Research Assessment Exercise 2020
<u>Impact Case Study</u>

University: The Hong Kong Polytechnic University (PolyU)
Unit of Assessment (UoA): 16 – Civil Engineering and Building Technology

Title of case study: High Performance Structures

(1) Summary of the impact

Economic development worldwide has resulted in longer, taller, and more complex civil engineering structures, which are often required to serve in harsh environments, sustain material deterioration and survive multiple hazards. The research team at HK PolyU has conducted pioneering research to achieve enhanced structural performance through innovative structural materials/forms, advanced computational/design methodologies and improved performance monitoring technologies. The research has produced a significant impact on structural engineering internationally including: (i) adoption into design codes/guidelines, (ii) widely utilised design software and (iii) application in numerous landmark structures worldwide. Very significant improvements have been achieved in structural safety, technical capabilities and costs.

(2) Underpinning research

The research team whose work underpins this case study consists of nine current academic members: Siu-Lai Chan, Tak-Ming Chan, Kwok-Fai Chung, Jian-Guo Dai, Yi-Qing Ni, Jin-Guang Teng, Yong Xia, You-Lin Xu and Song-Ye Zhu. Since October 2013, they have led the supervision of 98 PhD students and 268 research staff in investigations into different aspects of high-performance structures. The following sections summarise, under three headings, the research conducted regarding: the choice of materials/systems, design approaches, new analysis methods and maintenance guidance - including considering health monitoring and retrofit strategies

<u>Emerging structural materials and forms</u>: The UoA's structural team was the first to research how new high-performance FRP-steel-concrete structures could be designed and optimised [see Reference 1, R1 in short]. It was shown that corrosion-resistant fibre-reinforced polymer (FRP) composites offer effective elements to construct new structures and help strengthen existing structures, so enhancing their performance, service life and hence sustainability. Systematic, extensive, in-depth research has been carried out into the strengthening of existing concrete structures with FRP composites, leading to a systematic theory for predicting their behaviour and approaching their design [R2]. The team has also conducted substantial research into the seismic retrofitting of concrete structures with FRP, the performance of FRP-strengthened concrete structures in fires, and the FRP strengthening of metallic structures.

A second stream of research comprised extensive experimental and numerical investigations into how high strength steel materials perform in structures, including their ultimate strength and ductility behaviour. The team investigated the effects of cross-sectional geometry as well how members resisted compression and bending. The effects of welding were also addressed, considering variable heat energy input and associated changes in steel microstructure. It was shown how adverse residual stress and microstructural effects could be quantified successfully for welded sections and controlled through careful design and specification of procedures and robotic welding parameters.

<u>Advanced computation and design methodologies</u>: The UoA's team has developed an innovative and practical computational structural and design method called the second-order direct analysis [R3, R4], which allows for imperfections in practical structures, bypassing the effective length assumption and the prescriptive use of charts and tables in Codes. Based on the theory, the team developed the commercial software program NIDA (Nonlinear Integrated Design and Analysis), which helps designers design safer, more efficient, more economical and reliable structures.

Innovative performance monitoring technologies: Research into how supertall structures and long-span bridges perform has been carried out by the UoA for over 20 years. As demonstrated in references [R5, R6] the primary research topics have been: (i) design of performance-based monitoring systems, including sensors and sensor networks; (ii) multi-scale structural modelling, modal identification, model updating, and damage detection based on real-time data obtained from the monitoring system; and (iii) structural loading identification, fatigue prognosis, performance assessment, and infrastructure resilience. These aspects link to sustainability, life cycle management, and rating systems based on long-term monitoring data.

Evidence regarding the quality of the research is given by the team's total research grant income of HK$321.5m since 2000 and their national and international awards won over the past six years, including three State Science and Technology Awards covering FRP composites and structural monitoring and one HKIE/IStructE Award covering analysis [Source 1, S1 in short].

