Contributions of Gustave Magnel to the Development of Prestressed Concrete

by L.R. Taerwe

Synopsis: In the early 1940's Prof. G. Magnel performed extensive research programmes on real scale prestressed concrete beams at Ghent University (Belgium) in order to elaborate design methods for this new material. He also developed his own anchorage system which was used until the mid 60's in Belgium. He gave many lectures in several countries in which he explained in a simple way the principles of prestressed concrete. He was also instrumental in the design of the first prestressed concrete bridge in the USA, the Walnut Lane Bridge in Philadelphia and he was the author of the first English textbook on prestressed concrete. He designed one of the first PC railway bridges in Europe and the first statically indeterminate PC bridge in the world. In the 1950's many engineers from abroad spent some time in Magnels lab in Ghent to perform research and to get acquainted with practical realizations.

Keywords: history; Magnel; prestressed concrete

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THE "REINFORCED CONCRETE" PERIOD

Gustave Magnel (Fig. 1) was born in 1889 and graduated as civil engineer at Ghent University in 1912. From 1914 until 1919 he was employed by a London contractor and in 1919 he started his career at Ghent University. Due to his stay in London, he was not only fluent in French and Dutch (Flemish) but he was also very fluent in English which would turn out to be extremely useful for his later contacts in North-America. In those days, French was the main language used by engineers in Belgium and also a common language in international contacts within Europe.

In 1923 he published his first book "Pratique du calcul du béton armé" on the design of reinforced concrete. In the same year the Belgian Standards Institute published the first design guidelines for reinforced concrete structures, Magnel being the main contributor. One of his first technical papers dealt with the influence of column stiffness on the stresses in continuous reinforced concrete beams.

For Magnel it became clear that for the further development of reinforced concrete it was necessary to perform research, in other words, he needed a laboratory. After many political and financial difficulties he succeeded in founding the "Laboratory for Reinforced Concrete" in 1926, which was located in the basement of a former hotel. In this lab, Magnel had at his disposal a 300 kN universal testing machine and a 3000 kN compression testing machine. About the efforts he has to made to realise his laboratory and keep it operational he wrote the following : *"The ultra-rapid evolution of technology, forces university institutes to adapt themselves continuously to the actual requirements at the risk of failing in their task. This adaptation can not happen on the initiative of the university management which, by definition, is not competent for it and, moreover, rather looks for savings than for new expenditures. Hence, it is the task of the professors to do the impossible to keep their teaching and research at the required level."* He continued by stating the following : *"It not only goes about having a laboratory : the question is to keep it operational, which requires additional funding. We obtain an extra income from testing we perform for contractors, companies and public authorities, …".*
In 1937 the laboratory moved to a new building of the engineering faculty where much more space was available and some new testing machines were installed. By 1940, it had become the most advanced and sophisticated research and testing laboratory for reinforced concrete in the world. Magnel had little use for tests on small-scale models and in 1950 a special testing floor was installed, thus enhancing the facilities for loading tests on real scale reinforced and prestressed concrete elements. In 1975 the laboratory moved to a campus at the outskirts of Ghent where it is still located[1,2]. In the 1990's the

name was modified into "Magnel Laboratory for Concrete Research", indicating that research on both material and structural aspects is performed.

EARLY CONTRIBUTIONS TO THE DEVELOPMENT OF PRESTRESSED CONCRETE

The first mentioning by Magnel of the principles of pretensioned concrete and post-tensioning by external cables was in 1940. These techniques were already used abroad and Magnel tried to convince Belgian companies to apply it as well.

