Experimental Investigation on the Static Shear Stiffness of an Immersion Joint

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ABSTRACT

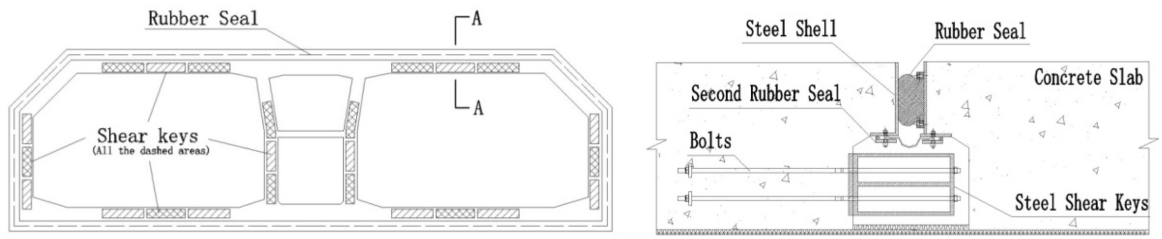
The static shear stiffness of an immersion joint subjected to combined compression and shear forces is investigated by experiments in a test set-up. To explore the performance of the immersion joint, the compression-shear loads, which are applied on a specimen according to test protocol, are determined based on real design situation. In this test, the main focus is on the steel shear keys and the rubber sealing. For the applied loading schemes, different levels of axial force, corresponding to the water depth of the joint, are considered as well as the changing amplitudes of the shear force. The force-displacement curve is obtained and the hysteresis is observed during the whole test. The joint's static shear stiffness is calculated, showing to increase linearly with respect to the magnitude of the axial force. Moreover, it is found that the rubber sealing has a significant influence on the shear behavior of the joint.

INTRODUCTION

An immersion joint is the connecting part between two adjacent elements of an immersed tunnel. Compared to that of the bulk elements, the stiffness of the immersion joint is relatively small. When it is subjected to shear actions, whether resulting from vertical foundation settlement or horizontal earthquake movements, shear-resistance of the joint is the main concern for a safe and reliable water-proof design.

A flexible immersion joint, which normally consists of a rubber seal and shear keys installed at an element end is a common solution in practice. The way in which the shear keys and the rubber seal behave in the joint together is of vital importance to a comprehensive understanding of the shear behavior of the joint. However, in literature very few experiments on the shear behavior of immersed joints are available although the flexible joints are applied in practice for more than 50 years already. O. Kiyomiya (2004) carried out both a 3-dimensional experiment and a finite element analysis for a new type of flexible joint referred to as the Crown Seal. The results indicated that this new type of joint can be applied in practice because of the effective reduction of lateral deformation. A linear model was found in the paper of Anastasopoulos et al. (2007) to describe the behavior of the shear keys, which consider that the stiffness of the shear keys tends to infinity. R.S. van Oorsouw (2008) discussed the shear capacity of concrete shear keys in segmental joints, by analyzing the influences of reinforcement and friction force between shear keys.

Although the shear-keys play an important role in an immersion joint, no published reports on experiments concerning their mechanical behavior are found. The use of a linear or bi-linear model to simulate a shear key, in a numerical analysis of a joint under lateral shear actions, is based on simplified assumption. To clarify the mechanical behavior of an immersion joint under transverse action, this paper presents an experimental investigation. Compression-shear quasi-static loading is cyclically applied to a specimen of a flexible immersion joint, with a geometric scale of 1/10 with respect to a real design. The patterns of compression-shear are set-up according to a certain axial water pressure on a joint, to which it would be subjected during its service life at typical buried depths, and to transverse shear movement due to seismic actions. The lateral forces are applied cyclically at increasing amplitude in the horizontal plane. Measuring devices are systematically installed to record the applied loads, extension and closure of the joint, as well as strains of the steel shear keys. Through observed load-deformation curves, the static shear stiffness of the scaled joint is obtained.



