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SPECIAL ISSUE
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Unspoken Modernity: Bamboo-Reinforced Concrete, China 1901-40

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Abstract: Engineering science in the China of 1901-40 had unique characteristics that disrupt the idea of a universal approach to its history.[1] The following case study describes the ideas and trials of introducing bamboo into the seemingly globalised technology of reinforced concrete—an innovation developed across the borders of mechanical, naval, civil, and aeronautical engineering. The article showcases a way of knowing and working by twentieth century engineers that has not been fully acknowledged, and is not only a phenomenon of China. While bamboo was a complicated and somewhat marginal object for engineering, it did make the European concrete technology more viable in the construction sites of China, and stimulate engineers' experimental and resourceful spirit in mobilising both craft and scientific knowledge. It also opened up a challenge to engineering science of the time.

Keywords: bamboo; craftsmanship; engineering; modern science; transdisciplinary knowledge

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[1] JoAnne Yates and Craig N. Murphy, *Engineering Rules. Global Standard Setting since 1880* (Baltimore: Johns Hopkins University Press, 2019).

Introduction

On the issue of knowledge making and circulation, recent scholarship has shown that twentieth century Chinese science cannot be interpreted only according to Western epistemological patterns, and that significant indigenous factors determined how science developed in that country.[2] But there is still an apparent bifurcation between approaches to imperial and modern China in science and technology studies. Dagmar Schäfer has recently sought to overcome this, offering a *longue-durée* account of the political roles Chinese bridge engineers played within Chinese societies from the premodern to modern ages.[3] Taking a similar position of stressing continuity, this study looks into engineers' expertise and details of practice *in situ*, especially problem-based matters and intellectual challenges that they acted on in fields and labs. The rise of academic disciplines and industrialisation, which largely shaped modern engineering science in the West,[4] had not yet been really established in China by the turn of the twentieth century.[5] Western engineering science, however, was already transforming the Chinese landscape on an ever-growing scale.

I concentrate on a group of engineers who had international and intercultural experiences related to China. They consisted of both practitioners and professors of engineering science, and included Chinese, Americans, and Europeans. While they applied science-based practices, universal for all engineers, they also shuttled between their expertise and dealing with the materiality of local environments, including fresh and difficult situations about Chinese sites that transcended their previous education and work experiences. Dealing with the unique

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[2] For some recent works on natural, agricultural, and medical knowledge see: Carla Nappi, *The Monkey and the Inkpot: Natural History and Its Transformations in Early Modern China* (Cambridge MA: Harvard University Press, 2009); Sigrid Schmalzer, *Red Revolution, Green Revolution: Scientific Farming in Socialist China* (Chicago: The University of Chicago Press, 2016); Sean Hsiang-lin Lei, *Neither Donkey nor Horse: Medicine in the Struggle over China's Modernity* (Chicago: The University of Chicago Press, 2014); Liz P. Y. Chee, "'To Cure a Hundred Diseases': Animal Blood Therapies in Mao's China," *Science, Technology & Society* 23, no. 2 (2018): 195-213.

[3] Dagmar Schäfer, "The Historical Roots of Modern Bridges: China's Engineers as Global Actors," in *Technology and Globalisation: Networks of Experts in World History*, ed. David Pretel and Lino Camprubi, 27-40 (London: Palgrave Macmillan, 2018).

[4] For two accounts on the Western disciplinary structure with very different standpoints see: Bernard V. Lightman, "The Evolution of the Scientific Disciplines," in *Victorian Culture and the Origin of Disciplines*, ed. Bernard Lightman and Bennett Zon (London: Routledge, 2019); and Bryan Pfaffenberger, "Social Anthropology of Technology," *Annual Review of Anthropology* 21 (1992): 491-516. For an earlier synthetic account see: Jan Golinski, *Making Natural Knowledge: Constructivism and the History of Science. With a New Preface* (Cambridge: Cambridge University Press, 2005), esp. 67.

[5] On the academic level, engineering science was established in China only from 1895. Prof. Dr. Li Shu-Tian, the then President of Pei-Yang University, offered an authentic overview on building engineering as a modern science in China: Shu-Tian Li 李书田, Engineering Education in China during the Past Four Decades, 1937. Collection of the American Society of Civil Engineers, T151.L5 1937 ESL, Linda Hall Library, Kansas City, MO.

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situation in China motived them to develop a broad professional network of institutional, social and personal connections from the nineteenth century onward. Meanwhile, the engineering community became a critical agency engaging China in the circulation of specialist knowledge. From 1901, engineers founded their own societies in Chinese cities like Shanghai, Beijing, Guangzhou and Wuhan, generating highly informative accounts discussing matters involving China in an expert capacity. In the forms of minutes, reports, periodicals and offprints, their publications were circulated across varied countries of Asia, Europe and North America. Young Chinese (student) engineers also brought fresh ideas and experiences to Western countries from the 1870s.[6] Engineering knowledge did not simply diffuse as one-way traffic from the West to China, as we shall see below.

My sources are unpublished laboratory reports and theses, and the previously uncharted files produced by four major engineering organisations based in China: The Shanghai Society of Engineers and Architects (hereinafter SSEA, 1901-11; later names ESS, 1912-13; ESC, 1913- c. 1950) and its annual *Proceedings of the Society and Report of the Council* (*PSRC*, 1901-39);[7] the Association of Chinese and American Engineers (ACAE) and its monthly *The Journal of the ACAE* (*J. ACAE*, Chinese title 中美工程師協會月刊, 1920-40) (Figure 1); the New York - Shanghai based Chinese Engineering Society 中國工程學會 (CES, 1918-31) and *The Journal of the Chinese Engineering Society* 中國工程學會會刊 - 工程 (*J. CES*) released from 1925; and fourthly, the 1931 regenerated Chinese Institute of Engineers中國工程師學會 (CIE, 1931-present) with its *Engineering Weekly* 工程週刊published from 1932.[8] These China-based societies systematically collected books, journals, proceedings, and transactions from their Western counterparts, including the Institution of Civil Engineers, Institution of Mechanical Engineers, and Institution of Electrical Engineers based in Britain, and the American Society of Civil Engineers, Franklin Institute of Philadelphia, and American Institute of Electrical Engineers based in the USA. Conversely, some American institutions like the Society of Civil Engineers collected engineers' accounts from China in a prompt and orderly manner.[9]

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[6] Shu-Tian Li, Engineering Education in China, 1937, T151.L5 1937 ESL.

[7] The SSEA was a British network active between 1901 and c. 1950, later named The Engineering Society of Shanghai (ESS, 1912-13) and The Engineering Society of China (ESC, after 1913). Two recent accounts analysed this organisation's activities in 1901-39: Michiko Kobayashi and Hideo Izumida, "Bulletins of Architects and Engineers Association in Modern China. A Study of the Engineering and Architectural Society in Modern China, Part 1," *Journal of Architecture and Planning* 76, no. 669 (2011): 2247-53; Michiko Kobayashi, "Analysis of Occupation and Working Place of the Members of 'the Engineering Society of China'," *Journal of Architecture and Planning* 80, no. 718 (2015): 2935-42.

[8] For a recent monograph on the institutional history of the Chinese Institute of Engineers, see: Fang, Zheng 房正, 近代工程师群体的民间领袖: 中国工程师学会研究 1912-1950 [*A Study on the Chinese Institute of Engineers, 1912-50*] (Beijing: Jing-ji ri-bao chu-ban-she, 2014).

[9] The China collections by the American Society of Civil Engineers are now conserved in Linda Hall Library, Kansas City, USA.

Figure 1. Members at the Annual Convention of the ACAE, Beijing, October 1924.
Source: *J. ACAE* 5, 10 (1924), no page number.

These sources also give us a detailed picture of the engineers' way of working, or what Karin Knorr-Cetina has called their "epistemic culture."[10] The term "modernisation" frequently appears in the materials, and this ideal constitutes an essential motive and motif in engineers' accounts, whether Chinese or foreign. Their themes varied from theoretical discussions to practical problem solving in a broad range of fields, as well as professional education and institutional development. Immersed in Western modern models and trained with Western knowledge, the engineers still devoted notable space to concrete local conditions and problems, and showed their intellectual and pragmatic capacities in coping with new challenges. The dichotomy of *episteme* and *techne*, which are sometimes presented as distinct forms of knowledge,[11] does not apply to the engineering experiences that I have examined. More important were new struggles and tensions that arose between applying established science from the West and new circumstances and their solutions that arose in China. Among the societies, the Chinese CES and CIE devoted comparatively less space to theoretical discussions than did the SSEA and ESC. The SSEA and ESC in nearly every aspect followed the model set by the nineteenth

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[10] Karin Knorr-Cetina, *Epistemic Cultures: How the Sciences Make Knowledge* (Cambridge MA: Harvard University Press, 1999).

[11] Paul Richards, "Cultivation: Knowledge or Performance?" in *An Anthropological Critique of Development: The Growth of Ignorance*, ed. M. Hobart, 61-78 (London: Routledge, 1993), 61.

century British scientific societies and periodicals,[12] while the CES and CIE contained patriotic sentiment and anxieties about establishing modern science in China, similar to what Grace Shen found in her study of the Chinese geological community.[13]

The fact that some engineers mobilised, interpreted and transformed traditional Chinese experience in their practice and knowledge building provides an interesting counterpoint to their stated intention to "modernise." To elucidate this phenomenon, I borrow tools from current anthropological and sociological approaches to science, where actors are often described as "making" and "crafting" knowledge rather than discovering it through science.[14] Francesca Bray in particular has proposed a redefinition of "science," "technology," and "techniques" based on her broad studies of late imperial Chinese knowledge and practice.[15] This redefinition offers me a powerful theoretical tool to examine the knowledge, data, and information intrinsic to long-term Chinese experience as recorded in the engineering sources, while keeping a distance from what the authors purported in their writings. As far as material-based experience is concerned, my investigation is not restricted by any artificial boundaries between disciplines or fields of science. For this tactic I refer to, among others, Maikel Kuijpers's strategy of "blurring the boundary between science and craft" derived from his studies of prehistoric metal.[16] The strategy works well with studies of modern engineering because the division between fields has constantly evolved over time and is still evolving.

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[12] Gowan Dawson, Bernard Lightman, Sally Shuttleworth, and Jonathan R. Topham, eds., *Science Periodicals in Nineteenth-Century Britain. Constructing Scientific Communities* (Chicago: The University of Chicago Press, 2020).

[13] Grace Shen, "Periodical Space. Language and the Creation of Scientific Community in Republican China," in *Science and Technology in Modern China, 1880s-1940s*, ed. Jing Tsu and Benjamin A. Elman, 269-95 (Leiden: Brill, 2014).

[14] Knorr-Cetina, *Epistemic Cultures*; Joan H. Fujimura, *Crafting Science: A Sociohistory of the Quest for the Genetics of Cancer* (Cambridge: Harvard University Press, 1997); Paul Rabinow, *Making PCR: A Story of Biotechnology* (Chicago: University of Chicago Press, 1996); Steven Shapin, *A Social History of Truth: Civility and Science in Seventeenth-Century England* (Chicago: University of Chicago Press, 1994).

[15] Francesca Bray, "Science, Technique, Technology: Passages between Matter and Knowledge in Imperial Chinese Agriculture," *British Journal for the History of Science* 41 (2008): 319-44, on 320: "'Science' I define as knowledge about natural, material processes expressed in declarative, transmissible form; its representations generally aspire to be authoritative beyond the time and place of their production. 'Techniques' I define as the skilled practices that go into the material production of knowledge as well as the production of artefacts. 'Technology' denotes social–material networks or systems, including sets of techniques and equipment, but also trained personnel, raw materials, ideas and institutions. Technology in this sense of networks or systems is here of twofold interest, first as generating material goods and social relationships, and second as contributing to the production or reproduction of the kind of knowledge I have termed 'science.' Thus defined, science, techniques and technology are not separate kinds of activity but rather overlapping phases of an organic process of knowledge production."