During the second World War, Magnel was not allowed to teach. However, the Germans still allowed him to remain director of the lab he founded. During the secluded years at the laboratory, Magnel had the opportunity to conduct full-scale research on prestressed concrete girders. He also investigated on the phenomena of creep of high-strength steel wires and creep and shrinkage of concrete. During the war period, it was impossible for him to obtain the prestressing system developed by Freyssinet in France. Hence Magnel developed himself a post-tensioning system which became known as the "Belgian" or "Magnel-Blaton" system (Fig. 2). The anchorages of this system consist of several so-called "sandwich plates", arranged parallel to each other, and in contact with a cast-steel bearing plate. Each locking plate is provided with four wedge-shaped grooves in each of which two wires are secured with a steel wedge. In this way the stress in the different wires (typically Ø 5 mm) of one tendon is more uniform than in the case all the wires are stressed at once. Moreover, a fairly small jack could be used for stressing the wires (Fig. 3). The cable is placed in a sheet-metal sheath, or holes are formed in the concrete to permit the cable to be passed through the beam after concrete has hardened. Over the full length of the tendon, vertical and horizontal spacers were provided at regular distances which assured that the relative position of the wires remained the same along the tendon. Due to this arrangement there was a free space around each wire which allowed a good cover by the injection grout which is essential for protection against corrosion.

The Blaton-Magnel post-tensioning system was used in almost all prestressed concrete bridges in Belgium until the early 1960's. In these years it went out of use because it turned out to be quite laborious and strands were introduced to provide higher capacity tendons.

In 1946 he published his design method for statically determinate beams. He formulated the following four stress conditions under service loads in the critical section :

1. tensile stress at top fibre under initial prestressing and dead weight smaller than allowable tensile stress.
2. compressive stress at top fibre under prestressing and full load smaller than allowable compressive stress.
3. compressive stress at bottom fibre under initial prestressing and dead weight smaller than allowable compressive stress.
4. tensile stress under long-term prestressing and full load smaller than allowable tensile stress.

These inequalities were drawn as straight lines in a diagram with axes $1/P_i$ (P_i : initial prestressing force) and e (eccentricity) and resulting in a kern showing admissible combinations of P_i and e (Fig. 4). In principle, the eccentricity giving the smallest value of P_i was chosen.

For shear design he took into account the beneficial effect of the prestressing force on the total shear force. He then looked for the section and the fibre where the principal tensile stress was maximum and compared this stress with an allowable value.

For the design of the end-blocks he proposed to calculate the shear force and bending moment in horizontal sections, which is the so-called deep beam analogy. The resulting shear and normal stresses were combined with the stress components from other sources to calculate the principal tensile stress.

In 1951 Magnel stated the following[3] : *"In my opinion, for each beam two calculations have to be made : the first based on stresses using the elastic theory, the other on ultimate load. However, it seems to be impossible at present to make this latter calculation accurately because all known methods require the use of coefficients, the value of which we really ignore. This is mainly true when the failure occurs by crushing of the concrete. I recommend the design based on stresses as the fundamental one, but as it does not always give the same factor of safety against ultimate failure, an attempt must be made in each case to check whether this factor of safety is sufficiently high."*

In 1946 he had already tested a partially prestressed beam for which the cracking load was lower than the full service load as opposed to the original concept of prestressed concrete in which no longitudinal tensile stresses were allowed under service conditions. Although Freyssinet was heavily opposed to the use of partially prestressed concrete, Magnel realized that it could offer some advantages.

In 1947 he developed a practical solution for the case of statically indeterminate post-tensioned beams. He introduced the concept of secondary bending moments $M_{P,sec}$ generated by the prestressing force P, and defined the equivalent eccentricity as

$$e_{eq} = e + M_{P,sec}/P \qquad (1)$$

In this way, he could use a similar diagram $1/P_i$, e_{eq} as for statically determinate beams. The relationships between the actual (geometric) eccentricities and the equivalent ones were calculated on the basis of expressions for the secondary moments.

As he had gathered sufficient theoretical knowledge and practical experience about PC, he wrote his first book on the subject[4]. It was first published in French in 1948 and was soon translated in English and Spanish.

FIRST PROJECTS IN BELGIUM

In the railway bridge over the "Rue du Miroir" in the Brussels' north-south train connection, two of the six bridge decks were realized in prestressed concrete (Fig. 5). For a span of 20 m a total depth of 1.15 m proved to be sufficient while a solution in reinforced concrete would have required an increase in slab depth by 0.7 m. This bridge was considered a pilot project and the related research project was partly sponsored by the Belgian Fund for Scientific Research. Hence, in 1944 Belgium was one of the first countries with a prestressed concrete railway bridge. On this project Magnel concluded the following : *"In our opinion, prestressed concrete is the building material of the future. Over 10 years, very few bridges will still be built in reinforced concrete because everybody will be convinced of the advantages of prestressing. The realization of the pilot project in the Rue du Miroir will have been the catalyst of this evolution and all who were involved in it can be proud of the results obtained."*

The first prestressed road bridges in Belgium were built in Zammel (start in 1944 ; 12 m span) and in Eeklo (1945-1946 ; 20 m span).

