U.S. Department of Transportation
Federal Highway Administration

PRECAST CONCRETE SEGMENTAL LINERS FOR LARGE DIAMETER ROAD TUNNELS

Workshop Report

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Increased roadway traffic demands have led to a notable increase of large diameter tunnel boring machine-driven tunnels across the world. The technological advancements of tunnel boring machines have made them a viable technical option for tunneling in difficult conditions in urban environments at ever increasing diameters. Such tunnels utilize precast concrete segmental linings. Although precast concrete segments have been widely used and designed in the US, the significant increase in diameter brings about new challenges in design and construction. This document is part of an FHWA research initiative focused on the design of large diameter precast concrete segmental linings. This document provides a summary of the industry workshop held on January 17, 2020. The workshop was held to garner industry input on proposed computer modeling and laboratory testing research plans suggested to close knowledge gaps described in the literature survey and synthesis under a separate cover.</td></tr>
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ACRONYMS

ABBREVIATION	DETAIL
2D	Two Dimensional
3D	Three Dimensional
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AFTES	French Tunneling and Underground Space Association
ASTM	ASTM International
BSI	British Standards Institute
BTS	British Tunneling Society
EN	European Commission Joint Research Center
EPB	Earth Pressure Balanced
FD	Finite Difference
FEA	Finite Element Analysis
FEM	Finite Element Method
FHWA	Federal Highway Administration
FRC	Fiber Reinforced Concrete
JSCE	Japan Society of Civil Engineers
LRFD	Load and Resistance Factor Design
NZTA	New Zealand Transport Agency
SFRC	Steel Fiber Reinforced Concrete
SPB	Slurry Pressure Balance
US	United States

FORWARD

The Federal Highway Administration (FHWA) sponsors research about the use of large diameter precast concrete segmental tunnel linings in highway tunnels. The basic technology of conventionally reinforced precast concrete segments is relatively mature for smaller diameter tunnels. It has been in use in the United States for nearly 40 years (and even longer in other parts of the world). However, recent advances in the use of steel fibers for concrete reinforcement, joint hardware and details, gasket technology, high-strength concrete mixes, and material durability warrant study to provide uniformity of application, identification of practices and details for use in large-diameter tunnels. The work of this research includes a literature survey to identify gaps in the current body of knowledge ("knowledge gaps"), computer modeling and laboratory research, and engagement of industry stakeholders through a workshop that will be used to solicit input on the research plans. The work herein will also build on prior research work performed on design approaches for Tunnel Boring Machine (TBM) excavated tunnels.

The objective of this research is to provide technical expertise to advance the current state of practice for the analysis, design, detailing, fabrication, installation, inspection, and maintenance of precast concrete segmental tunnel linings for large diameter highway TBM-tunnels in the US. The research includes several elements:

- conducting a literature survey and development of a literature synthesis of the current state of the practice;
- development of computer modeling and laboratory testing workplans;
- hosting an industry workshop to solicit input from technical organizations, designers, contractors and researchers regarding the workplans;
- executing research workplans and presenting research results in reports that summarize the finding of the research;
- development of document presenting suggested practices for design of large diameter precast concrete segmental tunnel linings.

This document is the industry workshop report. The workshop was held on January 17, 2020 in Washington, DC. Section 2 of this document provides a summary of workshop attendees and logistics, Section 3 provides workshop notes, and Section 3.3 summarizes the actions arising in terms of adjustments to the proposed workplans and the proposed next steps for research.

The FHWA is the source of all figures and photographs within this document unless noted otherwise.

UNIT CONVERSIONS

SI	US
1 m	3.28 ft
1 mm	0.039 in
1 m^3	35.32 ft^3
1 N	0.2248 lb
1 kN-m	737.56 lb-ft
1 W	0.00134 hp
1 tonne	2,204.62 lb
1 Pa	0.000145 psi
°C	9/5(°C)+ 32 °F

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1 INTRODUCTION

The Federal Highway Administration (FHWA) is currently researching the design of precast concrete segmental linings for use in large diameter highway tunnels. The objective of this project is to identify and address knowledge gaps in the design process and to then develop a set of suggested practices for the design of the precast concrete segmental linings. The technical approach to this research project is divided into the following five distinct tasks:

1. Literature survey and synthesis (FHWA Report HIF-20-035)
2. Workplans and workshops
   - Computer modeling workplan
   - Laboratory testing workplan
   - Industry workshop and report
3. Computer modeling research
4. Laboratory and full-scale testing
5. Research report and suggested practices

This document is the industry workshop report. Relevant to the basic goal of this research, the following key areas were suggested in the literature survey and synthesis (FHWA-HIF-20-035) for further investigation as part of the computer modeling and laboratory testing. Summaries of these items were presented at the workshop.

1.1 Computer Modeling Workplan

1.1.1 Muir Wood/Curtis Solution

This solution suggests empirical equations to account for the effect of joints in the stiffness of the tunnel lining ring. As tunnel diameters have increased, so has the thickness of the tunnel linings. The intent of this research is to determine if modifications to the empirical equations is warranted due to larger contact area between segments and the stiffening effect due to the thrust in the tunnel linings.

1.1.2 Bedded Beam Method of Analysis

The single and double-ring bedded beam analysis are used in the tunnel design industry due to their effectiveness and despite their limitations. See Figures 1-1 and 1-2.

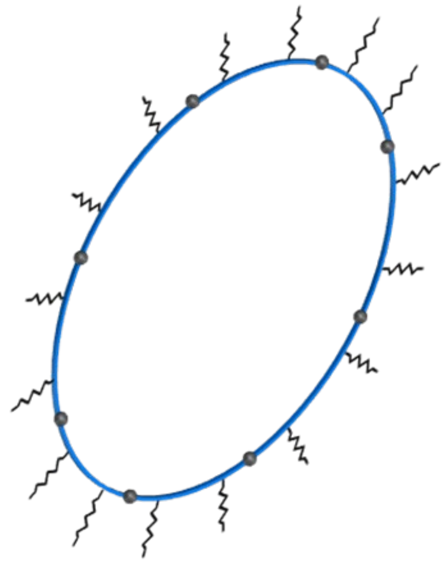


Figure 1-1: Single ring bedded beam model.

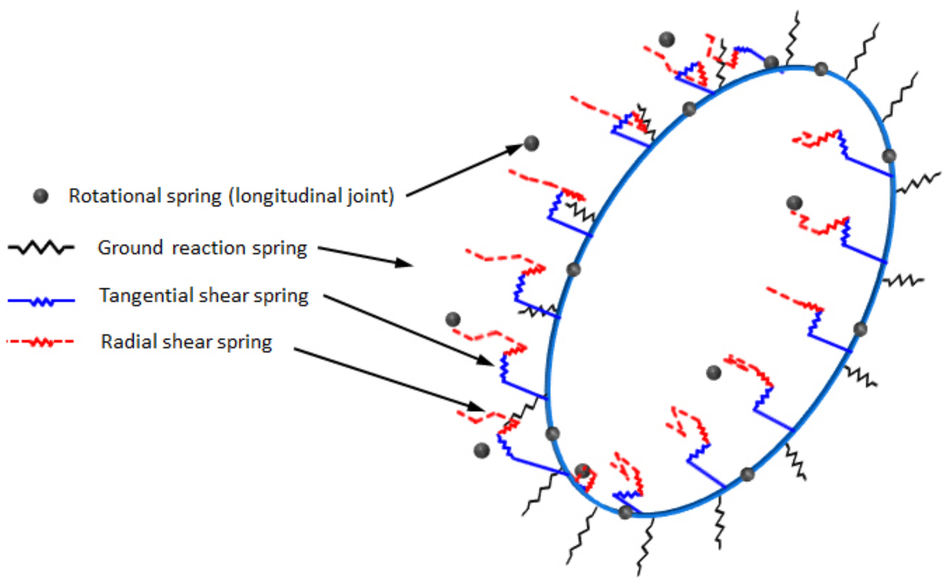


Figure 1-2: Double ring bedded beam model.

The double ring model is suggested in many publications as it takes the stiffening effect of staggered rings into account. However, the input assumptions with respect to the ring to ring coupling influence the results.

Given that the bedded beam analysis is, compared to other methods, not a work intensive, computational task, this suggested series of parametric studies is an effective way of highlighting possible trends in the calculated load effects and structural behavior. The results of these parametric studies could serve designers as a reference to quickly obtain a better estimate of expected member load effect changes when different segmental lining configurations are examined at preliminary design levels or the effect of changing ground conditions are being assessed. The double ring bedded beam method in comparison with the single ring bedded beam method is more work intensive. However, it is not known if the double ring method provides significantly different and/or more realistic results to justify the additional effort. The purpose of this study is to compare the single ring, model to the double-ring model by comparing the results of a single ring versus a double ring bedded beam analysis for the following parameters in a parametric study:

- Ground pressure range corresponding to shallow and deep alignments and low to high horizontal earth pressure ratio
- Tunnel diameter
- Segmentation.

Results are proposed to be compared between two models having the same segmentation, segment dimensions, spring constants, and external loading,. Using a range of ground pressures, diameters and segmentation, differences in predicted loading magnitudes would be quantified and trends would be identified. For all scenarios analyzed, the Muir Wood/Curtis or Hartmann solution is proposed to be used in parallel with the same parameters. The results of the Muir Wood/Curtis or Hartmann solution would be compared to those of the bedded beam study.

1.1.3 Sensitivity Assessment of Bedded Beam Method to Soil Profile

The springs in bedded beam model are typically oriented radially toward the center of the ring. In addition, tangential springs may be added to the model as well. Non-homogeneous or stratified soil profiles (see Figure 1-3) with different soil stiffnesses through the profile influence the reaction of the model, but it is not known how sensitive bedded ring models are to non-homogeneous ground profiles. The purpose of this study is to quantify and identify trends of bedded beam models in non-homogeneous ground. Given that the bedded beam analysis is, a relatively low work intensive computational task, this series of parametric studies could be an effective way of highlighting possible trends in the predicted load effects depending on the general soil profile.

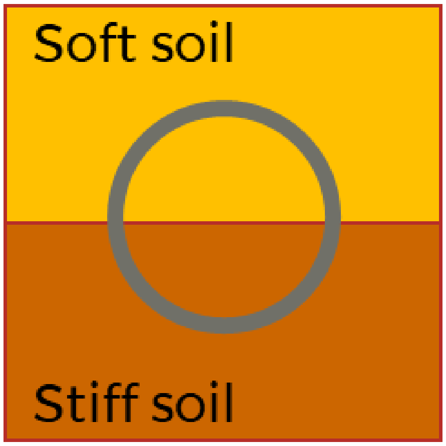


Figure 1-3: Varying Soil Profile.

This parametric study is proposed to be performed using a series of subsurface profiles to investigate the influence of stratigraphy and the resulting load effects in the tunnel lining. Models for four ground profiles are proposed to be investigated. For simplicity, spring constants are proposed to be developed based on typical ground parameters of two types of soft ground and one medium-hard rock.

1.1.4 Joint Behavior Modeling

Incorporation of a reasonable joint model in a 3D segmental tunnel lining numerical model is a key step in the process – for both shell element based and 3D continuum-based analyses. Designers frequently opt to use actual thickness 3D continuum elements to represent the lining segments in an analysis as this assumption respects the true geometry of the problem and the excavation boundary but also allows for inclusion of temporary effects, such as thrust loads, under the same 3D computer model. This assumption also allows for possible inclusion of a specialized constitutive model for the concrete itself which is typically unavailable in shell analysis software. The availability of computationally efficient numerical codes makes this an attractive alternative for lining modeling. Despite the computational efficiency of modern codes, the lack of adequate published research on the assumptions relative to the radial and circumferential joints complicates the setup of such a 3D model. A type of special contact interface should be used in between the segments and in between the rings to represent full coupling within the lining. Based on the literature survey, even the most advanced numerical models typically assume flat joints and a contact interface to couple the segments.

