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Article

Compression-Shear Behavior and Water Impermeability of Rubber Seal in Precast Concrete Structures

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Abstract. This paper attempts to apply the precast construction system on concrete swimming pools. Elastomeric bearings are chosen to be used as rubber seals in order to provide both shear resistance between segments and leakage prevention to the structures. The study methods involve 2 main experiments, accordingly. To simulate the conditions of immersed structures, the prototype of precast swimming pool and the joint between segments are designed. The compression-shear tests of such joints are conducted subject to direct shear and confinement to investigate the shear resistance of the rubber seals. The test results show that the final shear stress under confinements of 1 and 2 MPa and rubber hardness levels of 60 and 70 are considerably higher than the required shear stress while the rubbers prevent the slippery. The water impermeability test is conducted on the specimen made with full depth and thickness of the prototype. Three-dimensional finite element models are also created using ANSYS to determine the stresses caused by the post-tensioned BBR bars. Results from numerical models exhibit non-uniformly distributed stresses in the rubber seal. Two other important factors are found to have influence on impermeability performance: the creep effect of rubber and the surface finishing of contacted precasts.

Keywords: Immersed precast concrete structure, compression-shear behavior of joint, water impermeability, elastomeric bearings.

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1. Introduction

Precast construction system has advantages over cast-in-situ system on many aspects: less on-site construction time, less curing time, less energy and water consumption, lower environmental impact and lower overall construction cost [1-3]. Moreover, on quality aspect, cracks and leakages are still found in cast-in-situ system since the quality of work heavily relies on workmanship and the frequent problems are segregation, under-consolidation and improper curing process [4-5]. Consequently, precast system is increasingly utilized and continuously replacing the use of cast-in-situ system [6-8].

In precast system, joints are important parts to the strength of the precast structures [9-10]. These joints must be capable to resist and transfer shear force between segments [11-12]. On the other hand, in immersed tunnel structures, joints with rubber seal are assumed to resist no shear force. All segments are laid mainly on aggregate just like pavement design as shown in Fig. 1. Hence, no shear force occurs between segments. The rubber seal so called "Gina rubber gasket" as shown in Fig. 2 is installed only for leakage preventive purpose [13]. However, the recent study on immersion joints [14] showed that the rubber seals contribute substantial shear resistance to the joints of the precast structures and further study is needed.

In other cases of smaller immersed structures, such as water tanks and swimming pools, concrete has to be cast in-place with the help of rubber water stops at the construction joints. This makes construction process complicated and take such a longer time, which may end up with a very high construction cost of the whole project, as a result.

This paper attempts to apply the precast construction method to a concrete swimming pool so that the construction time could be remarkably reduced. In such case, the behavior of rubber seal joints for both shear resistance and impermeability needs to be investigated. Here, elastomeric bearing pads are chosen to be used as rubber seals since they are widely used to support vertical loading and allow horizontal shear movement of the super-structures [16-18]. The results on compression-shear behavior of elastomeric bearings and capability of leakage prevention provide the possibility of this new application.

2. Problem Statement

To apply the concept of precast construction method to swimming pool structures, the critical problem is the design of joints for strength and leakage preventive mechanism. In this study, dry flat joints in conjunction with elastomeric bearings are chosen and their compression-shear behavior as well as leakage prevention performance are investigated.

The prototype of swimming pool structure designed for this experiment conforms to real conditions including shear force from panel weight and water pressure. The dimensions of the concrete swimming pool segment are 2400 mm × 4000 mm × 1500 mm with the thickness of 200 mm as shown in Fig. 3(a). Here, the ultimate load is computed according to ACI 318-89 [19] as shown in Eq. (1)

$$U = 1.4\,D + 1.7\,L \tag{1}$$

where U is ultimate loads, D is dead loads and L is live loads.

The weights of concrete segment and water cause an average shear stress of 0.1256 MPa on the rubber seal. The rubber seals are installed at all joints as shown in Fig. 3(b). All segments are connected together under the confinement of external post tension tendon. Concrete compressive strength of 20 MPa is used for our prototype.

First, the experiment of compression-shear test is conducted in dry condition to study the shear capacity of the rubber seals. The test setup allows direct shear without moment in concrete joints. Hardness, rubber type and loading rate all have influences on the shear capacity [17, 20]. These factors are controlled and essentially prescribed to the experiment. The second experiment concerns the leakage preventive mechanism of the rubber seals. The precast concrete joint with a rubber seal, submersed under water, is tested subjected to a required shear force in order to verify the impermeability performance. The natural bearing pad rubber according to Thai Industrial Standard 951-2533 [21] is used in both experiments.

3. Compression-Shear Test

3.1. Test Setup

The objective of this test is to investigate the ability to resist shear force of elastomeric bearings in joints of precast. The test setup is similar to Zhou et al. [12] which allows direct shear in concrete joints with confinement as shown in Fig. 4(a). The horizontal force from hydraulic jack represents the normal stress from post-tensioning. The contact surface is 200 mm × 200 mm. The pressure on rubber seal is set at 1 MPa and 2 MPa in order to compare with normal flat joint of Zhou et al. The load cells are installed for both horizontal and vertical direction. The LVDTs measure the vertical displacements at both sides of the specimen as shown in Fig. 4(b). The loading is applied at strain rate of 0.04 per second until the final shear strain is equal to 1. The selected loading rate is half of the lowest rate of Wei et al. [20] The natural bearing pad rubber with the hardness level of 60 and 70 are used and their properties are according to Thai Industrial Standard 951-2533 [21].