[16] See in the forum "History of Science, Technology and Medicine: A Second Look at Joseph Needham": Maikel H.G. Kuijpers, "Materials and Skills in the History of Knowledge: An Archaeological Perspective from the 'Non-Asian' Field," *Technology and Culture* 60, no. 2 (2019): 604-15.

Between materiality and science: modern reinforced concrete and the ersatz in China

The origins and development of modern reinforced concrete have been extensively discussed by architects and engineers in the context of construction history.[17] Modern reinforced concrete is both a composite material and a technology for building structures, with huge advantages in flexibility, efficiency and fire-proofing. In Europe, the continuing development and industrialisation of modern cement, iron and steel throughout the long nineteenth century shaped and boosted reinforced concrete technology, considering its antique origins. Its innovativeness lay in the combination of two parts. The concrete part, which was a mixture of granulates and cementing mortar, was still being refined in the mid-nineteenth century when modern cement—representatively Portland cement—was industrially produced as a binder in Britain. The reinforcing part, usually made of iron or steel in varied forms like girders or bars, was buried inside the concrete, which ensured the crucial advantage of fire-proofing. In terms of mechanical-structural behaviour, the reinforcing material provided a high toleration for tensile strain while the concrete resisted compression. By designing appropriate forms and composition of the materials, each part played a specific and complementary role so that, as a whole, multiple unprecedented advantages for construction could be achieved.

In England, the earliest reinforced concrete innovations were often recorded as patents.[18] During the period of 1850-1914, its use rapidly extended from foundations and floor systems to wall and column structures. Engineers were at the forefront of this development in construction industry, which only subsequently caught the attention and enthusiasm of architects.[19] By the

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[17] Among many studies of concrete, see: Joyce M. Brown, "W. B. Wilkinson (1819–1902) and his place in the history of reinforced concrete," *Transactions, Newcomen Society for the Study of the History of Engineering and Technology* 39 (1966): 129-42; Patricia Cusack, "Agents of Change: Hennebique, Mouchel and Ferroconcrete in Britain, 1897-1908," *Construction History* 3 (1987): 61-74; Stuart Tappin, "The Early Use of Reinforced Concrete in India," *Construction History* 18 (2002): 79-98; Roberto Gargiani, *Concrete, from Archeology to Invention 1700-1769* (Lausanne: EPFL Press, 2013); Armande Hellebois and Bernard Espion, "Structural Weaknesses of the Hennebique Early Reinforced Concrete System and Possible Retrofitting," *Structural Engineering International (IABSE)* 23, no. 4 (2013): 501-11; Edwin A. R. Trout, "The Deutscher Ausschu Für Eisenbeton (German Committee for Reinforced Concrete) 1907-1945. Part 1: Before World War I." *Construction History* 29, no. 1 (2014): 51-73; id., "The Deutscher Ausschuß Für Eisenbeton (German Committee for Reinforced Concrete), 1907-1945. Part 2: Between the Wars." *Construction History* 29, no. 2 (2014): 83-102; Federica Scibilia, "Earthquake-resistant Construction Techniques in Italy between 1880 and 1910: Alternatives to Reinforced Concrete," *Construction History* 32, no. 1 (2017): 63-82; Manuel Arturo Román Kalisch, "Construction Technology Development in Merida, Yucatan, Mexico: From Reinforced Concrete Structures to Reinforced Concrete Shells (1903-64)," *Construction History* 32, no. 2 (2017): 109-30.

[18] Cusack, "Agents of Change," 62-5.

[19] Charles Drake, "Concrete Building, Its History and Advantages. A Paper Read at the Civil and Mechanical Engineers' Society, London, by Charles Drake, 13th March, 1874" (London: R. Tilling, 1874), 1-16, on 9. Zi-Ka-Wei archival collection, code AL 14-739, Shanghai Library. For examples of

turn of the twentieth century, it had become a popular and fast growing technology in both Europe and America. The Western processes of developing reinforced concrete involved both practical know-how and scientific know-why.

Reinforced concrete technology generated different institutional and social patterns of use across different countries. For instance, the social historian Amy Slaton has revealed how the technology drove change in the American building world by redistributing and reconstituting expertise, labour, production processes and commercial enterprises between 1900 and 1930. Gregory Clancey has described the unique role "ferro-concrete" played in Japan's adoption of earthquake engineering, and how this in turn shaped Japan's complicated urban design politics and particularly its seismic challenges.[20] China, on the other hand, had not yet developed the capacity to produce cement and steel in satisfactory quality and sufficient quantity by 1900. This constituted a new struggle and set of opportunities distinct from those of either the US or Japan.

In the West and Japan, mathematisation and codification stood at the core of the theoretical approach to reinforced concrete. One milestone occurred in 1886 with the publication of a calculating method by the German engineer Matthias Koenen (1849-1924).[21] Koenen had a special interest in the use of mathematics in construction. The accuracy of his 1886 method for designing reinforced concrete slabs was later corroborated, at a time when most calculation methods were graphic (graphostatics).[22] In 1902, the Belgian civil engineer Paul Christophe produced a book entitled *Le béton armé et ses applications* (Reinforced concrete and its applications), which is currently considered the most comprehensive, state-of-the-art study of that period.[23] In 1906, the first codes for controlling the quality of reinforced concrete

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floor systems, see: Francis N. Spon, *Spons' Engineers' and Contractors' Illustrated Book of Prices of Machines, Tools, Ironwork, and Contractors' Materials for 1876* (London: Spon, 1876), 447 and 479; The Expanded Metal Co., *Expanded Metal and its uses in Fire-Proof Construction* (London: The Expanded Metal Co., Ltd., 1897); Louis Lefort, *Calcul des poutres droites et planchers en béton de ciment armé* (Paris: Librairie Polytechnique, 1899).

[20] Amy Slaton, *Reinforced Concrete and the Modernization of American Building, 1900-1930* (Baltimore: Johns Hopkins University Press, 2001); Gregory Clancey, *Earthquake Nation: The Cultural Politics of Japanese Seismicity, 1868-1930* (Berkeley, CA: University of California Press, 2006), esp. 224-25.

[21] Koenen's theory was firstly published as: Matthias Koenen, "Berechnung der Stärke der Monierschen Cementplatten," *Centralblatt der Bauverwaltung* 6, no. 47 (1886): 462.

[22] For recent accounts by engineer scholars on the pre-WWI practical-theoretical developments in Germany, see: Trout, "The Deutscher Ausschuβ Für Eisenbeton," 51-73; Wieland Ramm, "Über die faszinierende Geschichte des Betonbaus vom Beginn bis zur Zeit nach dem 2. Weltkrieg," in *Gebaute Visionen – 100 Jahre Deutscher Ausschuss für Stahlbeton 1907-2007*, ed. Deutscher Ausschuss für Stahlbeton im DIN Deutsches Institut für Normung (Berlin: Beuth Verlag, 2007), 27-130.

[23] Armande Hellebois and Bernard Espion, "The Role of the Belgian Engineer Paul Christophe on the Development of Reinforced Concrete at the Turn of the 20th Century," *Beton- und Stahlbetonbau* 108, no. 12 (2013): 888-97.

technology appeared in France.[24] Engineers in the US also collated information into a code of practice, organizing the first Joint Committee on Standard Specifications for Concrete and Reinforced Concrete in 1904.[25]

The theoretical framework for reinforced concrete was built upon the then prevailing methodology of experimental science. The aim was to predict the mechanical-structural behaviour of the material through abstract, mathematical models based on empirical observation. The data resulting from experimenting with reinforced concrete was codified with calculating models and mathematical formulae, which by then had become the primary language of science. These attempts at codifying knowledge represent a "scientification"[26] process in engineering that is deeply rooted in the classical hierarchy of modern Western science, led by mathematics and physics. The theoretical development did assist engineers in looking for the most efficient ways of understanding and manipulating materials, so that the resulting structural behaviour could be evaluated in an accurate, precise and predictable manner. This scientification and standardising process of reinforced concrete, in effect, shortened the distance between knowledge and practice, and thereby led modern building construction to become a far more efficient part of the Western system of engineering. This was a general trend in engineering science, covering even relatively traditional materials and construction methods based on brick and stone.

One result was the birth of a new genre of technical literature. In the long nineteenth century, both engineering knowledge in general, and the developing technology of reinforced concrete in particular, were amply documented in monographs, text books, handbooks, manuals and periodicals.[27] Parts of this literature reached China in the second half of the nineteenth century,

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[24] Michel Moussard, Patricia Garibaldi and Manfred Curbach, "The Invention of Reinforced Concrete (1848 – 1906)," in *High Tech Concrete: Where Technology and Engineering Meet. Proceedings of the 2017 FIB Symposium, Maastricht, the Netherlands, June 12-14, 2017*, ed. Dick A. Hordijk and Mladena Luković, 2785-94 (Cham: Springer, 2018), 2793.

[25] Joint Committee on Standard Specifications for Concrete and Reinforced Concrete, American Society for Testing, *Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete: Submitting Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete* (Detroit: American Concrete Institute, 1940), Preface.

[26] "Scientification" has been discussed regarding science-technology relationship in the context of building the Cathedral of Milan, with extended discussions from Renaissance to the twentieth century: Gernot Böhme, Wolfgang Van Den Daele and Wolfgang Krohn, "The 'Scientification' of Technology," in *The Dynamics of Science and Technology. Sociology of the Sciences. A Yearbook. Vol. 2*, ed. Wolfgang Krohn, Edwin T. Layton and Peter Weingart (Dordrecht: Springer, 1978); Gernot Böhme, Wolfgang Van Den Daele and Wolfgang Krohn, "The Scientification of Technology," in *Finalization in Science. Boston Studies in the Philosophy of Science*, ed. Wolf Schäfer (Dordrecht: Springer, 1983), 173-205.

[27] For a recent collation of the English-speaking works, see: Edwin A. R. Trout, *Some Writers on Concrete: The Literature of Reinforced Concrete, 1897-1935* (Dunbeath: Whittles, 2013). For some representative books then, see: Albert W. Buel and Charles Hill. *Reinforced Concrete* (New York: Engineering News Publishing, 1904); Homer Austin Reid, *Concrete and Reinforced Concrete Construction* (New York:

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mainly printed in the English or French languages.[28] At first, the readership of those technical materials was mainly the community of foreign engineers and technicians working in China, but it grew to include Western-trained Chinese engineers from the 1870s onwards. This kind of abstract and codified knowledge was efficient and powerful, yet it was also idealised and reductionist.

Practically speaking, China had to rely on imports of modern cement throughout the period of 1867-1930s; the recorded sites of export included Great Britain, Hong Kong, Haiphong of Vietnam, and Japan.[29] On Chinese building sites, the tension between the increasing demand for modern engineering materials and the shortage of supply was relieved, albeit only slightly, after several modern cement factories opened in Tangshan, Hubei and Guangdong provinces starting in the 1890s.[30] The Tangshan factory, later named Chee Hsin Cement Co., Ltd. 啟新洋灰有限公司, related to the British-led exploration of coal mining there. The same mining activities promoted the formation of Tangshan College of Railway and Mining Engineering 唐山路礦學堂 in 1906, with roots in two earlier special railway schools nearby.[31] The Tangshan factory offered a steady supply of quality Portland cement for decades.[32] Steel reinforcing bars of sufficient quality, however, remained scarce and expensive since modern steel-making had just been initiated in China.[33]

Clark, 1908); Napoléon De Tedesco and Victor Forestier, *Manuel théorique et pratique du constructeur en ciment armé* (Paris and Liège: Librairie Polytechnique, 1909); George A. Hool, *Reinforced Concrete Construction* (New York: McGraw-Hill, 1912); Charles Frederick Mitchell and George A. Mitchell, *Building Construction* (London: Batsford, 1912), 595.