Laboratory testing of joints can provide validation for rotational model mechanisms to be used in shell analysis, as well as provide valuable input toward the development of input data for contact interfaces to be used in continuum-based liner models. As part of this workplan, an inverse type of analysis is proposed to derive contact interface input values based on the radial joint testing results. The intent of this research phase is to develop a suggested practice for modeling segment coupling in the case of continuum analysis and better consistency with rotational models being used for bedded beam or 3D shell analyses. For this work, the geometry, boundary conditions and loadings are assumed in the laboratory testing phase. They are proposed to be used as input for a two-segment numerical analysis model, which should include a contact interface representing a simplified flat joint. It is noted that although actual segments have detailed geometric features such as segment groves, bearing area steps, guide rods, etc. a simplified planar joint is typically assumed in tunnel lining models as such features are too fine to incorporate adequately.

Therefore, a planar contact interface is proposed for investigation. A planar contact interface is typically represented by a series of axial and shear coupling spring elements. In addition to the stiffness behavior, normal springs typically have compression and tensile strength limits, while shear springs are characterized by a shear strength in one or two planar directions. For the baseline case, a simple linear elastic material should be assumed for the concrete segments. Testing of the effects of SFRC and different mix designs in the joint model itself, is proposed to be performed in conjunction with the research on the concrete constitutive model. A simplified schematic is shown in Figure 1-4. This series of numerical analyses should be closely coordinated with the laboratory testing research for consistency in procedures, assumptions, loading, and geometry.

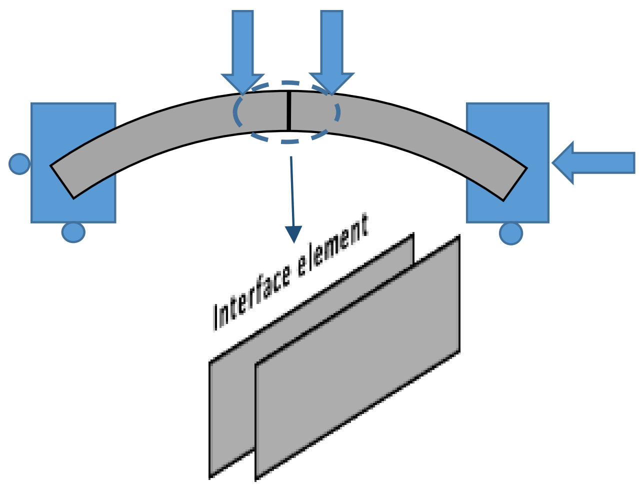


Figure 1-4: Conceptual continuum modeling layout for the investigation of radial joints.

The parameters suggested to be researched for radial joints include:

- Axial force and applied moment
- Segment thickness
- Segment radius
- Joint skew angle
- Radial and longitudinal tolerance
- Concrete material type and composition

- Effects of bolting

For ring to ring interfaces a series of numerical models in coordination with the associated laboratory testing program is proposed to be performed. A simplified schematic of a four-segment staggered joint model is shown in Figure 1-5. Due to the complexity of this geometry and the multitude of possible configurations between rings, depending on the rotation of one ring relative to another, only one simplified layout is proposed at an initial stage: two half-width end segments are coupled to two half-length segments in between them. The model should be subject to the same loading and boundary conditions as applied in the laboratory testing. The performance of the circumferential joint contact interfaces is proposed for observation with properties adjusted to match the observed displacements and rotations of the actual test. The analysis should be correlated with the following parameters:

- Longitudinal force, axial force and applied moment
- Segment thickness
- Effect of alignment dowels or bicones

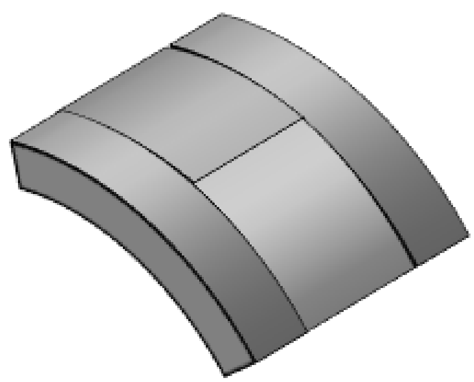


Figure 1-5: Conceptual continuum modeling layout for the investigation of circumferential joints.

1.1.5 Segment Bursting Stress

Segment damage during construction by TBM jacks exerting large thrust forces are one of the major causes of damage to lining segments (spalling and cracking) (Figure 1-6). This load case only happens once during the lifetime of the project, but the damage can be severe. Proper design supported by modeling can reduce this type of damage. A parametric numerical analysis study could be performed to explore the TBM thrust effect on a single-segment. With the use of larger diameter shields, there is a trend for continuously increasing thrust loads being imposed to segmental linings of reduced aspect ratio. The suggested numerical analysis builds upon a concept presented by Behnen et al. (2016). In this concept, each segment is proposed to be modeled as a 3D solid continuum model (finite element or finite difference based). In the model, the segment is positioned so that it rests along one of its circumferential edges.

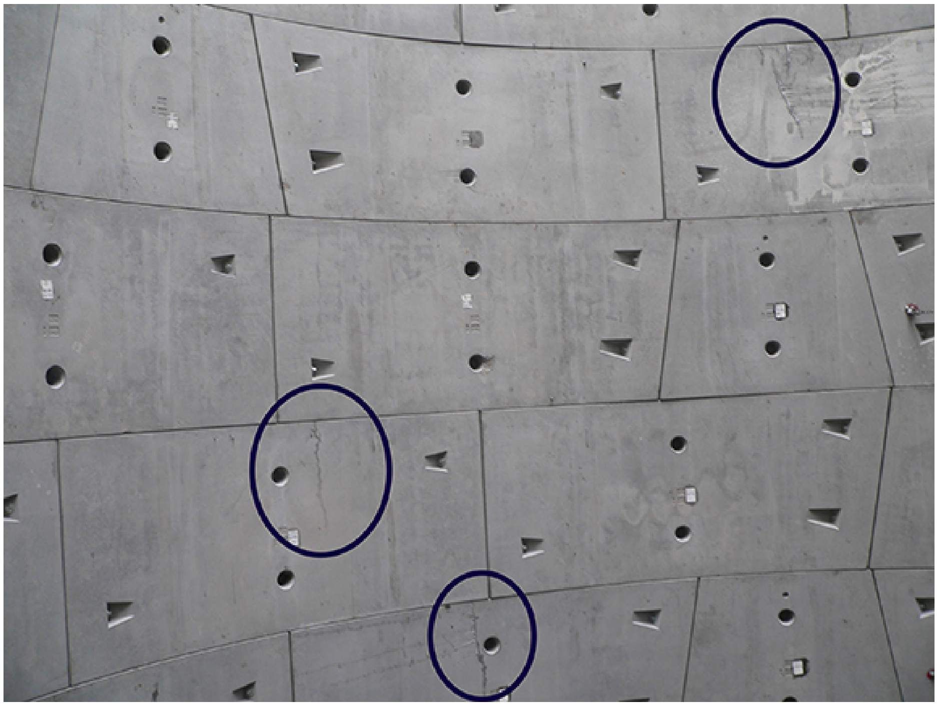


Figure 1-6: Observed segment cracking in precast segmental lining.

TBM thrust shoe configurations consisting of one, two and three shoes would be applied as parameter in the computational study as shown in the schematic Figure 1-7. Pressure loads should correspond to typical load ranges of twin and triple cylinder Earth Pressure Balance (EPB) and Slurry Pressure Balance (SPB) TBM's and correlated to the theoretical side bearing capacity of each segment. A range of four to five different values of load could be applied. The analysis should consider varying segment thickness with three typical values based on the international cases of large diameter tunnel projects identified in the Literature Survey and Synthesis FHWA-HIF-20-035. Initially, two different radii of tunnel segments could be explored. If the results demonstrate appreciable differences an additional radius would be analyzed. The following parameters should be varied:

- Number of thrust pads
- Thrust load magnitude
- Segment thickness

  Segment radius

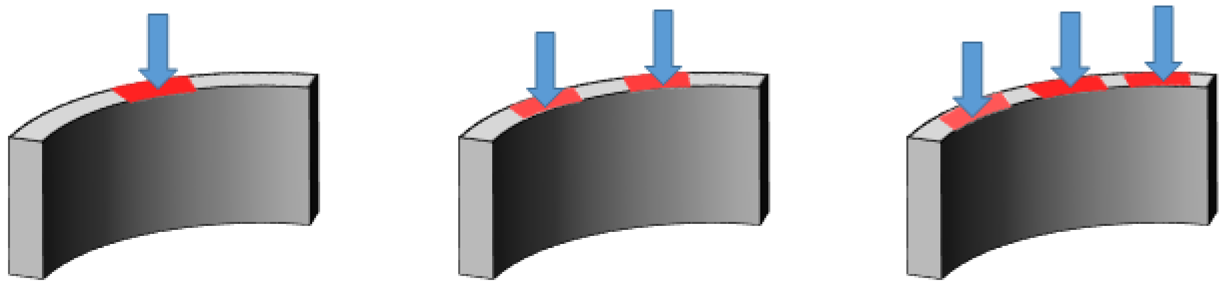


Figure 1-7: Conceptual layout for single segment bursting stress FE analysis.

All analyses would be performed assuming, as a baseline, a linear elastic model for the concrete with properties based on a typical 28-day strength used for large-diameter tunnels (typically 7 to 10 ksi). Although the actual segment response at high stresses may differ between different segment reinforcement designs (conventional, FRC and hybrid) it is proposed that a simple elastic model be used so as not to increase the number of unknowns allowing faster execution speeds for multiple loading scenarios.

The results of the parametric analysis would be summarized in a matrix of segment dimensions, TBM thrust shoe configurations and thrust values versus splitting tensile stresses. It is envisioned that this parametric study and the resulting matrix, would provide preliminary information to designers for identifying TBM thrust limits for segments.

For the basic parametric study, the thrust load should be assumed to be applied perpendicular to the edge of the segment. This condition, however, is not always the case during construction. Slight misalignments of the thrust shoe orientation, and eccentric loading – either inward or outward, can occur. Typically, the shoe of the thrust cylinder is connected with a spring-assisted hinge connection so that the shoe can self-adjust each time it is being pressed against the segment edge. Eccentric loading can occur while the TBM is operating in curved portions of the tunnel alignment, or it may happen randomly due to pivoting of a ring around its contact with the previous ring. A parametric study would be performed based on the single shoe models described above, assuming varying eccentricity at both inward and outward directions and the segment stresses calculated (Figure 1-8).

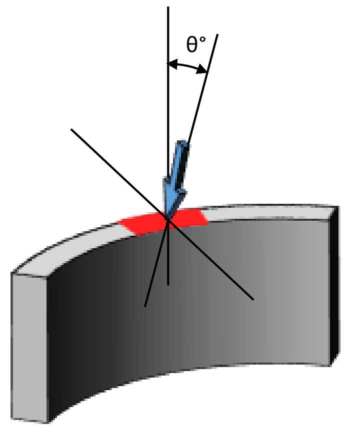


Figure 1-8: Conceptual model for thrust loading eccentricity.