The test identifier is denoted as Mi-XX-TT-n, where M represents monotonic loading following with i representing confinement from post-tensioned tendon (in MPa). XX is the hardness level of rubber which is 60 or 70. TT represents the thickness of the bearing pad. Lastly n represents the test number under the same condition. Since design practice limits the shear strain at 50 percent, this experiment is observed until strain reaches 100 percent.

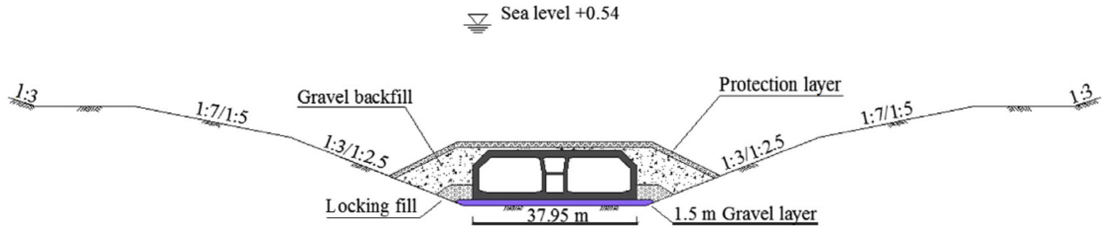


Fig. 1. Cross-section of the Hong Kong–Zhuhai–Macao immersed tunnel [15].

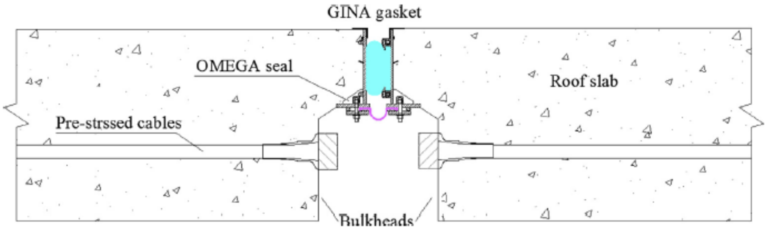


Fig. 2. Detail of immersion joint and Gina gasket [15].

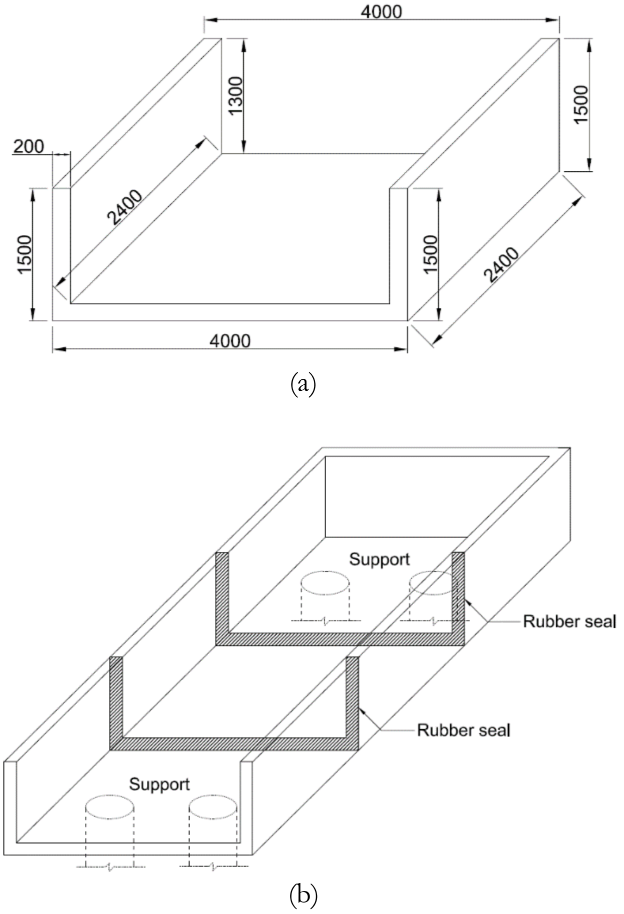
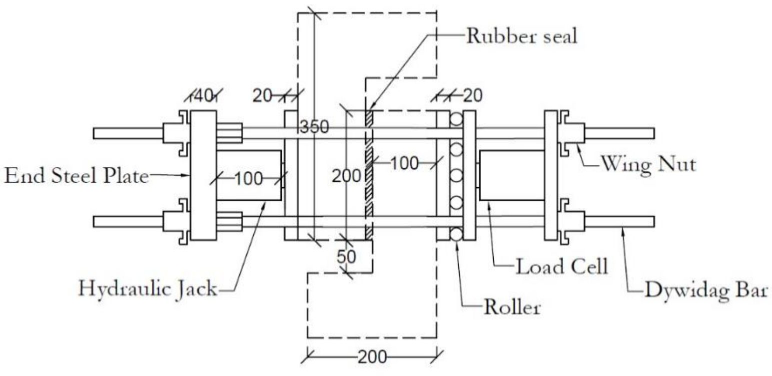


Fig. 3. Prototype of a precast swimming pool; (a) Dimensions in mm of the precast concrete segment; (b) The connections of precast segments and rubber seals.