(a) Front view of a typical immersion joint (b) Details of A-A cross-section

Figure 1 A typical immersion joint

BACKGROUND

Immersion Joints

As mentioned in available literature (Hung 2009, Baber 2011), the immersion joint is a vital part not only for the connection between elements but also ensuring water tightness. As the rubber seal becomes more popular, the techniques for the immersion joints have been developed maturely. Generally, the front view of a typical immersion joint is shown in Figure 1(a). It mainly involves a first rubber seal, a second rubber seal, shear keys and steel shells, as can be seen in Figure 1(b).

When the immersed tunnel is installed, the rubber seal between elements will be pressed tightly with a minimum compression, resulting in a waterproof seal due to initial water pressure. If the rubber seal fails, the second rubber seal will start to work to avoid severe leakage. After installation of the elements, the shear keys will be situated in the walls or slabs. As a result of deformation of the joint, a lateral force on the joint occurs as well as an axial force and bending moment. The shear keys are mainly used to transfer the lateral force from one element to another and the rubber seal may also be involved in it.

Deformation of Immersion Joints

Under different loading conditions, a tunnel will respond in different deformation modes. One among them is curvature deformation (Owen et al 1981), also known as the “snaking effect” related to the moving motion of a snake (van Oorsouw 2008). In this situation, the tunnel will be bended in the longitudinal direction, resulting in compression on one side and “tension” on the other side in the same cross section, which is illustrated in Figure 3. Regarding immersed tunnels, due to the “snake effect”, a lateral deformation will occur, resulting in shear deformations in the joint (Figure 2). Both the shear deformation and the internal force will be transferred by the shear keys, of which the capacity in this loading case determines the shear capacity of the whole immersion joint.

In this study, the effect of lateral deformation is mainly considered to express the shear mechanical behavior of immersion joints. When both the axial and shear forces are applied to element B (Figure 3), the joint is compressed and at the same time a lateral deformation occurs. When the deformation is small, remaining in the elastic stage, the stiffness can easily be calculated. The failure mode is also analyzed when the deformation exceeds the allowable one. Hence, cyclic shear loading needs to be applied to analyze these shear issues.

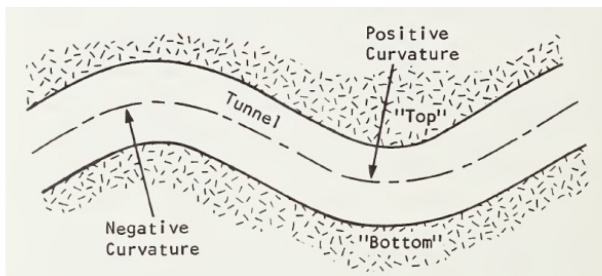


Figure 2 Curvature deformation of the tunnels (Owen et al 2008)

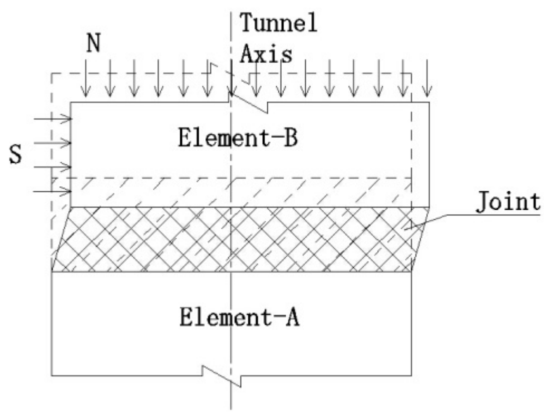
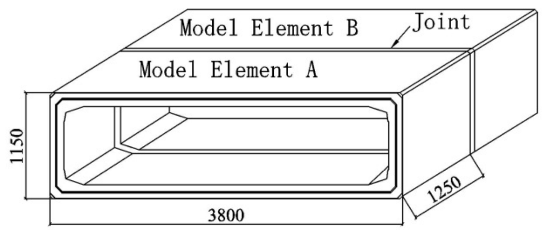


