Numerical Study on Performance of Single-Keyed Dry Joint of Ultra-High Performance Concrete (UHPC) Under Combined Shear and Torsion Load

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Abstract. Under the vehicle load, segment joints are subjected to coupling effects of bending, shear, and torsion, while for dry joints, they are mainly subjected to a combination of shear and torsion, making them more prone to failure. In this study, to investigate the performance of single-keyed dry joint of ultra-high performance concrete (UHPC) under combined shear and torsion load, finite element model (FEM) was carried out considering the effect of confining pressure. Then AASHTO code equations was chosen to predict the shear-torsion capacity of UHPC single-keyed dry joints. The results of FEM indicated that the increase of confining pressure can effectively improve the shear-torsional load capacity of the dry joints. Whereas the increase of confining pressure has little effect on the improvement of stiffness. From the failure mode of specimens, the specimens are damaged in the root of the shear key when confining pressure is less than 18 MPa. However, in view of the high confining pressure (when the confining pressure is greater than 18 MPa), the damaged surface of the specimen changes from the root of the male key to the feminine key. In addition, the evolution of AASHTO equation shows that the AASHTO code equations were overestimated the ultimate capacities of UHPC single-keyed dry joints under shear-torsion load.

Keywords: Precast Bridge · Ultra-High Performance Concrete (UHPC) · Dry Joint · Finite Element Model (FEM) · Combined Shear and Torsion Load

1 Introduction

With the advancement of bridge industrialization, assembled precast bridges have been promoted and applied widely. As a new type of bridge, Ultra high performance concrete (UHPC) segmental girder bridge is an important study direction to promote the industrialization of bridges. However, the structural integrity of segmental bridges is the main issue affecting its flexural and shear performance [1, 2]. In actual bridge operation, segment joints are subjected to coupling effects of bending, shear, and torsion, while for dry joints, they are mainly subjected to a combination of shear and torsion, making them more prone to failure. Therefore, for segmental pieced bridges, joints are fragile

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structural components that require special attention and treatment, especially in terms of shear resistance and load capacity. In the past decade, a large number of scholars have conducted test to study UHPC dry joints. The shear strength of segmental joints (especially dry joints) is mainly provided by shear keys, and the shear key material properties have a significant effect on enhancing the strength of the key and improving the shear resistance of the joints. In order to reasonably reflect the effect of shear keys materials on shear strength, the mechanical properties such as strength were measured in the study, literatures [8] investigated different specimens f_c and shear strength based on the push-off test. To understand the shear characteristics of UHPC dry joints, Tongxu Liu [3, 4] found that the multi-tooth bond dry joint reduction coefficient gradually increased with the increase of lateral pressure under high lateral pressure, and the reduction coefficient was greater than 1 when the lateral stress reached a certain size and remained basically constant through direct shear tests of UHPC dry joints. In addition, in order to predict the shear load capacity of UHPC dry joints accurately, Yuqing Hu [5] of Southeast University proposed a load capacity prediction formula for UHPC large-tooth bond dry joints considering the effect of steel fiber bridging based on the modified pressure field theory, and the method was proved to have high prediction accuracy.

From on the above discussion, past research on joints has focused on shear resistance, while little research has been done on the mechanical properties of joints under shear-torsional coupling. To investigate the performance of single-keyed dry joint under combined shear and torsion load, a total of 10 specimens were conducted, which took into account the three influential factors of offset distance, normal stress, width-to-depth radiate the combined shear and torsion effect on the shear capacity of the single shear key. And concluded that both the cracking load and ultimate capacity were enhanced with the confining pressure increased. However, there is limited study on the mechanical properties of UHPC dry joints under shear-torsional composite action.

Based on the above discussion, to investigate the performance of single-keyed dry joint of ultra-high performance concrete (UHPC) under combined shear and torsion load, numerical study was carried out considering effect of confining pressure.

2 Specimen Design

Based on the literature [1], considering the load moving space of shear-torsion compound action, the upper part of the specimen is set 200 mm thick area, and a 200 mm $\times$ 200 mm $\times$ 200 mm trigonal concrete axil is designed to strengthen the projection area; the size of the lower part of the specimen is 500 mm $\times$ 1, 250 mm $\times$ 200 mm, and the size of this part is increased to prevent the whole load process. In order to ensure that the joint position is destroyed before the non-key area, the specimen is equipped with HRB400 reinforcement, except for two φ18 mm bars in the lower part of the specimen, the rest are φ16 mm bars in each group, the specimen size are shown in Figs. 1 and 2. Of note, load eccentricity is 200 mm in specimens (see Figs. 1 and 2).

