Bridge Structure and Detail Behavior and Design

Bridge structure system and detail constitution is the basis for bridge structure to undertake their engineering function. Along with the use of high performance materials and the geometrical layout optimization, the performance of bridge joints, components and structures are continuously improved. Recent research works in BE at Tongji University that address bridge structure and detail behavior and design include: Combined shear and bending behavior of joints in precast concrete segment beams with external tendons; Experimental and analytical study on fatigue behavior of composite truss joints; Experimental investigation of movable hybrid GFRP and concrete bridge deck; Experimental study on shear behavior in negative moment regions of segmental externally prestressed concrete continuous beams; Shear behavior of partially encased composite I-girder with corrugated steel web; Shear design of concrete beams reinforced with grid reinforcement; Parametric study of cable-stayed-suspension bridges; Behavior of wires in parallel wire stayed cable under general corrosion effects.

Combined Shear and Bending Behavior of Joints in Precast Concrete Segmental Beams with External Tendons

When loads are directly applied in the immediate vicinity of joints, the failure mode in which cracks occur in the joint plane, instead of diagonal cracks, are obtained. Specimens are tested under pure bending to develop a better understanding of the behavior of joints in PCSBs. This paper presents the testing data of nine models and analyzes the effects of different design parameters. The results obtained from the formulas are compared with the testing results to verify the proposed simplified failure modes and formulas.

Objective: Precast concrete segmental bridges with external tendons are becoming widely constructed all over the world. The main objective of this study is to obtain a further understanding of the behavior of joints when they are subjected to combined shear and bending.

Approach: Nine specimens of precast concrete segmental beams (PCSBs) with external tendons were match cast and tested: six of the specimens were tested under combined shear and bending; two specimens were tested under pure bending; and one specimen was tested under direct shear. Failure processes and modes, joint resistance, and strains of stirrups and prestressing tendons were recorded in the tests.

Significant Result: Based on the results of the experiment, the study analyzed the mechanism of combined shear and bending resistance for dry and epoxied joints when loads were located in the immediate vicinity of the joint. Additionally, simplified failure modes of dry and epoxied joints subjected to combined shear and bending were presented in this paper. On the basis of the simplified failure modes, formulas were deduced for evaluating the resistance of joints when failure occurred in a joint section with loads applied in the immediate vicinity of the joints. The formulas provided a rational prediction of the joint resistance under combined shear and bending, which in turn verified the rationality of the proposed failure modes.

Principal Investigator:

Guoping Li, Donghui Yang; and Yu Lei **Funding:**

Key Publications:

Li G, Yang D, Lei Y. Combined Shear and Bending Behavior of Joints in Precast Concrete Segmental Beams with External Tendons [J]. Journal of Bridge Engineering, 2012, 18(10): 1042-1052.



Fig. 3. Dimensions of key models (millimeters)



Fig. 11. Actual failure modes and cracking sketches of epoxied joints: (a) SE-1; (b) SE-2; (c) SE-3; (d) SE-4



Fig. 15. Comparison of calculating and experimental results for PCSB joints under combined shear and bending: (a) epoxied joint; (b) dry joint

Experimental and analytical study on fatigue behavior of composite truss joints

The performance of composite girders depends largely on the effectiveness of joints at steel-concrete interface. Connections or joints in composite truss bridges should possess high strength and stiffness as well as fatigue performance, since truss diagonals are connected directly to concrete slabs, and complicated forces are transmitted through connections or joints. This paper introduced a composite truss bridge with double decks in China. All the results of experimental and numerical investigations on composite joints of truss bridges in this study may provide reference for the design and construction of such type bridges.

Objective & Approach: In order to fully understand the performance of composite joints in a truss bridge with double decks, fatigue tests of three composite joints with different connectors such as headed studs, concrete dowels and perforated plates under constant repeated loading were carried out, and the responses of displacement, strain distribution, crack development, relative slip between concrete and steel were observed after different loading cycles.

Significant Result: The experimental results showed that the defection increased almost linearly with applied load even after certain repeated loading cycles, but the stiffness reduced gradually with the repeated loading cycles. No serious damage occurred except tiny cracks at the steel–concrete interface caused by slip after 2 million repeated loading cycles, which means all three composite joints have good fatigue performance. Based on experimental works, three dimensional finite element models of composite joints were established. The results from finite element analysis were consistent with those from tests in terms of strength and stiffness. Finally, the fatigue details involving reinforcing bars, welding seams and shear connectors were evaluated according to related speculations. The presented overall investigation may provide reference for design and construction of composite joints in composite truss bridges.

