Three Case Studies of Construction History Applied to the Assessment of Engineering Heritage Structures

B. Espion, Y. Rammer

École Polytechnique de Bruxelles, Université Libre de Bruxelles, Brussels, BELGIUM

A. Hellebois

Bureau Greisch, Liège and Brussels, BELGIUM

M. Provost

ORIGIN Architecture & Engineering, Brussels, BELGIUM

Contact: bespion@ulb.ac.be

Abstract

The paper will illustrate the contribution of research into Construction History in condition assessment or residual carrying capacity situations for three old types of concrete constructions. We will address:

- the problem of assessing the actual carrying capacity of "Hennebique" reinforced concrete type beams with their characteristic reinforcement system, widespread in many countries before the First World War.

- the replacement of the external post-tensioning tendons within a hollow box girder railway bridge built in the early 1960s with the "Blaton-Magnel" anchorage system developed in Belgium from 1941 onwards, and used until the early 1960s, in Belgium and abroad.

- the structural assessment of thin concrete hyperbolic paraboloid shells, which were highly popular with architects and engineers in 1950s-1960s.

Keywords: reinforced concrete, prestressed concrete, post-tensioning, bridges, thin concrete shells, hyperbolic paraboloid, assessment, engineering heritage.

1 Introduction

When a structural engineer has to evaluate the carrying capacity of an old concrete structure in view of extending its service life, or even a change of function, he is first faced with the issue of documentation on the structure studied, in particular looking for information about the materials used (type of cement, concrete composition, type of reinforcement, ...) and all the construction layouts. While formwork and reinforcement drawings can sometimes be found, these data should be clarified by the results of research into construction history and by the analysis of the scientific, technical, architectural and commercial literature dating back to the time of construction. These construction details of old concrete structures sometimes obey empirical rules which are very different from the current ones. Furthermore, reinforcement details of some types of structures may have been dictated by structural calculations models that are no longer taught in engineering schools today because the kind of evaluated structure is no longer found in common practice. The old analytical models, however, are very useful in understanding the behaviour of a structure ... before applying numerical modelling which, when indiscriminately practiced by engineers without historical knowledge, is often unrelated to reality. Knowledge of the construction processes of the times also helps to understand how a structure was built and its overall performance. The synthesis of these informations can help to understand the current state of an old structure, and to refine the evaluation of its reliability compared with current regulations and to propose minimal repairing or strengthening solutions that respect the engineering heritage.

In this paper, the authors intend to illustrate the fruitful relationship between research in construction history and condition evaluation or residual carrying capacity situations for three types of old concrete constructions: reinforced concrete structures of the "Hennebique" type, prestressed concrete bridge decks with external post-tensioning and thin concrete hyperbolic paraboloid shells.

2 First generation reinforced concrete structures

Reinforced concrete, a new construction system combining steel reinforcements and concrete, was developed from the 1880s in Europe. At its origin, and certainly until about 1906, publication date of the first official French regulations relating to reinforced concrete, the "market" of reinforced concrete constructions was governed by a purely commercial system of semi-empirical provisions for the reinforcement with patents filed in by entrepreneurs or inventors. These are generally called "systems". The mechanical efficiency of these systems strongly varies, as demonstrated by more or less memorable accidents at the time.

One of those systems that proved the most effective is the "Hennebique" system developed in the 1880s by François Hennebique (1842-1921) who, from Brussels, established in 1892 an international commercial empire consisting of a central engineering office (first in Brussels and then in Paris) and a large number of contractors (the "agents" of the "Hennebique" system) that implemented the reinforcement according to the Hennebique patent and the drawings provided by the central office.

The "Hennebique" system, which spreads from 1892, is characterised by three characteristics highlighted by Hennebique (besides the recurring argument of resistance to fire):

- The "monolithism" (Figure 1), i.e., in practice, the construction of continuous structural systems (statically indeterminate), thanks to the reinforcement located at the top of the sections near the intermediate supports, and concrete gussets between beams and columns;

- Flat stirrups, whose cross section and longitudinal density were justified in relation to the shear force;

- Bent up rebars, raising from bottom of the cross sections in the spans to the top of the cross sections near the intermediate supports (Figure 1).

