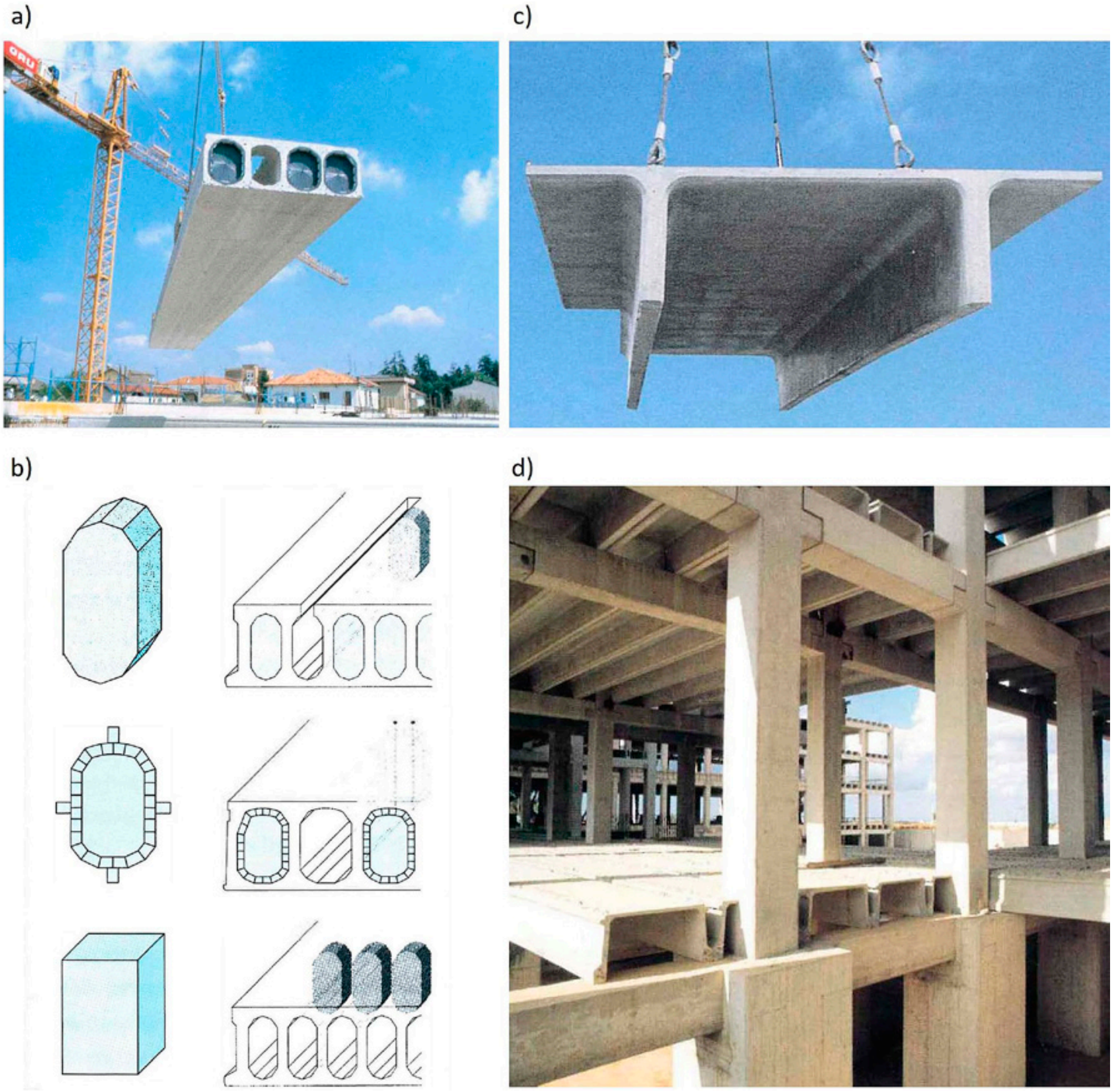

Fig. 8. *(a) Hollow core slabs and (b) diagram of the construction of horizontal lightening voids; (c) Pi and (d) Omega elements. Source: [23].*

Regarding horizontal structures, production categorises products into slabs and decks. A constant thickness characterises slabs, while decks are ribbed solutions that exhibit mixed slab-beam behaviour. In industrial construction, where reducing on-site castings is crucial, mixed panel solutions, as previously mentioned, and hollow core panels are predominantly used for flooring (Figs. 8a and 8b) [17]. The differences between these two products are significant, particularly in load-bearing capacity and design spans, which are limited to 8 m for the former and extend to 15-20 m for the latter.

