Research Assessment Exercise 2020
Impact Case Study

University: The University of Hong Kong
Unit of Assessment (UoA): 16 Civil Engineering (incl. Construction Engineering & Management) and Building Technology

Title of case study:
Development of a Novel Coupling Beam to Enhance the Structural Safety of High Rise Buildings for Extreme Loads

(1) Summary of the impact

Research within the Department of Civil Engineering (CivE) has improved the ability of tall buildings to withstand extreme wind and/or earthquake loads. A novel plate-reinforced composite (PRC) coupling beam has been developed, which is better able to withstand extreme shear and seismic loads in comparison with conventional reinforced concrete coupling beams, thereby improving the safety of high rise buildings. The PRC beam also has the minimal impact in reducing the available floor area of a building. Design guidelines for the PRC coupling beam were published in 2009 and have since been used worldwide in the construction of tall buildings, such as Trump International Hotel, in Waikiki, Hawaii.

(2) Underpinning research

Dr Ray Su and his team (including Prof Albert Kwan, Dr HJ Pam and a number of research fellows and students) in the Department of Civil Engineering (CivE) have undertaken pioneering research on the design of tall buildings, focusing specifically on the building's capability to withstand extreme wind and/or earthquake loads. Coupled shear walls are commonly used to resist these lateral loads. The coupling beams that connect two wall piers can help reduce the base moments in the walls, thereby increasing the resistance of a building to wind-induced forces and/or dissipating the energy during a severe earthquake. However, conventional reinforced concrete (RC) coupling beams have limited ductility and shear capacity, and are prone to brittle failure under severe earthquake loading.

The research team has focused on increasing the deformability and resistance to shear of traditional reinforced coupling beams. Since 2003, with the financial support from the HK Research Grants Council, the team has developed a novel PRC coupling beam, which is fabricated by embedding a steel plate into a conventional RC beam and using shear studs to couple the steel plate and the concrete. This beam has been shown through detailed experiments to have a particularly high shear strength. It also has the advantage of being small in size and flexible in design. It is particularly suited to slim floor systems with restrictive height limits and the beam is easy to construct. The insertion of a steel plate causes the least disturbance to the reinforcement, so that walls, slabs and coupling beam reinforcements can be seamlessly integrated together. The vertical arrangement of the steel plate allows concrete to be filled and compacted easily within the shuttering, so that honeycomb defects can be avoided. The cast-in steel plate is also naturally protected by the surrounding concrete against fire and lateral buckling. Thus, the PRC coupling beam provides an easy-to-adopt design solution, enabling tall buildings, particularly those over 50 stories in height, to resist strong wind and/or earthquake forces.

The PRC coupling beam has undergone extensive half-scale laboratory testing over many years, supported by non-linear finite element modelling using advanced computational techniques. The results have shown that the PRC coupling beam has an increased load-carrying capacity, enhanced ductility and increased energy dissipation ability. Multiple experimental studies (3.1-3.3) were also conducted to investigate: (i) the effectiveness of PRC coupling beams in shear strength enhancement; (ii) the inelastic performance of PRC coupling beams under reverse cyclic loads; (iii) the role of shear studs during the interaction between the steel plate and the RC component; and (iv) the load that is distributed between the RC beam and the steel plate. Test results have demonstrated that PRC coupling beams can achieve an 80% higher shear capacity and a 90% higher deformability than conventional RC coupling beams. In addition, comprehensive non-linear finite element analyses (3.4 and 3.5) were carried out to quantify the shear stud forces in the beam span and to establish the wall anchor design model, including: (i) the axial force induced in the wall anchor; (ii) the optimum plate anchorage length in the wall region; and (iii) the moment from the vertical and horizontal bearing forces. Based on these studies, Su and Lam (3.6) proposed design guidelines for PRC coupling beams in accordance with British Standards in 2009.

(3) References to the research

[3.1] Lam,W.Y., Su, R.K.L. and Pam, H.J. (2005) Experimental study on embedded steel plate composite coupling beams, *Journal of Structural Engineering*, ASCE, 131, 1294-1302.

[3.2] Su, R.K.L., Pam, H.J. and Lam, W.Y. (2006) Effects of shear connectors on plate-reinforced composite coupling beams of short and medium-length spans, *Journal of Constructional Steel Research*, 62, 178-188.

[3.3] Su, R.K.L., Lam, W.Y. and Pam, H.J. (2009) Experimental study of plate-reinforced composite deep coupling beams, *The Structural Design of Tall and Special Buildings*, 18(3), 235-257.

[3.4] Su, R.K.L., Lam, W.Y. and Pam, H.J. (2008) Behaviour of embedded steel plate in composite coupling beams, *Journal of Constructional Steel Research*, 64, 1112-1128.

[3.5] Lam, W.Y., Li, L.Z., Su, R.K.L. and Pam, H.J. (2013) Behavior of plate anchorage in plate-reinforced composite coupling beams, *The Scientific World Journal*, Article ID 190430, 1-12.

