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Crashworthiness of protection structures for mining machine operators: numerical analysis and experimental validation using Optical 3D Coordinate Measuring Devices

The aim of the work was to perform comparative tests based on strength analysis and experimental research of the structure protecting the operator of the self-propelled mining machine. The first stage was to develop a numerical model of the protection structure in accordance with the technical documentation provided by the manufacturing company and to analyse it with the use of finite element method. The analysis was conducted in the dynamic range, taking into account material and geometric non-linearity. Performed calculations included simulation of the strength test of a protective structure's impact with falling mass in accordance with PN-92 / G-59001 (RSPS - Rock slide protective structures). Basing on the documentation, geometric and then discrete model were developed and the numerical calculations were performed. Then, in order to verify the computer simulation, experimental tests of the analysed cabin were carried out.

Keywords: *protective structure, photogrammetry, finite element method, high speed camera, strain gauge measurements, comparative testing*

1. INTRODUCTION

Assessment of the self-propelled machine operators safety by numerical methods in order to obtain approval for sale and usage of the machine is related to the experimental validation of the method used. The most often performed procedures are FOPS (Falling Object Protective Structure) and RSPS (Rock Slide Protective Structures) tests. They are a means of testing the characteristics of the structures used to protect the operator from localized impact penetration and, indirectly, of the load-carrying capacity of the supporting structure to resist impact loading [1]. The experiment consists in dropping the object with mass and shape defined in standards onto the cab roof from height, which will provide the required impact energy (FOPS-11.6 kJ, RSPS - 60 kJ). The evaluation of the protective structure after the test consists in the measurement of the deflection of the roof by a simple ruler in the area where the machine operator is located. The authors of the paper decided to go one step further and perform more accurate measurement of the cab structure before, after and during the impact of the falling object [2]. Additionally, the measurement of other elements of the protective structure was made. The research was carried out using innovative measurement methods based on photogrammetry. Finally, they were compared to the results obtained from numerical analysis.

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2. NUMERICAL CALCULATION

The objective of the study was the strength analysis of the protective structure with the use of numerical method, in the dynamic range, considering material and geometrical nonlinearity. The analysis encompassed a simulation of the impact test of the protective structure with the falling object in compliance to norm PN-92/G-59001 (RSPS - Rock slide protective structures).

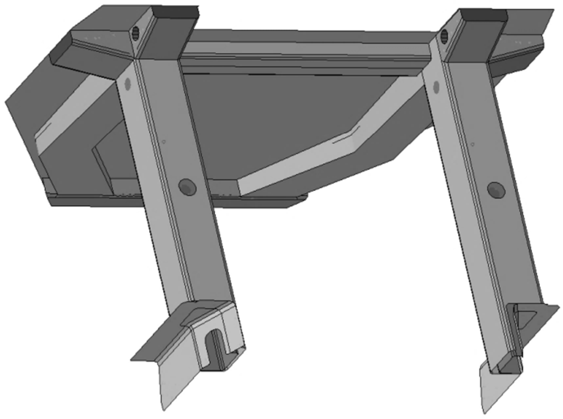
On the basis of the technical data of the cab received from the manufacturing company, geometrical and then discrete models were built. Strength calculations were performed with use of finite element method (FEM) [3]. Impact energy was equal 60 kJ.

From the structural analysis contours of the displacement, stress and strain were obtained.

The entire research encompassed the following issues:

- building a geometrical model of the cab on the basis of the technical documentation (Fig. 1)
- creating a discrete model of the protective structure (Fig. 2)
- nonlinear strength calculation of the load-bearing structure with the use of FEM in the dynamic range [4],
- discussion of the results.

a)



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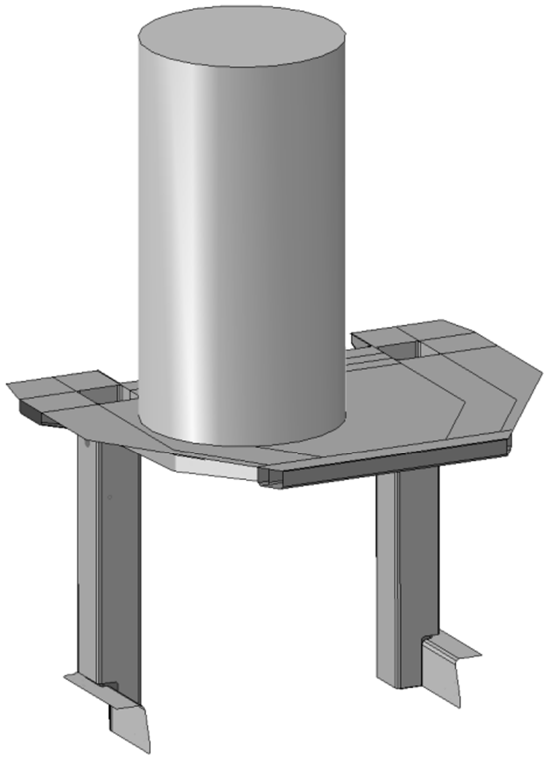