The use of mixed panels has declined since the 1990s and is now confined mainly to double-pitch roofs on single-aisle buildings. Hollow core slabs, prestressed with pre-tensioned adhered reinforcement, derive their mechanical properties from gradually improving concretes dosed with very low water-cement ratios to ensure immediate shape stability. The ribbed slab family is highly versatile, with design spans ranging from 10 m to 30 m. This category primarily includes Pi and Omega slabs (Figs. 8c and 8d). These are prestressed elements featuring a minimum slab thickness, which has been increased since the 1990s to 0.05 m, with ribs recalculated to form a specific section. A collaborating top slab is used to enhance their load-bearing capacity, and for Omega-slabs, the filling between two consecutive ribs further increases strength. These components' large lateral surface area makes them particularly vulnerable to fire, leading to a significant increase in rib thicknesses following the introduction of UNI 9502:2001 [18].

2.4. SPECIAL ROOF ELEMENTS

In the late 1980s, specialised roof elements emerged on the market, with the aforementioned Silberkuhl serving as a key inspiration [7]. These structural components were designed specifically for terminal solutions of large spans, ideally ranging between 15 m and 30 m. Beyond their functional roles – such as providing lighting, thermal insulation, and water drainage – these elements also represent a shift toward finding formal solutions that give industrial buildings more identity, moving beyond mere functional containers.

This period marked significant advancements in industrial precasting, with all major companies striving for product customisation and offering at least one type of *roof slab*. By the late 1980s, nearly a hundred different types were available. The term *wing element*, derived from the distinctive shape of various cross-sections, aptly describes this category of roof slabs. These elements refine the aesthetics of support and intersection details with other structural components and optimise internal volume by reducing parasitic volumes and enhancing structural performance, as evidenced by the ratio of self-weight to load-bearing capacity.

Generally, wing elements consist of a central longitudinal prestressed core and two raised wings, which are not necessarily symmetrically reinforced and have a limited thickness of 0.05-0.08 m. The use of special formwork, self-compacting concrete, and, later, introducing fibres into the mix for the wings were crucial in maintaining these reduced thicknesses while eliminating complex secondary reinforcement, thereby allowing for greater formal flexibility. Shaped support saddles on the end beams enable different solutions based on the varying rotations of the component's vertical axis.

From a construction efficiency standpoint, the width of the roof slab is standardised at 2.50 m to take advantage of road transport limitations. It is worth noting that each transport load can supply approximately 150 m² of fully prefinished roofing, including the subframes of any window assemblies, with a potential installation rate of around 600 m² per day, assuming a 3-hour radius from the factory. Production in the 1980s and 1990s can be classified into wing elements, composite sheds, and microsheds [19].

Generally recognised by their V-shape, wing elements are characterised by the close relationship between design shape and static behaviour. The prolific production of these components can be statically classified according to their flexural behaviour along the longitudinal axis and the combined torsional actions due to the wings. The following types can be identified (Fig. 9a): a) single-rib elements with a solid core or closed box-type configuration, where tangential stress flow develops torsional resistance; b) two-rib elements, where torsional actions are resolved into two opposing flexural actions applied to the longitudinal ribs; c) box systems of three or more non-converging slabs, where torsional actions are decomposed into a complex combination of bending in the individual slabs; d) star systems of slabs with V or Y profiles, or similar, converging at a single axis, where torsional action is decomposed into torsional moments within the individual slabs; e) specially shaped elements, including unique solutions such as thin vaults and hyperbolic paraboloids [20].

