Journal of Young Scientist, Volume IX, 2022
ISSN 2344 - 1283; ISSN CD-ROM 2344 - 1291; ISSN Online 2344 - 1305; ISSN-L 2344 – 1283

MONITORING STEEL STRUCTURES OVER TIME BY USING TERRESTRIAL LASER SCANNING TEHNIQUE FOR DISASTER PREVENTION

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Abstract

This paper aims to present monitoring the behaviour in time of a steel structure using a revolutionary method, known as Terrestrial Laser Scanning and the advantages of this technique in researching the effects of extreme actions on buildings. The demand for developing new strategies in designing buildings against accidental actions like external explosions has increased significantly in recent years due to the global political and social instabilities. Accelerated technological progress, as well as the need to acquire three-dimensional data for buildings, have led to the development of this new method for acquiring data using laser waves. In this study, laser scanning was used during real-scale field tests, to monitor the behaviour of energy-absorbing envelope systems for a steel structure subjected to external explosions. Based on the obtained data it will be possible to draft new design strategies for non-structural elements like the envelope of a building, reduce the potential for more serious structural failures and protect the occupants of the building.

Keywords*: deformation monitoring, external explosion, façade systems, real-scale field tests, terrestrial laser scanning.*

INTRODUCTION

The overarching goal of researching the effects of extreme actions on buildings (explosions, blast, snow overloading, fire, tsunami, terrorist attacks, vehicle impacts, other actions due to local failure from an unspecified cause) is to better understand and estimate the risks and threats occurring to buildings and occupants and try to implement new design rules or design strategies that will prevent further human losses during this kind of disasters. The current social and political instabilities of the 21st century have led to an increased number of explosions caused by terrorist attacks in densely populated areas and in the immediate vicinity of buildings, so that engineers must provide designs that can resist to this category of actions. At present, there are several strategies for buildings, implemented so that structures can resist explosive threats or blasts such as: mitigation of debris from the damaged façade, isolating internal threats from occupied spaces and establishing a secure perimeter. Unfortunately, there are not sufficient design rules, or the current guidance is limited yet to develop an official framework, because quantifying the effects of extreme actions like blasts can be difficult.

The Eurocode EN 1990 guidance for buildings requires for all structures, survival of local damage, sufficient warning at collapse, low sensitive structural form, and tying members.

Eurocode 1990 also provides a classification of buildings by consequences class which must be considered in the design for accidental actions.

The current version of Eurocode 1991-1-7 (accidental actions) is providing basic requirements and design strategies for internal explosions only (gas explosions, dust explosions or other natural explosions) and not for external explosions (natural or intentional). Moreover, the risks caused by fragmentation and debris resulted from non-structural elements are not quantified at all in this code.

The main challenge, when considering accidental actions in designing a building, is the identification of the threat. Annex A of Eurocode 1991-1-7 includes strategies for identified and unidentified accidental actions but they are mainly prescriptive rules and prevention methods of the action itself.

For buildings subjected to accidental actions it is simply insufficient to consider a strength-based design method alone. Because of the large deformations that are resulting from these kind of actions, ductility-based design approaches are more appropriate because it must be guaranteed that transfer of loads between structural elements of the building continues even if subjected to accidental actions, to avoid a progressive collapse.

The lack of specific design rules for structural and non-structural elements subjected to accidental actions like external explosions, led to an increased interest in conducting real-scale tests and creating numerical models using advanced non-linear analysis software tools.

Politehnica University of Timisoara in partnership with the Technical University of Cluj-Napoca and the National Institute for Research and Development in Mine Safety and Protection to Explosion: INCD-INSEMEX developed a research project entitled “Safety of building walls and claddings against accidental explosions (SAFE-WALL)” in which the main objective was to study the behaviour of enclosure walls and façade systems and increase their safety level against direct effects (pressure wave) and side effects (fragmentation and debris) following an external explosion. Within this project, the research group conducted full-scale blast tests on wall-frame structure systems and acquired three-dimensional data using a revolutionary technique based on laser waves called Terrestrial Laser Scanning.

MATERIALS AND METHODS

The tested structure within this project was designed based on the existing rules of the Eurocodes and evaluated for permanent loads, live loads, and low seismicity actions with a PGA equal to 0.10g without considering the provisions regarding to accidental actions. The structure was tested at the INSEMEX testing-site in Petroșani, Romania (Figure 1).

