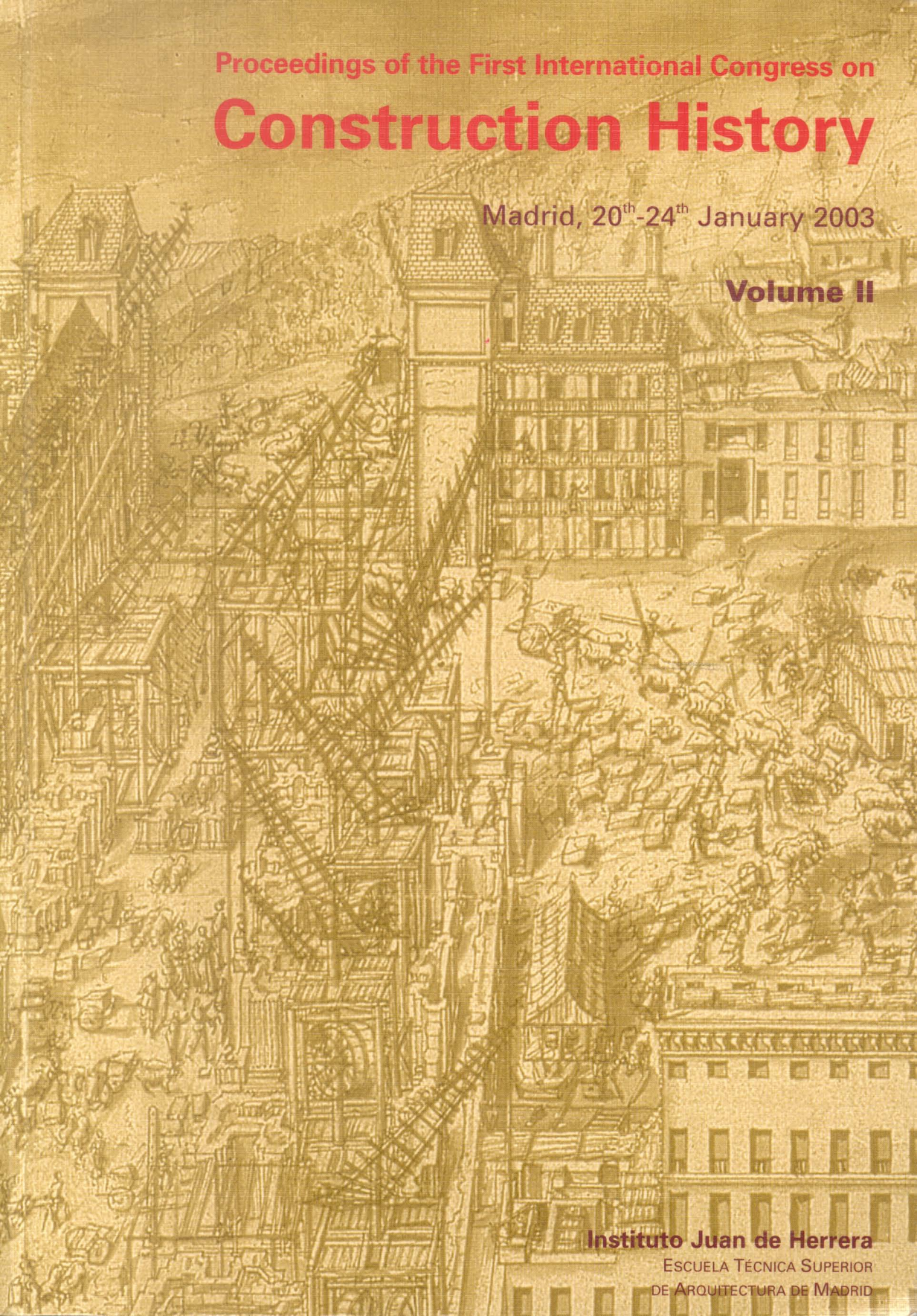
Proceedings of the First International Congress on

Construction History

Madrid, 20th-24th January 2003

Volume II



Instituto Juan de Herrera
Escuela Técnica Superior
de Arquitectura de Madrid

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Edited by
Santiago Huerta

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Prestressed concrete: First developments in Italy

Tullia Iori

In February of 1939, at the height of the autarchy campaign in Italy, Gustavo Colonnetti, wrote from the pages of the journal *Il Cemento Armato*, attempting to persuade Italian engineers, scientists and politicians that «iron conservation must not be sought in absurd returns to decidedly outdated building technologies— nor in the adoption of no less absurd surrogates— but rather by proceeding, unperturbed, using all means available and the aid of science and experience, with the development of more advanced technologies» (Colonnetti 1939a, 22).