Another classification of winged slabs can be made based on their arrangement in the composition of the roof. Winged slabs can be arranged as follows (Fig. 9b): a) juxtaposed for blind roofs; b) alternated with lightweight single- or double-walled translucent slab elements to form zenithal skylights; c) alternated with thin curved concrete or micro ribbed sheet metal slabs; d) spaced with the insertion of plates or connecting concrete slabs to achieve a shed configuration, resulting in so-called composite sheds [20].

As previously mentioned, microshed types can be obtained by rotating the winged slab, installing shaped support saddles, or using specific elements designed with asymmetrical wing sections (Fig. 9c). The production of microshed components has led to a market upswing for this type of roofing, offering remarkable improvements in the natural lighting of production spaces. These systems provide diffuse lighting modulated over a 2.50 m span, which performs much better than traditional shed solutions that require glazed surfaces to be positioned on the pitch of the vertical structures, necessitating the production of beams with complex geometries [20].

Initially, skylights were limited to widths of about 0.40 m, but they now reach widths of 2.00 m to 2.50 m

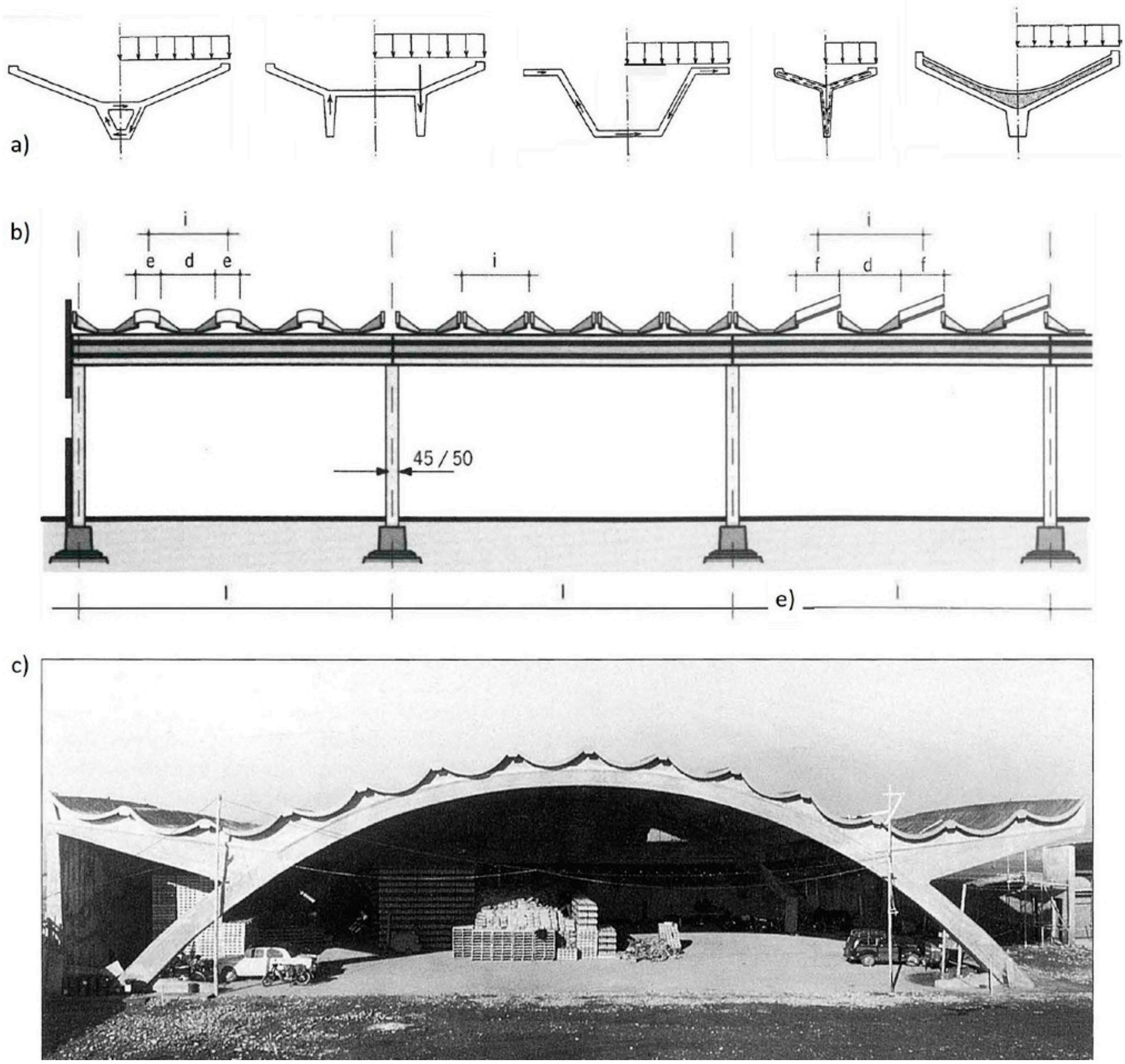

Fig. 9. *(a) Wing types and diagram of overall flexural behaviour and torsional actions on wings; (b) diagram of different wing layouts (spaced, juxtaposed or alternating); (c) historical image of roofing made with microsheds. Source: [23].*

using structural polycarbonates, with ratios of blind surfaces to translucent surfaces ranging from approximately 20% to 50%. This change has led to obvious benefits in terms of foundation loading as well. The dimensions of the skylights help compensate for dimensional tolerances in design, production, and assembly. Microshed types now also allow for the energy upgrading of existing industrial buildings by incorporating solar absorbers on the soffit of the elevated wing, which typically has its blind side facing south or southeast [20].

Winged slabs and microsheds utilise the double slope created by prestressing and the variation in the central core to dispose of stormwater laterally, necessitating their coupling with channel beams, preferably of the H-section type. Non-optimal support on inverted I, L, and T beams requires additional on-site work to create impermeable channels. In such cases, the level of industrialisation achieved through total factory precast – often including insulation and waterproofing agents within the forming cast – is partially reduced.

The production of winged slabs has altered the module of rectangular structural meshes. Previously organised with double-sloped or straight beams on the long side (12-30 m) and floor components on the short side

(8-12 m), these systems are now designed with H, I, L, or T beams on the short side (10-12 m) and slabs on the long side (15-25 m).

3. THE WALL PANELS

