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POINT LOAD TESTING OF FLEXURAL BEHAVIOR OF SEGMENTED TUNNEL LINING

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Abstract: In tunnel, design of precast tunnel lining are not merely about the strength, but how much its allow to move to account the deflection comes from movement of surrounding soil and load. Thus, the design of tunnel lining is not straight forward. Understanding the flexural behavior of segmented lining is a bonus to optimize design lining in cost effective way. Tunnel lining are designed in segment and have joint that allows tunnel to become flexural and allow deformation taken by the lining load carrying capacity. The objective of this paper is to present some of the research works on segmented tunnel lining conducted in the laboratory. A series of laboratory testing of point load test have been developed to imitate behavior of segmental tunnel lining condition in real. Two types of support system were introduced namely pin-pin and pin-roller condition to imitate both rigid and hinge condition of lining. Support mechanisms of pin-roller support condition shows variation trend in stress-strain and moment readings and meanwhile for pin-pin it show mirror trend for both result. High stiffness of lining is important at the edge of segment.

Keywords: *Tunnel; segment lining; point load test; laboratory; flexural*

1.0 Introduction

Tunnel just laid in the excavated bed soil where lining is allowed to move. Lining also induces bending moment both in negative and positive bending moment simultaneously. The proper criterion for judging lining behavior is therefore not adequate strength to resist bending stresses, but adequate ductility to conform to imposed deformations. In short, the lining is a confined flexible ring. Lining cannot fail in flexure – unless there is unfilled void, or exceedingly soft surrounding medium, behind the lining. Design of tunnel lining is not independent structural problem, but a ground-structure interaction problem, with the emphasis on the ground (Bickel, 1996). Thus, bending moment in tunnel lining is not a straight forward prediction.

Considerable research on movement and stresses for a single and multiple tunnels has been undertaken (Peck, 1964; Sagaseta, 1987; Verruijt and Booker, 1996; Louganathan and Poulos, 1998; Park, 2004; Kim, 1996; Blom *et al*, 1999; Karakus and Fowell, 2005; and Moeller, 2006). However, lack of investigation exists for extreme details conditions of structural response (i.e., flexural bending moment in tunnel lining) especially in longitudinal seam. The soil stiffness, the rigidity of lining, the interaction of soil-lining and response of joint mechanism were included factors that should be taking into account in bending moment investigation to achieve a perfect prediction. Blom *et al*. (1999) and Cavalaro *et al*. (2011) previously both carried out research on circumferential seam behavior. Blom *et al*. (1999) found out that changes in stress distribution occurred in a ring of segment. Circumferential seam of lining were comfortable to analyses and quite easily to understand their behavior but different manner investigation need for longitudinal seam. Both concluded that longitudinal joint is crucial to investigate but complex analysis to fulfill (Blom *et al*., 1999 and Cavalaro *et al*., 2011).

Recently, Teachavorasinskun & Chub-uppakarn (2010) and Arnau and Molins (2011) had carried out research on the longitudinal seam behavior. Teachavorasinskun & Chub-uppakarn (2010) focus on load and displacement in jointed two segmented lining applied with two point load test in laboratory. They validated their partial-scale laboratory lab with FEM and learned that an angular joint stiffness is in range of 1000-3000 kNm/rad could be adopted for joints to be incorporated in the flexural moment calculations. Meanwhile Arnau and Molins (2011) validated in-situ full-scale testing of slender tunnel of new Line 9 (L9) of the metro of Barcelona with FEM simulations. Nonlinear stress occurred in lining. In general, tensile stresses yield at extrados and compression stresses depicted at intrados of lining. Those stresses trend change when there are concentrated load applied at specific position. This agreed with theoretical bending moment behavior in tunnel where tunnel bulge outward and inward to react with surrounding soil affect.