The words of the most famous —and troublesome— Italian scientist in the construction field amounted to a censure of the reactionary impositions of the regime, which favoured a return to traditional bearing walls and the autarchic vaulted ceilings. Analogous criticism was at the same time directed to parallel visionary experiments which aimed to substitute the iron reinforcing in concrete with wood or bamboo rods, irresponsibly disregarding the very low elastic modulus of these surrogates. These experiments were encouraged by the concrete industry, in search of rapid solutions in the face of the crisis determined by laws against the use of reinforced concrete in civil construction (Iori 2001).

The more advanced technology to which Colonnetti referred had already been under development for the last several years in Europe —the work of Eugène Freyssinet in France, and of Wayss & Freytag and Dywidag in Germany: the so-called «prestressed concrete».

Why was Colonnetti so enamoured with prestressing, to the point that he considered it to be the solution to the economic problems of the building sector?

There were at least two reasons.

The first is that the Italian scientist, respectively in agreement with Freyssinet, Eduardo Torroja and Ove Arup, had always considered reinforced concrete an "absurd", "strange" and "difficult" material. The two elements of which it is composed have almost opposite structural qualities, and the strength of their union lies precisely in this complete difference: one absorbs the stresses which the other is unable to withstand. But the paradox consists in the fact that the static reliability of reinforced concrete is based on a guaranteed adherence between the iron and the concrete, while adherence is actually heavily compromised by the inability of concrete to withstand tensile stresses and thus to match the deformation of iron. The inevitable cracks in the concrete in areas under tension had already raised doubts at the beginning of the century, during the pioneering stage of experimentation with reinforced concrete. Nor did the diffusion, towards the end of the 1930s, of special high-strength concretes provide a solution to the problem, because the performance of these concretes improved only in terms of compressive strength, while tensile strength did not increase significantly. Even the possibility of using high-strength steels, which would permit considerable material savings, was questioned, because of the low tensile strength of concretes and its tendency to crack as soon as it is subjected to expansion over a certain limit. Yet it appeared clear to Colonnetti —just as it did to his European colleagues— that with the technique of prestressing, the reciprocal relationship between

concrete and iron would be completely turned around: the reinforcement would no longer serve to withstand a given part of the stresses due to external loads, but rather to create in the concrete itself a preventative state of tension, opposite to that resulting from the external forces. The collaboration between the two materials is transformed into "coaction": the steel precompresses the concrete, which is then able to withstand tensile stresses due to the mechanism of the sum of the effects. This separation of roles solved the paradox of cracking in tension zones and immediately revalidated the use of both high-strength steels, which would be subject to extremely high tensile stresses, and of special concretes, required to withstand only compressive stresses. In concrete which is prestressed by means of pretensioning, both concrete and steel are stressed in conformance to their particular strength characteristics, thereby greatly increasing efficiency: the technique thus resulted in a considerable economy of materials.

The second reason for which Colonnetti pushed in favour of prestressing is that the new technique might finally begin to heal an open wound in the side of the building science community.

Colonnetti's clearly stated his opinion on the value of the theory of reinforced concrete formulated by Edmond Coignet and Napoléon de Tédesco more than forty years earlier, in 1894, and still used in 1939. He quite simply regarded the design methods as «lacking, absolutely lacking any scientific foundation, not only in the sense that, based as they are on unjustified and unjustifiable hypotheses, they arrive at conclusions which experience notoriously contradicts, but also in the sense that as the hypotheses themselves are incompatible and contradictory, one cannot even concede to the resulting theory the quality of a logical construction, capable of withstanding the most elementary criticism» (Colonnetti 1938, 61).

Those who had introduced these calculation methods into the building codes and to general use had not been misinformed about their validity; only later had the process assumed a permanent status, authorising the blind application of the simple and well-known methods of the elastic theory.

Colonnetti was a gifted theoretician. From 1917, as a young university professor at Pisa, he had studied the definition of equilibrium of a body in the presence of non-compatible deformations —a state of residual stress which he defined as a state of "coaction"; in 1924 he had formulated a theorem of minimum deformation energy which still carries his name: a generalisation of the theorem of Menabrea in the presence of elastic residual stresses. From 1937, he reorganised the corpus of the mathematical theory of the elastic solid, adapting it to a solid which is not perfectly elastic, but rather elasto-plastic, a hypothesis which is closer to the behaviour of reinforced concrete.

Without going into detail about his intuitions, by 1939 Colonnetti fully understood that states of artificial residual stress can improve the static performance of structures, and in parallel, that the "classic" design methods for reinforced concrete were in urgent need of substitution by rigorous scientific theory.