In 1947-1948, a new textile factory was built for the UCO company (Union Cotonnière) in Ghent which had, in those days, the largest roof structure worldwide in prestressed concrete, covering a surface of about 35000 m^2 and which is still intact (Fig. 6). One hundred primary beams with a span of 20.5 m and 600 secondary beams with a span of 13.7 m were necessary. All these beams were precast at the site at a rate of 3 primary beams and 18 secondary beams per week which required a perfectly organised casting yard. Magnel writes about this achievement : *"During the last 3 to 4 months, this project attracts numerous architects, engineers and contractors both from Belgium and from abroad. They want to qualify themselves in the field of prestressed concrete, firstly in our lab and secondly at the building site".*

In the same period a hangar for planes at Melsbroek, the former Brussels airport, was erected. The roof was supported by 17 post-tensioned beams having a total depth of 2.9 m and a mass of 300 tons (Fig. 7). Similarly as in the previous project, the beams were cast on the ground and, after post-tensioning, they were lifted into their final position.

In 1949, the famous Sclayn bridge over the river Meuse was constructed (Fig. 8). This was the first continuous prestressed concrete bridge in the world (Figs. 9 and 10). With two spans of about 63 m each, the bridge was also the longest prestressed bridge in the world. Due to the variable depth of the girder, the external cable profile was almost straight except for the kink at the central support. At that section, the secondary moment due to prestressing was equal to about 68 % of the local bending moment due to dead weight.

THE WALNUT LANE BRIDGE

In 1946, Magnel visited for the first time the United States of America as an "advanced fellow" of the Belgian-American Educational Foundation, founded by Herbert Hoover in

1920. The trip was organized by the late Charles C. Zollman, a former student of Professor Magnel at Ghent University[5]. Later he became Magnel's unofficial respresentative in the United States, responsible for the detailed arrangements of Magnel's several trips to this continent. Mr. Zollman's early consulting services for the design and construction of pretensioning plants throughout the United States, his activities in the field of precast concrete as well as his many contributions to the PCI, have identified him as a pioneer of this industry in North America. During his first visit to the United States, Magnel lectured on prestressed concrete at several places, a subject almost unknown at that time in that country. Magnel had the rare gift to explain complex theories and difficult problems in a simple way and thus captivated large audiences.

Two significant effects occurred during Magnel's first visit to America which had a direct bearing on the development of prestressed concrete in America and which culminated in the realization of Philadelphia's Walnut Lane Bridge, the first prestressed concrete bridge in the USA (Fig. 11). The first event was the fact that Magnel was introduced to the Preload Corporation of New York, which eventually became a sub-contractor for the construction of the Walnut Lane Bridge girders. The second event was the fact that Magnel asked Zollman to translate the French manuscript of his book on prestressed concrete into English. After a lot of efforts and difficulties the book was published in London in 1948. The 6000 copies of the first edition were promptly sold out. Eight thousand copies of the second revised and expanded edition were published in 1950 and a third further edition was published in early 1954. During those early years, Magnel's book was the practical tool to which engineering students and practicing engineers referred to for the design and analysis of prestressed concrete structures. The impact of this treatise, as well as many of Magnel's other publications, had on the prestressed concrete industry is indeed significant. In the early 1950's, T.Y. Lin spent one year in Magnel Laboratory and after his return to the United States he published his book on "Design of Prestressed Concrete Structures" (1955).

