# Smart analysis of infrastructures through system engineering and AI


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## Introduction

The existing infrastructure heritage is currently experiencing a decrease in safety levels, especially due to aging and degradation effects. Bridges and tunnels are the most important large civil engineering infrastructure items. They perform strategic functions, allowing communication routes to be connected to overcome natural obstacles. As a result, there has been a noteworthy increase in interest in structural health monitoring (SHM) research over the last decade. The current diagnosis paradigm for road tunnel health assessment requires a knowledge phase based on original drawings, documentation, structural testing reports, material and periodic visual inspections. This procedure would be prohibitively expensive. As a result, non-destructive and indirect techniques have been successfully integrated into cost-effective diagnosis and maintenance plans as Ground-penetrating radar profiles (GPR), laser scanners, and thermography acquisitions.

When GPR is used to monitor the health of a tunnel, the GPR linings require experienced personnel to detect and classify any defects. To reduce the influence of different experts' subjectivity and to limit the considerable economic investment it is unthinkable not to exploit deep learning (DL) methods, as they provide modern and powerful tools for automatic image processing and classification. Nowadays, machine learning tools are in the spotlight because of their outstanding capabilities to deal with data coming from even heterogeneous sources and their ability to extract information from the structural systems, providing highly effective, reliable, and efficient damage classification tools.

The application of these tools, combined with systems engineering principles, could enrich the world of civil infrastructure that has not been designed from the perspective of optimal inspection maintenance and durability.

## Research Activities on the AI topic

The starting point was the development of the results from the thesis. Where a **Multi-defect Damage Classification** of the concrete lining of tunnels was defined through the use of a **Convolutional Neural Network ResNet-50**.
The classification was based on the creation of a database containing various defects of the concrete lining. The images used for the damage classification were there of a GPR campaign and their intepretations were used to define the database labels (Fig.1).

Subsequent enrichment of the available database of possible defects found in tunnel linings and implementation of valuation tool were adopted. To perform tunnel lining condition rating, the methodology was developed in six levels, as depicted in the flowchart in Fig. 2. Moving from the lower to the higher levels, it is possible to achieve more detailed knowledge about the presence and the type of structural damage.