The technology of prestressed concrete gave him, on the one hand, a chance to promote the elimination of arbitrary design methods, and on the other, recognition and direct application of the precious studies of his youth.

In September of 1939, Colonnetti completed and published a design method for beams with pretensioned tendons, direct application of his elegant theory of "elastic coaction" (Colonnetti 1939b). In this new configuration, the hypotheses of the elastic theory could be scientifically applied: the compressive action of the steel on the concrete in fact throws the neutral axis to the exterior of the concrete section, which thus becomes entirely reactive, entirely compressed, and homogeneous, as it is no longer the reinforcing which must resist to external loads. The behaviour of the material can thus be described perfectly without resorting to unlikely procedures of homogenisation by bonding the steel to the concrete, or to the use of coefficients whose validity was not only false but lacking any physical significance.

Examples of prestressing thus far

Apart from his internationally recognised theoretical contributions, Colonnetti did not have an instrumental role in the pioneering phases of the development of prestressing. The leading figures were French and German engineers —as had been the case many years earlier with ordinary reinforced concrete.

In fact, prestressing had already been used for several different applications.

To cite a few examples in the specific field of construction, the technique of tamping the joints in stone arch bridges was widely used. It consisted in forcing mortar into the joints at the haunches, comparable to forcing a wedge between the stones, creating reactions which are normal to the foundation and thus shifting the pressure curve. In another example, the Howe truss, Figure 1, the vertical members, consisting of threaded iron tie-rods, were post-tensioned by tightening nuts at the ends, so as to induce sufficient compression in the two systems of sloping timber members as to cancel out any tensile stresses resulting from dead or live loads (Guidi 1928, 190).

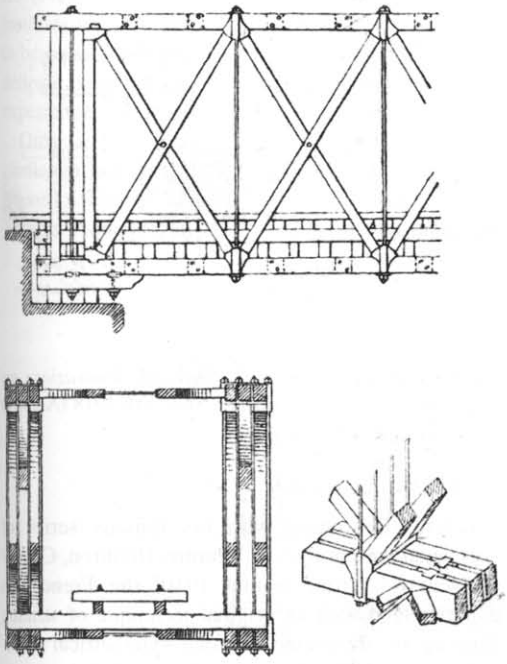


Figure 1
Howe truss: the vertical elements are threaded iron tie-rods, put under tension by tightening nuts at each end (Guidi 1928)

Around the mid-nineteenth century, a type of reinforced cast iron beam with pre-stressed reinforcing was in use. The beams, Figure 2, were pre-stressed by means of pre-tensioned horizontal iron bars, completely independent of the cast iron section (Zorgno 1988, 139-61).

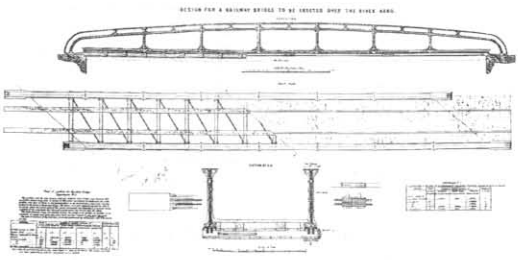


Figure 2
Beam in prestressed cast iron in the bridge over the Arno at Camaioni, designed in 1848 by Robert Stephenson and Charles Heard Wild (Zorgno 1988)

And it was precisely this experimentation with prestressed cast iron, a material extraordinarily similar to concrete, at least in terms of strength behaviour, that had the most analogies to early attempts to prestress concrete by means of iron tie-rods.

While Doering's patents of 1888 are often cited, François Chaudy's work is lesser known. Yet already in 1894 it clearly foreshadowed the potential of post-tensioning by threading tendons through blocks of concrete. Chaudy, who based his reasoning on the well-known concerns regarding the inevitable cracks in concrete in the tension zones, suggested forming the beam, Figure 3, in concrete only, with a canal along the bottom for housing an iron tie-rod, to be put under tension, once the concrete had cured, by tightening at the ends of the beam (Chaudy 1894).