As is well known, the wall panels realise the internal-external boundary and take on different values regarding the formal connotation of the project, their physical-technical performances, and their static performances, including their self-supporting in the absence of deformations and/or cracks, their capacity to transfer actions to the structure, and their safety against detachment in the case of special events such as impacts and earthquakes [21].

In contrast to housing, where load-bearing partition systems are developed, the wall panel has the exclusive function of enclosing the frames in industrial construction. The wall panel subsystem, despite its obvious intersections with the structural subsystem, therefore, constitutes a field in itself that responds to completely autonomous performance, aesthetic, and functional criteria [22].

The development of the wall panels in the period under examination presents three phases: the first includes the 1950s and 1960s, the second is typical of the 1970s and partially of the 1980s, and the third crosses the century to the present day. The three phases represent the progressive development of material and production technologies, adaptation to standard updates, especially in the energy field, and changes in the formal sensibility of designers [8]. Industrial wall panels are geometrically two-dimensional rectangular slabs whose primary material is reinforced concrete; regarding the longest side, they can be positioned horizontally or vertically.

In the first phase, brickwork still prevails for lightening and providing a minimum of thermal insulation, which is incorporated in the casting. The production phase takes place on horizontal formwork, whereby the process comprises the following steps: reinforcement and casting of the first 0.02 m concrete layer; positioning of the bricks; reinforcement of the internal stiffening ribs and the second layer; completion of the casting with the 0.02 m layer for total thicknesses of 0.14-0.20 m and lengths of 4 to 8 m (Fig. 10a) [8].

Vertical formwork, also in series, produces load-bearing solid slabs. The presence of ribs considerably reduces the insulating capacity of the panel, favouring the typical phenomena of thermal bridges. Hollow brick panels are preferably of the horizontal type and, concerning the columns, can be positioned in front or inserted in the span. In this case, the pillar takes on T or H sections. Since a maximum of two panels of module 1.20 or 2.40 m can be installed, the possible infill heights are 2.40, 3.60, and 4.80 m. The finishing up of the edge beams is generally achieved through glazing. The vertical hollow brick panels (with a short supporting side of 1.20 m and thickness of 0.18 m) reach 8.50 m. For greater heights (up to a maximum of 10 m), a solid concrete panel with a reduced thickness of 0.13 m and two reinforced side ribs of 0.20 m thickness is used. The finishing of the hollow brick panels is limited to the eventual clay floor covering for the external surfaces. In the vertical ribbed panels, the clay is positioned between the ribs, which always remain in exposed concrete. For this type of panel in the 1960s, production technology allowed the first experiments with specially washed grits in white or coloured marble; the internal finish is always in plastered mortar.