(3) References to the research

R1. Teng, J.G., Yu, T., Wong, Y.L. and Dong, S.L., (2007), "Hybrid FRP-concrete-steel tubular columns: concept and behaviour", *Construction and Building Materials*, 21 (4), 846-854.
R2. Teng, J.G., Chen, J.F., Smith, S.T. and Lam, L., (2002), *FRP-Strengthened RC Structures*, John Wiley and Sons Ltd., UK, 266 pp, ISBN: 978-0-471-48706-7.
R3. Chan, S.L. and Chui, P.P.T., (2000), *Non-linear Static and Cyclic Analysis of Steel Frames with Semi-Rigid Connections*, Elsevier Science, Oxford, UK, 353 pp, ISBN: 978-0-08-042998-4.
R4. Liu, S.W., Bai, R. and Chan, S.L., (2016), "Second-order direct analysis of domelike structures consisting of tapered members with I-sections", *Journal of Structural Engineering*, 142 (5), Article no.: 04016009.
R5. Xu, Y.L. and Xia, Y., (2012), *Structural Health Monitoring of Long-Span Suspension Bridges*, Spon Press, London, UK, 369 pp, ISBN: 978-0-4155-9793-7.
R6. Ko, J.M. and Ni, Y.Q., (2005), "Technology developments in structural health monitoring of large-scale bridges", *Engineering Structures*, 27 (12), 1715-1725.

(4) Details of the impact

Further details of the impact achieved are outlined below under the same three headings.

(i) Emerging structural materials and forms

The team's research of FRP composites in construction has been widely accepted as a source of reliable models/methods, as demonstrated by its adoption by China, US, UK, Australia and Germany in their structural design codes/guidelines [S2 and S3]. The UoA's theory for the behaviour and design of FRP-strengthened RC structures, including beams and columns and also the fire resistance assessment method for FRP-strengthened RC structures have been adopted in the second edition of the Chinese "Technical Standard for FRP Composites in Construction" (GB 50608 2018) [S2]. The fire resistance design procedure and some design examples have been used to demonstrate the feasibility of using FRP to rehabilitate the Central Market Building of Hong Kong. The new hybrid FRP-concrete-steel double skin tubular members (DSTMs, Figure 1a) invented by the team have led to follow-on studies at many universities around the world and are being applied in a new arch bridge system under development in Australia by Arup and three other partners (Figure 1b) [S4].

The absence of scientifically based design rules for structural design involving high strength steels has held back their use in construction very significantly. The UoA members are leading new research to fill this gap through the Hong Kong Branch of the Chinese National Engineering Research Centre for Steel Construction, whose research work has been adopted by Working Group for High

Strength Steel of Structural Eurocode. This is allowing the Eurocode to extend its scope from 460 MPa (S460) to 690 MPa (S690) yield stress steels [S5], so allowing the structural benefits of employing such steels to be taken internationally.

