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3D LASER SCANNING TECHNIQUE FOR THE INSPECTION AND MONITORING OF RAILWAY TUNNELS

Summary. Railway tunnel inspection and monitoring has predominantly been a visual and manual procedure, which is time-consuming and subjective, giving rise to variance in standards and quality. Thus, alternative, novel, automated techniques need to be developed, for more efficient and reliable tunnel examination. The reported research aimed to investigate the application of a laser scanning technique for the inspection of tunnel degradation and structural integrity. The proposed method may either substitute or supplement traditional survey techniques, being more efficient, and contributing thus to the standardisation of tunnel inspections. For the purpose of investigating the applicability and accuracy of laser scanning in tunnels, a set of tunnel lining models was constructed for laboratory tests, with the objective of determining the quality of the imaging. Initial tests were carried out using a performant laser scanner and demonstrated the feasibility of the concept. As a result, refined laboratory models were built, and experiments conducted, to establish the quality and precision of laser scanning imaging, for condition monitoring of tunnels. The experimental results indicate that the laser scanning technique used in this research has high potential for detecting the tunnel condition, monitoring the depth of weathered mortar, spalling bricks etc. with high accuracy in static scanning mode.

TECHNIKA SKANOWANIA LASEROWEGO 3D DO KONTROLI I MONITOROWANIA TUNELI KOLEJOWYCH

Streszczenie. Kontrola i monitoring tuneli kolejowych w przeważającej mierze to procedura, która jest czasochłonna i subiektywna, co powoduje zróżnicowanie standardów i jakości badań. Stąd też muszą być opracowane alternatywe, nowoczesne, zautomatyzowane techniki do bardziej skutecznych i rzetelnych badań. Przedstawione badania miały na celu wskazanie zastosowania techniki skanowania laserowego do kontroli degradacji tunelu i integralności strukturalnej. Proponowana metoda może zastąpić, bądź uzupełnienić, tradycyjne techniki pomiarowe. Jest ona bardziej wydajna i może przyczynić się do standaryzacji kontroli tuneli. Aby zbadać przydatności i dokładności skanowania laserowego w tunelach, skonstruowano zestaw modeli do testów labolatoryjnych, w celu określenia jakości obrazów. Wyniki doświadczalne wskazują, że technika skanowania laserowego zastosowana w badaniu ma wysoki potencjał do charakteryzowania stanu tunelu, monitorowania głębokości zwietrzenia zaprawy, odpryskiwania cegieł itp., z dużą dokładnością w trybie statycznym skanowania.

1. INTRODUCTION

Most railway tunnels in the UK were built many decades ago, with some dating back to the mid-nineteenth century. They are subject to degradation during their cycle life, for instance spalling, ring separation, perished mortar and loose bricks. Tunnels can also be subject to ground stresses which can cause severe deformation (as shown in Fig. 1) and damage to the tunnel lining and support. Degradation and tunnel deformation are serious major threats to a tunnel's structural strength and durability which, uncontrolled, may lead to a tunnel collapse.

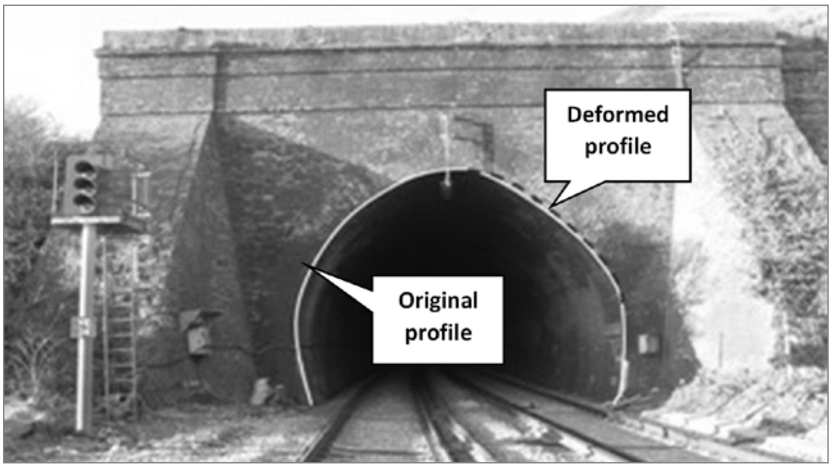

Fig. 1. A typical tunnel deformation (Courtesy of Golder Associates Ltd.)
Rys. 1. Typowe odkształcenia tunelu (dzięki uprzejmości Golder Associates Ltd.)