The proposed solution had no real possibility of application because, as is well-known, the allowable tensions for reinforcing available on the market at that time permitted such modest amounts of elastic stretching that it would be rapidly cancelled out by concrete shrinkage and by slow deformations.

Yet the idea of pretensioning reinforcing bars was not discarded, despite the lack of success due to technological limits. Concerned about the durability of the reinforcing following cracking in the concrete

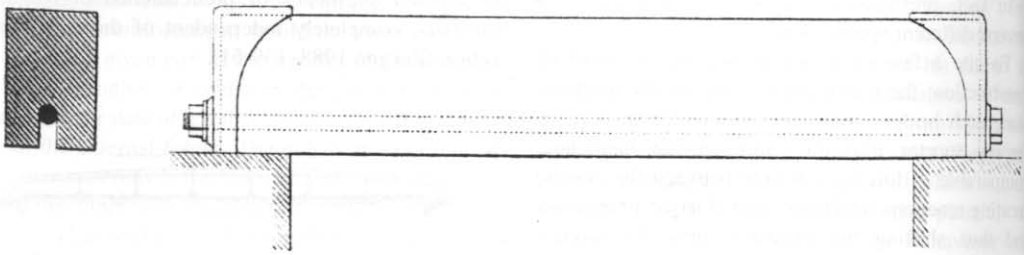


Figure 3
Concrete beam type, to be prestressing by means of a tie-rod, according to ideas by F. Chaudy in 1894 (Chaudy 1894)

in areas under tension, in 1907 Matthias Koenen — the first to have carried out systematic experimentation and to have proposed a design method for reinforced concrete— invented a rudimental device for putting reinforcing bars under tension before concrete placement. His «stretching» procedure, Figure 4, was meant to increase the «tonicity» of the iron and thus, all loads being equal, result in less deformation, thereby reducing the risk of cracking of the surrounding concrete.

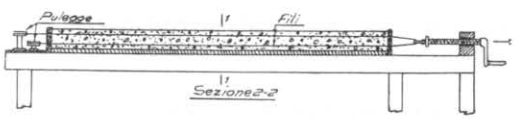


Figure 4
Device by Matthias Koenen for tensioning the reinforcing rods before placement of the concrete, 1907 (Cestelli Guidi 1947)

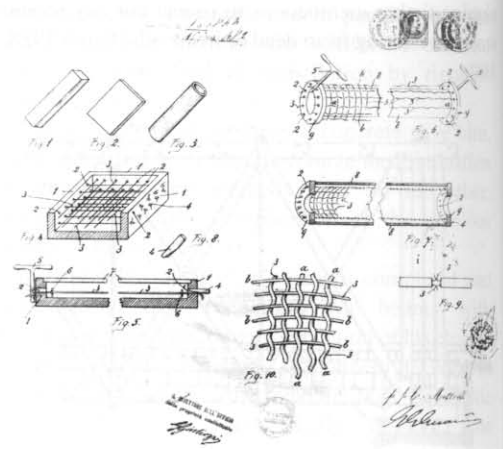


Figure 5
Italian patent n. 166844 by E. Mezzetti: *Innovazione nei sistemi di armatura del cemento*, May 20th 1918 (Archivio Centrale dello Stato)

With the same goal in mind, an Italian in 1918, Ernesto Mezzetti, patented an easily applied system, Figure 5, using wedges and keys for stretching the iron reinforcing bars. As an illustrious antecedent to his system, he cited the traditional practice of forcibly stretching the tie-rods of arches and vaults (Mezzetti 1918).

Modern prestressing: systematic deformations

As is well known, Eugène Freyssinet is the structural engineer who developed modern prestressed concrete. Beginning with his famous series of segmental arch bridges —Veurdre, Boutiron, Châtel-de-Neuvre— from around 1910, the Frenchman experimented with an original technique of striking centring by distancing the two symmetrical semi-arches using hydraulic jacks positioned at the crown and operating horizontally. His first prestressing system, known as the «systematic deformation method», hinged on this technique.

"The idea behind this method ,wrote Freyssinet, consists in not accepting the elastic state of a structure as the necessary result of its usual conditions of implementation, but, on the contrary, to endeavour to discover, by means of an initial deformation

artificially imposed on certain elements, if it can be favourably modified» (Freyssinet 1928, 1033).

In the case of arch bridges, it is known that at the moment of striking centring, the elastic deformation, the inevitable distancing of the abutments, the shrinking of the concrete, and temperature variations, all contribute to inducing a change in mean fibre direction, which, non longer coinciding with the lines of pressure, determines ulterior stresses. Freyssinet's method consists in correcting, by means of jacks, the curve of the centres of mass, so that once again it coincides with the pressure curve, cancelling out these parasitic loads. Artificially induced stresses were introduced in the structure, in the opposite direction of the design loads, in order to best take advantage of the strengths of the material.