(a)

(b)

Fig. 4. Compression-shear test; (a) Specimen dimensions in mm; (b) Actual test setup.

3.2. Experimental Result & Discussion

Eleven flat joints with elastomeric bearings were tested. Throughout the loading process, none of the specimen exhibits any slippage. The stress-strain curves for both levels of confinement, as shown in Figs. 5 and 6, shows similar trends. The slope is higher at the beginning and gradually decreases until it reaches 100% strain. In Fig. 5, M1-60-10-1 is an outlier and excluded since the rubber slipped at the beginning of loading process. The rubbers of hardness 70 have, on average, higher shear stress than the rubbers of hardness 60. All 3 specimens with 20-mm thickness rubber are plotted in Figs. 7 and 8. They resist considerably lower shear stress than 8 specimens with 10-mm thickness rubber at both confinement level. Hence, the 10-mm rubber is chosen to be used in impermeability test.

Final shear stress and shear modulus of eleven specimens are summarized in Table 1. Shear modulus is calculated according to ASTM D 4014 [22]. The average final shear stresses for 10 mm-thick rubbers are compared with the results of unsealed joints by Zhou [12] as shown in Table 2. The final shear stress increases with the higher levels of the confinement and hardness. The confinement of 2 MPa yields final stresses 38.03 % and 41.11 % more than those of 1 MPa for rubber hardness level of 60 and 70, respectively. Hardness level of 70 yields final stresses 11.03 percent and 12.51 percent more than hardness level of 60 for confinement of 1 MPa and 2 MPa, respectively. However, in all cases, the final shear stress is considerably more than the required shear stress due to the concrete segment and water weights.

The final shear stress comparison in Table 2 shows that the shear resisting mechanism of the rubber seal joint is different from that of unsealed joint. The rubber seal joint resists shear by the shear properties of rubber while the unsealed joint resists shear by friction between concrete surfaces. At the lower confinement at 1 MPa, rubber seal joints have higher final shear stress than unsealed joints. At the higher confinement at 2 MPa, rubber seal joints have lower final shear stress than unsealed joints. The shear resistance in rubber grows at the lower rate than the shear resistance from friction.

4. Impermeability Test

4.1. Specimens and Test Setup

The objective of this study is to investigate appropriate stress distribution on contact surface between concrete and rubber seal for leakage preventive purpose. The test is conducted with actual water pressure and shear force according to our prototype as shown in Fig. 3. Hence, the test is designed with full depth to simulate shear force from the panels and water weight. The specimen consists of 2 parts which are attached by six post-tensioned BBR bars as shown in Fig. 9. Two levels of post-tensioning force are applied on each post-tensioned BBR bar. Each post-tensioning force on the first trial is 123.56 kN and on the second trial is 247.13 kN as the post-tensioning process is shown in Fig. 10. One part of the specimen is attached to strong wall with four post-tensioned BBR bars in order to assume this part as rigid and ensure no horizontal and vertical movement. The vertical force is applied to the other part of the specimen by hydraulic jack and measured by load cell. The magnitude of jacking force, 110.71 kN, computed from to the weight of water and segment of prototype plus shear force carried by rubber seal (required shear stress times contact area of rubber seal). The water is applied to the specimen and observed.

4.2. Numerical Model

Three dimensional finite element models were created using ANSYS. Geometric and material properties were both taken into account. Eight-node hexahedron elements (SOLID185) were used to study stress distribution on contact surface between concrete and rubber seal. Since both concrete and rubber specimens are symmetric volume, the half modelling is used as shown in Fig. 11. The near-strong-wall segment is fixed on x-axis, y-axis and z-axis. The far-strong-wall segment is fixed on only y-axis. The boundary conditions can be described below.

1) At y = -H; given displacement in Y direction equals to zero

2) z = 0 is set as symmetric boundary condition to simplify the model

3) At (x,y) = (0,-H); given displacement in X and Y direction equal to zero to prevent rigid body motion

4) 40 kN post-tensioning forces are applied at 3 positions of this segment as shown in Fig. 11 according to the experimental setup as shown in Fig. 9.

The Materials properties are shown below. The concrete compressive strength is according to the prototype assumption in section 2. The rubber Young's modulus, shear modulus and Poisson ratio are according to AASHTO specification [23].

- Concrete compressive strength = 20 MPa
- Concrete Poisson ratio = 0.2
- Concrete Young's modulus = $4733*\sqrt{f_c'}$
- Rubber Young's modulus = 4.5 MPa
- Rubber shear modulus = 1.5 MPa
- Rubber Poisson ratio = 0.49

In Fig. 11, color chart shows that the post-tensioning force of 40 kN distributes lowest compressive stress at the bottom of the specimen of 0.01 MPa. As shown in Fig. 12, the stress distribution of rubber is studied on 3 planes which are far symmetric plane, mid thickness and near symmetric plane. Each plane is plotted according to mid rubber and contact surface. Figure 13 shows that both far and near symmetric planes have lower compressive stress than mid thickness of concrete segment because of the displacement of rubber along the concrete segment edge. This is similar to the top edge of the concrete segment which has lower compressive stress than the other part of rubber surface. At the same plane, compressive stress at contact surface is higher than those of the mid-rubber position.

