The Application of FRP in the Shear Reinforcement of Bridges

Songsong Guo and Haifang He

***Abstract*—Combined with the research results of scholars, analyze and summarize the research status of FRP from the main factors affecting reinforcement effect, the calculation formula of shear bearing capacity, bond-slip relationship, nonlinear finite element analysis. Then analyze and consider the practical application of FRP in the bridge reinforcement. The analysis concludes: (1) FRP type, spacing, binder, effective anchorage length, FRP number, the strength of concrete will affect final reinforcement effect; (2) the calculation formula in the existing FRP specification should be revised in practical application; (3) the relationship of the bond-slip will have an effect on the reinforcement and analysis of bridge; (4) the finite element analysis of FRP can be more accurate to analyze the effect of bearing capacity of strengthened bridge. With the study deeply of the performance characteristics and application methods of FRP, it will be applied more in the bridge reinforcement and the reinforcement effect will be greatly improved.**

***Index Terms*—FRP, shear reinforcement, finite element analysis, application.**

I. Introduction

In recent years, the application of FRP materials in bridge reinforcement has increased gradually and the diversification trend of the application mode has highlighted. Scholars at home and abroad have studied and analyzed the application methods and reinforcement effects from the perspective of theory and experiment. At present, the application methods of FRP in bridge reinforcement are externally bonded method (EB), near surface mounted method (NSM), and embedded through-section technique (ETS). The application of externally bonded method is more mature, but it is easier affected by the external environment, easy to break off and can not give full play to material performance. Near surface mounted method and embedded through-section technique are being studied and analyzed. FRP material has advantages of light weight, high strength, good corrosion resistance, strong plasticity and good insulation. It has obvious advantages in bridge reinforcement and has bright prospects for development. With the increasing application of FRP in bridge reinforcement, the factors that affect the reinforcement effect gradually come out. Therefore, many scholars have done a lot of researches and analysis on the factors affecting the effect of FRP reinforcement, the bond-slip relationship of FRP and the nonlinear finite element analysis method in order to realize the full play of the properties of the FRP materials and improve the effect of the FRP reinforcement.

II. Research and Analysis on the Strengthening Effect of FRP

FRP is widely used in practical engineering. In order to guarantee the strengthening effect of FRP material, scholars at home and abroad, through the combination of theoretical analysis and indoor tests, analyze the factors that affect the effect of FRP reinforcement, give reasonable suggestions and guide the application of FRP in practical engineering. The main factors considered in the experiment are the layout spacing, type of binder, concrete grade, specimen size, effective anchorage length and anchorage form of FRP.

Salvador J. E. Dias [1] etc. analyzed the effect of CFRP reinforcement for T beams on the tests of externally bonding method. The results showed that the shear bearing capacity of T beams increased gradually with the increase of CFRP content, but the increase gradually decreased; for the T beams with abdominal tendons, the bonding direction of CFRP and the inclination angle of the beam axis is 60 degrees when the strengthening effect is best. But for the non-abdominal tendons, the reinforcement effect of 45 degree direction is better. And the spacing between CFRP bars should be consistent with the spacing of internal reinforcement.

M. C. Sundarraja [2]etc. observed the initial cracking time, ultimate bearing capacity and failure mode of reinforced concrete beams strengthened with GFRP, pointed out that the bearing capacity of the reinforced beam is far higher than that of the contrast beam.

Barros, J.A.O. [3] etc. illustrated the reinforcement effect of the near surface mounted method of CFRP and compared it with the externally bonding CFRP with theoretical analysis and test. The analysis pointed out: 1) NSM technology makes the damage of CFRP transformed from brittle failure to ductile failure; 2) For NSM technology, the reinforcement effect of 45 degree arrangement of CFRP is better than that of vertical arrangement; 3) The increase of the shear capacity of the bridge is close to 72% compared with the externally bonding method, and the ultimate strain is improved obviously.

Javad Sabzi [4] contrasted the reinforcement effect of externally bonding FRP method and near surface mounted FRP method. Analysis pointed out that the near surface mounted reinforcement effect is better than externally bonding for small and medium beams; for beams with high reinforcement ratio, the reinforcement effect is roughly the same and both of them are stripped and damaged. Therefore,

Manuscript received May 5, 2018; revised July 12, 2018.

Songsong Guo and Haifang He are with Research Institute of Highway, Ministry of Transport in China, China (Corresponding author; Haifang He; e-mail: bridge0707@163.com, hf.he@rioh.cn).