Figure 3 Shear deformation in the joint

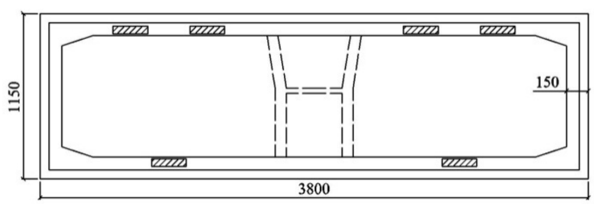
EXPERIMENTAL DESIGN

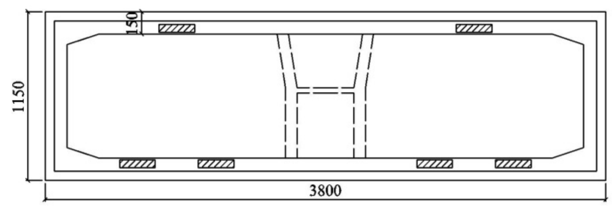
Model Element

The typical geometry of a cross-section of a tunnel element is shown in Figure 4(a). Shear deformation of the immersion joint can happen either in the vertical or horizontal direction. In the test, here only a horizontal shear force is applied. As the outer part of the shaped corners in passages and the middle walls contribute insignificantly to compression or shear of the joint, the cross-sectional profile of the model element was simplified as rectangular and the middle walls were not considered as shown in Figure 4(b) and (c) display, compared to the original cross-section. Furthermore, the shaded parts refer to the horizontal steel shear keys. 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 the model is the same as the original one. Figure 4 provides the dimensions of a single tunnel element 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 structure (GB50010-2010), the types of concrete and reinforcement are C50 and HRB335 respectively.



(a) Model tunnel



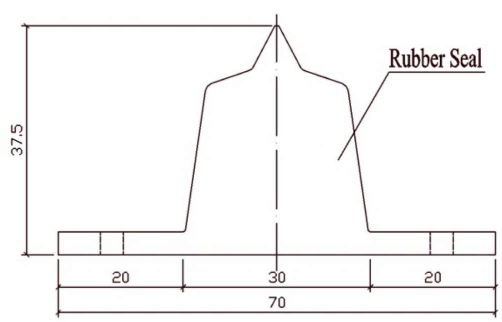


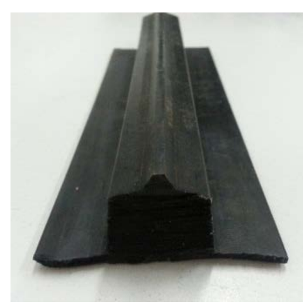
(b) Model Element A (c) Model Element B

Figure 4 Cross-section of model immersed tunnel (units: mm)

Model Immersion Joint

The model immersion joint follows the design of the real project and the lay-out is also simplified according to the experiment. The steel shell and second rubber seal are not adopted in this model joint due to the lack of contribution to shear behavior of the immersion joint.





(a) Dimensions of the model rubber seal (b) Profile of model seal

Figure 5 Dimensions and profiles of the model rubber seal (units: mm)

Model Rubber Seal. The GINA-type solid rubber seal is designed and manufactured especially for this experiment based on the design of the related project. Figure 5 displays the dimensions and the profiles of the model rubber seal and the physical parameters of the used rubber are listed in Table 1. Figure 6 shows the load-compression curve of model rubber seal, which is obtained from a material test. The loading rate is 1 kN/s. It can be seen that the rubber seal becomes stiffer when the compression force increases. The variation in slope can partly be attributed to the specific geometry of the rubber seal (see Figure 5) for which the total height of the smaller top part is about 8.5mm. A detailed view of the rubber seal after installation is shown in Figure 7.