1.1.6 Effect of Installation Tolerance

Radial Tolerance

Out of tolerance ring-build can result in damage and conditions where a segment should be replaced or the damage repaired after the segment has been installed and is part of a complete ring. A worse scenario appears if a following ring(s) has/have been installed and the damage manifests later in the tunnel drive. International publications provide suggestions for ring build tolerances but it is ultimately up to the designer (or Design-Builder) to specify segment production tolerances and ring-build tolerances. When each finished ring is being acted upon by the TBM shield during advance, this is the time of highest probability of segment cracking. Cracks can develop somewhere within the last ring or even in the closest previously installed rings behind the leading ring. The trend in the modern large diameter tunneling industry is to be proactive and limit the ring-build tolerances as much as possible using alignment hardware such as cones and dowels. Electronic monitoring systems are also available in modern TBM shields that carefully monitor the extension of thrust cylinders to determine ring edge planarity. Despite such efforts and developments, segment cracking or damage is not completely avoidable in large-diameter tunnels.

The design can provide larger allowable tolerances, but this results in more expensive designs for the segments due to higher moment force effects and for the gaskets since wider gaskets are used with larger tolerances. FRC is especially sensitive to out of tolerance installations. The tolerance adds eccentricity to a high thrust force and causes an additional moment that is added to other design moments. Tolerance is usually handled separately in computations and is not integrated with numerical analysis or bedded beam analyses.

As part of this research, a parametric study with a single segment loading case is proposed to be performed. The segment model concept is shown in Figure 1-9. The segment would be simply supported along its two longitudinal edges, and subject to bending by a distributed load. A specific offset value (two typically accepted values and one extreme) would be imposed by a gap along with the longitudinal edge fixity condition. The study would vary the following parameters:

- Load magnitude – a simple uniform load condition would be assumed and the magnitude of the load would be varied
- Segment thickness
- Longitudinal edge offset

The results would be compared in terms of stresses (compression or tension) with the idealized case of no offset. See Figure 1-9.

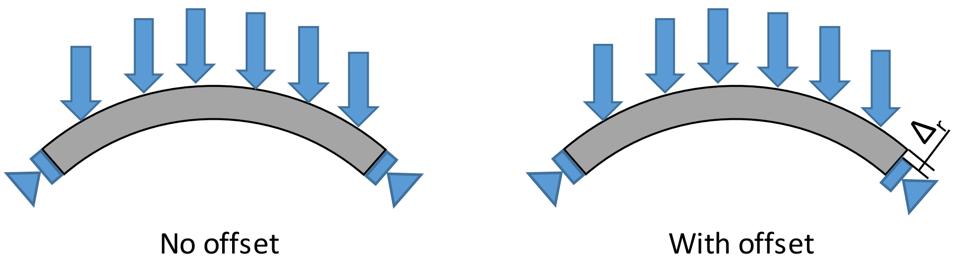


Figure 1-9: Layout for single segment radial tolerance analysis.

Circumferential Tolerance

Circumferential tolerance issues occur when there is local mismatch between segments of two adjacent rings. This can manifest as a "shadow" or "lip" in-between rings or problems arise at staggered segment corners where bearing areas may be uneven. Significant stress concentrations can occur at the backside of a newly installed ring or even in the second or third ring behind the leading ring. Unlike the radial offset case, this wide range of circumferential tolerance effects and the random nature of their appearance would make a systematic approach involving numerical analysis difficult to implement. For this reason, it is suggested to examine the damage mechanism involving staggered joints with purposely built-in circumferential inaccuracies. Mismatch between these contact surfaces would lead to rapid stress increase during TBM thrust cycles.

The conceptual model for this condition is presented in Figure 1-10. The model assumes the case of two segments with a slight longitudinal offset between their short edge (radial joint). This causes a mismatch condition on the circumferential plane. A third segment is positioned in a staggered manner above the two-segment pair, and thrust-loaded at varying levels. The joint for the baseline case is assumed to be in the center of the base of the upper segment. The stress development around the affected staggered joint would be determined within all three segments and the levels and trends catalogued. A baseline set of typical strength and elastic properties for precast concrete would be used initially. Upon review and interpretation of the results, additional configurations of staggered joints or other materials can be considered as an option. Interface elements would be used for all planar joints based on the results obtained from prior numerical analyses.

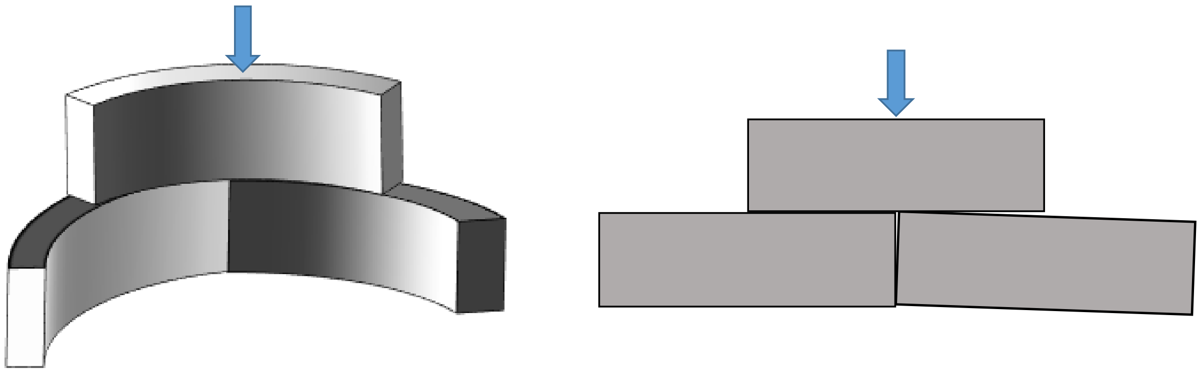


Figure 1-10: Conceptual continuum modeling layout for the investigation of staggered joint tolerance.

1.1.7 SFRC Modeling

When using SFRC segments, many project owners, internationally as well as in the United States (US), adopt the International Federation for Structural Concrete (*fib*) Model Code 2010 (MC2010 – voluntary and non-binding) as a basis for the design. The notched beam test of European Commission Joint Research Center (EN) 14651 used in MC2010 is an essential element of the *fib* code. A frequently observed trend in the design practice is to treat SFRC in computations such as the bedded beam or 3D numerical analyses, as being a linear elastic material, and essentially the same as conventional, unreinforced, un-cracked concrete, although SFRC has behavioral features that differentiate it from regular cast concrete, especially when it is subject to loading close to its yield and tensile strength.

To provide a more realistic constitutive modeling of SFRC it was proposed that a numerical analysis program be performed alongside the large scale and laboratory testing, to enhance the knowledge of SFRC behavior in segmental lining design. Developing a custom-made full constitutive model for any numerical analysis program is a very complex work and expensive endeavor. Research for a constitutive model for SFRC would, therefore, focus on developing stress-strain relationships up to and beyond yield (first crack) to be used in the lining model.

It is proposed that testing data from four-point (ASTM International (ASTM) C1609) and three-point notched type (EN 14651) beam bending tests (and compression tests) performed under the Laboratory Testing Plan be used to select and calibrate an appropriate constitutive model for concrete. It is proposed that the research be based on a generalized form of an existing model, which can be developed and be the basis for an SFRC material model in 3D continuum analyses (structural or geotechnical) of large diameter segmental tunnel liners.

Each laboratory test type (compression and bending) should provide insight and stress-strain data for the compression and tensile section of the SFRC-element. The intent is that material properties would be correlated to specific mix designs. Once a preliminary model and parameters have been identified and developed, a numerical analysis would be performed to simulate three- or four-point bending tests of single segments performed within the proposed laboratory testing research plan associated with this research. The results of the numerical analyses would be compared to the laboratory testing results and parameters would be recalibrated as necessary. A close agreement between test data and back-analyzed numerical analyses would indicate if the material can be used further for modeling of complete rings or a complete tunnel lining. The segment geometry, boundary conditions, and imposed loads used in the numerical modeling would be coordinated with the laboratory testing.

1.1.8 Soil Structure Interaction

Soil-structure interaction analysis, including three-dimensional modeling is considered a the state-of-the-art method and has become a tool to aid in segmental lining design either as a primary method or to augment and validate results of other structural-analysis based methods of design. The selection of the type of model and properties of the surrounding ground should be done carefully. Furthermore, soil-structure interaction analysis is typically performed to represent a service limit state only. As such, the effects of ground loading during and after excavation, ground water, surcharge, etc. are considered to be un-factored. Thus, the implementation of LRFD practice for roadway tunnel designs is a critical point that designers should consider when interpreting and using service limit state results from finite element (FE) computations for structural design. In advanced modeling cases, temporary conditions relevant to ultimate limit states such as the actions of TBM thrust loads, can also be included within the same analysis.

As part of the proposed computer modeling research program, a parametric study to compare solutions from the double ring bedded beam method and equivalent models using geotechnical based three-dimensional FE analysis would be performed. Parameters should be chosen carefully in order to use the results for comparison to parametric studies mentioned further above, i.e. for the embedded beam study.

The embedded beam and the FE method are inherently different as the ground-structure interaction solution of a FE-model does not rely on a discrete set of reaction points as the bedded beam does. The ground reaction mechanism of the FE solution would depend on the selected ground properties, ground model, and its deformation during the solution. Nevertheless, from a design standpoint, it would be useful if certain comparisons can be made, especially when there is significant difference in the time investment to set up and run a bedded beam versus a full three-dimensional geotechnical tunnel model.

For this scope item, several tunnel loading cases performed for the bedded beam study described in Paragraph 1.1.2 would be selected and equivalent large diameter tunnel models would be developed using FE analysis. Baseline cases would be analyzed assuming simple and widely adopted ground constitutive models including the simple elastic and Mohr-Coulomb models. The results would be summarized in a matrix indicating the calculated member load magnitude and the location of the peak values along the tunnel lining perimeter. For consistency, the same segment to segment and ring to ring coupling assumptions would be used for the geotechnical FE models.

1.2 Laboratory Testing Workplan

During the literature research, numerous knowledge gaps were identified. The suggested experimental test program addresses for four key topics related to large diameter segmental tunnel lining with significant knowledge gaps. These four topics include:

- Radial joint behavior
- Jack load-bearing, bursting and torsional shear behavior
- Long life, high-pressure concrete durability
- Harmonizing steel fiber reinforced concrete (SFRC) *fib* Model Code 2010 to United States (US) practice

In the following paragraphs, a summary of each of the addressed knowledge gaps is provided and the suggested testing program, parameters and an approximate number of tests is introduced.

1.2.1 Large Diameter Joint Behavior

The influence of radial (longitudinal) joint behavior is significant in segmental lining system response, e.g. for deformation, flexural stiffness, and internal load development. In addition, this influence is amplified in large diameter tunnel rings. However, the behavior of radial joints in large diameter segmental lining rings and the influence of both radial and circumferential joint behavior on the overall performance of segmental lining (e.g., stiffness, deformation, and internal moment generation) is an area of limited understanding. Most experimental joint research conducted has focused on smaller, metro-size tunnels, in a typical range of 20 to 24 feet in diameter.