[28] For a short list of this kind of engineering literature that has physically been circulated into China, see: Chang-Xue Shu, "Towards Western Construction in China: Views from Shanghai Brickwork and Printed Technical Resources 1843-1936," *Construction History* 33, no. 1 (2018): 83-110, on 90-1.

[29] The continuous data of imports can be found in the maritime customs archival collection: *Returns of Trade at the Treaty Ports in China. Open by Treaty to Foreign Trade. For the years 1859-1910. Published annually by order of the Inspector General of Customs*. Shanghai: Imperial Maritime Customs Press, 1860-1911. For a synthetic account from frontline engineers, see: Joseph H. Ehlers, "Chinese Engineering Materials," *J.ACAE* 5, no. 1 (1924): 21-35.

[30] An early record of the Tangshan cement was mentioned in Charles Beresford, "Openings for Mechanical Engineers in China," *Institution of Mechanical Engineers. Proceedings. 1899 Parts 3-4*, 527-65, on 531. There was also the British owned Green Island Cement Company producing in Macau from the 1880s, see: "Green Island Cement Co., Ltd. 1904," *The Far East Review*, December 1904, 19; "Green Island Cement Co., Ltd., Hong Kong 1905," *The Far-Eastern review*, March 1905, 35.

[31] The two railway schools were established by the Imperial North China Railway Bureau 北洋鐵路總局 in Shan-hai-guan in 1896 and Tangshan in 1905, respectively.

[32] A commemorative book for thirty-year anniversary of Chee Hsin Cement Co., Ltd. 啟新洋灰有限公司叁拾週紀念冊 (Tianjin: Chee Hsin Cement Co., Ltd., 1935). Tangshan Archive, available at: http://www.cnbksy.com/, accessed on 8 October 2017; Liu, Da-Jun 劉大鈞, *Zhong-guo gong-ye diao-cha bao-gao*中國工業調查報告 [Report on a survey of China's industry] (Nanjing: The Military Affairs Commission 南京軍事委員會統計處, 1937), 25.

[33] Ehlers, "Chinese Engineering Materials," 21-35; Yi-Bing Fang 方一兵, *Han-ye-ping Gong-si Yu Zhong-guo Jin-dai Gang-tie Ji-shu Yi-zhi* 汉冶萍公司与中国近代钢铁技术移植 [Han-Ye-Ping Iron and Steel

Tangshan's cutting-edge cement production in all likelihood impressed Hou-Kun Chow 周厚坤 (1889-?), a student enrolled at the new Tangshan College in 1906-10, who would become a major figure in the present story. Prior to that, Chow studied in Nan Yang Pubic School 南洋公學, Shanghai, set up in 1896 and transformed into Nan Yang Technical College in 1905. Both the Tangshan and Shanghai institutions played leading roles in educating Chinese engineers. Specialised schools for railway and mining, in particular, characterised China's earliest stage of developing modern engineering education from 1895 to 1900. From 1901 to 1910, a number of "Technical Colleges" were established, essentially modelled on the Japanese Technical Colleges of Tokyo and Osaka, with their teaching staff consisting of foreign engineers.[34]

One of these engineers was Herbert Chatley (1885-1955), who became Chow's professor at the Tangshan College and would become an active discussant on the issue of bamboo-reinforced concrete. Chatley had lectured in civil engineering at the Municipal College, Portsmouth from 1906 to 1908. Residing in China between 1909 and 1937, he worked in the Nanking-Hunan Railway (1915-16), assisted in the production of the first complete geological maps of the Yangtze valley (1918-19), and conducted the Shanghai Harbour Investigation from c. 1920. Chatley was a member of the Institution of Civil Engineers of Ireland and an associate fellow of the Royal Aeronautical Society. He served *The Engineering Society of China* (ESC) as President for two terms in 1927-29, and as Chairman of the Shanghai Association of the British Institution of Civil Engineers for three terms until 1936.[35]

It was Chatley's student Hou-Kun Chow who conceived the idea of utilising bamboo as a reinforcing agent for concrete structure technology sometime between 1906 and 1912, and made it as his MIT thesis topic in 1913-14 (Figure 2). Chow came from Wuxi, Jiangsu, a region at the eastern end of Yangtze River Delta rich in bamboo plants. Later in his career Chow would describe his vision this way:

> Although reinforced concrete has been used in China only to a limited extent, time will come when the wave of concrete construction in the West will spread far and wide in the East. For structures for which steel reinforcing will be too expensive, and where bamboo can do as well as steel, bamboo can displace steel.[36]

Company and the Transplantation of Steel-Making Technology in Modern China] (Beijing: Science Press, 2010).

[34] Shu-Tian Li, Engineering Education in China, 1937, T151 .L5 1937 ESL.

[35] Herbert Chatley, "The Geology of the Yangtze Valley Below Wuhu in Relation to Engineering Development," *PSRC-ESC* 19 (1920): 67-84, paper no. 3; Herbert Chatley, "Chairman's Address," *PSRC-ESC* 34 (1937): paper no. I.C.E. 1; "Obituary. Herbert Chatley, D.Sc. (Eng.), 1885-1955," *Proceedings of the Institution of Civil Engineers* 4, no. 4 (1955): 632-33.

[36] Hou-Kun Chow, "Bamboo as Reinforcing Material for Concrete" (unpublished Bachelor's S. thesis, Dept. of Naval Architecture and Marine Engineering, MIT, 1914), 1.

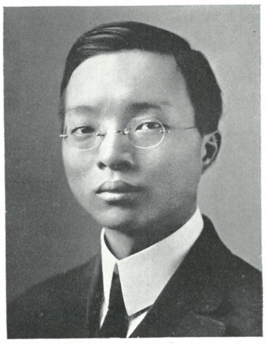

Figure 2. Hou-Kun Chow, *Senior Class Portfolio* 1914.
Courtesy of MIT Department of Distinctive Collections.

In the science of reinforced concrete, however, the commonly used mathematical models depended on high degrees of homogeneity in material, which the highly industrialised iron and steel girders could satisfy. Bamboo, a natural material which existed in varied hollow, non-homogeneous forms, introduced uncertainty into an engineering science then refining neat theoretical models. Could bamboo really be used as ersatz steel in concrete?

Knowledge across fields: bamboo becoming an engineering material

My historical sources show broad and frequent exchanges of ideas and information among early twentieth-century engineers across fields of specialty. Such exchanges in China occurred among civil, hydraulic, geodetic, railroad, municipal and architectural engineers (who all belonged to civil engineering in a broader sense) but also with mechanical, marine, electrical, chemical, mining and metallurgical engineers. Inter-field communication constituted an important way of developing engineering practice and knowledge. A recent study on the birth of "ceramic engineering" in modern-time China also provides firm evidence for such circulation.[37] It is within this culture of exchange across disparate fields that the novel idea of bamboo reinforced concrete emerged. As Chow described the inspiration for his insight:

> Bamboo has been extensively used in aeroplane work on account of its strength combined with its lightness. On modern machines, like the German Taubes, the tail spars are made of this material, being flexible to allow for sudden changes due to gusts. However, as in ships, steel has displaced wood, so steel tubings will displace bamboo poles when the final stage of development is reached. For small run-about aeroplanes, bamboo can be used to advantage beyond question.[38]

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[37] Chang-Xue Shu and Thomas Coomans, "Towards Modern Ceramics in China. Engineering Sources and Manufacture Céramique de Shanghai," *Technology and Culture* 61, no. 2 (2020): 437-79.

[38] Hou-Kun Chow, "The Strength of Bamboo," *Journal of the Association for Chinese and American*

Chow was awarded a Boxer Indemnity Scholarship to study in the USA, which he reached in September 1910. Enrolled at MIT, Chow firstly studied mechanical engineering (1912) and then naval architecture (1914); he received Bachelor of Science degrees in both fields and completed two theses on different subjects related to engineering materials.[39] Later he obtained the first American master of science degree from the newly established MIT program of aeronautical engineering (1915), a field which was not then really established in China.[40] Interested in the extensive use of bamboo in airplane construction, Chow joined the Curtiss Aeroplane and Motor Company in 1915. Afterwards, he began working on creating a Chinese typewriter.[41]

In the history of aeronautical engineering at MIT, two early milestones are attributed to, respectively, the mechanical engineering student Albert Wells, who in 1896 constructed a thirty-square-inch wind tunnel, and to Jerome Hunsaker, a graduate student in naval construction, who studied aeronautical literature and built a new wind tunnel to test aircraft models in the 1910s. Chow is acknowledged as the first person to earn the M.Sc. degree in aeronautical engineering at MIT, but he also assisted Hunsaker in the writing of the classic *Dynamic Stability of Aeroplanes* (1916).[42] This MIT history offers another example of the mobility of knowledge between the domains of mechanical, naval, and aeronautical engineering in the early twentieth century. The emerging field of aeronautics in particular provided Chow favourable conditions to test his ideas about bamboo at MIT. As he recalled in 1914, "the great tensile strength of bamboo inspired the author [Chow himself] to attempt to use it as a material for reinforcing concrete."[43] However, this rough description of "great tensile strength of bamboo" was

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Engineers 2, no. 4 (April 1921): 28-31, on 31.

[39] Hou-Kun Chow and S. S. Keh, "The Effect of Time on the Elongation and Set of Copper and Composition Wires" (unpublished bachelor's thesis, Mechanical Engineering, MIT, 1913); Chow, "Bamboo."

[40] Hou-Kun Chow, "Experimental Determination of Damping Coefficients in the Stability of Aeroplanes" (master's thesis, Dept. of Aeronautical Engineering, MIT, 1915). Zhong-guo Hang-kong Gong-ye Shi Bian-xiu Ban-gong-shi 中国航空工业史编修办公室, ed., *Zhong-guo Jin-dai Hang-kong Gong-ye Shi* 中国近代航空工业史 1909-1949 [A history of modern aviation industry in China] (Beijing: Hang-kong Gong-ye Chu-ban-she, 2013).

[41] A biography of Hou-Kun Chow is available at: http://chinacomestomit.org/chou-houkun/, accessed on 19 May 2018. The following work discusses Chow's invention of the Chinese typewriter in early computing studies of China: Thomas S. Mullaney, *The Chinese Typewriter: A History* (Cambridge MA: MIT Press, 2018).

[42] Lauren Clark and Eric Feron, "A Century of Aerospace Education at MIT," in *Aerospace Engineering Education During the First Century of Flight*, ed. Barnes W. McCormick, Conrad F. Newberry and Eric Jumper (American Institute of Aeronautics and Astronautics, 2004), 31-43; a condensed version available at: https://aeroastro.mit.edu/about/history. Philip N. Alexander, *A Widening Sphere: Evolving Cultures at MIT* (Cambridge MA: MIT Press, 2011), 265.

[43] Chow, "Bamboo," Preface, iv.

essentially a hypothesis based on Chow's Chinese experience with bamboo works and Western education in engineering. At this conceptual stage, he had yet to gather evidence.

Chow and his contemporaries could augment their experience with bamboo with the knowledge of European natural history. Bamboo was exotic in Europe, one of the enormous number of plants that continuously enriched European knowledge as colonization was accompanied by scientific discovery.[44] The nineteenth-century European knowledge of bamboo came from the Indian Peninsula, Middle and South America, East Asia, and regions of North America. Industrial and economic interests always accompanied the naturalists' studies of new raw materials outside Europe, such as bamboo.[45] By the turn of the twentieth century, bamboo's indigenous uses and processes, as well as its characteristics and economic potential, had well been noted, documented and studied by Europeans. Forestry and civil engineers had acknowledged bamboo's advantageous qualities as a construction material among its many other functions. Meanwhile, the knowledge of bamboo had become more popular and spread beyond foresters and botanists, thanks to its representation and propagation via museums, international exhibitions, and technical handbooks and manuals.[46] By 1911, the industrial use of bamboo for paper making had been well developed with manipulated chemical processes.[47] All the literature that resulted from these studies became references for Chow's MIT research on bamboo.

