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Precast Concrete Tunnel Segments: A Review on Current Research

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Abstract – T*unnel lining design is an interactive problem, which is not merely about the strength, but on how much the tunnel allows to flexure to overcome the ground movement. When tunnel interacts with soil, stress from the ground is distributed into the structure. In the case of precast segmental bolted tunnel lining, it is critical to investigate the lining joint reaction, as this affects the overall flexural behaviour of the tunnel lining. Understanding the segmental behaviour is important to optimize the design of lining, leading to cost effective production and maintaining the good services during its design life. The objective of this paper is to present a short review on research works conducted in the past pertaining on the joint effect in longitudinal seam in tunnel lining. Review on numerical simulations and laboratory testing were carried out in order to understand the basis of the tunnel lining mechanical behaviour response. A series of flexural bending laboratory testing conducted by the authors was also presented to discuss the mechanics of segmental tunnel lining along the longitudinal joints. In conclusion, results indicate that the measured curvatures and deflections are nonlinearly changed with the increased of applied loads. Different support systems show that appropriate joints could help reduce the maximum moment but an excessive allowable joint movement could lead to high flexural moment which could endanger the global structure stability.*

Keywords: segmental lining, longitudinal seam, finite element, flexural test.

1.0 INTRODUCTION

The design of tunnel lining is not straightforward. It is not an independent structural problem, but a ground-structure interaction problem, with the emphasis on the ground. Therefore, the lining design process should be approached as iterative process in order to gain an appreciation on how the ground and lining are likely to interact.

Linings are assembled in the segmental part connected with bolt, which give effect to the overall structural behaviour. It resists an axial thrust based on the overburden and groundwater pressure at spring line, plus bending stresses resulting from an arbitrary percentage distortion of the diameter of the ring. The design code of the Japanese Society of Civil Engineering empirically recommends in its popular simplified design method that a lining should be designed to carry only 60–80% of the maximum bending moment carried by the main segment [1]. The bending strength and stiffness of the structural linings are small compared with those of the surrounding ground [2].

Large deformation can often be accommodated in the tunnel lining by rotation or shear at the joints between segments inducing high stresses in the linings themselves. When taking in accumulative for both longitudinal and circumferential joint, shield segment damage that occurs around the segment joint more than once within two to three rings is almost 30% from the total occurrences [3]. This percentage is similar to the leading shield damage factor; cracking in axial direction. Cracks reported mainly to occur near bolt holes and hand holes which affect the overall joint performance [4]. This brings a notion that understanding the behaviour of segmental joint tunnel and then carefully design it is important. Therefore, focusing on bending the moment of lining as to gain benefit from designing the lining is a must, in order to obtain more cost effective way and safety of the design.

Considerable research on the movement and stresses for a single and multiple tunnels has been undertaken [2, 5-11]. However, lack of investigation exists for extreme detail conditions of structural response (i.e., flexural bending moment in tunnel lining) and the behaviour of the joint conditions; both in longitudinal and circumferential joints. Research has been carried out via numerical analysis, laboratory, and full-scale test that included the joint tunnel response but not in a specific way [2, 12-16].

Intensive review on the previous flexural test both in numerical simulation and laboratory testing on tunnel are presented in this paper. The aim of this paper is to show future researchers on the direction of future research field available regarding the investigation of performance in joint connections in tunnel lining. Current research works performed by the authors regarding segmented tunnel lining loading tests are also presented. A series of laboratory testing of the point load test have been developed to imitate the flexural behaviour of the segmental tunnel lining condition in real. In addition, numerical simulation of single and jointed segmental tunnel lining of three-dimensional model has been developed and briefly presented here.

2.0 JOINTED TUNNEL LINING MODEL DEVELOPMENT IN FINITE ELEMENT

Review of the tunnel lining model developments in finite element is presented herein. Several model tests and analyses have been carried out to examine the behaviour of the lining joints. Review was also carried out to grasp the idea of the interaction modelling of longitudinal joint tunnel simulation. Table 1 shows the adopted segment modelling technique by earlier researcher.

Blom et al. [2] presented the behaviour of segment connections of the southern high-speed line of "Green Heart" shield driven tunnel investigated via ANSYS finite element software. Simulation indicates that the lining stresses measured in the construction field are not uniformly distributed in radial, axial and tangential directions. In reality, the axial normal forces found tend to have eccentricity and sectional forces, and moments are measured twice higher compared with the conventional models. Contact element at the lining interface was used to simulate the behaviour of connections between segments. Contact element located at the circumferential seam, four contact elements; each for one segment; behaved as the linear spring until sliding occurs. The stiffness of spring took similarly to the stiffness of packer.