Figure 1. General view of the test setup

The experimental model is a prefabricated steel frame structure with two bays in transversal direction with a length of 4.5m each, two bays in longitudinal direction with a length of 3.0m each and two stories of 2.5m each. The columns are made from HEB 260 steel profiles, transversal beams are made from IPE 270 steel profiles, longitudinal beams are made from IPE 200 steel profiles and the secondary beams are made from IPE 180 steel profiles. The used steel grade is S275. On the transversal direction, the beams are rigidly fixed to the columns with M24 gr.10.9 bolts and end plates with a nominal thickness of 16mm. On the longitudinal direction, the structure was designed with bracings.

The longitudinal and secondary beams are pinned to the columns, respectively to the main beams. The columns are fixed at the base.

Two different solutions were adopted for the façade system of the structure:

- PUR100/0.5mm sandwich panels fixed to the columns with C150/2mm wall rulers. The distance between the wall rulers for the sandwich panel solution is 1.9m.
- MBS KS100/600 cassette panels with a thickness of 0.88mm.

In this experimental test, small amounts of explosive charges (143g TNT) were placed at moderate distances from the panels (1.5-3.0m). The two solutions were monitored during the explosion tests and data was collected regarding their behaviour under blast loads (deformations, displacements, load capacity).

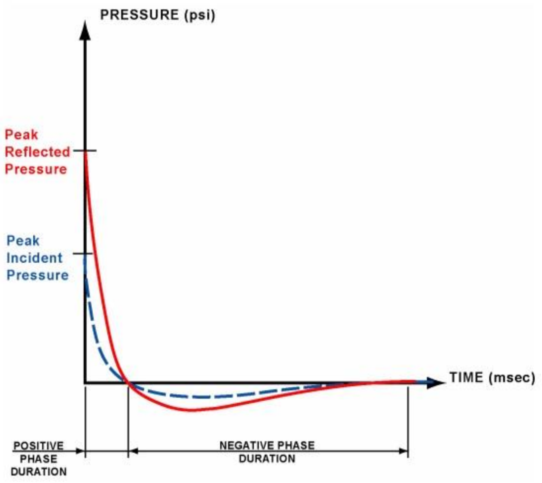

Figure 2. Air-blast as a function in time (FEMA 427)

Evaluating the characteristic parameters of blast waves such as blast pressure, impulse, load duration and shock wave velocity is a key step in defining the blast load (Figure 2). To collect these data in conjunction with the blast waves and its effects on the structure, several systems were used for measuring: pressure sensors, strain gauges, accelerometers, digital image correlation and laser scanning.
Surveying methods based on laser scanning are very effective to obtain accurate visual documentation of full-scale structures while monitoring the deformed shape and maximum values of displacements.
The terrestrial laser scanner Z+F IMAGER 5010C was used to monitor the deformations of the two façade systems of the steel structure caused by the external explosion.
The Z+F IMAGER 5010C scanner is a static ground scanner mounted on a rigid tripod and has a fixed position throughout the data acquisition. It also belongs to the category of active scanners, which emit controlled radiation in the form of a laser wave and determinate the position of the laser point on the scanned object using the built-in camera.
The integrated HDR camera (High Dynamic Range) has a resolution of 60 megapixels, and it is perfect for capturing high-resolution, high-quality images.

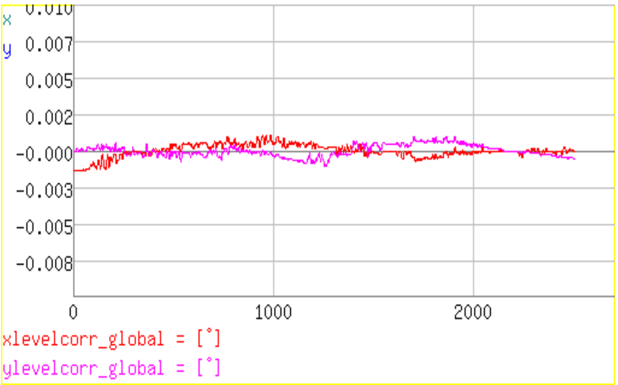

Figure 3. Detected tilting changes between two low encoder positions (< 0.007○)