Table 1 Physical characteristics of the model rubber seal (Provided by producers)

Characteristic	Value
Hardness	55~60 Shore A
Breaking Tenacity	14 MPa
Extensibility	>450%
Allowable Compressive Strength	10 MPa
Shear Modulus	0.98~1.47 MPa
Friction Coefficient	Steel:0.2; Concrete:0.3

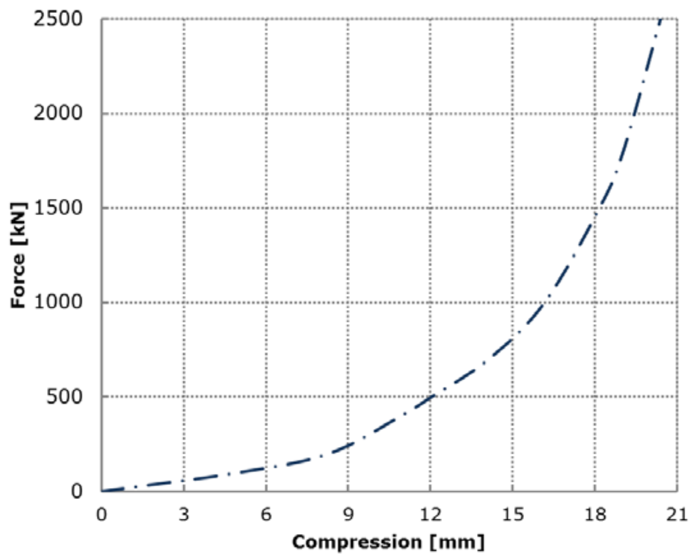


Figure 6 Load-compression curve of model rubber seal (scaled)

Figure 7 Detailed view of model rubber seal after installation

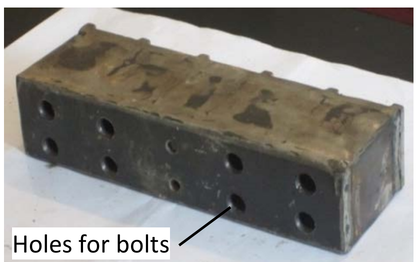
Model Shear Keys. In a real immersion joint, shear keys will be situated in walls and slabs as shown in Figure 1(a). As the joint is only submitted to horizontal shear, only horizontal shear keys are considered in the test, which are installed in both roof and bottom slab. The steel shear keys are connected to the element by bolts through the keys (see Figure 1(b)). The mechanical parameters of the steel and the bolts are listed in Table 2.

There are two types of horizontal shear keys in the test, HSK1 and HSK2 respectively (Figure 8(a) and (b)). They are staggered in different elements, making that HSK1 is loaded in two directions (Figure 8(c)). The main part of each steel shear key is composed by several steel plates, welded to each other. In the top face there are holes for bolts, connecting the shear keys and the embedded components in the tunnel element.

When the shear keys are loaded by a horizontal shear load, the shear force is distributed to the bolts. Hence the shear resistance is provided by the shear strength of the bolts, which determine the capacity of one shear key. In this way, the capacity of a shear key is determined by the strength of the bolts. Based on calculation, the capacity of one shear key (HKS2) is 180kN while that of the immersion joint is 720kN. Moreover, it should be noted that in the real project, there are rubber bearings between the shear keys. However in the design of the test, a gap of 5mm is adopted instead of the rubber.

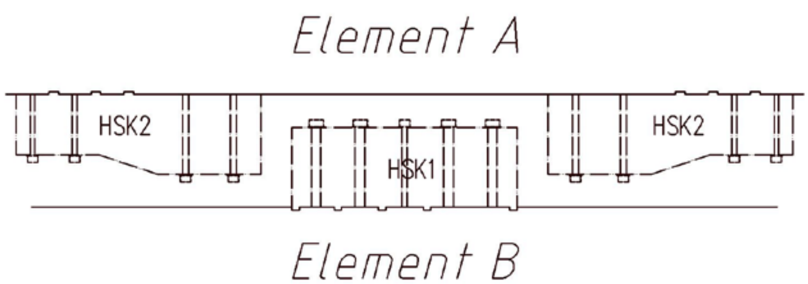
Table 2 Mechanical parameters of materials in shear keys[MPa]