Figure 1. Geometrical model of the cab (a) and assembly with platform and falling mass (b)

a)

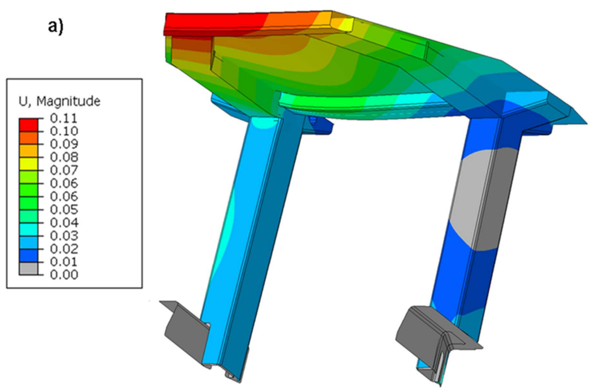
b)

Figure 2. Discrete model of the cab (a) and assembly with platform and falling mass (b)

The results of the simulation are presented in figure 3.

Verification of the structure according to the standard is based mainly on the results of the roof deflection above the operator's head. Tests are considered positive when the operator model (DLV) remains intact by any element puncturing the protective structure and by any deformation of the structure in elastic and plastic range [5]. DLV is situated inside the cab, in the location of real operator, with the same seat index point (SIP) position.

a)



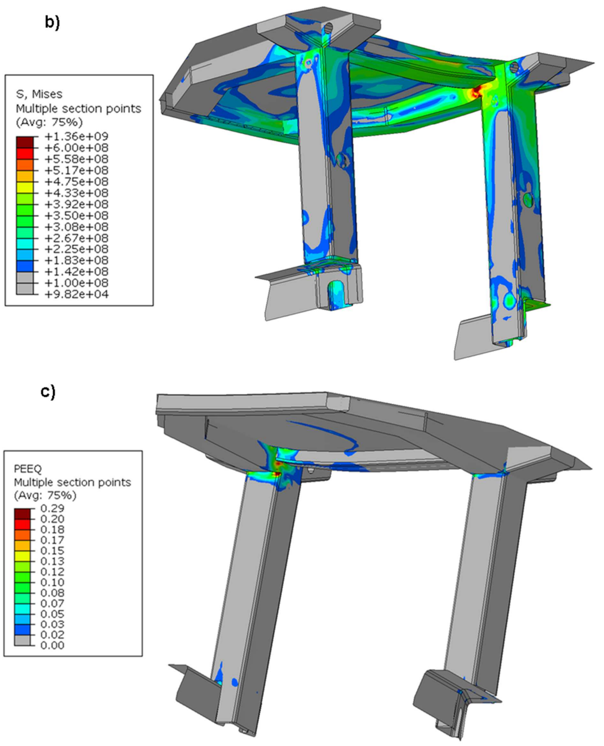


Figure 3. Results of the numerical simulation; a - displacement, b – HMH stress, c – plastic strain

For the purpose of numerical calculations, measuring points above the operator were selected in nodes of finite elements for which courses of displacement were determined (Fig. 4).