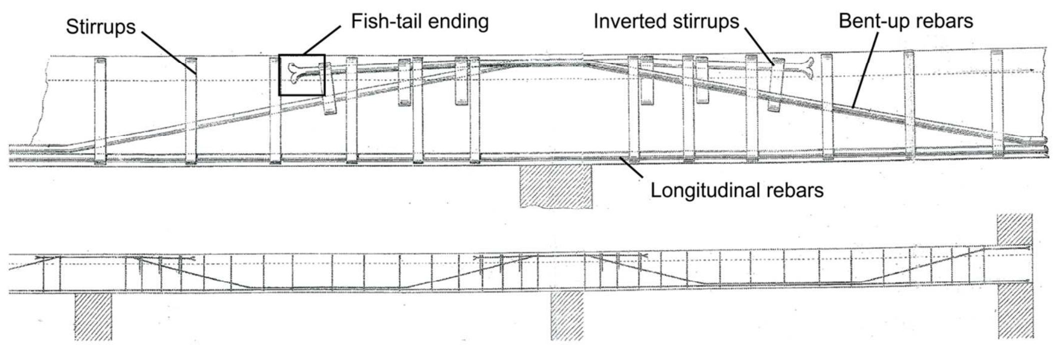

Figure 1. Reinforced concrete continuous beams according to the "Hennebique" system [1]

The "Hennebique" system was dominant in many countries for several years: France, Belgium, Italy, French-speaking Switzerland, Spain, Great Britain,... Mainly Germanic countries did not follow (German Empire, the Netherlands, Austria-Hungary, German-speaking Switzerland, ...). Nowadays, it is not uncommon to find concrete structures in some countries that were reinforced according to the "Hennebique" system (or one of its imitators ...). Many of them are now or are set to become part of the architectural heritage.

A huge advantage for the engineers in charge of a rehabilitation or transformation study today is that many studies of "Hennebique" reinforced concrete structures are still available in accessible archives, particularly those of the central office of the company (at the IFA, Paris). Although this is not sufficient to carry out an assessment of the real state of carrying capacity, those archives often provide the drawings of the reinforcement intended for these structures. In addition, the very standardised nature of "Hennebique" reinforced concrete structures must also be considered, which at the time were always reinforced following the same rules, the same principles of calculation and built using the same specifications for concreting. It is clear that it is impossible to assess a reinforced first generation "Hennebique" concrete structure (Figure 1) as safe according to modern regulations like the EC2. However, countless structures of this type behaved without accident for decades, and some are bound for an extension of their service life. The study of their actual carrying capacity is therefore of definite interest.

In 2010 Hellebois and Espion were informed of the imminent destruction of a "Hennebique" reinforced concrete narrow gage railway viaduct located in Braine-l'Alleud (Belgium) dating from 1904. A few spans of 6m long remained from a set that originally consisted of more than 12 spans without expansion joint (Figure 2).

Fortunately, the reinforcement drawings of the structure were still available in the Hennebique archives in Paris. They confirmed that it was indeed a typical continuous beam of the "Hennebique" system. It was therefore decided to undertake a thorough investigation of this structure from the viewpoint of its carrying capacity in order to contribute to the evaluation of the carrying capacity of early reinforced concrete structures. A first step was an on site assessment of the concrete strength by means of NDT testing with the Schmidt hammer. The second step was to core concrete samples and saw sections of the continuous beams. They were brought to the laboratory of Civil Engineering of the Université Libre de Bruxelles for loading tests up to failure. Indeed, it was difficult to organise this type of test on site: in the laboratory, it is possible to perform load testing according to strict protocols in order to provide scientifically useful results, in particular loading with imposed displacement to effectively control the influence of softening phenomena.

The detailed experimental investigations and modelling are reported in [1,2,3,4]. The main conclusions that could be deduced from these investigations are:

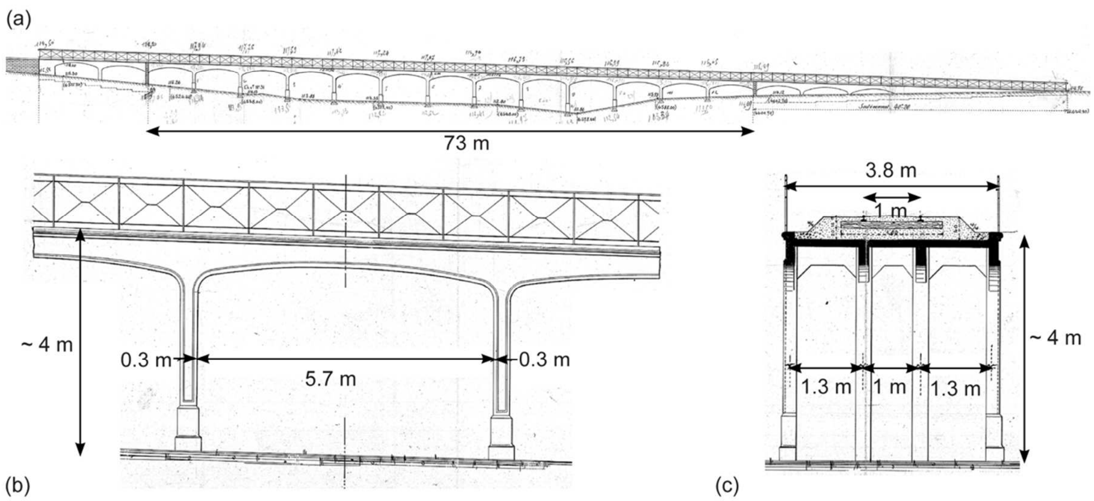

Figure 2. Railway viaduct in "Hennebique" reinforced concrete in Braine-l'Alleud (Belgium), 1904 (IFA).

- The layout of reinforcement in place, including their section, corresponded very well with the drawings available in the Hennebique archives;

- The concrete of the structure clearly showed three different strength classes each connected with the columns, beams and slabs. The concrete strength could be reasonably linked to an estimation of the cement content and the W/C ratio of the mixture [2]. Despite the fact that in 1904 no effective concrete compacting methods were available, concrete was nevertheless of good quality and the carbonation remained limited overall except for some honeycombs;

- The longitudinal reinforcement consists of smooth bars. Modern regulations, intended for the design of new structures and not for assessing old ones, obviously no longer consider the specificities of the calculation for smooth mild steel reinforcements (low bond). The tests revealed that one of the specific features of the "Hennebique" system, i.e. the fish-tail bar endings (Figure 1) did not compensate a lack of anchorage length of the main reinforcement on both sides of intermediate supports: during bending tests of this zone, the ultimate behaviour observed corresponded to the sliding of the main reinforcement before its yielding; however, sliding of the bars resulted in a plastic (ductile) behaviour after cracking of the concrete;

- It has therefore been established in the tests that the resisting moment at the level of intermediate supports - in negative bending - was linked to the sliding of the main reinforcement for a stress level well below their yield strength; however, in span - positive bending - it is perfectly possible to reach yielding of the reinforcement. A non linear structural analysis proved that it is possible to reach the design carrying capacity [4].

Open research question generated by this investigation

Obviously one of the main characteristics that constituted a specificity of the "Hennebique" system in the 1890s, namely the flat stirrup, is unacceptable according to our modern regulations as it is not closed; its mechanical efficiency to carry a part of the shear force at ultimate is very doubtful. The literature search revealed that the resisting mechanisms to shear considered by the Hennebique engineers (certainly before knowing the work of Mörsch) are impossible to justify with modern concepts. On the contrary, although we can hardly count on a contribution of open stirrups for resisting - even partially – the shear force, it seems pretty obvious that the bent-up bars must contribute. However, resisting contributions of this type are no longer taken into account in modern regulations, while the use of bent up bars was previously not uncommon, even until the 1970s. Thus, there is still a bright future for basic research on the mechanisms that contribute to the resistance to shear, an inexhaustible subject since the origin of reinforced concrete!