Item	Tension/Compression Strength	Shear Strength
Steel Plate	310	180
Welding	310	180
Bolts	170	140



(a) HSK1

(b) HSK2



(c) Staggered installation of two types of shear keys

Figure 8 Two types of steel shear keys

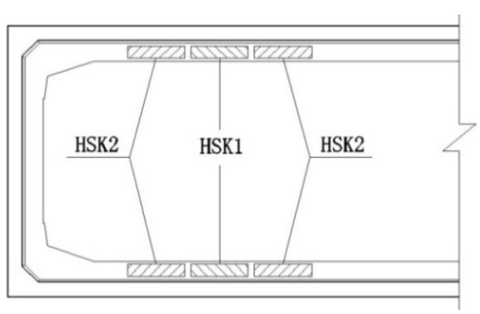
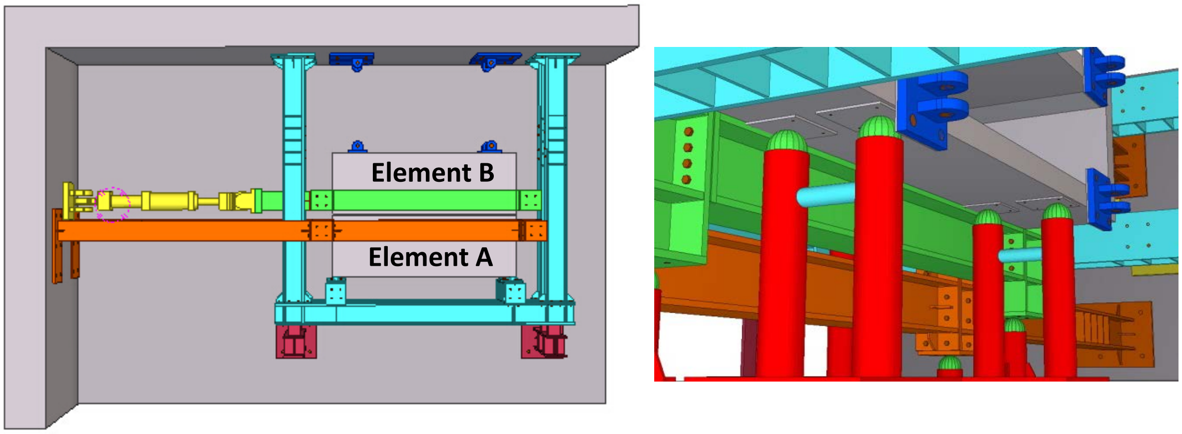


Figure 9 The lay-out of the shear keys

Loading Test Set-up



(a) Plan view (b) Bottom view

Figure 10 View of the set-up

The tunnel model was placed in a steel loading frame. As illustrated in Figure 10, each part of the frame is shown in different colors. During a typical experiment, one tunnel element (Model Element A) is fixed horizontally while the other one (Model Element B) is movable in two directions, resulting in a deformation of the immersion joint. This test set-up, which was designed by our research group, mainly consists of an axial part (light blue) and a transversal part (orange and green) in order to meet the demand of the experiment. The main function of this reaction frame is to provide one model element with 2 degrees of freedom in the horizontal plane while the other one is fixed. Moreover, to avoid friction between the element and the reaction floor, several columns with spherical hinge bearings on its top (red) are installed before the elements are placed.

As mentioned, the axial forces are applied to Element B. Figure 10 demonstrates the 4 loading points (dark blue) for the axial force. Four hydraulic jacks, which only provide pressure but no tension, are situated between this element and the reaction wall. The jacks are controlled synchronically to avoid rotation of Element B. Regarding the shear force, it is applied by the actuator (yellow), which can pull and push the element. Hence the shear force can be cyclic with changing amplitudes.

