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When FRP is applied to the S hear R reinforcing B ridges

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ABSTRACT

The main elements influencing the reinforcing effect, the shear bearing capacity calculation method, the bond-slip connection, and nonlinear finite element analysis are analyzed and summarized, together with the research findings of scholars, to determine the current state of FRP research. Next, evaluate and take into account the real-world use of FRP for bridge reinforcement. The analysis comes to the following conclusions: (1) the type, spacing, binder, effective anchorage length, FRP number, and concrete strength will affect the final reinforcement effect; (2) the finite element analysis of FRP can be more accurate to analyze the effect of bearing capacity of strengthened bridge; (3) the bond-slip relationship will have an effect on the reinforcement and analysis of bridge; and (4) the calculation formula in the current FRP specification should be revised in practical application. More FRP will be used in bridge reinforcement as a result of a thorough analysis of its performance characteristics and application techniques, which will significantly increase the reinforcement impact.

Keywords: FRP, shear reinforcement, finite element analysis, application.

INTRODUCTION

The use of FRP materials for bridge reinforcement has steadily grown in recent years, and the trend of application mode diversification has been seen. From a theoretical and experimental standpoint, researchers both domestically and internationally have examined and evaluated the reinforcing effects and application techniques. Currently, the embedded through-section technique (ETS), near surface mounted method (NSM), and externally bonded method (EB) are the ways used to apply FRP in bridge reinforcement. Although the use of the externally bonded approach is more developed, it is more susceptible to environmental influences, is more likely to break off, and does not allow for complete material performance. The embedded through-section approach and the near surface mounted method are being researched and examined. Light weight, high strength, great plasticity, corrosion resistance, and superb insulation are all benefits of FRP material. It offers clear benefits for reinforcing bridges and has promising development prospects. The elements influencing the reinforcement effect steadily become apparent as FRP is used more and more in bridge reinforcement. Therefore, in order to fully realize the properties of the FRP materials and enhance the effect of the FRP reinforcement, numerous scholars have conducted extensive research and analysis on the factors affecting the effect of FRP reinforcement, the bond-slip relationship of FRP, and the nonlinear finite element analysis method.

II. Investigations and Evaluations of the Strengthening Impact of FRP

Practical engineering makes extensive use of FRP. Through a combination of theoretical analysis and indoor testing, researchers both domestically and internationally examine the factors that influence the effect of FRP reinforcement, provide logical recommendations, and direct the use of FRP in practicasl engineering to ensure the strengthening effect of FRP material. The layout spacing, binder type, concrete grade, specimen size, effective anchorage length, and FRP anchorage shape are the primary variables taken into account in the experiment.

The impact of CFRP reinforcement for T beams on external bonding method testing was examined by Salvador J. E. Dias [1] and others. According to the results, the shear bearing capacity of T beams increased gradually as the CFRP content increased, but the increase also gradually decreased. For T beams with abdominal tendons, the optimal strengthening effect occurs when the CFRP bonding direction and the beam axis inclination angle are 60 degrees. However, the 45-degree orientation has a stronger reinforcing impact on the non-abdominal tendons. Additionally, the distance between CFRP bars and the distance between internal reinforcement should match. M. Sundarraja C. [2] et al. noted that the bearing capacity of the reinforced beam is significantly more than that of the comparison beam after observing the initial cracking time, ultimate bearing capacity, and failure manner of reinforced concrete beams strengthened with GFRP. Through theoretical research and testing, Barros, J.A.O. [3] et al. demonstrated the reinforcement impact of the CFRP near surface mounted approach and contrasted it with the CFRP that is externally bonded. According to the analysis, 1) NSM technology causes CFRP damage to change from brittle to ductile; 2) the reinforcement effect of a 45-degree CFRP arrangement is superior to that of a vertical arrangement; 3) the bridge's shear capacity increases by nearly 72% when compared to the external bonding method, and the ultimate strain is clearly improved.

The reinforcement effects of the near-surface mounted FRP approach and the externally bonded FRP method were compared by Javad Sabzi [4]. According to analysis, for small and medium-sized beams, the near-surface mounted reinforcement effect is superior to external bonding; for beams with a large reinforcement ratio, the reinforcement effect is about the same and both are stripped and damaged. Thus, the reinforcement impact of FRP is greatly influenced by the efficient connection of the FRP and concrete beams.

