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Experimental Investigation on the Flexural Mechanical Behaviour of an Immersion Joint

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Topic: Immersed and Floating Tunnelling

Summary: The immersed tunnelling technique is commonly used for river or sea crossings worldwide. Seismic safety criteria of immersed tunnels involve the shear stiffness, axial stiffness, flexural stiffness, and opening deformations of the immersion joints. Therefore, it is necessary to conduct the mechanical analysis of the joint between the immersed tunnel elements. An experiment of an immersion joint is presented in this paper, mainly dealing with the experiment design, axial behaviour and flexural behaviour of the immersion joint. The geometric scale of this experiment is 1:10. The model joint in this paper includes two 3.8m x 1.15m x 1.2m segments with a rubber gasket and horizontal steel shear keys between them. Different levels of water pressure were considered due to the significant changes of water depth in real project. The displacements of an immersion joint under multi-level loads were measured and analysed considering the hyperelastic property of a GINA gasket. It can be found that the mechanical behaviour of a GINA gasket is significantly affected by both flexure and axial loadings. Moreover, the flexural stiffness ratio of the joint with respect to that of the tunnel element in service states ranges from 1/27 to 1/272. The results are useful for the further numerical analysis of immersion joint and more related publications are expected in the future.

Keywords: *Immersed tunnel, Immersion joint, Compressive-bending test, Scaled model, Stiffness*

1. Introduction

The immersed tunnelling technique (Figure 1) is widely used for river or sea crossings. An immersed tunnel consists of precast tunnel elements. The immersion joints, which are connecting tunnel elements, are the weakest units of the whole tunnel (C. Ingerslev, 2010, J. Baber et al., 2011). According to the stiffness ratio of the joint to the element, immersion joints can be divided into three categories: rigid joints, flexible joints and partial-rigid (or partial-flexible) joints. Whatever the type of immersion joint is, the design of them has to consider various actions during service life, such as temperature fluctuation, earthquake, differential settlement of foundation, shock from shipwrecks and other actions. The knowledge of the deformation of a joint under complex loadings is vital for a safe, reliable water-proof design. Hence, it is necessary to conduct the mechanical behaviour of the joint between tunnel elements.

Theoretically, the mechanical behaviour of an immersion joint was considered under imposed deformation (Z. LIU, 2009) or under seismic action (I. Anastasopoulos et al., 2007). (H. YU et al., 2014) deduced a bi-linear formula to account for the stiffness of a flexible joint, which was also verified through numerical modelling.

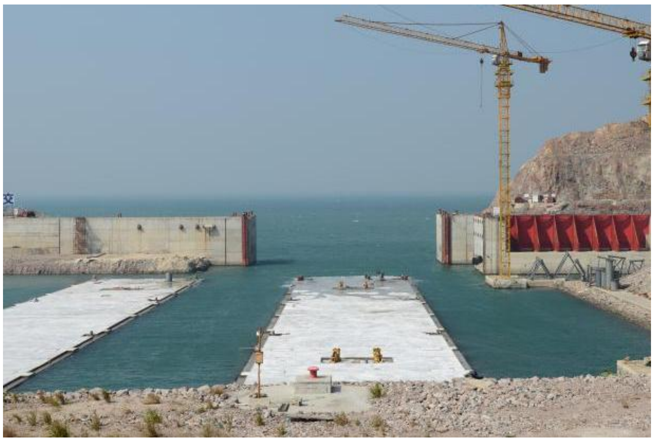


Fig.1 *Immersed tunneling technique*

It should be noted that there is not much experimental works reported on immersion joints even though they came to practical applications for more than 100 years. (O. Kiyomiya et al., 1992) performed a quasi-static test for the mechanical properties of a flexible joint with 1/4 geometric scale. In this test the flexural and compression properties of a joint were determined. The results showed that the immersion joint behaved non-linearly in quasi-static and quasi-dynamic cases. (O. Kiyomiya, 2004) also carried out both a 3-dimensional experiment and a finite element analysis for a new type of flexible joint called the Crown Seal. Results of both tests indicated that this new type of joint can be applied in practice because of the effective reduction of opening and moment with this particular design. However, former research mostly was dealing with the response of a complete tunnel. Results in the tests done by (O. Kiyomiya, 1992) also proved this. Moreover, only a few experiments were found about the flexural mechanical behaviour of large-scale immersion joints as well as its flexural stiffness.

