

Concrete Spalling Depth Change Monitoring Using Directional Lighting Images

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ABSTRACT

This study investigates the use of directional lighting images to monitor depth changes in concrete spalling. A neural-network-based photometric stereo method (named NFPS) was applied to images of a surface illuminated from varying angles and directions to generate 3D surface reconstructions. A controlled dataset was created by progressively removing material from a wooden block, representative of concrete, using a CNC machine to simulate increasing levels of spalling severity. Directional lighting images were captured at each stage using a mini-ALICS device, producing three samples: D-0 (undamaged), D-6 (6 mm maximum depth), and D-16 (16 mm maximum depth). In captured images under diffused lighting, damage severity was not visually distinguishable; however, directional lighting enhanced image surface texture and shadows, revealing depth differences. The NFPS method successfully reconstructed the 3D topography of each sample, clearly differentiating between sample spalling depths. From the 3D reconstructions, it was visible that sample D-16 had the most severe spalling depth, despite the spalling surface area from plan view being identical to that of sample D-6. This study's results demonstrate that directional lighting images, combined with photometric stereo, provide an effective means of monitoring concrete spalling depth changes.

INTRODUCTION

Concrete spalling refers to the deterioration of a concrete surface, resulting in the exposure of the underlying aggregates. Spalling is typically caused by a combination of environmental and physical factors. Traditionally, spalling is identified and measured manually by human inspectors [1]; however, this process can pose physical safety risks and suffers from variability due to differences in inspector judgment and repeatability [2, 3].

Remote image capture methods can be paired with neural network analysis for automated spalling identification [4]; however, such methods do not provide the depth information necessary for three-dimensional (3D) measurement of concrete spalling volume, which is a common severity metric used by human inspectors. This limitation has led to research in image-based spalling 3D reconstruction methods, such as depth cameras [5] and photogrammetry [6]. However, these methods typically require training and experience to utilise and interpret the raw captured data.

Dow et al. [7] demonstrated that directional lighting images combined with photometric stereo can be used for 3D reconstruction and measurement of concrete spalling. Directional lighting images are captured by illuminating the same scene multiple times, each with light projected from a different angle. This approach offers the advantage of

using conventional image data that is intuitive for humans to interpret without specialised knowledge.

However, while identifying and measuring defects is valuable, the ability to track changes in damage over time holds greater practical significance for industrial applications. This study aims to investigate whether directional lighting images and photometric stereo techniques can be used not just for detection, but to identify the progression of concrete spalling.

PHOTOMETRIC STEREO 3D RECONSTRUCTION

Traditional photometric stereo, proposed by Woodham et al. [8], estimates surface normals (vectors perpendicular to the surface at each point) by analysing shading variations across images taken under different lighting directions. These normals show the orientation of surfaces which allows a 3D shape of the surface to be estimated. Traditional methods assume distant light sources, which limits their effectiveness in real-world setups.

A black-box, neural network-based photometric stereo method, named "Fast, lightweight near-field photometric stereo" (NFPS), proposed by Lichy et al. [9], is used in this work. The NFPS method allows lighting sources close to the surface to be used for processing. NFPS estimates per-pixel surface normals and depths from multiple directional lighting images through a two-stage pipeline: initialisation and recursion. Each stage uses separate networks for normal and depth prediction, totalling four networks in the architecture.

In the initialisation stage, images at a reduced resolution (64×64 pixels) and assumed flat depth are used to estimate initial lighting and generate the first normal and depth maps. Subsequent recursion stages refine these predictions at increasing resolutions, using outputs from previous iterations and updated lighting estimates from a dedicated lighting feature extractor.

Dow et al. [7] utilised the NFPS method for rapid and accurate 3D reconstructions of concrete spalling (see Figure 1), which is used in this work. Directional lighting images are captured using mini-ALICS (shown in Figure 2), a smaller version of the Adaptive Lighting for the Inspection of Concrete Structures (ALICS) platform first proposed by McAlorum et al. [10]. Detailed specification of the mini-ALICS device and captured image requirements can be found in [7].