Gaps/Questions Regarding Individual Joint Behavior

- Several joint rotation behavioral models have been proposed over the years; the Janssen (1983) model is the most widely accepted and is a simple theoretical model. However, are these joint rotation behavior models applicable to large-diameter tunnels?
- The literature discussing the different rotational behavioral models proposed over the years have some contradicting conclusions about the influence of connection bolts. What is the source of the contradictory results and which results are applicable for large diameter tunnels?
- While the practical use of rotational springs in numerical simulation to model joint behavior is discussed widely in the literature (Leonhardt & Reimann 1965, Janssen 1983, Blom 2002, Arnau and Molins 2011, and more), joint behavior between adjacent rings using nonlinear lateral springs connection (as done by Grubl 2006) is not discussed widely in the literature. Does this coupled ring behavior have additional significance in large-diameter tunnels?
- The ultimate failure mechanism of metro size tunnel segmental rings is mostly due to compression failure at the joints. Is the failure mechanism of large diameter tunnel also at the joints, and if so, is the mechanism influenced by the characteristics of large diameter segments?

Gaps/Questions Regarding Full Ring Behavior

- The empirical ring stiffness equation provided by Muir Wood (1975) ignores the stiffening effect of axial load, which results in an overestimation of the design moments using the Muir Wood equation. How can this be incorporated into Muir Wood's equation?
- Is the Muir Wood (1975) equation applicable to large diameter tunnel linings with great numbers of joints?
- For shallow large-diameter tunnels, the difference in axial force at the tunnel invert and crown is not negligible. Is the Muir Wood (1975) equation applicable to shallow large-diameter tunnels?
- Staggered jointed adjacent rings are known to increase the overall ring stiffness. How does this influence individual joint behavior (e.g., magnitude of rotation)? How do different connecting elements (dowel vs. bolts) and longitudinal force influence this? Is the Muir Wood (1975) equation applicable when a staggered joint arrangement is considered?

These gaps in knowledge listed above can be closed through combined computational modeling and experimental testing (lab and field).

Large diameter rings have significantly thicker segments (typically 20-30 in.) compared to metro-size tunnels (typically 8-12 in.). Because overlying ground and building settlement limits are the same regardless of tunnel diameter, large-diameter segmental joints experience different deformations and normalized convergence (u/D) than metro-size tunnels. Typically, large diameter linings have more segments (9-10 on average, as high as 13) compared to metro-size tunnels (5-7 segments). Large diameter segments also have lower segment slenderness ratios (arc length/thickness) than metro-size segments.

Given the noted difference between large diameter and metro-size diameter lining systems combined with the lack of research and the influence of joint behavior, there exists a gap in knowledge that can be filled via further computational and experimental study.

Experimental Laboratory Testing

The behavior of single radial joints can be investigated through full-scale laboratory testing of segments as follows.

Two-segment testing. Tests on a two-segment configuration with a joint located at mid-span (Figure 1-11) are proposed. The joint, segment thickness, and segment width would be full-scale. The radius of curvature of the segments would be matched as this is of considerable interest (as opposed to testing two flat slabs connected at a joint). Two half-length segments would be used (see Figure 1-11). Table 1-1 summarizes the parameters to be varied during testing to determine their influence on joint rotational stiffness. Each row in Table 1-1 summarizes one proposed test series variable for investigation, the suggested values of the variable, and minimum total number of samples to be tested (each sample includes two half-length full-scale segments). The two-segment setup is loaded by a horizontal and vertical actuation system allowing a variation of bending moment and axial force combinations. Each test series detailed below would be repeated

2-3 times to build confidence in results and to capture inherent variability in the results. As currently proposed, the minimum number of samples for each test series reflects the number only for the variable listed, e.g., three samples for segment thickness = 16, 24 and 30 inches. Each of these segment thickness values includes a segment curvature, reinforcement type, joint skew angle, etc. The research team proposes to maintain all other sample characteristics (other variables) constant so that the test series isolates the influence of the intended variable. It may be necessary, however, to adjust some characteristics to maintain some lining norms. For example, to maintain a thickness/diameter ratio within a practical range (e.g., 1/18 to 1/30), it might be necessary to increase the segment curvature with thickness. It is also considered valuable to test additional variable combinations such as the three thickness values at each of the segment curvatures. For this reason, the listed number of test samples is to considered a minimum.

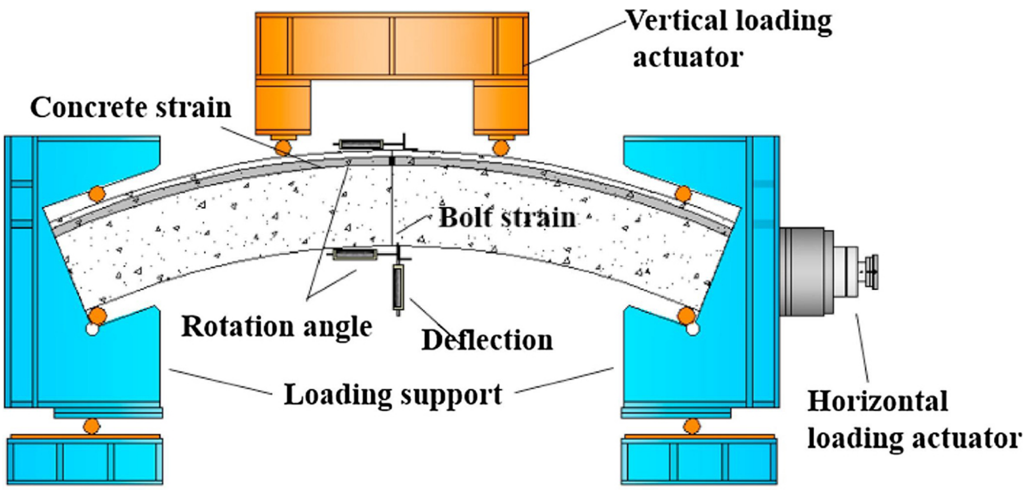


Figure 1-11: Two segment test configuration for joint behavior testing.

Source: Liu, X., et al, 2018

Table 1-1: Suggested parameters to be tested for their influence over the joint rotational stiffness.

TEST SERIES	VARIABLE	SUGGESTED MAGNITUDES	MIN. # OF SAMPLES*
1	Axial force and bending moment combinations	(0.5·M, 0.5·N), (0.5·M, 0.8·N), (0.8·M, 0.5·N), and (failure, 1.0·N) **	1
2	Segment curvature	Tunnel diameters: 40, 50, 60 feet	3
3	Segment thickness	16, 24, and 30 in.	3
4	Joint skew angle	0˚ (perpendicular), 5˚, and 10˚	3
5	Tolerances (placement inaccuracy)	For 2 segment thicknesses 12, and 24 in. Radial inaccuracy – 2, 4, 12 mm Longitudinal inaccuracy – 2, 4, 12 mm	6
6	Reinforcement type	Conventional steel rebar, Steel fiber reinforcement (SFRC), and hybrid reinforcement (both conventional and SFRC)	3
7	Bolt distance from the neutral axis	No bolt, 0·t, and 0.2·t (t = segment thickness)	2
8	Joint asymmetry	Single/double gasket grooves, guide rods, and corner geometry	5

Source: Colorado School of Mines
* Each sample includes two half-length full-scale segments
** M and N are service load bending moment and axial force.

The first test series would be conducted to gather sufficient data to examine the applicability of the widely-used Janssen (1983) rotational stiffness model on large diameter tunnels. This testing series would investigate the rotational stiffness at the joint of two conventionally reinforced concrete segments of a large diameter size tunnel 50 ft and would serve as the benchmark case in the subsequent tests. One test sample (two half-length segments) would be tested under different combinations of axial force and bending moment (Table 1-2), within the lining service loads to measure joint rotation angle as a function of bending moment. In the last test, the sample would be loaded to failure to investigate the failure mechanism, e.g., is it compression of the joints?

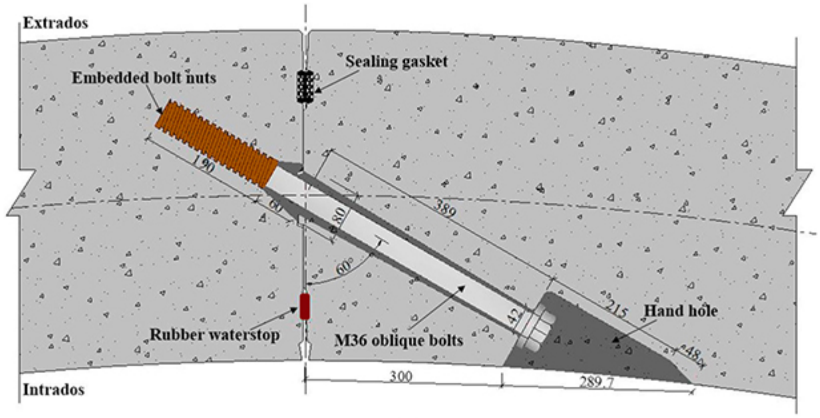
Table 1-2: Validation of the Janssen rotational stiffness model.

TEST #	MAX BENDING MOMENT	MAX AXIAL FORCE
1. Baseline	0.5·M	0.5·N
2. High axial force	0.5·M	0.8·N
3. High moment	0.8·M	0.5·N
4. Low combination	0.2·M	0.2·N
5. High combination	0.8·M	0.8·N
6. Loading to failure under constant axial force	Increase to failure	1.0·N

Source: Colorado School of Mines
*M and N are service load bending moment and axial force.

The second test series would be conducted to investigate the influence of segment curvature on the joint rotational stiffness. In this testing series, two test samples of two large-diameter tunnels (40 feet and 60 feet) would be tested under the same loading scenarios as shown in Table 1-2.

The remaining testing series would be conducted to investigate the influence of factors and detailing on the rotational stiffness. Six variables are suggested, including segment thickness, joint skew angle, reinforcement type, joint asymmetry, bolt distance from the neutral axis (Figure 1-12) and tolerance (Figure 1-13).



a)

Figure 1-12: Bolt passing through the segment neutral axis.
Source: Feng K., et al, 2018

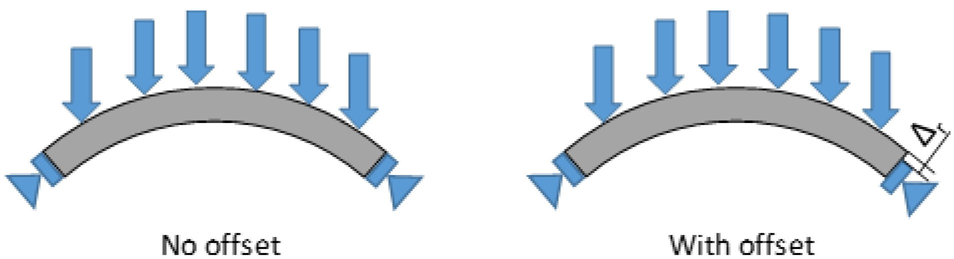


Figure 1-13: Radial Joint Testing.

To investigate the influence of coupling behavior between rings, a series of staggered joint two-segment and three-ring configuration testing is suggested (Figure 1-14). This testing setup would contribute to the understanding of how adjacent rings work together under different longitudinal forces and with different connection details. Like the two-segment test setup described above, the middle ring would have a full-scale width, two-segment configuration. In addition to the middle ring, a half-width single segment is positioned at each side of the center ring. The three-ring setup is loaded in the two horizontal directions, transverse (like the two-segment testing), and longitudinal direction (simulating Tunnel Boring Machine (TBM) jacking forces). The three-ring setup would be loaded by a vertical actuation system, allowing a different vertical load on the center ring and the end rings. Table 1-3 summarizes the parameters to be varied during testing to determine their influence on joint shear and rotational stiffness. The table shows the total number of samples recommended to test 1 segment per variable.