Principal Investigator:

Yuqing Liu, Haohui Xin, Jun He, Dongyan Xue, Biao Ma **Funding:**

Key Publications:

Liu Y, Xin H, He J, et al. Experimental and analytical study on fatigue behavior of composite truss joints[J]. Journal of Constructional Steel Research, 2013, 83: 21-36. 447-461.









Fig. 21. The Von-Mises stress of steel structure, MPa.

Experimental investigation of movable hybrid GFRP and concrete bridge deck

To overcome such disadvantages and to make the best use of materials, combinations of FRP and conventional materials as concrete with low cost but high compressive performance have recently been widely used. Each of the developed deck showed its own advantages and disadvantages. The main problems that occurred were premature web buckling of hollow FRP sections, a brittle behavior, insufficient interface capacity to provide full composite action between the FRP and concrete. This paper proposed a new hybrid FRP-concrete bridge deck that should allow preventing some of these problems.

Objective: This paper proposed a novel cost-effective movable hybrid GFRP and concrete deck consisting of corrugated pultruded GFRP plate with T-upstands for the tension part and concrete with reinforcing bars for the compression part.

Approach: First, the strength and stiffness of GFRP plate serving as formworks for concrete casting under construction stage was verified by sand filling test. Then, static tests on six full-scale models with different penetrating bars and surface treatment under sagging moments were conducted to evaluate the load-carrying capacity and failure modes of proposed hybrid deck. The load and displacement relationship, ultimate flexural resistance, strain distribution on GFRP plate and concrete slab were measured during the test.

Significant Result: Experimental results indicated that both surface treatment and penetrating bars improve the connection between GFRP plate and concrete, and promote the ultimate strength and rigidity of hybrid deck. In addition, the concrete used for encasing corrugated pultruded GFRP plates not only increases its stiffness, but also prevents local buckling failure of the GFRP plate with T-upstands. The comparison of experimental and theoretical ultimate strength results showed ACI 440 flexure and shear equation can effectively predict the ultimate capacity for the hybrid deck. The overall investigation showed the presented hybrid GFRP and concrete concept is a better alternative for beam-and-slab bridges.

Principal Investigator:

Jun He, Yuqing Liu, Airong Chen, Liang Dai

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Key Publications:

He J, Liu Y, Chen A, et al. Experimental investigation of movable hybrid GFRP and concrete bridge deck[J]. Construction and Building Materials, 2012, 26(1): 49-64.



(a) Foam packing at support

Fig. 5. Test set-up of sand filling.



(b) Stress distribution along longitudinal direction Fig. 9. Normal stress on the bottom of GFRP plate in longitudinal direction under construction stage.



Fig. 25. Load-neutral axis relations of hybrid decks.



(a) Load-stress relationship



(b) Stress distribution along transversal direction

Fig. 10. Normal stress on the bottom of GFRP plate in transversal direction under construction stage.



Experimental Study on Shear Behavior in Negative Moment Regions of Segmental Externally Prestressed Concrete Continuous Beams

It should be beneficial to study shear behavior in negative moment regions of segmental externally prestressed concrete continuous beams and to investigate the whole process from the initiation of cracks to the failure of beams under loading. In this paper, a total of 10 externally prestressed cantilever concrete beams were designed and tested to simulate the negative regions of segmental externally prestressed continuous beams.

Objective: External prestressing technology has achieved wide application in bridges. Although previous tests have made great progress in shear behavior of externally prestressed concrete beams, the research mainly focused on simply supported beams. **Approach:** To study the effects of joints and large negative moments on the shear behavior of segmental externally prestressed concrete continuous beams, a series of cantilever beam specimens were designed to simulate the negative moment regions in continuous beams. Then, the crack developing behavior, failure mode behavior, and mechanical behavior of specimens with different shear span to effective depth ratios, joint types, joint locations, and ratios of internal to external tendons were investigated in this experimental study.

Significant Result: The test results show that failure cracks of segmental specimens are web shear cracks, whose locations and inclination angles are independent of joints. Eventually, both sides of the specimens move relatively along failure cracks and the specimens fail suddenly. The results also reveal that the deflections of segmental specimens after cracking develop very quickly, and the stress increments of prestressing tendons reach 20–24% of the tensile strength, which are larger than those of monolithic specimens. In addition, the shear strength provided by the concrete effects in regions near the interior supports of continuous beams is lower than that in regions near the supports of simply supported beams, and the contributions of the stirrup and prestressing tendon to the shear strength are 14–21 and 8–18%, respectively, in which the contribution of stirrup is greater than that of simply supported beams.