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Results showed tangential stresses along the lining did not change much because of the hardening of grout, but the distribution in the lining ring changed. However, the range of how much stress distribution changed in the lining is not mentioned in the exact amount/percentage.

Table 1: Adopted modelling simulation by previous researcher

Researcher & Year	**Blom et al. [3]**	**Teachavorasinskun & Chub-Uppakarn [14]**	**Cavalaro et al. [13]**	**Wang et al. [16]**	**Arnou and Molins [15]**
FE Program	ANSYS	SAP2000	DIANA 9.3	ABAQUS 6.7	DIANA 2005
Tunnel outer diameter (m)	14.5	4 - 8	11	7.1	11.6
Width of lining (m)	NA	1.5	2	1.225	1.8
Thickness of lining (m)	0. 6	0.3	NA	0.445	0.35
Segment model	Solid volume elements	Shell element	8 node brick element	3D nonlinear brick reduce integration element (C3D8R)	Shell element
Joint interaction model	Contact elements: linear spring	Rotational spring with angular joint stiffness	Interface element	Nut of the bolt were embedded in the segments & contact surface	Interface elements

Simplified FEM analyses using shell element for lining segment and spring to model the joint connections have been carried out by Teachavorasinskun and Chub-uppakarn [14]. Results were compared with a true scale model test. Based on the model test, the accepted practical angular joint stiffness is in the range of 1000-3000 kNm/rad. From their numerical work, it was found that the jointed lining produced smaller magnitude of the maximum bending moment than the non-jointed one. A parameter called the moment reduction factor expressed by a function of angular joint stiffness and number of segment was introduced.

The effects of the influence of packing material configurations, their thickness and stiffness and width and thickness of concrete segments to the critical contact deficiencies in tunnel using DIANA 9.3 were also investigated by Cavalaro et al. [13]. Contact elements were also used to model the joint connections. The initial work was verified with the analytical developed equations. Results concluded that the packing stiffness, width and thickness of the segment do influence the critical contact deficiency.

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Arnou and Molins [15] carried out numerical modelling simulated an in situ testing of the slender tunnel of new Line 9 (L9) of the metro of Barcelona that has been developed to investigate the performance of rings placement. Three hydraulic flat jacks were embedded at the extrados of the loaded ring. Longitudinal joint were simulated as the shell interface elements. From the simulation, the nonlinear tensile stress behaviour of joint was depicted at the extrados side of the segment joint and the concentration of compression stresses occurred in intrados side. The concentrated rotation occurs in longitudinal joints. These resembled the behaviour of joint in full-scale test [17].

From these reviews, in short, previous researchers concluded that longitudinal joint is crucial to be investigated but the analysis is complex to be fulfilled [3, 13]. A joint stiffness was introduced in the previous studies. Angular joint stiffness was reported in the range of 1000-3000 kNm/rad. However, previous numerical modelling was accomplished with a simple manner of joint element modelling. Only “fixed-fixed” conditions were considered. Whereas, the segment connection in partially fix or hinge was still not fully understood. In conclusion, abundant useful information was obtained from previous researcher; unfortunately the mechanics of the segmental joint stiffness was not explored in great detail and not verified certainly. Therefore, a study of the lining joint in longitudinal is crucial.

3.0 SEGMENTAL TUNNEL LINING MODEL DEVELOPMENT IN LABORATORY TESTING

Short review of tunnel lining laboratory and full-scale testing are carried out to understand the behaviour and respond of the segment lining especially the joint interactions when applied with load.

A development of a prestressed and precast concrete segmental lining (P&PCSL) for shield tunnel was presented by Nishikawa [18]. In order to conform to its basic performance and build ability, a bending testing was performed on the P&PCSL. The load applied, horizontal and vertical displacements, tensile force, surface strain of concrete, and joint gaps were measured. However, as the authors were discussing the capability of the new type of lining; i.e., prestressed and precast concrete segmental lining (P&PCSL), there are still uncertainty in the behaviour of jointed precast concrete tunnel lining.