Table 1-3: Suggested parameters to be tested for their influence over the ring joint stiffness.

TEST SERIES	VARIABLE	SUGGESTED MAGNITUDES	MIN # OF SAMPLES*
1	Longitudinal force, axial force, and bending moment combinations	Variation of longitudinal force based on real TBM thrust force experience in combination with the loads described in Table 2-2	1
2	Dowel at ring joints	No dowel, two different standard dowels	1-2
3	Segment thickness	16, 24, and 30 inches	3

Source: Colorado School of Mines
* Each sample includes two half-length full-scale segments for the middle ring and two half-width single segments on each side

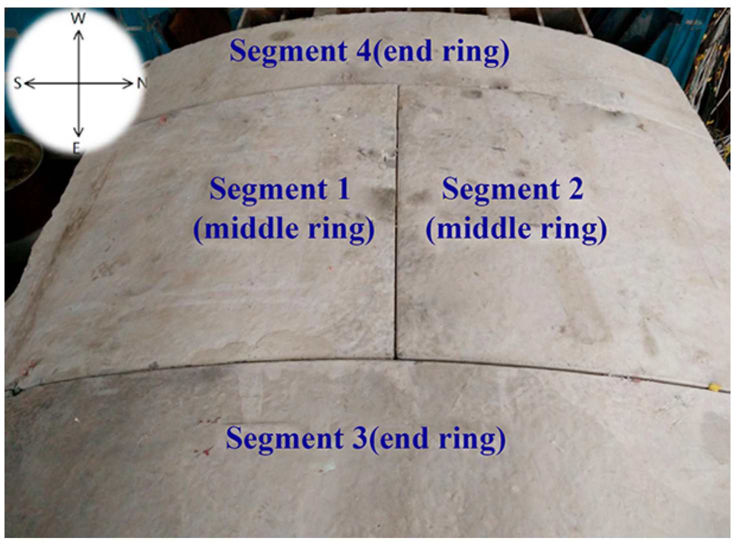


Figure 1-14: A full scale staggered joint two-segment three-ring configuration
Source: Liu, X., et al, 2018

The longitudinal force and shear dowels play important roles in the coupling mechanism and would be tested in the two first testing series of this three-ring testing program, as part of an effort to develop a quantitative coupling model for use in numerical analysis.

A follow-up test series would investigate the influence of the segment thickness on the coupling mechanism because the large diameter lining segment thickness can be more than twice the thickness of a standard metro-size tunnel.

This experimental program would enable the validation and/or further development of appropriate joint models for large diameter lining. These joint behavior models play a crucial role in computational modeling of full rings and connected full rings. To this end, experimental and computational efforts would be carried out hand in hand to build an understanding of single joint and multiple joint system behaviors.

1.2.2 Field Monitoring of Full Ring Behavior

The research team deems it to be cost-prohibitive to perform full-scale testing of large diameter rings in a laboratory setting. Considering the size of large diameter rings, the magnitude of the external load frame combined with the suggested number of actuators (50-100) would be cost-prohibitive within this program. Instead, the research team proposes to instrument complete large diameter rings installed as part of forthcoming tunneling projects, e.g., Hampton Roads Bridge Tunnel, Silicon Valley Bay Area Rapid Transportation (BART) Extension, Los Angeles (LA) Metro Sepulveda Pass, Toronto Scarborough line, etc.

The instrumentation program would include embedded strain gauges and pressure cells (Figure 1-15), displacement transducers to measure joint rotation, and light detection and ranging (LIDAR) scanning to measure ring displacements. Segment instrumentation would be installed during casting. Multiple rings would be instrumented throughout the tunnel. Adjacent rings should also be monitored to capture load-sharing behavior.

It is proposed to begin measurements after complete ring erection within the shield, prior to the next push, including the capture of gravity-only loaded readings of all segment strains/stresses and joint rotations (just due to weight of rings). Measurements would then be recorded as the ring is subjected to thrust jack loading and annulus grout loads, and eventually earth and water loads. The monitoring would be continued over days to weeks to months. Further, such instrumentation could provide valuable information throughout the service life of the tunnel, including during seismic events, e.g., if installed in seismic active areas like the Silicon Valley BART Extension tunnel.

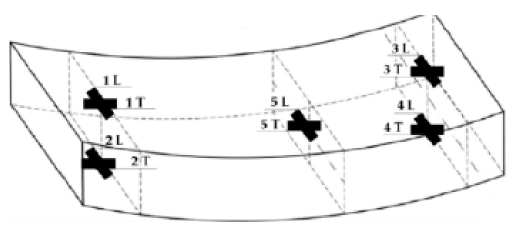


Figure 1-15: Strain gauge layout used in the Metro Line 6 of Naples
Source: Fabozzi et al., 2017

The aforementioned field instrumentation would be limited to service loading behavior and would not examine the ultimate load. In-field examination of ultimate load behavior could be examined by instrumenting and loading sacrificial rings that are installed during TBM launch to failure. There are typically 5-7 sacrificial rings that are removed after TBM launch. An economical load frame and select actuators could be constructed, using adjacent rings, to apply load cases that would bring portions of the ring to failure. This would provide valuable information about joint rotation behavior when embedded within a multi-ring system.

Appropriate lead time and coordination with the project owner, designer and contractor are good practices for field instrumentation/testing. The research team has successfully done this before, e.g., on the Seattle Sound Transit Northlink tunnel project.

1.2.3 Transient Thrust Jack Load of Lining

Through a series of thrust jacks, TBMs apply a longitudinal force (jacking loads or thrust force) to the end face of the most recently installed ring (Figure 1-16). This thrust force is needed to move the TBM forward during excavation. These TBM jacking loads can induce tensile stresses in the concrete segments (also known as splitting stresses) that might result in longitudinal cracks in the segments. This is particularly concerning in large-diameter tunnels because the magnitude of thrust force increases with cross-sectional tunnel area and with depth in the ground (due to water pressure). The magnitude of total thrust increases with diameter squared, yet the ring end/bearing area against which thrust jacks apply this load increases only with diameter. Therefore, large-diameter tunnel linings experience higher jacking loads and greater tensile and splitting stresses.

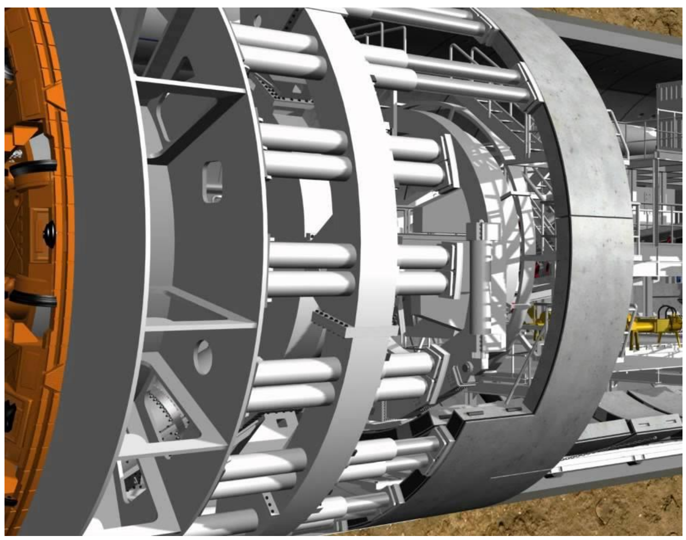


Figure 1-16: Illustration of TBM thrust jacking loads applied to ring end/bearing area of most recently installed segments.
Source: Herrenknecht, 2015

In addition, TBM torque increases disproportionately to the ring end/bearing area. TBM torque increases with diameter cubed whereas the ring area against which the torque is applied increases only with diameter. Therefore, the torque-induced shear forces applied to segments are anticipated to be relatively much higher for large diameter tunnel linings.

Compounding this is the fact that, as large diameter TBMs more commonly employ bentonite slurry shield gap injection to control ground deformation, there is a secondary lubrication effect that transfers more of the cutterhead torque directly on the segments during excavation.

The transient jacking forces can become one of the governing load cases for large diameter segment design, and the torsion-induced shear loading has created a new load case that has not traditionally been considered for metro-size tunnel lining. To this end, experimental research including laboratory testing and field monitoring is used to improve understanding of these loads and liner performance when subjected to these loads.

Gaps/questions regarding TBM thrust and torque influences on large diameter segmental lining:

- Different possible layouts of thrust pads and thrust forces for one or two typically large-diameter tunnels can result in different splitting stresses. Can the general optimization of the thrust pads layout be determined? Or can a set of tabulated results be published to be used as rough preliminary information for designers?
- Bakhshi (2014) suggests the use of Finite Element Modeling (FEM) methods or analytical solutions such as Iyengar Diagram for determination of tensile splitting stresses that result in more cost-effective reinforcement distribution compared to the simplified equations presented in voluntary and non-binding American Concrete Institute (ACI)/Deutscher Ausschuss für unterirdisches Bauen e. V. (DAUB)/Eurocode (EN)/British Standards. What is the difference between the available analysis methods and the actual tensile splitting stresses? And how important is the use of one over the other for economic yet safe designs in large-diameter tunnels?
- With the high expected torque-induced shear forces applied to segments anticipated for large diameter tunnels, are any additional reinforcement measures needed at the segment edge? Is the nominally 3 in. of cover on traditionally reinforced segments vulnerable to shear failure, splitting stresses, and/or localized crushing?
- Installation and segment dimension tolerances tend to be relative to the tunnel size, and as tunnel diameter increases, segment thickness increases as well. How does tolerance influence jacking loads? For large-diameter tunnels, should the tolerance limit be relative to the tunnel diameter or segment thickness or is there a limit only on an absolute value?
- What benefit do SFRC and hybrid reinforcement provide to shear and tensile capacity for jacking loads?

Experimental Laboratory Testing

Tests on full-scale segments, both single segments and two segment / joint configurations as illustrated in Figures 1-17 to 1-20, are proposed. The vertically-oriented actuators apply the longitudinal load to simulate jacking forces observed in large diameter TBMs. Multiple actuators with varying pad sizes and spacing between actuators would be used. In addition, a laterally oriented actuator would simulate the torque-induced shear load applied to segments.

The segments and joints would be instrumented to capture behavior during loading. Segments would be instrumented with strain gauges and pressure plates. Joints would be instrumented with pressure cells and rotation sensors. Digital imaging would be employed to capture and map induced cracking during testing.

Each test sample would be loaded incrementally by a vertical actuator (simulating the longitudinal jacking force) up to failure. The first test series would study the development of splitting stresses and crack formation with different pad layouts. The common methods of design can be evaluated with the first, second, and third test series' and allow for estimations of the degree of conservatism of simplified equations compared to Iyengar Diagram and FEM methods.

The fourth test series would evaluate the splitting capacity of SFRC and hybrid reinforcement compared to conventional reinforcement of segments with equivalent load capacity. The last test series would evaluate the influence of tolerance limits on splitting stresses and crack formation (Figure 1-17). Various construction practices can influence the splitting stress and crack formation during installation. This includes a single jack loading over a longitudinal joint, previous ring not being in proper alignment and circumferential ring to ring contact. The proposed testing to apply a single jack load over a longitudinal joint induces ring to ring contact near the jack. Table 1-4 shows the minimum number of samples suggested to test 1 segment per variable. Each test series detailed below would be repeated 2-3 times to build confidence in results and to capture inherent variability in the results.