Engineers began mobilising bamboo as a resource, recognising its natural advantages of strength, lightness, and availability. Prior to WWI, in Germany and the USA, mechanical and civil engineers tested bamboo to understand its mechanical-structural strength, either independently or in the context of airplane and bridge construction; the data were published

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[44] Although Fa-Ti Fan did not devote particular space to bamboo, his wonderful monograph demonstrates the way British naturalists were changed by their work in China: Fa-Ti Fan, *British Naturalists in Qing China: Science, Empire, and Cultural Encounter* (Cambridge MA: Harvard University Press, 2004).

[45] For three extensive accounts on bamboo published between 1868 and 1896, see: William Munro, "A Monograph of the Bambusaceae, including descriptions of all the species," *Transactions of the Linnean Society of London* 26, no. 1 (1868): 1-157; Auguste Rivière and Charles Rivière, *Les bambous: végétation, culture, multiplication en Europe, en Algérie et généralement dans tout le bassin méditerranéen nord de l'Afrique, Maroc, Tunisie, Egypte* (Paris: Au Siége de la Société d'Acclimatation, 1878), 11-39; James Sykes Gamble, "The Bambuseae of British India," *Annals of the Royal Botanic Garden, Calcutta,* vol. 7 (London: Bengal Secretariat Press, 1896), 1-133.

[46] For popular accounts originated from engineers, see: James Sykes Gamble, *A Manual of Indian Timbers; an Account of the Growth, Distribution, and Uses of the Trees and Shrubs of India and Ceylon with Descriptions of Their Wood-Structure* (London: Sampson Low, Marston & Co., 1902), see the "Introduction," and 751-57, esp. 751; Gamble, "The Bambuseae of British India," 1-133; Paul Nooncree Hasluck, *Bamboo Work* (New York: Cassell, 1901), 9-18; Charles Henry Snow, *The Principal Species of Wood: Their Characteristic Properties* (New York: Wiley, 1909), Preface, 184-5 and 190-3.

[47] James Beveridge, *The Papermakers' Pocket Book: Specially Compiled for Paper Mill Operatives, Engineers, Chemists, and Office Officials* (London: McCorquodale, 1911), 82-3.

in engineering journals and textbooks.[48] From the late nineteenth century, bamboo was largely adopted for aeroplane design, especially in the wings and tails of the early "flying machines." Between 1903 and 1914, well-known examples such as the British Samuel Franklin Cody models, the German Taube and American Curtiss airplanes all employed bamboo as a construction material.[49] Bamboo was thereby pushed from a raw material of mostly colonial relevance to the forefront of engineering.[50] It was only after WWI that metal gradually replaced bamboo and other wooden materials in aeronautical design.[51] In botany, authoritative works on bamboo became rarer in the West between 1914 and 1926.[52] But this same period proved crucial for the new technology of bamboo-reinforced concrete.

The literature on bamboo resulting from both botany and aeronautical engineering provided a solid foundation for considering the use of bamboo in concrete structural technology. In the Shanghai of 1923, after years of pragmatic use of bamboo-reinforced concrete, engineers still referenced the 1908 methods of the Cody airplane and naval architecture in solving the problems of bamboo. For instance, in the annual meeting of the SSEA, American professor A. E. Richard de Jonge asserted that around 1908 "bamboo was proposed as a suitable material on account of its lightness, for the masts and spars of sailing yachts," and numerous experiments were made for improving bamboo's strength, which he himself engaged in. De Jonge shared

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[48] For the data of bamboo in the very popular textbook of engineering: John Butler Johnson, *The Materials of Construction: A Treatise for Engineers on the Strength of Engineering Materials* (New York: Wiley, 1904), 689. Two other studies of bamboo for aviation and bridge technology: Max Stuttgart Ulrich, "Festigkeitseigenschaften von Bambus-, Akazien-, Eschen- und Hickoryholz, sowie von Holzrohren," *Zeitschrift für Flugtechnik und Motorluftschiffahrt* 4, no. 18 (1913): 246-57; P. S. Bond, "Some Experiments in the Use of Bamboo for Hasty Bridge Construction," *Professional Memoirs* 5, no. 23 (1913): 593-602.

[49] For some early accounts from pilots and engineers, see: E. Meyer [a German pilot], "The Motorless Airplane, or Glider, in Germany," *U.S. Air Service* 5, no. 5 (June 1921): 32-3; William B. Stout, "A Thrill for Mankind at the Detroit Meet," *U.S. Air Service* 7, no. 9 (October 1922): 9-11, on 11; Bertram W. Williams, "Freaks That Flew," *Flying Magazine* 4, no. 5 (May 1929): 11-12, 84-6; Bruce Reynolds, "Pioneer Mechanic," *Flying Magazine* 62, no. 4 (April 1958), 40-6, on 41-2; Bureau of Naval Personnel, ed., *Naval Orientation* (Washington DC: U.S. Government Printing Office, 1961), 298. For historians' accounts see: Maurice John Bernard Davy, *Aeronautics, Heavier-Than-Air Aircraft. Volume 1. A Brief Outline of the History and Development of Mechanical Flight with Reference to the National Aeronautical Collection, Science Museum* (London: H.M. Stationery Office, 1949), 31; Peter Lewis, *British Aircraft 1809–1914* (London, Putnam, 1962).

[50] Another example is the use of gutta-percha in telegraphy cables. See: Bruce J. Hunt, *Imperial Science: Cable Telegraphy and Electrical Physics* (Cambridge: Cambridge University Press, 2021), 116, 120-4, 133-8, 142; Helen Godfrey, *Submarine Telegraphy and the Hunt for Gutta Percha* (Leiden: Brill, 2018), 39-59.

[51] Eric Schatzberg provided a provocative account on the change from wood to metal in the context of USA's airplane making: Eric Schatzberg, *Wings of Wood, Wings of Metal: Culture and Technical Choice in American Airplane Materials, 1914-1945* (Princeton: Princeton University Press, 1998).

[52] See the account by William Porterfield, a botanist and professor in biology: Willard M. Porterfield, *Bamboo, and Its Uses in China* (Shanghai: Chinese Government Bureau of Economic Information, 1926), 2-3.

his technical suggestion for bamboo-reinforced concrete with experimental data resulting from yacht designs made fifteen years before. The aforementioned Chatley also reminded engineers that the same method had already been successfully used by Samuel Franklin Cody in his 1908 aeroplanes.[53]

MIT 1914: revising knowledge of bamboo in the lab

In considering the use of bamboo as a structural material following the First World War, the China engineering societies widely acknowledged and quoted from two MIT theses authored by Chow and, another Chinese student Li Sing-Dji (sic). These were entitled, respectively, "Bamboo as a Reinforcing Material for Concrete" and "An Investigation of the Strength of Bamboo under Cracked and Weathered Conditions." The theses were submitted to Naval Architecture (Course XIII) and Mechanical Engineering (Course II) for the Bachelor of Science degree in 1914 and 1915.[54] Li's study built on Chow's, and both investigated the strength and properties of bamboo and the composite bamboo-reinforced concrete.

Figure 3. The first batch of Chinese bamboo poles arrived at MIT, May 1913. Source: Chow, "Bamboo," Preface.

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[53] For Chatley and de Jonge's accounts and the context see: Helge Fugl-Meyer and Bo Ekelund, "Tests of the Mechanical Property of Bamboo," *PSRC-ESC* 22 (1923): 141-64, on 161 and 164.

[54] Chow, "Bamboo"; Sing-Dji Li. "An Investigation of the Strength of Bamboo under Cracked and Weathered Conditions" (bachelor's thesis, Dept. Mechanical Engineering, MIT, 1915).

At MIT, for their thesis work, Chow conducted tests in the Applied Mechanics Laboratory, Institute Cement Laboratory, and Pierce Laboratory in 1912-14, and Li in the Testing Material Laboratory in 1913-15. Two batches of raw bamboo arrived at MIT in May 1913 and the winter of 1914, departing from Shanghai via trans-Pacific ships and over trans-continental railroads. The batches were in the form of bamboo poles (Figure 3) and strips respectively, indigenous to Zhejiang ("Chikiang" in Chow's spelling) province of China. But the climate in Boston (with its abrupt weather changes) cracked 80% of the twenty to thirty large canes in air storage,[55] which impacted the whole research scheme of Chow and necessitated Li's follow-up study. The cracked and weathered conditions of bamboo would indeed prove a challenge to engineering practices in China later on. Still, the raw materials were prepared at MIT into specimens for testing. A Beam Machine was used for beam tests, an Emery Machine for compression tests, a Rope Testing Machine and Wire Testing Machine for tension tests, and an Olsen Machine for column tests (Figure 4). Dean Peabody (1888-1951), instructor in the Department of Theoretical and Applied Mechanics, assisted Chow in the making and testing of the beam specimens.[56] Later on Peabody would write a textbook on reinforced concrete structures and become a proponent for the new technology of pre-stressed concrete at its earliest stage.[57]

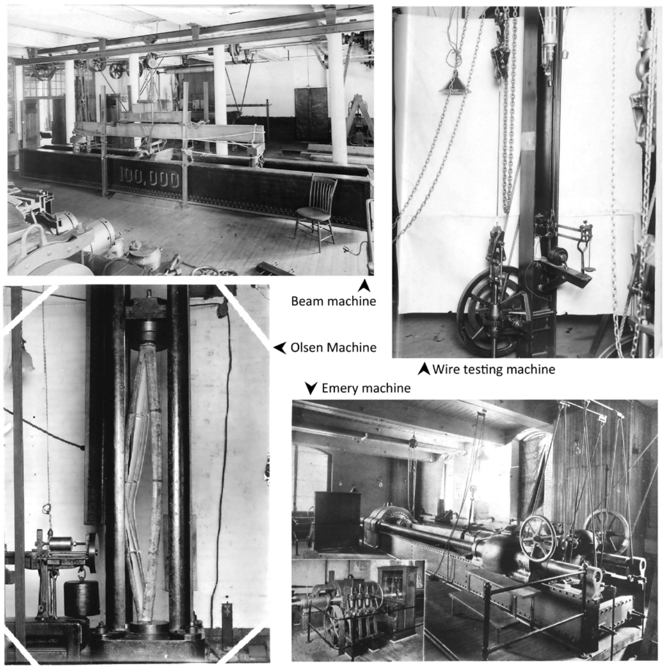

Figure 4. The MIT instruments used for testing, 1913-14. Source: Chow, "Bamboo," 1, 13, 31, 66.

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[55] Chow, "Bamboo," 63 and 76.

[56] Chow, "Bamboo," Preface, v.

[57] Dean Peabody, *Design of Reinforced Concrete Structures* (New York: Wiley, 1947).

Both Chow's and Li's studies had a strong practical orientation, aided by their experience and observations in China. Both also relied on theoretical and experimental approaches, combined with quantitative and qualitative analyses. The conventional engineering method of destructive testing was always used; it relied on finding points of failure in a specimen so as to understand that specimen's performance under different loads and conditions in question. Comparison between bamboo and other kinds of better-known materials—steel and other types of wood—became a shared approach; such reasoning by analogy extended from theoretical assumptions to discussion of results. Strength of material was always codified in the engineering language of compressive, tensile and shearing attributes that could provide quantitative data.