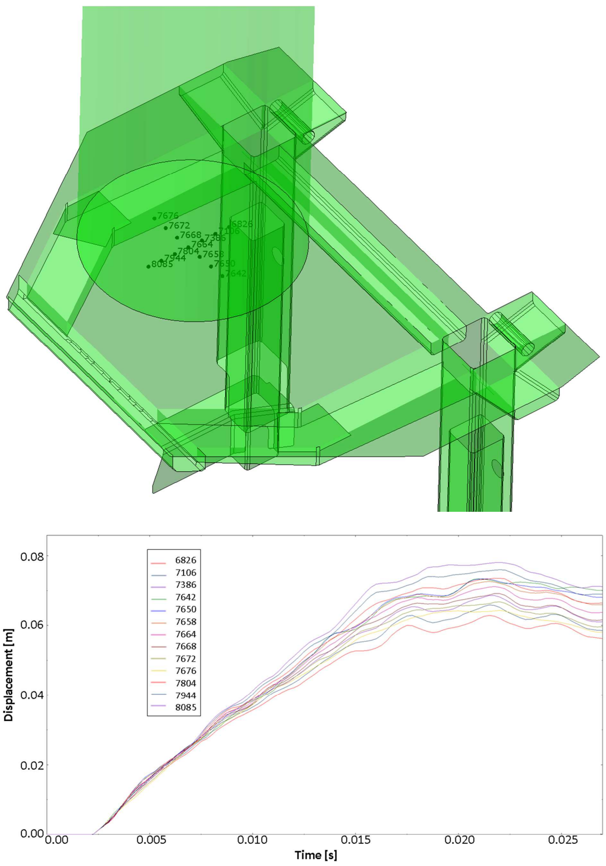


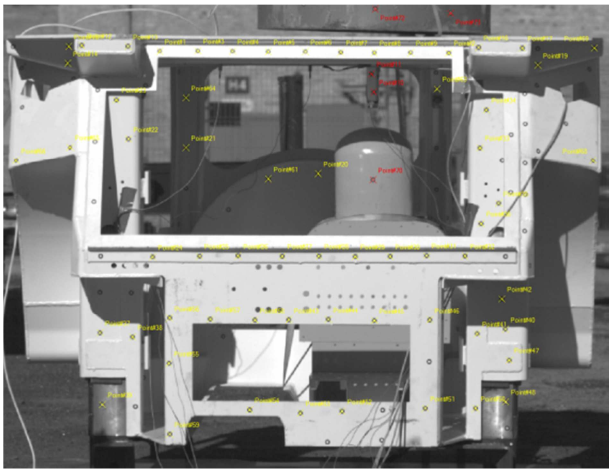
Figure. 4. Deflection courses for selected measuring points above the machine operator

3. EXPERIMENTAL TESTING

In order to verify numerical calculations performed within the accredited laboratory, authors are obliged to carry out experimental validation of the computational method once a year. Beside standard measurements with the simple measuring devices (ruler, tape measure) more complex methods were used [6].

2.1 High speed camera

One of the proposed methods to verify the numerical calculations were high speed camera measurements [7].



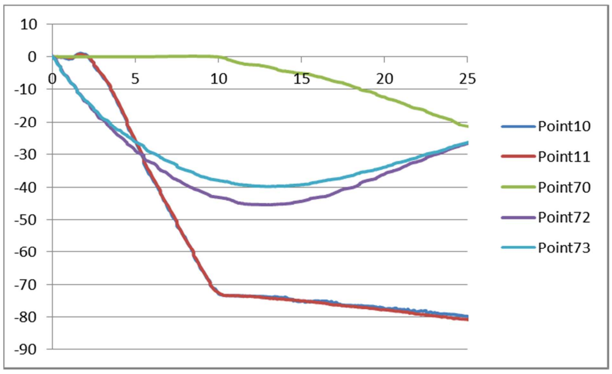
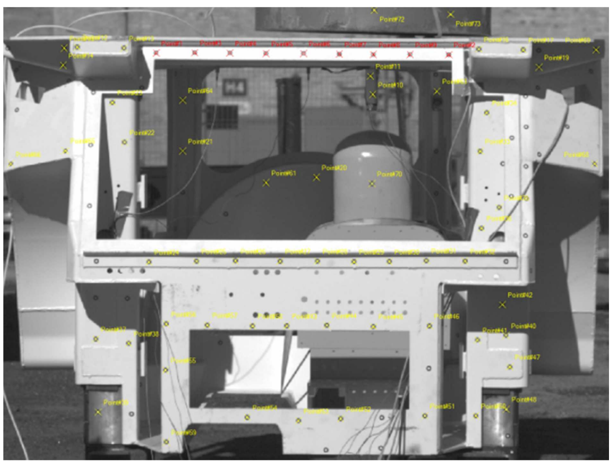


Figure. 5. Vertical displacement courses for selected sampling points (10, 11, 70, 72, 73)