Peng Hui [5] experimented with using near surface mounted prestressed fiber-reinforced polymer (FRP) technology to reinforce reinforced concrete beams. The outcome showed that the inlay approach successfully improves the bonding area of the FRP and the connection between the FRP and the concrete. Peeling of the bonding resin at the interface and tearing of the concrete protective layer are the failure forms of the reinforced component on the surface. Brittle failure is a defining feature of the failure form, and FRP cannot function well. Therefore, future study should focus on ways to increase the cohesive capability of FRP-concrete and prevent the concrete protective layer from tearing.

The current state of embedded prestressed FRP plate research was eloquently presented by Zhang Chunsheng [6] and others. 1) The embedded prestressed FRP reinforcement method can effectively increase the stiffness of the reinforcement beam, limit the development of cracks, and reduce the width of the cracks; 2) the application of embedded prestress and the anchorage method still requires study; and 3) the analysis of domestic and international research status revealed that this method can significantly increase the bearing capacity, particularly the cracking load and yield load. The component's tensioning technique and the use of the self-locking anchorage are currently more feasible.

Chen Mingxiu [7] and colleagues examined the current state of FRP technology's use to reinforce concrete both domestically and internationally, identified the primary determinants of FRP reinforcement's effectiveness, and compiled the impact of FRP on reinforcing efficiency. 1) The reinforcement effect of FRP will be affected by the high steel ratio of the beam; 2) the number of FRP bonding layers does not increase linearly with the bearing capacity; 3) the bonding angle of FRP has a greater effect on the strengthening effect, with the U shape bonding effect being the best; and 4) the maximum tensile strain of FRP gradually increases as the shear span ratio increases. The efficacy of reinforcing can be enhanced by increasing the shear span ratio.
Guan Yanhua [8] and others examined the impact of using FRP to reinforce presplit RC beams. The findings indicate that: 1) FRP bolt reinforcing technique can significantly increase the use efficiency of FRP; 2) cracks significantly impact the bonding and strengthening of FRP and contribute to its peeling. Therefore, before strengthening the reinforcement, the surface fractures should be fixed.

Through the destructive loading test of 17 test beams with a precut slit in the span, Zhang Feng [9] et al. investigated the effects of bonding properties, anchorage distance, and the appropriate anchorage length on the shear bearing capacity of the FRP-bolt joint reinforcing technology. According to the findings, the HB-FRP (FRP-anchorage Combined Reinforcement Technology) system outperforms the EB-FRP (external FRP reinforcement) system in terms of ductility, bearing capacity, and peel stress. When FRP is cut off at the precutting seam, the load will gradually diminish and the deflection will continually increase. The increase in shear capacity becomes less noticeable when the anchorage level exceeds the effective length.
In order to examine the bonding impact using 16 shear test beam tests, Li Shuchen [10] and others applied the innovative composite bonding technology, which combines the bonding of FRP with the mechanical anchorage method. The findings demonstrate that: 1) the innovative composite bonding technology increases the specimen's final shear bearing capacity and ductility; and 2) the number of FRP bands has less of an impact on the FRP strip's shear bearing capacity than does strip spacing.

The shear capacity increases with decreasing FRP separation. 3) The number of strengthened beams increases linearly with the ultimate bearing capacity.
M. The reinforced effect of beams with varying stirrup rates using CFRP reinforcement and steel bars, respectively, was investigated and examined by Breveglieri [11] and others. The findings are as follows: 1) ETS reinforcement technology's effectiveness is primarily dependent on the length and direction of effective anchorage; 2) ETS's strengthening effect gradually decreases as the stirrup rate increases; 3) EB technology's strengthening effect surpasses that of NSM technology; and 4) CFRP reinforcement outperforms reinforcement for bridges with the same shear reinforcement rate.
Researchers like Aishwarya R [12] have looked into how ETS technology might increase bridges' shear bearing capability. According to the analysis, 1) the reinforcement effect improves with increasing steel diameter. When the diameter of the reinforced bar is increased from 8mm to 10mm, the ultimate bearing capacity rises by 11.22%. The bearing capacity improves by 7.145% between 10mm and 12mm; 2) the ETS tendon spacing has an impact on the beams' final bearing capacity.