Chow drew upon a rich set of studies to supplement his own. He quoted not only the German and American structural engineers such as Max Stuttgart Ulrich, Paul Stanley Bond, and John Butler Johnson, but also foresters like James Sykes Gamble (1847-1925) and S. Kurz (?-?), French horticulturalists like Auguste Rivière (1821-77), English botanist and agrostologist William Munro (1818-80), the field entomologist Henry Guernsey Hubbard (1850-99), the chemical engineer James Beveridge (?-?), the civil engineer Charles Henry Snow (1863-1957) specialising in forestry and botanic topics, and the British diplomat and collector Algernon Bertram Freeman-Mitford (1873-1916).[58] Chow's great curiosity, keen discernment and powers of observation are apparent in his thesis.

Chow also interwove engineering methods with carpenter's methods and tools. In designing appropriate shapes for specimens, he revised the standard section of steel-reinforced concrete beam as recommended by the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete.[59] This decision was based on his theoretical examination of the factor of safety in section and his actual use of stirrup.[60] After the design, he made four specimens of beams from bamboo strips, steel bars and stirrups, cement, sand and water, and prepared them for beam tests. To obtain more referable data, he prepared seven groups of plain bamboo strips for tension tests, two bamboo canes for column tests,[61] and six plain concrete cubes for

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[58] Chow, "Bamboo," 119-20.

[59] Chow, "Bamboo," 2, 4-5. For his reference books see: John P. Brooks, *Reinforced Concrete: Mechanics and Elementary Design* (New York: McGraw-Hill, 1911); Ira Osborn Baker, *A Treatise on Masonry Construction* (New York: J. Wiley, 1909).

[60] Stirrups are often used for binding steel bars for shear reinforcement, i.e., to preclude the possibility of a shear failure. The design of stirrups got largely developed in the 1910s. See the then specialist knowledge on this matter: Ernest L. Ransome and Alexis Saurbrey, *Reinforced Concrete Buildings* (New York: McGraw-Hill, 1912), 1-17, 57; Frederick Winslow Taylor and Sanford E. Thompson. *Extracts on Reinforced Concrete Design: Selected from Concrete, Plain and Reinforced* (New York: Wiley, 1910), on 443, 446-8, 452-5, 472-3; Frederick Winslow Taylor, Spencer B. Newberry, Frank P. McKibben, William B. Fuller, R. Feret, and Sanford E. Thompson. *A Treatise on Concrete, Plain and Reinforced* (New York: Wiley, 1917), 372-3, 416, 419, 518, 522-6, 528-30, 557, 575, 585, 682.

[61] As mentioned earlier, Boston weather severely cracked the raw material. There were few bamboo remains appropriate for column tests. Only two were tested, which was insufficient for a scientific study.

compression tests. All the specimens used in these experiments were processed by hand. Chow depicted the handicraft details and architectonic methods at length in the making and using of wooden moulds, the preparing, placing and fastening of the stirrups, pouring concrete, and preventing other risks that might nullify the tests. The great care taken with those details, as Chow himself stated, was in order to "secure uniform results" and ensure "the greatest degree of accuracy as well as uniformity," which engineers had been pursuing. Also, Chow explained in detail his peculiar methods and techniques of fastening the tensile specimens in a machine for correct tension tests, since the conventional clamps could not hold bamboo sufficiently. Any tiny ignorance or lapses might impact or invalidate the tests, so he had to proceed with great care.[62] To explore bamboo's qualities in texture and hardness, Chow glued and trimmed bamboo by hand (Figure 5). He studied carpenter's tools and methods as they were used on bamboo, and referred to Hasluck's *Bamboo Work*.[63] By doing small experiments subsidiary to the main tests, Chow discovered that temperature was not an essential factor in bending bamboo strips by steaming. He even expressed the idea of inventing a machine for veneering Bamboo.[64] After the destructive tests, he dismantled the composite beams and, carefully examined the encased bamboo strips, stirrups, and bonding between bamboo and concrete, without mentioning if or not he used a magnifying glass.

Figure 5. Chow's handwork of bamboo for exploring its physical properties, 1913-14. Source: Chow, "Bamboo," 75.

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[62] Chow, "Bamboo," 33-6.

[63] Paul Nooncree Hasluck, *Bamboo Work,* 19-40.

[64] Chow, "Bamboo," 75-6.

The resulting data about bamboo-reinforced concrete beams did not always fit into the established theoretical models of steel-reinforced concrete. In the beam tests, for instance, a significant discrepancy was found between the theorised and actual loads. Chow ascribed the discrepancy to the wrong value of tensile strength of bamboo that he borrowed from the German airplane engineer Ulrich (1913). Chow's data on tensile stress of bamboo appeared much lower than Ulrich's. Chow thus revised a theoretic attribute that he previously used for designing the sections of the beam specimens.[65]

Chow devoted two sub-chapters entitled "The Cracks of Bamboo" and "Cross Sectioning of Bamboo" to an issue that conventional engineering methods could hardly cope with. He provided a noteworthy morphology of the cracks, and associated the microstructure of bamboo with the cracking problem and the tensile strength.[66] Chow intended to use new thin-section specimens of bamboo to examine its microstructure by microscopy, and turned to an esteemed maker of wood cross sections, Romeyn Hough of Lowville, New York. But Hough reported his failure in cross sectioning bamboo, though he did not reveal the reason to Chow. Chow thus had to rely on the old thin-section images of bamboo published by Ulrich. The microscopy method had already been used by the above-mentioned forester Gamble (1902) and civil engineer Snow (1909) for other species of wood, and these constituted Chow's references.[67] Cross sectioning in order to prepare specimens for microscopy was a high-level craft, and it is still an essential technique supporting cement and concrete studies today.[68] Hough's failure in making cross sections of bamboo in effect prevented Chow and Li from using microstructure-based methods. In 1914-15, Li still used the conventional method of destructive testing to study cracked and weathered bamboo's fitness for engineering purposes.

Chow concluded that bamboo could contribute to the strength of a concrete beam, as the bamboo in concrete behaved very much like steel. In the absence of any better information, he proposed a very simple and practical methodology for designing bamboo-reinforced concrete, where bamboo strips were intended to substitute for steel bars:

> Design the beam as if it were reinforced with steel. Multiply the reinforcing areas of steel thus obtained by the ratio of the tensile stress of steel to that of bamboo (usually less than 3), and the product will be the reinforcing area for bamboo. This gives a factor of safety of 5.[69]

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[65] Chow, "Bamboo," 27-31.

[66] Chow, "Bamboo," 76-7.

[67] James Sykes Gamble, *A Manual of Indian Timbers*, Plate 1 after p. 4; Snow, *The Principal Species of Wood*, 13, 188.

[68] The mineralogist Jan Elsen provides a chronology of using thin-section method for mortar studies: Jan Elsen, "Microscopy of Historic Mortars: a Review," *Cement and Concrete Research* 36 (2006): 1416-24.

[69] Chow, "Bamboo," 31-2.

MIT 1915: the ignored discoveries

Both Chow and Li had observed that weathering and cracking were common flaws of bamboo. As Li summarised, bamboo fibres were prone to become bent and deformed; the material always cracked on account of weathering, and it absorbed moisture which caused deterioration. All these factors impacted its strength and other properties.[70] Thus a cause-and-effect connection between moisture and weathering was hypothesized. Chow and Li decided to increase moisture content in the bamboo specimens aggressively so as to obtain weathered conditions for follow-up tests.

In 1913-14, Chow immersed a specimen for a year in the dirty water of the pumping well under the floor of Pierce Laboratory at MIT, and afterwards conducted a tensile test upon it. The results could not prove that the immersion in dirty water caused general decay of the specimen. The test seemed to contradict the hypothesis that cracking was linked to moisture content. Chow thereby stated that "it is justifiable in concluding that the weather quality [i.e., durability] of bamboo is good."[71] This conclusion would become problematic, as later studies would prove.

In 1914-15, Li moistened bamboo specimens using three types of treatment. One was waterlogging, as Chow had done. The second was steam-moistening. The third treatment was drying up the specimen to its normal condition after either waterlogging or steam-moistening. Li controlled the tests and recorded the data, and made three important discoveries after comparing the results across shorter and longer periods of moistening. First, the combined treatment of firstly waterlogging and then drying up did harm the strength (compressive and elastic tension) of the bamboo specimens. Second, the steam-moistening treatment, compared to waterlogging, had more direct impact in reducing the strength (compressive and elastic tension) of the bamboo. Third, "bamboo strips have their maximum tensile strength developed when they contain about 24 per cent [of their own weight] of moisture. For 30 per cent moisture and perfectly dry specimens, the strength is not far below the maximum value."[72] As it turned out, the physical-mechanical-biological properties of bamboo were much more complex than Chow's initial reasoning of "tensile strength"[73] alone could codify.

In retrospect, questions of deterioration were then highly novel in the engineering domain of building materials. Li's discoveries were pioneering, yet are largely unknown today. The third discovery, that a certain degree of moisture content could favour tensile strength of bamboo, was still awaiting further investigation. Bamboo, or wooden material in general, has

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[70] Li, "An Investigation," 2; Chow, "Bamboo," 36-7.

[71] Chow, "Bamboo," 37-8.

[72] For the quotation see Li, "An Investigation," 21.

[73] Chow, "Bamboo," Preface, iv.

high sensitivity to moisture. However, the roughly established cause-and-effect connection between moisture and weathering, which formed the base of Li's plan of the tests, is itself problematic. Moisture is a necessary condition for "weathering" bamboo but not a sufficient one. The core difference between waterlogging and steam-moistening is that, in effect, the former provides anaerobic conditions while the latter creates an oxygen-rich atmosphere. Waterlogged anaerobic conditions generally favour preservation of wooden materials, while the combination of moisture and oxygen in sufficient amounts do harm to wooden materials. Moreover, it is moisture changes, not moisture itself, that accelerates deterioration of wood; repeated drying and wetting can quickly lead to cracking.

These insights come from more recent studies of wood deterioration, thanks to the growing domain of cultural heritage conservation after WWII, called heritage science today.[74] It has been well acknowledged that rich biotic and abiotic agents favour decay and deterioration (incl. cracks) of wooden materials, triggering complex biological-chemical-physical processes. Reducing surface moisture changes has become one of the conventional methods of preventing weathering in outdoor exposed wood. These findings have been achieved via other multidisciplinary methods, and supported by much richer evidence than was available in the early twentieth century.[75] Moreover, heritage science accompanied increasing interest in protecting and preserving valuable historical materials, backed up by international organisations like UNESCO and ICOMOS. Their missions were very different from Li and Chow's, whose motives were solving the practical problems of a shortage of iron and steel for civil engineering China.

Retrospectively, Li's first and second discoveries are essentially compatible with those which later conservation scientists have reported in more precise and accurate forms, and with better defined scientific language. Already in 1915, Li explicitly mentioned that his treatment of moistening-and-drying (i.e., moisture changes) induced "certain physical or chemical defects" in the bamboo specimens, which he was unable to explain.[76] Although Li's scientific discoveries

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[74] A short explanation of heritage science available at: https://www.iccrom.org/section/heritage-science.

[75] For example see: Robert A. Zabel and Jeffrey J. Morrell, "Wood Deterioration Agents," in *Wood Microbiology: Decay and Its Prevention*, ed. Robert A. Zabel and Jeffrey J. Morrell, 19-54 (Amsterdam: Academic Press, 2020); Nicola Macchioni, "Wood: Conservation and Preservation," in *Encyclopedia of Global Archaeology*, ed. Claire Smith, 11265–70 (New York: Springer, 2014); Mei-Ying Li, Bei-Song Fang, Yang Zhao, Tong Tong, Xiao-Hui Hou and Hua Tong, "Investigation into the Deterioration Process of Archaeological Bamboo Strips of China from Four Different Periods by Chemical and Anatomical Analysis," *Polymer Degradation and Stability* 109 (2014): 71-8; Nicola Macchioni, Benedetto Pizzo, Chiara Capretti and Gianna Giachi, "How an Integrated Diagnostic Approach Can Help in a Correct Evaluation of the State of Preservation of Waterlogged Archaeological Wooden Artefacts," *Journal of Archaeological Science* 39, no. 10 (2012): 3255-63; Olaf Schmidt, Dong Sheng Wei, Hong Thi Kim Tang and Walter Liese, "Bamboo and Fungi," *Journal of Bamboo and Rattan* 12, no. 1-4 (2013): 1-14.