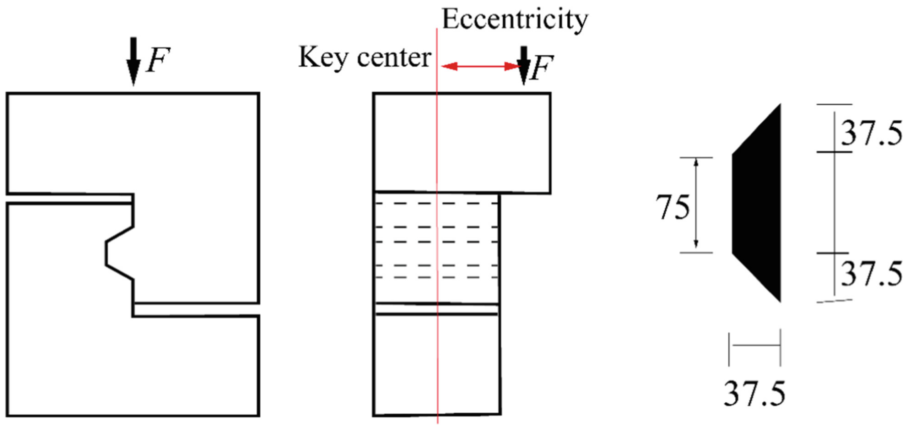

Fig. 1. Structural drawing of specimens [1].

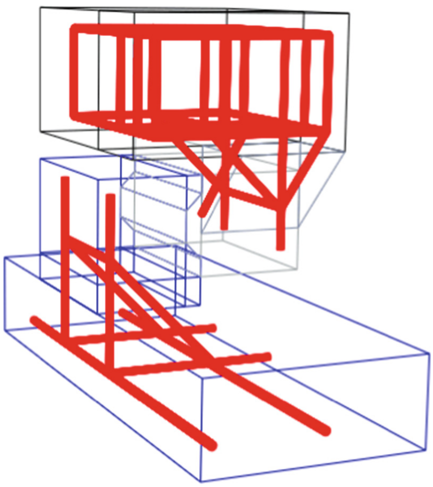

Fig. 2. 3D rendering of specimens.

3 Finite Element Analysis

3.1 Finite Element Model (FEM)

To understand the shear-torsion behavior of UHPC epoxy joint interface, finite element modeling and analysis were conducted based on the Abaqus platform (2020). 3D finite element models of the tested specimens were established in Abaqus (see Fig. 3), which considers the effect of confining pressure, namely, 2 MPa, 6 MPa, 10 MPa, 14 MPa, 18 MPa, 20 MPa, 25 MPa, and 30 MPa.

Using concrete damage plasticity material model (CDP) to simulate the stress-strain constitutive behavior of UHPC. In detailed, the stress-strain relationship of UHPC is modelled in consistent with that in the study of Chen et al. [6], and the detailed information are illustrated in Fig. 3 and Eq. 1–3. Of note, the peak compressive and tensile stresses of UHPC are taken as 133 MPa, 7.0 MPa, respectively.

The C3D8R solid elements are used to present the UHPC part (see Figs. 4 and 5), while the T3D2 truss elements are chosen to simulate the behavior of steel reinforcement. Fraction model is chosen to simulate the interface between male part and female part in dry joints, and the fraction fact is 0.65 based on AASHTO codes [7].

For reinforcement,

$$\sigma_s = \begin{cases} E_s \varepsilon_s & (0 \le \varepsilon_s \le \varepsilon_y) \\ f_y & (\varepsilon_y \le \varepsilon \le \varepsilon_u) \end{cases} \tag{1}$$

For the compression model of UHPC,

$$y = \begin{cases} ax + (6-5a)x^5 + (4a-5)x^6 & 0 \le x \le 1 \\ \frac{x}{b(x-1)^2 + x} & x \ge 1 \end{cases} \tag{2}$$

$y = \sigma/f_c$, $x = \varepsilon/\varepsilon_0$, $\varepsilon_0 = 3500\mu\varepsilon$,

$$a = \frac{E_0}{E_c}$$

For tension model of UHPC,

$$\begin{cases} E_c \varepsilon_t & 0 \le \varepsilon_t \le \varepsilon_{t0} \\ f_t & \varepsilon_{t0} < \varepsilon_t \le \varepsilon_{tp} \\ \frac{f_t}{[1 + (\varepsilon_t - \varepsilon_{tp}) l_c / \omega_p]} & \varepsilon_{tp} < \varepsilon_t \end{cases} \tag{3}$$

In which, $f_t = 8\ Mpa$, $\varepsilon_{tp} = 0.002$, $\omega_p = 1.0$ mm, l_c =400 mm, $p = 0.95$.

