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Modes of Failure Analysis in Reinforced Concrete Beam Using Laser Scanning and Synchro-Photogrammetry

How to apply optical technologies in the diagnosis of reinforced concrete elements?

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***Abstract*—The following paper reveal the limitations and possibilities of terrestrial laser scanning technology adaptation in diagnostics of reinforced concrete beams. In this paper, authors present potential spectrum of TLS use in modes of failure analysis of R-C beams and determines under which conditions the laser technologies might be applied. Research was carried out at the Regional Laboratory of Structural Engineering at Gdansk University of Technology, as a part of experiments, effectuate by Faculty of Civil and Environmental Engineering. Beam has been properly prepared in order to maximize quality of obtained data. Reinforced concrete beam was progressively overloaded and finally failure by shear and bending. The failure process was attentively tracing and registering by terrestrial laser scanner during the survey. Collected data were post-processed using the software dedicated to scanner (Leica Cyclone) and moreover GPL software (MeshLab). Also in order to validate results, separately resistance strain gauge survey was provided. Furthermore, authors used non-meter synchronous digital cameras to perform a Photogrammetric Process. Main subject of this particular paper is to demonstrate efficiency of laser scanning for the diagnosis of reinforced concrete beams deterioration. Analysis of the data from survey allow to assess whether the displacement can be measure with accuracy not worse than 1 mm. Efficiency of TLS can be a great advantage in multiplied studies or inspections of structural elements. As a result of authors' research it was achievable to create the consistent procedure to particularize modes of failure in reinforced concrete beams.**

***Keywords*—beam, cracks, deformation measurement, laser scanning, modes of failure, reinforced concrete, synchro-photogrammetry**

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I. Introduction

It is no exaggeration to admit that concrete is the most common construction material in all sort of widely understood engineering structures. During the time of building the first concrete structure, the character and condition of concrete materials and construction technology have been remarkably varied. Simultaneously, our knowledge about phenomena occurring in the concrete expanded. Despite great efforts of many extraordinary minds, an inevitable fact is that the concrete, as each and every material, decays with time or when the structure is exposed to fire, overload or seismic activity. This continuous change affects the appearance and behaviour of the structure. Proof for gradual and continuous loss of strength and durability of concrete might be visible as enormous deflection or crack. Cracks may stimulate corrosion of rebars and lead to loss of adhesion which consequence is the decline of load carrying capacity. In many cases, preservation measures can augment the structure lifetime cycle by many years. Proper repair strategy should depend on accurate diagnosis and right assessment of structure problems. Appropriate decisions made by stakeholders, based on real information of concrete condition can save money and reduce risk associated with an investment. Comprehensive analyses of concrete elements are widespread issue that has been described in the literature [1-3]. The authors decided to assess modes of failure, through analysis of cracks on a surface of reinforced concrete beams using the terrestrial laser scanning. For study purposes, experimental station for the analysis and realization of measurement procedures was prepared. Approach described in the article can be used not only for an analysis of reinforced concrete beams, but also for other construction elements as well. The method described in the article presents an analysis based on the intensity of light reflection, resulting from the laser scanning combined with measurement of geometry – on the basis of scanning and photogrammetry and synchronous photography. This solution is innovative in comparison to the previously used methods using TLS [4-8]. It is an extension for the solution presented in [9].

M.Sc. Eng. Patryk Ziółkowski: Most striking advantage of Terrestrial Laser Scanning on the contrary to typical diagnosis method of concrete deterioration, is the complexity of obtained results. Final product of TLS is a complete, fully operational, and three-dimensional virtual model of structure.