[76] Li, "An Investigation," 13.

were path-breaking, his engineering approach and data on the deterioration problems of bamboo remained limited and insufficient.

Li provided practical suggestions for using bamboo in temporary and light structures on a theoretical basis since the laboratory analysis was limited. He again recommended bamboo for aeronautical construction for its lightness. Li's deterioration experiments confirmed what Chow had revealed with non-decayed bamboo strips: "They [bamboo specimens] either failed by splitting along the fibre or broke at the joint."[77] This "new" knowledge about the weakest points of bamboo, which was obtained through modern scientific methods, would be very useful for the engineers' fieldwork. In all likelihood, however, this knowledge was not new at all to any bamboo craftsmen, who had accumulated abundant experiences through working with the material.

When he returned to China in 1916, Chow first worked for the Commercial Press, Shanghai. Sometime between 1921 and 1923, he entered the Han Yeh Ping Iron and Coal Company 汉冶萍公司 as Chief Engineer. A 1921 record shows that Li had also been working for the same company at the site of Han Yang Iron and Steel Works 汉阳铁厂, Hubei province.[78] Both Chow and Li had good contacts with the engineering societies based in China, and were invited to comment in later discussions of bamboo.

New trials in the field, China 1916-21

Outside the MIT studies, the application of bamboo to modern concrete remained largely uncharted territory within engineering science. In 1914, Chow conservatively proposed that "bungalows, cottages, water tanks, culvert pipes, foot bridges, etc., can be reinforced with this material [bamboo]."[79] In the coming years, however, bamboo was employed on construction sites of China in ways that Chow did not anticipate. This usage attracted engineers' attention far more extensively in China than in the USA or Europe.

WWI suddenly caused a shortage of engineering materials and raised their cost in China, including the "inability to obtain steel girders." The prices of ordinary metal materials, such as steel reinforcing bars, steel plates and angles, and cast iron, increased by two to three times. From

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[77] Li, "An Investigation," 13, 17-22. See Chow's similar conclusion in: Chow, "Bamboo," 36-7.

[78] In response to an ACAE request in 1920, MIT provided Chow and Li's newest contact information as: "Hou-Kun Chow, c/o Commercial Press, Shanghai, China" and "Sing Dji Li, c/o Hanyang Iron & Steel Works, Hanyang, Hupei, China." The ESC member list, for the year 1923, records "1923 Chow Hou Kun, Han Yeh Ping Iron and Coal Co., S'hai." See: C. J. Carroll, "Progress Report of the Committee on Investigation of Bamboo as a Reinforcing Agent," *J. ACAE* 2, no. 4 (1921): 24-7, on 25; the "List of members," in: *PSRC-ESC* 22 (1923): 186.

[79] Chow, "Bamboo," 1.

1916, serious problems began to surface on construction sites, and engineers became annoyed at the high prices of timber, steel and iron, paint, etc. In the ESC, for the years 1916 and 1917, the Society's successive presidents, Reynolds and Cooper, opened their annual meetings by addressing problems of material supply at length. Cooper's 1917 speech particularly centred on local production; the locally produced cement and brick were considered satisfactory while iron and steel remained highly challenging.[80]

Meanwhile, the idea of utilising "native" materials—a growing trend among architects and engineers working in colonial contexts—found its opportunity in China. Discussions of "native" materials greatly increased in both the SSEA, ESC, and the ACAE. Into the 1920s, increasing attention was paid to "local interest" and traditional Chinese practices and techniques, the skilled Chinese labour, and political-cultural facets.[81] From November 1925, the ACAE changed its journal title from "The Journal of the Association of Chinese and American Engineers" to "The Oriental Engineer" (vol. 7, no. 1).[82] Even Chinese bridges and other forms of architecture came into the consciousness of engineers, stimulating technical discussions on "the use of the new reinforced concrete construction for buildings in the old Chinese style of architecture."[83] This trend was particularly evident among engineers rather than architects, offering new scientific viewpoints for indigenous building practices. It also coincided with the movement of "indigenisation" in Christian and Catholic missions to China.[84] The ideas

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[80] Frank Oswald Reynolds, "Presidential Address," *PSRC-ESC* 16 (1917): 3-20, on 5-6 and 16; John Sisson St. George Cooper, "Presidential Address," *PSRC-ESC* 17 (1918): 3-14. The "inability to obtain steel girders" is stated by Reynolds, "Presidential Address," 5.

[81] For two early accounts by engineers about local matters, see: William Barclay Parsons, *An American Engineer in China* (New York: McClure, 1900), esp. 198-220; Thomas Bunt, "Presidential Address," *PSRC-SSEA* 4 (1904): 3-28. For the emphasis on "local interest" see: Charles Joseph Carroll, "The Journal," *J. ACAE* 6, no. 10 (1925): 1, the Editor and Publisher's note. For an account on local relations between Chinese and foreign engineers see: John Sisson St. George Cooper, "The Engineer in China," *The Engineering Society of China. Proceedings of the Society and Report of the Council*, 1920-21, 20 (1921): 43-64.

[82] The English language used in *The Oriental Engineer* became very plain, sometimes anecdotal, and in a kind of newspaper-magazine style, compared to the earlier issues under the old name of Journal of ACAE.

[83] Henry Killam Murphy, "The Adaptation of Chinese Architecture," *The Oriental Engineer* (*J. ACAE*) 7, no. 3 (1926): 3-7, on 3; "Old Wine in New Bottles: Concrete and Ideas Retain Old Beauty of Orient and Add Strength of West," *The Oriental Engineer* (*J. ACAE*) 7, no. 2 (1926): 3-8.

[84] Here two architectural historians' works are very relevant. Jeffrey Cody's study on American architects and builders abroad already shows the use of indigenous building knowledge in both practice and education. See: Jeffrey W. Cody, *Exporting American Architecture, 1870-2000* (London: Routledge, 2003); effrey W. Cody, "'Results from Junk': Teaching Construction in China, 1926-1937," in *Proceedings of the 1997 ACSA International Conference, Berlin*, eds. Beth Young and Thomas C. Gelsanliter, 32-6 (Berlin: Association of Collegiate Schools of Architecture, 1997). Thomas Coomans has exhibited the similar phenomenon through studying Western Christian architecture in China. See: Thomas Coomans, "East Meets West on the Construction Site. Churches in China, 1840s-1930s," *Construction History* 33, no. 2 (2018): 63-84; Thomas Coomans, "The 'Sino-Christian Style': A Major Tool for Architectural

of localisation, combined with the consequences of the war, unceasingly pushed bamboo to become an engineering material for modernizing the country.

In Shanghai, on 21 November 1916, the previously-mentioned Chatley, Chow's former professor at the Tangshan College, read a paper about strength of materials at the ESC meeting. Referring to the MIT study of his student, Chatley only lightly touched on the subject of bamboo reinforcement for concrete, but the matter spurred lively discussions when new technical questions were raised by four other members. At this stage, the engineers were concerned by problematic adhesion between bamboo and concrete, especially the different degrees of expansion between the two materials in changing temperatures, a subject that was not addressed in the 1914-15 MIT studies. They also considered the decay of bamboo a serious question. Moreover, foreign engineers observed and specifically mentioned that the Chinese had already been "reinforcing" the hydraulic lime concrete with bamboo in Shantou, and many buildings built of bricks were reinforced with bamboo in Ningbo. Bamboo was recognised as "the universal structural material of China" according to one discussant.[85] In 1918, a certain E. J. Muller used ¼ inch square split bamboos, which were well soaked in water, as part of the reinforcement for a two-inch wide concrete wall designed as a protection for ten-inch cork insulation of a cold store for the International Export Co. in Nanjing. This wall construction met all expectations.[86]

Regarding the actions of engineers throughout the 1920s, it is hard to differentiate explicitly between "laboratory" study and field application in terms of their use of bamboo technology. Experiments were conducted not only in labs but also in the field. Construction sites all over China constituted a total laboratory, at a time when national regulations and codes were not really established. Important steps were taken to explore the novel hybridity of bamboo and cement concrete, yet in highly diverse circumstances and geographical and geological conditions. At times, the same actions occurred on very different sites without communication between them. Above all, the engineering potential of bamboo and the relative quality-price efficiency of bamboo reinforcement were always acknowledged.

The ACAE held its first General Meeting in Tianjin, on October 6-8, 1920, where Charles Joseph Carroll's paper entitled "Bamboo Reinforced Concrete Foundation Piles used on the Szechuan-Hankow Railway," was the first subject discussed. This is probably the earliest recorded discussion about a work of bamboo-reinforced concrete, with fresh data, bold

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Indigenization," in *Sinicizing Christianity*, ed. Yangwen Zheng, 197-232 (Leiden: Brill, 2017).

[85] Herbert Chatley, "Some New Notions as to the Strength of Materials," *The Engineering Society of China. Proceedings of the Society and Report of the Council*, 1916-17, 16 (1917): 21-39, on 29, 37-8. Chatley later recalled this 1916 discussion in a 1923 debate, see: Fugl-Meyer and Ekelund, "Tests," 160-61.

[86] Fugl-Meyer and Ekelund, "Tests," 163.

decisions, and great uncertainties expressed from the field. The audience were members from Beijing, Tianjin, Shanghai, Guangzhou, Hankou and other places of China, covering a broad geography. Carroll, an American engineer based in Hankou, wrote this piece without knowing about the earlier MIT studies in Boston or the ESC discussions in Shanghai. He then was serving as Chief Engineer of the Yichang-Guizhou Section and Acting Chief Engineer of the Hankou-Yichang Section in the Sichuan-Hankou Railway, responsible to the Director General, Jame Tien Yow 詹天佑, the "Father of China's Railroads." The 1919 formation of ACAE was motivated by the Chinese Government Railways, with political supports from both the Chinese Beiyang Government and the American side. A Committee on Construction Materials was formed as part of the ACAE mission. Carroll's presentation led to the formation of a special ACAE "Committee on Investigation of Bamboo as a Reinforcing Agent," which included Teh-Ching Yen from the Canton-Hankou railway, and Jick G. Wong and Carroll from the Sichuan-Hankou railway as members. Their follow-up studies were communicated in the next ACAE meeting held in Beijing, on April 6-7, 1921, where Chow also reported his 1914 MIT study.[87]

According to Carroll, the August 1919 Tienmen flood of the Han River, a source of the nearby Yangtze River, broke the Han River dykes and inundated the west of Hankou for approximately 100 miles in length by 15 miles in width to an average depth of about 18 feet. This brought up new risks to the foundations of the railway lines. The sub-soil timber piles of various bridges had to be replaced with concrete ones. In order to save the cost in reinforcing bars, Chinese engineers of the Sichuan-Hankou Line decided to experiment on site with bamboo as the reinforcing material. Amongst several hundred concrete piles, 28 of them were reinforced with bamboo instead of steel in three different types of design; 24 piles were of 22 feet length and the other 4 of 30 feet length. The 28 piles were used for several bridges "under various foundation or driving conditions." The paper reported that "the design, the construction, and the immediate supervision of the work were carried on under the able and efficient direction of the Chinese Resident Engineers." In installing bamboo-reinforced piles, the weight of the hammer-fall was reduced accordingly, and greater caution in handling was always used and emphasised; some defects appeared, which were not considered peculiar to the bamboo reinforcement but common to both the steel and bamboo types. As a result, the bamboo reinforcement was considered very satisfactory from a technical perspective, and with a cost 50% lower than the steel reinforced piles used in Hankou.[88] In these two ACAE reports,

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[87] For the historical context see: "The list of officers and Introduction," *J. ACAE* 1, no. 1 (1920): 1-3, on 2; King Yang Kwong, "General Meeting of the Association of Chinese and American Engineers; Address by President K. Y. Kwong," *J. ACAE* 1, no. 2 (1920): 2-3; "Annual Spring Meeting of the Association, Peking, April 6 and 7," *J. ACAE* 2, no. 4 (1921): 7; Saunders R. Blundstone, ed., *Universal Directory of Railway Officials. 1919* (London: The Directory Publishing, 1919), 205-6. American Society of Civil Engineers, *Year Book, February 10th, 1920* (New York, 1920*)*, 95; Chow, "The Strength of Bamboo."

