The great era of thin concrete shells is probably nowadays over, at least in developed countries where the construction costs render this kind of structures uneconomic to build and where they appear obsolete from the point of view of the present day architectural tastes. It should nevertheless be pointed that this construction technique is an important legacy in the history of concrete construction and structures. It was an attempt to cover large spans with the most widely used construction material of the Twentieth Century and yielded structures that are now regarded as architectural masterpieces. The design of thin concrete shells also fostered theoretical developments in structural analysis, in the mathematical theory of shells and in the theory of finite elements.

We may distinguish roughly two periods in the history of thin concrete shells: a period of precursors before the Second World War with eminent engineers such as Eugène Freyssinet (Fernandez Ordoñez 1979) in France and Eduardo Torroja (Torroja 1958) in Spain, and a period of blooming development after the war which ended abruptly in the 1970s, except for some kinds of industrial structures like cooling towers and offshore platforms.

In Belgium, the key figure in the design, construction and popularisation of concrete thin shells was certainly André Paduart (1914–1985). This paper endeavours to record all major thin concrete
shells designed by André Paduart and to describe their originality in the context of the history of thin concrete shells.2

A SHORT BIOGRAPHY OF ANDRÉ PADUART

André Paduart was born in Dover (G. B.) on November 4, 1914. He was educated in Ostend (Belgium) and graduated in civil engineering from the University of Brussels in 1936. After some months of employment with a naval construction yard at Hoboken (Belgium), he joined in 1937 the staff of engineers of SECO in Brussels, an office founded in 1934 by the insurance companies in order to enforce the technical control of the constructions. All plans of major and innovative structures in Belgium were and are still submitted to the approval of SECO before the beginning of their construction. For example, during the war years, Paduart was associated with the testing of the first prestressed concrete structure built in Belgium.3

He only became involved personally in structural design in 1944 when he joined as technical director the engineering company SETRA (Société d’Etudes et de Travaux), which was at the forefront in the application in Belgium of the new developments in concrete construction like prestressed concrete and thin concrete shells.

In 1946, Paduart presented a Ph.D. dissertation on the shear strength of reinforced concrete at the University of Brussels, and became in 1954 professor of civil engineering at his alma mater. He then left SETRA, but kept a private consulting practice, leading to the foundation of the structural engineering office SETESCO in 1957. At the head of this office up to his death in 1985, he designed or supervised the design of hundreds of buildings, bridges and other constructions.

From the mid-1950s to the mid-1960s, Paduart was a pioneering member of the Comité Européen du Béton (CEB) and of the Fédération Internationale de la Précision (FIP), especially working in the committees on shear of these international associations.

André Paduart was also and particularly an active member of the International Association for Shells Structures (IASS) founded by E. Torroja in Madrid in 1959. He was a member of the Administrative Council of this body since its foundation and organized in Brussels in 1961 one of the very first symposia of this association (Paduart and Dutron 1962).


In 1965 Paduart received a special commission from the HAMON Company, which was and still is worldwide known for the design of cooling towers. The HAMON Company wanted Paduart to review the problems associated with the design and construction of large reinforced concrete hyperbolic cooling towers (Paduart 1968a, Paduart 1968b). Interestingly, it should be noted that this assignment occurred some time before the well known accident at Ferry Bridge (U. K.) on 1 November 1965 which saw the collapse in less than an hour of three large hyperbolic cooling towers under wind loading. With the support of the HAMON Company, Paduart gathered around him an international team of experts, which eventually became the Working Group 3 of IASS in 1970. Between 1970 and 1980, Paduart was the chairman of this WG3 and organized in Brussels two colloquiums on the subject (1971, 1975). The IASS WG3 issued its recommendations on the design of hyperbolic cooling towers in 1977 (Paduart 1979).

Meanwhile, in 1971, Paduart had been elected as 3rd president of IASS (after Torroja and Haas). He remained in that position until 1980. On the same year, he became honorary professor at the University of Brussels. In 1984, the IASS awarded him its prestigious Torroja medal.4

André Paduart passed away in Brussels on February 27, 1985.