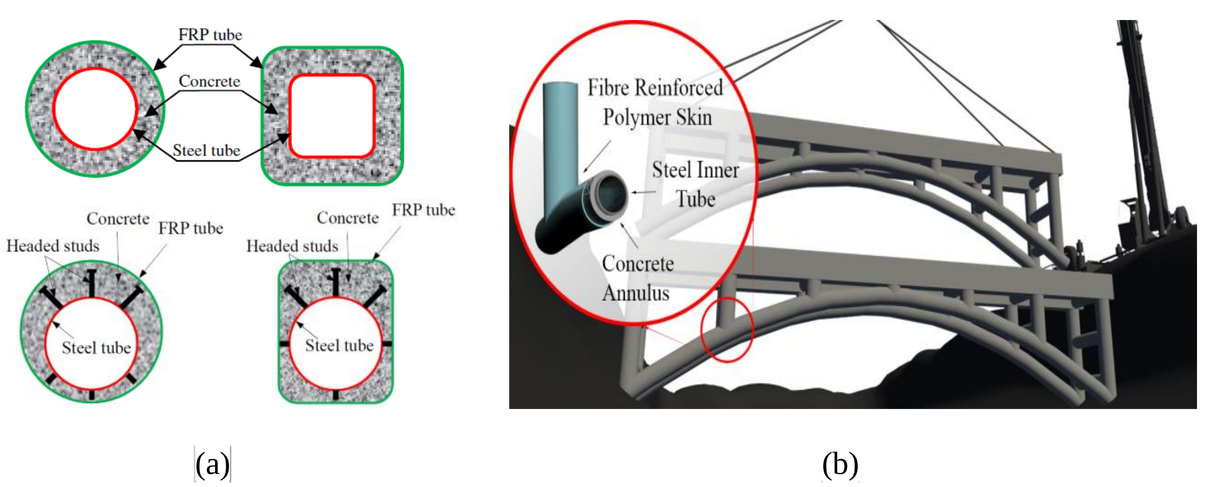


Figure 1. (a) Cross-sections of FRP-concrete-steel double-skin tubular members (DSTMs); (b) Arch bridge system based on DSTMs

(ii) Advanced computation and design methodologies

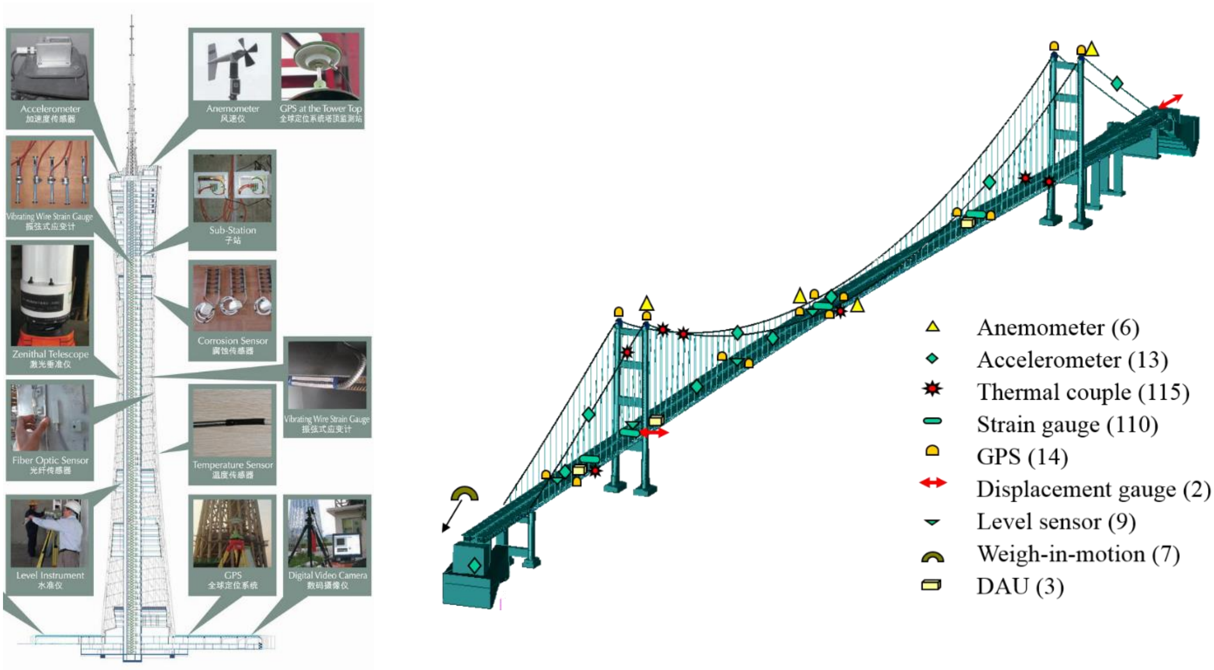
The UoA's second-order direct analysis method of design addresses explicitly key aspects of structural behaviour which are not covered in other major national codes. Equations have been developed to provide stability checks for sections taking account of P-D-d imperfections for unavoidable defects in the manufacturing process of members and fabrication of structure and beam buckling. The approach represents the most complete nonlinear analysis treatment available for use in practical design. The method is specified in Hong Kong's *Code of Practice for the Structural Uses of Steel* (2011) and also referenced (as 'Direct Analysis') in the US *Specification for Structural Steel Buildings* (ANSI/AISC 360-16), which is widely used internationally.