Loading Protocol

Table 3 Loading cases of the test

No.	Axial force [kN]	Shear amplitude [kN]
CSS-0-40	0	±40
CSS-440-40	440	±40
CSS-850-40	850	±40
CSS-1760-40	1,760	±40

The compression-shear test combines loading pattern of imposed axial and shear loading. Firstly the axial force is applied because of the simulation of the initial water pressure. After that, the shear force is applied while the axial force remains constant. Actually, as the immersed tunnel elements will be located at different water depths, the pressure acting on an immersion joint will vary from its location.

Therefore, different levels of water depth are considered, corresponding to axial forces of 0kN, 440kN, 850kN and 1,760kN respectively (scaled down). Regarding the lateral behavior of the joint, a quasi-static loading mode for shear force is applied, as displayed in Figure 11, with a loading rate of 1kN/s. A survey of the different loading cases is given in Table 3.

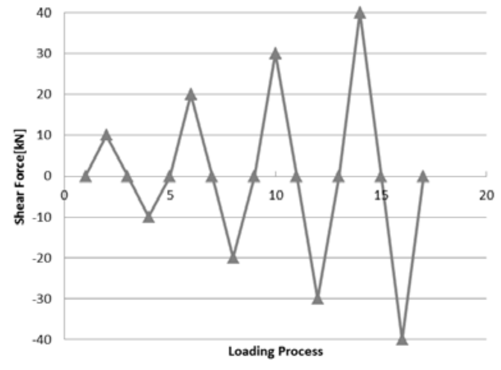
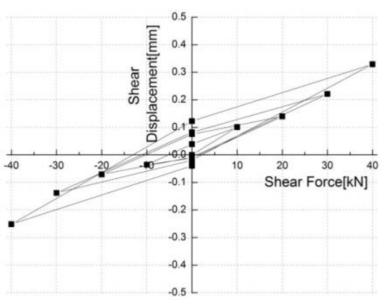


Figure 11 Loading patterns for shear force

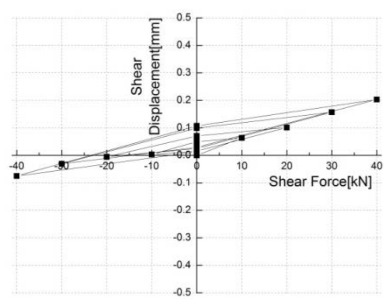
EXPERIMENTAL RESULTS AND ANALYSIS

Shear-Displacement Curve

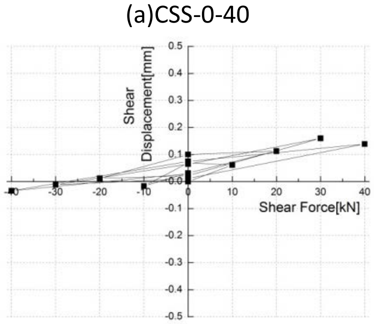
Figure 12 shows the force-displacement curves of the four cases. It can easily be seen that the shear displacement of the joint increases with the shear force under the same level of axial force. With the same shear force, the displacement decreases along with the axial force. The shear displacement in CSS-1760-40 is about 10 times that in CSS-0-40. Moreover, the joint behaves almost elastically, showing little hysteresis.



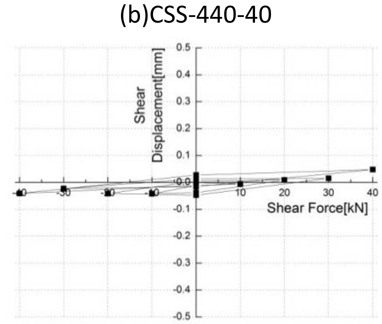
(a)CSS-0-40



(b)CSS-440-40



(c)CSS-850-40



(d)CSS-1760-40

Figure 12 The force-displacement curves of four loading cases

Static Shear Stiffness of the Joint

With the force-displacement curve of the joint, the static shear stiffness can be defined by the following equation.

$$k_j = \frac{\Delta Q}{\Delta d} \tag{1}$$

where k_j represents the static shear stiffness of the immersion joint; ΔQ and Δd represent the differences of the maximum and minimum value of the shear force and the displacement respectively.