A full-scale test was carried out using dual segment attached with curved bolts by Teachavorasinskun & Chub-uppakarn [14]. The ring of the lining is four meters for the outer diameter. Each segment has four numbers of socket for the curved bolts at longitudinal joint (i.e., two for each side) and four numbers of similar socket for circumferential joint (four of each side). Samples were taken from a water supply network tunnel in Bangkok with M22 curved bolts of grade 6.8 (f_y=480 Mpa). A load-displacement curve with angular joint stiffness, k_w, and variation results of maximum bending moment with number and orientation of joints were plotted. They validated their laboratory result with FEM and learned that an angular joint stiffness for joints is to be incorporated in the reduced flexural moment calculations. The authors presented the segment flexural behaviour but with fixed-fixed support system which lack in representing real joint behaviour in tunnel lining.

An experimental research on the possibility of using fibre reinforced concrete (FRC) precast tunnel segments instead of traditional reinforced concrete (RC) via full-scale test in bending test and point load test was carried out [19]. The behaviour of the segments under the flexural

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actions, point load – simulate the thrust force induced by TBM, and effect of load concentration and splitting phenomena were carried out. Results show that fibre reinforced concrete can substitute the traditional reinforcement and improved in terms of controlling the cracking opening. Flexural test presented by Caratelli et al. [19] indicated that FRC has a higher bearing capacity (yield force of 140 kN, with lower crack opening). Point load test gave assurance that both types of the tunnel lining are able to carry the design load for maximum bearing capacity system; a 4000 kN load. Although reviewing this paper helps out on the discussion of the model support development, there is lack discussion on the jointed segment matters. The discussion focused on the splitting phenomena in a single segment testing only.

From this short overview, we could conclude that the influence of the segmental joint stiffness was not explored in detail. Whereas, in laboratory testing, flexural bending test was carried out, but not with the precast RC segments and at the same time, jointed connections especially in the longitudinal joint were not counted. Teachavorasinskun and Chubuppakarn [14] presented a study of the segment flexural behaviour but only with fixed-fixed support system. Meanwhile, Caratelli et al. [13] have limited the discussion on the splitting phenomena instead of bending moment tunnel response. Therefore, in the laboratory testing perspective, there is still lacking information of longitudinal and circumferential joint effect on the segmental tunnel lining, thus, the investigation of such testing is highly desirable.

Ideas of two different support mechanisms have been developed in order to imitate the rigid and hinge jointed segment tunnel. A flexural testing using hogging segment condition and segments with curved bolt joint were developed. The details of laboratory testing are discussed later in 4.2.

4.0 RESEARCH WORK

This research involves two major parts of work; one is laboratory testing and another is simulation using Finite Element Method (FEM).

The research flow in Numerical Modelling involved simulating one single segment in three-dimension (3D) and followed by two jointed 3D segments. The results shall be used to compare data obtained from the laboratory experiments.

In particular, testing was carried out to analyse the complex lining joint behaviour in the longitudinal direction and to understand the structure response with more certainty. Support mechanisms were designated at the first place to resemble the real joint behaviour in lining. Two support mechanisms are introduced namely; Pin-Pin support (Phase 1 and 3) and followed by Pin-Roller support (Phase 2 and 4). For laboratory testing, this paper discussed the single intact segment testing results of Phase 1 and Phase 2 only.

After laboratory testing, numerical simulation will be continued to calibrate the laboratory testing and extend the simulation with the extended parametric studies. However, this scope of research will only be reported in the future publication.

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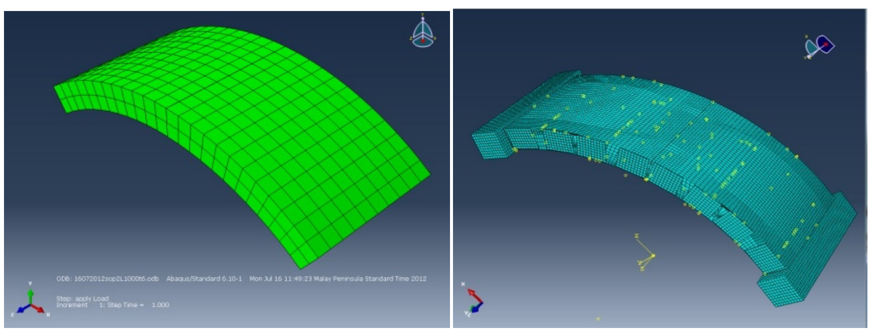
4.1 INITIAL MODEL DEVELOPMENT OF JOINTED SEGMENT TUNNEL INTERACTIONS IN ABAQUS

In the first place, numerical modelling of continuum model via ABAQUS 6.10 has been carried out. This initial numerical simulation helps to get an idea of the range of loading and support mechanism to be developed in the laboratory testing.