3.2 FEM Results

Figure 5 plots the load-displacement curves of finite element model, obviously, the increase of confining pressure can effectively improve the shear-torsional load capacity of the dry joints (see Fig. 6). Whereas the increase of confining pressure has little effect on the improvement of stiffness. Compared with specimen m2 (confining pressure is 2 MPa), the ultimate load of specimens m6, m10 and m14 are increased by 134 kN, 239 kN and 302 kN. Respectively. And more detailed information about ultimate load is presented in Fig. 7.

The failure mode of specimens is present in Fig. 7, the specimens are damaged in the root of the shear key when confining pressure is less than 18 MPa. However, in view of the high confining pressure (when the confining pressure is greater than 18 MPa), the damaged surface of the specimen changes from the root of the male key to the feminine key (see Fig. 8f-g). Thus, to enhance the shear-torsion behavior of UHPC dry joints, reinforcements can be used in structures.

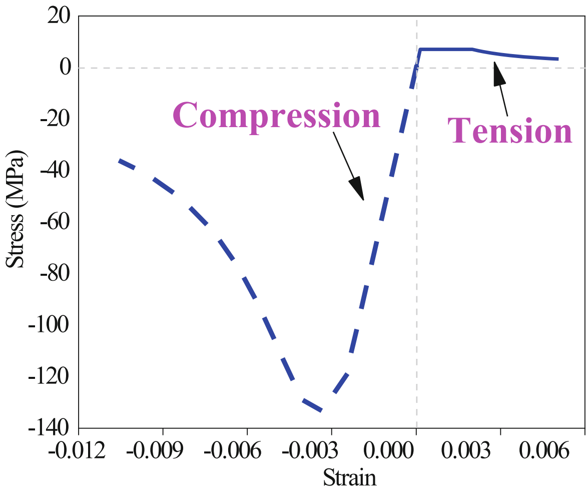

Fig. 3. The stress-strain relationship of UHPC.

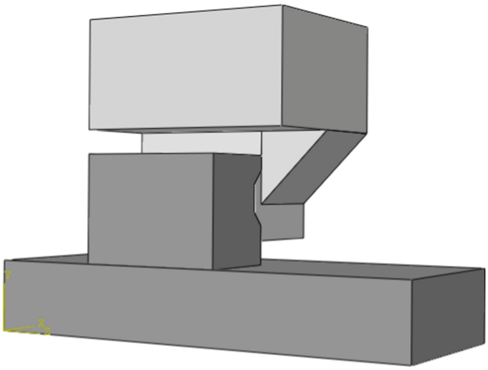

Fig. 4. Model schematic.

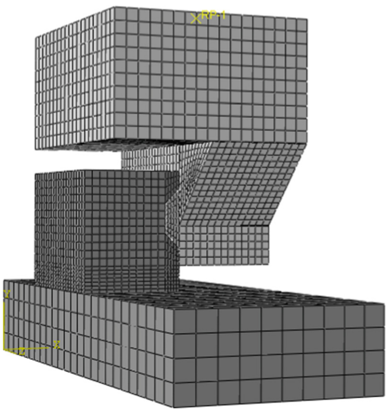

Fig. 5. Mesh schematic of FEM.

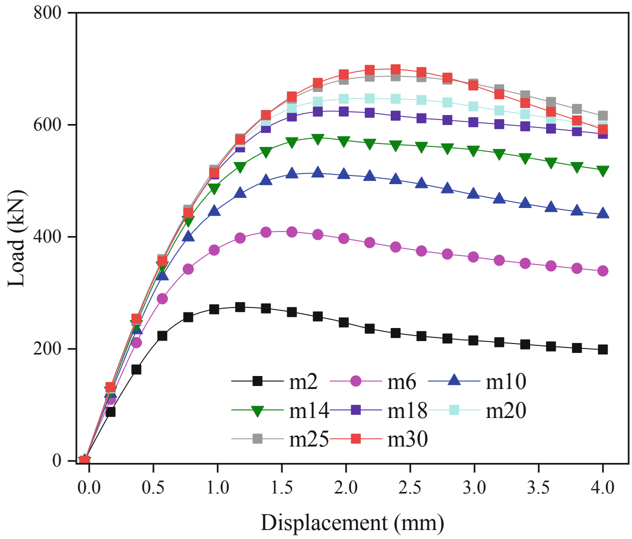

Fig. 6. Load-displacement curves of UHPC single-keyed dry joint.