This research is focusing on bending moment of lining as to gain benefit from designing the lining in more cost effective way. In parallel, it is important to determine the safety measurement of bearing capacity of lining to withstand soil surrounding and additional unexpected range of future external loading for lining. Intensive review on previous flexural test on tunnel had been carried out to construct perfect test arrangement for our specimens. Ideas of testing arrangement especially designing the support mechanisms have been developed. In this paper, research works regarding the developed segmented tunnel lining testing were presented. A series of laboratory testing of point load test have been developed to imitate flexural behavior of segmental tunnel lining condition in real. Two types of support system were introduced namely pin-pin and pin-roller condition. Pin-pin used to imitate rigid tunnel meanwhile hinge condition of lining were represented with pin-roller support.

2.0 Development of Model Experiments

Flexural bending test using an appropriate hogging segment taken from nearby factory has been carried out. Laboratory testing of single segmental lining and dual jointed tunnel lining tests were conducted. Testing had been done in 4 different phases with one segment and dual jointed of halves of segment using pin-pin support and pin-roller support to simulate tunnel behavior. In particular, testing was carried out to analyses the complex lining joint behavior in longitudinal joint circumstances and to understand the structure respond with more certainty. Initial simulation of three dimensional of one segment and two jointed segment firstly carried out before proceed the experiment base. Support mechanisms were designated at first place to resemble the real joint behavior in lining. Two support mechanisms are introduce namely; Pin-Pin support (Phase 1 and 3) and followed by Pin-Roller support (Phase 2 and 4). This paper discussed the single segment testing results of Phase 1 and Phase 2 only.

2.1 Test Facility

Figure 1 (a) and (b) present schematic of the test facility for a laboratory test facility of segmented tunnel lining. Reinforced concrete lining specimen with 67.5^o of hogging angle, almost 3.5 meter span, 1.4 meter width, 3.175 meter outside radius and 0.275 meter thickness were prepared. As concrete is not perfectly half of rounded shape, a support system were developed to make sure the edge of segment lies comfortably in the testing area. The support system was designed and fabricated using combination of steel beam support to form triangle beam shape. One of the supports was designed in such way it could move are attached with 1.4 meters long of three steel roller (i.e., roller support). The roller steel applied heavy Gris roller to function as a roller support and fixed with H-beam (Phase 2 test) and bolted anchor to the floor to function as a pin support (Phase 1 test). At another side of support, a triangle steel support were layered with 18mm x 350 x 1500 x 5 pieces plywood and hold by boxes of steel box with 2m anchored steel bolted to the laboratory floor (i.e., pin support). The triangle steel beam also supported laterally with H-beams. This support system was expected to minimize the triangular beam translation during the testing. To attach segment to the triangle steel beam, wall plug of 220mm length and 50mm thread with diameter of 25mm were specially designed to help fixed the segment in position to the hole of triangle steel beam support system.

Testing was carried out with a designed loading system. Axial load, imitating the ground static load was applied vertically to the middle of load system. The load from hydraulic ram system was performed using load controlled system. The servo-hydraulic ram had their own load cell. Another load cell was laid below the load hydraulic load ram to double check the load applied to the segment. Frame system help to distribute loading. Distribution mechanisms of load system consist of load cell, layered of steel, boxes of steel and two pieces of long steel arranged accordingly so the load are distributed symmetrically at both side of segment longitudinally. 200 tan of load cell are attached with computerized system used to verify the applied load from hydraulic ram of Dartec system.

The strain gauges were properly mounted onto test specimen both extrados and intrados of segment. It is important that strain is accurately measured transferred from the test specimen, through the adhesive and the strain gage backing to the foil themselves. Strains data were measured for every load step. LVDTs were mounted at possible higher movement place. Two LVDTs were used to measure the vertical displacement occur in the mid span of segment when applied with load. Translation readings and displacement readings were also being monitored at the support system. One LVDT is placed at roller support side to measure movement of segment. Two more LVDTS, both mounted at pin support side; one placed at opposite direction of triangular steel beam to measure movement if any and another is mounted to the bottom of triangular steel beam(that layered with plywood) to measure any downward movement of the support.

