Review on Seismic Behavior of Precast Bridge Column with Socket Connections

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Abstract. Accelerated bridge construction (ABC) technology has been widely used due to its many advantages. However, the lack of well-developed and engineering proven connection details have limited the use of prefabricated substructures in seismic zones. The socket connection is one of many different ways of connecting precast substructure, which is characterized by convenient transportation and simple construction. This paper introduces the socket connections of precast bridge columns and reviews it from those aspects including theoretical research, experimental research and research on the application of advanced materials. The socket connection belongs to the emulative monolithic connections, which has good strength and ductility. But there exists a disadvantage of large residual displacement after the earthquake for socket connection. At present, there are many researches on the design of socket connection, but there are few studies on the repair of piers after the earthquake. Therefore, it is necessary to study a quick and economic repair method in the future to exert the functionality of bridge structures following earthquake event.

1. Introduction
Accelerated bridge construction (ABC) is used more and more because it has many advantages over traditional on-site construction. A lot of engineering practice shows that ABC can greatly reduce on-site working hours, shorten traffic delays, minimize construction risks faced by workers and reduce project cost. Currently have developed and evaluated the different ways of connection of precast column, in order to meet the seismic design standards, such as bar couplers, grouted ducts, and socket connections. However, due to the lack of adequate understanding of the seismic performance of these connections, their application in high seismic areas is limited.

The socket connection is to set a reserved hole in the foundation or the cap beam, insert the prefabricated pier into the reserved hole, and then inject high-strength non-shrink grout into the hole, as shown in Figure 1. This type of connection is simple, the requirements for on-site construction accuracy are low, and it has a good development and application prospect. It has been successfully used in areas such as Washington State, USA, and has successfully accelerated the progress of on-site construction, as shown in Figure 2.
2. Research Status of Theory

2.1. Theoretical Research of Socket Connection with Conventional Materials

At present, the widely used materials for precast bridge bent systems are traditional materials such as concrete, grout, bars and prestressing strands, and many people have studied it.

Osanai Yutaka et al. [2] conducted a cyclic loading test on half-scale model samples to study the structural behavior of frame-column with socket connection, and analyzed the force transfer mechanism of shear key by combining the numerical model. For the different buried depths, some design suggestions for shearing keys are given. However, the shear key designed in the experiment is of a specific size and is not representative.

Canha et al. [3] carried out a theoretical and experimental analysis aimed at studying the transverse walls performance of the socket connections of precast concrete structures. A total of seven specimens were designed, four of which had smooth interfaces and three had rough interfaces. The results showed that the smooth connection of the top of the compression side of the transverse wall and the rough connection of the top of the two transverse walls are subjected to a combination of tension and bending moment, and the tension is greater than the bending moment. And for rough interfaces, the damage degree of the top of the transverse wall on the tension side is more serious than that on compressive side.

Canha et al. [4] studied the performance of the a precast column with smooth interfaces at the internal faces of the socket connection. Based on the experiment, a strut-and-tie model is proposed. The model considers the concrete confinement and the reduction of efforts in the foundation caused by friction. Research shows that the value of the friction coefficient has a greater impact on the calculation results of some theoretical forces. After analysis, it is recommended that the friction coefficient be 0.6. However, the friction forces at the precast column base is not considered in this model. Canha et al. [5] improved this model. The friction at the bottom of the column was also taken into account. Comparing the theoretical force of the two models with the experimental value, the new model provides more consistent results with the experimental value.

Canha et al. [6] proposed models and design suggestions for the analysis of socket connection with rough interfaces, considering the configuration of the shear keys. Based on the experimental results obtained by Nunes [7], Canha et al. refine the load transfer model originally proposed. The research results show that only when the size of the shear key is within the recommended range, the performance of the socket connection with rough interface is similar to that of the cast-in-place connection.

PIERALISI et al. [8] conducted a parametric study on the external socket base with smooth interface. The parameters included the column cross section, the embedded length of the column in the base and the wall thickness of the base. At the same time, a calculation model is proposed to facilitate designers to compare different design schemes. The results show that the proposed algorithm can simplify the design and find the optimal solution more quickly, which is very meaningful.
2.2. Theoretical Research of Socket Connection with Advanced Materials

Based on the experimental research of Nelson Mark[9], Sadeghian et al.[10] proposed an analysis model (referred to herein as the “general model”) to study concrete-filled fiber reinforced-polymer tubes(CFFT) with socket connections. The research results show that the theoretical calculation results of the model are in good agreement with the experimental results, so it can be used to predict the critical embedding length Xcr of CFFT under different parameters. When the actual embedding length is less than Xcr, the strength of the CFFT component is low and the failure occurs earlier. Sadeghian et al.[11] analyzed the results of the sensitivity analysis conducted by the general model. Some less influential parameters were approximately considered on the basis of the general model, and a new simple closed-form expression (referred to herein as the “simplified model”) was derived. The simplified model is suitable for general conditions including lateral and axial loads, enabling designers to design a specific critical embedment depth Xcr and draw the corresponding axial load-bending moment curve of the CFFT.

