Engineering Structures 175 (2018) 257–272

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Interface shear transfer of precast concrete dry joints in segmental columns

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ARTICLE INFO

Keywords:
Precast segmental column
Dry joint
Shear test
Direct shear loading
Failure pattern
Shear strength formula

ABSTRACT

Precast dry joints in segmental columns are important to ensure the structural integrity and continuous to transfer both shear and flexural forces. Though dry joints have the concern of durability problems, they are the trend for convenience in site construction and less climate influenced. Ten precast column joint specimens were fabricated and tested under direct shear loading. The failure patterns of solid section keyed specimens were shearing off of male shear keys and diagonal cracks in female shear keys. The failure sequence was from top to lower shear keys. But the failure pattern of hollow section specimens was flexural failure of upper male or lower female shear keys, shearing off of vertical shear keys, and diagonal cracks in vertical female shear keys. The shear force-relative slippage relations of specimens exhibited two or three stages. Higher confinement stress, solid section (or enough key cover concrete thickness), and enough number of keys were essential to maintain high shear strength and ductile responses. Two formulation methods of shear strength prediction formula were deduced. One is based on the failure envelope of uniaxial compression and tension strength of concrete, the other one is based on tension strength Mohr circle only. The proposed formula has comparable prediction precision for the joint shear test database. Shear key shear stress and shear strength contribution were analyzed with the test data. The specimen shear stress transfer and distribution were qualitatively investigated with a two dimensional FE model.

1. Introduction

Precast substructures are prevailing nowadays, from Europe to America and also in Asia areas. In Europe, water-proof layer is used on top of girder, so epoxy-free joint is permitted in practice. But in the U.S., for durability considerations, dry joints in precast components are forbidden. In the present stage of China, the most popular precast construction techniques of substructures evolve from cast-in-place joint to grout joint, and dry joint is the trend to reducing manual work in site.

The present design method of precast joint is to prevent the joint opening at service limit state (SLS). So under the SLS, the joint is compressed with a minimum of 0.5 MPa confinement stress remained in all joints. Under the act of higher load, the column reaches ultimate limit state (ULS), the interfaces at critical joints will open, and the reinforcement across the joint will prevent the joint opening. For the columns located in low seismicity area, mild steel deformed bar is used. For the columns in moderate to high seismicity areas, prestressed finished deformed bar or the combination of mild steel deformed bar and prestressing strand are preferred. Usually, in the SLS stage, the crack width controls the design, but in the ULS stage, the tensile or compressive stress of cover concrete and tensile stress of reinforcement will play the decisive role.

The shear transfer mechanisms of precast joint in columns or girders consists of two parts, the interlocking resistance provided by castellated or prismatic shear keys, and the friction force under the confinement pressure of flat interface provided by asperities. Several shear failure mechanisms are identified in castellated joints, such as S (Single curvilinear) cracks and M (Multiple diagonal) cracks. Many researchers have conducted push off test of precast joint, the experiment parameters include confining stress, dry or epoxy joint, epoxy thickness, flat or keyed joint and number of keys, key depth, distance between keys, monolithic joint and steel fiber joint [17,4,7,6,8]. The main findings include: (1) Failure sequence and pattern of keys, mostly in shear failure, part of three-keyed high pressure epoxied joint failed in bending, failure pattern of keyed dry joint is ductile, while keyed epoxied joint fails more brittle; (2) The epoxied joint strength was consistently higher than that of dry joints; (3) Sequential failure of multiple keyed joints was observed from test and was verified by finite element model, a reduce factor of 0.7 was proposed for the shear strength of three-keyed joint; (4) AASHTO [1] and Rombach and Specker's [13] formula both underestimated the shear strength of single-keyed dry joint, but overestimated the shear strength of three-keyed joints. Other researchers studied the response of segmental concrete beams with external prestressing under shear loading

