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Introduction

Muon tomography is being increasingly adopted within the civil engineering sector, particularly for the deep internal examination of reinforced and post-tensioned concrete structures that have previously been beyond the reach of traditional NDT methods.

Muon tomography is a passive, non-destructive examination technique that exploits the natural flux of cosmic-ray muons: high-energy sub-atomic particles that continually bombard the Earth's surface and penetrate deep into dense materials. By measuring how muons scatter and are absorbed as they pass through a structure, it is possible to reconstruct the internal density distribution and identify embedded objects such as steel reinforcement and post-tensioning systems, together with any associated defects.

This note has been prepared to assist engineering consultants, contractors and asset owners who are adopting muon tomography for the first time on their structures, by briefly setting out the stages of post- processing and results extraction from the raw measurements. A case study is also included, demonstrating how muon tomography has delivered real value to an asset owner in a way that was not previously possible.

Results - Reconstruction

Particle detectors placed on either side of the structure record the trajectories and energy ranges of incoming and outgoing muons. Reconstruction is the first stage of post-processing, in which the volume of interest is discretised into thousands of small cubes, known as voxels. The muon scattering and absorption behaviour within each voxel is analysed and reassembled in three-dimensional space to form the reconstruction, with voxel properties presented on an intensity scale representing scattering angle or material density.

In simplified terms, the reconstruction reveals both the internal structure of the element and its material composition: high-intensity (brighter) regions correspond to dense steel, moderate-intensity regions to concrete, and low-intensity (darker) regions to voids or areas of reduced density. Two-dimensional tomographic slices, akin to X-ray images, can be taken through the 3D reconstruction in any plane, allowing the internal structure to be examined at any depth within the scan volume.

Refer to Figure 1 for an example reconstruction taken through a post-tensioned concrete structure.

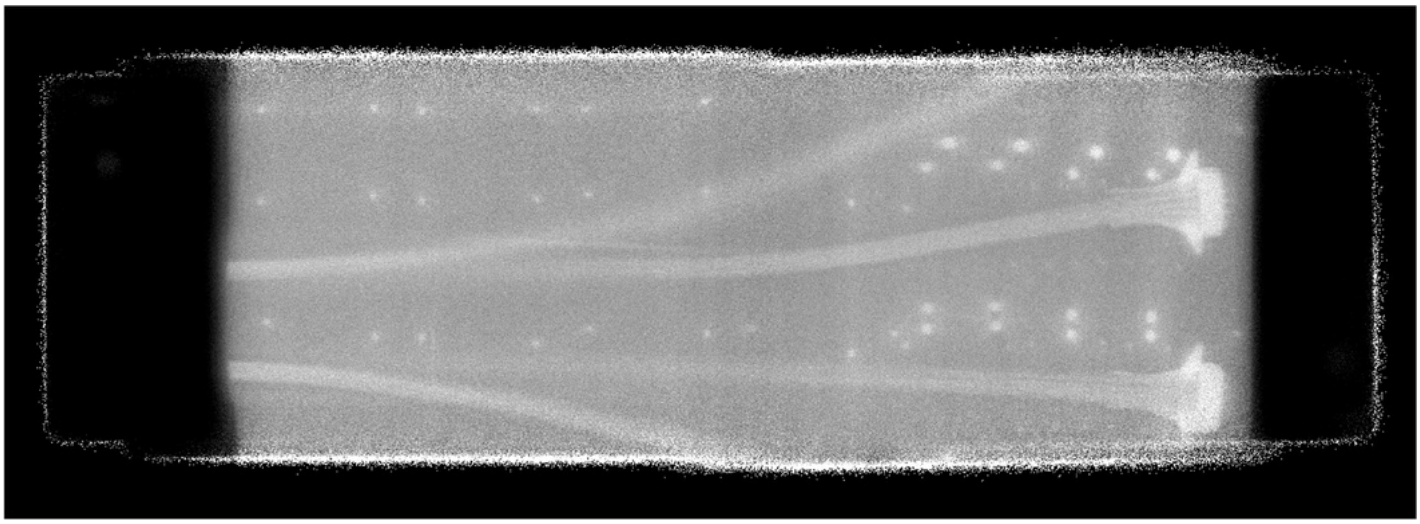


Figure 1 - Example reconstruction taken through a post-tensioned concrete structure

Results - Object Detection

To assist with interpretation of the reconstruction, a machine-learning-based object detection tool is applied to automatically identify and mesh the embedded steel elements, the reinforcing bars and PT tendons, generating three-dimensional solid models of these elements. Refer to Figure 2 for an example object detection from a half-joint in a post-tensioned concrete bridge.

