# Modern high precision high speed measurement of segments and moulds

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**ABSTRACT**

The precision that is required for the manufacture of the moulds that are used in the casting of segments for tunnel linings is frequently not stated. The tender documents for a typical segmentally lined tunnelling project frequently only give the dimensional tolerances for the finished segments. In some cases however only the tolerances for a sample build of 2 test rings is given. Increasingly tight tolerances that are now included in specifications for segment dimensional accuracy, demand a fast, accurate and reliable method for determining these values.
Delays in the overall progress of these projects are increasingly considered to be detrimental; consequently geometrical control of the moulds now frequently takes place at an early stage in the project, directly at the mould supplier's fabrication plant, this calls for easy to transport measurement equipment. In addition to checking linear dimensions, the angular properties of the moulds also need confirmation in order to fine tune the moulds, (if and when necessary) before any segment fabrication. Should any modification be necessary, the mechanics need to know exactly where to modify, how much and in what direction and have verification shortly after. The use of a Laser interferometer system now enables the accurate digitization of surfaces by direct polar coordinate measurement. Measurement to a single spherical retro-reflective prism enables the skilled operator to comprehensively measure the full profile of the object to be measured with over 20 segments per shift being achievable. State of the art software enables near real time processing of the measurements with comparison to original CAD drawings.
This paper will discuss the methods of rapid high speed measurement techniques and how they fit into a comprehensive QA/QC procedure, showing various examples from major projects in Europe and the Far East.

## 1. INTRODUCTION

Precast high quality concrete segments are typically used as liners in mechanical tunnelling. The assembly of these segments constitutes the tunnel's tube, which is circular in cross section.
The production of concrete elements is usually done within a manufacturing plant on site or close by. During the production process a concrete mixture is poured into precisely assembled steel moulds. Due to high demands for the geometrical properties of all moulds, the use of a proper quality control system is essential to minimize the fabrication of defective segments.
Theoretically such segments obtain their final geometric dimensions after the stabilizing of the concrete's shrink and creep. As a result of this the measurements should take place just before the elements are used for the tunnel construction. However, to ensure effectiveness of the production process monitoring in this way is not suitable.
Since a segment typically only gains maturity in about 28 days, quick reactions on any detected deviations would be prevented. In addition to this, in the case of almost constant conditions during

production and storage the assumption of a similar constant effect for shrink and creep can be made and therefore disregarded.
For this reason it is highly recommended to check the geometry at one specific phase of the production, i.e. between de-moulding  and gasket's fixing.

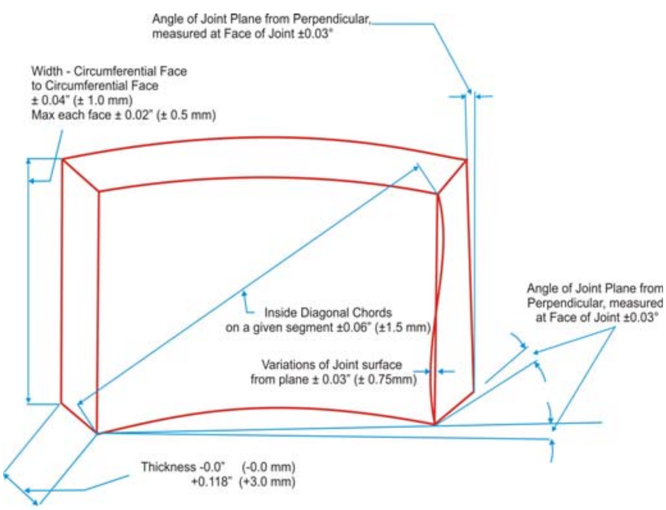



Figure 1 Segmental Tolerance Nomenclature

The required accuracies are usually gathered from the German Standard "Federal Railways Regulations DS853" and adapted to certain project specific parameters. As ring-built-tolerances range in cm, tolerances for segments themselves are consequently stated in mm or even less. In turn the measurement accuracy should not exceed some few tenths of a millimetre. Conventional instruments like micron rods or templates lack the global geometrical certification for an object. Theodolite measurement systems and photogrammetric systems lack the speed with the necessary accuracy. Only by the use of a 3D industrial measurement system can such requirements be met at a rate necessary for a high speed QA/QC programme.