This paper presents a compression-bending test of a half-flexible immersion joint with a 1:10 geometric scale. Modelling techniques for the scaled immersion joint were applied. For the experiment on the mechanical behaviour of the immersion joint, considering measurement system and loading patterns, were defined. Bending moments are applied cyclically at equal amplitude in the horizontal plane, by varying the load in the axial hydraulic jacks on each sidewall of the element. Through observed load-deformation curves, the flexural stiffness of the joint will be derived for use in practical design.

2. Background

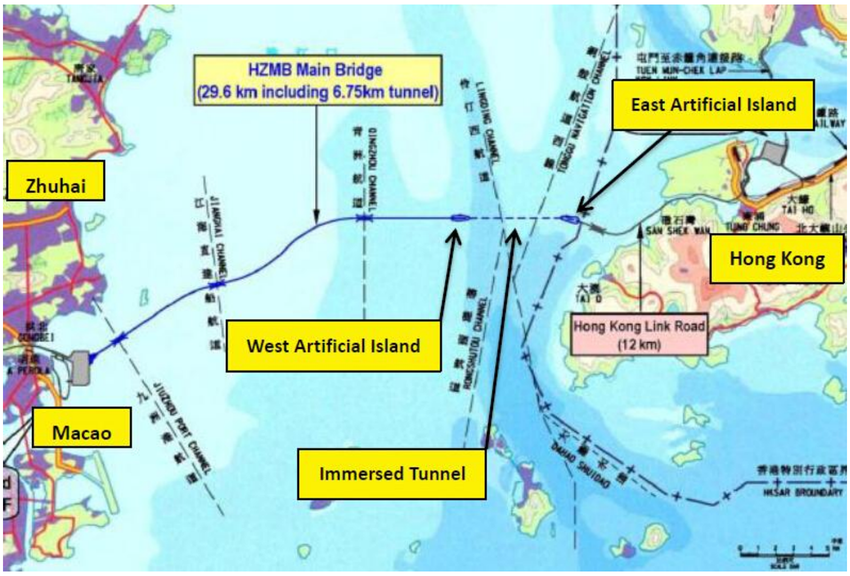


Fig. 2 *The location of Hong Kong-Zhuhai-Macao Bridge (N. Hussain et al., 2011)*

As mentioned above, the immersion joints differ in stiffness and in this paper, the half-flexible one is considered. This choice is based on the real project of the Hong Kong-Zhuhai-Macao Bridge

(Fig.2) which is under construction. The immersed tunnel in this project is approximately 5,664 m in length. It consists of 33 elements and is finally connected to two artificial islands, as can be seen in Figs. 2 and 3.

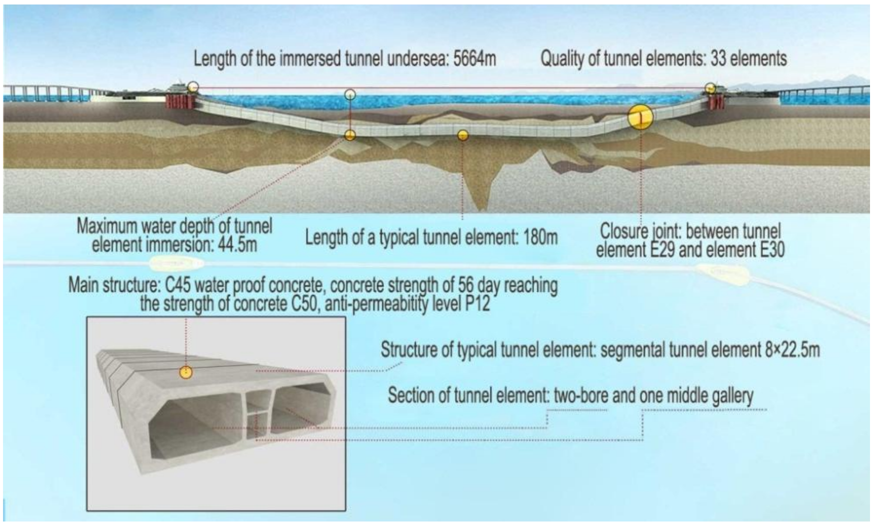
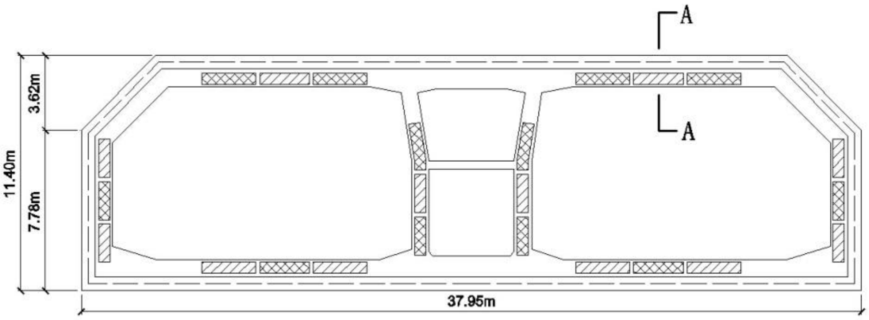
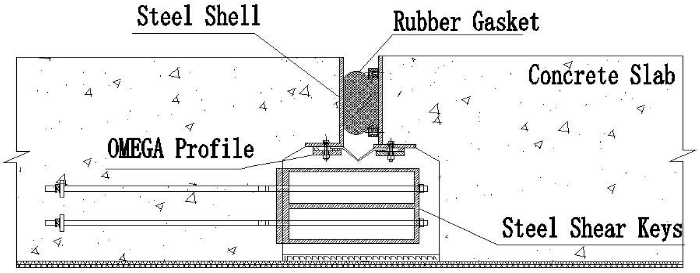