(a) (b)

Figure 1: Test arrangement for segmented lining (a) pin-pin support (b) pin-roller support

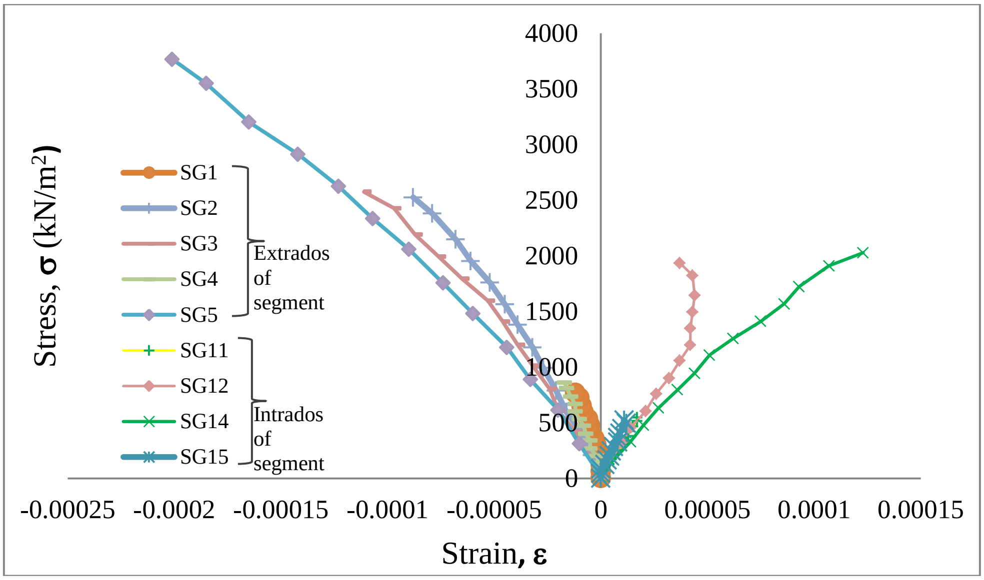
2.2 Experimental Conditions

Test was carried out to imitate behavior of tunnel when applied with point load. In real, a full ring of tunnel has 5 to 8 segmented lining that jointed. Joints allows tunnel either to flexural inward or outward thus allow tunnel to stay in a good service. Therefore, two support systems were chosen namely pin-pin support condition to imitate almost rigid condition and pin-roller support to imitate hinge condition (i.e., moveable segment).

In the first stage, first tunnel segment were laid as pin-roller and applied with load system. This test was carried out with a purpose of producing a damaged segmented lining specimen. Test was carried out in three different of load series, starts with small value (i.e., Test 1), continue with increment of value to double of initial magnitude (Test 2) and continued until segment cracks and finally failed with maximum load magnitude (Test 3). Testing then continued with another segment specimen but with similar properties and tested as pin-pin condition. In this test, a controlled loaded test was carried out, in two series of testing, similar like previous load phases of Test 1 and Test 2. To simulate effect of soil reaction, load has been applied in loop condition to take into account dynamic manner of soil in real conditions. In this load manner, axial force influence was not dominant (only have two points of applied load) thus bending moment will produce and imitate the lining behavior of flexural condition. Due to load manners, bending moment produced in hypotheses will be higher than the real cases. Results of strains at intrados and extrados of segment surface were collected. Displacement data of support and mid span of segmented lining were also measured. Both of the results were analyses in section 3.0.