Table 1. Experimental results of compression-shear test on joints.

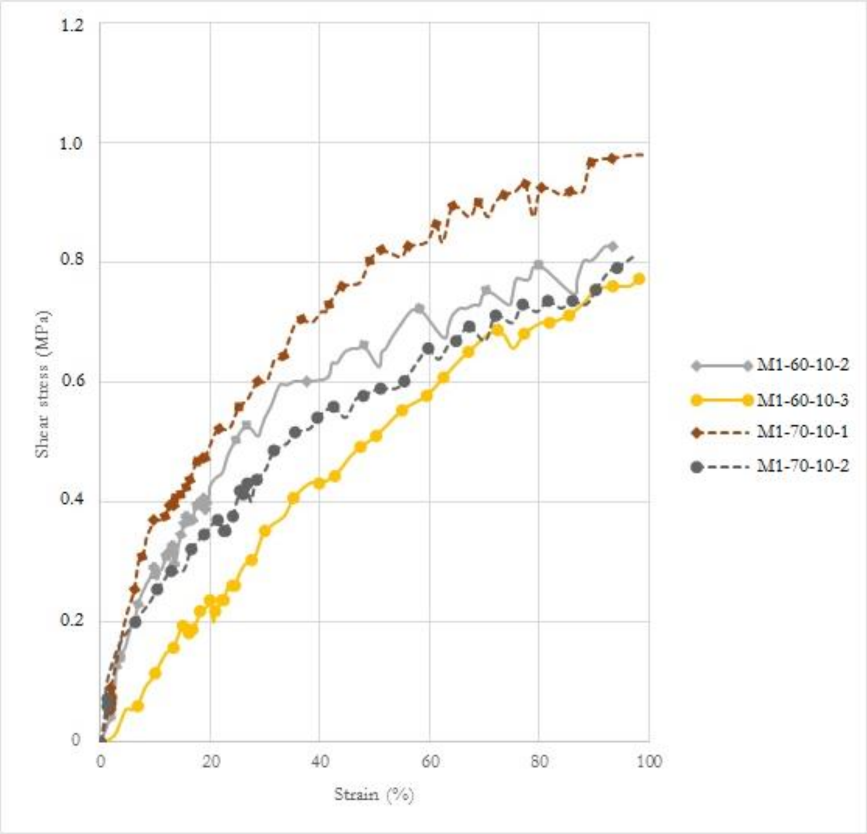
Specimen	**Final shear stress*** (MPa)	**Shear modulus**** (MPa)
M1-60-10-1	0.46	1.60
M1-60-10-2	0.81	1.96
M1-60-10-3	0.76	1.01
M1-60-20-1	0.77	0.95
M1-60-20-2	0.66	0.88
M1-70-10-1	0.95	2.05
M1-70-10-2	0.79	1.50
M2-60-10-1	1.06	2.25
M2-60-10-2	1.10	2.68
M2-60-20-1	0.80	0.91
M2-70-10-1	1.23	2.73

*Final shear stress is the shear stress at 100% strain.
**Shear modulus is calculated by taking the secant modulus from the point of 2% maximum stress to the point at 25% shear strain according to ASTM D 4014 [21].

Table 2. Average final shear stress comparison.

Confinement	**Final shear stress**		
	Mx-60-10 MPa	**Mx-70-10 MPa**	**Unsealed joints* MPa**
1 MPa	0.78	0.87	0.68
2 MPa	1.08	1.23	1.47

*Results by Zhou, X. (2005) [12].



Note: M1-60-10-1 is an outlier and excluded.

Fig. 5. Shear stress-strain curve of 10-mm-thickness rubber with confinement of 1 MPa.