Fig. 3 *The immersed tunnel in HZMB (CCCCHZMB, 2011)*



(a)Typical cross-section of immersion joint



(b)A-A view of immersion joint

Fig. 4 *Immersion joint in HZMB*

The length of a typical element is 180 m and is assembled through 8 segments which are 22.5 m in length, between which the segmental joints are located. The cross-sectional dimension of the immersion joint is about 37.95m x 11.40m (Figure 4 (a)). The partial-flexible immersion joint generally includes a rubber gasket, an Omega water proof, shear keys and steel shell as shown in Figure 4 (b).

When the immersed tunnel is installed, the GINA rubber gasket between elements will be pressed tightly with a minimum compression, resulting in a waterproof sealing due to initial water pressure. The initial water pressure varies from the depth of the immersion joint, resulting in different initial axial forces in the joints. Therefore, the purpose of the rubber gasket is to seal the immersion joints between two adjacent tunnel elements, ensuring the water tightness of the structure. If the rubber gasket fails, the Omega water proof, as the second water tightness defence, will start to work to avoid severe leakage.

From the researches done by (Owen and Scholl, 1981), the deformation mode of underground

structures subjected to earthquake loading can be divided into three categories: compression/extension, bending and racking. Regarding immersed tunnels, the first two modes dominate the deformation of immersion joints during earthquake. (Van Oorsouw, 2010)
In this study, the effect of horizontal bending is mainly considered to express flexural mechanical behaviour of immersion joints.

3. Design of the Experiment

3.1 Structural Model of the Experiment

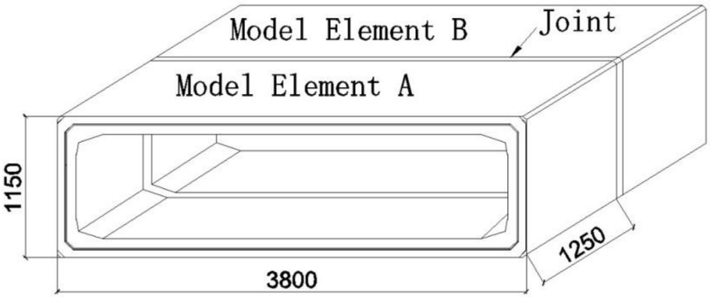
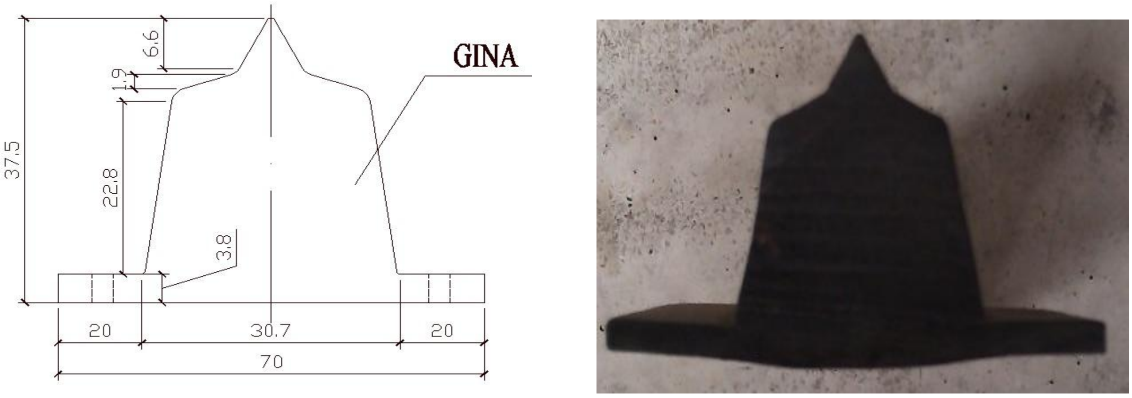