| | | | | |
|---|---|---|---|---|
| 1 | Circumferential length | +3mm | -0mm | |
| 2 | Thickness | +3mm | -1mm | |
| 3 | Width | +1mm | -1mm | |
| 4 | Internal Diameter of completed ring | +0.15% | -0mm | of theoretical diameter |
| 5 | Bolt Hole sizes | +1mm | -0mm | |
| 6 | Bolt hole and dowels: position | +1mm | -1mm | |
| 7 | E & M Fixing Holes | (TBA) | (TBA) | |
| 8 | Gasket Grooves: depth | +0.5mm | -0.5mm | |
| 9 | Gasket Grooves: width | +0.5mm | -0.5mm | |
| 10 | Longitudinal Joints<br>In plane containing axis of the tunnel (longitudinal)<br>In a Radial plane | <br>0.3mm<br><br>0.1mm | | <br>from theoretical plane with rate of deviation not exceeding 0.6mm/m<br>from theoretical plane with rate of deviation not exceeding 0.6mm/m |
| 11 | Circumferential faces | 0.5mm | | from theoretical plane with rate of deviation not exceeding 1mm/m |
| 12 | Smoothness of other faces<br>Back<br>Front | <br>+1.5mm<br>+1mm | <br>-1.5mm<br>-1mm | <br>smooth float<br>formed |

Table 1. Typical Segmental Dimensional Tolerance as given in tender documents.

## 2. PRIMARY CONTROL

The precise control of the geometry of a mould by 3D survey before producing the first segment, as well as the control of the first produced segment itself is indispensable in order to check and verify any set of moulds. The direct comparison of the findings for related moulds and segments will permit the detection of deviations from the design values to sub-millimetre accuracy. The primary control is

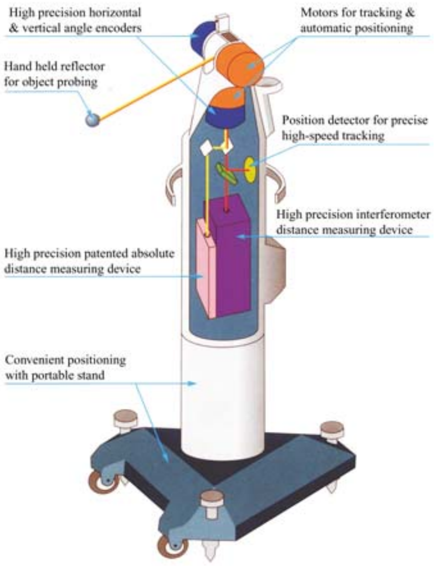
carried out ahead of, and independent to, the regular production. It comprises not only the geometric verification but the potential for verification of recesses for gaskets, bolts, identifiers, reference markers, etc.
Attention should be drawn to the requirement, that all moulds and segments shall be exposed to the same environmental conditions and are undergoing the same stock / storage conditions.
The most important results, the 3D-coordinates of the object points, will be obtained in the format "point-name X Y Z dx dy dz". These records are the object's coordinates in space along with an estimated accuracy of the internal quality criteria. The evaluation of the standard geometry and the comparison with design values and relevant tolerances will take place directly after the evaluation of spatial coordinates with help of the programme "TubGeo©".

## 3. SECONDARY CONTROL

Secondary Control is the term to denote the cyclic verification of complete sets of segments (i.e. complete rings) and related sets of moulds. Typical cycle times might be for example 'one ring and one set of moulds per week', or the results of the Tertiary Control may be referred to as the selection criteria. The object (segment or mould) to be checked will be taken from the production process (storage or carousel) and placed at a convenient location somewhere in the production hall. For a cyclic Secondary Control the verification of the 6 outer surfaces and from them the derived distances and angles, is essential.
The data processing runs semi-automatically by help of only a few menu functions. The main result of the data evaluation shall be displayed in a summary report, this includes the measurements and clear statements about the tolerances, whether they have been kept or exceeded.

## 4. LASER INTERFEROMETER SYSTEM

The use of a Laser interferometer system now enables the accurate digitization of surfaces by direct polar coordinate measurement. Measurement to a single spherical retro-reflective prism enables the skilled operator to comprehensively measure the full profile of the object to be measured (either mould or segment).
Laser Interferometer Systems are usually employed where large numbers of spot points are to be surveyed with the highest accuracy and the shortest interruption to the production process. Special attention has been drawn to the flexibility of the systems and the automated measurement and data evaluation process.