This type of scanner has also a dynamic compensation, which is designed to provide position corrections so that the instrument does not suffer any offset during measurements (Figure 3). The position of the laser scanner has been constantly corrected, so that the maximum offsets do not exceed ± 2°, resulting in very high accuracy holds.
To determine the points coordinates, the scanner uses the time-shift principle, making it ideal for lens scanning due to the speed of the scan and the higher resolution compared to the scanners based on the time-of-flight method. The maximum scanning speed is 1,016,000 dots per second.
Furthermore, operating this type of laser to retrieve dots was found safer for the users, which made the scanner more appropriate for the objective within this field test, due to the relative high number of participants that were present during the scanning process.
The time-shift method is often used in wave measurements. This method is used in both total stations using the laser function for distance measurements and in active laser scans. It involves the measurement of a phase difference between transmitted and received waves.
Paper targets also served as landmarks outside the area of influence of the explosion. These paper targets are made of two black triangles attached to the center of the paper, which is the representative point to be considered at the processing stage.
It was observed that site planning for scan stations and targets has a key role in optimizing and rationalizing the field measurement phase, particularly in static ground scanning.
In the case of the measurements within these field tests, the static ground scanning method

was used to ensure a higher accuracy and to obtain a point cloud of relatively small size so that the data processing is more facile.

To determine the optimal position of the stations, it is important to consider the range of the scanner, the maximum distance to which the scanner ensures maximum accuracy and coverage. With a view to optimize the number of stations, the distance between the stations should not be too short, as it would result in a very high percentage of repetitive information (the same points seen from several stations) which would be useless and inefficient.

It is also necessary to determine the positions that are providing the largest possible coverage area of interest, without any obstruction on the laser beam path. The position of the scanner was chosen so that the emitted laser beam intersects the scanned surface in a perpendicular direction, as the scanned surfaces diffuses light reflectance, so that if the angle of intersection is too sharp, the accuracy of determining the point would decrease considerably.

The scanning equipment was placed in a stable area, protected from unfavourable weather (e.g., strong wind, blizzard), vibrations, or other external factors that could cause unwanted movement of the scanner during data acquisition. Another important element was the positioning height of the device, depending on the purpose of the scan. In this case, the positioning was done to be able to observe as many targets as possible.

In addition, it was observed that the positioning of the paper targets played an essential role in achieving the alignment of the obtained point clouds after consecutive scans, but also to be able to define the same coordinate system of the scanned objective before and after the explosion. It is essential that their positioning is done so that there are at least 3 common targets between pre-explosion scanning stations and post-explosion scanning stations. Determining the location of these targets proved to be very difficult, as the targets located too far away did not provide satisfactory accuracy, and the targets located near the blast were destroyed or their position has changed, so that, they were classified as unusable.

During the monitoring of the panels at INSEMEX Petroșani, a series of scans were performed before and after the explosion. Each scan series consisted of two separate scans, carried out to capture all the details of the panels. The initial scan was used to capture the undeformed shape of the envelope panels and the second one was performed to determine the deformations after the explosion (Figure 4).

Figure 4. After-blast footage of the deformed panels

Also, 7 paper targets were placed, at distances between 20 and 70 meters from the two scanning stations, to collect several common points to be able to perform data processing in the dedicated software. Although the positioning of the targets was made so that they were at a safe distance from the blast, 3 targets suffered positional changes due to the shock wave caused by the explosion, and one target turned out to be too far away to provide a satisfactory accuracy.

The first step of the processing consisted in exporting the data acquired from the scan.

The Z+F Laser control program was used for data processing and after some intermediate steps, the point clouds were gained. In accordance with the obtained point clouds, a 3D model of the façade systems was acquired.

