T h e   I n t e r n a t i o n a l   C o n f e r e n c e
PRESERVATION OF ENGINEERING HERITAGE - GDANSK OUTLOOK 2000
Gdansk, Poland September 7-10, 1999

Roberto GORI
Dipartimento di Costruzioni e Trasporti, Università di Padova, Italy

EARLY THEORIES ON REINFORCED CONCRETE BEAMS AND SLABS SHEAR ANALYSIS AND DESIGN

A b s t r a c t

European and American countries, as well as many other states of the world, possess a very important heritage of reinforced concrete constructions built at the turn of the 19th century, such as bridges, buildings, silos, reservoirs, and so on. In that period, a number of studies were performed with a view to evaluating the stress conditions in the structures built with this new material in mathematical terms, even if relatively little was published, as the engineers working in the reinforced concrete field considered construction and computational methods as trade secrets. By the turn of the century there was a multiplicity of systems and methods with little uniformity in design procedures, allowable stresses and systems of reinforcing.
The large part of the early studies were dedicated to compression and bending design. The problem of shear was not so much felt, giving very often to the concrete the task of absorbing the shear forces, mainly for slabs. The early introduction of ties and stirrups was given by practical suggestions and it was not directly accompanied by theoretical studies regarding the shear resistance capacity.
The various calculation methods of shear behaviour of beams and slabs, available from the scientific literature around the turn of the century are compared in this paper to investigate whether and to what degree these verification and/or design methods are still reliable. A purpose of the paper is also to verify whether there is any historical continuity between the hypotheses lying behind the early theoretical formulations and our understanding of today. The endpoint of this research is thus to provide an operator planning rehabilitation or restoration work with more efficient tools to facilitate a better philological interpretation of the structural behaviour of historical reinforced concrete structures.

1. INTRODUCTION

At the turn of the 20th century, still exists a very large number of constructions, bridges, fabrics, reservoirs, silos, sea piers, buildings, retaining walls, towers, with reinforced concrete structure, erected at the turn of the 19th century. They represent an inestimable richness in the wide panorama of industrial archaeology heritage of their countries, such as in Europe and in North America, where they are also a strong lively testimony of the development of contemporary engineering knowledge.
If, by one side, it should be present the need of conservation and preservation of such a technical cultural heritage, taking into account the complex phenomena of durability, very

often the main problems of planning rehabilitation or restoration projects reside in the lack of information about the actual mechanical characteristics of the structures, and in particular the hypotheses assumed by the earlier designer about the material behaviour, the safety criteria, the loading conditions, and so on. In the period in which such constructions have been erected, a large number of theories, often discordant, were developed and applied to the new constructions. A verification of the structural theoretical performances of such structures appears very important. Thus, the paramount role of a philological interpretation of the structural behaviour of historical structures made of reinforced concrete, appears evident for a designer planning restoration and rehabilitation projects. In addition, further structural analyses based on current international safety criteria, starting from the loading conditions assumed (or presumed assumed) by the actual early designer, are necessary for the validation of the existing structures. Of course a deep critical revision of loading hypotheses must be done, if required by the actual problem.

In previous works of the author [19, 20] the various calculation methods of bending behaviour of beams and slabs, available from the scientific literature around the turn of the 19th century have been already compared by the author to investigate whether and to what degree these verification and/or design methods are still reliable. In the present contribution a deep research carried out for the analysis and design of theoretical behaviour under shear internal forces according to the early theories, developed until the twenties, is reported.

2. EARLY RC CONSTRUCTION SYSTEMS AND THEIR RELATIONSHIPS WITH THEORETICAL APPROACHES

A number of *reinforced concrete patented systems* for civil structures were proposed in the second half of nineteenth century in Europe and North America, often (especially at the beginning) without a theoretical support. In Europe, after the early experimental proposals by J.L. Lambot (1855) and F. Coignet (1861), the first patents were due to Monier (1867-1869-1878), and then Ransome (1885), Cottancin, Bordenave, Bonna, Sociètè de Porte de France (1880-1900), Wayss (1879-1885-1890) [10]. In the last decade of the century other improved systems were proposed by Hennebique (1892-1899), Emperger (1892), Golding (1896), Lefort (1899), Chaudy, Khan, Möller, Locher, Baroni-Lüling (1895-1900). At the turn of the century a large number of systems were registered, between which De Vallière, Matrai, Münch, Luipold, Boussiron, Dégon (1895-1905), Coularou (1900-1910), Leonardi (1901), Siegwart (1902), Visintini (1903), Piketty (1906), Cemento Semiarmato (1906), Cicogna (1900-1910), Brazzola (1905-1909), Lehmann and Ercole (1905-1910) [10].