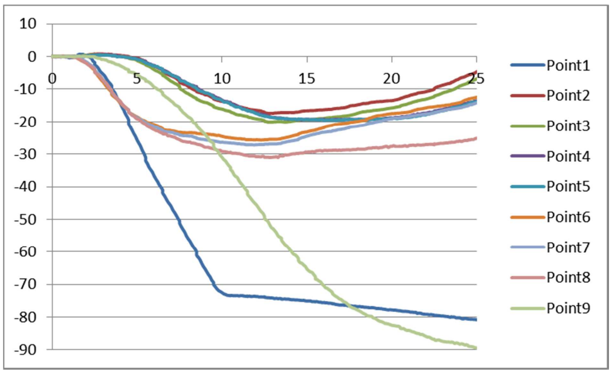


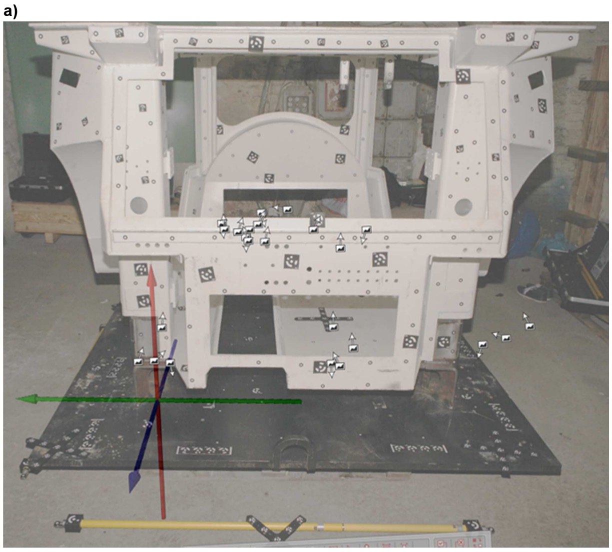
Figure. 6. Vertical dynamic displacement courses for selected sampling points (1-9)

The experiment was recorded using the VISION research high speed monochrome digital camera Phantom V12 to determine the dynamic vertical deflection of the cab roof (Fig. 5 and 6).

2.2 TRITOP measurements

The protective structure was also measured before and after the test by means of the GOM's TRITOP device used for quick and precise measurements of the coordinates of three-dimensional objects [8]. The system accurately defined the 3D coordinates of the object points. As a result, the cloud of the sampling points and the deflection of the protective structure were obtained (Fig. 7).

a)



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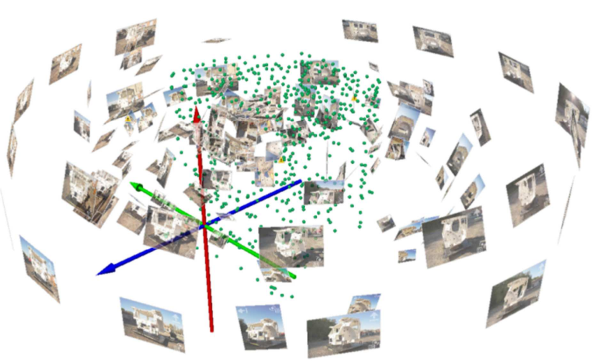

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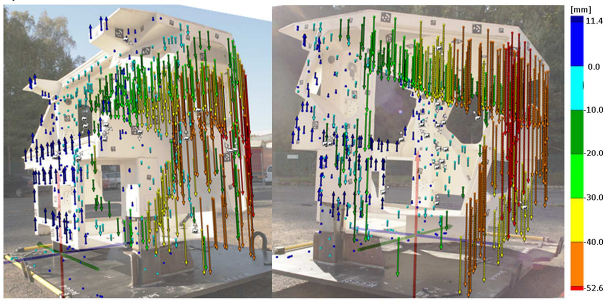


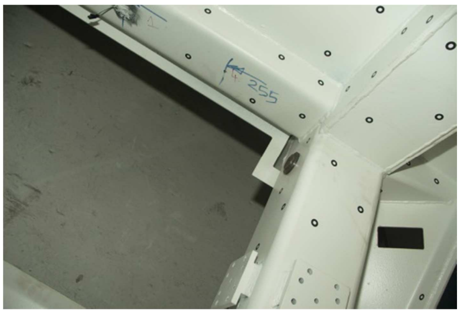
Figure. 7. TRITOP measurements; a – sampling points, b – cloud of points, c – vertical permanent displacement of the sampling points (1-9)