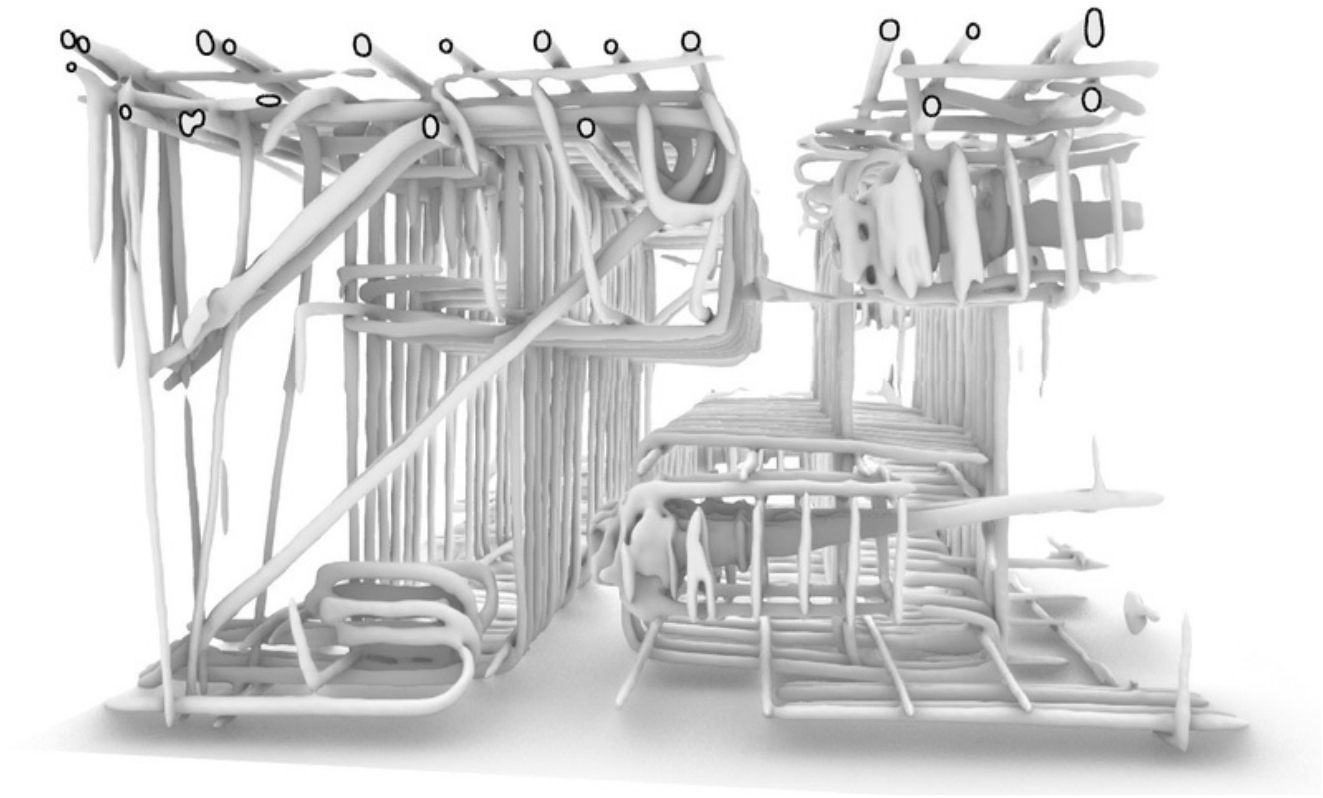


Figure 2 - Example object detection from a half-joint in a post-tensioned concrete bridge

Beyond enabling easy interpretation of the arrangement and detailing of the embedded parts, the object detection also allows cross-sectional areas and diameters to be extracted. Previous measurements have demonstrated that this process can achieve an accuracy of within ±2mm of the actual diameters.

Results - Tendon Analysis

In addition to mapping the arrangement and dimensions of the embedded steel, a more advanced post-processing step, referred to as tendon analysis, can be applied to detect potential defects such as loss of section through corrosion, breaks in the prestressing steel, or incomplete tendon duct grouting.