In the late 1940's Ch. Zollman, who had joined the Preload Corporation in the meantime, could convince the Bureau of Engineering of the City of Philadelphia to realize the superstructure of the Walnut Lane Bridge in prestressed concrete on the basis of a proposal elaborated by Magnel. The Preload Corporation was awarded the sub-contract to fabricate the girders in 1949. In October 1949 a loading test was performed on a 49 m long and 2 m deep test girder, identical to the girders forming the center span of the bridge (Fig. 12). This test demonstration attracted some 300 engineers from seventeen states and five countries who stood in the rain for the entire day to witness the event. The successful testing to destruction at the job site, far away from the comforts of a laboratory, was a significant achievement which instilled public confidence in prestressed concrete. Ch. Zollman formulated it as follows : *"No single event was more instrumental in launching the prestressed and precast concrete industry in North-America than the construction of the Walnut Lane Bridge in Philadelphia in 1950. More than anything else however, it was the charisma, the dynamism and engineering talent displayed by the man who designed the Walnut Lane Bridge, namely Prof. Gustave Magnel of Belgium, that gave the impetus necessary for the acceptance and development of prestressed concrete in the United States."*

Prior and during the execution of the bridge, some problems needed to be solved because Magnel required a "zero slump" concrete. According to American practice this was not possible to realize but Magnel had to approve all execution details. Finally, a practical solution was found but several girders showed honeycombs and other imperfections[6] (Figs. 13 and 14). The controversary had gone far enough to be published in the influential "Engineering News Record" with the headline[7] : *"Americans make soup, not concrete, says Belgian professor"*.

In October 1950, Prof. Magnel was awarded the Frank P. Brown Medal from the Franklin Institute in Philadelphia for his exceptional contributions to the development of prestressed concrete.

During the service life of the Walnut Lane Memorial Bridge, some of its girders underwent major repairs and finally it was decided to replace the entire superstructure. Site preparations to remove the existing girders began in 1989. The reconstruction of the bridge and the realignment of its approaches in 1990 stirred up nearly as much interest and curiosity in the engineering and construction community as did the original structure in 1949. The new girders, based on a modified hybrid standard AASHTO Type V girder, were all manufactured in a PCI-certified plant instead of the girders being constructed and post-tensioned on site.

THE SEQUEL

In the early 1950's several famous American researchers visited Magnel and his Laboratory, among which T.Y. Lin, David P. Billington (Princeton University) and Robert N. Bruce (Tulane University, New Orleans).

Together with other European pioneers of prestressed concrete, Magnel founded in 1952 the "Fédération internationale de la Précontrainte", abbreviated as FIP, which became a successful international technical organization. In 1996 it merged with CEB (Comité Euro-International du Béton) into fib (International Federation for Structural Concrete).

Magnel not only authored more than 180 technical papers but also published an impressive series of books on structural analysis and on the design of reinforced and prestressed concrete structures. In all these text-books practical design methods were given which use was facilitated by numerous tables and graphs.

During his last years, Magnel devoted a lot of energy to the preliminary design of a high TV-tower, which was planned for the World Expo 1958 in Brussels. The planned tower in reinforced concrete would have had a diameter of 100 m at its base and a height of 500 m. On top of the concrete part came a steel mast with a height of 135 mm. In those days this would really have been a world wide attraction. However, there was a lot of technical and political controversy about this project and finally it was decided not to build it.

Gustave Magnel passed away quite suddenly on July 5, 1955. This sudden loss was received with great sadness in Belgium as well as abroad.

In October 1956, an academic session was organized in Ghent for the commemoration of Gustave Magnel, where also several of his former colleagues and friends from abroad were present. At that occasion Prof. R. Evans from Leeds University mentioned the following : *"... His concrete laboratory was recognized as one of the best in the world. Hundreds of members of staff and research workers from a large number of universities have had the pleasure and privilege of visiting this excellent laboratory. Magnel always warmly welcomed at his laboratory those who wished to improve their knowledge. .... His gift of friendly intercourse enriched us all by their genial and mellow qualities. Although he often had strong views on technical questions, he was by nature so generous that it was a pleasure even to disagree with him."*

In order to continue the commemoration of Prof. Magnel's exceptional achievements at long term, the General Association of Engineers graduated from Ghent University (AIG), bestows the "Golden Medal Gustave Magnel" every fifth year on the designer of a structure which is deemed to be an important and remarkable application of reinforced or prestressed concrete. The first ten recipients are : N. Esquillan (1959), P. Blokland (1963), F. Leonhardt (1968), U. Finsterwalder (1973), R. De Keyser (1979), H. Wittfoht (1984), R. Greisch (1988), O. Olsen (1994), M. Virlogeux (1990) and J. Schlaich (2004).