Principal Investigator:

Guoping Li, Chunlei Zhang and Changyan Niu

Funding:

Key Publications:

Li G, Zhang C, Niu C. Experimental Study on Shear Behavior in Negative Moment Regions of Segmental Externally Prestressed Concrete Continuous Beams[J]. Journal of Bridge Engineering, 2011, 18(4): 328-338.



Fig. 4. View of test setup



Fig. 7. Load-deflection curves and load-external prestressing tendon stress curves for (a) M-1; (b) M-2; and (c) M-3



Fig. 17. Comparison of experimental to predicted shear strengths



Fig. 16. Comparison of results from the tests in this paper and previous tests conducted by Li (2007)

Shear behavior of partially encased composite I-girder with corrugated steel web: Numerical study

Prestressing can be efficiently introduced into the top and bottom concrete slabs due to the so-called "accordion effect" of corrugated webs. The strength, stability of structures and material efficiency can be improved by concrete slabs combined with corrugated steel webs. This paper pays more attention to the analytical and numerical studies of the shear behavior for steel and composite girders with corrugated web. he present overall investigation can serve as a basis for shear design of partially encased composite I-girders with corrugated web.

Objective: Shear behavior of partially encased composite I-girders with corrugated web has been investigated analytically and numerically in this paper.

Approach: A 3-D finite element model with geometric and material nonlinearity is established and verified by the experiments. Subsequently, a parametric study is carried out to examine the effects of geometric and material properties on the shear behavior which includes corrugation, height, thickness, connection degree between steel web and concrete encasement.

Significant Result: It is found that the ultimate shear strength of steel I-girders is improved with increases in the thickness, height and yield strength of corrugated web, while the ultimate shear strength of partially encased composite I-girders increases with the thickness, yield strength of corrugated web and the thickness, compressive strength of concrete encasement. However, the stud stiffness has little influence on the ultimate shear strength. Moreover, the concrete encasement improves the shear strength of steel I-girders, the degree of improvement increases with the thickness and compressive strength of the concrete, but decreases drastically with the thickness of corrugated web. Therefore, it is suggested that concrete should be poured on the corrugated web with thin thickness or low yield strength to prevent buckling occurrence before yielding of steel web. Finally, shear strength prediction equations are proposed and verified by numerical results. The calculated shear strength agree well with the numerical results for steel I-girders before and after composite with concrete, which indicates that the proposed analytical equations can be applied to predict the shear strength of such partially encased composite girders with corrugated web.

Principal Investigator:

Jun He, Yuqing Liu, Zhaofei Lin, Airong Chen, Teruhiko Yoda

Key Publications:

He J, Liu Y, Lin Z, et al. Shear behavior of partially encased composite I-girder with corrugated steel web: Numerical study [J]. Journal of Constructional Steel Research, 2012, 79: 166-182.



Fig. 4. Finite element model of partially encased composite I-girder with corrugated steel web.



Fig. 10. Failure modes obtained from test and FEA. (a) S1. (b) SC1.

Shear design of concrete beams reinforced with grid reinforcement

Literature search reveals the inconsistency between different codes when designing reinforcement for resisting shear flow arising from shear effect or based on torque. Hence, a unified approach for shear reinforcement design in concrete structures is lacking. In this paper, a new concept of shear reinforcement – orthogonal grid reinforcement – is proposed, and a corresponding design method of such shear reinforcement for any beam is also derived, considering sectional stress distribution and failure criteria of concrete.

Objective: A new method for designing orthogonal steel grids as shear reinforcement in concrete members is proposed, considering sectional stress distribution and failure criteria of concrete.

Approach: The concept and formulations of this method have been applied to the analysis and design of reinforced concrete beams subjected to combined shear and bending. An accurate formula for calculation of shear reinforcement ratio is deduced, leading to innovative results. Shear strength of reinforced concrete beams is assumed as the sum of contributions from orthogonal grid reinforcements in the cracked zone and from concrete in the shear compression zone. Eleven reinforced concrete beams with grid reinforcement were tested under bending and shear to validate the accuracy of the proposed method.

Significant Result: It was found that the proposed model predicts the experimental behavior accurately and that grid reinforcement can enhance the shear behavior of concrete beams.