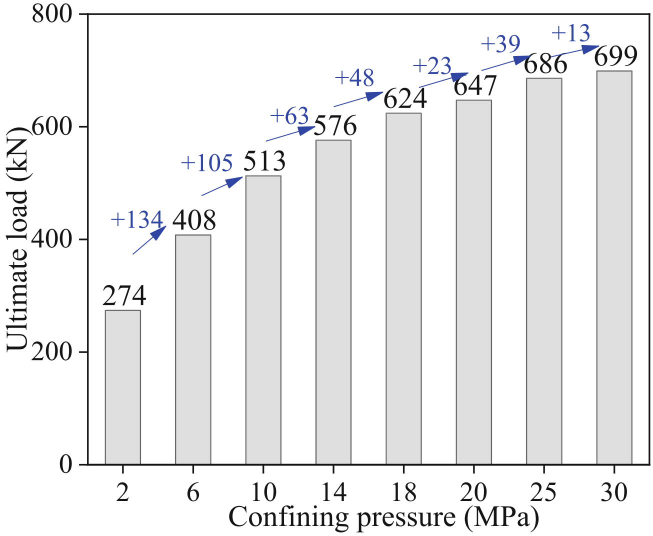

Fig. 7. Ultimate load of UHPC single-keyed epoxy joint.