The inspection and monitoring of tunnels is therefore important, to diagnose deterioration and conduct repair work, before serious damage occurs.

Traditionally, visual inspection and manual contact methods have been used, which provide a variable standard of quality and include subjective judgement. Direct contact measurements using simple steel tapes and tape extensometers [1], can be extremely time consuming to use. Haack et al. [3] used the methods of georadar, infrared thermography and multispectral analysis for tunnel applications, using an experimental wall. This work showed that there are benefits in using all three methods, under certain circumstances.

Gyro-theodolites and, more recently, inertial positioning systems, have been useful tools in working underground. The remote measurement techniques of laser scanning and digital photogrammetry have been thought of as potentially useful methods, having been used in many natural environment and engineering applications [2, 4, 5, 8, 10]. However, none of the advanced monitoring techniques have been thoroughly studied and validated for the inspection and monitoring of railway tunnels, especially with respect to the ageing phenomenon.

Laser scanning, photogrammetry and laser-lit photogrammetry techniques may be considered for this aim. Each technique has its benefits and problems for this type of application [9, 6, 7]. The laser scanning method was chosen as the inspection technique for this study. Other techniques will be investigated and applied in the future research.

2. AIMS AND OBJECTIVES

The overall aim of the study is to develop and investigate an automated technique which may substitute or augment the manual tunnel examination survey. The aim of the reported research was to investigate the feasibility of using the laser scanning technique as an efficient and reliable alternative to the inspection and monitoring of railway tunnel condition.

The particular objectives of the study were to examine the applicability and accuracy of a laser scanning system for the inspection of tunnel degradation and the monitoring of structural integrity. Specific objectives included setting up a series of tunnel lining models for laboratory tests, to determine the quality of the imaging and test the utilisation of laser scanning for this application.

3. EXPERIMENTAL WORK

3.1. Initial tests

A terrestrial laser scanning system, model RIEGL LMS-Z420i from RIEGL Ltd., was selected and used to scan a number of brick walls to test its ability to measuring brickwork and its surfaces. The system instantly acquired and provided high-quality 3D image data of the brick walls, through the associated software RiSCAN PRO.

The application of RIEGL LMS-Z420i made it possible to collect detailed data of the railway tunnels, without a major disruption to traffic, and to analyse the point clouds from the scanner to identify the degradation and displacement issues in tunnels. Table 1 provides technical data, as well as an overview of the rangefinder and scanner performance of the instrument.

Table 1

Overview of RIEGL LiDAR LMS-Z420i technical specifications from RIEGL Ltd.

Rangefinder Performance:		**Scanner Performance:**	
Measurement range	2m-1000m	***Vertical scan range***	0° to 80°
Accuracy	10mm	***Scanning mechanism***	rotating / oscillating mirror
Measurement rate	up to 11000 pts/sec	***Scanning rate***	1 scan / sec to 20 scans
General Technical Data:		***Angular resolution***	0.002°
Main dimensions	463 x 210 mm (Length x Diameter)	***Horizontal scan range:***	0° to 360°
Weight	16 kg	***Scanning mechanism***	rotating optical head
Temperature range	0° C to +40°C (operation), -10°C to +50°C (storage)	***Scanning rate***	1 scan / sec to 15 scans
Protection class	IP64, dust and splash-water proof	***Angular resolution***	0.0025°

The scanner was operated for each test, following the next two steps:

• A 360° overview scan at a distance of approximately 2.5m from the surface of the selected brick wall (scanning resolution — 0.201°);

• Scanning a smaller area to be analysed in detail: the scanning was repeated 4 times, to obtain an average and to reduce noise (the resolution was settled at 0.041°).

All scanning processes in this research were carried out in static mode (Fig. 2, left & mid).

The analysis of digital images demonstrated that the terrestrial laser scanning system RIEGL LMS-Z420i is suitable for the task of monitoring tunnels and thus proved the concept feasibility. Spalling bricks and perished mortar can be clearly identified as 3D images in the processing software (Fig. 2, right). However, it is still hard to measure precisely and determine the accuracy of the scanning, without a custom-made model.

Thus, brickwork models were designed, to test the utilisation of the laser scanner RIEGL LMS-Z420i for monitoring tunnel structural integrity.