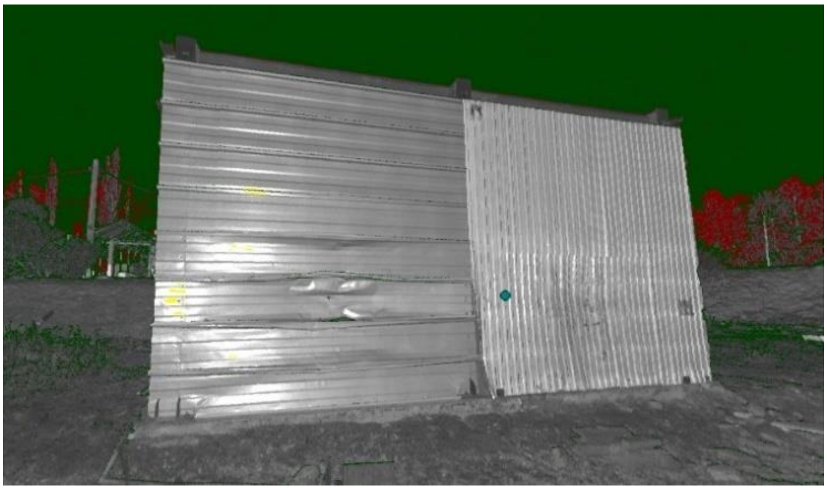

Figure 5. Initial monochrome point cloud

Initially, the point cloud is grayscale (Figure 5), but during the process, each point is coloured by using panoramic images which are taken by the camera incorporated into the laser scanner.
A significant process involves the alignment of the scan stations using paper targets.
The centre point of each paper target will be selected and named in the same manner in each scan.
To achieve the highest accuracy, the distance between the scanner and the paper targets should be in the range 3-10m.
A particularity observed within this case study was that the paper targets placed at a short distance from the panels were destroyed during the explosion.
Theoretically, the most ideal positioning of the targets during the scanning process, is perpendicular to the direction of the laser wave. Nevertheless, in practice, it is difficult or almost impossible to replicate this ideal case, but very sharp or obtuse angles must be avoided at any cost, during the placement of the paper targets.
The existence of a minimum of three common points between the consecutive laser scanning stations is compulsory. If this condition is not fulfilled, the achieved point cloud will be rotated in a particular direction and the obtained image is distorted.
Based on three paper targets, the alignment of the point clouds, obtained during the two scans which were taken before the explosion and the two scans taken after the explosion, was performed.
The accuracy obtained in the alignment of the scan is very high and showed an average error of only 1.7 millimetres.
During the measurement phase, a series of points were collected.
However, some of the acquired points were classified as redundant because they contained unnecessary information regarding the object of interest (e.g., trees, bushes, terrain) (Figures 6 and 7). This data is not relevant for this case study and makes it difficult to process the information using the large amount of data.
With the purpose to remove the ineffectual data and obtain the final results, the point cloud was cleaned using the CloudCompare program (Figures 8 and 9).

RESULTS AND DISCUSSIONS

As mentioned previously, to obtain consistent results, it is mandatory that the scans taken before and after the explosion have the same system of coordinates, this step being achieved during the initial processing within the Z+F LaserControl software. For this scope, the coordinates of the paper targets used in the scans taken before the explosion are the baseline data for the post-blast coordinates of the paper targets. The average error in alignment of the point clouds was only 4.3 millimetres.
Processing using CloudCompare software reduced the number of points from 2.7 million points to 300,000 points. This step was essential to reduce the thickness of the point cloud and to obtain the final results in terms of deflections. The deformations were already visible in the CloudCompare software (Figure 10), but due to the limitations of the software, the reduced point cloud was exported in DXF format, and with the

aim to obtain the final results, the AutoCAD software was used instead (Figures 11 and 12).