The reconstructions are initially reviewed manually, slice by slice, for any evidence of anomalies, similar to the approach typically used in radiography. Additional insight into smaller defects can then be gained through further post-processing: the methodology locates the position and alignment of each tendon within the object detection model and automatically generates enclosing cylinders around each tendon, encompassing the prestressing steel, grout and duct wall. A suite of sliding window metrics is then computed along the length of each cylinder, including mean scattering angle and signal-to-noise ratio, with cross-correlation from multiple independent data sources and analytical methods used to assess and assign a confidence rating to any identified anomaly.

Refer to Figure 3 for an example measurement containing a series of PT tendons, one of which is only partially grouted. Darkened lines are visible between the individual strands where the grout is missing, compared with a fully grouted tendon, where a bright signal is present across the entire tendon section.

Refer to Figure 4 for an example measurement containing a series of PT tendons, one of which includes a number of strand breaks. These are visible on the reconstruction, taken through the lower level of strands, as dark discontinuities in the otherwise bright prestressing steel. The same defects are also evident in the sliding window metric, where the dark blue areas show a localised reduction in muon scattering, indicating less dense material being present within the tendon duct in these locations.

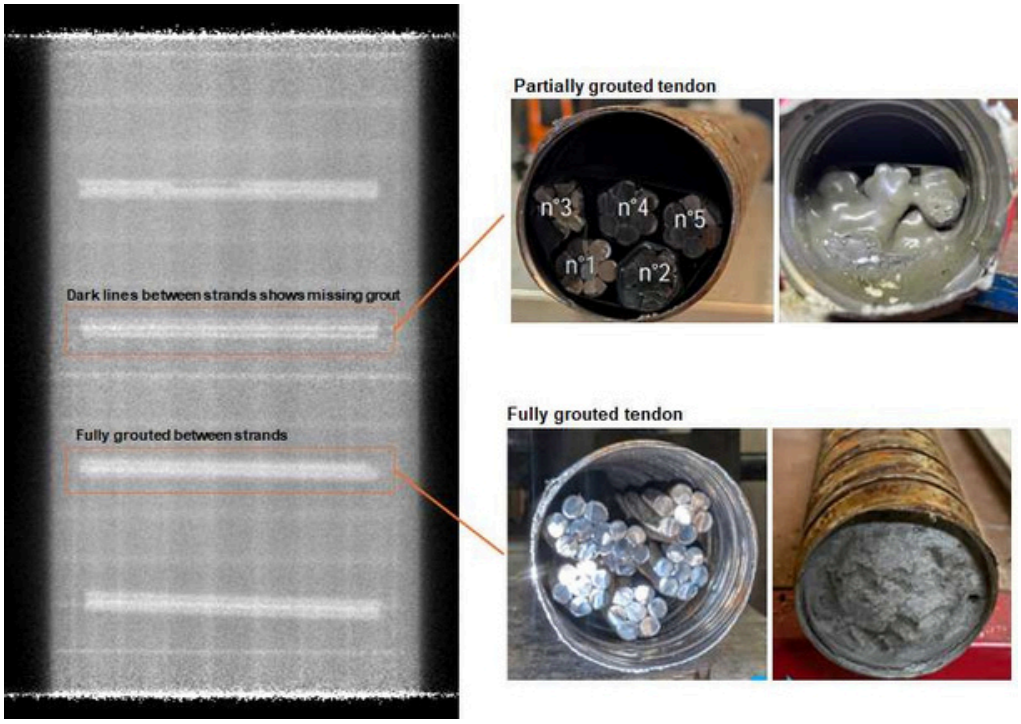


Figure 3 - Example results for partially grouted vs fully filled tendon duct

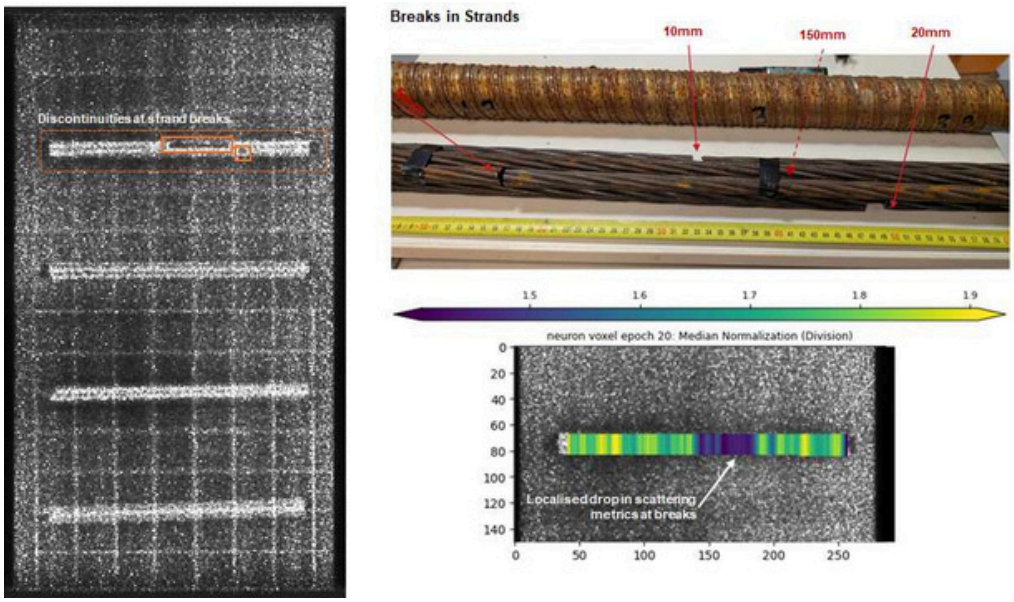


Figure 4 - Example results for broken strands inside a tendon duct

Case Study – Llanrhystud Bridge

Llanrhystud Bridge is a single-span post-tensioned concrete slab deck carrying the A487 Trunk Road over the Afon Wyre in Wales. The structure was originally constructed in 1962 and subsequently extended in 1994, when reinforced concrete edge beams were added to support the parapets and footways.