[88] For the two railway reports on using bamboo-reinforced piles see: Charles Joseph Carroll, "Bamboo

the tracks of thought and reasoning by analogy between bamboo and steel are the same. The theoretical concerns and questions were principally in line with those raised in the 1916 ESC meeting.

The novelty in this project was the extended application of bamboo to sub-soil foundations of cement concrete piles for railway bridges, which was an extremely bold action. The pile foundation in a hydraulic environment, was indeed a new condition for bamboo-reinforced concrete. Neither Chow, Li, nor Chatley had shown any expectation that bamboo would be used for this purpose. The Chinese engineers' inspiration probably came from the abundant uses of bamboo in the upper and middle Yangtze River regions where the Sichuan-Hankou Railway was located and where bamboo forests grew; the ethnic minorities like *Tujia*, *Miao*, *Zhuang*, *Hui* and *Dai* groups largely used bamboo for building their bridges and houses in hilly and flooding conditions. Ernest Henry Wilson (1876-1930), a British botanical explorer and plant collector, provided vivid accounts of such bamboo forests and crafts based on his travels in Hubei and Sichuan provinces between 1899 and 1910.[89] On the railway site, moreover, the ACAE Special Committee had experimentally prepared concrete beams and slabs with steel and bamboo reinforcements. They suggested carrying on a series of tests with bamboo, with more scientific conclusions based on laboratory tests to be made in technical schools and colleges of China to reach "intelligent conclusions."

Between scientific minds and crafting hands: the standard tests and a new culture

In 1922-23, Pei Yang University at Tianjin (supervisor Joseph H. Ehlers), Nan Yang University at Shanghai (Kong-Huai Shih 施孔懷 and H. S. Dickerson), and the Whangpoo Conservancy Board (WCB) 黄浦水運管理局委員會, Shanghai, all conducted additional tests independently of each other on reinforcing concrete with bamboo. In 1923, the WCB provided the earliest results, and launched a discussion integrating the unpublished Pei-Yang and Nan-Yang data. But the data from different laboratories were not comparable because of the different apparatuses and methods used, a flaw the engineers took note of.

The WCB conducted about 220 tests in its Conservancy Workyard in 1922. The Public Works Department of Shanghai Municipal Council assisted. Simple yet reasonable methods were

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Reinforced Concrete Foundation Piles used on the Szechuan-Hankow Railway," *J. ACAE* 1, no. 2 (1920): 4-9; Charles Joseph Carroll and Jick G. Wong, "Progress Report of the Committee on Investigation of Bamboo as a Reinforcing Agent," *J. ACAE* 2, no. 4 (1921): 24-7.

[89] Ernest Henry Wilson, *A Naturalist in Western China with Vasculum, Camera and Gun: Being Some Account of Eleven Years' Travel*. Vol. 1 (London: Methuen, 1913), 17, 29, 32, 36, 49, 50-1, 53, 61, 77, 81, 108-9, 132.

used given the lack of modern testing apparatus. August Werner Hugo von Heidenstam (1884-1966), a Swedish Engineer-in-Chief of the WCB, supervised the tests. Bo Ekelund (1894-1983) and Helge Fugl-Meyer (1894-1975), two Engineering Assistants from Stockholm and Copenhagen respectively, carried out the study (Figure 6). Ekelund, who had studied at Yale University, was in charge of the Construction Department of the WCB from 1921 to 1923. As a result of the test, sufficient data became available for analysing the bending, shearing and tension stresses of bamboo and the destructive behaviours of the bamboo-reinforced concrete beams and columns. The WCB engineers did not consider the tested beam behaviour satisfactory, and thus used bamboo only “as reinforcement of concrete plates below water for a vertical bunding.” Reacting to the two consensus questions—the adhesion between bamboo and concrete, and the decay of bamboo underwater and in concrete—the WBC cut bamboo into thin laths in order to increase adhesion between the materials, which was a step beyond the ACAE treatment in the railway piles. The WCB engineers presented their study in a paper submitted to the ESC for discussion. On May 15, 1923, engineers including Chow Hou-Kun debated the paper at length. Fugl-Meyer criticised the aforementioned design methodology that Chow proposed as one conclusion in his 1914 MIT thesis. Chatley from the same WCB came up with a new hypothesis for the unsolved splitting problems in bamboo. The WCB also planned tests for the rate of decay of bamboo, but (potential) results seem never to have been published. At this stage, engineers commonly reaffirmed that bamboo surpassed most other kinds of wood in compression and tension. However, the WCB engineers also concluded that “its weakness towards shear limits its use in modern European structures, but the same weakness renders the material suitable for the more primitive needs of the Chinese farmer.”[90] In other words, they dampened enthusiasm for applying bamboo on a larger scale to buildings using European construction methods.

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[90] Fugl-Meyer and Ekelund, “Tests,” 154.

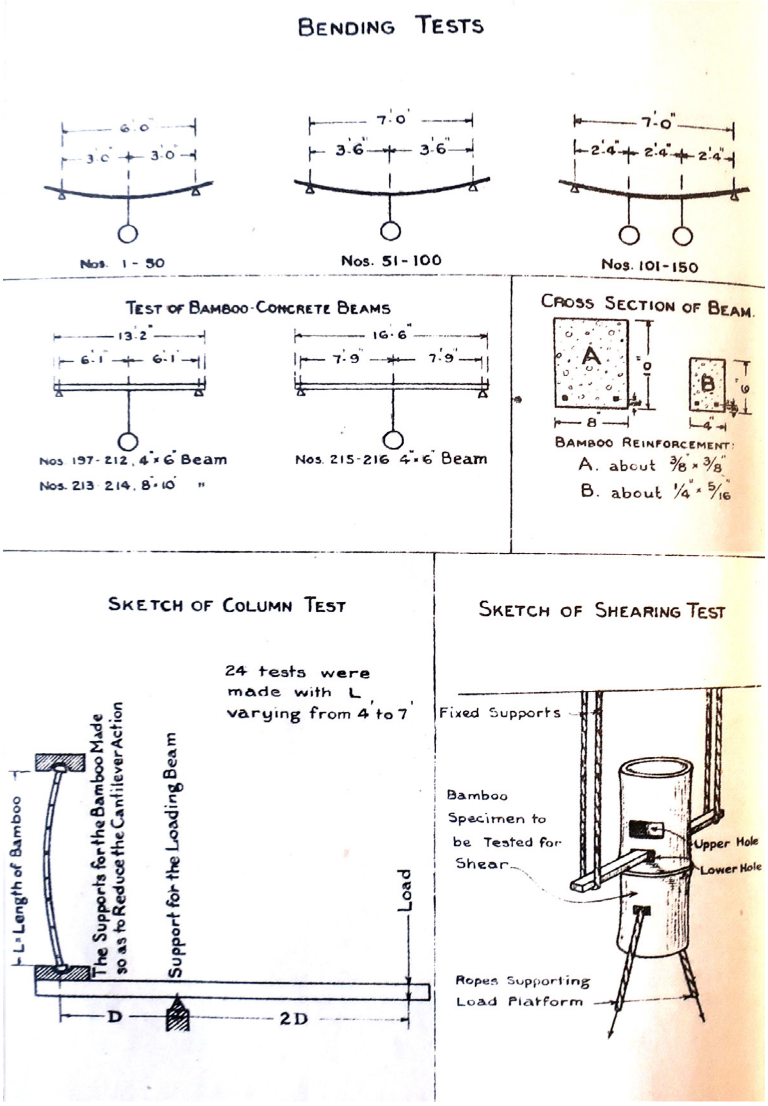

Figure 6. The methodology for testing bamboo's mechanical properties in the WCB, 1922-23. Source: Fugl-Meyer and Ekelund, "Tests," 142.

In the same 1923 meeting, a certain A. F. Gimson asked, "while everyone admires the bamboo structures erected in a purely empirical way by the Chinese, one often wonders whether better results might [or] not be obtained by employing a knowledge of the properties of the material in a technical sense."[91] But what was the "technical sense" for a modern Western engineer in the first half of the twentieth century?

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[91] Fugl-Meyer and Ekelund, "Tests," 162.

Nevertheless, the sharp contrast between many remarkable traditional Chinese crafts, such as bamboo work, and the scant technical literature about them impressed the European engineers and architects in China. They began to document Chinese science and arts in the field, and publicised the information within and beyond engineering societies.[92] Chatley, in particular, wrote about history of Chinese geology, the Chinese calendar and ancient astronomy in the 1920s and 1930s, amongst his over-forty papers and five books published in top intellectual journals and societies based in Britain, China, and the USA.[93] Helge Fugl-Meyer, meanwhile, published on Chinese bridges during his ten-year harbour construction experience in China.[94]

The WCB engineers well noted the aforementioned Ernest Henry Wilson's documentation of bamboo crafts as used in Chinese temples, farmhouses, bridges, canals, and the making of papers, sandals and ropes.[95] Inspired by Wilson, they studied bamboo materials and structures in varied sites along Yangtze river, including but not limited to, bamboo suspension bridges in west China on the Tibetan borders; bamboo ropes of the Upper Yangtze regions (for its tension stress); the innumerable Chinese ways of building bamboo houses, water-wheels, using bamboo as water pipe; and making bamboo furniture, carpets, and fences. They noted the

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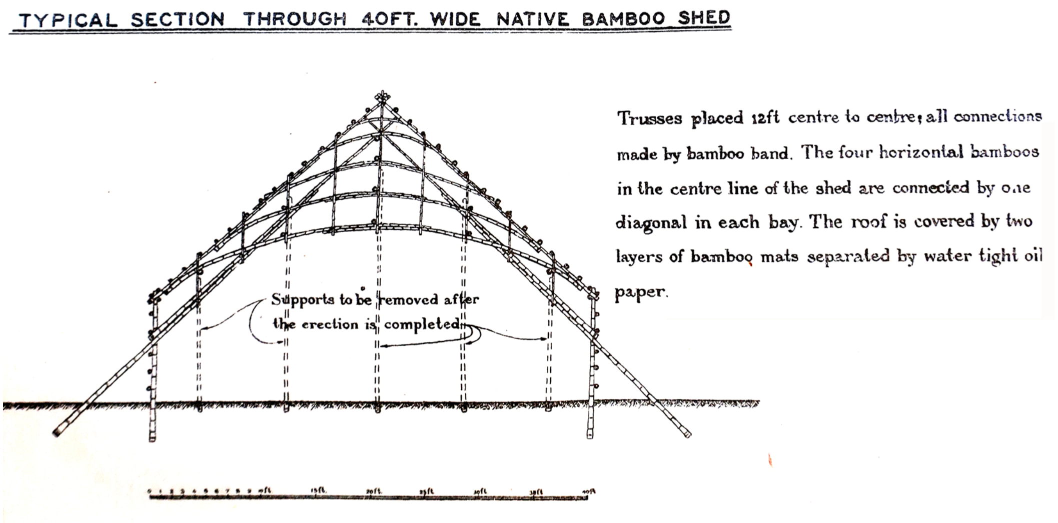
[92] For example: Wm. Barclay Parsons, *An American Engineer in China* (New York: McClure, Philips and Co., 1900); John D. Smedley, "Chinese and Japanese Art and Architecture," *PSRC-SSEA* 1 (1902): 75-89; John D. Smedley, "Chinese building," *PSRC-SSEA* 5 (1905): 155-69; Robert G. Skerrett and Joseph H. Ehlers, "Chinese Salt Wells and Equipment," *J. ACAE* 3, no. 1 (1922): 21-7; "White wax production in Sezechuen," *J. ACAE* 6, no. 2 (1925): 16-28; "Notes from Bureau of Economic Information," *J. ACAE* 6, no. 2 (1925): 28-32, on 29; James Hutson, "Irrigation works on the Min River岷山導江: From Mythical and Practical in Szechuen四川," *J. ACAE* 6, no. 8 (1925): 10-20; Alfred Emms, "The Practice of Joinery and Carpentry amongst the Chinese of the Yangtse Valley," *PSRC-ESC* 35 (1937): paper no. ESC.1, 1-78; Frederick Montague Gratton, "Notes Upon the Architecture of China," *RIBA Journal* 2, no. 3 (1894): 37-59, 59-64, 427; Ernst Boerschmann, *Baukunst und Landschaft in China: Eine Reise durch Zwolf Provinzen* (Berlin: Wasmuth, 1923); Ernst Boerschmann, *Chinesische Baukeramik* (Berlin: Lüdtke, 1927).