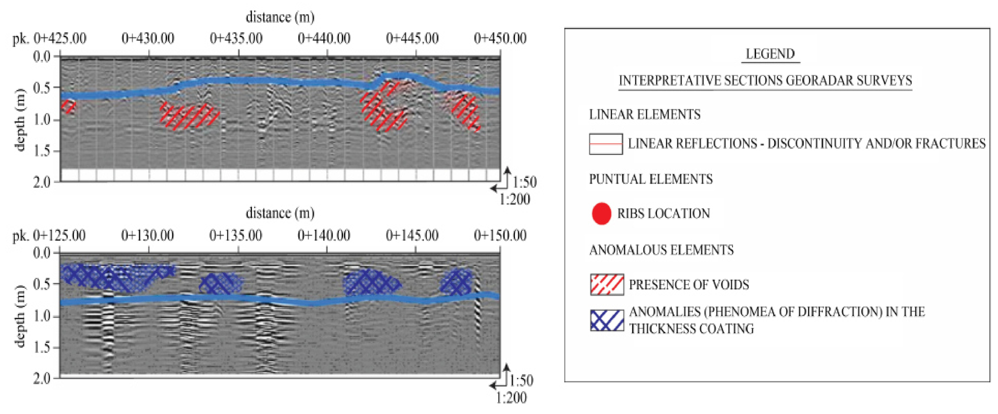


Figure 1. Interpretations of GPR longitudinal profiles

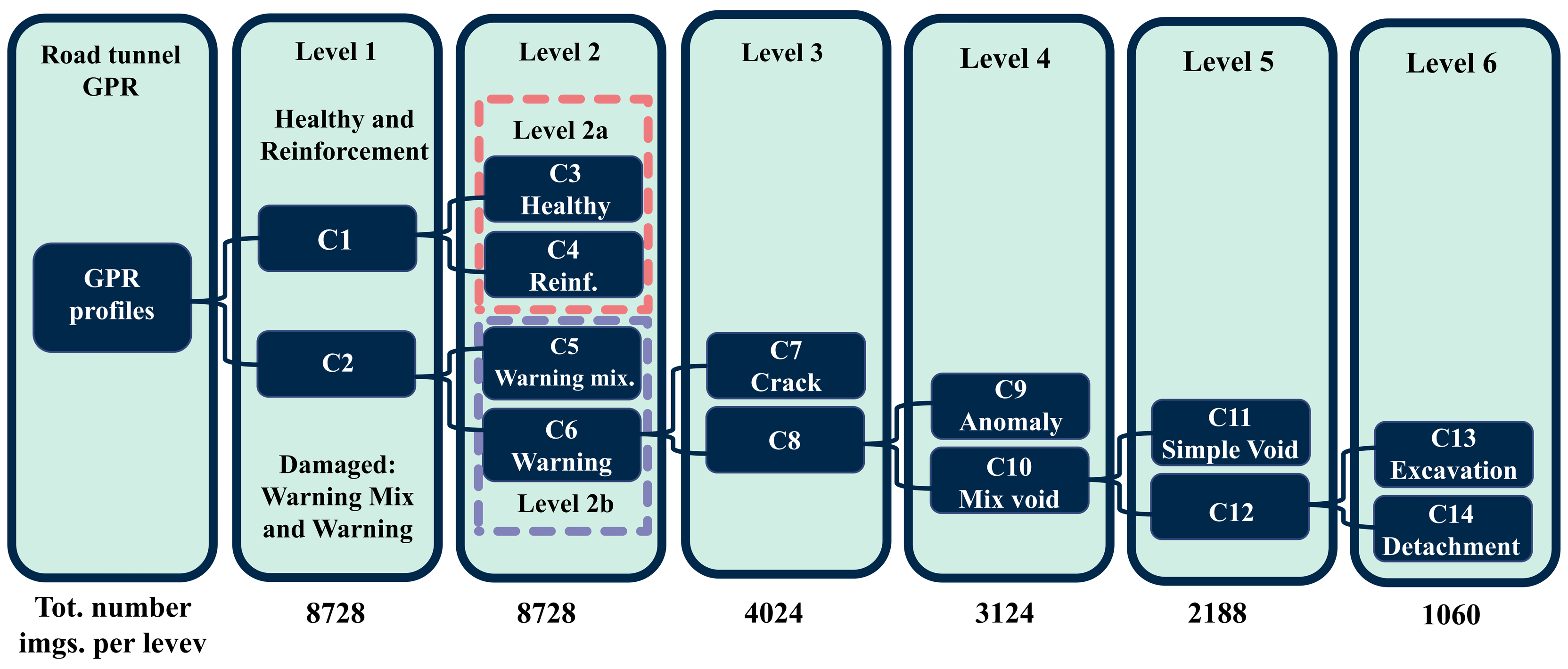


Figure 2. Hierarchical tree multi-level classification representation

The algorithm classification performance was valued by:

- Confusion matrix and accuracy (arithmetic mean through the K-fold validation technique)
- RMSE (Root Mean Square Error);
- Convergence graph (loss/accuracy versus number of iterations).

| Real class | C11 (predicted label) | C12 (predicted label) |
|---|---|---|
| C11 | 98.8% | 1.2% |
| C12 | 2.2% | 97.8% |

Table 2. Confusion matrix – Level 3

The **2D-FFT** has been adopted to perform **a pre-processing of the road tunnel GPR linings profiles**. This may help to compress data, maintaining the geometric structure of the starting digital image. The pre-processing phase probably produces an excessive compression of the data, providing lower accuracy levels with respect to the model trained on raw GPR images samples.

To analyze the effects of the model architecture on the GPR tunnel defects' classification, the results of ResNet-50 was compared with a different state-of-art convolutional architecture, i.e. the **EfficientNet.** The results evidenced that the recent EfficientNet architecture represents a sort of trade-off choice between efficiency and classification accuracy since it was able to reach in virtually all cases almost the same order of magnitude of accuracy levels.

With the same aim that led to the development of the previous algorithms, the same database was exploited for training two new types of configuration of the most recent state-of-the-art advanced neural architectures: **Neural Transformers.**

- **Vision Transformer (ViT),** whose core is an encoder entirely based on the innovative self-attention mechanism and does not rely on convolution at all.
- **Compact Convolution Transformer.** a ViT improvement that combines convolution and self-attention (CCT) taking the desirable properties of CNN, such as efficiency, learnable weight sharing, local information preservation and preservation of local information.