At present, the establishment and verification of theoretical analysis models of bridge piers are mainly single bridge pier. Since the mechanical performance of double bridge piers in the transverse bridge direction is different from that of single bridge pier. Therefore, it is necessary to further study the mechanical behavior of double bridge piers based on the experimental results of double bridge piers and put forward the theoretical model of double bridge piers.

3. Research Status of Experiment

3.1. Single Bridge Pier Study

Haraldsson et al.[12] studied the vertical bearing capacity, anti-seismic property, and constructability of a new prefabricated bridge piers with socket connection. The test results show that the socket connection show good performance, and the horizontal bearing capacity of prefabricated bridge piers is even better than that of traditional cast-in-place piers. Because the bottom diagonal bars have low stress during the test, so they are unnecessary. And in the following design, this kind of bars can be eliminated.

Torres et al.[13] used prefabricated bridge piers with socket connection in actual projects as prototypes to conduct a quasi-static loading test. There are two types of test specimens, one is a prefabricated pier without prestressing in the base, and the other is a prefabricated pier with prestressing in the base. The research results show that the damage forms of the two types of bridge piers are basically the same. And because of the pre-compression stress in the base, if the compressive stress is too large, the concrete of the base may be crushed, which will cause the bars in the base to lose the protection of the concrete and be damaged under the action of water or other external factors. The situation is not safe, so it is not recommended to use pre-stressed bars in the base.

Davis et al.[14] developed a new precast concrete bridge bent system and conducted a test under the cyclic quasi-static loading. Unbonded pretensioning in the pier can not only reduce the residual displacement of the pier after the earthquake, but also improve the durability of the pier, while factory prefabrication can ensure the quality of the pier. Davis compared the results with those of Pang[15]. The results showed that the horizontal bearing capacity of the specimen is similar to the original specimen without unbonded pretensioning. Under the same loading system, the lateral displacement of the top of the prefabricated pier reaches a drift rate of 10%, and the unloading is performed. The residual displacement drift rate of the pier is only 1%, and the rebound effect is good.

Cheng et al.[16] studied the socket connection of vertical prefabricated components using corrugated steel pipe (CSP), and evaluated the lateral shear strength of the socket connection under various connection parameters through experiments. The research results show that by intentionally roughening the surface of the embedded member, satisfactory shear strength can be obtained, and the embedded member can withstand the axial load in practical engineering applications without damage. However, for specimens with deep-amplitude surface textures, the increased gap between the CSP and the component requires more grouting, which reduces the stiffness of the connection between the CSP and the prefabricated component.
3.2. Double Bridge Piers Study

Mashal et al. [17] conducted experimental study on the seismic behavior of half-scale fully precast multi-column piers under the cyclic quasi-static loading. Emulative monolithic connections (called "high-damage" solutions) are used between prefabricated components. Bridge pier to footing connection is socket connection, and bridge pier to cap beam connection is grouted duct connection. The research results show that the prefabricated bridge pier using the "high damage" scheme under quasi-static loading has achieved good strength and ductility levels by forming four plastic hinges. The seismic performance is similar to that of cast-in-place pier, but the pre-fabricated bridge piers of the "high damage" scheme have higher maintenance costs and longer maintenance time after the earthquake.

Thonstad et al. [18] developed a new bridge system with pretensioned rocking columns and conducted a multi-shaking table test at the University of Nevada to research and analyze its seismic performance. The top and bottom of the column are specially designed. By focusing the deformation on the special area on the top and bottom of the column, the destruction of the column itself under the action of earthquake is eliminated. The test results show that the damage of the column concrete is very small, and the maximum residual drift ratio of the column does not exceed 0.1%. After 100% of the design level motion [peak ground acceleration (PGA) = 0.75 g], the column does not require any repair, and the seismic performance is superior.