When the spacing is reduced from l/4 to l/6, the ultimate bearing capacity rises by 13.27%. Wu Zhishen [13] examined the state of pasting FRP application at the moment, highlighting issues and potential fixes while anticipating its advancement. 1) Peeling, stripping, and spalling are the failure forms of the reinforced concrete structure with FRP, according to the analysis. Through research and a review of the literature, it is discovered that the critical interfacial shear stress is correlated with the fracture energy and the length of the corresponding fiber stress difference. The formula for this relationship is provided; 2) FRP material can be stretched to meet actual requirements. Prestress is utilized to increase flexion strength and lengthen the cracking time; 3) CFRP has a high tensile strength but a low ductility. One of the primary failure types is brittle failure. The use of hybrid fibers can increase ductility and prevent brittle failure, according to research on a range of fiber components; 4) the development of FRP is centered on structural performance design. It is possible to create a FRP structure reinforcing system with a high structural life and manageable damage.

Nguyen-Minh Long [14], etc. examined the bearing capacity of the FRP-strengthened T beam using both theory and test, and found that: 1) the strain of the FRP increases as the strength of the concrete increases; 2) the higher the shear-span ratio, the higher the utilization efficiency of the FRP; 3) the stirrup and longitudinal reinforcement do not comply with the standard assumption; 4) the empirical formula provided by the test is more accurate than 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 examined when the FRP is used in the future. Numerous experimental studies and analyses on the variables influencing the impact of FRP reinforcement have been conducted by both domestic and international researchers. It is referred to as follows: 1) The FRP's reinforcement efficiency is greater than the bolt joint's overall bonding. 2) A suitable anchoring length can guarantee strengthening efficiency and lessen workload. 3) The strengthening of FRP is influenced by the reinforcement ratio of reinforced concrete beams. The shear bearing capacity of the FRP-strengthened bridge is constrained when the stirrup ratio is large. As a result, a thorough analysis of the real-world implementation of FRP is necessary. 4) Due to the FRP material's different performance, the bridge can be reinforced with hybrid fiber to prevent brittle failure and fully utilize the material's benefits. 5) The analysis of the FRP reinforcement failure phenomenon reveals that the ETS method's strengthening primarily results in bending failure, the EB method's reinforcement is susceptible to FRP peeling damage, and the NSM method's reinforcement readily breaks down the concrete protection layer. The ETS approach has a stronger reinforcement impact in contrast. 6) The prestress FRP method can raise yield load and limit load while delaying reinforced concrete. 7) To prevent stress concentration and lessen the reinforcement effect of FRP, the fractures on the reinforced concrete surface should be repaired before FRP reinforcement.

III. SHEAR BEARING CAPACITY CALCULATION FORMULA

The formula for calculating the FRP's contribution to the bridge's shear bearing capacity in the externally bonding FRP method is currently well-expressed in both domestic and international standards; however, only the primary factors influencing the FRP's shear reinforcement are taken into account, while secondary factors are disregarded. Although it is somewhat accurate in real-world applications, there are still some distinctions from the real reinforcing effect. As a result, it is possible to greatly increase the accuracy of the modified shear capacity calculation formula in accordance with the theoretical analysis of confrontation and experimental data.

Fei Peng [15] et al. compared the CAN/CSA-8806-12, CAN/CSA-86-14, and JSCE-1997 calculation formulas for the shear strength of the FRP-strengthened beams. The calculation result of CAN/CSA-86-14 is conservative, whereas the shear strength of CAN/CSA-8806-12 is exaggerated, according to a comparison of the actual test results with the standard calculation results. The proportion of concrete to shear resistance is overestimated by JSCE-1997. Therefore, based on useful test data, the calculating formula still needs to be adjusted.