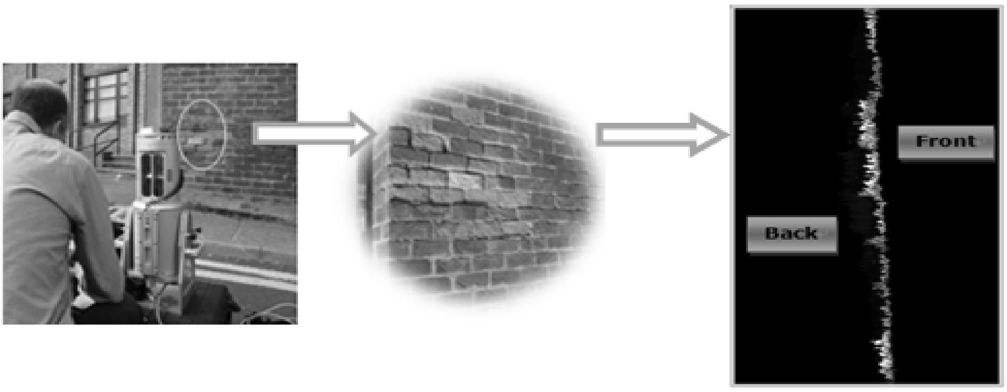

Fig. 2. The scanning process: the worn bricks (left & mid.) and the 3D model in the software (right)
Rys. 2. Proces skanowania: zużyte cegły (lewy i środkowy) oraz model 3D w oprogramowaniu (prawy)

3.2. Experimental models

Designed Model 1 (Bricks & Mortar)

The bricks used in the first model are brand-new, red, smooth, Norman bricks. Fig. 3 shows the whole model divided into 9 smaller parts. Horizontally, it is built with 20mm, 15mm and 10mm brick spacing, from the top down. Vertically, the mortar depth of 20mm, 10mm and 5mm is built separately from left to right.

This model was used to establish what the scanner could detect and form a base model.

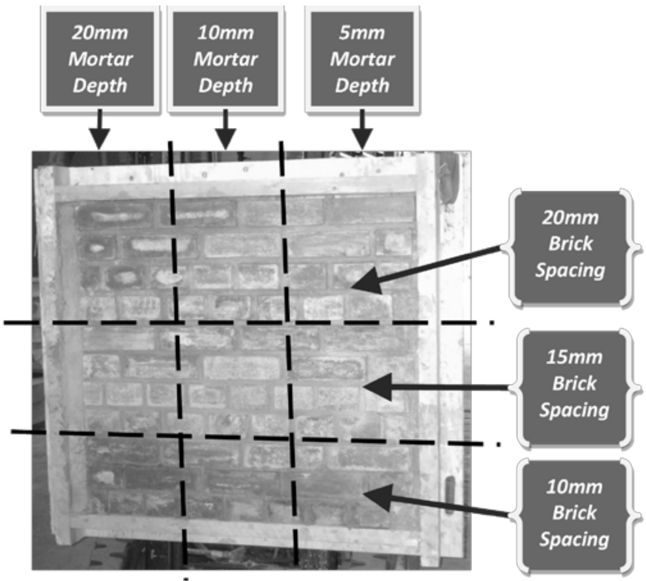

Fig. 3. The nine divisions of model 1 with varying brick spacing and mortar depth
Rys. 3. Dziewięć dywizji modelu 1 różne odstępy między cegłami i głębokości zaprawy

Designed Model 2 (Surface & Cracks)

The second model (shown in Fig. 4) was separated into 2 parts. The bricks of the upper part are a mixture of smooth, pattern textured, and some reclaimed bricks, simulating weathered bricks in tunnels. The lower part contains roughly 4 narrow, artificial cracks, throughout the area, each of which is approximately 3mm wide, plus a larger 12mm wide crack. The brick spacing is 10mm everywhere; the entire model was built without mortar to simulate heavily weathered mortar in real tunnels.

This model was to investigate the influence of the texture of the brick surface and determine the laser scanner’s visibility of deep narrow cracks and deep mortar depth.