Fig 6 *Cross-section of model immersed tunnel (Unit: mm)*

The original profile of cross-section of a tunnel element, which was adopted in the HZMB project, is shown in Figure 4. It consists of two vehicle passages and one gallery serving for emergency. Bending of the immersion joint could happen either in the vertical or horizontal plane. In the loading test, only horizontal bending will be applied. As the inclined upper corners in passages and the middle walls contribute insignificantly to compression or bending of the joint, the cross-sectional profile of the model element was simplified as a rectangular box and the middle walls were not considered as Figure 6 displays, compared to the original cross-section.

Based on the capacity of the available testing facilities and the goal of the experiment, a geometric scale of 1:10 is selected. The geometric reinforcement ratio for model is the same as that in the HZMB project. However in the vicinity of the joint, locally additional reinforcement was provided. Figure 6 also provides the dimensions of a single tunnel element as tested, with a width of 3800 mm, a height of 1150 mm, and a length of 1250 mm, as well as a 150 mm-thick concrete slab. Referring to the Chinese Code for Concrete Structures (GB50010-2010), the types of the concrete and the reinforcement are C50 (f_c=23.1 MPa and f_t=1.89 MPa) and HRB335 (f_y=300 MPa) respectively.

The model immersion joint also follows the design of the HZMB project and the lay-out is also simplified according to the experiment. The steel shell and omega profile are not provided in this model joint due to the lack of contribution to flexural behaviour of the immersion joint. A certain type of rubber gasket was designed and manufactured independently for this experiment. Figure 7 displays the dimensions of the gasket: model GINA profile.



(a) Dimensions of the model GINA profile (b) Model GINA profile

Fig. 7 *Dimensions of the model GINA profile*

3.2 Compression-bending Test Set-up

As can be seen in Figure 8, when the joint is subjected to an axial force, an axial compression δ occurs in the joint. If the axial force and bending moment are applied together, the joint is compressed and rotates which means that both compression δ and rotation θ occur. Hence, various loading cases can be considered to analyse this bending behaviour by controlling the axial force and bending moment.

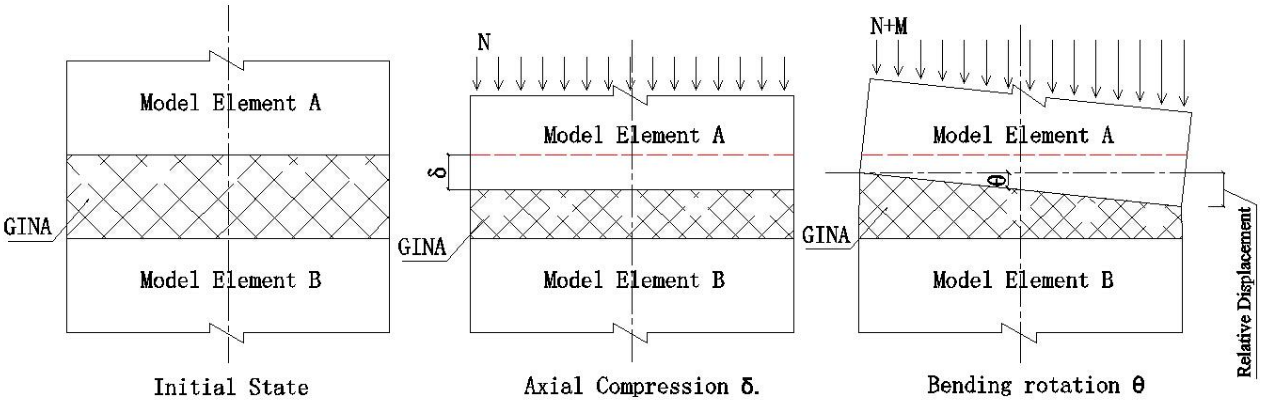


Fig 8 *Combined compression and bending of the immersion joint*

As illustrated in Figure 9, the tunnel model was placed in a steel frame. During a typical experiment, one tunnel element (Model Element A) is fixed horizontally while the other one (Model Element B) is movable, resulting in deformation of the immersion joint. Therefore, a set of reaction frames is designed, including the axial reaction frame and the supporting system.