With a delay of several years from the invention, theoretical approaches were proposed to investigate the actual behaviour of reinforced concrete simple elements, in particular for bent beams and slabs. The aim of such theories was to allow reliable analyses and design of reinforced concrete beams or slabs sections in a period during which only experimental tests had been carried out. The first *theories on bending* have to be assigned to M. Koenen (1886), and then to M. Demay (1887-1890), M. Coularou (1889), M. Melan (1890), E. Coignet - De Tedesco (1894), M. R. von Thullie (1896), L. Lefort and C. Rabut (1898). In 1899 the theories of W. Ritter, M. Considère, P. Christophe [14], F. Hennebique were published [10]. At the beginning of the new century other contributions were proposed by S. Canevazzi (1901) [12], Gen. Caveglia (1903) [28], F. Leonardi (1904) [26], Kersten (1906) [10, 19]. As already remembered, a large number of such early theories have been analysed and compared together in detail in previous works of the author [19, 20].

The diffusion of analytical theories regarding the description of behaviour under shear of r.c. beams and slabs began very late. The need of linking possible cracks due to shear was present in mind of the early builders. François Hennebique in 1892 proposed flat stirrups, distributed along the beam, with a shorter space at the supports [34]. Other methods were suggested for

distributing stirrups: Boussiron in 1899 proposed vertical stirrups with a constant spacing; Edmond Coignet, in 1894, and Pavin de Lafarge, in 1895-97, suggested to connect the lower longitudinal bars to the upper bars by means of a continuous iron wire [19]; Coularou, Berger and Guillerme in 1908 proposed to distribute the stirrups at a 45° angle [7].
Between the early *theoretical approaches* for the analysis and design of RC sections *under shear* should be remembered those developed by L. Lefort in 1898-99 [25], by F. Hennebique in 1892-99 [8], by Blesio [10], M. Considère [10], P. Christophe [14, 17] and M. Harel de la Noè [22, 17], all proposed in 1899. At the beginning of the century other methods were published: S. Canevazzi (1901) [12], German Builders Society (1902) [17], Gen. Caveglia (1903) [28], F. Leonardi (1904) [26], Kersten [10], M. Pendaries [32, 16, 11], M. Piketty [7] and C. Pesenti in 1906 [33], E. Mörsch (1902-06-10) [29, 30], Societé Stulemeyer (1908) [7], Aubry (1912) [5] and Landini (1914) [23].
As examples of the numerical analyses carried out by applying the early theories on shear [10], in Figs. 2-3-4 some diagrams concerning reinforced concrete rectangular sections are shown, according to the theories of Hennebique, Considère and Canevazzi, respectively.