2.3 Strain gauge measurements

On the basis of strength calculations, sampling points where the strain gauges should be located to measure cab deformations during the test were selected. Target points for acceleration sensors were also determined. Eventually, three points were chosen to measure deformations and six points to measure accelerations [9]. Figure 8 present sampling points on the protective structure.

a)

b)



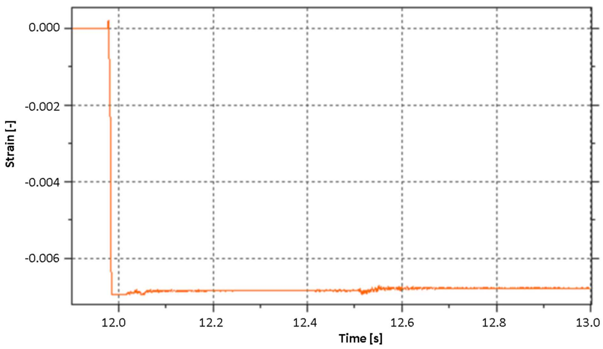
c)

d)

Figure. 8. Sampling point for strain and acceleration mearuments, points 1-3 – strain gauges, points 4-9 - accelerometers; a – points 2, 3 , 7, b – points 1, 4, c – points 1-5, 7, 8, d – protective structure (side view)

Results from strain gauges are shown in figure 9.

a)



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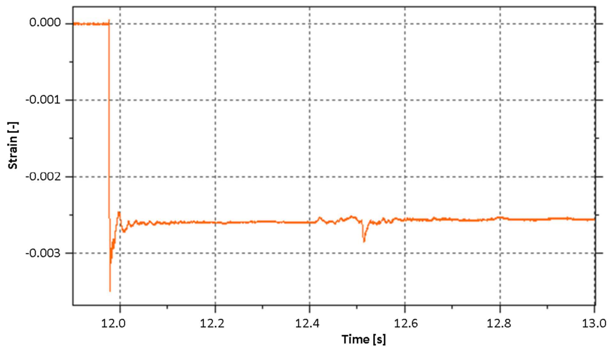

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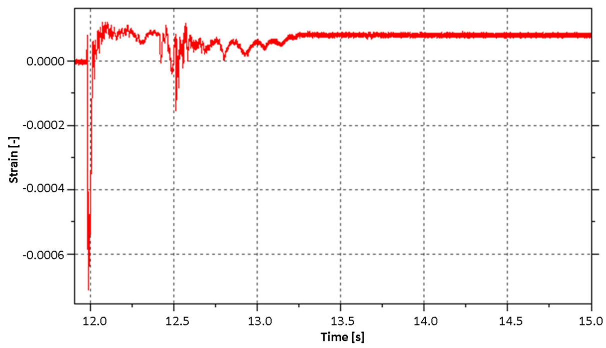

Figure. 9. Strain results recorded during the experiment; a – point 1, b – point 2, c – point 3

4. RESULTS COMPARISON

Results obtained from the experiment were compared with the numerical simulation.

Table 1 presents comparison of the permanent and maximal dynamic deflection. Measurements of the permanent deflection were taken after the experiment and it arises from yielding of the structure. The dynamic deflection on the other hand was recorded throughout the entire duration of the experiment. For the comparison, maximal value of the dynamic deflection was taken into consideration.

It may be seen that the relative error in case of permanent deflection is approximately 18-19% and for maximal dynamic deflection it is about 8-9%.

Table 1. Comparison of the deflection results obtained from simulation and experiments

Permanent deflection [mm]		Maximal dynamic deflection [mm]	
Simulation	Experiment	Simulation	Experiment
39	33	77	73

Visual overview of the methods used to analyse the deflection of the cabin is shown in figure 10.

Comparison of the strain results is shown in table 2. It was measured in three most loaded points, selected based on previously performed numerical calculations. The values in table presents maximal obtained strain during entire simulation (ε_{max}) and residual strain after yielding of the protective structure and removing the falling object ($\varepsilon_{after\ yield}$). Compared values appeared to be within the same or similar orders of magnitude.

Table 2. Comparison of the strain results for selected sampling points (1-3)

	ε_{max} [-]		$\varepsilon_{after\ yield}$ [-]	
	Simulation	Experiment	Simulation	Experiment
Pt 1	0.0062032	0.0069317	0.007025	0.006756
Pt 2	0.005254	0.00346	0.004019	0.002568
P 3	$8.4414\ e^{-4}$	$7.1108\ e^{-4}$	$1.1027\ e^{-4}$	$8.4426\ e^{-5}$

5. CONCLUSION

Validation of the computer analysis with the use of photogrammetry enabled the authors to verify the numerical simulations of the protective structure of the mining machine operator [10]. The results obtained from the simulation are consistent with the experiment.