The technique was without a doubt ingenious. However, added Freyssinet, "the use of indirect methods for creating a priori deformations which are to be equal and opposite to predicted loads is a very delicate task which must be carried out only by experienced engineers» (Freyssinet 1928, 1033).

Only a few engineers in Europe took up the challenge launched by Freyssinet. Among these was Eduardo Torroja. During the construction of the Tempul Aqueduct in 1925, he confidently made use of hydraulic jacks to correct the shape of the structure deformed under normal load conditions.

In Italy, only Eugenio Miozzi, an engineer for the Engineer Corps in Bolzano, had the courage to follow the footsteps of his two famous colleagues. In 1930, having passionately studied Freyssinet's accomplishments, Miozzi had a chance to experiment with a personal variation of the technique of systematic deformation in his non-reinforced concrete bridge over the Sojal river. He used jacks to re-centre the pressure curve, but instead of raising the arch by acting upon the crown, he lifted it just as efficiently from the impost (Miozzi 1930).

Development of prestressed concrete in Europe

On October 2, 1928, Freyssinet registered a patent in France —and a year later in Italy as well— in which he claimed the rights to a «manufacturing process of reinforced concrete elements» (Freyssinet and Séailles 1928; Freyssinet and Séailles 1929). One would never guess that behind this banal-sounding title lay a true «revolution in the art of building».

Freyssinet's prefabricated elements, Figure 6, were manufactured with straight reinforcing rods, pre-

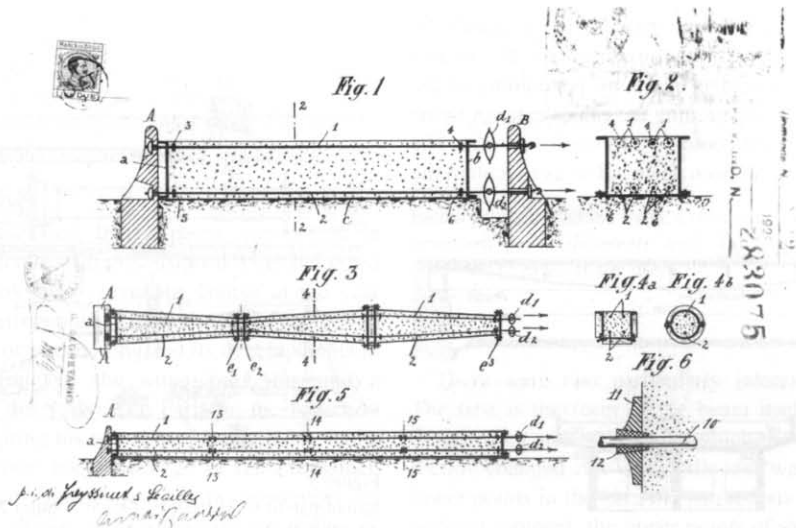


Figure 6
Italian patent n. 283075 by E. Freyssinet and J. Séailles: *Processo di fabbricazione di pezzi in cemento armato*, October 1st 1929 (Archivio Centrale dello Stato)

tensioned before the placement of the concrete. They were not merely pulled tight as with the many previous experiments, but rather, subjected to sufficient tensile stressing as to produce a significant amount of elastic strain. The tensioned rods had anchor devices for transmitting their stresses to the, by then cured, concrete.

In 1935, Freyssinet licensed his patent for Germany to the company Wayss & Freytag — already well-known for having bought Joseph Monier's patents for reinforced concrete fifty years earlier. Together with Matthias Koenen, they began the first systematic experimentation on the material. As always, the forward-looking company conducted a precise and expert evaluation of the system. The long experimental phase was concluded in 1939 with the construction of the first European bridge in prestressed concrete, a highway overpass with a span of approximately 33 metres. The project was by Emil Mörsch, technical director of Wayss & Freytag, in charge of all experimentation.

Another German, Franz Dischinger, the creator of the Zeiss-Dywidag thin vaulting system, claimed that he was the inventor of prestressed concrete, having also registered a patent in 1928 to that regard. In 1934, Dischinger deposited another patent for a system of beams for bridge-building. The beams, Figure 7, were to be prestressed using very large diameter braided steel cables in a parabolic conformation, positioned exterior to the beams themselves and held in place by pendulums to the cross beams. By positioning the cables exterior to the beams, the tension could be adjusted over time. The parabolic form had been designed so as to realign the stresses along the centre of mass of each section, thus resulting in a uniformly compressed beam.