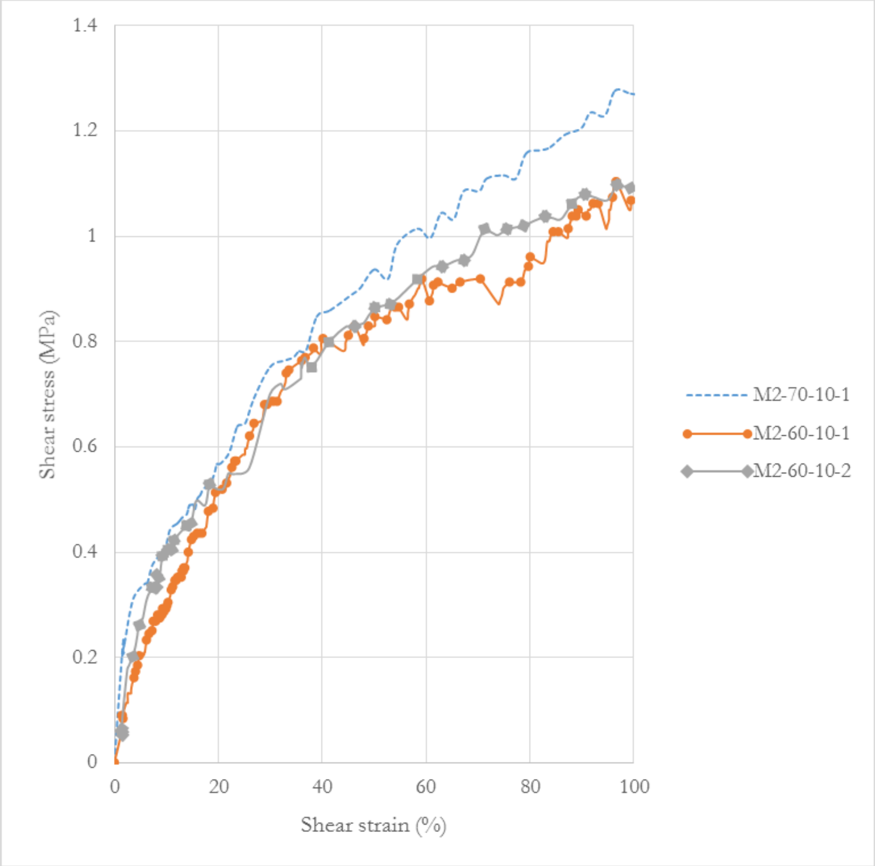


Fig. 6. Shear stress-strain curve of 10-mm-thickness rubber with confinement of 2 MPa.

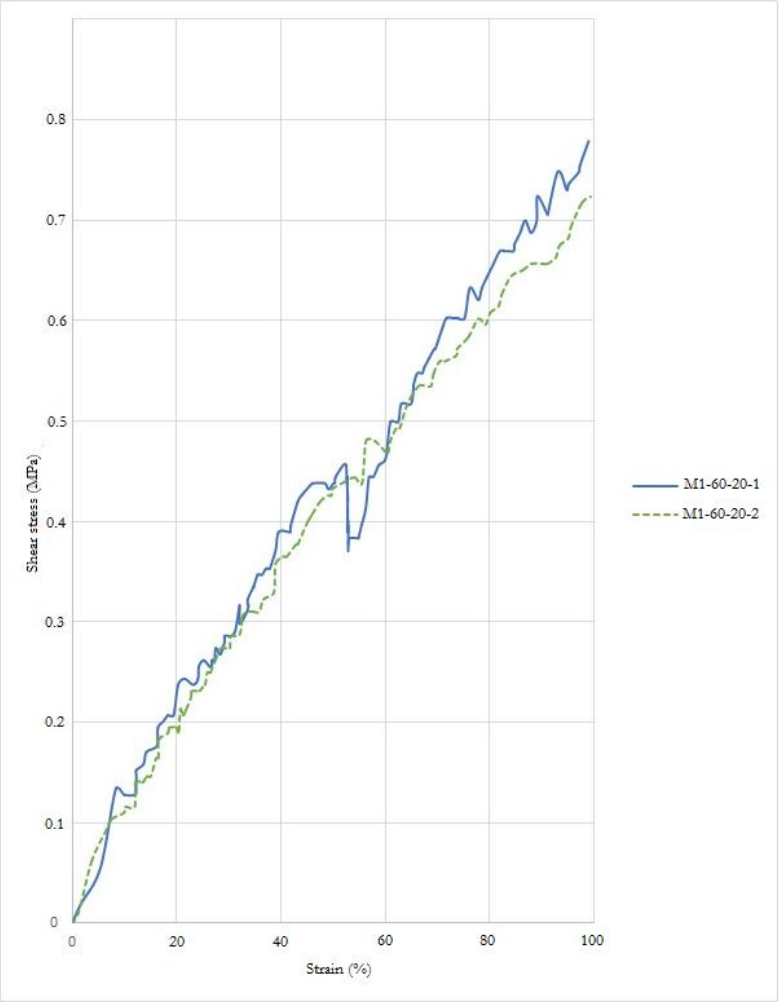


Fig. 7. Shear stress-strain curve of 20-mm-thickness rubber with confinement of 1 MPa.

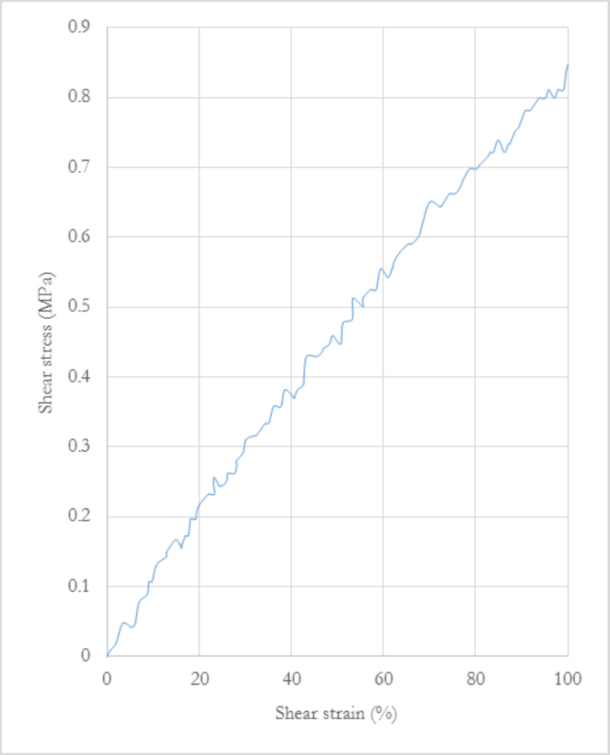


Fig. 8. Shear stress-strain curve of 20-mm-thickness rubber with confinement of 2 MPa.

