Damages of segmental lining

International Tunnelling Association (ITA-AITES)
Working Group 2 – Research
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In years 2016 – 2018 the Italian Tunnels Society - Società Italiana Gallerie (SIG) Working Group 2 - Research, under the coordination of Andrea Sciotti and animated by Enrico Maria Pizzarotti, has prepared the present draft report and submitted it to the ITA WG2 Animateur and to the International Team Leader, as technical core of a possible final report to be further developed.

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After an independent evaluation of two experts, SIG decided to publish this draft report, as an attachment to the issue of the magazine Gallerie e Grandi Opere in Sotterraneo published on WTC 2019 occasion.
This draft aims to be just a contribution to be reviewed and completed by the ITA WG 2 members, to achieve a conceptual and final agreement on the document, through further discussion and meetings and, possibly, taking advantage of the results of an international survey on the subject, before the formal approval process of ITA.
The draft report provides an overview of the aspects that affect the quality of the precast segment's production and of the complete precast tunnel lining, to provide the parties involved in tunnel industry with a set of tools that can help to improve the segments’ production and the precast lining quality, in terms of:

• currently applicable standards and guidelines (Chapter 3)
• quality control (Chapter 4)
• types, causes, mitigation and repair of possible damages (Chapter 5)
• appropriate design procedure (Chapter 6)
• useful tests and checks, both preliminary and on the finished product (Chapter 7)
• bibliographic references (Chapter 9).

All the phases of the segment life, from factory production, transportation and delivery on site, installation, until handover and service life are considered.

Special attention is devoted to two different kinds of damage:

• non-structural driven damages, identified as technological damages (Paragraph 5.1)
• structural driven damages, related to the stress-response of segments and precast linings during the production (Paragraph 5.2, Chapter 6),
4 QUALITY CONTROL
4.1 Introduction
4.2 The Parties
4.3 Production Phase
4.3.1 Traceability and Data Record
4.3.2 Inspections, Acceptance and/or Repairs
4.4 Transportation and Delivery on Site
4.4.1 Traceability and Data Record
4.4.2 Inspections, Acceptance and/or Repairs
4.5 Installation
4.5.1 Traceability and Data Record
4.5.2 Inspections, Acceptance and/or Repairs
4.6 Handover and Service
4.6.1 Traceability and Data Record
4.6.2 Inspections, Acceptance and/or Repairs
4.7 Quality Enhancements
5 TYPES, CAUSES, MITIGATION AND REPAIR OF DAMAGES
5.1 Technological damages
5.1.1 Post Casting, Demolding, Handling, Overturning, Storage
5.1.1.1 Concrete Surface Defects
5.1.1.1.1 Hollows
5.1.1.1.2 Exposed reinforcement
5.1.1.1.3 Exposed aggregates
5.1.1.1.4 Removal of concrete skin
5.1.1.2 Defects due to inserts presence
5.1.1.2.1 Grout or grease leakage in dowels sockets
5.1.1.2.2 Unscrewing/disconnection and insert absorption in the casting itself
5.1.1.3 Gaskets’ damages
5.1.1.3.1 Anchored gaskets
5.1.1.3.2 Glued gaskets
5.1.1.4 Chipping of sides and corners
5.1.2 Handling and installation of the ring
5.1.2.1 Gasket damaging (expulsion or pull out during installation)
5.1.2.2 Chipping of sides and corners during handling
5.1.2.3 Chipping of edges during installation
5.1.2.4 Chipping of corners during installation
5.1.3 Thrust phase
5.1.3.1 Gasket compression from jacks’ plate
5.1.4 Grouting and operational phases
5.1.4.1 Gap and Offset
5.1.4.2 Water leakage from joints and bolt holes
5.1.4.3 Damages caused by contact with aggressive water
5.1.4.4 Damage caused by oil or fire
5.1.4.5 Unscrewing joint bolts
5.2. Structural damages
5.2.1. Post-casting, demolding, handling, overturning, storage
5.2.1.1. Description of damages
5.2.1.2. Causes of damage
5.2.1.3. Mitigation actions
5.2.1.4. Restoring actions
5.2.1.4.1. Defects due to inserts presence
5.2.1.4.2. Cracks and Fissures
5.2.2. Handling and installation of the ring
5.2.2.1. Description of damage
5.2.2.2. Causes of damage
5.2.2.3. Mitigation actions
5.2.2.3.1. Corner shape
5.2.2.3.2. Length of the ring
5.2.2.3.3. Number of segment per ring
5.2.2.4. Restoring actions
5.2.3. Thrust phase
5.2.3.1. Description of damage
5.2.3.1.1. Splitting / bursting cracks (transversal cracks perpendicular to the thrust force)
5.2.3.1.2. Longitudinal cracks along the tunnel and spalling cracks
5.2.3.1.3. Chipping of sides and corners
5.2.3.2. Causes of damage
5.2.3.3. Mitigation actions
5.2.3.4. Restoring actions
5 TYPES, CAUSES, MITIGATION AND REPAIR OF DAMAGES
5.2 Structural damages
5.2.4 Grouting and service phases
5.2.4.1 Description of damage
5.2.4.1.1 Loss of connector and bolt performance
5.2.4.1.2 Spalling during fire
5.2.4.1.3 Leaks from cracks on segments
5.2.4.2 Causes of damage
5.2.4.3 Mitigation actions
5.2.4.4 Restoring actions
5.2.4.4.1 Loss of Connector and Bolt Performance
5.2.4.4.2 Spalling during Fire
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5.2.4.4.4 Leaks from Cracks
5.2.4.4.5 Cracks (Wet or Dry)
5.2.4.4.6 Cracks on Lining
6 CALCULATION METHODS TO AVOID STRUCTURAL-DRIVEN DAMAGES