II. Scanning and data acquisition

A. *Preparation*

A beam was placed in a hydraulic press. For this purpose, a crane hoist with a lifting capacity of 3 tons was used. Setting the beam had to be calibrated, in such a way to as faithfully as possible imitate static scheme which was designed for particular beam. For imitate pivot the semi-circular steel supports were used. On the other hand load from the hydraulic press was submitted by a steel I-beam traverse on metal supports to the beam. This arrangement was designed to imitate two symmetrically point loads. Strain gauge wires were assembled to the printed circuit boards and then combined with a portable computer, which was responsible for deformation measurements. Force was applied in increments of 10kN per step until failure. After each load applied, hydraulic press was stopped and a research team was scanning surfaces of the beams. Subsequently, the team was checking an occurrence or cracks propagation by classic method using Brinell Magnifier and measuring deflection by clock deflectometer. In the meantime, strains were measured using electrical resistance strain gauges. In order to obtain verification measurement and control results by digital close range photogrammetry method, two synchronous cameras were used.

B. *Measurement and data archiving*

Research was carried out at the Regional Laboratory of Structural Engineering at Gdansk University of Technology. Measurements were carried out with professional Leica ScanStation C10 laser scanner. The failure process was attentively traced and registered by terrestrial laser scanner during survey. Position of the scanner in relation to the beam did not change throughout the whole survey process. In order

Figure 2. Prepared laboratory station. Beam located under the hydraulic press and prepared for survey.

to avoid post-processing stage effects of errors correlation (linking and matching). Reinforced concrete beam was scanned and destroyed. The beam has been properly prepared [Fig. 2]. Lateral surface, which authors wanted to scan, was engobed and a symmetrical rectangular grid with a width of 0,01m was applied on this surface. In intersections of vertical and horizontal lines, round metal tags with a diameter of 6mm were put. The zero scan (no force) and scan after the first applied load were carried out in the medium resolution and scanning lasted approximately 3 minutes. For the second measurement, scanning resolution were increased (distance: 100m; horizontal: 0,05m; vertical: 0,01m), but real resolution was even higher (horizontal: 0,0025m; vertical 0,0005m). The difference in resolution (H, V) results from construction of the scanner and scanning technology. Increasing the resolution in subsequent measurements significantly improved reception of the point cloud in later post-processing stage. Instead of

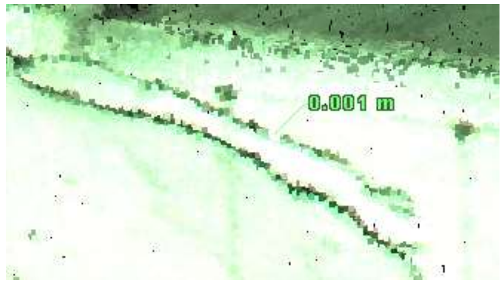

Figure 1. View of reinforced concrete beam support in the Cyclone 7 (measurement 6). Measuring width of a crack.

fragmentary scan, overall scan of the beam was performed. The beam reached its mode of failure by shear.

C. *Post-processing*

Survey data gained form scanner were processed in Cyclone 7 (default program provided by Leica). All scans from each measurement epochs were transferred into one space with common coordinate system. In order to facilitate work with points cloud and to provide improved usability, Leica implemented in its software a number of features to improve work. One of the most important functions is an optimization, its operation is based on compression and reorganization of points cloud and this makes it more consistent. Another very important feature is an unification, which improves model by partial reduction and compression of the cloud.

III. Analysis of assessing the cracking state possibility

One way to determine the modes of failure in reinforced concrete beams is to analyse the state of its cracks propagations over time. In case of failure due to bending, cracks appears in the middle of the beam. However, in failure due to shear, cracks appear at one of the supports.

A. *Analysis of points cloud distribution without superimposed maps of intensity*

Points cloud model of beam (failure by shear) was analysed, as we can see in Tab. I (No scheme view). Points cloud without applied maps of intensity is not sufficient to determine the beam's failure mode. Analysing such a model can show only the faint outline of main failure crack. This beam image can not constitute a basis for more precise study.