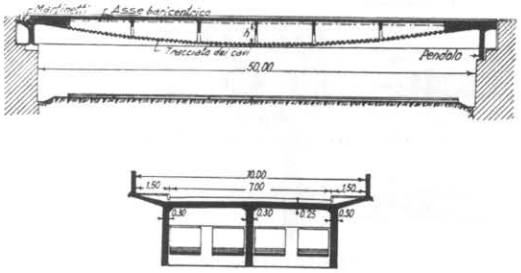


Figure 7
Prestressing system designed by Franz Dischinger in 1934 (Cestelli Guidi 1947)

Among the developments in Germany, where, in preparation for war, research aimed at conserving iron had been encouraged, perhaps the most easily applicable was a technique by Ewald Hoyer. His prefabricated floor beams were prestressed using very fine, adherent, piano wires (Hoyer 1939). Pre-tensioned close to the safe load capacity and without the need for anchoring devices, the wires immediately sparked curiosity in Italian journals as well, where they were published in April of 1939.

Developments in Italy: Gustavo Colonnetti's patent

The first true applications of prestressing in Italy mainly regarded concrete pipes. The prestressed concrete pipes manufactured by Vianini had already been the strong suit of the Italian delegation at the First International Congress on Concrete and Reinforced Concrete at Liege in 1930. The company in 1933 presented a new patent, Figure 8, which claimed the rights to a machine capable of prestressing the pipes using steel wire under tension: the technique consists in spirally wrapping and

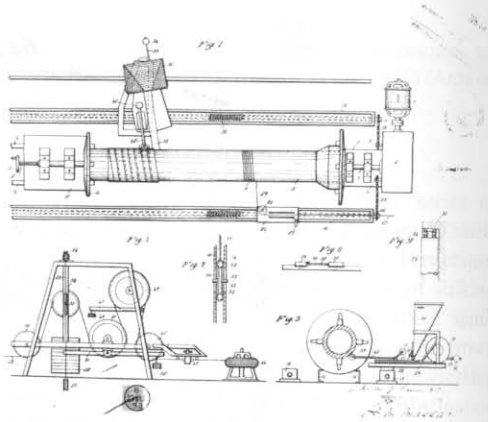


Figure 8
Italian patent n. 314685 by Guido Vianini & C.: *Macchina per fabbricare corpi cavi di materiale cementizio, fibroso o no, per rivestire tubi metallici con materiali plastici e per armare corpi cavi con armature metalliche in tensione*, June 6th 1933 (Archivio Centrale dello Stato)

weaving a steel wire around an already cured pipe, and then protecting it with a layer of fibre-reinforced concrete (Guido Vianini & C. 1933).

In June of 1939, the S.C.A.C., Società Cementi Armati Centrifugati, company further developed its already famous centrifuged concrete poles by inserting tensioned high-strength wires along their length, embedded into the concrete (SCAC 1939). The technique developed by SCAC, Figure 9, has clear analogies with the Hoyer method, not yet protected by patent in Italy.

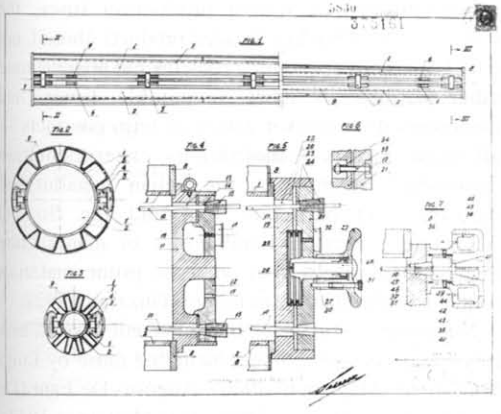


Figure 9
Italian patent n. 375161 by Società Cementi Armati Centrifugati SCAC: *Perfezionamenti nella costruzione di manufatti in cemento armato centrifugato con armatura sottoposta a tensione preventiva*, June 19th 1939 (Archivio Centrale dello Stato)

However, the first Italian patent for beams in reinforced concrete with pretensioned wires belonged to Gustavo Colonnetti. Over the course of the year 1939, Colonnetti published a long series of articles on the potentials of prestressing and its developments in Europe; in June of the same year, he held a conference at the Sorbone in Paris on the "coaction states", and during his trip abroad he probably had a chance to expand his knowledge of the Freyssinet, Dischinger and Hoyer systems; in September he published the already cited article on the design of prestressed beams; on the 12th of December he registered his patent, Figure 10, followed by another in January of 1940 (Colonnetti 1939c; Colonnetti 1940b; Colonnetti 1940a). Though the patent was based on ideas already present in the European patents, he distinguished himself for his highly original solutions.