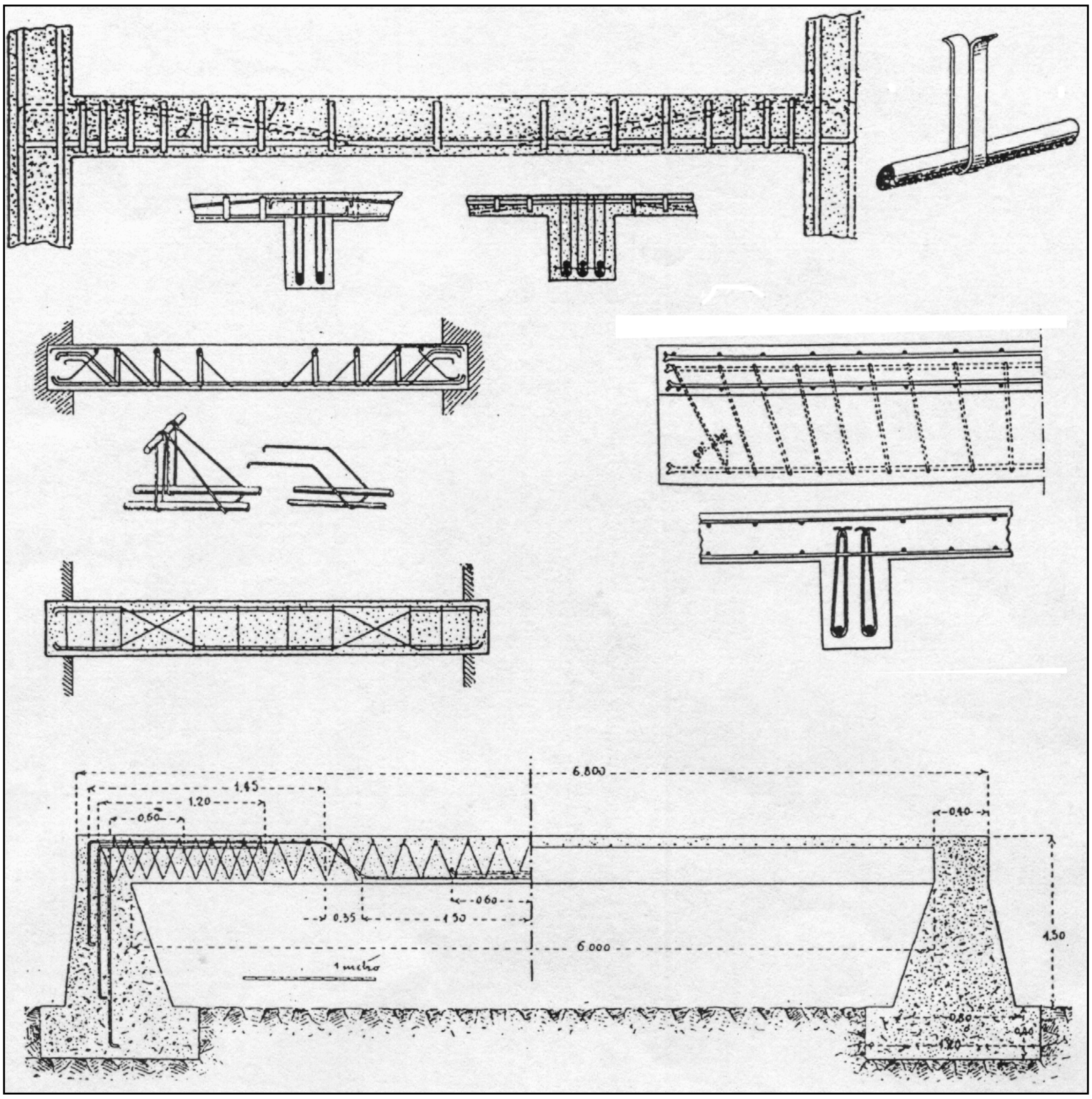

Fig. 1.
Some shear reinforcement systems for r.c. beams and slabs used at the turn of the century: Hennebique (1892-99), Münch (1900), Luipold (1905), Piketty (1906), Leonardi (1901-1904).

Fig. 2.
Analyses of r.c. rectangular sections by using F. Hennebique shear theory (1899).
Relationships between three of the parameters T (shear force), σ_{st} (stirrup stress), A_{sw} (stirrup area), b (width of the section), Δ_x (stirrup pitch), with the fourth one assumed constant (mean value), beam depth = 1 m, cover = 0.03 m, longitudinal bars area A_s = 80 cm^2.

Fig. 3.
Analyses of r.c. rectangular sections by using M. Considère shear theory (1899).
Relationships between three of the parameters T (shear force), σ_{st} (stirrup stress), A_{sw} (stirrup area), b (width of the section), Δ_x (stirrup pitch), with the fourth one assumed constant (mean value), beam depth = 1 m, cover = 0.03 m, longitudinal bars area A_s = 80 cm^2.

Fig. 4.
Analyses of r.c. rectangular sections by using S. Canevazzi shear theory (1901).
Relationships between three of the parameters T (shear force), σ_{st} (stirrup stress), A_s (longitudinal bars area), A_{sw} (stirrup area), b (width of the section), Δ_x (stirrup pitch), with the fourth and fifth ones assumed constant (mean value), beam depth = 1 m, cover = 0.03 m.

3. CONCLUSIONS

The theories for the shear analysis and design of the earliest r/c slabs and beams, developed in Europe around the turn of 19th century for the first time a number of years after the invention (and already a large diffusion) of this new construction material, have been examined here to investigate whether and to what degree these verification and/or design methods were correct and if they are still reliable for the control of stability of these structures. Several comparisons between the various approaches for the analysis of bent beams and slabs are extensively presented.