DOI: 10.7763/IJET.2019.V11.1117

the effective connection of the FRP and concrete beams has great influence on the reinforcement effect of FRP.

Peng Hui [5] conducted the experiment of reinforcing the reinforced concrete beams by applying the near surface mounted prestressed FRP technology. The result indicated that the bonding area of the FRP is increased by the inlay technique and the connection of the FRP and the concrete is improved effectively. The failure form of the reinforced component on the surface is the peeling of the bonding resin - the interface and the tearing of concrete protective layer. The failure form is characterized by brittle failure and the effective performance of FRP cannot be attained. Therefore, the research on how to improve the cohesive capacity of FRP-concrete and restrain the tearing of the concrete protection layer should be studied deeply in the future.

Zhang Chunsheng [6] etc. emphatically introduced the present research status of embedded prestressed FRP plate. The analysis of domestic and foreign research status showed: 1) this method can greatly improve the bearing capacity, especially the cracking load and yield load; 2) the embedded prestressed FRP reinforcement method can effectively improve the stiffness of the reinforcement beam, limit the development of the cracks and reduce the width of the cracks; 3) the application of embedded prestress and the anchorage method still need to be studied. At present, the application of the self-locking anchorage and the tensioning method of the component are more practical.

Chen Mingxiu [7] etc. analyzed the application status of FRP technology to reinforce concrete at home and abroad, put forward the main factors affecting the efficiency of FRP reinforcement and summarized its effect on the efficiency of reinforcement. The results are as follows: 1) the high steel ratio of the beam will influence the reinforcement effect of FRP; 2) the increase of FRP bonding layers does not constitute a linear increase relation with the bearing capacity; 3) the bonding angle of FRP has a greater effect on the strengthening effect, in which the bonding effect of U shape is better;4) the maximum tensile strain of FRP gradually increases with the increase of the shear span ratio. The increase of shear span ratio can improve the reinforcement efficiency.

Guan Yanhua [8] etc. analyzed the effect of strengthening presplitting RC beam with FRP. The results are as follows: 1) FRP bolt reinforcement technology can effectively improve the utilization efficiency of FRP; 2) the crack has a great influence on the bonding and strengthening of FRP and plays a significant role in promoting the peeling of FRP. Therefore the surface cracks should be treated first before the reinforcement is strengthened.

Zhang Feng [9] etc. studied the influence of the bonding property, anchorage distance and the reasonable anchorage length on the shear bearing capacity of the FRP- bolt joint reinforcement technology through the destructive loading test of 17 test beams with precut slit in the span. The results show that the HB-FRP (FRP- anchorage Combined Reinforcement Technology) system has a greater increase in the ductility, bearing capacity and the peel stress of the FRP system than that of the EB-FRP (external FRP reinforcement) system. The load will decrease slightly and the deflection increases continuously when FRP is cut off at the precutting seam. When the anchorage level is beyond the effective length, the increase of shear capacity is no longer obvious.

Li shuchen [10] etc. adopted the new composite bonding technology which combines the bonding of FRP and mechanical anchorage method to analyze the bonding effect through 16 shear test beam tests. The results show that: 1) the new composite bonding technology improves the ultimate shear bearing capacity and ductility of the specimen; 2) the influence of the number of FRP bands on the shear bearing capacity of the FRP strip is the smaller than that of the strip spacing. The smaller the FRP spacing is, the greater the shear capacity is. 3) the increase of ultimate bearing capacity is linearly related to the number of the strengthened beam.

M. Breveglieri [11] etc. studied and analyzed the reinforced effect of beams with different stirrup rates with CFRP reinforcement and steel bars respectively. The results are as follows: 1) the effectiveness of ETS reinforcement technology mainly depends on the length and direction of effective anchorage; 2) the strengthening effect of ETS is gradually reduced with the increase of the stirrup rate; and 3) the strengthening effect of EB technology is more than NSM technology; 4) for the bridge with the same shear reinforcement rate, the reinforcement effect of CFRP reinforcement is better than that of reinforcement.

Aishwarya R [12] etc. have studied the role of ETS technology in improving the shear bearing capacity of bridges. The analysis shows that: 1) the greater the diameter of the steel is, the better the reinforcement effect is. The ultimate bearing capacity increases by 11.22% with the increase of the diameter of the reinforced bar from 8mm to 10mm. From 10mm-12mm, the bearing capacity increases by 7.145%; 2) the space of ETS tendons affects the ultimate bearing capacity of beams. The ultimate bearing capacity increases by 13.27% with the reduce of the spacing from l/4 to l/6.