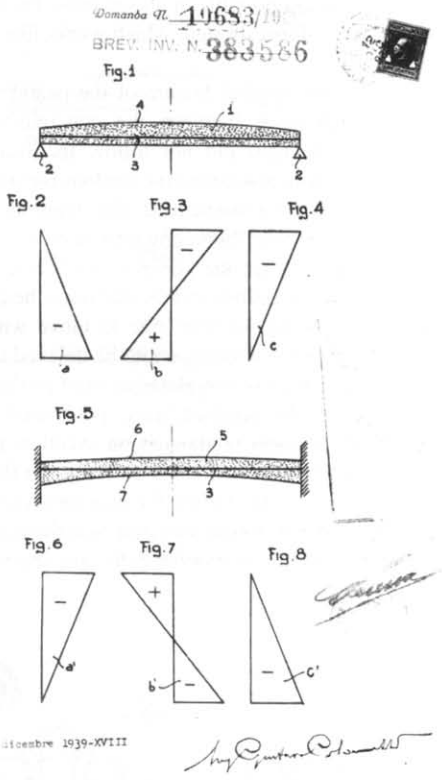


Figure 10
Italian patent n. 383586 by G. Colonnetti: *Trave armata ad armatura preventivamente tesa*, December 12th 1939. (Archivio Centrale dello Stato)

There were two particularly interesting aspects. The first is the form of the beam itself. Colonnetti designed an arched beam in which the height of the section changed constantly. His idea was to align the lower points in the kern of the sections of maximum positive moment, the upper points of the kern of the sections of maximum negative moment and the centres of mass of any sections of zero moment: this alignment also coincided with the line of action of the

resultant of the preventive tensioning of the tendons. In the beam thus formed, the static conditions of the arch were created, with the pressure curve contained entirely in the kern, but without thrust. The goal was obviously to make the materials work, each stressed according to its particular characteristics, at the maximum stress possible in all sections. The result is a beam of uniform strength which works like an arch without thrust.

The second original feature of the patent was the lack of adherence between the concrete and the tendons. Colonnetti did not follow the strategy of Dischinger, who positioned the tendons outside of the beam. Instead he embedded the tendons in the concrete, protecting them, however, with an isolating material which kept the concrete from coming into contact with the tendon: in this way once the concrete had cured, the tendon was free to move within the concrete and its tensioning could be delayed until the concrete had already completed most of its shrinkage. Furthermore, the tendons were positioned, unlike with the Dischinger method, in an excellent position with respect to the section for carrying out their task of pretensioning. Regarding the characteristics of the isolating material, Colonnetti proposed the use of thin metal foils, or more economically, by applying tar, bitumen or plastic cements based on rubbers, oils, and asbestos fibres, directly onto the tendons. In 1941, Colonnetti presented a simple system, Figure 11, for tensioning and anchoring tendons (Colonnetti 1941).

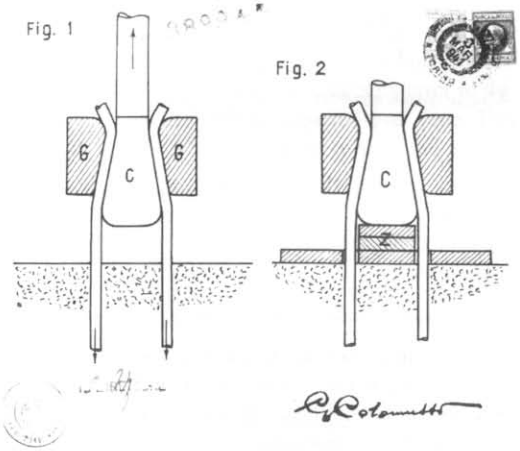


Figure 11
Italian patent n. 389946 by G. Colonnetti: *Dispositivo per la messa in tensione e l'ancoraggio delle armature nelle strutture in conglomerato cementizio*, March 3rd 1941 (Archivio Centrale dello Stato)

In the post-war period, the development of prestressed concrete substantially followed the path laid out by Colonnetti, though the tendons and not the beam took on a non-rectilinear configuration, sliding freely within specially shaped conduits.

But not even Colonnetti's immense enthusiasm could overcome the real limit to the development of prestressing in Italy: the unavailability of high-strength steel. A lack of prime materials, the incompatibility of Italian production lines, the impossibility of buying finished products abroad, not only because of economic problems but also because other nations in more favourable times had monopolised the market with long-term contracts — all these factors made serious experimentation impossible. Attempts by the Italian metallurgical industry —in particular Ilva and the Società Acciaierie e Ferriere Lombarde— to manufacture high strength steels from domestic prime materials resulted, unfortunately, in failure (Guzzoni 1942).