Figure 1 shows the model of single and dual jointed segments with 48850 numbers of elements. A pair of pedestals was introduced at two ends to simulate the complicated boundary condition of longitudinal seam. In the case of dual segments jointed by curved bolts, the curved bolt modelling is assigned with tie constraint interaction.

From this modelling, load-displacement curve of jointed lining tunnel was plotted. Results presented in Figure 2 shows the difference in magnitude between the single segment and dual jointed segment for the deflection of segments measured at the centreline. It is concluded that the existent of jointed region shall lead to higher movement. Laboratory testing was then proceeded with the idea of appropriate load range to be applied and support mechanisms to be developed.



(a) **(b)**

Figure 1: Segment lining in mesh (a) Single segment (b) Dual jointed segment with pairs of pedestal

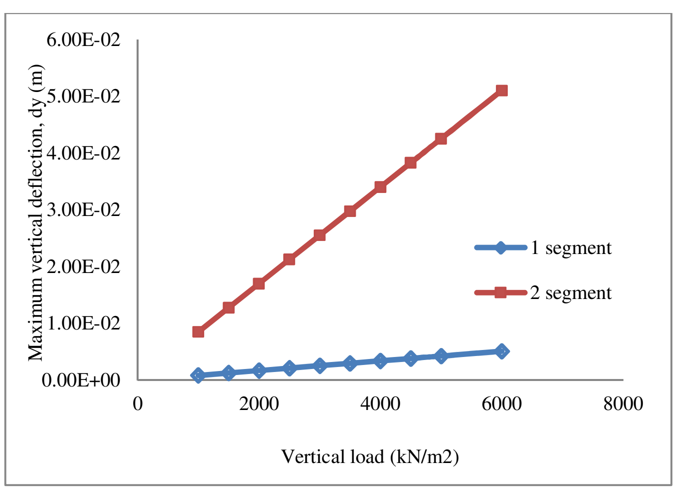


Figure 2: Load - deflection curves of one segment and dual jointed segment

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4.2 LABORATORY TESTING WORK

Flexural bending test using appropriate hogging segments taken from the nearby factory has been carried out. Reinforced concrete lining specimen with 67.5^{o} of hogging angle, almost 3.5 m span, 1.4 m width, 3.175 m outside radius and 0.275 m thickness was prepared.

As concrete is not a perfectly half rounded shape, a support system was developed to make sure the edge of the segment lies comfortably in the testing area. The support system was fabricated using the combination of simply supported steel beam to form triangular shape (Figure 3). In the first experiment (Phase 1), one of the supports, i.e. 1.4 meters long of three steel rollers (i.e., roller support on the right) was designed in such way that it could slide horizontally while the other end (on the left) is bolted to the floor to function as a pin support. The roller steel was applied with grease roller to function as a roller support. At the left support is a steel box with 2 m anchored steel bolted to the floor. The triangle steel beam is also supported laterally by H-beams to minimize the triangular beam translation during the testing. To attach the segment to the triangle steel beam, the specially designed wall plug of 220 mm length and 50 mm thread with a diameter of 25 mm was used to help fixed the segment in position and to the hole of triangle steel beam support system.

Testing was carried out using a Dartec hydraulic ram with a load-controlled system. A two-point vertical load (using a frame extension redistribute as strip loading), imitating the localised ground static load was applied to the middle of the segment. A 200 tonne of load cell are attached with a computerized system used to verify the applied load from the hydraulic ram of system. The strain gauges were properly mounted onto test specimen both extrados and intrados of segment. At the same time, LVDTs were mounted at locations with higher anticipated movement. Translation readings at the support system were also being monitored.

Tests were performed initially within the elastic region. In reality, a full ring of tunnel would consist of 5 to 8 segments jointed together. The joints allow the tunnel either to flex inward or outward, thus allowing the tunnel to stay in a good service. In the first stage, the first tunnel segment was laid as Pin-Roller and applied with load system (i.e., later known as non-jointed pin-roller test, NJPR) shown in Figure 3. In the pin-roller testing, a triangle steel support of one side was allowed to move to imitate hinge joint interaction. Three different load series, beginning within the "elastic" loading (i.e., Test 1), continued with double the amount of initial loading stage (Test 2) and finally loading to failure (Test 3).