3.3. Repair Study of Post-earthquake

White et al. [19] designed a nonemulative precast pier with socket connection and then conducted a biaxial quasi-static testing on the test model. The purpose of the experiment was to study how to repair damaged piers quickly and economically after a severe earthquake, so as to maximize the function of the bridge structure after the earthquake. Results indicated that the position of the preinstalled threaded inserts in the pier has been deviated, making the threads unable to be aligned. The repair method needs to be further developed and improved.

The experimental research results show that, with a reasonable design, the pier with socket connection shows a good level of strength and ductility, but the residual displacement of the pier after the earthquake is relatively large. At present, there are few studies on the reduction of residual displacement of piers with socket connection after earthquakes and their maintenance after earthquakes. It is meaningful to study how to reduce the residual displacement of piers and a reasonable method of repairing piers after earthquake to reduce bridge maintenance costs after earthquake.

4. Application of Advanced Materials

4.1. Fiber Reinforced Polymer

FRP (fiber reinforced polymer) has attracted people's attention for its advantages of light weight, high strength and corrosion resistance. There are more and more structures use FRP materials. In the prefabricated pier system, FRP can be used as an outer covering material for plastic hinges to provide binding for concrete in the core area.

In 2008, Mark Nelson et al. [9] studied the mechanical performance of concrete-filled FRP tubes with socket connection. Tube specimens with a diameter (D) of 219mm were embedded into a foundation with a depth ranging from 0.3D to 1.5D, and then push and pull the specimen until it fails to find the best embedment depth. The research results show that the shallowest embedding depth required for bending failure of the specimen is 0.73D.

4.2. Ultra-high Performance Concrete

UHPC is a new generation of high-strength, high-ductility, and high-durability cementitious materials. It is generally believed that the compressive strength of UHPC is between 150 and 250Mpa[20,21]. The mechanical properties of UHPC are far superior to ordinary concrete. From the perspective of the whole life cycle, UHPC can reduce engineering costs and is very suitable for the next generation of infrastructure construction.
Mohebbi et al.[22] conducted a shake table test on a new type of posttensioned precast bridge pier with socket connection, which used two new materials, Ultra-high performance concrete(UHPC) and carbon fiber–reinforced polymer (CFRP). The research results show that UHPC can eliminate the low-cycle fatigue fatigue that often occurs in traditional reinforced concrete piers under earthquake. In addition, CFRP tendons provides good restoring force so that the residual displacement of the pier is very small and can be ignored.

Mohebbi et al.[23] conducted shaking table tests on prefabricated two-column bent made of ultrahigh performance concrete (UHPC) and engineered cement composite (ECC) in the plastic hinge area on the top of the pier, and analyzed the effectiveness of advanced materials in reducing the damage of piers near the cover beam under earthquake action. Results indicated that both UHPC and ECC materials can effectively reduce the damage in the plastic hinge area of the pier. At the same time, because UHPC has higher stiffness and strength than ECC, the damage that occurs at the top of the UHPC column will be transferred to the joint, increasing the damage to the cap beam, while the ECC column has not undergone such damage transfer.

By using advanced materials with superior performance, the performance of civil engineering structures can be effectively improved. Prefabricated bridge piers with socket connection are not difficult to apply advanced materials due to the characteristics of factory prefabrication. The research of new materials may be the focus of the next prefabricated piers research.

5. Conclusions
The seismic performance of socket connection is a research hotspot, and many scholars have conducted research on it. Through the collation and analysis of the literature, this paper summarizes the seismic performance of the socket connection and puts forward suggestions for future research.

(1) Socket connections have the characteristics of quick construction speed and convenient transportation, and the installation is easy because of the low precision required. Therefore, it has a good development and application prospects.

(2) The socket connection achieves good strength and ductility levels comparable to those of a conventional monolithic connection, which is called “emulative monolithic connections”. However, the large post-earthquake residual displacements are the downside for socket connection, it is necessary to study how to reduce the residual displacement.

(3) The current theoretical research and formula derivation are mainly for single bridge pier, while the theoretical research on double bridge piers is less. The mechanical performance of double bridge piers in the transverse bridge direction is different from that of single bridge piers. In order to promote the application of prefabricated double bridge piers, it is necessary to further study the mechanical performance of the double bridge piers.

(4) At present, there are many researches on the design of column-to-foundation connection, but there are few studies on the repair of piers after the earthquake. It is necessary to study a quick and economic repair method to exert the functionality of bridge structures following earthquake event.

(5) The application of advanced materials effectively reduces the damage of prefabricated piers under earthquake action and improves the seismic performance of prefabricated piers. However, the use of new materials in piers with socket connection is still in the research stage, and is short of relevant theoretical support for the selection and optimization of the design parameters.

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