

CHAPTER 2 PHOTOACOUSTIC TOMOGRAPHY FOR WAVE PROPAGATION IN CONCRETE

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2.1 INTRODUCTION

Concrete remains the most widely used material in modern infrastructure due to its cost-efficiency, durability, and versatility. It is an essential component in buildings, bridges, tunnels, dams, and pavements. It provides both excellent compressive strength and adaptability to various structural designs. However, despite these advantages, concrete is prone to degradation. Over time, it is susceptible to internal defects, including voids, cracks, delamination, and microfractures (Zaki et al., 2015). Although often invisible from the surface, such subsurface anomalies can critically impair the mechanical performance, load-bearing capacity, and service life of concrete structures.

Studies have shown that poor concrete quality is one of the main causes of building collapse (Rubaratuka, 2013). This highlights the importance of early and accurate detection of hidden damage. Early diagnosis allows for preventive maintenance, targeted repair, and avoidance of catastrophic failures, all of which support infrastructure sustainability and public safety.

To address this challenge, non-destructive testing (NDT) offers valuable techniques that help identify hidden damage in concrete (Kot et al., 2021), including ultrasonic testing, impact echo, infrared thermography (IRT), and ground-penetrating radar (GPR) (Luca, 2025). These methods have been successfully used to locate cracks, voids, honeycombing, and delamination in a range of applications, from bridges to industrial floors. However, they often suffer from limited penetration depth, poor spatial resolution, and high sensitivity to surface conditions. Additionally, some techniques are time-consuming and require expert interpretation, which reduces their effectiveness for rapid or large-scale inspections (Yin et al., 2018).

In recent years, researchers have explored complementary methods that are capable of providing robust imaging in heterogeneous materials such as concrete. Photoacoustic tomography (PAT) is one of the emerging hybrid imaging techniques that integrates optical and acoustic modalities. Initially developed and widely used in biomedical applications, PAT is known for its ability to achieve high contrast, deep penetration, and fine resolution (Das et al., 2021; Li & Wang, 2021). PAT operates by using pulsed optical excitation to generate ultrasonic waves, which are then detected to form tomographic images. In soft tissue applications, PAT has demonstrated sub-millimetre resolution with imaging depths of several centimetres (Vu et al., 2019). These features suggest promising potential for adapting PAT to inspect concrete structures, particularly in detecting small internal voids. However, its application in the civil engineering domain remains underexplored. As of April 2025, a Scopus database search reveals fewer than 5 publications focused on PAT for concrete applications. This indicates a clear research gap in the field.

To date, very limited numerical studies have been conducted to simulate the photoacoustic waves in concrete and interact with embedded defects. A deeper understanding of these wave behaviours is essential before PAT can be translated into practical inspection tools for the field.

Hence, this chapter aims to analyse photoacoustic wave propagation in concrete using a numerical simulation approach.

2.2 BASIC PRINCIPLE OF PHOTOACOUSTIC TOMOGRAPHY

Photoacoustic tomography (PAT) is a hybrid imaging modality that combines the high optical contrast of laser-based techniques with the deep penetration and spatial resolution of ultrasound imaging (Das et al., 2021). The fundamental mechanism of PAT, illustrated in Figure 2.1, relies on the photoacoustic effect, which was first described by Alexander Graham Bell in 1880, whereby the absorption of modulated or pulsed light by a material generates sound waves (Thakur et al., 2022).

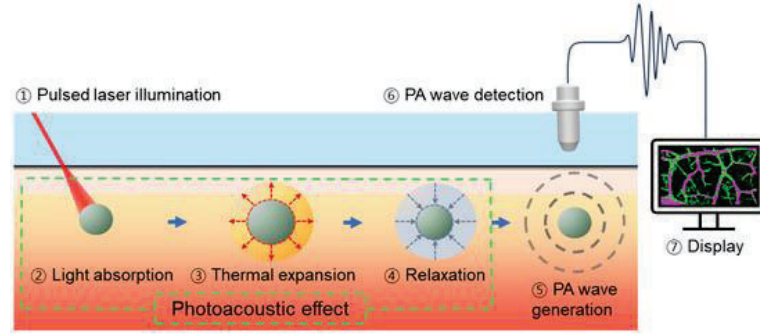


Figure 2.1 Fundamental mechanism of photoacoustic tomography
(Source: Song et al., 2025)

In PAT, short laser pulses are delivered to the object under test (OUT). When the light is absorbed, the optical energy is converted into heat. This rapid and localised temperature rise induces thermoelastic expansion, which in turn generates transient broadband ultrasonic waves (Wang, 2010). These waves propagate through the medium and are subsequently detected by ultrasound transducers placed around the sample.