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https://doi.org/10.1016/j.engstruct.2018.08.037
Received 1 December 2017; Received in revised form 25 June 2018; Accepted 11 August 2018
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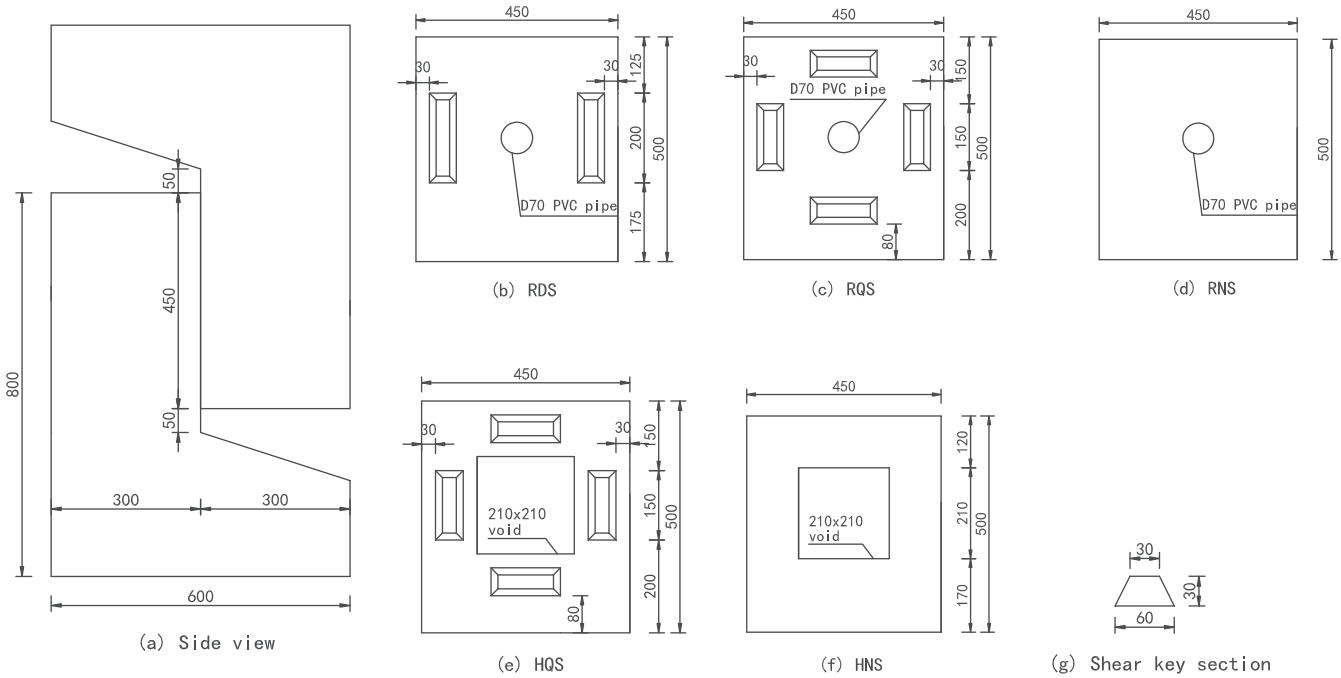

Fig. 1. Specimens configuration.

[15,16,11]. The main conclusions are: (1) The cracking that led to failure of structure arised from the joint, the shear failure of the beams was spatial, shear strength of the beams once the joint was open couldn't be predicted by the present formula for shear strength; (2) A simplified failure mode to such beams was suggested, and formulas to evaluate the resistance of the joints were proposed. Researchers also used finite element model to simulate response of push off test [14]. Theoretical mechanical model by combination of fracture mechanics and truss model theory was used to analyze the shear loading test of precast joints [9]. But the study on prismatic shear key is very limited, and the contribution of various mechanisms still has controversies.

1.1. Research significance

The preceding research on shear response of precast segmental bridge dry or epoxied joints greatly contributed to the fast application of this kind of bridge types. But the research still has inadequacy to be overcome, (1) Most of the research objectives are joints on the web or flange of girder in precast superstructures, shear response of joints in precast column is still debatable; (2) Most of the research is about castellated joints, the failure mechanism of prismatic shear key joints is seldom reported; (3) The shear capacity of precast joint predicted by current code is not well recognized.

In order to adapt the fast development of precast substructures application in moderate to high seismicity areas, a series of experiments were carried out to study the shear performance of dry joints in precast segmental bridge columns. Five groups of shearing off test specimens were fabricated for different confining stresses. Among them, two groups are flat joints with solid or hollow interface, three groups are keyed joints with different shear key geometries, numbers and solid or hollow interface. The failure sequence and pattern of cracking or push off of shear keys of the five group precast dry joint specimens were discussed firstly. Then the shear force versus relative slippage curves of test results were presented and explained. To revise the current code for shear response design of precast dry joints, shear capacity formulas deduced from failure plane of tensile and compressive envelope of concrete, or from the tensile failure plane of concrete were presented. The proposed formula was validated for shear capacity estimation of precast dry joint by the test results of this contribution and other researchers. Finally a planar finite element model was developed to study the stress distribution and direction qualitatively.

1.2. Specimen fabrication

In order to study the performance of specimens with different section and shear key configurations under direct shear loading, five batches of specimens were designed. Each batch had two same specimens which have 1 MPa or 2 MPa confinement stress, respectively. In reference of Anagnostopoulou et al. [3] for the design of shake table test specimen of precast column and girder bridge and practical design of common monolithic concrete bridges, a superstructure total load ratio of live load plus dead load was approximately $N/f_c'A = 0.10$. For concrete grade C30, the cubic compressive strength is $f_{cu,k} = 30$ MPa, the cylinder compressive strength is approximately $f_c' = 0.79\ f_{cu,k} = 23.7$ MPa. The compressive stress on the column section is approximately $\sigma = 0.1\ f_c' = 2.37$ MPa. So in the test, the stress on interface chose 1 MPa and 2 MPa.

The specimen configurations are shown in Fig. 1. The typical specimen side view after assembled in laboratory is illustrated in Fig. 1(a). One specimen is composed with two L type parts. If the specimen has shear keys, the male shear key part is always put underneath the female part in test. Fig. 1(b)–(f) designates the interface configuration. Fig. 1(g) presents the section of shear key. The specimen properties are listed in Table 1. The specimen identifier is represented as R(H)-D (Q,N)-S-n, where R represents section shape of rectangular, H means section shape of hollow, D indicates double (two) shear keys, Q is for quard (four) shear keys, N dictates no (without) shear key, S designates specimen, the number following S indicates the confinement stress (MPa) on interface.

2. Experiment setup and instrumentation

The test setup and instrumentation is shown in Fig. 2. The measurement instrumentation can be divided into three categories, namely strain, displacement, and force measurement. The shear force is applied as direct shear through the interface plane, and the interface has no flexural moment theoretically. The shear force is applied on top of the female part by a universal testing machine.

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