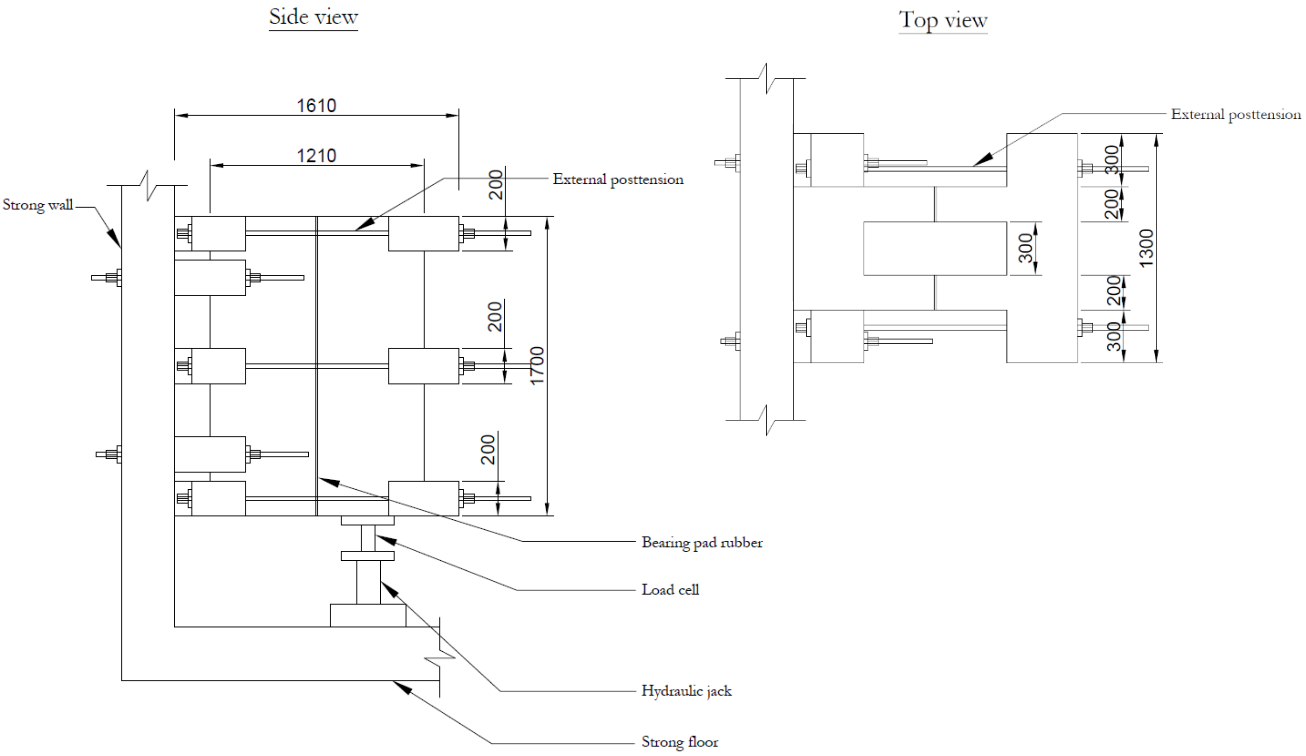
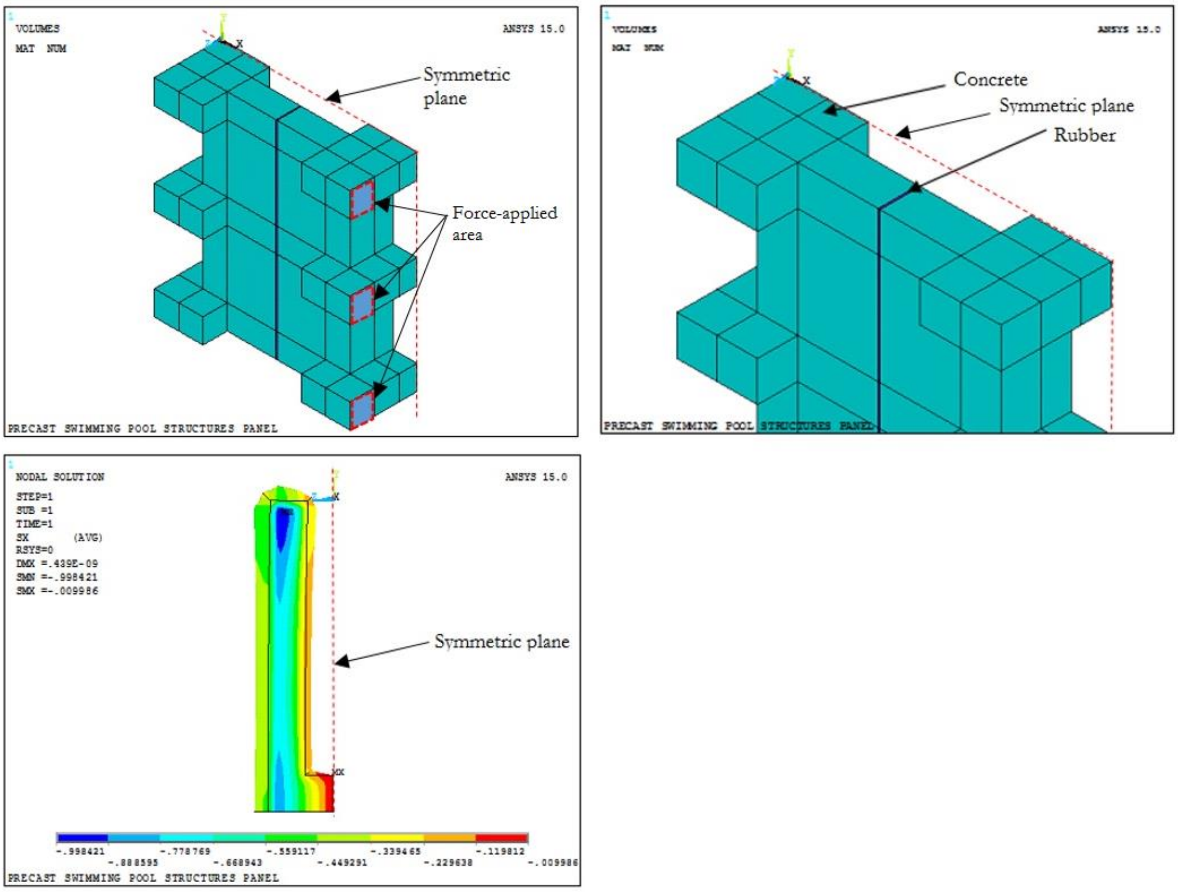