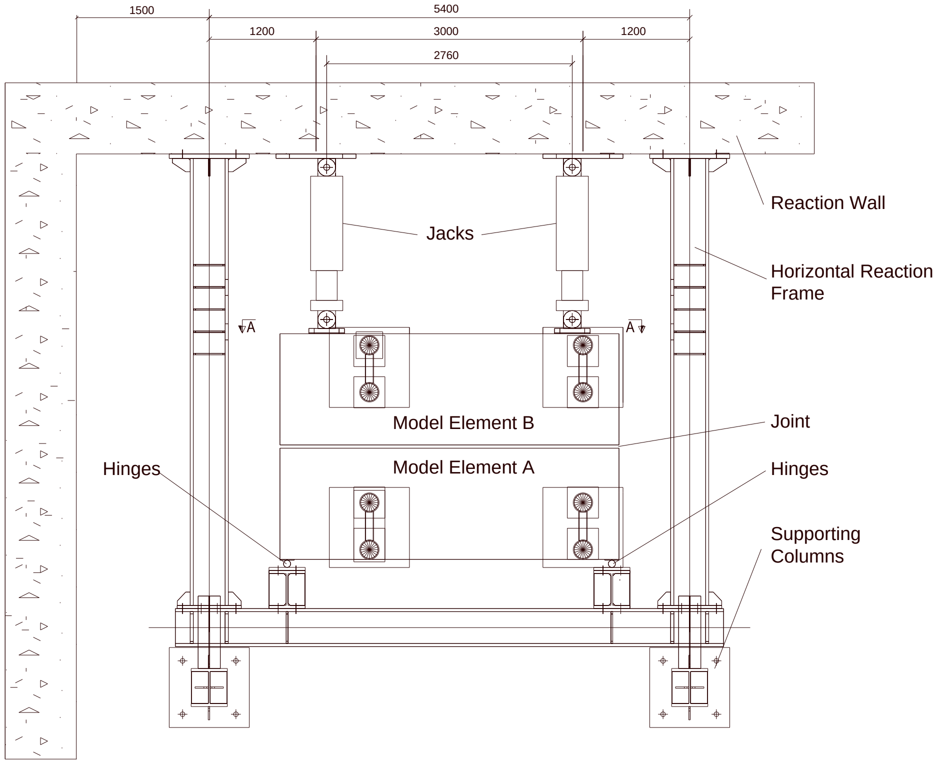


Fig. 9 *Plane view of the test set-up*

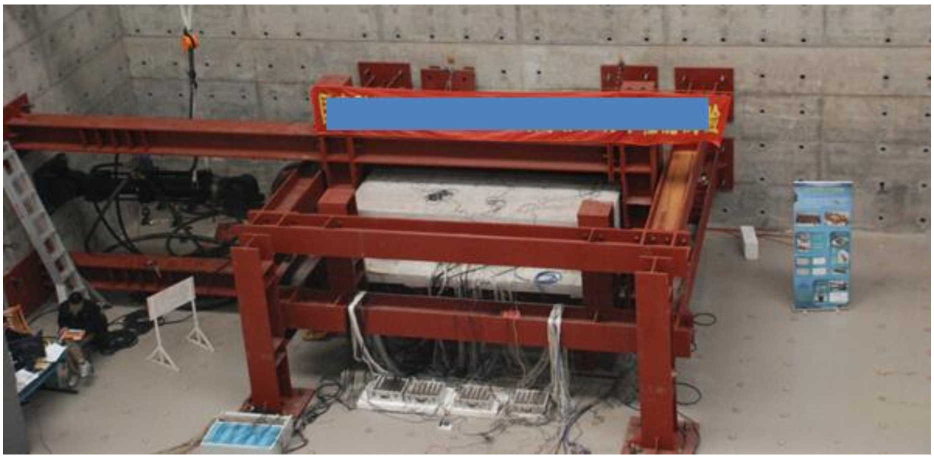


Fig. 10 *Full view of the test set-up*

3.3 Loading Patterns

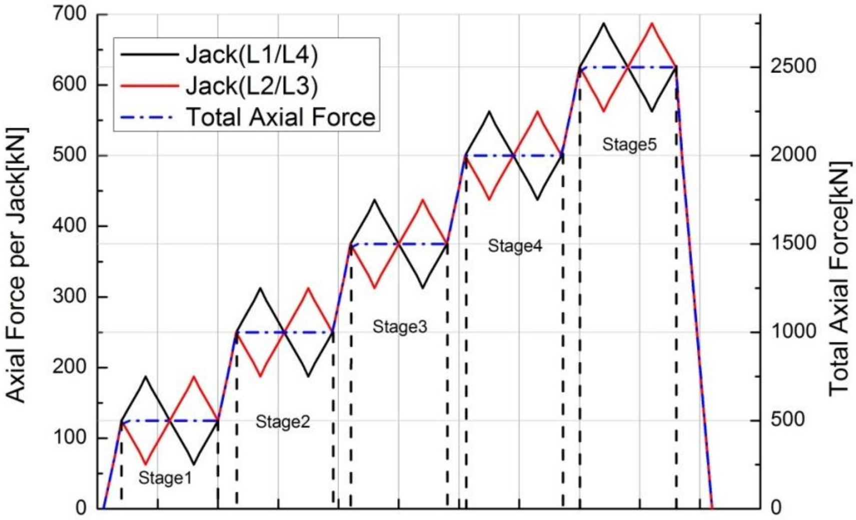


Fig. 11 *Quasi-static loading patterns*

Compression-bending testing combines the loading patterns of imposed axial load and bending moment. Hence, the loading is applied in 5 stages with different axial forces but the same bending moment, as Figure 11 displays. The bending moment, with maximum value of 350kN•m, is applied to the joint after the axial force has reached its target level.

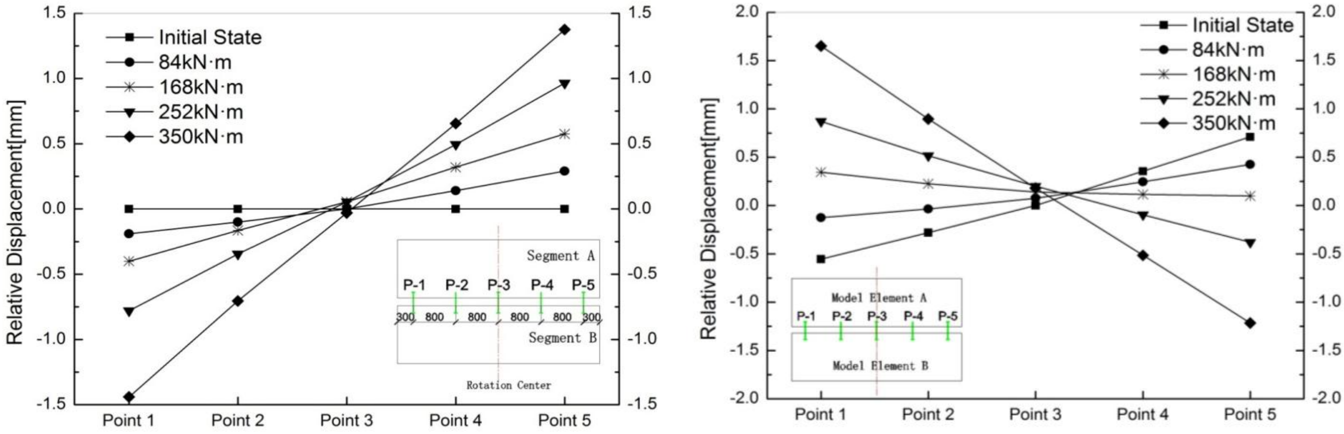
4. Test Results and Discussion

4.1 Flexural Performance of the Immersion Joint

Differential displacement of the joint would result from its unbalanced loading/unloading, when subjected to a bending moment. It can be calculated from the measured displacements at each logged point, with respect to its initial compressive state. Figure 12 illustrates the relative displacement of the joint under the axial force of 500kN when subjected to a bending moment of 350kN•m. The initial state refers to the current compression of the joint while no bending moment has been applied. That is, no relative displacement occurs in the initial state for no moment is applied.