G. M. Chen [16] and others examined the primary theoretical formulas for determining shear capacity and noted that the current theoretical formula does not account for the interaction between FRP and internal stirrup. The updated formula, which is based on the original FRP theory formula, takes into account the interaction between the FRP and the stirrup and adds the interaction coefficient (the stirrup's tensile strength, diameter, and ratio of the FRP and the stirrup). The experimental data, the current HB 305 (Standards Australia 2008), ACI 440.2R (ACI 2008), and CNR-DT200 (National Research Council 2004) are compared with the updated formula. Although the investigation shows that HB305 ignores the interaction between the steel and FRP and that the simulation of ACI440.2R and CNR-DT200 is deviant, the design method is straightforward and still applicable. The influence of interaction on the shear reinforcement design is demonstrated, and the calculation results of the formula taking interaction into account fit the test findings better. The corresponding calculation formulas were proposed by Ahmed Khalifa [17] and others, taking into account the various fiber types. They introduced the effective strain/ultimate strain coefficient based on the effective stress method and effect variation method, and they conducted a comparison analysis with the experimental data. It is noted that the effective strain approach can be used in the case of FRP peel failure, whereas the effective stress method is appropriate for FRP fracture failure. The author takes into account a number of parameters while determining the design formula, including the concrete's strength decrease coefficient, the FRP spacing, and the shear reinforcement's restriction. Lastly, the design formula's computation results are more closely matched to the experimental results. Furthermore, the author made the point that the design of shear reinforcement should not only concentrate on increasing shear capacity but also emphasize strain change and prevent brittle failure of the structure.

Before comparing and analyzing the influencing elements taken into account by different specifications through a survey of the literature, Amir Mofidi [18] and others first highlighted the calculation formulae of some design requirements against shear bearing capacity. With reference to both domestic and international experts, the consolidation model, effective strain, effective anchorage length, and anchorage breadth of FRP are examined. Shear capacity is examined in relation to FRP spacing, fracture angle, cracking mechanism, and stirrup affecting factor. Ultimately, the stirrup-FRP interaction is incorporated into the original model, and the outcomes are contrasted with the test findings. The findings indicate that it fits the test outcomes better than the other common formulas.

Using the shear design method based on the effective strain, Davood Mostofinejad [19] et al. created and examined the shear bearing capacity model of the CFRP-stripped reinforced concrete beams. A correction coefficient is added in line with the test results after taking into account variables including the concrete's compressive strength, the FRP's modulus of elasticity, and the material ratio. The simplified formula is created and contrasted with Bulletin 14 and ACI 440.2R's effective strain formula. The comparison of the experimental findings explains the simplified model's dependability.

1) HB305 (Standards Australia 2008), ACI 440.2R (ACI 2008), and CNR-DT200 (National Research Council 2004) have provided a clear formula for determining the shear capacity of the bridge following FRP strengthening; however, none of them take into account the interaction between the FRP and the internal stirrup, according to the analysis of the current theoretical results. The theoretical calculation results are in good agreement with the test results after taking their effect into account. 2) Between the theoretical calculation and the experimental results, the shear bearing capacity formula based on the finite stress and finite strain methods can satisfy the pertinent conditions. For FRP fracture failure, the effective stress approach works well, whereas for FRP stripping failure, the effective strain method works well. 3) The current research on the shear bearing capacity formula involves altering the original formula while taking particular influencing factors into account. The validity of the formula in the shear reinforcement is then confirmed by numerous researchers comparing the computation results with the test results. In order to make the shear resistance formula more in line with the site's actual circumstances, it should be adjusted accordingly.

IV. SLIP-BOND RELATIONSHIP

Practical tests are frequently used to establish the bond-slip connection of FRP. Due to variations in binders, FRP material, and concrete strength, the bond-slip relationship under various test settings frequently varies. The key to understanding why FRP peels is how they relate to one another. Consequently, the accuracy of the formula used to determine the shear capacity of FRP depends critically on a realistic bond-slip model.
The bond-slip relationship of the CFRP reinforced concrete structure that was installed close to the surface was examined by Hao Haixia, Zhang Jianren [20], and others. First, the three line bond-slip constitutive relation simplifies the interaction between the shear force and displacement as a double fold line model. The interface bond bearing capacity is then ascertained by solving the differential equation using the current boundary conditions after it has been determined by the equilibrium equation. The peeling load may be calculated based on the amount of slip and the theoretical calculation results match the experimental data, according to the relationship between slip value and load.