3 First generation prestressed concrete structures

The origins of prestressed concrete, particularly by the "post-tensioning" of tendons are also characterised by an abundance of patented cable and anchorage systems. Although the principles of prestressed concrete had been clearly stated by Eugène Freyssinet (1879-1962) in 1928, it was not until the eve of World War II however that he presented the first system of anchorages, cables and jacks allowing to consider practically the creation of prestressed concrete structures by "post-tensioning" and bridges in particular. But the outbreak of World War II delayed the diffusion of the "Freyssinet" system, both in France and abroad. In occupied Belgium, a specific system of cables and anchorages will be developed from 1941 at the initiative of Professor Gustave Magnel (1889-1955) and the Brussels contractor Blaton-Aubert. It will soon be known as the "Sandwich" or "Blaton-Magnel" system. It is inspired by the "Freyssinet" system and has been developed with the consent of the latter because during the war it was impossible to obtain components for his system in Belgium. Since 2013, the archives of the former Blaton-Aubert company for the period from 1900 to 1954 became available to researchers; they allow to properly document the development of the "Sandwich" system and prestressed concrete projects developed and built by Blaton-Aubert from 1941 to 1954 [5]. From 1950, a specific company "The Sandwich cable", a subsidiary of Blaton-Aubert, undertook the promotion and diffusion, both in Belgium and abroad, of the "Sandwich" system. During the war, a number of prestressed concrete structures were already built in Belgium [5]. Then the "Sandwich" system, based on the initial use of Ø 5mm and 7mm Ø (from 1947) wires was widely used in Belgium until the early 1960s. A number of projects were based on the concept of external prestressing, which means that the "Sandwich" cables remained visible inside the box section of the beams or bridge decks. The first large prestressed bridge with external post-tensioning is the two-span continuous Sclayn Bridge on the Meuse River built in 1949-1950.

Espion and Rammer have been involved as external experts in the project of replacement of the whole post-tensioning system of a railway bridge with a 60m span built in 1960 in Clabecq (Belgium), with a two cell box section of 4m height (Figure 3). This is one of the last applications of the "Sandwich" system in Belgium, and the cable density (30 tendons with 72 wires Ø 7 mm each) was particularly high (Figure 4, left).

The cables had a polygonal layout and were apparent inside the box. By the 1990s, a control inspection had revealed widespread and progressive corrosion of the wires (Figure 4, right) justifying a total replacement of the cables to ensure the future safety of the structure.

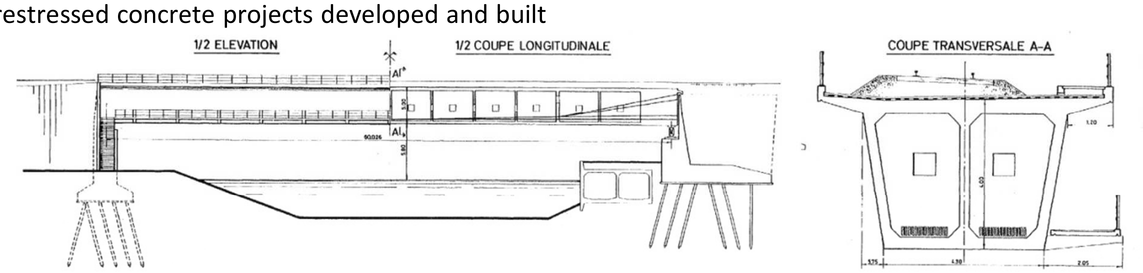

Figure 3. Longitudinal and cross section of the Clabecq railway bridge, Belgium [6].

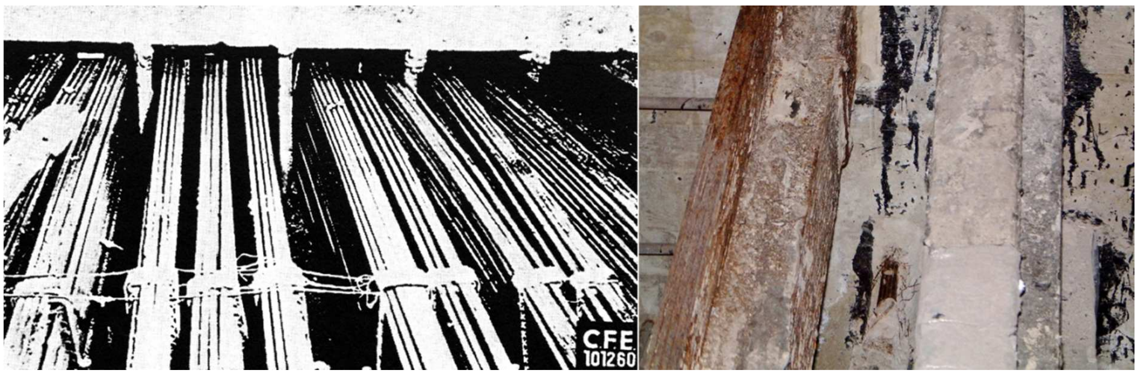

Figure 4. Prestressing cables (external post-tensioning) inside the Clabecq bridge at the time of construction in 1960 and in 2001 [6].