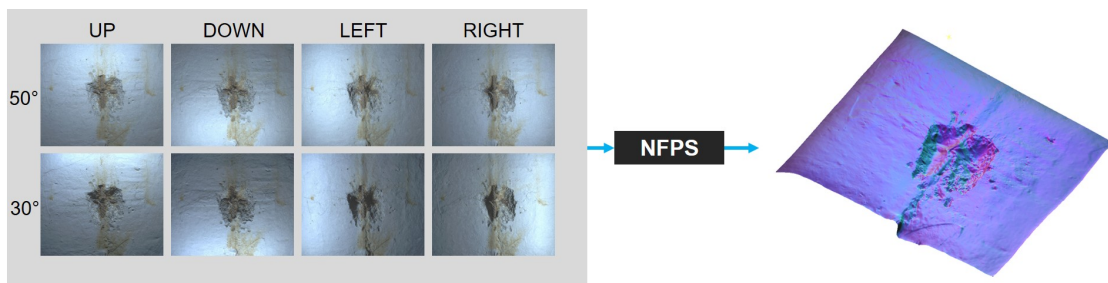


Figure 1. Flowchart showing NFPS method inputs and output.

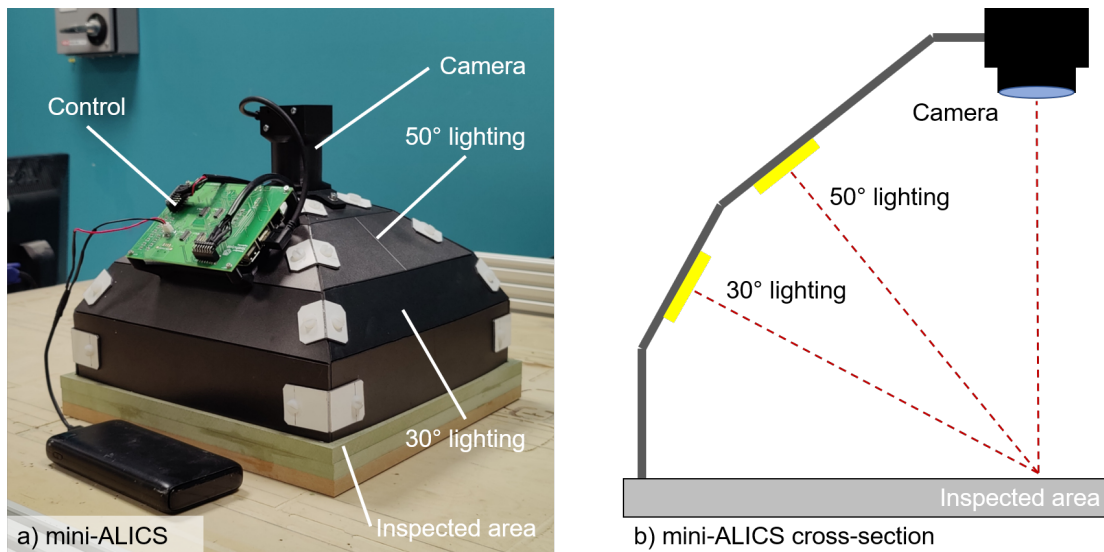


Figure 2. a) diagram of mini-ALICS device. b) cross-sectional view of mini-ALICS and lighting angles.

This study repeatedly deploys the mini-ALICS device on a spalling sample that is increased in depth. The NFPS method uses captured images to track the change in depth.

DATASET FORMATION

To create a dataset representing varying spalling depths, grey MDF wood was used to emulate concrete, with the spalling carved using a Computer Numerical Control (CNC) machine. Firstly, a rectangular block measuring $300 \times 300 \times 36$ mm was modelled using Autodesk Fusion. On the top surface of this model, the curve tool was used to draw an irregular outline representing a spalling pattern. A construction plane was then projected 6 mm below the top face, and a circle was sketched at the centre of this plane. Using the loft tool, material was removed between the spalling outline and the circular sketch, resulting in a spalled region with a maximum depth of 6 mm (see Figure 3). To create a deeper variant, the construction plane was lowered an additional 10 mm, making it 16 mm from the surface, and the loft process was repeated to generate a sample with an extended spalling depth of 16 mm. Figure 4 shows the Fusion models for the three damage states.