NOTABLE CONCRETE SHELLS DESIGNED BY ANDRÉ PADUART

Cylindrical barrel vaults at Antwerp Harbour

Cylindrical barrel vaults have probably been the most used form of concrete shells. «The reconstruction after the devastations of the Second World War required forms of building which offered economy of material. This gave an enormous boost to the use of shell roofing in Britain as well as continental Europe,
since materials, particularly steel, were in short supply everywhere (Morice and Tottenham 1996). The economy in construction, not the architectural value, was the key to its success and popularity of this kind of constructions. This explains certainly why the SETRA construction company was awarded the contract to build nearly 50,000 square meters of warehouses at the docks of Antwerp harbour between 1947 and 1950 (Paduart 1950; Wets and Paduart 1954; Shell roof construction in Belgium 1952).

At the Albert dock, in front of quays 105, 107 and 109, SETRA built in 1948 a large shed 465 m long by 60.6 m in width. The shed consists of 31 bays, each covered with a self-supporting cylindrical shell spanning 15 m with a rise of 3 m (Figure 2). The thickness of the vaults varies between 8 cm at the crown to 12 cm at the springing. Each vault is pierced with a large rectangular opening 40 m by 3 m to provide natural lightning. The bays were constructed one after the other by reusing the same centering and holding back the outward thrust with temporary ties. The rate of construction reached one bay per week. Particular features of this construction were the absence of permanent internal tie rods, the absence of edge beams, and the absence of any expansion joint along the entire length of 465 m.

These sheds built at Antwerp by Paduart and Wets are the only concrete shells of that period in Belgium documented in detail and which were noticed abroad. They were the sole non-U.K. structures presented at the symposium on concrete shell roof construction held in London in 1952. Well-known U.K. specialist designers of the time underlined the originality of this construction in the discussion of the paper presented by Paduart (Wets and Paduart 1954, 222). Years later, the famous French engineer N. Esquillan still mentioned the centering used in Antwerp in 1948 as an interesting example of well-conceived moveable formwork.5

Two similar sheds, each measuring 255 m by 47 m and consisting each of 17 bays spanned by the same kind of shells were built by SETRA at the Leopold dock in 1950 (Paduart 1958). The centering that had been built for the construction of the sheds at the Albert dock was used again.

**Airplane hangars**

Thin concrete shells hangars had already been built during the First World War, notably by Freyssinet (Fernandez Ordoñez 1979) but a significant breakthrough was achieved with the construction of the two celebrated huge airship hangars built by Freyssinet at Orly in the early 1920s (Freyssinet 1923). On this occasion, the principle of the corrugated form for the concrete shell was introduced to obtain the necessary stiffness required to span 70 m. Freyssinet also applied the same principle of corrugated shell roofing for the construction of two airplanes hangars spanning 55 m at Villacoublay in 1924 (Gotteland 1925; Fernandez Ordoñez 1979).