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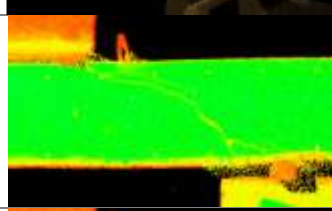
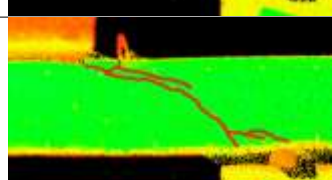
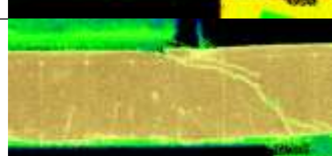
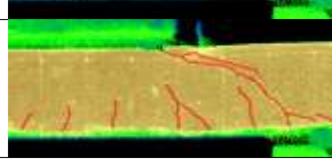
B. *Analysis of points cloud distribution with superimposed maps of intensity Units*

Points cloud model of beam was analysed, as we can see in Tab. I (Multi-Hue/Rainbow or Topo 3 scheme view). Points cloud with applied maps of intensity provide us much more detailed data. Such prepared image allowed us to see exact nature of cracks and their precise courses. It is possible to modify imposed intensity map. Points cloud has always a specific range of intensity, arising from maximum and minimum intensity values of sample points. The maximum and minimum values are applied to the extreme colour of the specified range. Adopted mapping for different points clouds are selected individually by the program. Colour intensity ranges (hereinafter called “Schemes”) may vary depending on the specific needs. As we can notice by comparing (Tab. I) Multi-Hue/Rainbow with marked cracks and Topo 3 with marked cracks, change of scope in the intensity map significantly changed the visibility of cracks.

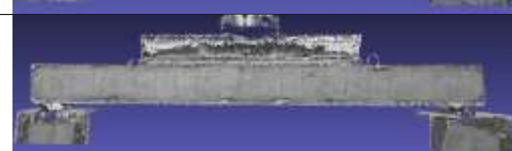
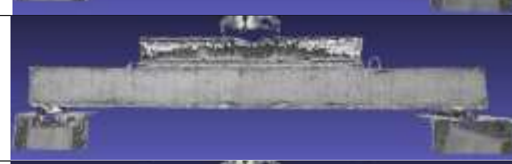
TABLE I. ANALYSIS OF POINTS CLOUD DISTRIBUTION WITH AND WITHOUT SUPERIMPOSED MAPS OF INTENSITY UNITS.

Scheme	ANALYSIS OF FAILURE MODE
	View of the scan
No scheme	
No scheme with marked crack	
Multi-Hue/Rainbow	
Multi-Hue/Rainbow with marked cracks	
Topo 3	
Topo 3 with marked cracks	

C. *Proper analysis of the cracking*

Despite of analysis in Cyclone 7 which is default program proposed by Leica, authors decided to use MeshLab. This is a program using Open Source license and it allows for more customize implementation of colour mapping schemes. The analysis was performed in order to find the most suitable scheme for determination of cracks occurrence or propagation. Data were exported from Cyclone 7 into main format (.PTX) and then imported into MeshLab. Tab. II shows the process of failure with used one of the analysed schemes called „SAWTOOTH GRAY 8”. Analysing the state of cracks propagation for various schemes, it is visible that the cracks occur only at 5th (90.0kN) and 6th (140.7kN) stage. Crack width must be sufficiently large to be able to change the laser beam intensity. In terrestrial laser scanning, the accuracy is closely correlated not only with the distance between, but with scanning resolution as well. The influence of the scan resolution is best illustrated by difference in appearance of the model from the study of the beam (measurement 1 and 2). Precision of measurement no. 1 (wherein used the average scan resolution) differs significantly in relation to accuracy of subsequent measurements already performed at a higher resolutions. Width of cracks should oscillate around 1mm, so that it could be effectively analysed in the program.

TABLE II. MILEAGE OF DESTRUCTION PROCESS OF BEAMS IN THE MESHLAB.