The target of this study was to give a further contribution to better understand the original choices of early structural designers and to allow a more correct and efficient restoration of old and historical reinforced concrete constructions by providing more efficient tools to facilitate a philological interpretation of their actual behaviour, from the structural point of view.

Acknowledgements

The research discussed in this paper was supported by Italian *Consiglio Nazionale delle Ricerche* through the grant CNR 93.02246.CT07 and CNR 95.0141.CT07.

REFERENCES

1. A.A.: Solai di ferro e cemento. *Giornale del Genio Civile* (1890), Istituto Poligrafico dello Stato, Roma, 204-208; Sulla deformazione del calcestruzzo di cemento armato. *Giorn. Genio Civile* (1902), Ist. Poligr. Stato, Roma, 379-382; Solidi di cemento armato sistema Visintini. *Giorn. Genio Civile* (1903), Ist. Poligr. Stato, Roma, 378-379; Le travi a traliccio sistema Visintini. *Il Cemento* (1904-05), S.E.T.S., Milano, 25-28; Le travi in cemento armato - travi sistema Siegwart. *Il Cemento* (1904), 145-148; Travi in béton armato sistema Demay. *Il Cemento* (1906), 198-199; Le costruzioni in cemento armato del sistema Brazzola. *Il Cemento* (1909), 17, 262-265; Solai in calcestruzzo armato. *Il Cemento* (1910), 132-134; Un nuovo tipo di solaio. *Il Cemento* (1911), 150-151; Disastri edilizi. *Il Cemento* (1908), marzo, 89.
2. AA.VV.: *Expérìences. Rapports & Propositions Instructions Ministerielles relatives à l'Emploi du Béton Armé.* Dunod et Pinat, Paris 1907.
3. ALBENGA, COLONNETTI, DANUSSO, GIANNELLI, KRALL, MARTINELLI: *Tecnica del Cemento Armato.* Edizioni della Bussola, Roma 1946.
4. ARGAN G.C.: *L'arte Moderna 1770/1970.* Sansoni, Firenze 1987.
5. AUBRY C.: *Calcul du beton armé.* H.Dunod et E.Pinat Éditeurs, Paris 1912.
6. BACH C., GRAF O.: *Spannung* σ_{bz} *des betons in der zugzone von eisenbetonbalken unmittelbar vor der rissbildung.* Wilhelm Ernst & Sohn, Berlino 1913.
7. BERGER C., GUILLERME V.: *La construction en ciment armé. Applications générales - Théories et systèmes divers.* H.Dunod et E. Pinat, Paris 1908.
8. BIGLIERI A.: Travi in Cemento Armato (sistema Hennebique) del Policlinico Umberto I° in Roma. *Giornale del Genio Civile* 28 (1899), Ist. Poligr. Stato, Roma, 581-589.
9. BLESIO D.: Costruzione di un solaio in Cemento Armato. *Giornale del Genio Civile* 11 (1899), Ist. Poligr. Stato, Roma, 99-112.
10. BOLZONELLA S., SOMMAGGIO G.: *I sistemi costruttivi del calcestruzzo armato in Europa tra fine '800 e inizio '900: aspetti tecnologici e analitici.* Grad. Thesis (rel. Roberto Gori), IUAV, Venice, a.a. 1997-1998.
11. CAMPANELLA G.: *Costruzioni in Cemento Armato.* Cav. N. Povene & C., Napoli 1910.