Wu Zhishen [13] analyzed the current situation of the application of pasting FRP, pointed out the existing problems and solutions and looked forward to its future development. The analysis points out: 1) the failure forms of the reinforced concrete structure with FRP are peeling, stripping and spalling. Through literature review and research, it is found that the critical interfacial shear stress is related to the fracture energy and the length of the corresponding fiber stress difference and the corresponding calculation formula is given; 2) FRP material can be stretched according to the actual needs. Prestress is used to prolong cracking time and improve flexion strength; 3) the tensile strength of CFRP is high, but ductility is poor. Brittle failure is a main failure type. Through the study of a variety of fiber components, it is found that the application of hybrid fibers can improve ductility and avoid brittle failure; 4) the direction of development of FRP is based on structural performance design. The construction of FRP structure reinforcement system with high structural life and controllable damage can be achieved.

Long Nguyen-Minh[14]etc. analyzed the bearing capacity of the T beam strengthened by FRP through the test and theory ,pointed out: 1) the strain of FRP increases with the increase of concrete strength; 2) the greater the shear-span ratio is, the higher the utilization efficiency of the FRP is; 3) the longitudinal reinforcement and the stirrup are not in conformity with the standard assumption; 4) The empirical formula given by the test is more accurate than that of the standard and the relevant standard design formula is too conservative; 5)the U type anchorage and the stress- strain changes of the bending bar should be studied when the FRP is applied in the future.

The domestic and foreign scholars have carried out a series of experimental researches and analysis on the factors affecting the effect of FRP reinforcement. It is known as follows: 1) the reinforcement efficiency of the FRP is higher than that of the general bonding of the bolt joint. 2) The reasonable anchoring length can reduce the workload and ensure the strengthening efficiency. 3) The reinforcement ratio of reinforced concrete beams affects the strengthening of FRP. When the stirrup ratio is high, the shear bearing capacity of the bridge strengthened by FRP is limited. Therefore, the actual application of FRP should be analyzed comprehensively. 4) Because of the difference of performance of the FRP material, the hybrid fiber can be used to reinforce the bridge in order to avoid brittle failure and give full play to the advantages of the material. 5) Through the analysis of the failure phenomenon of FRP reinforcement, it is found that the reinforcement of the EB method is prone to FRP peeling damage, the concrete protection layer is easily broken down for the reinforcement of the NSM method while the strengthening of the ETS method is mainly bending failure. In comparison, the reinforcement effect of the ETS method is better. 6) The prestress FRP technology can delay the reinforced concrete and increase yield load and limit load. 7) The cracks on the reinforced concrete surface should be treated before FRP reinforcement so as to avoid the stress concentration and reduce the reinforcement effect of FRP.

III. Calculation Formula of Shear Bearing Capacity

At present, the calculation formula of the contribution of FRP to the shear bearing capacity of the bridge in the externally bonding FRP method has been clearly expressed in the domestic and foreign norms, but the only main factors affecting the shear reinforcement of the FRP are considered and the secondary factors are ignored. It has certain accuracy in practical application, but there is still a certain differences compared with the actual reinforcement effect. Therefore, the accuracy of the modified calculation formula of the shear capacity in accordance with the experimental results and theoretical analysis of confrontation can be improved significantly.

Fei Peng [15] etc. contrasted the calculating formulas on the CAN/CSA-8806-12, CAN/CSA-86-14 and JSCE-1997 for the shear strength of the beams strengthened by FRP. According to the comparison of the actual test results and the standard calculation results, it is pointed out that the calculation result of CAN/CSA-86-14 is conservative and that CAN/ CSA-8806-12 is overestimated on the shear strength. JSCE-1997 overestimates the contribution of concrete to shear resistance. Therefore, the calculation formula still needs to be corrected based on effective test datas.