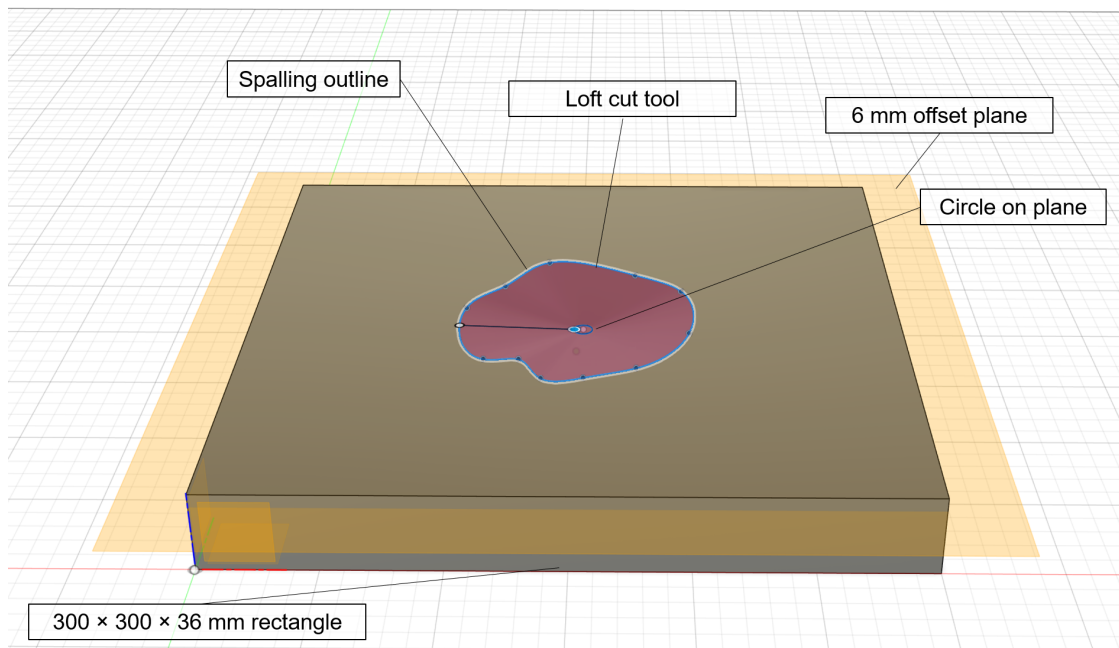


Figure 3. Autodesk Fusion construction of spalling sample.

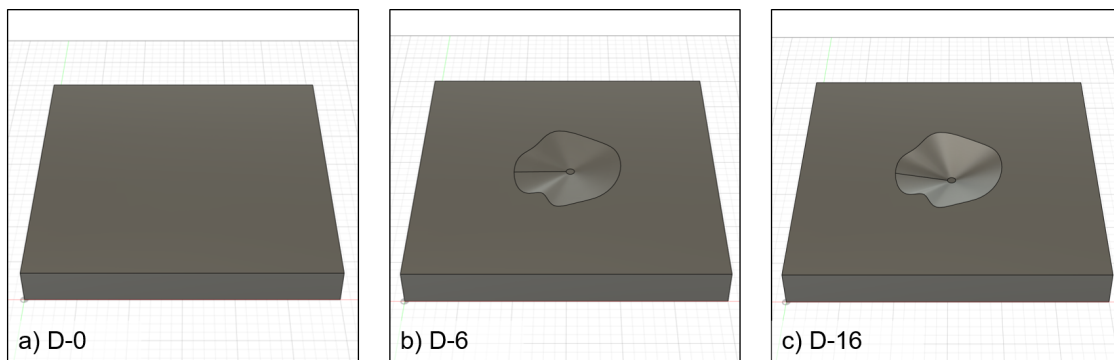


Figure 4. Autodesk Fusion 3D models of different spalling dataset sizes. a) D-0, undamaged state; b) D-6, 6 mm maximum depth; c) D-16, 16mm maximum depth.

A block of wood, also measuring $300 \times 300 \times 36$ mm, was mounted to an Ooznest Workbee CNC machine. The machine was fitted with a Makita RT0700CX4 Compact Router and 6.4 mm diameter flat-end drill bit. Prior to any machining, directional lighting images of the undamaged (D-0) surface were captured using the mini-ALICS device. The CNC machine was then programmed using G-code exported from Autodesk Fusion, and the 6 mm deep spalling profile was milled into the wood block (see Figure 5). After machining, a second set of directional lighting images was captured using the mini-ALICS device to record data for the 6 mm depth damage state (D-6). The CNC process was repeated with the modified model to extend the spalling depth to 16 mm, and a final set of directional lighting dataset images were captured to record data for the 16 mm depth damage state (D-16).