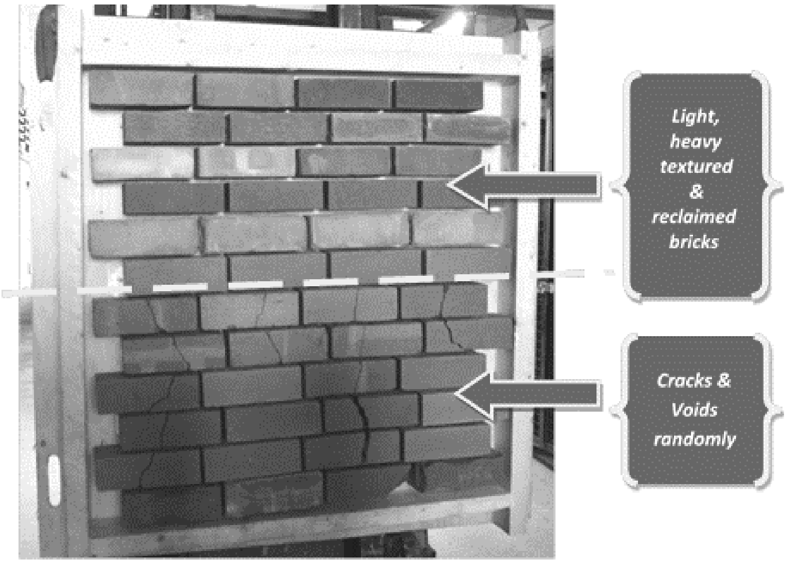

Fig. 4. Two divisions of model 2 varying brick textures and crack dimensions
Rys. 4. Dwa podziały modelu 2 - różne struktury cegły i wymiary pęknięć

3.3. General scanning procedures

The scanning operations included the following steps:

- A 360° overview scan at a distance of 2m from the model, setting a resolution of 0.201° (as shown in Fig. 5);
- Selecting approximate sub-sections of the model in the panorama, setting a resolution of 0.041°, 0.081° and 0.201° for each scan, and repeating the scan 5 times, to obtain an average and reduce noise;
- Changing the measuring distance to 4m and then 6m, by moving the model, and iterating the above steps.

The two models were tested in turn, following the steps above.

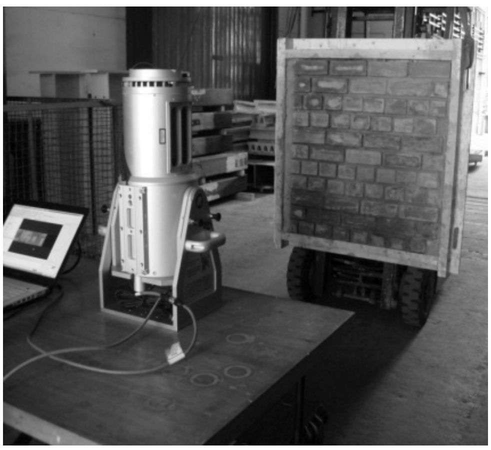

Fig. 5. The 360° overview scanning process of model 1 (bricks & mortar), at 2m
Rys. 5. Przedstawienie procesu skanowania 360° do modelu 1 (cegły i zaprawy) w 2m

3.4. Data processing with the Triangulation Method

After the experimental work, the scan data were transformed into 3D models, with point cloud data in the software. The 3D models in the form of point clouds can be seen clearly, but are not accurate enough for the measuring work.

The triangulation method is required to connect these points together for improving the measurement. This method consists of gathering the close points and forming planes. For each plane, 3 close points are needed. Thus, triangular planes are connected with each other, giving a better visual 3D model for measuring (Fig. 6).

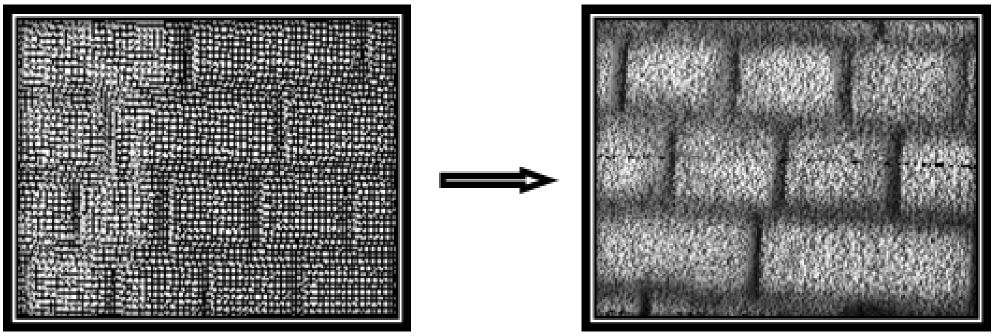

Fig. 6. ‘point-cloud 3D model’ transformed to ‘triangular 3D model’
Rys. 6. „Point-cloud 3D model” przekształcony do “triangular 3D model”

4. RESULTS AND ANALYSIS OF EXPERIMENTAL WORK

3D model data were achieved after the experimental work, using the laser scanner. The following section presents the data analysis for validating the utilisation of the scanner.