Through theory and experimentation, Yao Jian [21] et al. examined the bond carrying capacity of the reinforced concrete beam reinforced using the near surface mounted FRP method. First, the test results were used to illustrate the bond-slip relationship of FRP. The differential equation based on the peeling failure hypothesis was then used to determine the strain of FRP and the shear carrying capacity. Ultimately, the predicted theoretical results agreed well with the bond slip test results. When the insertion length is short, the bond-slip test suggests that the concrete and FRP are stripped. The test indicates that the FRP plate is shattered when the embedded length is comparatively considerable. Furthermore, the binder's thickness, as determined by repeated analysis, cannot be too thick or thin.

Through experimental and theoretical research, Su Peng [22] et al. investigated the stress transfer behavior of reinforced concrete beams strengthened with prestressed CFRP slab. In terms of anastomosis degree, the experimental results outperform the theoretical calculation. The analytical solution of the CFRP slab's bond stress differential equation is obtained in accordance with the boundary condition and is adopted based on the bond-slip relationship. Following the insertion of the prestressed CFRP slab, the analysis model of the CFRP's tensile stress and interfacial bond stress is produced. As long as the CFRP concrete interface does not peel following discharge, the theoretical formula analyzes the maximum permissible prestress.

By using ECC as bonding agents to join FRP and concrete, Lili Suia [23] et al. successfully improved the FRP's slip distance and bearing capacity. The results of the investigation into ECC thickness, concrete surface treatment, and construction technique were as follows: 1) increasing ECC thickness significantly increases the structure's bearing capacity; 2) FRP and concrete bonding effect can be effectively enhanced following concrete grinding. As a result, a suitable binder will prevent FRP peeling with concrete and enable a solid connection between FRP and concrete. Jincheng [24] and others noted that by regulating the order of prestressing tension, prestress can be progressively decreased from the middle to the end. Until the CFRP end's prestress is zero, no anchorage needs to be placed. This can effectively increase the shear capacity, prevent peeling failure of FRP, and prevent anchoring failure. By exercising adequate control over the application of FRP, engineers may prevent the flaws in FRP materials and completely eradicate the hidden risk of brittle failure.

It is noted that the suitable bond-slip model is established following the comparison and analysis of the bond-slip relationship by the field test, based on the research findings of the bond-slip relationship of FRP by both domestic and international researchers. After applying the trustworthy bond-slip relation to the differential equation, the validity of the connection is ultimately resolved in accordance with the boundary conditions. It is possible to achieve effective strain and shear bearing capability. The shear bearing capacity greatly depends on the bond slip relationship calculation. Consequently, it ought to be acquired in accordance with the real test in the reinforcement design. A suitable anchorage system should be used when using FRP in order to prevent brittle failure and affect the ultimate reinforcement effect.

V. ANALYSIS OF FINITE ELEMENTS

Finite element analysis is being used in structural analysis more and more as computer technology and software advance. The shear bearing capacity of the FRP-reinforced bridge is computed and analyzed using the nonlinear finite element method. It may be more accurate to assess the impact of reinforcement and offer guidance for the bridge's reinforcement design.
The problem of peeling failure of reinforced concrete beams bending was the primary focus of research by Lu Xin Zheng [25] and others. Using microscale finite element analysis, the failure mechanism of bending dissection is examined and a twofold stripping failure criterion is proposed. The findings of the finite element computation show good agreement with the experimental data when the concrete element of the dispersion crack model is simulated. This demonstrates that when there is a crack in the concrete element attached to the interface unit, the bond slip model differs from the crack-free concrete element. To guarantee the accuracy of the simulation findings, the size and category of the simulated unit in the finite element simulation should be changed.
The number of FRP layers, the FRP's tensile stress, the FRP-concrete's bond slip constitutive relation, and the distance between the top of the support and the first crack at the top of the support were among the primary factors that Ye Su Rong [26] and others examined in order to determine how the end FRP-concrete interface stripping was affected. The findings indicate that the most significant variables influencing the peeling failure of the FRP-concrete interface layer at the end of the beam are the FRP's tensile stress and the number of FRP layers. The bond quality, which influences the development of peeling failure, is reflected in the bond slip constitutive relation of

FRP-concrete. The peeling failure load decreases as the distance between the initial crack and the reinforced concrete's support increases.