Using three different measuring methods allowed the authors to verify many different results obtained during the experiment and also precise validation of the numerical model.

TRITOP device enabled accurate measurement of the 3D coordinates of sampling point selected on the analysed structure. On this basis permanent deflection of the cab was determined.

High speed camera Phantom permitted to obtain dynamic deflection of the protective structure in near real-time as an experiment was running.

Finally, strain gauge measurements enabled to determine strain (and then stress) values on the most loaded areas of the structure.

Additionally, values received from the numerical model are slightly higher, thus meaning that the computational calculations provided a safety margin in the structure examination.

REFERENCES

[1] Kalita, M. Konstrukcja ochronna operatora ładowarki górniczej w świetle przepisów i badań niszczących, *Maszyny Górnicze*, 2013, 1, 16-21.

[2] Saska, P., Czmochowski, J., Iluk, A., Piterusiak, D. Application of high speed camera to determine the blast impulse generated by a small explosive charges, *Modelling in Engineering*, 2014, 21 (52), 186-192.

[3] Hughes, TJR. The finite element method: linear static and dynamic finite element analysis, 2012.

[4] Sun, J.S., Lee, K.H., Lee. H.P. Comparison of implicit and explicit finite element methods for dynamic problems, *Journal of Materials Processing Technology,* 2000, 105(2), 110-118.

[5] Karliński, J., Rusiński, E., Smolnicki, T. Protective structures for construction and mining machine operators, *Automation in Construction*, 2008, 17(3), 232-244.

[6] Clark, B.J. and Thambiratnam, D.P., Perera, N.J. Analytical and experimental investigation of the behaviour of a rollover protective structure, *The Structural Engineer*, 2006, 84(1), 29-34.

[7] Dziopa, Z., Stefański, K. Using the high-speed camera as measurement device in the dynamic material tests, *Journal of Vibroengineering*, 2012, 14 (1), 22-26.

[8] Koutecký, T., Paloušek, D., Brandejs, J. Method of photogrammetric measurement automation using TRITOP system and industrial robot, *Optik - International Journal for Light and Electron Optics*, 2013, 124 (18), 3705-3709.

[9] Czmochowski, J., Maślak, P., Przybyłek, G., Stańco, M. Numerical and experimental identification of crack in the stacker construction. *Materials Today: Proceedings,* 2018, 5 (13), 26642-26647.

[10] Koruba, Z., Osiecki, J. The operator protective structures testing for mining machines, *Solid State Phenomena*, 2010, 165, 256-261.

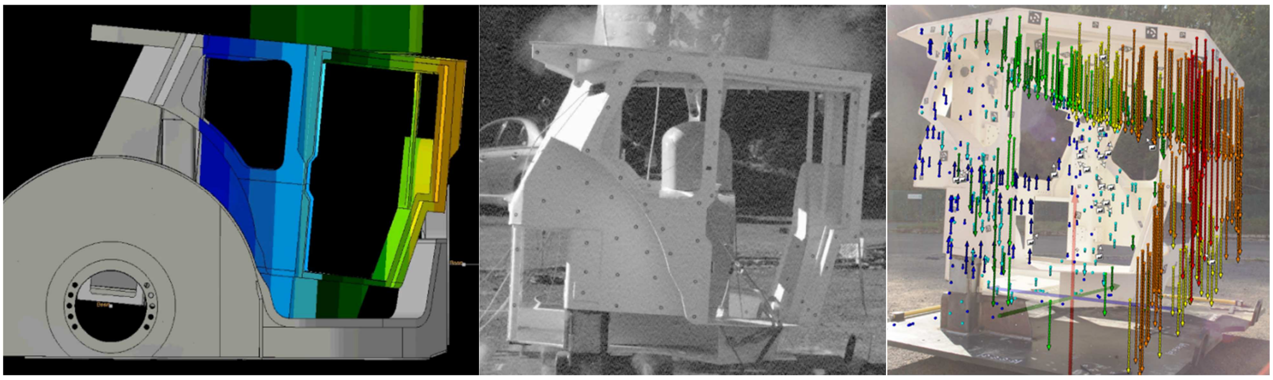

Figure 10. Overview of the methods measuring the deflection of the protective structure