Illustration of general observations from data and the measuring method are presented in the first part, followed by a detailed analysis of both models.

All of the following analyses use 3D model data after triangulation.

4.1. General observations from experimental data

The basic aim was to observe cracks, texture, brick spacing, mortar and brick depth. It is also interesting to measure brick spacing, mortar and brick depth.

After scanning, the software processes the depth of the flat identation on the mortar surface, and visualise it as a ‘V’ or ‘U’ shape (Fig. 7).

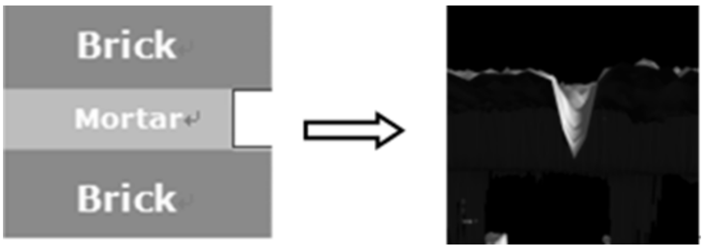

Fig. 7. Flat indentation (left, in red) changes into ‘V’ shape indentation (right, in white)
Rys. 7. Płaszczyzna wcięcia (po lewej, na czerwono) zmienia się w płaszczyznę wcięcia w kształcie „V” (po prawej, na biało)

4.2. Measuring methodology

Measuring Method of Brick Spacing

The measuring method of brick spacing is undecided, because it is not clear where the true brick spacing is against the ‘U’ or ‘V’ shape indentation line (Fig. 8).

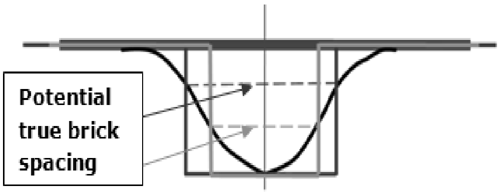

Fig. 8. The potential true brick spacing against ‘V’ shape indentation
Rys. 8. Potencjalny rozstaw cegły i "V" kształt wcięcia

Brick spacing seems to be determined by the geometrical relationship between the true brick spacing and the ‘U’ or ’V’ shape indentation, as well as the scanning characteristic of the scanner. Therefore, both the related geometric algorithm and the scanning characteristic may be considered to solve the problem in the future study. In addition, the fact that some parts of bricks cannot be perfectly reflected, due to inclined scan direction (Fig. 9), is one of the main reasons why the scanner may not accurately find out the brick spacing or the depth of mortar.

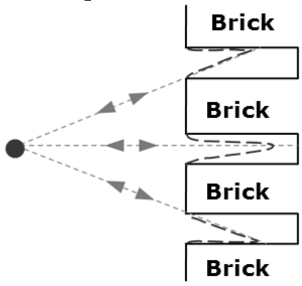

Fig. 9. The potential indentation between bricks
Rys. 9. Potencjalne wgłębienia między cegłami

Measuring Method of Mortar and Brick Depth

By using the associated software RiSCAN PRO, a way to measure the depth of mortar and bricks has been developed. It comprises the following steps:

- Create a plane (tick 3 points on the surface of bricks) almost parallel to the surface of the brick model;
- Measure the depth of the ‘V’ or ‘U’ shape, from the highest point at back, to the plane, as Fig. 10 shows.

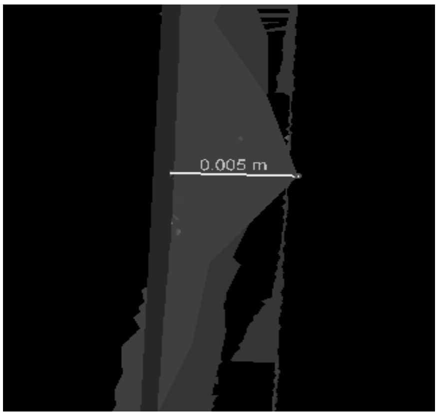

Fig. 10. Measuring the mortar depth
Rys. 10. Pomiar głębokości zaprawy

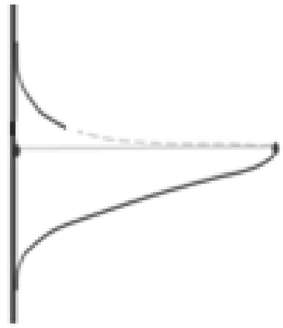

Fig. 11. A special case for measuring the mortar depth
Rys. 11. Szczególny przypadek pomiaru głębokości zaprawy

In some cases, the 'V' or 'U' shape cannot be formed completely, possibly because of the effect of inclined scanning direction (as shown in Fig. 9). Although the deepest part may be lost, an average depth from the higher side is also required to be collected (Fig. 11).