G. M. Chen [16] etc. analyzed the main theoretical formulas for the calculation of shear capacity, pointed out that the interaction between FRP and internal stirrup is not considered in the present theoretical formula. On the basis of the original FRP theory formula, the revised formula considers the interaction between the FRP and the stirrup and introduces the interaction coefficient (the tensile strength of the stirrup, the diameter of the stirrup and the ratio of the stirrup and the FRP). The revised formula is compared with the experimental data, the existing HB 305 (Standards Australia 2008), ACI 440.2R (ACI 2008) and CNR-DT200 (National Research Council 2004). The analysis indicates that the simulation of ACI440.2R and CNR-DT200 is deviant and HB305 does not consider the interaction between the steel and FRP, but the design formula is simple and can still be used in the design. The calculation results of formula considering the interaction are better fitted with test results and the influence of interaction on the shear reinforcement design is proved.

Ahmed Khalifa [17] etc. put forward respectively the corresponding calculation formulas considering the different fiber types and introducing effective strain / ultimate strain coefficient based on effective stress method and effect variation method and made the comparison analysis with the experimental datas. It is pointed out that the effective stress method is suitable for the fracture failure of FRP and the effective strain method is applicable to the case of FRP peel failure. In the derivation of the design formula, the author considers the factors such as the strength reduction coefficient of concrete, the spacing of FRP, the restriction of the shear reinforcement. Finally, the calculation results of the design formula is verified better with that of the experiments. In addition, the author pointed out that the design of shear reinforcement should not only focus on the improvement of shear capacity, but also pay more attention to the change of strain and avoid the occurrence brittle failure of the structure.

Amir Mofidi [18] etc. first pointed out the calculation formulas of some design specifications against shear bearing capacity and then compare and analyze the influence factors considered by various specifications through literature review. The consolidation model, effective strain, effective anchorage length and anchorage width of FRP are analyzed with reference to domestic and foreign scholars. The influence of FRP spacing, crack angle, cracking mode and stirrup influencing factor on shear capacity is discussed. In the end, the interaction between the stirrup and the FRP is added to original model and the results are compared with the test results. The results show that compared with the other standard formulas, it is better fitting with the test results.

Davood Mostofinejad [19] etc. designed and analyzed the shear bearing capacity model of the reinforced concrete beams with CFRP strips using shear design method based on the effective strain. The factors such as the modulus of elasticity of the FRP, the ratio of material and the compressive strength of the concrete are considered, and the correction coefficient is introduced in accordance with the test results. The simplified formula is synthesized and compared with the effective strain formula of ACI 440.2R and Bulletin 14. The reliability of the simplified model is explained by the comparison of the experimental results.

The analysis of the existing theoretical results shows: 1) HB305 (Standards Australia 2008), ACI 440.2R (ACI 2008) and CNR-DT200 (National Research Council 2004) have given a definite formula for calculating the shear capacity of the bridge after FRP strengthening, but none of them consider the interaction between the FRP and the internal stirrup. After considering the effect of them, the theoretical calculation results are in good agreement with the test results. 2) The formula of shear bearing capacity based on the finite stress method and the finite strain method can meet the relevant requirements between the theoretical calculation and the experimental results. The effective stress method is suitable for the fracture failure of FRP and the effective strain method is applicable to the case of FRP stripping failure. 3) At present, the study on the formula of shear bearing capacity is to modify the original formula by considering the specific influence factors. Then many scholars compare the calculation results with the test results to verify validity of the formula in the shear reinforcement. Therefore, the formula of shear resistance should be corrected according to the actual situation of the site to make it conform to the actual situation.

IV. Bond-slip Relationship

The bond-slip relationship of FRP is often determined by practical tests. The bond-slip relationship in different test conditions is often different because of the difference of binders, FRP material and concrete strength. The relationship between them is the key to study the peeling failure of FRP. Therefore, a reasonable bond-slip model is very important for the accuracy of the formula for calculating the shear capacity of FRP.

Hao Haixia, Zhang Jianren [20] etc. analyzed the bond-slip relation of the near surface mounted CFRP reinforced concrete structure. First, the relationship between the shear force and displacement is simplified as a double fold line model by the three line bond-slip constitutive relation. Then the differential equation is established by the equilibrium equation and solved by applying the existing boundary conditions, determining the interface bond bearing capacity. According to the relationship between slip value and load, the peeling load can be determined according to the slip amount and the theoretical calculation results correspond to the experimental values.