At the beginning of the study, the authors of the renovation project (PMD and R. De Keyser) had few documents at their disposition except the initial design calculations. A first study, entrusted by the authors of the project to Espion, was to try to experimentally evaluate the residual prestressing in the concrete. It was proposed to apply the partial stress release method (stress release by notching and restoration by flat jacks) that had already been successfully used at the request of the same project authors for measuring the stress state on site in a large masonry arch bridge [7]. The results of the experimental evaluation of the residual prestressing can be found in [8].

An underestimation of the prestressing losses by delayed deformations of concrete in the original calculations alone justified the replacement of the post-tensioning system regardless of reinforcement corrosion. The renovation project involved the replacement of the original cables with 24 tendons each consisting of 15 T15S sheathed and greased strands and housed in HDPE pipes of Ø 125mm. The work was difficult because the space between the anchorages and cables of the old and the new systems was very restricted. The hole drillings led to serious unanticipated setbacks delaying the progress of the work and resulting in unbudgeted costs. Then Rammer, called in as external expert, undertook a thorough historical study of bridge construction, unearthing documents published at the time of construction that were not available to the authors of the renovation project. In that light, and taking geometric uncertainties on the absolute position of the cables into account, resulting in particular from creep deformations, the incidents that had occurred with the drilling could be easily explained. If the detailed historical study had been conducted before the renovation project, it is likely that the incidents would have been avoided. In such projects, it is therefore essential to have - in the absence of detailed drawings - a comprehensive documentation on the old prestressing systems, obsolete long ago.

Open research question arising from this investigation

Maybe the most surprising result of the study concerns the *in situ* concrete stress assessment with the stress release method. It leads to the fundamental question: is it currently possible to directly estimate the stresses in a concrete structure? Are we not too intellectually dependent from our calculation models that in this case assume an idealised stress distribution in the walls of the box? Already published evidence suggests that, in this type of construction, self-equilibrated states of stresses induced by the drying of the concrete considerably modify the distribution of stresses induced in service by prestressing and other permanent loads.

4 Thin reinforced concrete hyperbolic paraboloid shells

The great era of thin reinforced concrete shells, started in the 1920s and culminated in the late 1950s, although some engineers and architects have continued to build them in the 1960s, or even later, following some local favourable economic circumstances.

Thin concrete shells exert some fascination on the imagination of engineers: they visually and tangibly represent the optimisation of the use of concrete in lightweight structures before the appearance of computers. Many of these structures, now aged over 50 years, are still very present and potentially require renovation. Some "iconic" thin shells of the 1930s (Boulingrin Halls in Reims by Freyssinet, domes of market hall in Leipzig by Dischinger, awning of the grandstands of the Zarzuella racecourse in Madrid by Torroja) have recently undergone deep rehabilitation. Moreover, given their efficient use of concrete, it is possible that sustainable construction economics could favour a reintroduction of thin concrete shells, disappeared from architecture for some forty years.

Among the thin concrete shell types, there is a particular form that presents many advantages: the hyperbolic paraboloid (HP or "hypar"). It appeared in the 1930s, after the dome, the long barrel vault (Zeiss-Dywidag vault) and the conoïd. Its "inventor" is the French engineer Fernand Aimond who built many hypars in France in the 1930s [9], but this form became only popular with engineers and architects through the many formally very diverse creations of Félix Candela in the 1950s in Mexico. Aimond published the model of structural calculation of the hypar in 1936 and provided a whole typology of elementary HP assemblies that would inspire many engineers and architects from the 1950s onwards. The model of Aimond, which was probably the design basis for all HP built, is a membrane model that only meets the equilibrium equations.

The Belgian engineer who designed the largest number of thin concrete shells is André Paduart [10], and his preferred shape was probably the HP. One of the HP he projected is a canopy built in 1966 on the campus of the Université Libre de Bruxelles (Figure 5). The canopy consists of an assembly of four HPs. The cantilever is 12.65m on one side and 9.65m on the other. The balance is achieved through a difference of thickness of the shells (7cm on one side, 12cm on the other).

Figure 5. Canopy of the Institute of Sociology of the ULB (© M. Provost).

The state of the canopy, about 50 years old, shows no pathological defects. However, during a careful inspection in the summer of 2012 by students participating in the 2nd *European Summer School in Construction History*, at the intrados of that HP, open cracks of around 0.45 mm opening were detected (Figure 6). It may be tempting to associate the cracks in the HP segments with the principal stress directions of the membrane theory. However, the magnitude of the tensile stresses computed by this simplified theory is definitely not large enough to justify this cracking.