Figure 6. Uncleaned point cloud of the panels before the explosion

Figure 7. Uncleaned point cloud of the panels after the explosion

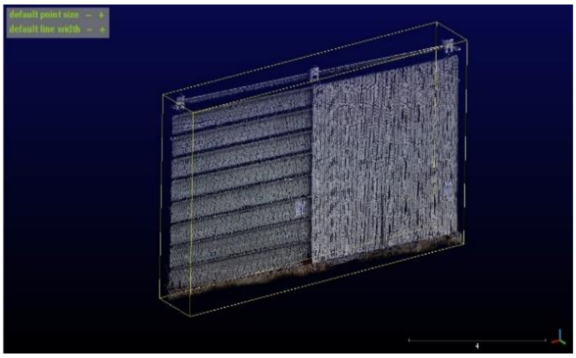

Figure 8. Cleaned point cloud of the panels before the explosion

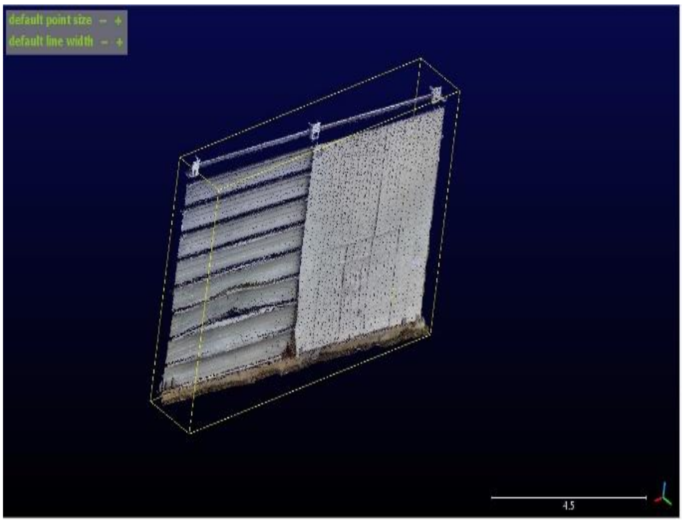

Figure 9. Cleaned point cloud of the panels after the explosion

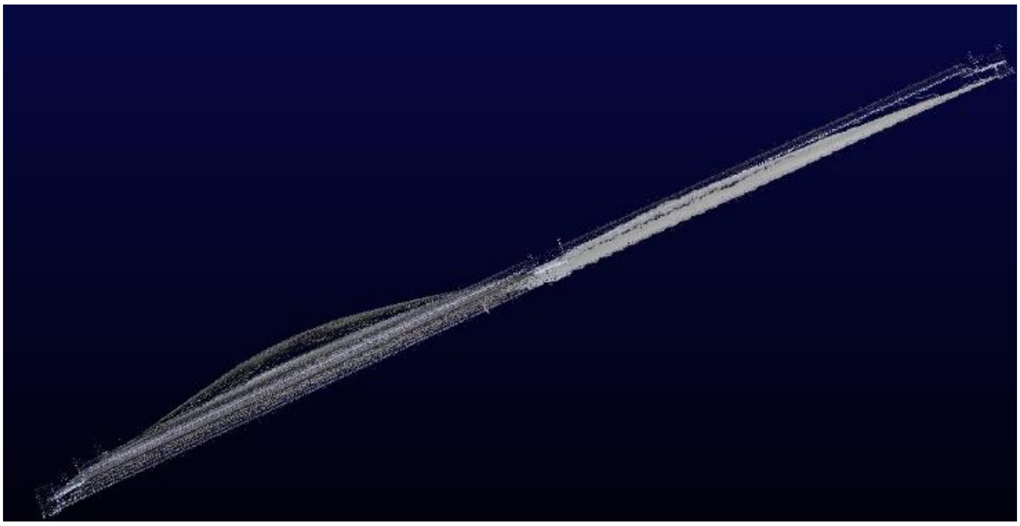

Figure 10. Top view of the cleaned point cloud of the deformed shape

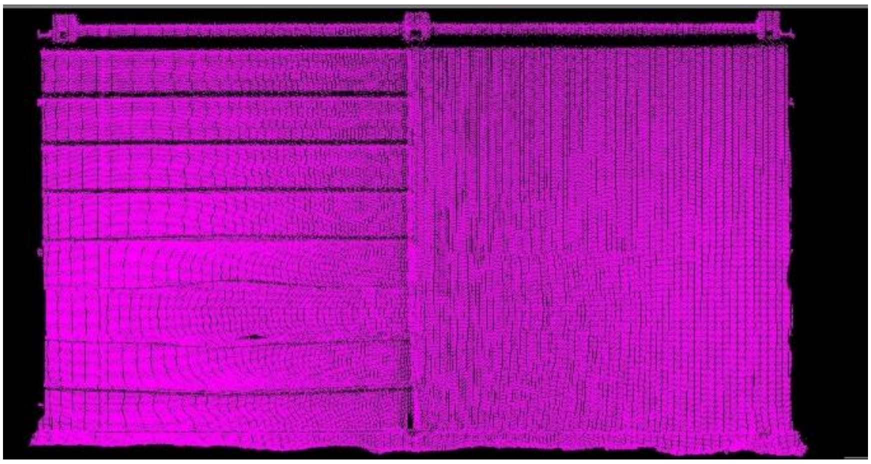

Figure 11. Final point cloud of the deflected shape in AutoCAD

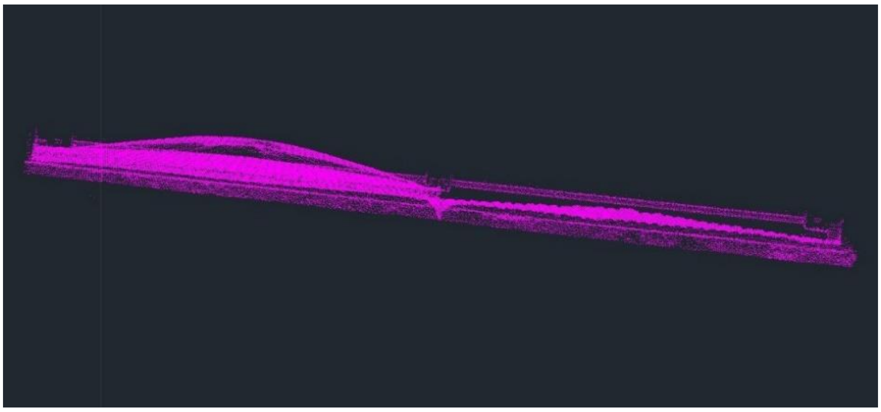

Figure 12. Final point cloud of the deflected shape in AutoCAD – top view

During the field tests, it was observed that the dynamic response of the two façade systems is beneficial for mitigating explosive effects and very similar, due to fact that, both are lighter and more flexible systems and possess enough ductility to avoid a brittle failure mode. The two systems suffered comparable permanent damages but absorbed enough energy through deformation to transfer lower forces into the connections and then into the supporting elements of the structure. In the case of the steel cassette, the failure occurred in the connections between the panel and column (failure of the fastener), moreover large deformations appeared in the interior zones. In the case of the sandwich panel the failure mode is comparable but larger deformations occurred only on the exterior sheet of this system; showed also a higher ultimate strength capacity and a superior blast response reduction capability.

Basically, the foam core absorbed the energy during the blast, dissipated kinetic energy, and as a result, lower impulse was transferred to the structure.

Both panel systems underwent inelastic deformation and very small tearing but failed in a ductile mode such as flexure rather than a brittle mode such as shear and showed a membrane/catenary like behaviour that indicates enough robustness to reduce hazards associated with fragmentation.