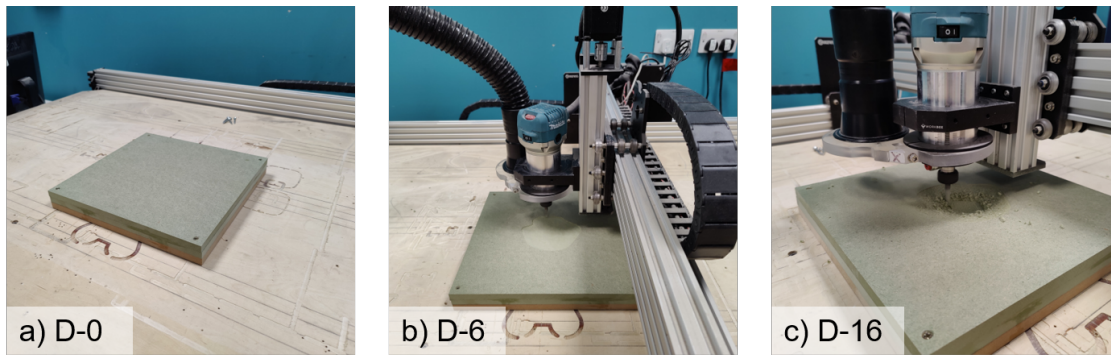


Figure 5. Manufacturing of different dataset samples using CNC machine to subtract material from $300 \times 300 \times 36$ mm grey MDF wood block.

RESULTS

Figure 6 shows the mini-ALICS captured images of the three dataset samples (D-0, D-6 and D-16) under diffused and right-directional lighting, representing a subset of all captured images for brevity. In the diffused lighting images of samples D-6 and D-16, the spalling areas from plan view appear similar, making it difficult to distinguish their depths. However, the right-directional lighting reveals a clear difference between D-6 and D-16. The shadows and enhanced surface topography under this lighting condition visually show that D-16 contains a more severe spalling despite the surface area from plan view being the same as D-6.

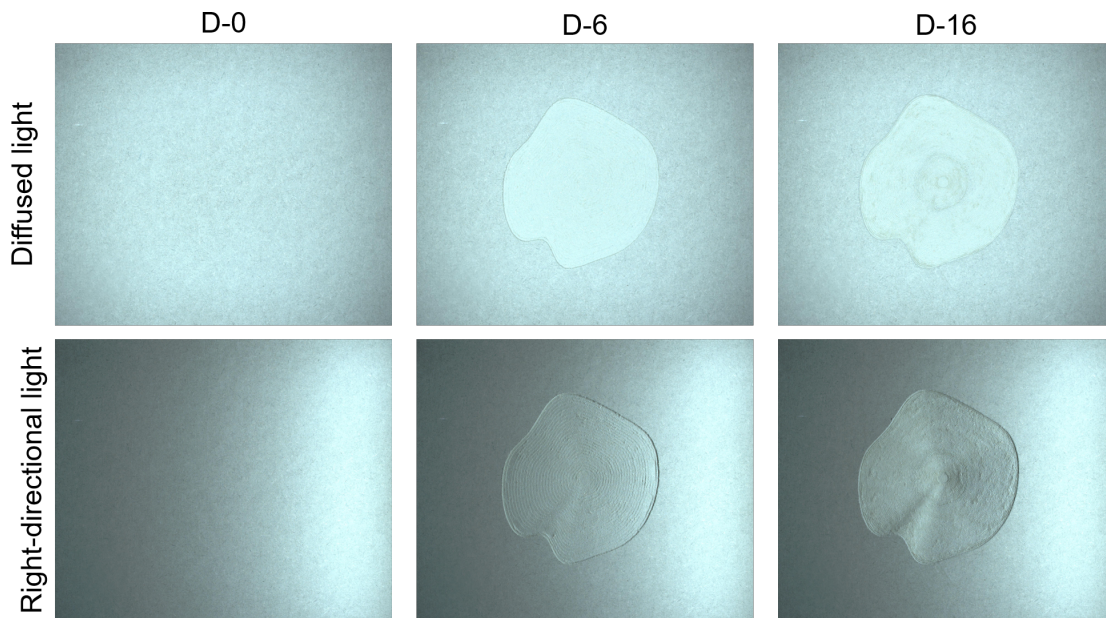


Figure 6. Diffused and right-directional lighting images of dataset samples D-0, D-6 and D-16 captured using mini-ALICS device.