Table 1-4: Suggested parameters to be tested for their influence on splitting stresses and crack formation.

TEST SERIES	VARIABLE	SUGGESTED MAGNITUDES	MIN. # OF SEGMENTS*
1	Jacking pad size	To be determined (TBD)	3-5
2	Jacking pad spacing	TBD	3-5
3	Segment thickness	16, 24, 30 inches	3
4	Reinforcement type	Conventional steel rebar, Steel fiber reinforcement (SFRC), and hybrid reinforcement (both conventional and SFRC)	3-6
5	Tolerances	For 2 segment thicknesses 16 and 24 inches reaction surface inaccuracy: Irregular reaction surface: 2, 6, 12 millimeters	12

Source: Colorado School of Mines

* A sample is a single segment or a two-segment combination used to perform one test

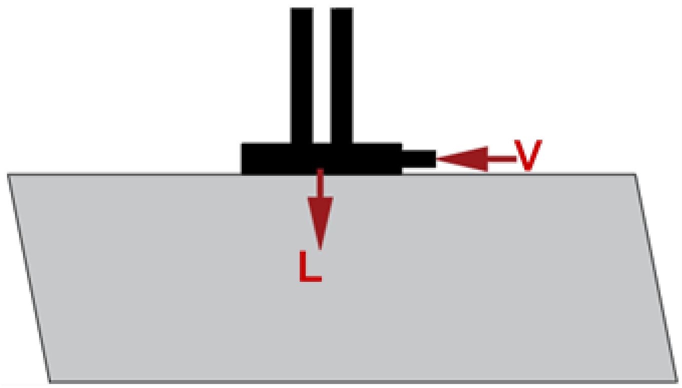


Figure 1-17: Single vertical actuator with a laterally oriented actuator to simulate the torque-induced shearing load applied to segments.
Source: Colorado School of Mines

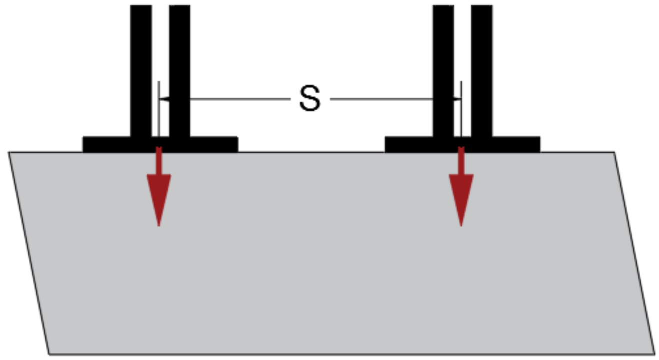


Figure 1-18: Schematic of a two-jack loading configuration with variable jack spacing. Shear loading can be included.
Source: Colorado School of Mines

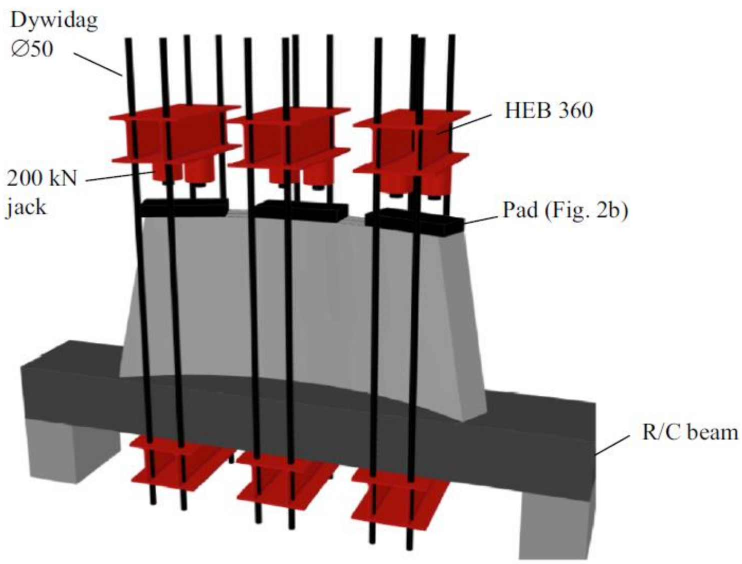


Figure 1-19: Schematic of a three-jack loading configuration with variable jack spacing. Shear loading can be included.

Source: Meda et al., 2016

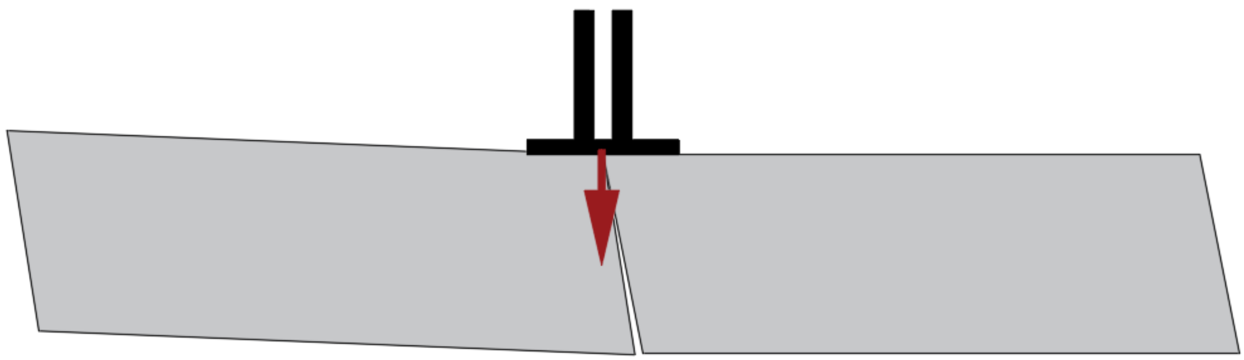


Figure 1-20: Schematic of a single jack loading over the longitudinal joint with reaction surface inaccuracy. Shear loading can be included.

Source: Colorado School of Mines

Test segments would be designed using typical standards by the American Association of State Highway and Transportation Officials (AASHTO) (23 CFR 6.25.4(b)), *fib* model code and ACI code (voluntary and non-binding). The magnitudes of maximum longitudinal jacking force (L) and torque-induced shear force (V) used to design the segments would be determined from large diameter TBM projects (e.g., Seattle SR99, Hampton Roads Bridge Tunnel). Testing would involve a combination of L and V load cases to failure. For example, a worst-case scenario for torsion-induced shear is when L = 0; however, such a case is not realistic because TBM torque-to-segment shear transfer is bound by jacking pad/segment interface friction. Therefore, V would vary between tests as a ratio of L (Table 1-5).

The test set up would consist of a single segment loaded by a single vertical actuator with a laterally oriented actuator to simulate the torque-induced shearing load (Figure 1-17). Only one test series would be conducted to investigate the influence of torque-induced shear force on different reinforcement types (Table 1-5). Each test sample would be loaded via a combination of longitudinal and shear forces (Table 1-6) to failure, using a total of 12 segments.

Table 1-5: Torque-induced shear force (V) as a function of longitudinal jacking force (L)

LOAD CASE #	MAXIMUM SHEAR FORCE
1	0.1·L
2	0.15·L
3	0.3·L
4	0.5·L

Courtesy Colorado School of Mines

Table 1-6: Suggested parameters to be tested for their influence on torque-induced shear force.

TEST SERIES	VARIABLE	SUGGESTED MAGNITUDES	TOTAL # OF SEGMENTS
1	Reinforcement type	Conventional steel rebar, Steel fiber reinforcement (SFRC), and hybrid reinforcement (both conventional and SFRC)	12

Source: Colorado School of Mines

1.2.4 Long Life, High Pressure Concrete Durability

The AASHTO Load and Resistance Factor Design (LRFD) Road Tunnel Design and Construction Guide specifications describes a service life for the structure of 150 years. However, little is known about the durability performance of concrete segments, including reinforcement steel corrosion, over that long period.

Large diameter road tunnels are bored deeper and therefore are subject to high groundwater pressures. The influence of elevated pressure on chloride ion penetration is unclear. To our knowledge, this has not been examined. Standard test methods to examine chloride ion penetration are performed under atmospheric pressure.

Little is understood about chloride ion penetration, and the resulting corrosion, through concrete containing micro-cracking. Micro-cracking is generally permitted in segmental lining design by relevant design codes and specifications. The presence of cracks could accelerate chloride ion penetration and reinforcement corrosion. However, the influence of micro-cracking is not considered in chloride ion testing and durability design calculations.

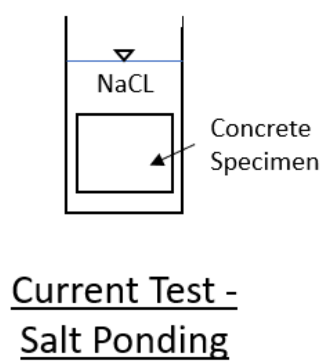
Gaps/Questions Regarding Durability in Large Diameter Applications

- How does the presence of water pressure at depth affect chloride ion penetration into concrete segments?
- How does the presence of micro-cracks and allowable crack widths affect the chloride ion penetration?
- How should durability life prediction models used in segment liner design be modified to account for crack width limits and pressure? As a corollary, what should allowable crack width be to meet extended service life?

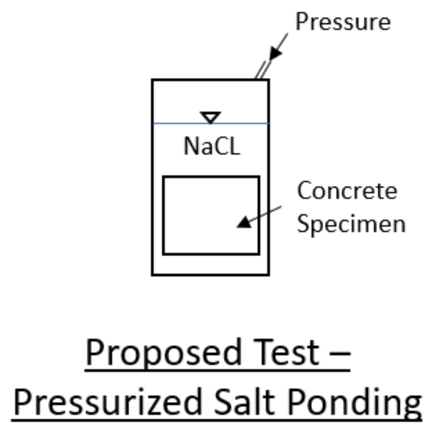
Experimental Laboratory Testing

Salt ponding testing under pressure to examine chloride ion penetration under more field-realistic conditions is proposed. Salt ponding testing, conducted per the AASHTO T259 specification for 90 days, is considered the most accurate long-term indicator of chloride ion penetration. As shown in Figure 1-21a, the current test is performed under atmospheric pressure. The research proposes to perform the test per AASHTO T259 except under elevated fluid pressure (Figure 1-21b). There is precedence for testing concrete permeability under pressure, e.g., DIN 1048, US Army Corps of Engineers CRD-C48. The research team will review these publications and develop suggestions for pressure application into the proposed salt ponding test setup.

Concrete specimens (3 in. thick, 4 in. diameter) would be placed in a pressurized chamber with 3% Sodium Chloride (NaCl) solution for a duration of 90 days. Pressures would vary as summarized in Table 1-7. Test specimens would be cored from the previously tested full-scale segments. Plain and fiber reinforced concrete would be tested. The influence of fiber dosage would be investigated. In addition, the research team would test samples that include micro-cracks to examine this influence (Figure 1-22). Table 1-7 shows the minimum number of samples to test 3 samples per variable.



(a)



(b)

Figure 1-21: (a) Current salt ponding test and (b) proposed pressurized salt ponding test.
Source: Colorado School of Mines

Table 1-7: Durability testing parameters.

PARAMETER	SUGGESTED MAGNITUDES	MINIMUM # OF SAMPLES*
Concrete Compressive Strength	6,000 and 10,000 psi	Included in the numbers below
Fiber dosage	0, 0.5, 1.0, 1.5 lb/yd^3	24
Pressure	0, 5, 10 bar	18
Crack Presence	0, 0.1, 0.2 mm	18

Source: Colorado School of Mines
* 3 in. thick, 4 in. diameter from concrete cores.