Yao Jian [21] etc. analyzed the bond bearing capacity of the reinforced concrete beam reinforced by the near surface mounted FRP method through theory and experiment. First, the bond-slip relationship of FRP was first presented according to the test results. Then the strain of FRP and the shear bearing capacity were obtained by the differential equation based on the hypothesis of peeling failure. Finally, the theoretical results calculated were in accordance well with that of bond slip test. In the bond- slip test, the test appears that FRP and concrete are stripped when the inserting length is short. When the embedded length is relatively large, the test appears that the FRP plate is broken. In addition, the thickness of the binder obtained by repeated analysis can not be too thick or too thin.

Su Peng [22] etc. studied the stress transfer behavior of reinforced concrete beams strengthened with prestressed CFRP slab through experimental and theoretical analysis. The experimental results are better in the degree of anastomosis compared with that of the theoretical formula. Based on the bond- slip relationship, the analytical solution of the bond stress differential equation of the CFRP slab is adopted and the analytical solution of the equation is derived according to the boundary condition. The analysis model of the interfacial bond stress and the tensile stress of the CFRP after the insertion of the prestressed CFRP slab is obtained. According to the theoretical formula, the maximum allowable prestress is analyzed provided that the CFRP concrete interface does not peel after the discharge.

Lili Suia [23] etc. applied ECC as bonding agents to connect FRP and concrete, which effectively increased the bearing capacity and slip distance of FRP. The study of the thickness of ECC, the treatment of concrete surface and the construction method found that: 1) the increase of the thickness of ECC effectively improves the bearing capacity of the structure; 2) the bonding effect of FRP and concrete can be effectively improved after the grinding of the concrete. Therefore, reasonable binder will make FRP and concrete form reliable connection and avoid FRP peel with concrete.

Jincheng [24] etc. pointed out that prestress can be gradually reduced from the middle to end by controlling the order of prestressing tension. No anchorage is needed to be set until the prestress of CFRP end is 0. This can avoid the occurrence of anchoring failure, effectively improve the shear capacity and avoid the peeling failure of FRP. In the engineering, the defects of FRP materials can be avoided and the hidden danger of the brittle failure of FRP can be eliminated from the source through the reasonable control of the application of FRP.

Based on the research results of the bond-slip relationship of FRP in the domestic and foreign scholars, it is pointed out that the reasonable bond-slip model is determined after bond-slip relationship is compared and analyzed by the field test. The validity of the bond-slip relationship is finally solved according to the boundary conditions after the reliable bond-slip relation is applied to the differential equation. Effective strain and shear bearing capacity can be obtained. The calculation of bond slip relationship is very important to the shear bearing capacity. Therefore, it should be obtained according to the actual test in the reinforcement design. In the application of FRP, a reasonable anchorage system should be chosen to avoid the brittle failure of FRP and influence final reinforcement effect.

V. Finite Element Analysis

With the development of computer technology and software, finite element analysis is applied more and more in structural analysis. The nonlinear finite element method is used to calculate and analyze the shear bearing capacity of the bridge reinforced by FRP. It can be more accurate to judge the reinforcement effect and provide reference for the reinforcement design of the bridge.

Lu Xin Zheng [25] etc. studied mainly the phenomenon of peeling failure of reinforced concrete beams bending. The failure mechanism of bending dissection is studied and a double stripping failure criterion is put forward through micro scale finite element analysis. The concrete element of the dispersion crack model is simulated and the finite element calculation results are in good agreement with the experimental ones. This shows that the bond slip model is different from the crack free concrete element when there is a crack in the concrete element connected with the interface unit. In the finite element simulation, the size and category of the simulated unit should be adjusted to ensure the reliability of the simulation results.

Ye Su Rong [26] etc. analyzed the main factors affecting the interface stripping of the end FRP- concrete, including the number of FRP layers, the tensile stress of the FRP, the bond slip constitutive relation of the FRP- concrete and the distance between the top of the support and the first crack at the top of the support. The results show that the tensile stress of the FRP and the number of FRP layers are the most important factors affecting the peeling failure of the interface layer of FRP-concrete at the end of the beam. The bond slip constitutive relation of FRP- concrete reflects the bond quality, which affects the generation of the peeling failure. The greater the distance between the first crack and the support of the reinforced concrete is, the smaller the corresponding peeling failure load is.

Liao Zhigang [27] etc. pointed out that the tensile-shear failure is an important failure form of the single shear bond specimen with the externally bonding FRP method. The results of the finite element analysis of the single shear bond specimen of FRP- concrete show that the width ratio of the FRP- concrete has greater influence in the tensile shear failure. With the increase of the width ratio, the ultimate bearing capacity of the concrete increased gradually. The thickness and elastic modulus of FRP have a certain effect on the tensile shear failure, but the influence is far below the width ratio. Therefore, the width ratio and modulus of elasticity should be considered to make it better in agreement with the experimental value in the calculation formula of actual tensile shear failure capacity.