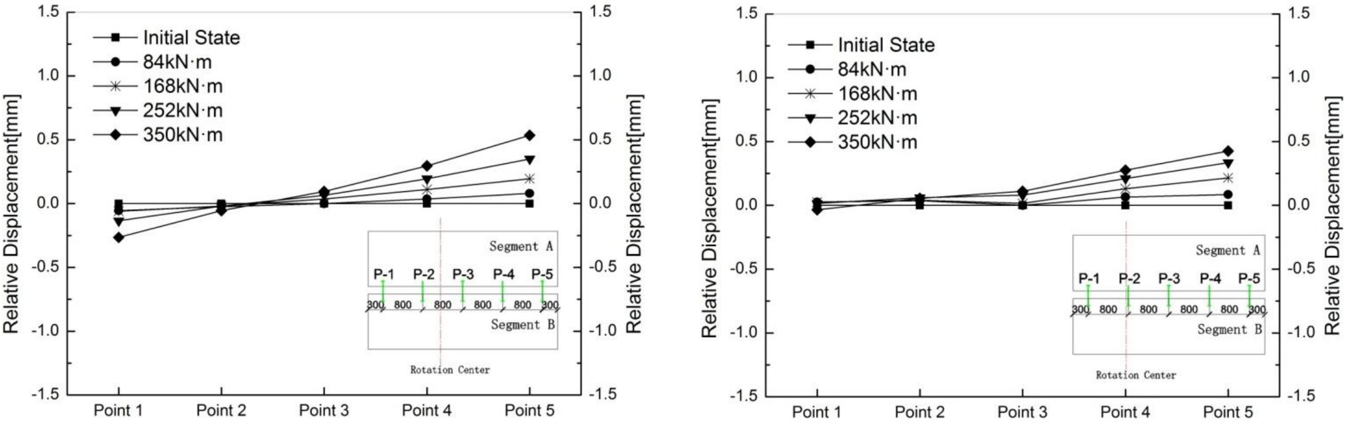
In this situation, it is obvious that the relative displacement increases with the moment. The displacement of the joint behaves symmetrically and the symmetry axis of the joint nearly remains in its geometric centre during the cyclic bending. After unloading, the deformation of the joint dose not return to the initial state, which is shown in Figure 12(b). During the loading and unloading stage, it can be observed that the joint remains plane during compressive bending. The residual displacement can also be found.

In this situation, it is obvious that the relative displacement increases along with the moment. The displacement of the joint behaves symmetrically, as displayed in Figure 12, and the symmetry axis of the joint nearly remains in its geometric center during the cyclic bending.

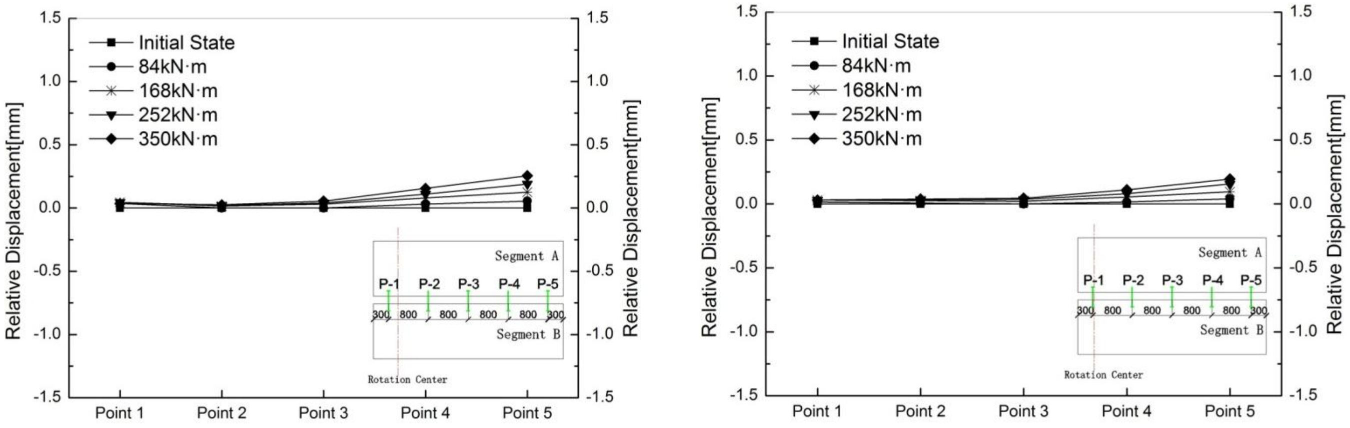


(a) Loading Stage *(b) Unloading Stage*

Fig. 12 *Rotation of immersion joint (with axial force of 500kN)*



(a) Axial force of 1000kN *(b) Axial force of 1500kN*



(c) Axial force of 2000kN *(d) Axial force of 2500kN*

Fig. 13 *Rotation of immersion joint subjected to different levels of axial force*

While the axial force increases to 1000kN (see Figure 13(a)), the maximum relative displacement of the joint decreases remarkably. The joint behaves anti-symmetrically and the center of rotation starts to move away from the geometric center of the joint. As the axial force continues to boost, the same behavior can be observed. In Figure 13(d), the maximum relative displacement, measured at Point 5, is 0.20mm, which is almost 7 times higher than that measured at Point 1. Moreover, the center of rotation is located around Point 1 in this case.