In Phase 2, a non-jointed pin-pin test (NJPP) was performed (Figure 4). For NJPP test, a triangle steel support of one side (which previously allowed moving) was then fixed with bolted floor anchor and H-beam. This was carried out to imitate the almost rigid ground condition surrounding the tunnel. Similarly, the incremental loading has been applied up to 130 kN (Test 1) (i.e., "elastic" loading) and 300 kN (Test 2) and the performance of segment was investigated. Strains at intrados and extrados of segment surface were measured. Both of the results are analysed in the next section.

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Figure 3: Test arrangement of pin-pin support for single segment

Figure 4: Test arrangement of pin-roller support for single segment

5.0 RESULTS AND DISCUSSION

In general, the loading caused compression strain at the extrados of segmented lining and tensile strain at the intrados. Load versus the segment deflection for both pin-roller and pin-pin support condition was plotted in Figure 5. As expected, the deflection measured at the mid-span of segments showed pin-roller segment leads to more deflection compared to pin-pin support condition.

Using the data inferred from the strain gauges, the flexural moment versus the segment span of selected load range was plotted in Figure 6. An inward moment is represented by a negative flexural moment. Symmetrical curve of the outward bending moment is depicted for pin-pin support system which is generally true for rigid tunnel condition. Whilst, for the pin-roller support system, higher moment embraced at the mid span segment was followed with an imbalance distribution of flexural moment occurred; lower moment occurred at pin side and higher moment measured at the quarter roller support side followed with sudden drop of moment magnitude. In the pin-roller, which purposely carried out to imitate the jointed hinge longitudinal condition, the moment of structure shows higher in magnitude when came to the middle position and decreased dramatically at the edge of the roller side as the segment tried to response to the interactions that occur. In conclusion, the pin-roller support mechanisms (i.e., hinge jointed segment's connection) gave excessive response for the tunnel to flex thus leading to the higher mid span deflection compared to pin-pin support.

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Figure 7 and Figure 8 are the comparisons of results of the bending moment diagram calculated using FEM and laboratory data of non-jointed single segment with pin-pin support (NJPP) and non-jointed single segment with pin-roller support (NJPR) for load of 100 kN, respectively. FEM showed continuous plotted moment diagram for the segment in the whole segment span which gave more accurate moment reaction when compared to laboratory results (i.e., only few points measured). The pin-pin segment reaction shows mirror pattern to the middle of segment. In contrary, the pin-roller segment reaction shows a different flexural movement in the segment at roller side. The moment was initially lower (i.e. bending inward) then increased gradually to the midst of segment and reached its peak followed by the decreasing moment magnitude and reached zero towards the roller support. It is also found that the triangle support model of the segments in laboratory gave effect to the overall results. Therefore, the appropriate model of support and material property model have been carefully adopted in FEM to represent the real laboratory settings condition.

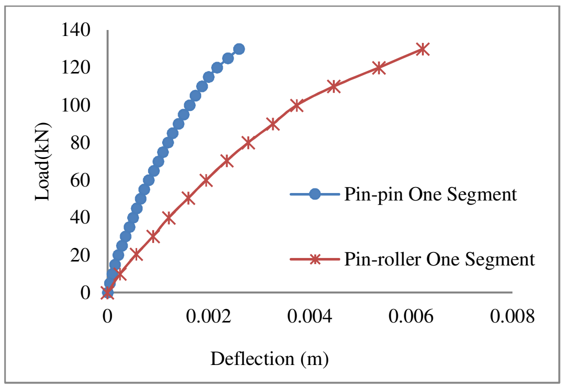

Figure 5: Load vs. deflection at mid span of segment

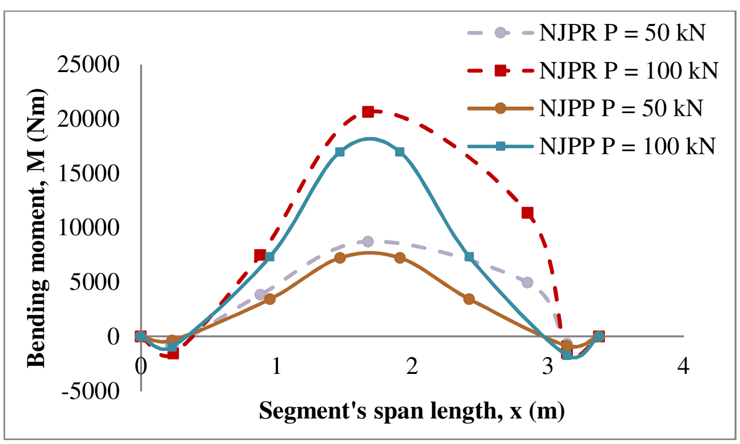

Figure 6: Bending moment for non-jointed pin-roller test (NJPR) and non-jointed pin-pin test (NJPP) of single segment