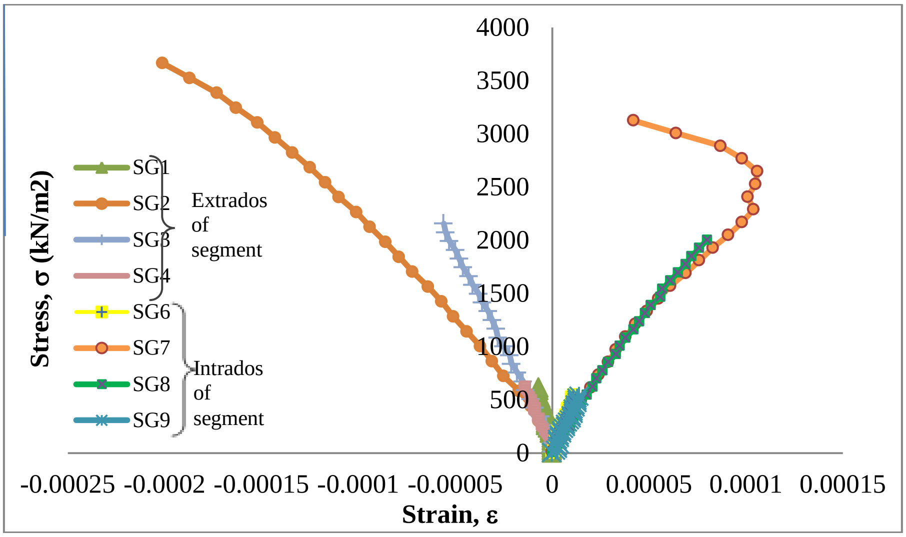
3.0 Experimental Results and Discussion

In this point load testing, the behavior of segment investigated. In general, compression strain was measured at extrados and tensile strain at the intrados of segmented lining. The strain gauge position is described in Table 1. Figure 2(a) and (b) plotted stress-strain curves for both pin-roller and pin-pin testing results of point load loading of 100kN. In figure 2, general trend of stress-strain plotted. However, strain gauge at intrados of quarter pin position, B' (i.e., SG12 for Pin-Roller and SG7 for Pin-Pin test) both show increases of tensile strain but end with different manner (i.e., compression reading). This show that segment starts to have transition behavior at the location. Tunnel bulge out and inward and flexure to bear the load applied.



(a)

Figure 2(a): Stress-strain curve of (a) pin-roller testing

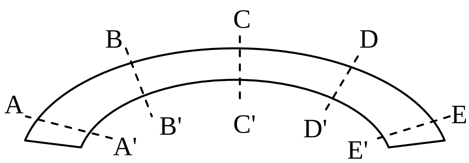


(b)

Figure 2(b): Stress-strain curve of (b) pin-pin testing

Table 1: Strain gauge position on segmented tunnel lining

Strain Gauge (SG)Position		Pin-Roller SG No.	Pin-Pin SG No.
Extrados	Edge of Pin (A)	SG1	SG1
	Quarter of Pin (B)	SG2	SG2
	Quarter of Roller (D)	SG3	SG3
	Edge of Roller (E)	SG4	SG4
Intrados	Edge of Pin (A')	SG11	SG6
	Quarter of Pin (B')	SG12	SG7
	Quarter of Roller (D')	SG14	SG8
	Edge of Roller (E')	SG15	SG9