In the late 1940s, free spans slightly exceeding 100 m were achieved with thin concrete shells for roofing airplane hangars. The state-of-the-art led to radically different solutions in the U.S. and in Europe. In the U.S., the record span (103 m) was obtained with the two hangars designed by Roberts and Schaefer Company and built in 1948–49 at Limestone (Maine) and Rapid City (South Dakota). The free surface covered by each hangar is 10000 square meters. The form is basically a 13 cm thick cylindrical shell stiffened at the extrados by external ribs (Allen 1950; Tedesco 1950). In France, the record span (101.5 m) was held by two hangars designed by Esquillan and built at Marignane (Esquillan 1952; Marrey 1992). The structure is much more delicate and appealing. Each hangar (101.5 m by 60 m) is covered by six arch shells 6 cm thick with double curvature. Prestressed ties equilibrate the thrust of the arches. The hangars at Marignane were achieved in 1952, but they were basically designed in 1942 (Esquillan 1952).
In 1950, SETRA received the commission to build thirteen identical hangars on several military airfields in Belgium. Although the blueprints from 1950 mention Birguier as consulting engineer, the authors, who have known Paduwart very well, believe that the driving force behind the design of these hangars was Paduwart and Wets. Paduwart mentions these structures with a rare discretion—perhaps because they were military constructions—in only one of his publications (Paduwart 1958). The dimensions of these airplane hangars were 60 m (span) by 40 m (depth). Each roof consisted of 6 corrugated shell arches 6 cm thick spanning 60 m with a rise of 5.73 m, the thrust of each arch being equilibrated by two high strength steel rods (Figure 3). There was no need here for the large record spans of the time, but the design bears certainly some similarity in principles with the hangars of Villacoublay (Gotteland 1925) and Marignane (Esquillan 1952). The hangars were built 1950–1952 at Chièvres (now a U.S. AFB), Beauvechain and Coxyde airfields, but most of them have now been removed or altered. They were certainly bold structures, maybe too bold, because it is known that one arch of a hangar under construction at Chièvres collapsed on June 6, 1951 a few time after decentering. The investigation yielded no explainable reason. On another part, measurements made in the early 1990s on several of the hangars at Chièvres revealed that the arches were significantly deformed.

The "Civil Engineering Arrow" at the Brussels 1958 international exhibition

The sheds at Antwerp and the airplane hangars designed by Paduwart and Wets and built by SETRA were clearly engineer’s structures with a strong utilitarian function. For all his later thin concrete shell
structures, Paduart would always collaborate with an architect.

For the 1958 Brussels international exhibition, Paduart and architect J. Van Doosselaere received an official commission from the Belgian government to design a structural symbol testifying of the «victory of [Belgian] civil engineering over nature» (Paduart and Van Doosselaere 1960). The structure (Figure 4) had to support a footbridge overhanging a 1/3500 map of Belgium where the civil engineering and public works were highlighted. The final structure, which was to be known as the «Civil Engineering Arrow», was a spectacular thin wall (4 cm thick at the tip!) reinforced concrete cantilever beam 80m long with an inverted A-section, balanced by a triangular shell roof with 29m-sides and a thickness of 6 cm (Figure 5). This concrete architectural structure gives a bold impression of equilibrium and «tour de force». This construction, which made Paduart internationally known, has been described in detail by Paduart and Van Doosselaere (1958, 1960). The engineer and the architect jointly received the 1962 Construction Practice Award of the American Concrete Institute for their «Arrow» . The «Arrow» was dismantled in 1970.

**Church in Harelbeke**

The next involvement of Paduart with the design of a thin concrete shell structure was for a church in Harelbeke built in 1966 (Paduart 1968c). The architects were Léon Stynen, Paul de Meyer and André Vlieghe. The structure looks like a truncated pyramid with an irregular hexagonal basis (Figure 6). The inclined bearing walls consist of thin corrugated concrete plane shells 6cm thick. The natural lightning flows from the inclined top through a grid that stiffens the rim of the truncated section.

**Hypar shells**

From the mid-1960s through the mid-1970s, Paduart was associated with the construction of several
The use of such kind of structural form for shell roofing dates back to the experiments by Lafaille (1934, 1935) and the theoretical developments by Aimond (1933, 1936) in the 1930s. The success of this structural form rests for the architect in its appealing aspect, for the structural engineer in its simple structural analysis (under the oversimplifying assumptions of membrane behaviour!), and for the contractor in its economical formwork consisting in a system of straight planks supported by another system of straight lines. This structural form has been especially popularised by the architect-engineer Felix Candela who built numerous hypar roofs in Mexico during the 1950s and 1960s (Faber 1963; Joedicke 1963; Billington 1983). We mention here only two hypar shells for which Paduart was the leading structural engineer, but several others designed by him or under his supervision still exist in the Brussels area.