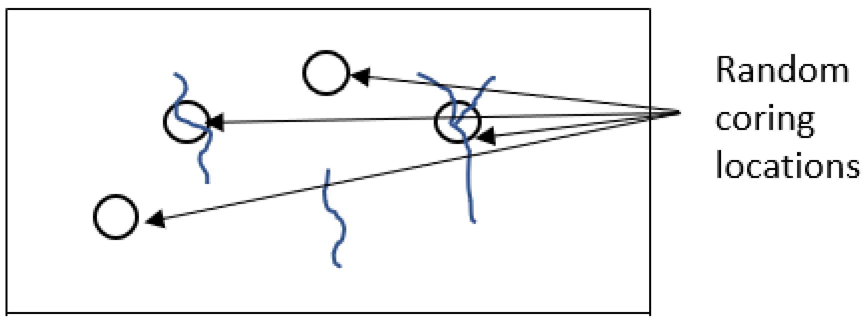


Figure 1-22: Cores with and without micro-cracking to be tested.
Source: Colorado School of Mines

1.2.5 Harmonizing SFRC *fib* Model Code to US Practice

Tunnel specifiers and designers in the US are trending to use the *fib* Model Code 2010 (voluntary and non-binding) for fiber-reinforced concrete segments. The *fib* Model Code uses the notched flexural beam test per EN 14651. However, most US-based projects use US-based codes for design. This causes a challenge because currently, US-based codes do not have an equivalent standard to the European notched beam test. When projects do allow the use of international standards, quality control laboratories in the US have limited availability to perform the notched beam test. Due to this limitation, many US designers refer to the American Society for Testing Materials (ASTM – voluntary and non-binding) C1609 test instead of the notched beam test. In using the ASTM C1609, test the designer then applies unproven assumptions in order to incorporate the test results into the *fib* Model Code design methodology.

There has been extensive debate in the tunnel design industry regarding which of the different flexural beam test is more applicable and accurate. The notched beam test pre-determines a crack at mid-point due to the notch creating the weakest plane. The pre-determined location allows for accurate monitoring of crack width, termed the Crack Mouth Opening Displacement (CMOD). However, the midpoint of the beam might not be the actual weakest point in the specimen (due to inherent variability). The ASTM C1609 beam test is a four-point load test, creating a constant moment over the middle third of the beam. This setup allows the first crack to occur at the weakest location within the middle third of the concrete specimen. The deflection of the beam in the center is measured during the test. Due to the randomness of the crack location, the crack width is not measured during the standard procedure.

Parallel testing is proposed to systematically compare the ASTM C1609 beam test to the EN 14651 notched beam test to determine: (a) if ASTM C1609 can be used in lieu of the notched beam test with or without calibration; (b) if a US-based notched beam specification should be developed; or (c) if a relationship or set of calibration factors can be derived to correlate the two beam tests. If (c) is the case, then the calibration factors should be developed from the test results.

Experimental Laboratory Testing

A series of comparison EN 14651 and ASTM C1609 beam tests with various SFRC mix designs is proposed. Both tests are displacement controlled. For the EN 14651 notched beam test (see Figure 1-23), a 1 in. deep, 0.12 in. wide notch is cut at the midpoint on the bottom edge of the 6 x 6 x 22 in. simply supported beam (20 in. between supports). The notch concentrates the weak plane and forces the crack to occur at the minimum cross-section above the notch. A clip gauge is fixed at both edges of the notch to measure the notch opening during testing. Vertical beam deflection is measured by linear variable differential transformer (LVDT). The applied loading is increased until the crack opening (increase in notch width) reaches 0.16 in. ASTM C1609 is performed on a 6 x 6 x 20 in. simply supported specimen (18 in. between supports) using a third-point loading method that applies a constant bending moment over the middle third of the beam (see Figure 1-23). Beam deflection is measured via LVDTs. In addition, the crack width in the ASTM C1609 beam is documented with high-resolution time-lapse photography to link the crack width to the load-deflection results.

Both tests would provide a load-deflection and load-crack width response similar to Figure 1-24 as well as the identification of a number of characteristics summarized in Table 1-8. The deformation would initially increase with applied load until initial crack formation. Thereafter, the load typically decreases suddenly for SFRC mixes typically used in tunneling. Due to the fibers within the concrete matrix, the beam would continue to support load while deflecting. In addition to the load vs. deflection plot, Table 1-9 describes the additional information received from each of the testing procedures. Four different fiber reinforcement ratios would be evaluated (Table 1-8); three tests would be performed for each variable.

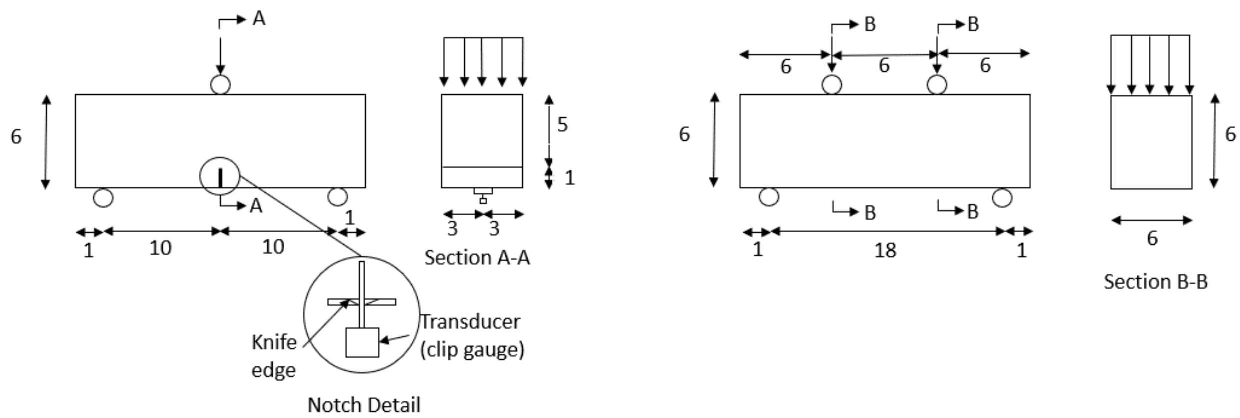


Figure 1-23: EN 14651 (left) and ASTM C1609 (right) flexural beam tests.
Source: Colorado School of Mines

Note: Dimensions in inches.

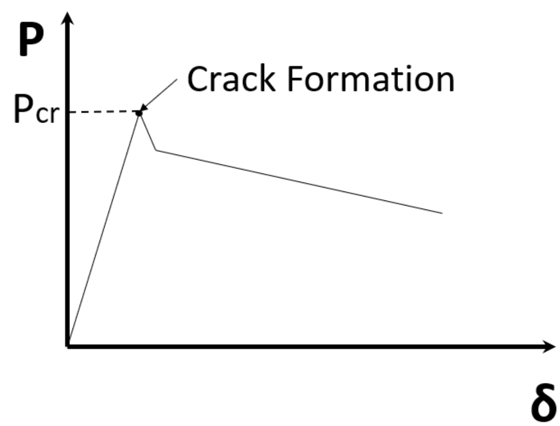
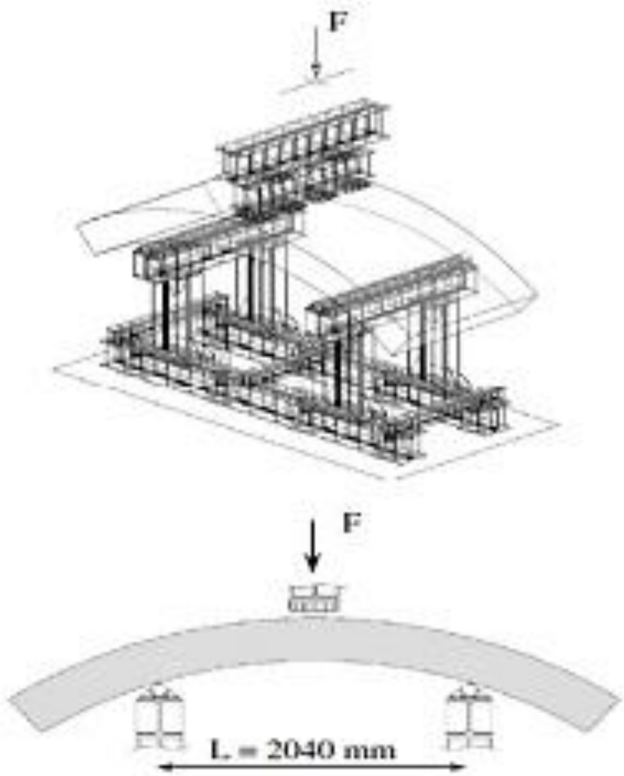


Figure 1-24: Typical Load vs. Deflection flexural beam plot
Source: Colorado School of Mines

Optional full-scale segment testing may be pursued using a three-point flexure set up in which the segment is placed onto two supports (Figure 1-24). Full-scale segment testing can be used to verify the expected behavior based on the flexural beam test results and potential scaling factors. During segment testing the load is applied along the midline (Figure 1-24). Load-deflection, peak load, crack propagation and crack width information can be determined from this test.



(a)

(b)

Figure 1-25: (a) Schematic of Flexure segment test (b) Side view of flexural test.
Source: Catatelli et al., 2010

Table 1-8: Summary of parameters produced by flexural tests

VARIABLE	ASTM C 1609	EN 14651
First-peak load	X	X
Residual strength	X	
Specimen toughness	X	X
Equivalent flexural strength ratio	X	
First-peak deflection	X	X
Load-deflection curve	X	X
Net deflection	X	X
Crack width	X	
Crack mouth opening displacement (CMOD)		X
Residual flexural tensile strength corresponding with CMOD		X
Limit of Proportionality		X
Ultimate moment capacity		X

Source: Colorado School of Mines

Table 1-9: Material Property testing parameters

PARAMETER	SUGGESTED MAGNITUDES	TOTAL # OF SAMPLES
Concrete Compressive Strength	6,000 and 10,000 psi	12
Fiber dosage	0, 0.5, 1.0, 1.5 lb/yd^3	12

Source: Colorado School of Mines

2 WORKSHOP LOGISTICS

The workshop was held from 9 am to 4 pm on January 17, 2020 in Washington, DC.
The workshop agenda was as follows:

09:00–09:20	Welcome/Introductions/Safety Moment (Bill Bergeson/John Wisniewski)
09:20–10:00	Literature Synthesis (Soto Vardakos & Michael Mooney)
10:00– 10:30	Discussion and Questions
10:30–10:45	Break
10:45–11:15	Computer Modeling Research Workplan (Soto Vardakos)
11:15–12:00	Discussion and Questions
12:00–13:00	Lunch
13:00–13:30	Laboratory Testing Workplan (Michael Mooney)
13:30– 14:30	Discussion and Questions
14:30–14:45	Break
14:45–15:45	Discussion
15:45–16:00	Closing Remarks
16:00	Adjourn

Table 2-1: Workshop attendees.