Segmented tunnel lining

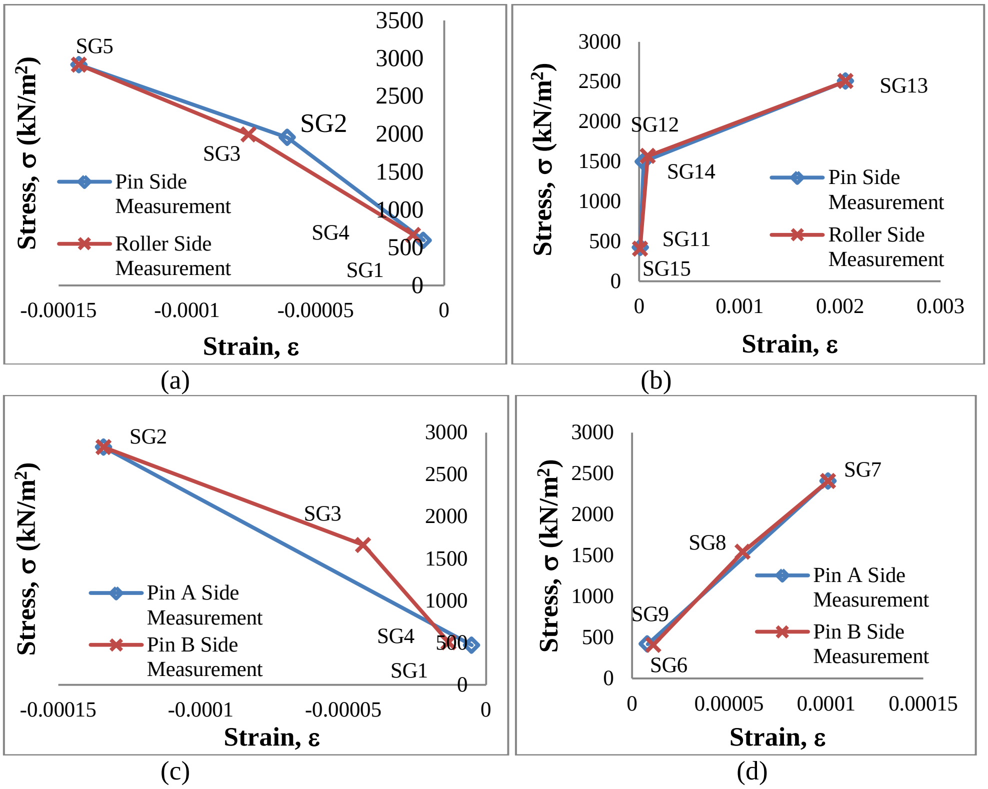


Figure 3: Stress vs. strain for 100 kN load of (i) pin-roller testing: (a) extrados and (b) intrados, and (ii) pin-pin testing: (c) extrados and (d) intrados

Figure 3 shows another result of strain when plotted with angle of segment. Similarly, strain reading at intrados shows tensile strain meanwhile extrados gave compressive strain. Higher compressive strain measured at SG13 due to position of strain gauge that was mounted near to the existing bolt hole in the specimen. This lead to misleading reading and higher value of strain. In pin-roller testing, a triangle steel support of one side was allowed to move to imitate allowable or flexural bending of tunnel. Results shows roller side have slightly higher of strain measured at quarter span of segment at roller side (D) when compare to quarter span of pin side (B). Mid span gave highest strain reading and both edge of segment have lowest strain readings. Edge of roller support did give slightly higher strain. In the mean time, in pin-pin testing, a triangle steel support of one side which previously allowed to move now fixed with bolted floor anchor and H-beam to imitate almost rigid condition of a tunnel. Similarly, a trend of segment behavior was observed. However, results show differently. Pin-pin testing gave stable slightly higher strain reading compare to pin-roller.

Both pin support behavior were mirrored to each other. Figure 3 (c) and (d) shows a set of readings for 100 kN load for extrados and intrados of pin-pin testing measured simultaneously.

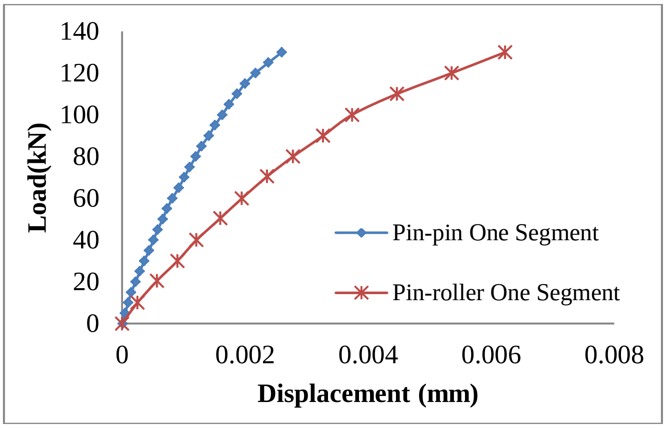


Figure 4: Load vs. displacement at mid span of segment

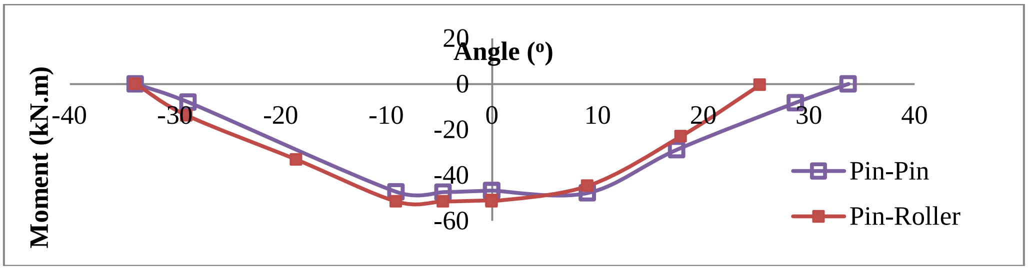


Figure 5: Moment vs. angle for pin-roller and pin-pin

Figure 4 depict the load-displacement measured by LVDT at the midspan of the tested segment. Obviously, pin-roller support lead to higher displacement when compare to pin-pin condition. Pin-Roller support mechanisms gave more room for tunnel to flexural thus lead to higher vertical displacement of mid span of segment and decrease amount of bending moment (Figure 5).