4.3. Data analysis

Data Analysis of Model 1 (Bricks and Mortar)

Model 1 emphasises the accuracy of brick spacing and mortar depth. Since it is not possible to measure brick spacing, there is only the mortar depth to be measured at specific brick spacing and measuring distance.

Model 1 is divided into 9 parts; from left to right the mortar depth varies (0.02m, 0.01m, 0.005m) and from top to bottom the brick spacing varies (0.02m, 0.015, 0.01m) (Fig. 12).

There are 16 areas in total, to be measured at specific measuring distance. The odd numbers represent the areas in the horizontal direction, while even numbers represent the areas in the vertical direction. A table is listed to compare the mortar depth required between designed value and an average value of the whole series. (Note: The designed and average values are accurate to ±0.002m, to allow for human error.)

As can be observed in Table 2, there is little difference (usually less than 3mm) between these two parameters, with the exception of the deeper mortar depth (0.020m) at a distance of 6m.

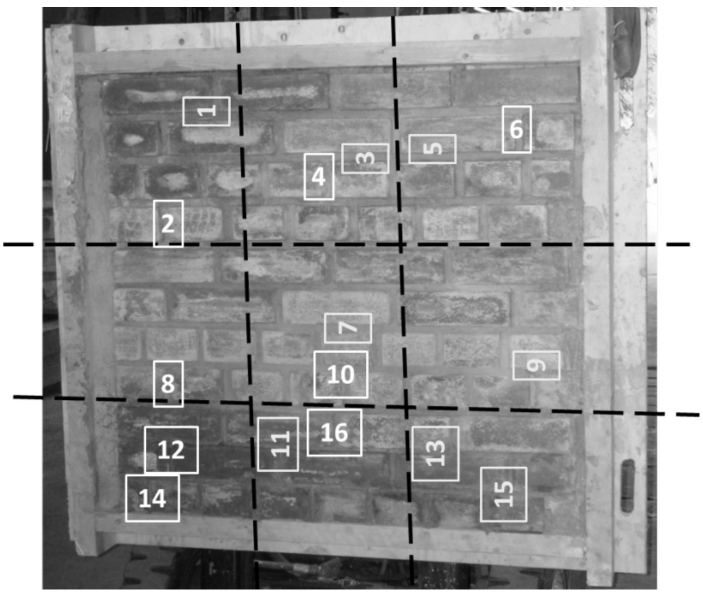

Fig. 12. Division parts and scanning areas of model 1
Rys. 12. Podział na częśc i obszary skanowania w modelu 1

Table 2

Original and scanned mortar depth difference in Model 1

Distance	Original mortar depth (m)	Mortar depth difference (mm)
2m	0.020	1-3
	0.010	0-2
	0.005	0-2
4m	0.020	0-3
	0.010	0-3
	0.005	0-1
6m	0.020	3-6
	0.010	1-3
	0.005	0-1

Data Analysis of Model 2 (Surface and Cracks)

Model 2 highlights the influence of texture on the brick surface, crack visibility, and the scanner's depth capability, particularly:

• Fig. 13 clearly shows a large crack and a large void, together with rough visibility of small cracks at a distance of 2m. These small cracks are difficult to observe at both 4m and 6m;

• Textural differences cannot be really identified; the image shows bricks in a dark blue colour;

• The gaps between bricks are deep in Model 2 (more than 100mm); imperfect reflection may easily occur if the scan direction is inclined towards the bricks, as shown in Fig. 9. Gap depth would be analysed in both vertical and horizontal direction separately, since it may perform differently.