Nonetheless, stimulated by Colonnetti's work, new Italian patents soon arrived, including those by Luigi Magistretti (Magistretti 1940), Augusto De Fant (De Fant 1942), and Franco Mattiazzo (Mattiazzo 1942), Figure12, improving upon the techniques of tensioning and anchorage of the tendons in beams of prestressed concrete.

Experimentation soon followed in academic laboratories: in 1941, in the laboratory of the Construction and Bridges Institute of the Politecnico di Milano, Luigi Stabilini conducted load tests on partially pretensioned "Varese" type floor beams, having first built a special machine for tensioning rods to be incorporated in the concrete placement.

Industry was also very interested in the system. In 1941, the Società Anonima Cemento Armato Precompresso, Anonymous Society for Precompressed Concrete, or SACAP., was founded in Turin, encouraged by the engineer Giovanni Agnelli in order to favour development of the system (SACAP 1941). The SCAC company, having already experimented with its system of adherent wires in concrete poles, bought the rights to the Hoyer patents for beams, which had been deposited in Italy as well (Hoyer 1942a; Hoyer 1942b; Hoyer 1942c). They

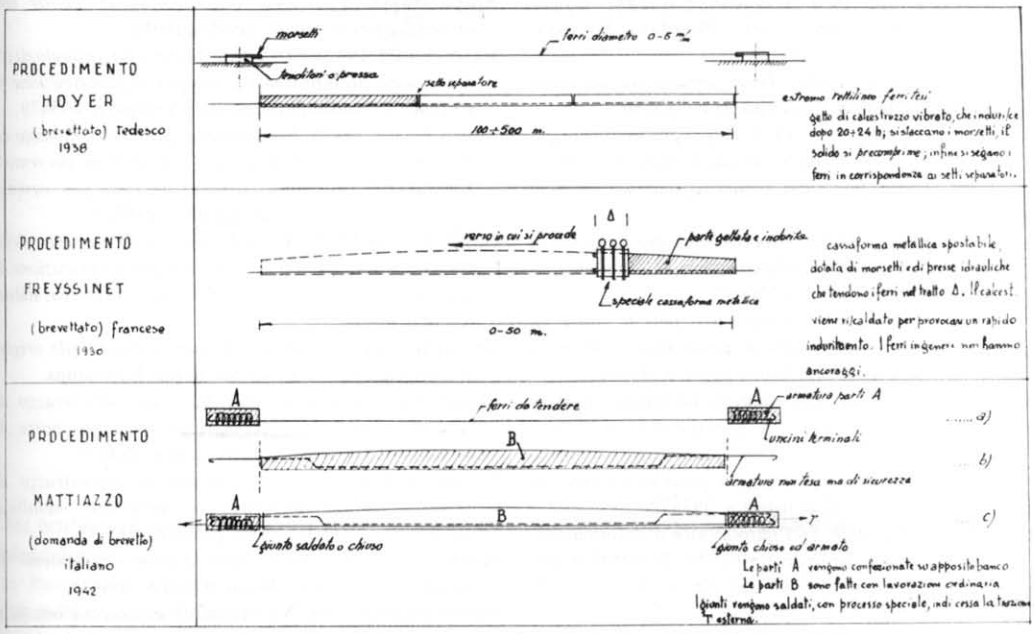


Figure 12
Comparison of the methods by Hoyer, Freyssinet and F. Mattiazzo in the Italian patent n. 402837 by F. Mattiazzo: *Struttura in calcestruzzo di cemento armato provvista di armatura metallica preventivamente tesa*, April 2nd 1942 (Archivio Centrale dello Stato)

built the first industrial plant for pretensioning in their factory at Monterotondo, making use of an «Ultracem»-type cement furnished by the Civitavecchia branch of Italcementi. Towards the end of 1942, they began experimental production in series of floor beams with an inverted T-section in concrete, prestressed with adherent wires (Cestelli Guidi 1947). However there is no documentation of the use of these beams, nor of any other structure in prestressed concrete, at least until the end of the war.

It was the war itself which restored a balance in the situation: the forced pause in large-scale building in general, the complete suspension of conferences and seminars, the irregular publication of books and journals, all favoured interest in the new technology.

The best engineers, aware of the new developments, took advantage of the interruption of design activity by conducting experiments in their own studios. In February of 1944, Riccardo Morandi appeared on the scene, registering his first patent which claimed the rights to a process for prestressing tendons by means of low voltage electrical current (Morandi 1944). Over the following years, this young Roman engineer would obtain exceptional results, redeeming the efforts of Colonnetti and all those who together with him had only been able to hypothesise the unattainable.

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