In the second phase, the hollow brick panel solution is progressively abandoned for concrete slabs lightened with polystyrene layers of low specific weight (12-15 Kg/m^3). The internal ribs, for panels of standard widths of 2.00, 2.40, and 2.50 m, fill the external perimeter and divide the length at the lifting inserts and in any case so that the distance between the ribs does not exceed 40 times the thickness of the polystyrene (Fig. 10b). It is indifferent whether they are used horizontally or vertically, but even more evident for the through-ribs is the criticality of these components with respect to the thermal performance of the envelope. Ribbed panels allow significant heights since, where necessary, prestressing is applied to the ribs. Regarding external finishes, there is a certain general regression as clients, for reasons of economy, tend to prefer the grey exposed concrete panel, thus slowing down research into different production technologies [23].

The third phase, which began at the end of the 1980s and continues to the present day, sees at least three guidelines for the development of components: the improvement of thermal performance, research into formal characterisation and the approach for free geometries to be combined with other materials [24]. In the mid-1990s, C.E.N., (*Comitato Europeo di Normazione* - European Committee for Standardisation) within the Technical Committee *Precast concrete products*, activated Task Group 8 Wall elements, dedicated to this category of precast products, which will produce the European reference standard for Italian product quality regulations. In this context, it is definitively established that the "lightened" panel with low-density polystyrene layers and through-ribs (which, for environmental reasons, has replaced polystyrene) does not have the thermal performance that sandwich-type multilayer panels with thermal break and aerated panels can guarantee. In industrial construction, where load-bearing walls are not used, a specific product is employed: the lightened sandwich panel. This design incorporates lightweight layers into the internal concrete section while maintaining the thermal break, which would otherwise serve a load-bearing function (Fig. 10c) [23]. The complex stratigraphic articulation of the panels is also enabled by the considerable development in recent years in the production of metal inserts intended for the various connections. The increasing height of the panels also imposes greater attention on the minimum thicknesses of the slabs, 0.06 m for the outer protective ones and 0.08 m to 0.30 m for the inner load-bearing ones. The insulation thickness, min 25 kg/m^3, generally does not exceed 0.20 m to avoid excessive torsional effects between the concrete slabs.

Surface finishes, which define the material appearance of the panel, exploit the possibility of colouring the conglomerate with oxides, introducing surface layers of marble grits of various kinds, shaping the concrete with matrices, and applying different materials. Also significant here is the contribution made by developing production technologies for processing castings before and after their solidification. In summary, processing on panels, whose exposed face can be the one in contact with the formwork or the one above the casting surface, can be divided into:

- formwork finishes without further processing after the formwork: pigmentation of concrete, preparation of formwork bottom of matrices to give relief patterns to the face, "fresh" treatments with mechanical intervention on the non-solidified mix (scratching) [25];
- off-site formwork finishes, that is, performed after the formwork has been broken down with specific equipment: washing with a waterjet, sandblasting and matriline work with a jet of varying power of metal microspheres, sanding with a "polished" effect obtained by passages of diamond wheels, acid etching bath, chemical treatments with the application of a liquid film that alters the visible surface at will, and silk-screen printing obtained with numerically controlled machines that etch the conglomerate, reproducing any image. The different work processes can also be combined on the same panel [19].