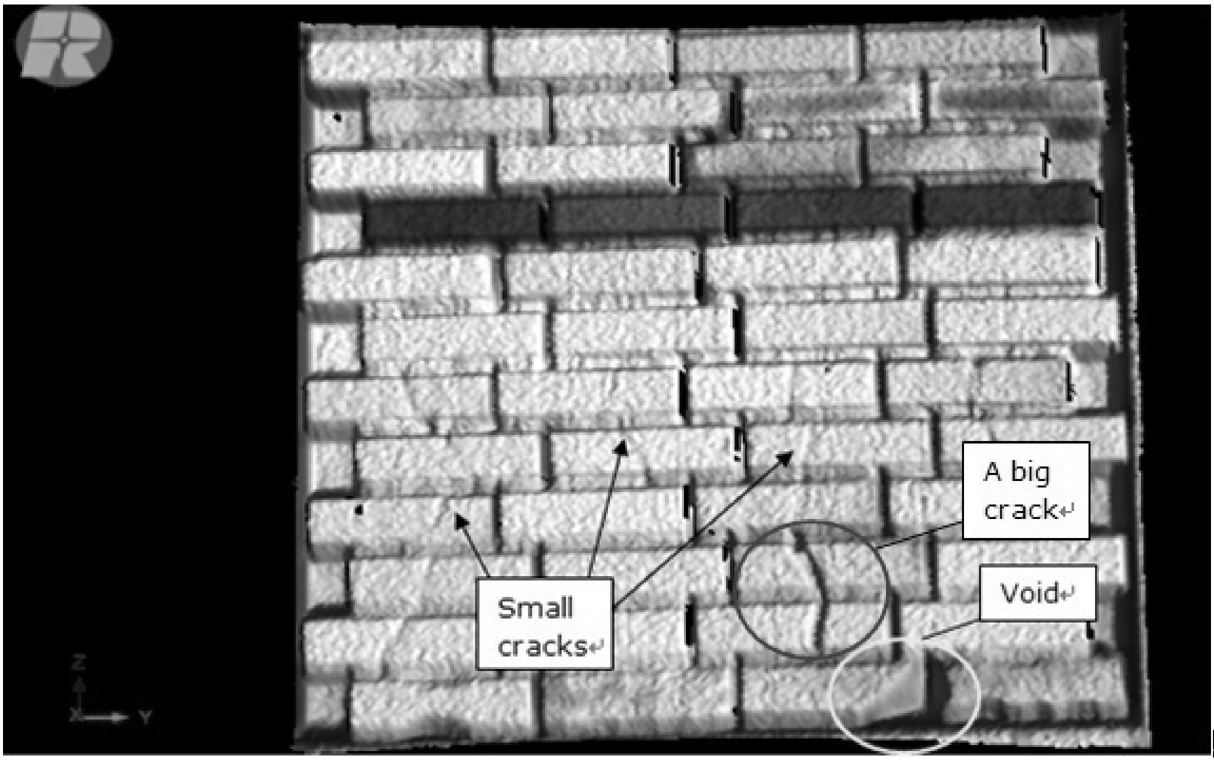

Fig. 13. The 3D model in the software (model 2)
Rys. 13. Model 3D w oprogramowaniu (model 2)

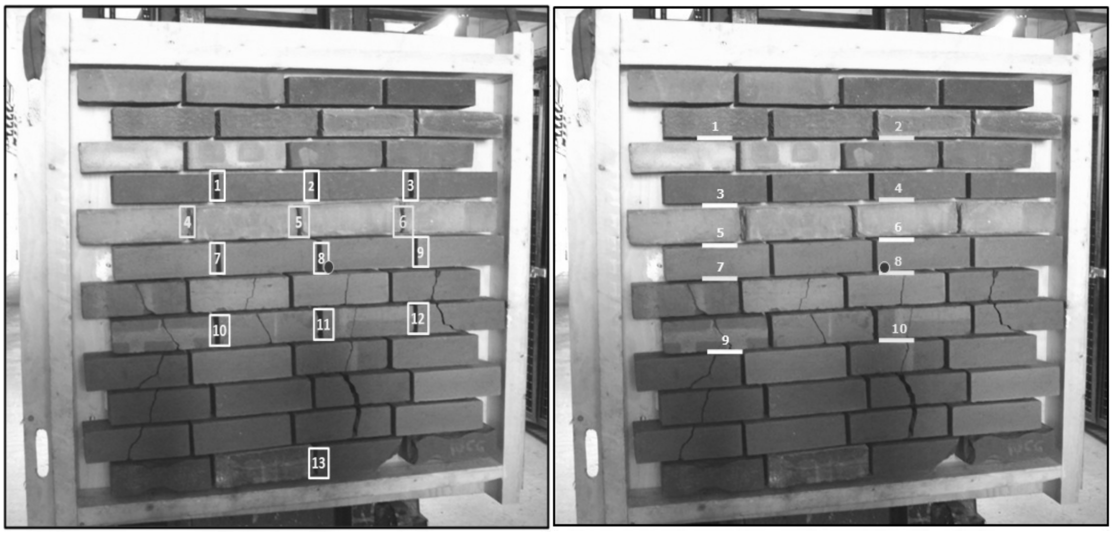

Fig. 14. Scanning areas of model 2 in vertical (left) and horizontal (right) direction
Rys. 14. Obszary skanowanie modelu 2 w pionie (z lewej) i poziomie (z prawej)