Fig. 9. Specimen and experimental setup in mm.

Fig. 10. Post-tensioning process.



Note: Stress value in MPa is shown as 40 kN post-tensioning force is applied.

Fig. 11. Solid volume and stress distribution on rubber surface.

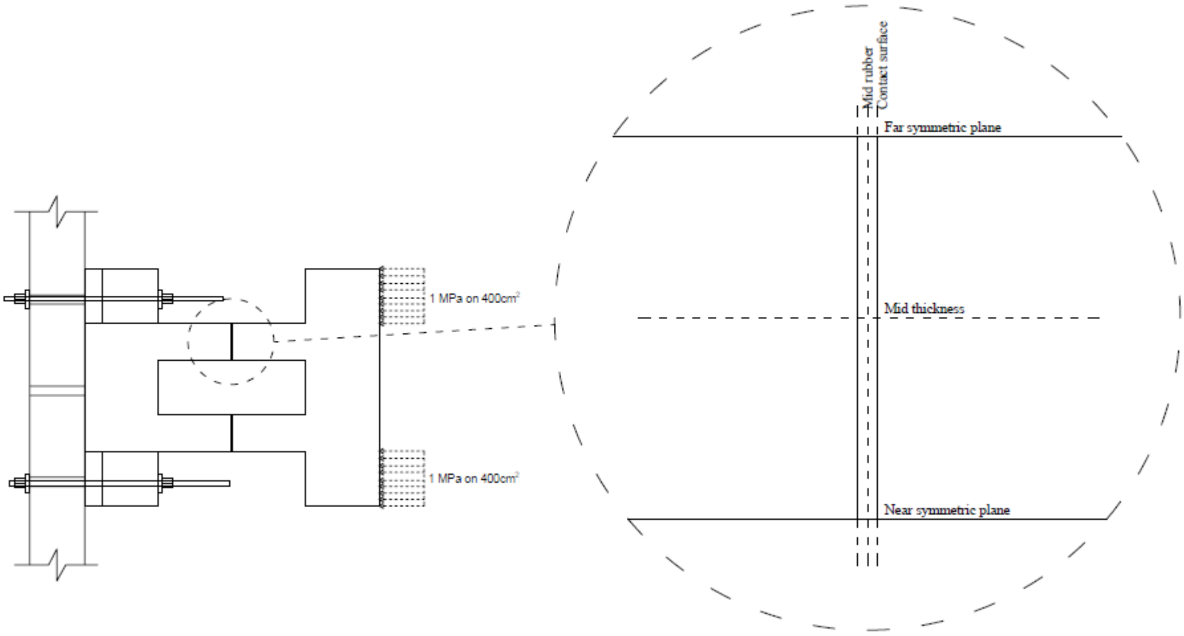


Fig. 12. Rubber plane explanation.

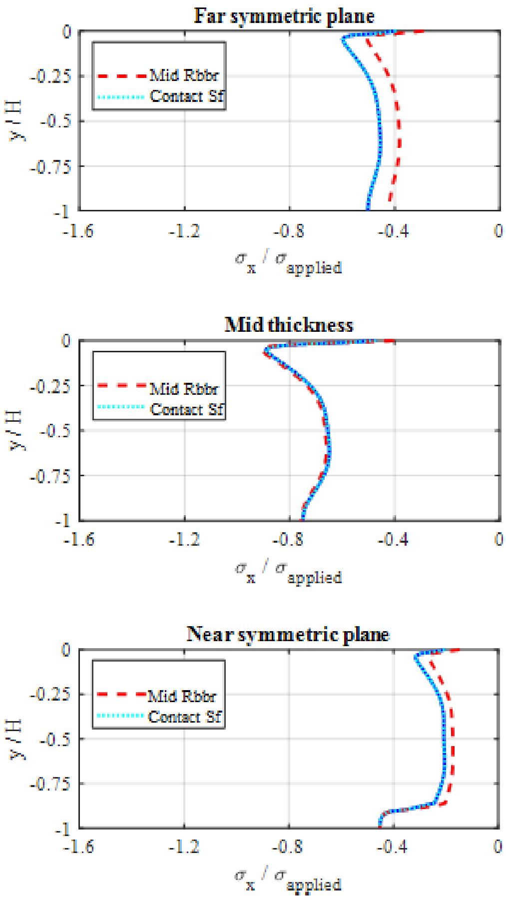


Fig. 13. Axial stress in X direction of rubber.