In Figure 5, inward moment were represented by negative moment flexural and vice versa for outward moment. From the figure, we could see the imbalance distribution of flexural moment in pin-roller support condition; higher moment embraced the pin span segment where as reduced moment occurred at roller support side. Whilst, in pin-pin condition, the flexural moment shows mirror phenomena of inward bending moment which generally true for tunnel condition. In addition, both support (i.e., A and B support at -33.75^0 and 33.75^0) show negative readings of moment, indication of an outward bending for lining.

From stress-strain and moment results, a simple investigation of magnitude of Young Modulus has been carried out for linear condition. From pin-roller testing, Young Modulus (E) obtained was ranged from 7 to 20GPa. In pin-pin condition, it is in a range of 10 to 27 GPa. As pin-roller testing show variation in results trend, the Young Modulus at each strain gauge position were obtained and show that the magnitude is critically higher at the edge of pin side. The magnitude decreased dramatically when came to middle position and increased slightly and edge of roller side as segment were tried to hold whole body together. Theoretical calculation of Young Modulus by referring data from factory and equation by American Concrete Institute, the calculated E is 33 GPa. The contribution of the steel reinforcement has been generally neglected with an error of less than 5% on the calculated value. Although the Young Modulus value obtained slightly small compare to calculate one, the overall conclusion is accepted. Young Modulus obtained from laboratory testing starts with small value due to support condition, where non uniform stress distribution occurred. Testing also neglected the fact of significant joint interactions for longitudinal and circumferential seam of lining. The choice of simple manner load system of only two point loading system instead of uniform distribution radius load also lead to this inaccurate results.

In conclusion, despite the lack of lad system application in the testing, pin-roller support condition shows variation trend in stress-strain and moment readings and pin-pin have mirror trend for both result. Young Modulus was high depicted at the edge of segment. Therefore, to optimize the services and cost of design, it could be proposed to have variation of stiffness with high stiffness at the edge and lower at the mid span of segmented tunnel lining.

4.0 Conclusions

The present study showed that segmented tunnel lining could be used as a potential precursor for the preparation of low cost tunnel lining design for optimum usage with satisfactory of factor of safety. A point load test illustrated flexural behavior of tunnel are increased with increases of surrounding load. Deflected diagram show consistent pattern with theoretical prediction. Tunnel are bulging inward and outward to absorb the affect of soil surrounding. This test also shows the basic response of tunnel which allow for amount of deflection instead of carrying maximum bearing capacity. Over the range of applied load studied, the maximum point load could be taken by single segmented lining is 420 kN. Support mechanisms of pin-roller support condition shows variation trend in stress-strain and moment readings and meanwhile for pin-pin it show mirror trend for both result. High stiffness of lining is only important at the edge of segmented lining, thus the design of the lining could be revised. The experimental results revealed that the flexural segmented tunnel lining design could be guidance to design the tunnel effectively in future.

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6.0 Appendix A

In order to obtain Young Modulus, E value, American Concrete Institute (ACI) has draw the equation of:

$$E = 57\,000\ x\ (f_c')^{1/2} \text{ or} \qquad \text{(Eq. 1)}$$

where
f_c' =compressive strength of concrete at 28 days (psi)

From factory, we knew, compressive strength of concrete, f_c is = 42.8 N/mm^2 so that, f_c' = 6990.82 psi

$$E = 57\,000\ x\ (6990.82)^{1/2} = 4765834.05 \text{ psi}$$

converting the value into SI units,

$$E = 32859268 \text{ kN/m}^2 = 33 \text{ GPa.}$$

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