Analysis in vertical direction (Fig. 14, left)

13 areas including vertical brick spacing, with different rotation angles, were selected for measuring work. Areas 1-3 represent a brick depth of about 100mm; areas 4-6 are reclaimed bricks with a depth of around 110 mm, and the rest represent a brick depth of 105mm.

The location of the red dot on the figure is the scanning centre, perpendicular to the scanner, where the rotation angle is equal to 0.

The centre sections, which are almost perpendicular to the scanner's infrared beam, seem to demonstrate greater accuracy than the sides. The accuracy of the centre sections varies from 0.002m to 0.076m.

For most areas, the accuracy of brick depth improves to some degree as the measuring distance increases.

Analysis in horizontal direction (Fig. 14, right)

Similarly, 10 areas including horizontal brick spacing were selected and measured. The even numbers are areas with a small angle of rotation, while the odd numbers are in areas with a larger rotation angle, on the left.

Table 3 includes the average brick depth, horizontally, at different measuring distances.

Most of the depth values dramatically double at 4m, and then keep steady (with a small fluctuation) at 6m. Depth values in areas 7 and 8 are almost the same at 2m and 4m, while values at 6m drop somewhat, indicating the influence of measuring distance.

5. CONCLUSIONS

Due to the time-consuming, variable and inaccurate process of manual inspection for tunnels, the importance of developing an substitutable automated technique is undoubted. The utilisation of laser scanning, as an alternative to manual procedures, has been investigated by the presented research.

Initial tests carried out showed encouraging results for the ability of the laser scanner RIEGL LMS-Z420i in condition monitoring.

The experimental work conducted indicated that the scanner has the potential to detect condition indicators such as the depth of weathered mortar, spalling bricks etc., with high accuracy, in static scanning mode.

However, further study is required to enlarge inspection areas, using the latest, high-accuracy scanner, the RIEGL VZ-400, and to test the use of other inspection techniques, such as photogrammetry and laser-lit photogrammetry, to find the optimally suited automated technique for tunnel examination.

Considering the results achieved in static scanning mode within this study, testing with a continuously moving scanner would also make an interesting future investigation.

Table 3

Original and scanned brick depth in the horizontal direction in Model 2

<table>
<tr><th>Distance</th><th>Original brick depth (m)</th><th colspan="2">Scanned brick depth (m)</th><th colspan="2">Difference (m)</th></tr>
<tr><td rowspan="4">2m</td><td>0.100</td><td colspan="2">0.023</td><td colspan="2">0.077</td></tr>
<tr><td rowspan="2">0.105</td><td>0.031</td><td>0.031</td><td>0.074</td><td>0.074</td></tr>
<tr><td></td><td>0.025</td><td></td><td>0.080</td></tr>
<tr><td>0.110</td><td colspan="2">0.021</td><td colspan="2">0.089</td></tr>
<tr><td rowspan="4">4m</td><td>0.100</td><td colspan="2">0.058</td><td colspan="2">0.042</td></tr>
<tr><td rowspan="2">0.105</td><td>0.053</td><td>0.054</td><td>0.052</td><td>0.051</td></tr>
<tr><td></td><td>0.052</td><td></td><td>0.053</td></tr>
<tr><td>0.110</td><td colspan="2">0.065</td><td colspan="2">0.045</td></tr>
<tr><td rowspan="4">6m</td><td>0.100</td><td colspan="2">0.051</td><td colspan="2">0.049</td></tr>
<tr><td rowspan="2">0.105</td><td>0.049</td><td>0.055</td><td>0.056</td><td>0.050</td></tr>
<tr><td></td><td>0.058</td><td></td><td>0.047</td></tr>
<tr><td>0.110</td><td colspan="2">0.058</td><td colspan="2">0.052</td></tr>
</table>

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