Principal Investigator:

Dong Xu, Yu Zhao, Chao Liu, Jose Turmo **Funding:** Kwang-Hua Foundation

Key Publications:

Xu D, Zhao Y, Liu C, et al. Shear design of concrete beams reinforced with grid reinforcement [J]. Magazine of Concrete Research, 2012, 65(2): 93-107.



Figure 9. Test layout



Figure 3. Stress and strain distribution of cracked section. (a) Flexural-shear crack; (b) cross-section; (c) flexural strain; (d) normal stress; (e) shear stress





Figure 12. Strain values of test beams in series T40: (a) strain gauge attached to the longitudinal flexural reinforcement; (b) relation between strain in the longitudinal flexural reinforcement and applied load (*P*) for beam T40-1 and beam T40-2

Analysis Strategy and Parametric Study of Cable-Stayed-Suspension Bridges

This paper presents a new systematic analysis strategy for cable-stayed-suspension bridges, including a four-step approach for determining the reasonable finished dead load state, a nonlinear traffic load analysis strategy, and a load combination method. An example of a 1400 m span cable-stayed-suspension bridge is presented for illustration. This design is also used as a basic scheme in the parameter study later, in which three key geometric parameters: the suspension-to-span ratio, the sag-to-span ratio, and the number of crossing hangers are studied for their effects on the bridge's structural behavior.

Objective: This paper presents a systematic analysis strategy for cable-stayed suspension bridges.

Approach: A four-step approach for the determination of the reasonable finished dead load state is established, focusing on the optimization of the tension forces and shapes of all cables. The critical distribution of the traffic load is imposed on the bridge simultaneously with the dead load to calculate its nonlinear effect. Taking the finished dead load state as the initial state, the nonlinear effect of each load in the service state is analyzed independently. The superimposition principle is adopted to obtain the load combination. A 1400 m span cable-stayed-suspension bridge is presented as a case study. Finally, three key geometric parameters are studied from the viewpoint of the structural behavior.

Significant Result: As a result, a suspension-to-span ratio of 0.4 to 0.6, a larger sag-to-span ratio up to 1/11.0, and two to four crossing hangers are recommended. With a higher structural rigidity and stability, this type of bridge is proven as an excellent alternative to cable-stayed bridges and suspension bridges.

Principal Investigator: Bin Sun, C.S. Cai and Rucheng Xiao

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Key Publications:

Sun B, Cai C S, Xiao R. Analysis Strategy and Parametric Study of Cable-Stayed-Suspension Bridges [J]. Advances in Structural Engineering, 2013, 16(6): 1081-1102.



Figure 10. 1400 m cable-stayed-suspension bridge (unit: m)



(d) Bottom side of girder

Figure 25. Stress amplitudes under traffic load

Behavior of wires in parallel wire stayed cable under general corrosion effects

Cables, as one of the ideal high-strength components, are widely used for suspension bridges, cable-stayed bridges and tied arch bridges. These bridges, however, cannot overcome the major limitation that their cables are prone to corrosion and their service life is much shorter while the maintenance cost is much higher than other members of the bridges. To overcome the limitation, bridge engineers employ various anti-rust treatments such as cement grout, galvanizing, grease, high-density polyethylene (HDPE) pipe, polyvinyl fluoride tape, or their combination.

Objective: Many cable-stayed bridges around the world have their stayed cables replaced due to corrosion problem. The problem has in fact led to a worldwide concern about corrosion damage evolution in stayed cables.

Approach: To have a deep understanding of the corrosion effects, an investigation regarding mechanical properties of wires at different corrosion extents and corrosion distributions at cable cross sections was conducted on the stayed cables replaced from Shimen Bridge in Chongqing, China.

Significant Result: The result of the investigation was a contribution to the establishment of a model for mechanical behaviors of corroded wires and a support to the presumption of the corrosion distribution at cable cross sections. A numerical cable based on a parallel-series system was modeled to observe the mechanical behaviors of corroded cable in terms of given service load, cable length, and corrosion rate. It is noted in the paper that strain hardening begins from the worst corroded wire, and the residual deformation of the wire is leveled off after a period of rapid growth, which indicates a significant decrease of distributed loads of the wire.

Principal Investigator:

Jun Xu, Weizhen Chen

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Key Publications:

Xu J, Chen W. Behavior of wires in parallel wire stayed cable under general corrosion effects [J]. Journal of Constructional Steel Research, 2013, 85: 40-47.



Fig. 5. Cable section with wires numbered.



Fig. 9. Probability density function of live load effect.



Fig. 10. The ultimate traffic load effect during T period with 95% confidence interval.



Fig. 17. Effects of cable length on wire tension.