12. CANEVAZZI S.: *Ferrocemento. Formule di Elasticità e Resistenza.* Succ. Negro e C., Torino 1904
13. CAPOMOLLA R., VITTORINI R.: *Studi sull'Edilizia in Italia tra Ottocento e Novecento.* Edilstampa, Roma 1999.
14. CHRISTOPHE, P.: Le Béton armé et ses applications. Capitre IV, Theorie, *Annales des Travaux Publics de Belgique* (1899), 961-992.
15. DANUSSO A.: La logica e l'estetica nelle costruzioni in calcestruzzo armato. *Il Cemento* (1906); Sulla funzione delle staffe nelle travi in calcestruzzo armato. *Il Cemento* (1907), 1-7; Il cemento armato nella costruzione moderna. *Il Cemento* (1908), feb., S.E.T.S., Milano, 29-31.
16. DE TEDESCO N., FORESTIER V.: *Manuel Thèorique & Pratique du Constructeur en Ciment Armè.* Chap. 10, Libr. Pol. Ch. Béranger, Paris 1909.
17. DE TEDESCO N., MAUREL A.: *Traité Théorique et Pratique de la Résistance des Matériaux Appliquée au Bèton et au Ciment Armè.* Libr. Pol. Ch. Béranger, Paris 1904.
18. FUMAGALLI E.: Relazione tecnica sulla caduta del ponte in cemento armato presso Luino. *Il Cemento* (1905)*,* S.E.T.S., Milano, 55-56.
19. GORI R.: Theoretical performances of RC structural elements built at the turn-of-the century. *Journal Performance of Constructed Facilities*, ASCE 13 n.2 (1999).
20. GORI R.: Evaluating performance of RC beams using turn-of-the century theories. *Journal Performance of Constructed Facilities*, ASCE 13 n.2 (1999).
21. GUIDI C.: *Le costruzioni in Bèton Armato - Conferenze tenute nel maggio 1900.* Libreria S. Lattes & C., Torino 1901.
22. HAREL DE LA NOE: Théorie et applications nouvelles du ciment armé. *Annales des Ponts et Chaussées* (1899), 1° trim., E. Bernard, Paris, 1-21.
23. LANDINI A.: *Le Costruzioni in Cemento Armato.* Stab. Poligr. Emiliano, Bologna 1914.
24. LAVERGNE G.: *Étude des Divers Systèmes de Constructions en Ciment Armé.* Le Génie Civil, Baudry et C.ie, Paris 1899.
25. LEFÒRT L.: *Calcul des Poutres Droites et Planchers en Bèton de Ciment Armè.* Libr. Pol. Baudry ed C.ie, Paris 1899.
26. LEONARDI F.: *Cemento Armato. Sistema Ing. Leonardi,* Impresa F.lli Vender, Milano 1903; Ponte in Cemento Armato sul torrente Quisa. *Il Cemento* (1904), nov., 194-198; Influenza dei collegamenti nelle travature in cemento e ferro. *Il Cemento* (1905), S.E.T.S., Milano, 162-166.
27. MANDL J.: Zur Theorie der Cementeisen-Constructionen. *Zeitschrift des Österreichischen Ingenieur und Architekten Vereines* 45 (1896).
28. MARZOCCHI C.: Le applicazioni del Cemento Armato fatte dal Genio Militare. Sistema di solai del Gen. Caveglia. *Giornale del Genio Civile* 33 (1903), 497-527, and 43 (1903), 609-639; Le applicazioni del Cemento Armato fatte dal Genio Militare. Sistema di solai del Gen. Caveglia. *Giornale del Genio Civile* (1904), Ist. Poligr. Stato, Roma, 22-45.
29. MÖRSCH E.: *Der Eisenbetonbau, seine Anwendung und Theorie*, 1st edition, Wayss & Freytag, A.G., Im Selbstverlag der Firma, Neustadt, A.D. Haardt, Germany 1902.
30. MÖRSCH E.: *Teoria e Pratica del Cemento Armato.* Hoepli, Milano 1910.
31. NELVA R., SIGNORELLI B.: *Avvento ed Evoluzione del Calcestruzzo Armato in Italia: il Sistema Hennebique.* AITEC, Milano 1990.
32. PENDARIES M.: Note sur le calcul et sur la répartition des étriers dans Ies poutres droites en Ciment Armè. *Annales des Ponts et Chaussees* 3 (1906), E. Bernard, Paris, 73-96.
33. PESENTI C.: *Il Cemento Armato e il Cemento Semiarmato.* Ist. Italiano d'Arti Grafiche, Bergamo 1906; *Il Cemento Armato e la sua Applicazione Pratica.* Hoepli, Milano 1913.
34. RÉSAL J.: *Stabilité des Constructions.* Ch. Béranger, Paris 1901.
35. REVERE G.: Devonsi regolamentare le opere in cemento armato? *Il Cemento* (1906); Sul calcolo dei solidi inflessi in cemento armato. *Il Cemento* (1906), 277-280, 300-303.
36. VACCHELLI G.: *Le Costruzioni in Calcestruzzo ed in Cemento Armato.* Hoepli, Milano 1913.