The calculated shear stiffness is given in Table 4 and the relationship between stiffness and the axial force is presented in Figure 13. The fitted curve, with a correlation coefficient of 0.99, is also shown. Obviously, the static shear stiffness increases linearly with the axial force despite the non-linear axial performance of the joint as found in previous research (Xiao et al 2015).The shear stiffness under the maximum axial force is three times that without axial force.

The static shear stiffness ratio of the joint and the tunnel element is shown in Figure 14. The shear stiffness of the tunnel element can be easily calculated based on the dimensions of its cross-section. It can be seen that the shear stiffness of the tunnel element is one to two orders of magnitude larger than that of the joint, which varies from 24 to 156 times. In the beginning, when the axial force is 0kN, the ratio is 1/156.8. When the axial force increases up to 440kN, the ratio soon increases up to 1/76.1. Then the stiffness ratio gradually increases. The obtained shear ratio can be used in numerical analysis.

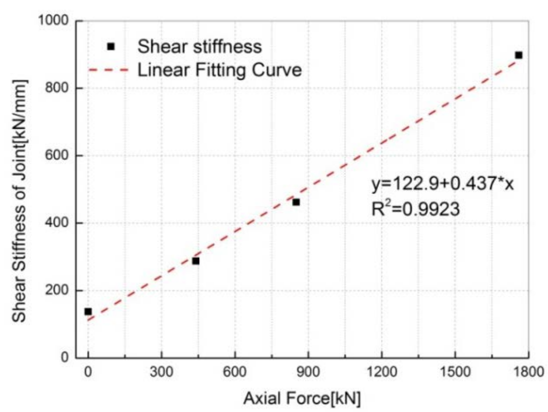


Figure 13 The relationship between shear stiffness and axial force

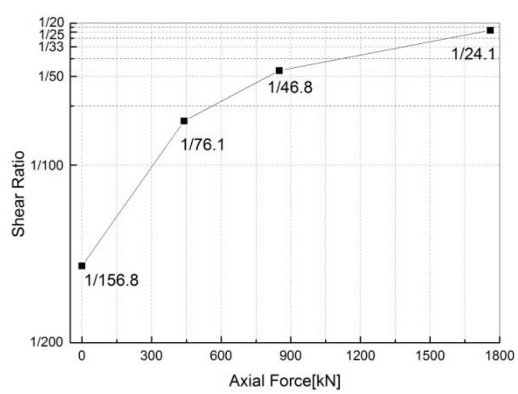


Figure 14 The stiffness ratio of joint and tunnel element

Table 4 The calculated shear stiffness of the joint [kN/mm]

Case	CSS-0-40	CSS-440-40	CSS-850-40	CSS-1760-40
Stiffness	137.84	287.67	462.16	897.90

CONCLUSIONS

This paper presents the results of an experimental study on the static shear stiffness of a scaled immersion joint subjected to compressive-shear loading. Based on a real project, a certain level of compressive load is applied as well as a cyclic horizontal shear force. From the analysis of the experimental results, the following conclusions can be derived.

1. The shear displacement increases linearly along with the shear force; With the increasing of axial force, the shear displacement decreases.

2. The static shear stiffness of the joint is calculated and the fitting equation is used to describe the relationship between stiffness and axial force. A linearly increasing trend with the axial force is found.

3. The stiffness ratio of the joint and tunnel element is presented, indicating the variation trend of shear stiffness ratio which ranges from 1/156.8 to 1/24.1, which can provide the support for further research.

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