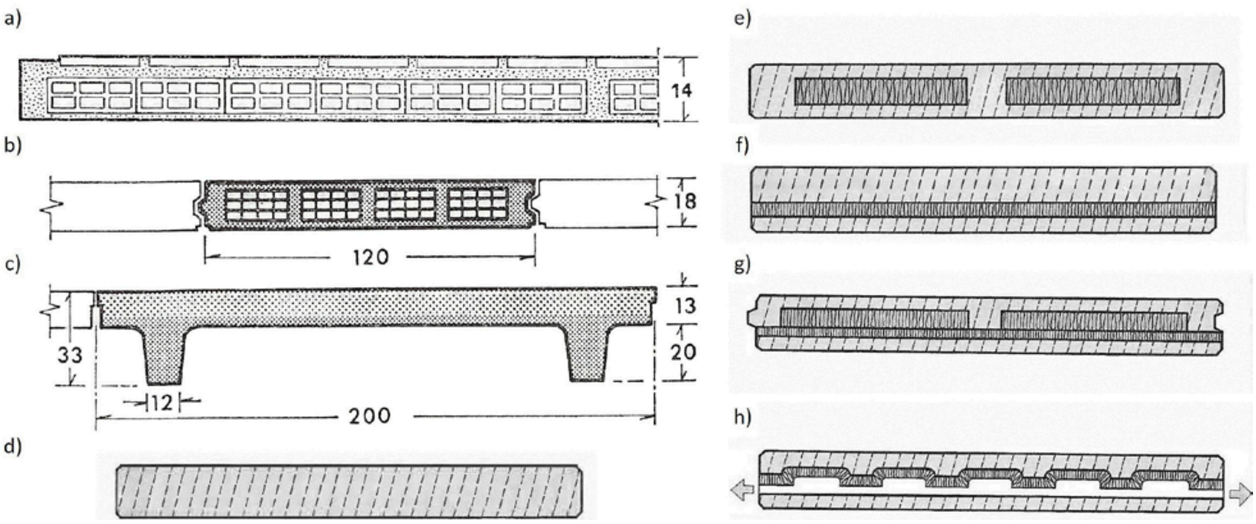

Fig. 10. *The wall panels: (a) horizontal hollow clay block panel; (b) vertical hollow clay block panel; (c) ribbed panel; (d) monolithic panel; (e) lightened panel; (f) sandwich panel; (g) complex panels with lightening of the load-bearing slab and (h) presence of air gaps. Sources: a-c: [8]; d-h: [23].*

4. CONCLUSIONS

The industrial construction sector has served as a testing ground for precast techniques. Following World War II, there was a gradual shift from metallic solutions to those employing prestressed reinforced concrete. This experimentation was driven by the proliferation of large industrial entities capable of introducing new technical solutions to the market.

Initially, the industry used hollow blocks to create elements supporting large spans, eventually progressing to complex vaults made of brick and thin concrete. This process allowed of most construction work to be precast, with only finishing touches required on-site. From the 1980s onwards, improvements in materials and infrastructure led to the development of fully precast constructions, eliminating the need for on-site work. This shift was particularly notable in developing structural components such as foundations, columns, beams and roofing elements, as well as the introduction of new products like winged slabs and micro shreds.

Alongside the evolution of structural systems, it was essential to outline the evolutionary path of wall systems, which transitioned from massive brick-based solutions to lightweight elements consisting solely of concrete and insulating material. This transition addressed the demands for versatility and the high thermal performance characteristics required in contemporary buildings.

The discussion presented in this article is situated within the context of the gradual rediscovery and new evolutionary impetus for prefabrication in industrial construction in recent years. The overview of construction systems provided here contributes to the ongoing debate in two ways. On the one hand, the knowledge of precast techniques has been fundamental in restoration projects aimed at preserving the historical and technical significance of built artefacts. On the other hand, the increased digitisation of the design and construction process has enabled the realisation of highly complex structures using the precast systems developed between the post-war period and the end of the 20th century, adapting them to the new technical and aesthetic requirements characteristic of 21st-century architecture and construction. These aspects demonstrate the resilience and adaptability of precast concrete elements in the face of evolving architectural demands, highlighting their pivotal role in shaping the future of sustainable and efficient building practices.

Authors contribution

The research presented in this contribution is the result of a collaborative effort. The individual contributions of the authors are as follows: Conceptualisation and supervision, E.D.; Investigation, E.D., S.P, and C.V.; Writing-original draft preparation, review, and editing, S.P. and C.V.

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