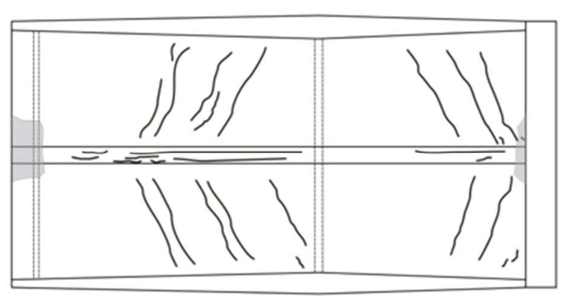

Figure 5.Cracking pattern at the intrados of the canopy in 2012.

Open research question generated by this investigation

It has been suspected for a long time that the membrane theory of the HP is a too simplistic model to assess the actual behaviour of this kind of structures in service. Observations (cracks, deformation) on that HP should now enable Provost, Rammer and Espion to reconsider the actual long-term structural behaviour of thin hypar shells. In view of the large number of built HPs around the world and in need of evaluation of their condition, this contribution could prove useful.

5 Conclusions

- Applied to first generation reinforced concrete structures, research in construction history reveals many reinforcing features, most of which, probably, have unacceptable technological details according to modern regulations; however, it is a fact that, apart from problems of durability, these structures sometimes have unexpected resistance reserves;

- The study of the conditions for the emergence of prestressed concrete and the first calculation rules of these structures can explain the weaknesses of the old prestressed constructions; providing detailed documentation of the post-tensioning systems technology is essential to tackle a renovation project;

- The study of the origin of thin concrete shells with HP shape explains why they correspond to a typology which led to a certain standardisation: it results from the bare application of a model of elementary calculation. But is this model satisfactory for assessing the actual behaviour of these structures in service?

6 References

[1] Hellebois A. *Theoretical and experimental studies on early reinforced concrete structures. Contribution to the analysis of the bearing capacity of the Hennebique system* (unpublished PhD thesis). Brussels: Université Libre de Bruxelles; 2013.

[2] Hellebois A., Launoy A., Pierre C., De Lanève M. and Espion B. 100-years old Hennebique concrete, from composition to performances. *Construction and Building Materials*. 2013; **44**: 149–160

[3] Hellebois A. and Espion, B. Structural weaknesses of the Hennebique early reinforced concrete system and possible retrofitting, *Structural Engineering International (IABSE)*. 2013; **23**(4): 501-511.

[4] Hellebois A. and Espion B. Test up to failure of a reinforced concrete Hennebique T-beam, *Structures and Buildings (Proceedings of the ICE)*. 2014; **167**(SB2): 81-93.

[5] Espion B. The founding events of pre-stressed concrete in Belgium seen through the Blaton archives. In Bowen B., Friedman D., Leslie T., and Ochsendorf J. editors. *Proceedings of the 5th International Congress on Construction History*; 2015 June 3-7; Chicago, IL. Construction History Society of America; 2015; **2**: 41-48.

[6] Denoël J.-F., Espion B., Hellebois A. and Provost M. , editors. *Histoires de Béton Armé. Patrimoine, Durabilité et Innovations*. Brussels : FEBELCEM et FABI; 2013.

[7] Espion B., Elinck J.-P., Halleux P., Fox R., Didier G. and Stoll C. Mesure de contraintes par libération dans le pont Adolphe à Luxembourg: une grande voûte de P. Séjourné. *Bulletin des Laboratoires des Ponts et Chaussées*. 2000; **225**: 67-74.

[8] Rammer Y. and Espion B. A case study of replacement of external post-tensioning cables. *Bridge Engineering (Proceedings of the ICE)*. 2014; **167**(BE3): 183-192.

[9] Espion, B. Les premiers voiles minces de béton en forme de paraboloïde hyperbolique. Paper presented at the 2ème Congrès francophone d'Histoire de la construction; 2014 January 29-31; Lyon, France.

[10] Espion B., Halleux P. and Schiffmann J. Contributions of André Paduart to the art of thin concrete shell vaulting, In Huerta S., editor. *Proceedings of the 1st International Congress on Construction History*; 2003 January 20-24; Madrid, Spain. Instituto Juan de Herrera, Escuela Técnica Superior de Arquitectura Madrid; 2003; **2**: 829-838.