The advantages of the Laser Interferometer Systems are:-

- Mobility of the system for measurements of the objects directly at the production location
- Flexibility of the system can be configured to various control tasks
- Short time requirements to survey the objects
- Three-dimensional information about the objects
- Easy handling
- High accuracy
- High degree of automation
- Interfaces to a wide variety of evaluation programmes
- Interfaces to most usual CAD systems
- Interfaces to word processing and spread-sheet programmes (like Word, Excel, etc.)

Figure 2 Laser Interferometer schematic

## 5. OPERATING PROCEDURE

The process commences with the establishment of the frequency of measurement points to be taken. These may be at a time dependent interval, distance interval or by working to a grid matrix.
For the actual use of the Laser Interferometer System in the measurement of segments and moulds VMT has included dialogue aided scripting for the operator to clearly explain the processes of each measurement operation.

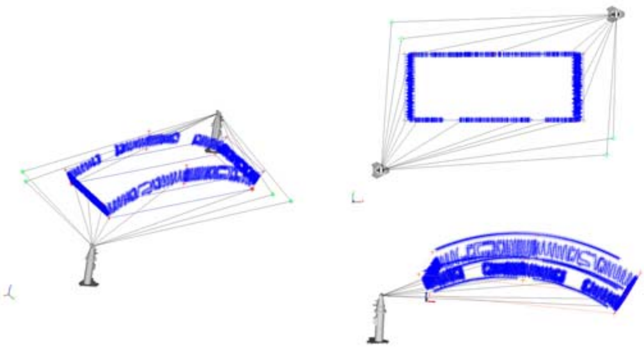


Figure 3 One man operation measurement of Mould

As the complete measurement of the mould or segment cannot be accomplished from a single standpoint it is necessary to relocate the Laser Tracker to a second standpoint.
To ensure that all the measurements taken can be reconciled within the same coordinate framework, index measurements are taken to the prism that is located in a "birds nest" cradle. Between 4 and 6 of these indexing locations are established and the dialogue control informs the operator when to locate the prism in the appropriate cradle.
Upon commencement of a measurement cycle the operator places the retro-reflective prism in the reference point receptacle on the Laser Tracker stand. The instrument is then able to carry out its own internal calibration and establish its zero reference point.
The operator then removes the retro-reflective prism and making sure that the laser beam from the instrument is always in line of sight of the retro-reflective prism. He will commence the systematic tracing of the prism over the surface of the mould or segment that is to be measured, making sure to include all the significant surface points.
If the line of sight between the LaserTracker instrument and the prism is broken then the prism must be relocated at a stable position to re-zero the system. The measurement can then recommence at the point where line of sight was broken.
The typical time taken to conduct the measurements for all six surfaces including the relocation of the Laser Interferometer Instrument as well as the analysis of the results is approximately 30 minutes. To increase the speed of segment measurement stacks of 3 segments in two groups enables 6 segments to be measured from only 3 instrument locations.

Figure 4 Instrument location for mould measurement

Figure 5 Stacked segments for rapid measurement

| **Equipment - Typical specifications:** | |
|---|---|
| The Leica LTD800 Laser Tracker is a high accuracy tracking 3D laser interferometer with high precision angular encoders for a measurement volume of up to 70 m diameter and a measuring rate of up to 3000 points per second. | |
| **Principle of operation:** | **Tracking** |
| Single beam heterodyne interferometer | Maximum target speed : |
| Class 2 Laser - < 0.3mW/CW | In direction of laser beam > 6 m/s |
| Wavelength - 633nm (visible) | Right angles to laser beam > 4 m/s |
| Beam Diameter ($1/e^2$) - ≈. 4.5mm | **Accuracy** |
| Beam divergence – no divergence collimated | Angle resolution 0.14 arc sec |
| **Flexible Application:** | Distance resolution 1.26 µm |
| Set-up independent of object size or space restrictions | Absolute accuracy (2sigma) of a coordinate for static targets ± 10 ppm (µm/m) |
| 3D determination of large objects | **Range of measurement** |
| Internal automatic function control | Horizontal ± 235° |
| Certified accuracy | Vertical ± 45° |
| Industry proven sensor head | Distance 0 - 40 m |
| Instrument is light and portable | **Measuring Rate** |
| Certified environmental sensor compensation | Measurement rate - 3,000 points per second |
| Rugged hardware largely insensitive against transportation | Measurement rate output – 1,000 points per second |

Table 2. Laser Interferometer specifications.