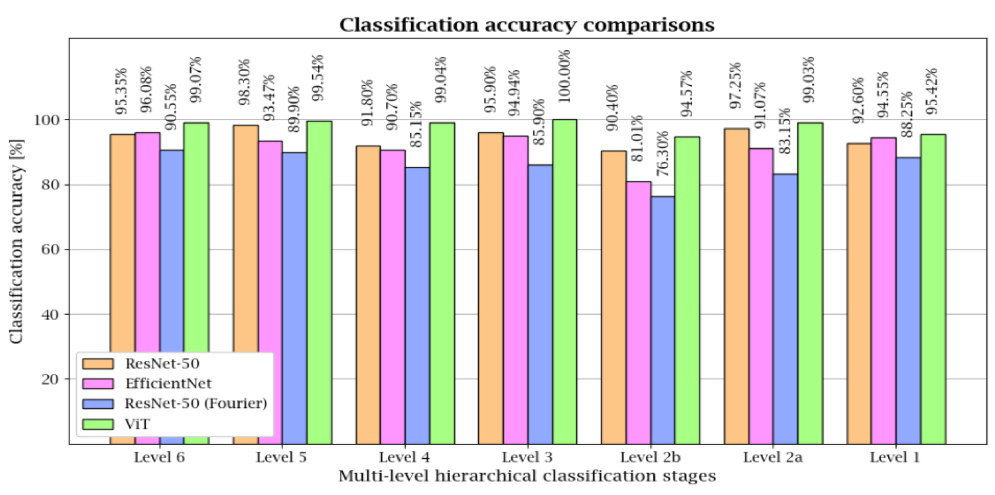


Figure 3. Accuracy values for every single level of the proposed hierarchical multi-level classification tree

## Analytical Models of Tunnel Lining Thickness Anomalies

GPR surveys of tunnel linings on the Italian highway network show local thickness reductions at the vault key.
Assumptions:
$h_1$ is the height of thickness reduction;
$h_2$ is the height of design thickness;
the analyses are limited to the calotte portion, i.e. the area where the thickness anomaly can be found;
the lining's curvature is assumed to be infinite. This assumption is supported by the fact that the extent of the defect is relatively limited;
the lining portions considered are not stressed by compressive forces along the middle plane;
the only forces at work are vertical forces (permanent load $P = \gamma_{cls} h$) and thermal ones;
the soil has a consistent and uniform temperature of $T_S$
linear variation of the temperature along the lining thickness (uniform gradient), given that the internal temperature, $T_i$, is higher than the soil temperature;