Following the processing of the measurements in AutoCAD, it resulted that the maximum deflection of the sandwich panel was just 13.90 centimetres, while the deflection of the cassette panel was 35.72 centimetres (Figure 13).

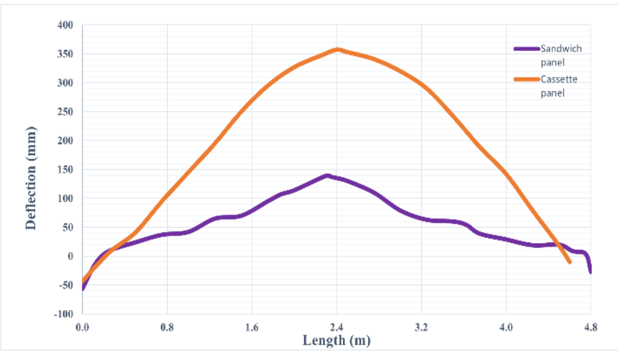

Figure 13. Deflection comparison between the two façade systems

CONCLUSIONS

The use of the Terrestrial Laser Scanning in measuring panel deformations has proved to be significant since the displacement sensors located on the panel have been destroyed during the blast tests, making it impossible to accurately determine the deformations using traditional methods.

Moreover, after the explosion it was established that, the maximum deflection of the cassette panel occurred above the area where the displacement measuring sensor was installed. This was subsequently confirmed by the analysis of the point cloud obtained from the terrestrial laser scanning.

Terrestrial laser scanning represents a new effective method that can be used to evaluate the behaviour of more suitable materials and systems used in blast response reduction for building envelopes. Reducing the potential of hazards that endanger the structural integrity of the building means to design the exterior envelopes of high-risk buildings to be more robust during these exceptional situations since they constitute the critical line of defense for protecting the structural elements and more important the occupants.

In conclusion, Terrestrial Laser Scanning is an innovative technology capable of providing more accurate and comprehensive results compared to traditional measurement methods in terms of monitoring a steel structure even in exceptional situations.

ACKNOWLEDGEMENTS

This research project was supported by a grant of the Romanian National Authority for Scientific Research, UEFISCDI, PN-III-P2-2.1-PED-2019-1765, contract nr. 279PED/2020.

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SECTION 04
CADASTRE