4.2 Flexural Stiffness Ratio of the Immersion Joint

Another concern for immersed tunnel design is the ratio of the flexural stiffness of the joint to that of the tunnel structure. An index for the ratio of stiffness is defined:

$$r_{bend} = \frac{k^j_{bend}}{k^s_{bend}} \qquad (1)$$

where k^j_{bend} and k^s_{bend} are the flexural stiffness of the immersion joint and the tunnel structure (per unit length) respectively. k^j_{bend} is obtained from the large scale model test while k^s_{bend} is constant, which is determined by the Young's modulus of concrete and the properties of the cross-section of the tunnel (per unit length). Based on these definitions, r_{bend} is calculated.

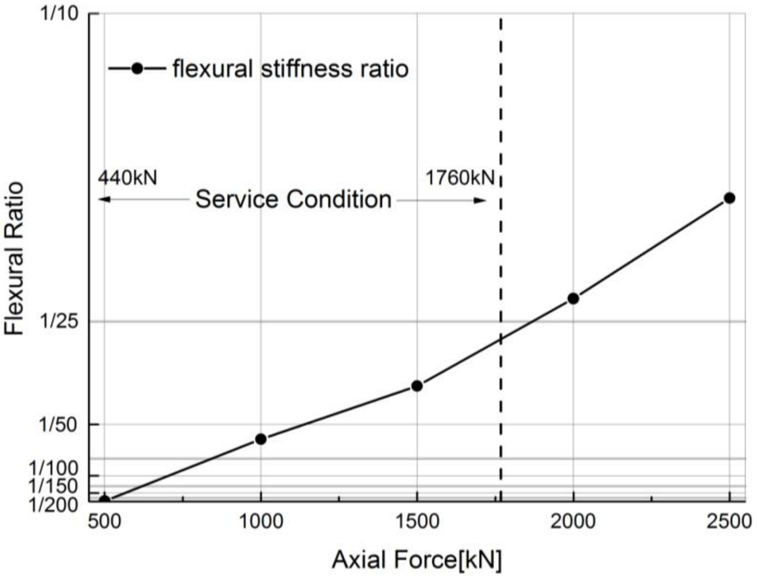


Fig. 14 *Flexural ratio of the tested immersion joint*

Figure 14 shows the flexural stiffness ratio of the tested immersion joint. During the test, the GINA gasket in the joint is compressed continuously and becomes stiffer as the axial force increases. At the beginning of the test, the flexural stiffness of the tunnel structure is about 1/196 of that of the immersion joint. Then the ratio increases up to around 1/58 for an axial force of 1000kN. A stage with continuous increase follows as the axial force increases from 1000kN to 2000kN. After that, the ratio remains around 1/22. The compression during this stage changes only a little, which can be seen in Figure 13(c). Based on the interpolation method, the flexural stiffness ratio in service condition is ranging between 1/272 and 1/27, depending on the water depth. Given the practical calculations, the axial and flexural stiffness ratios of the immersion joint can be predicted for different water depths, which could be useful for simulation.

5. Conclusions

This study presents the results of a loading test on a scaled immersion joint subjected to compression-bending. Base on the real situation of the immersed tunnel in the Hong Kong-Zhuhai-Macau Bridge project, equal amplitude of horizontal bending moment is applied at target axial forces. Analysis of the experimental results gives the following conclusions:

(1) The joint remains plane during bending. The relative displacement of the joint increases with bending moment but it decreases with axial force. A residual displacement is found after a cyclic loading.

(2) The rotation centre of the joint moves towards to one side when the axial force increases.

(3) The flexural stiffness of the joint increases with axial force during bending. The joint is in the nonlinear state at service condition. Its flexural stiffness varies between the low boundary of 1/272 of that of the element to the upper boundary of 1/27.

It should be noted, however, that the conclusions drawn are based on the scaled tests. Size effect should be taken into consideration for practical applications.

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