NAME	ORGANIZATION
John Wisniewski	Consultant, WSP
Sotirios Vardakos	Consultant, WSP
Axel Nitschke	Consultant, WSP
William Hansmire	Consultant, WSP
Michael Mooney	Professor, Colorado School of Mines
Ashley Wilson	PhD Candidate, Colorado School of Mines
William Bergeson	FHWA
William Geers	Baekert Maccaferri
Harley Smith	Baekert Maccaferri
Barzin Mobasher	Professor, Arizona State University)
Samer Sadek	Consultant, Jacobs
Nick Chen	Consultant Jacobs
Yang Jiang	Consultant, HNTB
Andy Stone	Consultant, HNTB
Tracy Brown	West Virginia DOT
James Parkes	Consultant, Schnabel Engineering
Matt Goff	Consultant, Schnabel Engineering
Steve Schaef	BASF
Michael Dutton	Consultant, ARUP
Leonard Worden	CSI Concrete Systems, Inc.

3 WORKSHOP FEEDBACK

The following summarizes feedback received from the workshop and responses to the feedback. On the day of the workshop, attendees were provided a hard copy of the slideshow summary of the research work plans described in Section 1. The feedback summarized below is based on the workshop presentations and the hardcopy summary slides distributed at the workshop. The feedback has been grouped per topic. Actions taken on the feedback are included with each topic.

3.1 Modeling and Modeling Parameters

The spring constants used to develop bedded beam models was discussed in the context of the equations used to calculate the spring constants used in the computer models. The research proposed includes a parametric study of spring constants (both radial and tangential) to evaluate the sensitivity of large diameter tunnel models to this input parameter. This study will also assist with the understanding of effects of varying soil profiles across the height of the tunnel.

The modeling research associated with the comparison of the single ring to double ring bedded spring models was discussed. Specifically, that double ring analyses could be done on a project by project basis. The intent of this research is make a comparison of the two methods to explore if there is an advantage to performing one method over the other. If an advantage can be identified, this could possibly lead to cost savings in design time.

Action: No changes to the research plans.

Seismic design for segmental liners in the context of modeling methodologies was discussed. It is unclear if tunnel diameter has any effect on this aspect of tunnel lining design.

Action: No action regarding changing the research plans, however, this is a topic for the final report for this research project that will offer suggested practices for segmental tunnel lining design

3.2 Bedded Beam Models versus Geotechnical (FEM Models)

The discussion involved the two basic analysis techniques for tunnel lining design, the bedded beam model using structural analysis software and geotechnical modeling using a finite element modeling software. The discussion focused on the use of the load resistance factor (LRFD) approach with the finite element modeling process. Since available software packages do not have the ability to apply load factors to different load sources, utilizing the LRFD approach when using finite element modeling is not possible. It was agreed that developing a process to incorporate LRFD into geotechnical modeling would be beneficial. However, this research would be complex, lengthy and expensive.

Action: This issue has been identified as a knowledge gap in the Literature Survey and Synthesis Report (FHWA -HIF-20-035). This is a complex issue worthy of a research study of its own. Consideration will be given to this topic in the final research report. The computer modeling research plan will focus on the comparison of the results of the two analysis methods at the service state to identify similarities and discrepancies. This can be considered a first step to developing an LRFD approach using FEM modeling. This topic will be included in the final report of this research.

3.3 Joints and Hardware between Segments and Rings

The various types of joint configurations were discussed during the meeting. Modeling of joints as well as laboratory testing would be useful to determining the impact of joint configuration on load effects in the segments, load transfer between segments through the joints and the durability of the joints from segment casting through installation of the segments. Although straight right-angle joints are indeed very common, they are not the only kind used and it would be extremely complex and expensive to model various kinds/shapes and test these as well. It is proposed to use segments from the Chesapeake Bay Bridge Tunnel project for testing. This is proposed because the segments could be obtained from the project at a cost lower than the procuring segments independently of an on-going production operation. .

The discussion continued with the topic of the effect of various hardware used in segmental lining construction: bolts in radial joints and gaskets, packing, alignment bars, bolts and bicones in circumferential joints. Computer modeling of various joint configurations would be useful to better understand the effects of these hardware items.

The use of the Muir Wood / Curtis model for determining the stiffness of the rings was extensively discussed. It was agreed that a key component of the laboratory research and subsequent computer modeling research would be to evaluate the Muir Wood / Cutis model in the context of large diameter tunnels that have linings significantly thicker than the tunnels for which the Muir Wood / Curtis model was adopted. The study will look for potential improvement to the empirical formula to remove conservatism that appears to result from its use and verify an approach for its use in large diameter tunnels.

The conceptual testing setup for the radial joint testing was discussed. Since the testing scheme presented during the workshop was schematic, further development of the scheme was suggested by the attendees. Further detail is provided in the first portion of this report, recognizing that further work would be performed to finalize the design of the test. The detailed experimental plan for joint rotation, including the detailed instrumentation design, will be developed as part of that effort. There is considerable prior work done with radial joint testing internationally, and the lessons learned from this work will be incorporated into this research. The results expected to be obtained and how the results would benefit the industry in the design and detailing of large diameter segmental linings will also be stated.

The attendees discussed using the information already developed from other research on smaller diameter tunnel linings when evaluating and developing use for the data collected as part of this research. It was pointed out that this research will build on research already performed for this topic.

Action: The joints tested in the laboratory would be skewed and inclined, with and without bolts. This is in accordance with the laboratory testing research plan that was presented during the workshop. No changes to the laboratory workplan would be made. Numerical modeling of various joint configurations and hardware is a complex issue and beyond the scope of the current research, however there are already provisions in the research plans to investigate the impact of various hardware between rings. The results of the laboratory research would be used to enhance the understanding of the contribution to ring stiffness of the joint configurations tested to be able to evaluate potential changes to the Muir Wood / Curtis solution. No change to the research plans.

3.4 Segment and Ring Behavior

The discussion regarding the application of TBM jacking thrust and the associated configuration of the jacking shoes revealed that this was a worthwhile area of study, if construction tolerances were considered as part of this study. Studying the behavior of the segments under this loading condition is proposed for both the laboratory testing research and the computer modeling research. There was consensus that information gleaned from this research would be useful to the design industry. This study is proposed to include bursting stresses created by TBM jacks under two different jack configurations.

Action: No action since this aspect of segment behavior has already been incorporated into the research plans.

There was discussion during the workshop about the effect of TBM torque on the segments and the completed ring. The issue revolved around the fact that larger diameter TBMs require greater torque to operate. The concern being that this torque could be transferred to the lining rings in the form of shear forces due to the contact between the thrust shoes and the segments. Since information about the magnitude of this force effect was not found during the literature survey, it presents a knowledge gap about the effect this has on the tunnel lining. The workshop participants were not aware of this force effect being measured during the construction of tunnel projects. This could be due to the fact that smaller diameter tunnels are not significantly affected by the force effect.

Action: Determining the magnitude of this force effect is beyond the scope of this research, however, the suggestion was made by the participants to reach out to TBM manufacturers during the development of the final report to attempt to get information about this topic. This will be considered for implementation at the time of the development of the final report'

One participant suggested that the tunnel lining is unlikely to a reach a non-linear state because of the jointed configuration. This suggestion brought into question the need to studying nonlinear behavior of the tunnel lining under load.

Action: The research team will include an attempt to confirm this suggestion as part of analyzing the data collected from the research that is performed.

3.5 Material Considerations

There was extensive discussion during the workshop about fiber reinforced concrete. The discussion included testing for behavior of the cured product. There was also a discussion about harmonizing the *fib* Model Code use of notched beam test results with typical US practice of using four-point beam load testing. It was brought to light that there is a study currently underway that is like that proposed in laboratory testing program (see Section 1.2.5 of this report). The results of that current study are not yet published and therefore were not available to the research team. Thus, the research team suggested to eliminate the proposed experimental research on EN 14651 and ASTM C1609 beam tests from the laboratory testing program.

There was also discussion about constitutive models for the analysis of segments constructed of fiber-reinforced concrete, investigation of the effect of fiber reinforcement on crack development and the importance of anisotropy in the distribution of fibers. Although this research would be of value to the design industry, there is considerable experimental research on fundamental SFRC behavior being performed. This fundamental behavior is not unique to large diameter tunnel lining behavior. Only research aspects that are unique/critical to large diameter tunnel lining behavior and that have not been performed before are included in the proposed plan.

Action: Modify the laboratory research plan to delete the work associated with harmonizing EN 14651 and ASTM C1609.

There was discussion during the workshop about the use of hybrid reinforcing (conventional reinforcement combined with steel fiber reinforcement and potentially synthetic fibers). The discussion included the improved performance of the segments under moment force effects when hybrid reinforcement is used. The participants agreed that this topic warrants further research. The further research could lead to better predictions of linear and non-linear behavior of hybrid reinforced concrete and improved computer modeling of the behavior.

Action: Due to the high cost of procuring large diameter segments with hybrid reinforcement, it was decided to defer this research to the future. Additionally, this topic is not considered unique to large diameter tunnels, but a material specific topic.

3.6 Final Report

The following topics were offered by the participants for possible inclusion in the final report beyond those that would be included because of the proposed research:

- Segment shapes currently in use.
- Devices for transferring shear between rings.
- Disposition (leave in place or remove) of bolts at radial joints.
- Minimum reinforcement (conventional reinforcing steel bars, fiber, etc.) for segments.
- Weight of segments for handling, transport and erection.
- Gaskets – single and double gaskets.
- Segments for other tunnel shapes such as rectangular or double – “O”.
- Methods of improving durability and predicting service life.
- The effect of fire on precast concrete segmental tunnel lining.

Action: Consideration will be given to this items when preparing the final report.

4 WORKPLAN REVISIONS

4.1 Computer Modeling Workplan

Incorporation of a reasonable joint model in any 3D segmental tunnel lining numerical model is a key step in the process – for both shell element based and 3D continuum-based analyses. The intent of this research was to develop suggested practice for modeling segment coupling in the case of continuum analysis and better consistency with models being used for bedded beam or 3D shell analyses. Computer modeling work associated with a detailed study of the joint rotation for radial and circumferential joints was removed due to cost of performing a comprehensive and meaningful numerical study of joints subjected to combined compression and rotation.

Numerical analyses to study the effect of thrust loading on segments, will assume that the loads act perpendicular to the segment edge. This condition, however, is not always the case during construction. Slight misalignments of the thrust shoe orientation, and often eccentric loading – either inward or outward, can occur. As explained in the originally proposed computer modeling workplan, eccentric loading can occur while the TBM is operating at curved tunnel alignment sections, or it may happen randomly due to pivoting of the last ring segment around its contact with the previous ring. A parametric computational study to study the effects of load eccentricity will negatively impact the cost and time to complete these 3D numerical studies and has thus been removed from this research plan.

For similar cost reduction reasons and given the lack of current ASTM standardization for performing notch beam testing on SFR concrete a detailed research dedicated to constitutive models of SFR concrete to be used in 3D numerical analysis was eliminated from the workplan. Details were added to elaborate which parameters will be varied for bedded beam, 3D bursting stress, tolerance (radial and circumferential) analysis and what combinations are expected.

4.2 Laboratory Testing Workplan

The proposed test on Harmonizing steel fiber reinforced concrete (SFRC) *fib* Model Code to United States (US) has been removed from the proposed workplan. Harmonizing steel fiber reinforced concrete (SFRC) *fib* Model Code to United States (US) practice was identified as a gap in the 2019 literature survey and synthesis. An experimental research plan was developed (see Section 1). During the industry workshop, it was learned that research on harmonizing steel fiber reinforced concrete *fib* Model Code to US practice is in progress. ASTM Committee C09 is currently in the revision stages of including a notched beam option within ASTM C1609. It was mentioned that this will be developed and published within the next 3-5 years.

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