4.3. Experimental Results

According to the numerical model, the lowest compressive stress distributes at the bottom of the specimen. However, the actual magnitude of stress might slightly differ from the model since the concrete-rubber contact surface in the simulation is perfectly uniform. On the first trial, the confinement to the rubber seal was induced by the post-tensioning force of 123.56 kN on each BBR bar. The water level was gradually increased up to 400 mm above the bottom of the specimen. The specimen failed to contain water and it leaked at both sides and at the bottom of the specimen at the rate of 800 ml per minute.

On the second trial, the post-tensioning force of 247.13 kN was applied on each BBR bar. The water level was gradually increased and the specimen was able to store water until the water level reached 1000 mm. Water leaked only at 6 spots on both sides of the specimen at much slower rate of 40 ml per minute without any leakage at the bottom. However, the waterproof behavior of the rubber seal improved with time as we found only 2 leakage spots 14 days later. Finally at 21 days later, there was no leakage and the specimen was able to store water to its full capacity, up to 1500 mm above the specimen bottom, as shown in Fig. 14. At this point, the rubber creep duration of 21 days significantly increases the impermeability of rubber.

On the same day, shear stress was applied to the rubber seal to simulate the real condition. A vertical jacking load of 110.71 kN was applied at the far-strong-wall segment. The vertical movement was measured 1.5 mm, and the water leaked at the same 6 spots on both sides of the specimen at rate of 75 ml per minute. Similar to what happen earlier, the waterproof behavior of the rubber seal improved with time as we found only 1 leakage spot left 14 days later. 21 days later, no leakage occurred as shown in Table 3. The rubber creep duration of 21 days significantly increases the impermeability of rubber.

Table 3. Impermeability test result.

	First trial	**Second trial**
Post-tensioning force per BBR bar	123.56 kN	247.13 kN
Day 1	Leakage occurred along both sides and bottom of the specimen at the rate of 800ml/minute	6 spots of leakage occurred at both sides of the specimen at the rate of 40ml/minute
Day 14	-	2 spots of leakage occurred
Day 21	-	no leakage occurred
Day 21 and apply jacking load	-	6 spots of leakage occurred at both sides of the specimen at the rate of 75ml/minute
Day 35	-	1 spot of leakage occurred
Day 42	-	no leakage occurred
Day 90	-	no leakage occurred
Day 90 and apply jacking load	-	no leakage occurred
Unload for 30 minutes and apply jacking load for the second time	-	leakage occurred at the rate of 6 ml/minute for 1 hour
Unload for 30 minutes and apply jacking load for the third time	-	leakage occurred at the rate of 40 ml/minute

Lastly, at day 90 we decided to unload the vertical force and no leakage occurred. The vertical jacking load was reapplied, and no leakage occurred. We unloaded for 30 minutes and applied vertical jacking for the second time. The water leaked at rate of 6 ml per minute for 1 hour. After no leakage left, we decided to unload again for 30 minutes and reapplied vertical jacking for the third time. The water leaked at rate of 40 ml per minute.


(a)


(b)


(c)

Fig. 14. Impermeability test (a) Water is filled up to the top level of 1500 mm above bottom; (b) Rubber seal at the connection of the precast segments; (c) Shear stress is applied to the segment by hydraulic jack at the bottom.

5. Conclusion

In this paper, the precast construction method is adapted to use with the swimming pool structure. Critical problems for such an application are found at the connections between the precast segments, concerning the capability to transfer shear force and the water leakage prevention. Elastomeric bearings are chosen to be used as rubber seals at the connections. Two experiments have been conducted: compression-shear test and impermeability test. Results from the first experiment indicate that elastomeric bearings is capable to resist shear force from precast segment and water weights of the swimming pool prototype. Shear capability of rubber increases with the confinement and hardness level. However, thicker rubbers tend to have lower shear capability than thinner rubbers.

Results from the second experiment indicate that elastomeric bearings can be used as rubber seal to prevent water leakage under our predetermined conditions. There are problems with non-uniform confinement stress in the rubber seal resulted from concentrated prestressing forces and unsmooth concrete surface. However, after the rubber creeps for 21 days, the rubber can fully prevent water leakage.

We note here that this paper limited only at 2 confinement levels for both experiments. The compression-shear test should be revisited at different confinement levels to confirm the relationship between final shear stress and confinement. For impermeability test, the higher confinement level and finished concrete surface may result in a shorter rubber creep time. The findings from this research lead to the new application of elastomeric bearings. This new knowledge can further apply to other kinds of watertight structures or immersed structures such as water tanks, man holes, and basements.

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Waranyoo Prombandankul, photograph and biography not available at the time of publication.

Watanachai Smittakorn, photograph and biography not available at the time of publication.