No.	BEAM (SCHEME: SAWTOOTH GRAY 8)
	View on the scan
1	
2	
3	
4	
5	
6	

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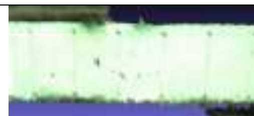
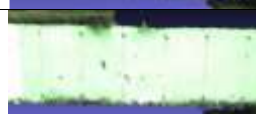
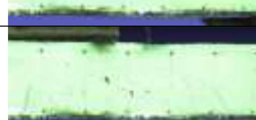
D. *Comparative analysis*

Comparative analysis indicates that the state of cracks propagations, which allowed to identify the failure mode, has been defined for pre-critical (90.0kN) and post-critical (140.7kN) stage. From the authors' analysis concluded in previous paper [9] it has been revealed that the displacement can be measured with an accuracy not worse than 0.001m. A major limitation of TLS is that the points cloud location coordinates are rounding to 1mm during post-processing in Cyclone 7.

TABLE III. COMPARATIVE ANALYSIS OF THE EXPERIMENTAL RESULTS WITH THE RESULTS OBTAINED FROM TLS SCANS.

No.	COMPARATIVE ANALYSIS			
	Load [kN]	***Cracks in real element***	***Cracks in virtual model***	***View on the scan***
1	0	-	-	
1	10	-	-	
2	30	-	-	
3	50	√ [a]	-	
4	70	√ [b]	-	
5	90	√ [b]	√ [b]	
6	140.7	√ [c]	√ [c]	

a. Flexural (bending) cracks. b. Shear cracks. c. Failure mode transitions.

IV. Photogrammetry and image analysis of geometry

The use of photogrammetry boils to the use of stereo pair of synchronous images on which the image of beam subject to the failure (Fig. 3) from two points in the space (centers of projection represented by camera lenses, that is O1 and O2).

In the pictures (cameras imaging planes) we identify the image of the actual point on the object (P) in the left picture (p1) and right picture (p2). When reproducing the stereoscopic model we combine the obtained images of points (p1, p2) with centers of camera projections (O1, O2) in order to obtain V1 and V2 vectors. Whereas the movement of the center of right camera O2 in respect of the center of left camera O1 is T vector (Fig. 4).

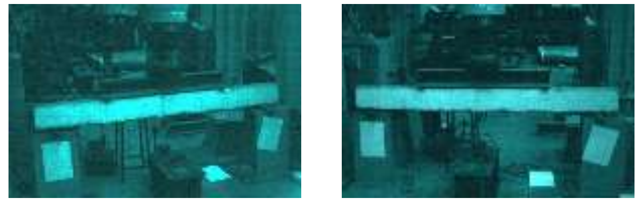


Figure 3. Stereo pair of the synchronous photos taken during the beam failure experiment (the sample of synchronic stereo images).

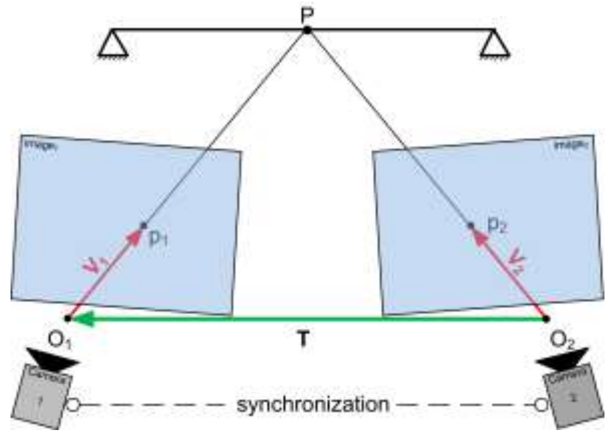


Figure 4. Scheme of the photogrammetry recording with the use of synchronous digital cameras.