[93] See for example: Herbert Chatley, "Geology of Shanghai," *The China Journal of Science and Arts* [*CJSA*] 5, no. 3 (1926): 148; Herbert Chatley, "How Silk Came to Europe," *CJSA* 8, no. 5 (1928): 226; Herebrt Chatley., "Water Transport in China," *CJSA* 10, no. 5 (1929): 219-21; Herbert Chatley, "The Chinese Calendar," *CJSA* 19, no. 2 (1933): 91; Herbert Chatley, "The Sixty Year and Other Cycles," *CJSA* 20, no. 3 (1934): 129-30; Herbert Chatley, "Further Notes on Ancient Chinese Astronomy," *CJSA* 22, no. 1 (1935): 4-6; Herbert Chatley, "'The Heavenly Cover': A Study in Ancient Chinese Astronomy," *The Observatory* 61 (1938): 10-30.

[94] Helge Fugl-Meyer, "Chinese Bridges," *PSRC-ESC* 27 (1929): 1-26; Helge Fugl-Meyer, *Chinese Bridges* 中國橋樑 (Shanghai: Kelly and Walsh, 1937), on 119 and 123. Fugl-Meyer was a member of the Danish Institute of Civil Engineers and associated member of American Society of Civil Engineers. His 1957 book was adopted as a standard textbook for the students in harbor construction at the Technical University of Denmark: Helge Fugl-Meyer, *The Modern Port* (Copenhagen: Danish Technical Press, 1957).

[95] For his photographs taken in 1908-1910 see: Ernest Henry Wilson (1876-1930) papers, 1896-2017. Archives of the Arnold Arboretum of Harvard University, Cambridge, MA. Z-58, Z-101, Z-102, Z-299, O-29, O-172, O-214, O-259, O-260, O-341; for text descriptions see: Wilson, *A Naturalist in Western China*, 52, 56, 111, 120-1, 154, 171, 189, and 232.

huge scale of transportation of bamboo from south China to the middle and the north. They described the soil, season, and methods for bamboo planting. They particularly mentioned that "even parts of the furniture are made of clay plastered on a bamboo skeleton," which was nearly a prototype for bamboo-reinforced concrete. They summarised the typical section of Chinese bamboo sheds in Shanghai from constructive viewpoints (Figure 7).[96]


TYPICAL SECTION THROUGH 40FT. WIDE NATIVE BAMBOO SHED

Trusses placed 12ft centre to centre; all connections made by bamboo band. The four horizontal bamboos in the centre line of the shed are connected by one diagonal in each bay. The roof is covered by two layers of bamboo mats separated by water tight oil paper.

Supports to be removed after the erection is completed.

Figure 7. A summary of Chinese bamboo sheds, 1923. Source: Fugl-Meyer and Ekelund, "Tests," 142.

Moreover, Fugl-Meyer and Ekelund began to explain the Chinese ways of doing things using the results of modern laboratory tests. For instance, their column testing results reassured that the material of the outer layer was stronger than the inner one in a bamboo stem. They immediately related this scientific fact to the Chinese usage of the extreme layer of bamboo for bamboo-ropes and basket work, commenting that the fact had been "known by the Chinese for centuries."[97] The WCB staff related their own knowledge, which was obtained through several "scientific" tests, to the traditional Chinese know-how that resulted from innumerable craft practices, but had not yet been well documented. Their observations and descriptions were nearly ethnographical, yet with engineering eyes and "scientific" judgements and justifications. This kind of effort in explaining traditional Chinese practice repeatedly appears in the engineering materials authored by Westerners in the late nineteenth and early twentieth centuries. What was common between the contemporary Chinese engineers, such as Chow, Wong, and Shih, and the European engineers, like the WCB staff, was a shared curiosity for understanding the traditional techniques and know-how, which inspired them intellectually in their modern work in one way or another. But the European engineers held a

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[96] Fugl-Meyer and Ekelund, "Tests," 142.

[97] Fugl-Meyer and Ekelund, "Tests," 150.

cultural admiration for Chinese techniques and documented them systematically, which the Chinese engineers hardly ever did. The WCB experience, in particular, presages some of the work and approach of Joseph Needham (1900-95). Needham would largely consult and quote Chatley's and Fugl-Meyer's writings about traditional Chinese astronomy and bridge-building, respectively.[98]

Minor? Universal? Modern? The culture of engineering science

In writing histories of science and technology, discipline-based discourses usually address the sciences that finally become accepted and widely utilized. How then should we treat this kind of minor knowledge—such as using bamboo for engineering—that was not yet sufficiently developed within either engineering or biology, but highly mobile at the fringes of science? In making modern knowledge around bamboo, colonial botany and forestry paved the way to the later use of bamboo as an engineering material. Inversely, engineering activities and approaches continued to push forwards the knowledge about bamboo in the 1910s-20s, moving it through naval, aeronautical and civil engineering. In the 1920s, the engineering experiences returned to botanists who gathered new inspirations and generated new contributions to botany in China into the 1930s.[99] Later on, conservation science and biological deterioration studies added to the knowledge of bamboo. Such a mobility of knowledge was not at all a minor phenomenon within the engineering sciences.

In the scholarship around modern science, attention to knowledge flows across disciplines and fields has been never absent, but is increasing in recent work. Rudolf Stichweh, for example, has argued that the modern system of scientific disciplines has been characterized by both specialization and interdisciplinarity. The latter, he believes, "depends on borrowing and transfers. One picks up a concept, theory or method that has proven itself in a different discipline, and tries to make it fruitful in one's own by a gradual process of naturalization." Rens Bod and his colleagues also proposed an inclusive historiography of knowledge, "a focus

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[98] Joseph Needham, "Astronomy in Classical China," *Quarterly Journal of the Royal Astronomical Society* 3 (1962): 87. Chatley is also largely quoted in the *Science and Civilisation in China* (SCC)-3 and SCC-5-5: Joseph Needham, *Mathematics and the Sciences of the Heavens and the Earth* (Cambridge: Cambridge University Press, 1959), 751; Joseph Needham and Gwei-Djen Lu, *Chemistry and Chemical Technology. Part V: Spagyrical Discovery and Invention: Physiological Alchemy* (Cambridge: Cambridge University Press, 1983), 435. About Fugl-Meyer see SCC-4-3: Joseph Needham, Ling Wang and Gwei-Djen Lu, *Physics and Physical Technology. Part III: Civil Engineering and Nautics* (Cambridge: Cambridge University Press, 1971), 163, 168, 170, 192, 196.

[99] The China Society of Science and Arts published twelve articles on Chinese bamboo in its *CJSA* in 1923-33. Ten of these were authored by Willard M. Porterfield, an American botanist. Porterfield's 1926 monograph engages both engineering and botanical knowledge of bamboo, with new data and knowledge resulting from his survey of bamboo in China. See: Porterfield, *Bamboo, and Its Uses in China.*

on epistemic virtues, or on principles and patterns."[100] My study, on the other hand, elucidates how a material condition not only became the incentive for mobilising knowledge, but also played an epistemic role in making the engineering innovations and sciences. Materiality should not be overlooked in addressing "flow of cognitive goods."

The effort of using bamboo for reinforcing concrete was not successful in the sense of discovering new science. This is not only because of the inadequate condition for research and the practical motivation of substituting bamboo for steel. All the above-mentioned engineering tests were principally of the same methodology, which was circulated universally. But the making of modern knowledge of reinforced concrete was not universal; it was, in fact, strictly conditioned to the industrially-produced steel bars and cement, as shown in its European history. This particular Western approach had shaped the science and technology of reinforced concrete in the form of particular theories, methods and material conditions, which could not simply be borrowed for studying bamboo-reinforced concrete. Bamboo's quality, strength and advantage for engineering could not be measured appropriately in the framework of the science established by steel. The then engineering theories and research methods at large were insufficient for studying the organic, non-industrialised material of bamboo.

Engineers' ideas about "modernisation," often referenced in the source materials, hardly become clearer to us in the case of bamboo, in which not only Western science but also traditional Chinese experience was used. The engineers mobilised varied sources and resources from different lines of science and crafts. They were not always dogmatic in either field or laboratory work. They deployed know-how largely and smartly. In practice, their scientific motives combined with industrial, economic, patriotic and cultural interests. They were always working with both empirical and theoretical knowledge, both accuracy and uncertainty, both standards and adaptive techniques. Their knowledge contained more subtle complexity than what could be reduced to mathematics. They were crafting not only things but also their knowledge of practices as codified in engineering theories and codes. They created factors of safety and the concept of acceptable discrepancy to procure satisfactory accuracy against uncertainty, which is still the case today.

This epistemic culture engendered a new process of rediscovering Chinese science. European engineers documented and studied Chinese science and techniques with Western tools, methods and intellectual curiosity and rationality. They "translated" and circulated Chinese knowledge and practice in codified forms. This cultural-historical interest was embodied in not

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[100] Rudolf Stichweh, "Interdisziplinarität und Wissenschaftliche Bildung," in *Fundiert Forschen*, ed. Hanna Kauhaus and Norbert Krause (Wiesbaden: Springer, 2017), 181-90; Rens Bod, Jeroen van Dongen, Sjang L. Ten Hagen, Bart Karstens and Emma Mojet, "The Flow of Cognitive Goods: A Historiographical Framework for the Study of Epistemic Transfer," *Isis* 110, no. 3 (2019): 483-96, on 488-9.

only their extensive fieldwork in China, but also in their broad social networks, constructed via scientific, political, missionary, and commercial activities. They returned home with new insight into Chinese science. The WCB engineers, in particular, helped shape the esteemed Needham work on Chinese science and civilisation. As Needham acknowledged in 1962:

> I cannot refrain from recalling the excellent survey of the late Herbert Chatley, "Ancient Chinese Astronomy" contributed to the Occasional Notes of the Royal Astronomical Society, 1939 (no. 5), 65; at the same time placing on record the debt which my collaborators and I owe to the constant kindness and encouragement of a former Chief Engineer of the Huangpo [Whangpoo] Conservancy.[101]

The relationship between the modern engineering experience and the approach in the Needham tomes deserves further study. Chinese engineers, meanwhile, were increasingly educated with Western science; they, too, reused conventional Chinese knowledge for modern practice.

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[101] Needham, "Astronomy," 87.