Figure 7 shows the 3D reconstructions of the dataset samples generated using all captured directional lighting images (up, down, left and right from from 30 and 50 de-

grees) as inputs to the NFPS method. Sample D-0 shows the undamaged surface, while samples D-6 and D-16 show increasing levels of spalling depth. The 3D reconstruction of D-16 highlights the greater depth of the spalling, confirming it as more severe than D-6 despite the surface area from plan view of spalling being identical. Additionally, the depth contours on the samples created by the CNC machining process are visible in the 3D reconstructions.

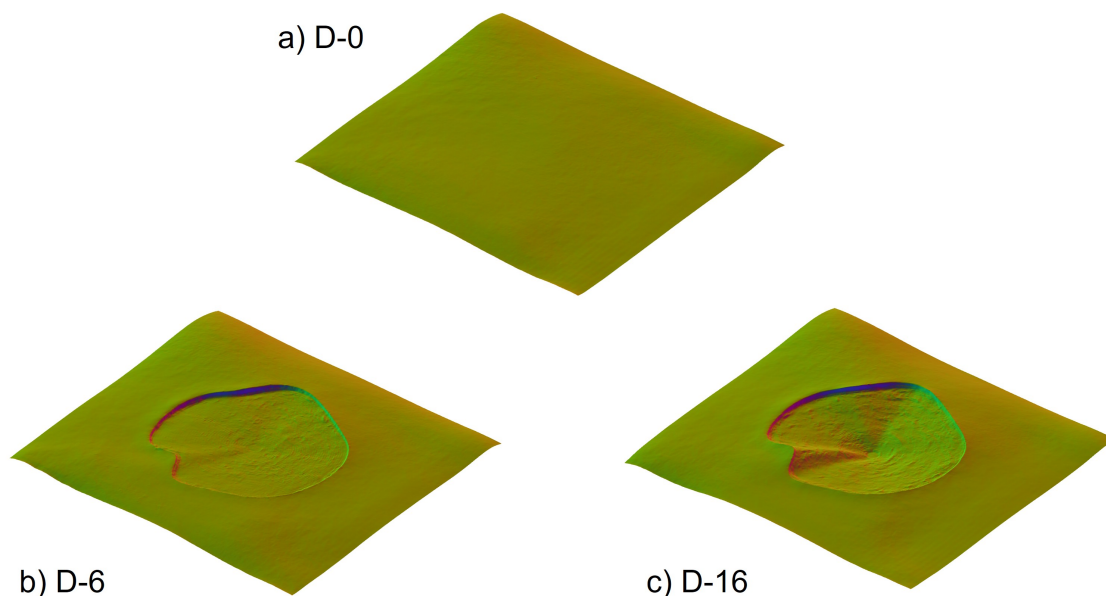


Figure 7. NFPS 3D reconstructions (generated from mini-ALICS directional lighting images) of surface for dataset samples: a) D-0; b) D-6; c) D-16. The colour in the 3D models visualises the surface orientation, with different colours corresponding to different normal vectors, which helps to highlight the topography.

CONCLUSION

This paper demonstrates how directional lighting images can be used to monitor changes in the depth of concrete spalling. The tested method (named NFPS and proposed in another publication) uses images of a concrete surface illuminated from different angles and directions and a lightweight neural-network-based photometric stereo method to produce a 3D reconstruction of the captured surface. To evaluate the method, a dataset simulating increasing spalling severity was created by progressively removing material from a wooden block using a CNC machine. Directional lighting images were captured between each material removal stage using a mini-ALICS device. Three samples were analysed: D-0 (undamaged), D-6 (maximum depth of 6 mm), and D-16 (maximum depth of 16 mm). In captured images with diffused lighting conditions, the surface appearance remained visually similar across all samples, making it difficult to distinguish between different severities of spalling. However, with directional lighting, shadows and surface textures became more pronounced, visually revealing that sample D-16 exhibited the greatest depth. For each damage state sample, all captured directional lighting images were processed with the NFPS method to generate 3D reconstructions.

These reconstructions confirmed that the D-16 sample had a greater depth of spalling than sample D-6. This study demonstrated that directional lighting images can be used to track the growth of concrete spalling. Future studies should expand the dataset size and seek to quantify the rate of change of spalling depth between inspection intervals.

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