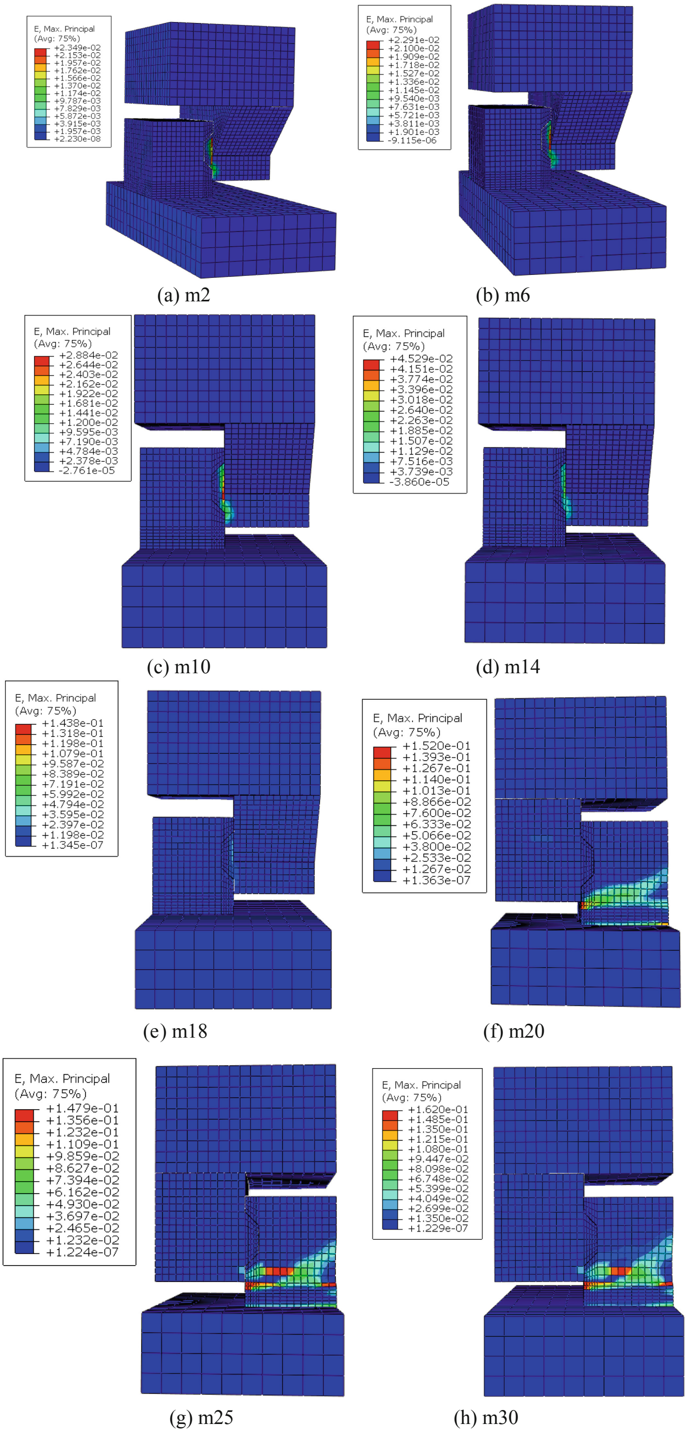

Fig. 8. Failure mode of dry joint specimens

4 Bearing Capacity Prediction of Joints Based on the AASHTO Code

According to the AASHTO *Guide Specifications for Design and Construction of Segmental Concrete Bridge* (1999) [7], the shear bearing capacity of the joint surface includes two parts: one is the provided by the shear keys, and the other is the frictional force provided by the concrete in the flat part. The equation for calculating the shear bearing capacity is as follows,

$$V_u = A_k\sqrt{f_{ck}}(0.2048\sigma_n + 0.9961) + 0.6A_{sm}\sigma_n \tag{4}$$

In which, V_u is nominal joint shear capacity (N), A_k is the root area of the shear key (mm^2), and $A_k = 60000\ \mathrm{mm}^2$, $f_c{}'$ is compressive cylinder strength of concrete (MPa), which is approximately equal to $f_\mathrm{ck} = 147.7$ MPa based on past research [6]. σ_n is the compressive stress of concrete (MPa). A_{sm} denotes the contact area of concrete (mm^2), and $A_{sm} = 33600\ \mathrm{mm}^2$.

In order to investigate the applicability of AASHTO equations to UHPC dry joints under shear-torsion load, the calculated shear capacities of specimens were compared with the FEM results, as depicted in Fig. 9.

For UHPC single-keyed dry joints under shear-torsion load, the difference between predicted value and FEM results was great than 100% in AASHTO equations. Thus, the calculated ultimate capacities of the joints showed significant discrepancies from the FEM values. The AASHTO code equations were found to overestimate the ultimate load of UHPC single-keyed dry joints under shear-torsion load.

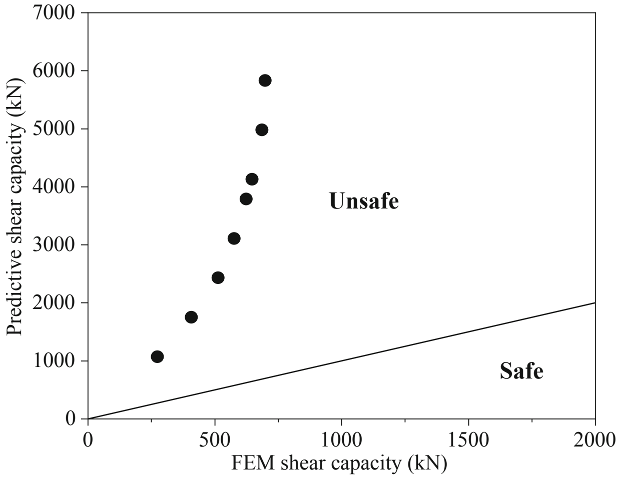

Fig. 9. Comparisons of the AASHTO equations to FEM results.

5 Conclusion

Based on the FE results of UHPC single-keyed dry joints under shear-torsion load, the following conclusions are obtained:

(1) The increase of confining pressure can effectively improve the shear-torsional load capacity of the dry joints. Whereas the increase of confining pressure has little effect on the improvement of stiffness. From the failure mode of specimens, the specimens are damaged in the root of the shear key when confining pressure is less than 18 MPa. However, in view of the high confining pressure (when the confining pressure is greater than 18 MPa), the damaged surface of the specimen changes from the root of the male key to the feminine key.
(2) For UHPC single-keyed dry joints under shear-torsion load, the difference between predicted results and fem data was great than 100% in AASHTO equations. Thus, the calculated ultimate capacities of the joints showed significant discrepancies from the FEM values. The AASHTO code equations were found to overestimate the ultimate capacities of UHPC single-keyed dry joints under shear-torsion load.

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