Chen Linjie [28] etc. studied the reinforcement effect of precracked concrete by the finite element method. It is pointed out that the shorter the distance between the loading end and the crack is, the easier the stress concentration to appear at the crack is. Under the load, the concrete crack is first loaded at the loading end, and the concrete between the support and cracks begins to bear force after the crack is softened. The FRP on the surface of concrete is stripped off instead of continuous because of the existence of preset cracks.

Zhang Zixiao [29] etc. simulated the whole process of shear peeling of reinforced concrete beams strengthened with U type FRP with ANSYS. By comparing the results of finite element analysis with the test results, the coincidence degree of the load-deflection curves and strain-deflection curves was good. In the three-dimensional finite element modeling, the FRP and the concrete interface unit are connected with the nonlinear spring element and the dispersion crack model is adopted. At the same time, the shear transfer coefficient of the open and the closed crack fracture are properly valued according to the test condition. The former is suggested to take the 1/10 of the latter. The distribution of cracks and stress transfer are discussed and analyzed appropriately in the calculation results.

Wang Wenwei [30] etc. carried out the nonlinear finite element analysis of reinforced concrete beams reinforced by FRP and compared the results with that of tests. The results show that both of them meet the requirements in a certain error. The ultimate load, peeling load, strain distribution of FRP, stress distribution of FRP end zone and stress mechanism of reinforced concrete beams strengthened with FRP are mainly analyzed in the nonlinear finite element modeling. The simulation results are better.

The finite element analysis of the bridge strengthened by FRP can reflect the state of the reinforced bridge. However, the nonlinear finite element method still faces many problems. The bond-slip relationship between FRP and concrete or between concrete and steel bar in the finite element model still need to be studied in the future.

VI. Conclusion and Prospect

The analysis of the research status of FRP in the reinforcement bridges indicates that FRP is a promising material in bridge reinforcement, but the full performance of FRP material still faces challenge. Only by optimizing the type of FRP and solving the outstanding problems in practical application can make FRP perform a greater advantage. Based on the research status of FRP in bridge reinforcement, we can see that:

(1) The shear capacity of the bridge is improved by externally bonding method, near surface mounted method and embedded through-section method. Compared with other reinforcement methods, the design and construction are convenient and the cycle is short.

(2) The main factors affecting the reinforcement effect are the type, the spacing, the layout, the connection with concrete, the effective anchoring length of FRP. The reliable connection mode and the reasonable anchorage length can effectively improve the reinforcement effect.

(3) The dissection of FRP has great influence on the application of FRP in bridge reinforcement. Therefore, the bond slip relationship of FRP is analyzed by test and is considered in the finite element analysis.

(4) At present, many countries have given their respective regulations for the FRP reinforcement calculation, but usually only consider the main factors. Therefore, in the actual FRP reinforcement design, the standard theoretical formula should be properly corrected in order to meet the actual requirements.

(5) The nonlinear finite analysis of the bridge reinforced by FRP can give a full understanding of the stress state of the bridge and give the appropriate maintenance measures to ensure the safe use of the bridge.

In addition, the elastic modulus of the general FRP material is small, which affects the application in practical engineering. However, the Issam Harik [31] has applied the FRP material whose modulus of elasticity is higher than that of the steel in the actual engineering. Therefore, with the improvement of the stiffness of FRP material, the effective anchoring method of FRP, the mixed use of fiber material and inorganic material, the reliability of nonlinear finite element analysis and the durability of the reinforcement system, the application of FRP in the bridge reinforcement will be more mature and the strengthening system is more perfect.

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Songsong Guo is a master graduate student in the Research Institute of Highway, Ministry of Transport, China. He majors in the study of the testing, evaluation and reinforcement of bridge bearing capacity. He attended many projects of the Ministry of transportation and transportation, such as the investigation and analysis on the durability of road and Bridge, research on damage assessment and safety reliability evaluation of concrete beam bridge.

At present, he is attending the construction of science and technology projects called technical system and equipment development for reliability inspection and evaluation of existing concrete beam bridges and arch bridges by the Ministry of transportation and transportation, China.