$$\Delta T = \frac{T_i - T_S}{2}$$

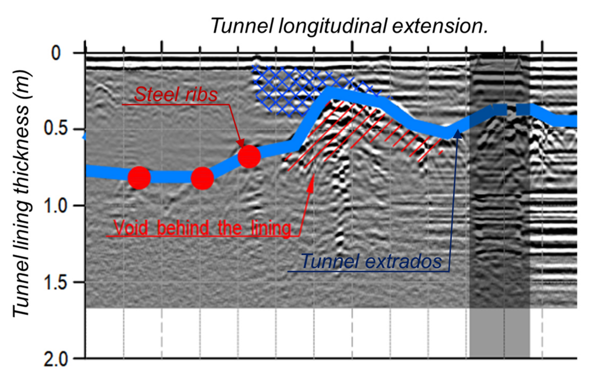


Figure 4. Thickness reduction detection from Georadar restitution

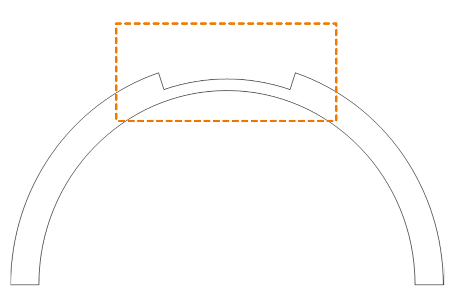
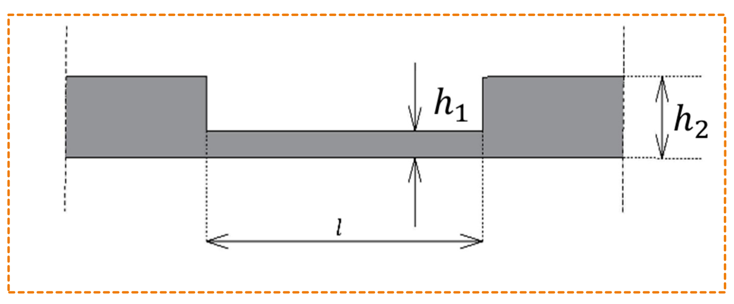
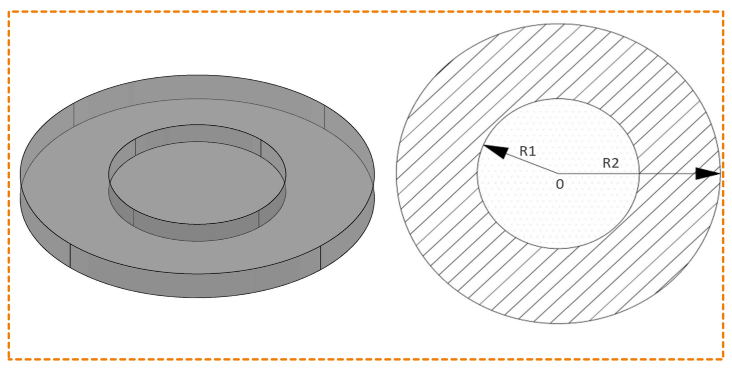


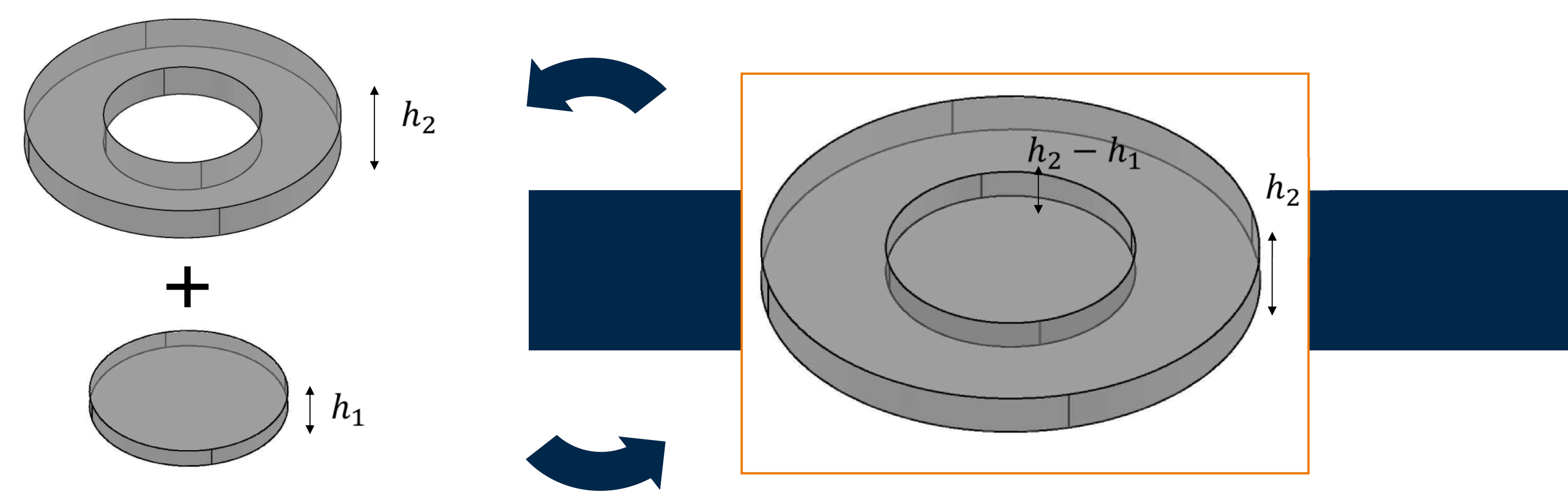
Figure 5. Schematic of tunnel lining with key lining thickness anomaly



**1 – dimensional model**: Equivalent beam of rectangular cross-section, with anomalous thickness and confined at the ends