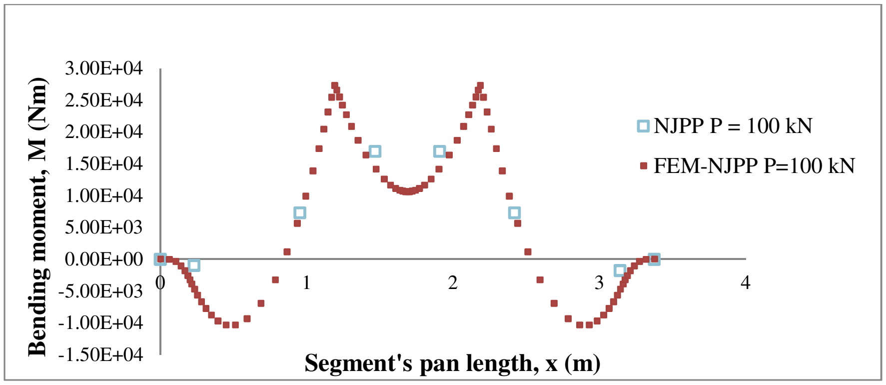

Figure 7: Bending moment for pin-pin support condition (NJPP) with numerical modelling result (FEM-NJPP) of single segment

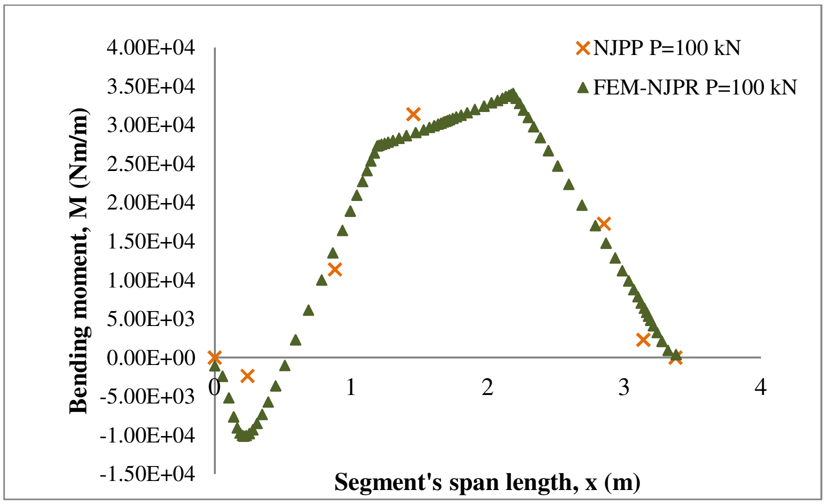

Figure 8: Bending moment for pin-roller support condition (NJPR) with numerical modelling result (FEM-NJPR) of single segment

6.0 CONCLUSSION

A review on the previous experimental and numerical studies on the segmental concrete tunnel lining was presented. The initial 3D simulation modelling by the authors was presented in this paper. A series of laboratory testing of the segmented tunnel lining had been carried out to conduct a flexural test. The load was applied on an arch configuration of the tunnel lining to record the movements of the segment in elastic-plastic range and to understand the flexural moment deflection response in the tunnel segments. In conclusion, results show compression strain measured at the extrados and tensile strain measured at the intrados of the segmented lining. The measured curvatures and deflections are nonlinearly changed with the increased of applied loads. From the strain measurements, tangential bending moments were calculated. A mirror curve of the tangential bending moment is shown in the pin-pin support system while in pin-roller support, the lining reacts in contrary. An unsymmetrically response of the flexural bending moment has occurred in the pin-roller with the highest bending moment is measured at the near mid span of the lining to the side of

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the roller support. These indicate that lining with appropriate joints (i.e., pin-pin) could help reduce the maximum moment but excessive allowable joint movement (i.e., pin-roller) could lead to higher moment which could endanger the structure stability. In addition, this research aims to understand the appropriate characteristics of the tunnel response especially related to ground load surrounding effects which are essential for long-term safety measurements. Further study is on-going to take into account of the joint interactions for both longitudinal and circumferential seam of lining.

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