The system of these three vectors is in one plane during the realization synchronized exposure for two cameras. Hence the realization of 3D model reproduction from the stereoscopic pictures uses the computer vision fundamental assumption of V1, V2 vectors co planarity what can be expressed as the vector triple product:

$$V_1 \cdot (T \times V_2) = 0 \qquad (1)$$

$$T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \qquad (2)$$

After applying the transformations described in [10] along with the eight-point algorithm [11] (using SVD – Singular Value Decomposition in computational processes) and obtaining references in the form of field coordinates of at least (that is without the supernumerary observations and the possibility of observation adjustment) three points from laser scanning or equivalent field measurement, it is possible to carry out measurements of coordinates in the system of isometric model in relation to the real system in stereoscopic images (Fig. 5).

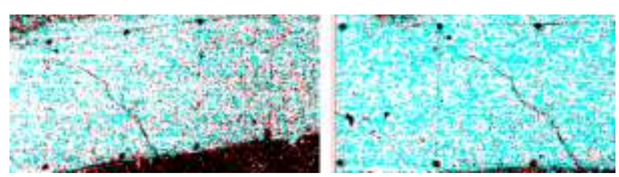


Figure 5. View of scratches in the left and right image – visible despite the reduction of the image and imperfect lighting conditions.

In addition, synchronous images stereo pairs can be made when adding another force loads on the beam. Thanks to this, it is possible to record the changes in the geometry of reinforced concrete element and the analysis of crack propagation in the function of time and applied force. At the same time, using the high-resolution digital camera, the cracks are better (uniquely) identifiable than in case of using TLS. Photogrammetric method was used in this case to verify the results obtained in scanning. The method of synchronous images can also be used independently. The accuracy of the study depends on the resolution of camera matrices, the distance from the object and lighting conditions. Be sure to obtaining the above field reference for at least scaling purpose (minimum of two landmarks or length) or preferably, also levelling (minimum three landmarks) of 3D model. To obtain correct results, cameras must be calibrated and they should be equipped with fixed focal lengths [12-17].

V. Summary and conclusions

Main objective of the study was to determine whether the laser scanning technology allows to determine the deformation and predict modes of failure in reinforced concrete beams. Assumption that the TLS allows to determine deformation and predict modes of failure in reinforced concrete beams can be considered as true, however, when certain boundary condition are met. It should be paid special attention to the conditions and limitations of TLS in this type of analysis. Determination of these conditions has allowed not only to confirm the thesis, but at the same time to determine the area of potential applications of TLS in the diagnosis of reinforced concrete elements. As a result of combining the synchronous photography, photogrammetrically prepared taking into account the SVD matrix, it has been confirmed that TLS can be used for the preliminary analysis of the failures of reinforced concrete beams and other concrete structures.

Knowing the limitations of precision concerning the use of TLS, authors indicate that the preparation of the experiment involves the elimination of errors associated with the combination of scans and the unfavourable albedo (reflective power) of the concrete surface. Therefore, the scanned object and the scanner must be in the same coordinate system. It is unacceptable to use links for locating signals. Links to the locating signals, generate itself a micro shifts which in macro scope measurements are irrelevant, but when determining the deformation they are much more significant. Therefore, the position of the scanner in relation to the object cannot be changed throughout the measurement process. White colour reflects light more intense than others colours, and provides better contrast between lateral surface of the beam and the developed crack. Therefore it is recommended to engobe scanned surface before the start of the survey. Density of points cloud depends on the scan resolution which should be configured before starting the measurement.

State of cracks propagations which allowed to identify mode of failure, has been defined for the pre-critical and post-critical stage. Therefore, scanning will be a perfect tool for archiving state of cracks propagations at predetermined stages. Using TLS to create records of disaster and accidents, we will be able to get the full three-dimensional, detailed mapping of the structure. Laser scanning as very fast method of data obtaining could be especially important when the damaged structure is removed quickly or an immediate repair is performed. TLS is a good tool to analyse the deformation of the reinforced concrete elements. Huge advantage of TLS over the conventional methods of measurement elements is the complexity of obtained results. As a final product of post-processing, a complete three-dimensional model of full operability can be obtained.

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