[3.6] Su, R.K.L. and Lam, W.Y. (2009) A unified design approach for plate-reinforced composite coupling beams, *Journal of Constructional Steel Research*, 65, 675-686.

(4) Details of the impact

The PRC coupling beams have been applied in projects as far afield as Hawaii and Dubai for tall buildings that face structural vulnerability due to high wind and/or earthquake loads. The team have published and promoted their research in open source form to enable the widest possible adoption by key stakeholders and end-users. Although it is not possible to know exactly how many tall building projects world-wide have adopted this approach, the team have been contacted directly by a number of key developers, who have acquired details of the benefits of PRC coupling beams through correspondence, meetings and publications and have frequently used these beams in their designs.

The developer BASE Construction (https://www.basecm.com/) has used PRC coupling beams in several projects, including: the Trump International Hotel, Waikiki, and the Pacifica Honolulu, both in Hawaii, and built in 2009, the Nikko Hotel in Guam and the Ritz Carlton Residences Waikiki Beach, Phase II, both of which are still under construction (2019). Each project has included a solution that addresses both extreme loads and tight building requirements. For example, The Trump International Hotel had to deliver 39 stories within a restricted height limit of 350 feet, which meant there was little room to spare. The company's President, Steven Baldridge, wrote about the decision to use the PRC coupling beams in a trade publication: *"A design procedure was developed using basic engineering principles along with research from the University of Hong Kong… This link beam system allowed the building to perform without additional structural elements"* (5.1). Similarly, with the Pacifica Honolulu, he said the solution: *"was not only highly efficient structurally but, from the developer's requirements perspective, high in usable and sellable ratios"* (5.2).

Given its experience with the Trump and Pacifica projects, the firm decided that the PRC coupling beams would also be appropriate for its Nikko Hotel and Ritz Carlton projects (in earthquake prone Hawaii), both of which are being built in challenging environments. Baldridge recently explained the continued appeal of the beams: *"Some of the sites where we build are subject to extremely high seismic and typhoon forces. We have used PRC link beams primarily because they enable us to meet US codes for shear strength without adding structural depth"* (5.3). Baldridge also noted their greater practicality and constructability in high-rise buildings compared to alternative coupling beams, such as wide flange and steel fibre-reinforced coupling beams, due to their increased shear (but not flexural) capacity and their compatibility with the capacity design philosophy adopted in high-seismicity regions.

Another developer that has adopted the team's research is WSP Global (www.wsp.com), which is using the PRC coupling beams in its Address Jumeirah Resort project, in Dubai. This 77-storey building, currently under construction, is being designed to cope with the high shear force induced by strong wind loads, through use of the PRC coupling beams. WSP Engineer Yamen Dannan said the PRC coupling beams were useful for addressing high-stress situations when there are architectural limitations on increasing the size of RC beams: *"We have used the PRC coupling beams at the double-height mechanical levels, where the shear force caused by lateral loads on our 300-meter tower could not be designed for using a conventional Reinforced Concrete beam. This is because we had limited head room to increase the size of beams… The method described in Prof Su's research has given us a reliable and clear basis for designing our PRC beams"* (5.4). A developer from India also notified Dr Su that they were using PRC coupling beams in a project in India, but for current confidentiality reasons the project cannot be identified herein (5.5).

A 2019 review of the structural performance and practical limitations of various types of coupling beams by Liao and Pimento (5.6) recently found that the PRC coupling beam can provide an 80% higher shear capacity and a wider applicable range of span-to-depth ratios than the diagonally reinforced concrete coupling beam. The PRC coupling beam also has better constructability than: steel coupling beams, encased steel composite coupling beams and diagonally reinforced coupling beams.

The impact of this research, undertaken within CivE on developing PRC coupling beams, has been further evidenced by keynote lectures given to industry and academia, such as Dr Su delivering a keynote lecture on "PRC Coupling Beam for Modern Building Design" at the 26th Assembly Advanced Materials Congress, Stockholm, Sweden in 2019.

(5) Sources to corroborate the impact

[5.1] Baldridge, S.M., Popp, D.R. and Mizue, E. (2009) Structural performance on Waikiki Beach, *Structural Engineer*, 3e, 30-33 (see 4th paragraph on page 32).

[5.2] Baldridge, S.M. (2012) 400 feet, 53 stories: How structural engineer was able to squeeze as many floors as possible under restrictive height, *Structural Engineer*, 7, 16-20.

[5.3] Letter from Baldridge, S.M. (2019) http://www.civil.hku.hk/Civil_RAE2020/Su_5-3_HK_Research_Support_Letter-Baldridge.pdf

[5.4] Letter from Yamen, D. (2019) http://www.civil.hku.hk/Civil_RAE2020/Su_5-4_HK_Research_Support_Letter-Yamen_Dannan.pdf

[5.5] Email from Jose, C. (2019) http://www.civil.hku.hk/Civil_RAE2020/Su_5-5_Email_from_Christ_Jose.pdf

[5.6] Liao, S. and Pimentel, B. (2019) Coupling beam types, *Structure Magazine*, 1, 8-13.