The commercial software code NIDA, which was developed by the team from this work, is employed widely by universities and design consultants in Australia, China, Greece, Hong Kong, Singapore, Taiwan, Ireland and the UK for practical work, teaching and research. This advanced computational tool has been applied in the design of numerous steel and composite structures in Hong Kong, Mainland, Singapore, Myanmar, Taiwan and Macau [S6], leading to improvements in safety and significant economic benefits. One example is the MGM project in Macau, constructed by Cotai theatre steelworks. Use of the second-order direct analysis method encapsulated in NIDA led to a saving of 90 tons of structural steel in a long span roof [S7], leading to an economic benefit of around HK$2m in this single application.

(iii) Innovative performance monitoring technologies

The UoA's structural health monitoring (SHM) research team is among the first in the world to pioneer the performance monitoring of large-scale structures. Over the past twenty years, the team has conducted in-construction and in-service monitoring of major projects such as Tsing Ma Bridge with a main span of 1377 m, Stonecutters Bridge with a main span of 1018 m, Sutong Bridge with a main span of 1088 m, Jiangying Bridge with a main span of 1385 m, 600 m tall Canton Tower, 632 m tall Shanghai Tower, and so forth. Some monitoring systems are illustrated in Figure 2.

For example, the team members have analysed real-time highway, railway, wind, earthquake and temperature data and the associated structural responses and assessed the performance of the Tsing Ma Bridge over the past twenty years [R5]. They also developed a number of SHM techniques in multi-scale modelling and model updating, optimal sensor placement and response reconstruction, conditional wind simulation, global thermal analysis, traffic loading simulation, SHM-aided fatigue assessment, hierarchical rating system and so forth. These techniques significantly advanced the SHM technologies for long-span cable-supported bridges. The monitoring system of the Canton Tower [S8] also provided real-time data of the structure's performance under 20 typhoon occurrences and so enabled evaluations of the structure's safety under such extreme loading. The system provided the wind characteristics applying above the boundary layer, filling gaps in current knowledge regarding the design and analysis of supertall buildings. In another example, the construction monitoring of the Shanghai Tower [S9] assisted the main contractor in maintaining the accuracy to which the floors' elevations could be constructed to within 5 mm of the ideal values, as compared to the 30 mm tolerance set in the original design specifications. Both of these two projects were completed in the assessment period [S10]. The benefits of transferring these performance monitoring technologies from the university environment to the outside world have been recognized by industry and government. The approach is recognised internationally and included in the Chinese SHM design guidelines [S11].



(a) Canton Tower (600 m tall) (b) Tsing Ma Bridge (1377 m main span)

Figure 2. Some performance monitoring examples undertaken by the PolyU team

(5) Sources to corroborate the impact

S1. Three State Science and Technology Awards and one HKIE/IStructE Award by the team members.
S2. Letter of evidence from the leading organization of Chinese Standard GB-50608 (2010 and 2018): *Technical Code for Infrastructure Application of FRP Composites*:
S3. Team member's models are adopted in ACI-440.2R (2017): *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*.
S4. Letter of evidence from Arup (Australia).
S5. *Technical Guide on Effective Design and Construction to Structural Eurocodes: EN 1993-1-1 Design of Steel Structures – S235 to S690*, June 2019.
S6. Acknowledgement letter from Arup (Hong Kong).
S7. Consultancy agreement between CSCJV and PolyU on the roof of MGM Macau.
S8. Appreciation letter from the client of Canton Tower, Guangzhou, China.
S9. Supporting letter from the design consultant of Shanghai Tower, China
S10. Certified letter from PolyU for the two consultancy projects on the Canton Tower and Shanghai Tower in China.
S11. Letter of evidence from the leading organization of Chinese standard CECS 333:2012: *Design Standard for Structural Health Monitoring Systems*.