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6.2 Geometrical dimensioning
6.2.1 Geometrical tolerances
6.2.2 Components
6.3 Concrete segment lining modelling
6.4 Structural verifications
6.4.1 Construction stages and main design verifications
6.4.2 Structural verifications for the Prefabrication processing (at the prefabrication factory)
6.4.3 Transportation, handling and installation
6.4.4 Structural verifications for the TBM-advance phase
6.4.4.1 Local verifications
6.4.4.1.2 Verification of the induced tensile stresses
6.4.4.2 Global verifications
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6.4.5.1 Segment section design
6.4.5.2 Structural fire design
6.4.5.3 Seismic design
6.4.5.4 Impact load design
6.4.5.5 Connection system design
6.4.5.5.1 Gasket design
6.4.5.5.2 Bolt and dowel socket/pocket design
6.4.6 Junctions and interface with existing assets
ON SITE & LABORATORY TESTS AND CHECKS

7.1 Generalities
7.2 Preliminary tests on steel materials
7.2.1 Tests on rebars
7.2.2 Chemical composition test
7.2.3 Tensile test
7.2.4 Bend test
7.2.5 Clamping force of the bolts
7.3 Tests for post-casting, demolding, handling, overturning and storage
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7.3.2 Pull out test on rebars and sockets
7.3.3 Rebound Hammer Test
7.3.4 Ultrasonic Pulse Velocity Test (UPV)
7.3.5 Impulse Response Test
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7.4 Thrust phase
7.4.1 Thrust load test (point load test)
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7.5 Grouting and service phases
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7.5.2 Tests on an assembled ring
7.5.3 Sealing tests
7.5.4 Durability tests
7.5.5 Creep on sockets
7.5.6 Rebars corrosion
7.5.7 Fire testing
To eliminate or, at least, statistically reduce the onset of defects in precast segments, they should be considered as an increasingly advanced industrial product, which presupposes complex and advanced production systems and equally advanced and expert workers.

All operators in the production chain should be trained and qualified, perhaps certified by a third body, even after specific training courses. Project Owners should contractually require the employment of certified and/or specialized personnel, suited for the different roles of the production chain.

Linings geometry (thicknesses, angles, lengths, no. of segments per ring, diameters, etc.) should also be the subject of guidelines and standards, that could lead to a kind of quality mark, with different benefits for Contractors, Manufacturers and Project Owner, together with certification of environmental compatibility.

Specific standards should be defined for segments storage, such as how and how many segments can be piled up, after how long they can be exposed to the external environment and put in place, how they have to be protected them from environmental/climatic conditions, also with reference to transport and handling.

All the accessories of the segments, which significantly affect the whole design and implementation, are considerably influenced by technical and commercial factors. All these components must be defined and qualified in the tender project.

Structural Fire Design and Seismic Design are becoming increasingly important, but standards and guidelines often do not fully support the designer. The Project Owner should provide guidelines to evaluate the loads from thermal actions and those resulting from an earthquake.

Other topics of future insights are the damages caused by chemically aggressive water or environment and by stray currents.

The reduction of defects occurrence and the improvement of segments durability could be achieved using/experimenting new technologies, such as:

- Surface protective layers on intrados or extrados of segments
- Steel, mineral and synthetic fiber reinforcements
- Edges’ and corners’ GFRP reinforcements
- GFRP perimetric rebar cages, combined with fiber reinforcements.

Another important subject to be developed is the study, at the design stage, of the interaction between TBM and lining, which should be duly analyzed to allow multiple successive TBM’s uses.

A final cause for reflection could be the use of double lining, particularly frequent in hydraulic tunnels, which combines precast segment rings with an internal cast in situ lining. In these cases, the long-term integrity of the first lining must not be ignored, not to compromise the integrity of the whole system.
Further possible developments on Damages of Segmental Lining:

- Project Management procedure for production and installation
- Interaction between segmental lining and TBM
- Exceptional load conditions (earthquake, fire, explosion, shock, etc.)
- Durability and aggressive agents’ exposition
- Quality control and certifications
- Standardization of design, production and installation
- New technologies and products
THANKS FOR YOUR ATTENTION!