No original construction drawings exist for the 1962 deck. Whilst a full set of as-built drawings is available for the 1994 widening works, these provide no detail of the PT systems beyond the anchor positions for the transverse tendons. As a result, the arrangement, dimensions and condition of the longitudinal and transverse PT systems, and of the reinforcing steel within the original slab, have remained largely unknown.

A Post-Tensioned Special Inspection (PTSI) confirmed the presence of longitudinal post-tensioning; however, the existence and arrangement of transverse post-tensioning remained uncertain, with prior GPR surveys and intrusive coring both proving inconclusive, largely due to foil-backed waterproofing at the deck surface and congested reinforcement in the regions of interest.

As an alternative, muon tomography was deployed at the bridge to:

1) Establish construction information.
2) Determine the location and dimensions of the reinforcement and PT apparatus.
3) Use the results to identify suitable locations for intrusive inspection of the PT systems.

Two pairs of XL-size particle detectors were installed on the bridge, with measurements conducted over 16 days for the 1.2m deep bridge deck.



Figure 5 – Installation of particle detectors at Llanrhystud Bridge

The full arrangement of longitudinal and transverse PT tendons, multiple layers of reinforcing steel, vertical shear links and dowel bars was resolved within the scan volume, addressing long-standing uncertainty about the internal construction of the 1962 slab deck. Calibrated cross-sectional area measurements, referenced against known bar diameters from previous concrete breakouts, enabled equivalent bar and tendon diameters to be estimated to within approximately 2 mm accuracy for all element types.

One of the practical outputs of the muon tomography examination was the identification of suitable locations for targeted intrusive coring to expose and directly inspect the PT tendons.

The muon tomography results provided sufficiently precise information on the position and alignment of the surrounding reinforcement to allow drilling coordinates and inclinations to be specified that would successfully sample each target tendon whilst avoiding damage to adjacent bars, refer to Figure 6.