The first of these hypar shells is a canopy in front of the Institute of Sociology at the University of Brussels (Figure 7). It was built in 1966 and the architect was R. Puttemans (Paduart 1967; Novgorodsky 1969; Paduart 1972). The canopy covers an area of 235 square meters and consists of an assemblage of four HP shells 7 cm thick resting on two inclined supports. The largest dimension of the cantilevered span is 12 m. Although much more pleasing visually, this structure bears some
resemblance in form and dimensions with the experimental shell built by Lafaille in Dreux in 1933 (Lafaille 1934, Lafaille 1935). Halleux (2000, 30) has suggested that this HP shell should be registered on a preservation list as the best example of thin concrete shells surviving in the Brussels area.

Much larger and original is the roof covering the swimming pool in Genk built in 1975 (Paduart and Schiffmann 1976, Paduart and Schiffmann 1977). The architects were I. Isgour and H. Montois. The form originated from a close collaboration with I. Isgour.10 The structure is an assemblage of five HP shells covering a hexagonal area (Figure 8). The entire roof is principally supported on two abutments linked by a prestressed tie lying underground. The free distance between the abutments (longitudinal main axis) is 73.8 m. Transversally, the free overhanging is 36 m. The thickness of the shell is 7 cm and not 5 cm as reported by Paduart at the preliminary design stage (Paduart 1972). Concreting of the whole roof was done without interruption in one day. Visiting the worksite, Paduart saw on one occasion a heavy compressor left standing by the contractor on this delicate shell. This gave him the idea to study the influence of concentrated loads on the behaviour of HP shells, which are generally designed to carry distributed loading only (Paduart and Halleux 1977a, Paduart and Halleux 1977b).

GRANDSTAND OF THE GROENENDAEL HIPPODROME

The last involvement of Paduart with the design of a thin concrete shell was for the grandstand of the Groenendael hippodrome near Brussels in 1980 (Paduart, Schiffmann and Clantin 1985). The prototype of all grandstands of this kind is probably the structure designed by Torroja in 1935 for the Zarzuela racecourse near Madrid (Figure 9). But whereas Torroja used vaults having the shape of hyperboloidal sectors, Paduart and architects from CERAU designed here a folded plate roof (Figure 11). The length of the cantilever (13.5 m) is nearly the same at Madrid (Figure 10) and at Groenendael (Figure 12.) The total length of the Groenendael roof is about 106 m, without any expansion joint (remember the sheds and Antwerp!). The thickness varies from 7 to 12 cm.

Conclusion

Paduart was working at the edge between academia and engineering practice. Although he designed also bridges and buildings, Paduart will probably be best reminded for his contribution in the field of thin concrete shells in which he specialized. His realisations are not numerous but his production during thirty years at the heyday of this construction technique is eclectic with barrel vaults, corrugated shells, hypar shells and folded plates. He could teach the intricate mathematical theory of shells at the university, but used himself very simple methods derived from the Strength of Materials to design his
own shells. This did not deter him from conceiving bold structures, at the limits of the utilization of the materials and construction techniques of his time, but he looked always forward with anxiety to the decentering of the shells, as testified by the careful records of the time-dependent evolution of deflection reported in many of his publications. He achieved international recognition by his pairs, not only for some of his own designs like the «Arrow», but also for the reliability of his personal involvement in international associations like the CEB and the IASS.

ENDNOTES

1. For an introduction to the history of thin concrete shells, especially in the pre-1960 period, see for instance Joedicke (1963), Billington (1983) and Malaragno (1991).
2. For an extended biography of André Padau and the full list of his publications compiled by B. Espion, see Schiffmann et al. (2002).
Contributions of André Paduart to the art of thin concrete shell vaulting

Association for Shell and Spatial Structures (Madrid) no. 86: 57-58.

5. «Un exemple intéressant et bien conçu [d’échafaudage roulant] est celui relatif à une réalisation de 1948 en Belgique (Fig.11)». (Esquillan 1960).

6. «La flèche est contrebalancée par une coque; l’ensemble donne ainsi l’impression d’un tour de force (Fig.181)». (Michelis 1963, 157).


9. The surface of an HP shell is characterized by a negative Gaussian curvature, with two sets of straight or ruled lines.


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