CONCLUSIONS

From the previous overview it is clear that Prof. Gustave Magnel was an exceptional personality both from an academic and a human point of view. The following achievements can be pointed out :

- Contributions to practical design methods for reinforced concrete.
- Development of his own prestressing system.
- Development of design methods for prestressed concrete and authorship of the first English text book on the subject.
- Involvement in the design and realization of the first continuous prestressed concrete bridge worldwide.
- Contribution to the realization of the Walnut Lane Memorial Bridge in Philadelphia, the first prestressed concrete bridge in the USA.

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Figure 1 – Prof. Gustave Magnel (1889-1955)

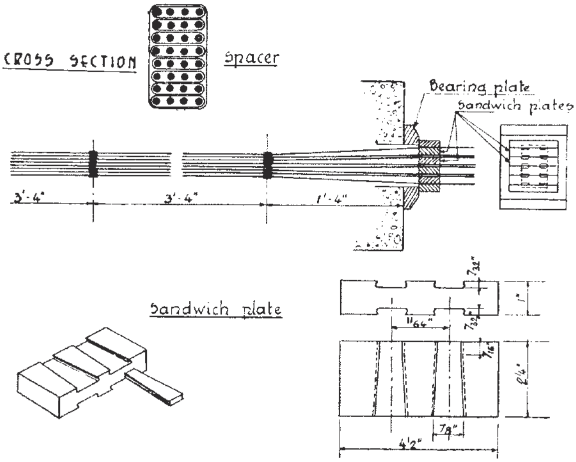

Figure 2 – Anchorage of the Blaton-Magnel system

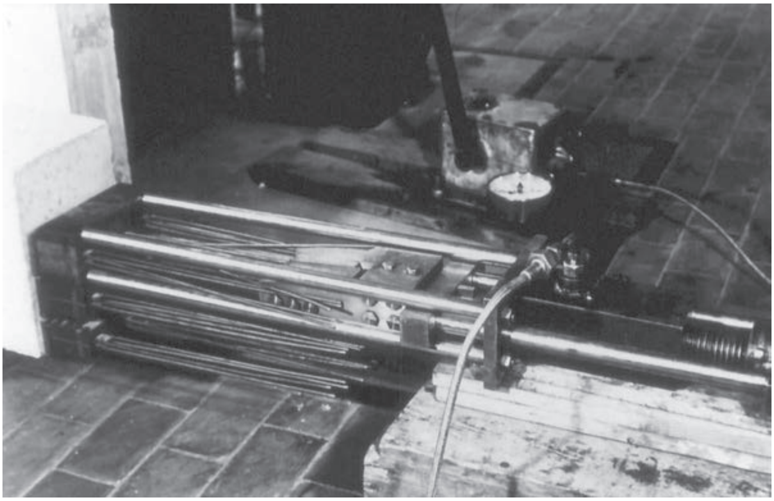

Figure 3 – Jack for the Blaton-Magnel system

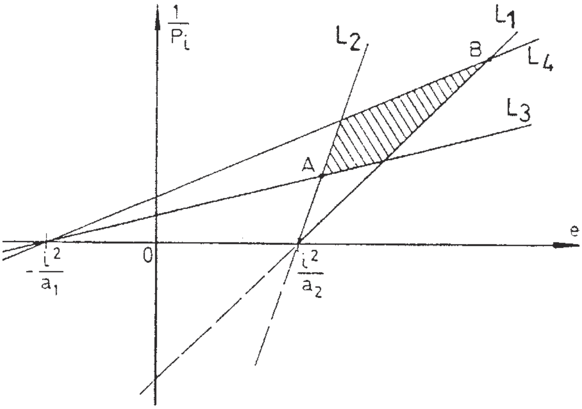

Figure 4 – Allowable kern for combinations of $1/P_i$ and e