Tensile-shear failure is a significant failure mode of the single shear bond specimen with the externally bonding FRP technology, according to Liao Zhigang [27] and others. According to the findings of the finite element analysis of the FRP-concrete single shear bond specimen, the width ratio of the material has a bigger impact on the tensile shear failure. The concrete's ultimate bearing capacity continuously increased as the width ratio grew. The tensile shear failure of FRP is somewhat influenced by its thickness and elastic modulus, but not nearly as much as by its width ratio. To improve agreement with the experimental value in the formula for calculating the actual tensile shear failure capacity, the width ratio and modulus of elasticity should be taken into account. Chen Linjie [28] and others used the finite element method to investigate the reinforcing effect of precracked concrete. It is noted that stress concentration at the fracture is more likely to occur at shorter distances between the loading end and the crack. The concrete crack is initially loaded at the loading end of the load, and once the crack has softened, the concrete between the support and the fissures starts to bear stress. Because of the presence of predefined fissures, the FRP on the concrete's surface is stripped off rather than continuous.

Zhang Zixiao [29] and others used ANSYS to model the entire shear peeling process of reinforced concrete beams reinforced with U-type FRP. The load-deflection curves and strain-deflection curves showed a good degree of coincidence when compared to the test results and the results of finite element analysis. The dispersion crack model is used in three-dimensional finite element modeling, and the FRP and concrete interface unit are linked with the nonlinear spring element. At the same time, the open and closed crack fractures' shear transfer coefficients are appropriately valued based on the test conditions. It is advised that the former take one tenth of the latter. The computation results suitably examine and analyze the distribution of cracks and stress transfer. Nonlinear finite element analysis of reinforced concrete beams reinforced with fiber-reinforced polymer (FRP) was performed by Wang Wenwei [30] and colleagues, and the results were compared with test data. The findings indicate that, with one exception, both of them satisfy the standards. Nonlinear finite element modeling is mostly used to study the ultimate load, peeling load, strain distribution of fiber-reinforced polymer (FRP), stress distribution of the FRP end zone, and stress mechanism of reinforced concrete beams strengthened with FRP. The outcomes of the simulation are superior.

The condition of the reinforced bridge can be reflected in the finite element analysis of the FRP-strengthened bridge. The nonlinear finite element approach still has a lot of issues, though. Future research is still needed to determine the bond-slip relationship between FRP and concrete or between concrete and steel bars in the finite element model.

VI. FINAL RESULTS AND THE FUTURE

Although FRP is a promising material for bridge reinforcement, there are still obstacles in the way of its full performance, according to an examination of the research state of FRP in reinforcement bridges. The only way to increase FRP's performance is to optimize its type and address any unresolved issues in real-world applications. We may observe from the current state of research on FRP in bridge strengthening that:

(1) External bonding, near surface mounting, and embedded through-section techniques all increase the bridge's shear capacity. The cycle is brief and the design and construction are convenient when compared to other reinforcement techniques.
(2) The kind, spacing, arrangement, connection to concrete, and effective anchoring length of fiber-reinforced polymer (FRP) are the primary elements influencing the reinforcement effect. The reinforcement effect can be efficiently enhanced by a dependable connection method and a suitable anchorage length.
(3) The utilization of FRP in bridge reinforcement is significantly impacted by its dissection. As a result, the finite element analysis takes into account the bond slip relationship of FRP and analyzes it through testing.
(4) Many nations now have laws for calculating FRP reinforcement, although they typically only take into account the most important aspects. Therefore, in order to fulfill the actual requirements, the standard theoretical formula should be appropriately modified in the actual FRP reinforcement design.
(5) A thorough understanding of the stress state of the FRP-reinforced bridge and the necessary maintenance procedures to guarantee its safe operation can be obtained from the nonlinear finite analysis of the bridge.

Furthermore, the standard FRP material has a low elastic modulus, which limits its use in real-world engineering applications. But in the real engineering, Issam Harik [31] used FRP material, which has a higher modulus of elasticity than steel. Therefore, the application of FRP in bridge reinforcement will be more mature and the strengthening system is more perfect 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.

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