**2 - dimensional model**: Equivalent circular plate, with anomalous thickness and confined at the ends




The two zones currently investigated in the two models are at the center of the plate(r = 0) and at r close to R1, where R1 is the radius of the zone where the thickness anomaly is recorded. For the two diemension model:

$$\Delta Tcr_{rr} = \frac{\sigma_{rr}(1-v^2) * \frac{D_1}{E\left(-\frac{h_1}{2}\right)} + K(r)}{(1+v)\alpha\left(-D_1\frac{1}{y}\left(\frac{D_1}{h_1}-\frac{D_2}{h_2}\right)\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)(1+v)-\frac{D_1}{h_1}\right)}$$

$$\Delta Tcr_{\vartheta\vartheta} = \frac{\frac{\sigma_{\theta\theta}(1-v^2)D_1}{E\left(-\frac{h_1}{2}\right)} + Q(r)}{\alpha(1+v)\left(-D_1\frac{1}{y}\left(\frac{D_1}{h_1}-\frac{D_2}{h_2}\right)\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)(1+v)-\frac{D_1}{h_1}\right)}$$

Where:
$y(r) = f(R_1, R_2, h_1, h_2, E, v)$
$K(r) = f(R_1, R_2, h_1, h_2, E, \gamma_{cls}, v)$
$Q(r) = f(R_1, R_2, h_1, h_2, E, \gamma_{cls}, v)$

## Publications


- **Aiello, Salvatore,** De Biagi, Valerio, Chiaia, Bernardino, Alessio, Carlo, Baccolini, Lapo, & Fantuz, Roberta. (2023). Analytical study of anomalies in tunnel lining thickness: Critical temperature variations. In Expanding Underground-Knowledge and Passion to Make a Positive Impact on the World (pp. 2951-2958). CRC Press.
- **Aiello, Salvatore**, De Biagi, Valerio, Cornetti, Pietro, & Chiaia, Bernardino (2023). Analytical study of a circular plate with thickness anomaly: critical temperature fluctuation in the tunnel. Procedia Structural Integrity, 47, 668-674.
- Rosso, Marco Martino; Marasco, Giulia; **Aiello, Salvatore**; Aloisio, Angelo; Bernardino, Chiaia; Marano, Giuseppe Carlo (2023): "Convolutional networks and transformers for intelligent road tunnel investigations", Computer and Structures
- Chiaia, Bernardino; Marasco, Giulia; **Aiello, Salvatore** (2022): Deep convolutional neural network for multi-level non-invasive tunnel lining assessment. In: FRONTIERS OF STRUCTURAL AND CIVIL ENGINEERING. ISSN 2095-2430
- Chiaia, Bernardino; Marasco, Giulia; **Aiello, Salvatore** (2022): Innovative strategies to preserve the Italian engineering heritage: the historical tunnels. In: XX International Forum World Heritage and Ecological Transition, Napoli (Italia);, 8-9-10 Settembre 2022, pp. 158-165. ISBN: 9788849245301
- Marasco, Giulia; Rosso, Marco M.; **Aiello, Salvatore**; Aloisio, Angelo; Cirrincione, Giansalvo; Chiaia, Bernardino; Marano, Giuseppe Carlo... (2022): Ground Penetrating Radar Fourier Pre-processing for Deep Learning Tunnel Defects' Automated Classification. In: EANN 2022: Engineering Applications of Neural Networks / S.N., S.L., Springer, pp. 165-176. ISBN: 978-3-031-08222-1
- **Aiello, Salvatore**; Borla, Oscar; Chiaia, Bernardino; Marasco, Giulia (2021): Holistic strategies for control of tunnel linings. In: 2nd fib Symposium on Concrete and Concrete Structures, Sapienza University, Rome, Italy, Nov 18th-19th, 2021, pp. 95-101. ISBN: 978-2-940643-13-4
- Rosso, Marco Martino; Marasco, Giulia; Tanzi, Leonardo; **Aiello, Salvatore**; Aloisio, Angelo; Cucuzza, Raffaele; Bernardino, Chiaia; Cirrincione, Giansalvo; Marano, Giuseppe Carlo (2022): Advanced deep learning comparisons for non-invasive tunnel lining assessment from ground penetrating radar profiles. In: 8th European Congress on Computational Methods in Applied Sciences and Engineering, Oslo, Norway, June 5th-9th.



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