## 6. EVALUATION SOFTWARE

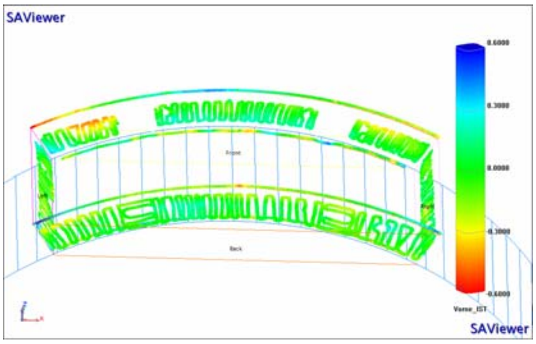


Figure 6 Vector Group Comparison

Spatial Analyzer (SA) is a traceable metrology 3D graphical software platform used for the running of the LaserTracker. SA software architecture is based on always maintaining fundamental data integrity by storing the basic metrology measurements and therefore maintains traceable links for Quality Assurance. SA's graphical environment allows the user to download the CAD model and use the spatial transformation capability for optimum fitting analysis (best Fit and bundling).

The Field proven TubGeo© software has already proven its functionality and enormous potential in numerous measurements. It has been developed employing modern software techniques in the programming language C++ with no restrictions in mind. With its help it is possible to calculate the external surfaces by “best-fit” and derive all relevant intersection measurements. The calculated output can be given numerically, graphically or in a combination of both. The resulting high-performance package including TubMes©, together with optional software such as CAD Import / Export, Freeform surface calculation etc. gives a tailor-made solution to suit individual needs.

## 7. DECISION MAKING PROCESS

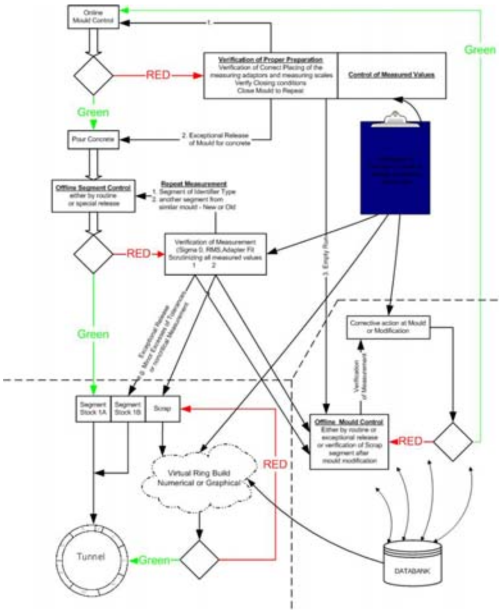



Figure 7. Decision Making Process

Segment fabrication for large size tunnel projects typically proceeds in cycles with the delivery of moulds, verification of their geometric properties, production of segments, verification of geometric properties, maintenance and refinement, if and where necessary, of the mould's mechanical and geometric properties. A proven approach to sensible, but economical quality control is the classification of checked moulds and segments into three classes: Green (released for production, unconditionally), Red (set aside, until remedied) and Yellow (released under certain constraints, subject to refinement at a later stage). The adjacent flow-chart illustrates some of the potentially resulting complexity of different cases that may occur. However, the benefits of never transporting deficient segments into the tunnel will quickly reward the additional efforts undertaken to keep the unwanted surprises as few as possible.

## 8. CONCLUSIONS

This paper outlined the sophisticated equipment that is now available for use at mould and segment productions facilities for the rapid measurement of the dimensional accuracy of segments. It should be noted however that whilst the fabrication management typically seems to be committed to the mould or segment's mechanical integrity, in the past the same attention to their geometric properties all along the production period has not necessarily been as strong. It has also been observed that there seems to be the beginning of a new way of thinking by fabrication managers, towards the prevention of failures in the first place, at least as far as the quality control of the moulds and segments geometric properties is concerned. This is a dynamic process, not so much insisting on a purely rigid sequence of verification measurements in terms of 'every 20$^{th}$ segment', or so, but by reacting flexibly with close follow-up of recognized problematic examples, and giving them the attention they deserve. We should also bear in mind that this approach will need very good equipment, operational procedures and equally or even more importantly highly motivated and skilled personnel, in order to capitalize on the equipment's potential for quality control and quality assurance.

## 9. REFERENCES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