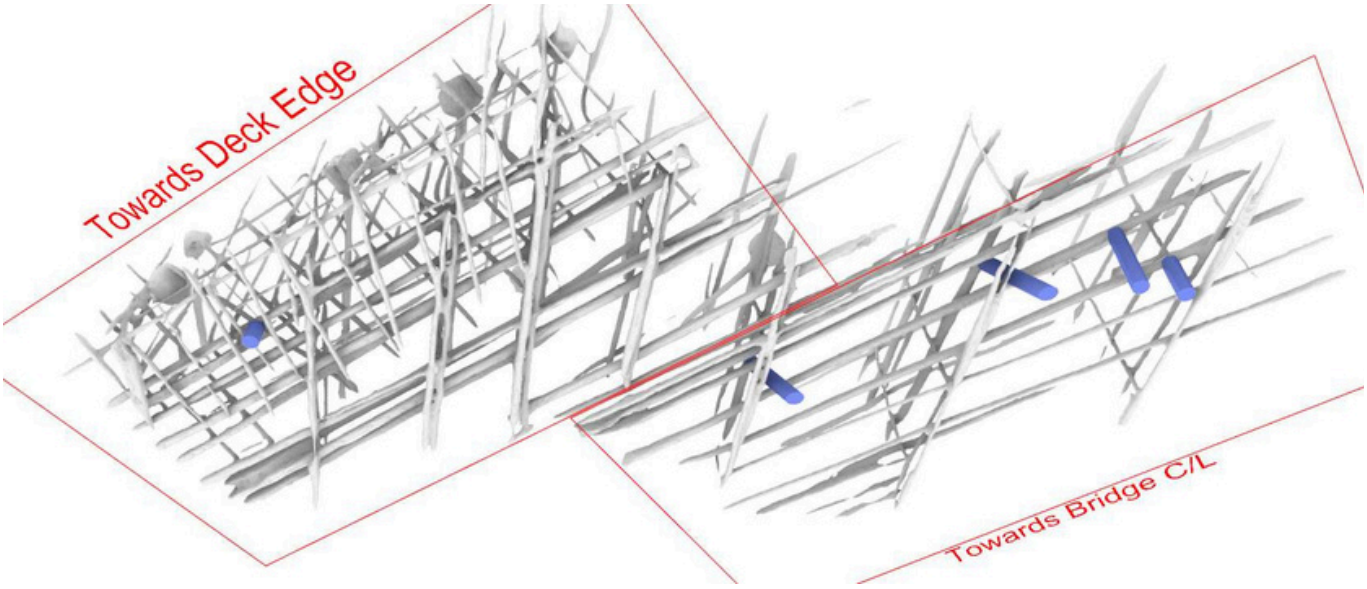


Figure 6 – Identified coring locations for targeted tendon exposures

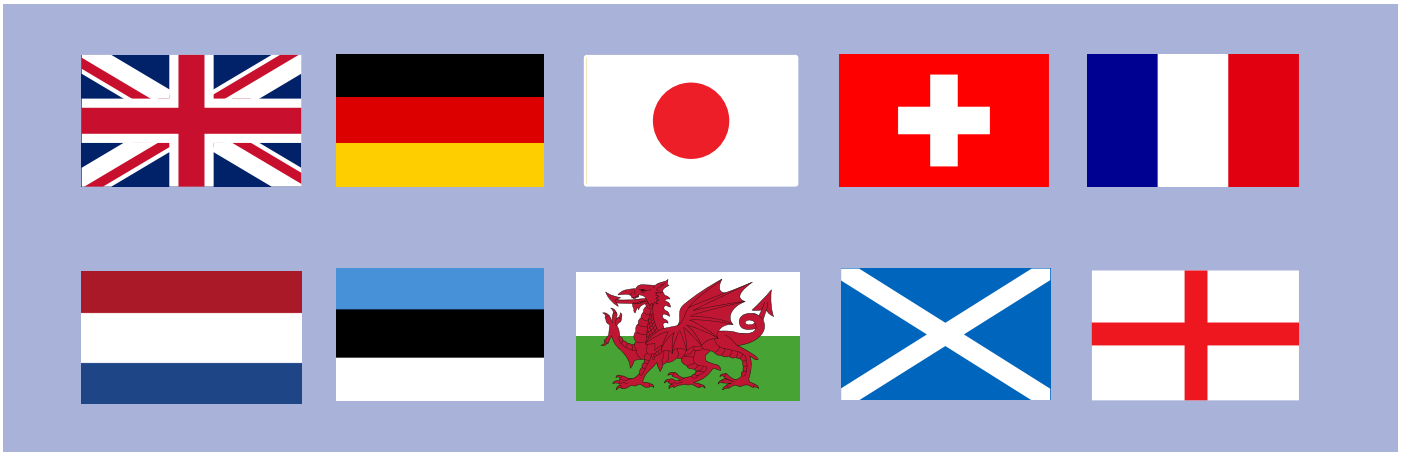
The physical locations of the tendons and reinforcing bars encountered during coring were consistent, in all cases, to within millimetre accuracy of the coordinates, drilling inclinations and depths specified from the muon tomography results. Areas of concrete voiding identified within the slab around the congested tendons were confirmed on site, as was a suspected anomaly identified through tendon analysis, which was confirmed as a grouting defect at one of the tendons.



Figure 7 – Intrusive coring works guided by muon tomography measurements, successfully confirming concrete voiding and tendon defects

The Llanrhystud case study demonstrates that muon tomography results can resolve long-standing construction uncertainty and withstand direct physical verification, providing a reliable basis for condition assessment and quantitative structural assessment of ageing, reinforced and post-tensioned concrete infrastructure.

Since officially launching in 2025, GScan's technology has been deployed in 10 countries, to 15 in-service bridges and 2 tunnels.



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