Computer Assisted Mechanics and Engineering Sciences, **15**: 53–66, 2008.

Use of reverse engineering method in verification of virtual prototypes

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(Received September 21, 2007)

The prototypes of *Falling-Object Protective Structures* (FOPS), which are used in self-propelled mining machines, undergo obligatory laboratory strength tests. The stand tests should be preceded with virtual prototyping of computer models to reduce the number of prototypes to an indispensable minimum. The Finite Element Method was used for the virtual prototyping. At the same time, after tests, the real protective structure was transformed by the Reverse Engineering method into a computer model. The deformations were compared on both models, at the same cross sections. The anthropometric model of operator was placed inside the reconstructed model.

Keywords: falling-object protective structures (FOPS), virtual prototyping, reverse engineering, human body modelling, finite element method

1. Introduction

The *Falling-Object Protective Structures* (FOPS) are used in self-propelled mining machines to protect the operators against objects falling from the roof, Fig. 1.

The prototypes of these structures undergo obligatory laboratory strength tests [8]. In the case when limitations, as regards amount of deformations, which are specified in the standard, are not met, the structure should be tested again, after modifications of the structure design. It means additional costs and a delay in delivery of the machine to final user. However, making the over-sized structures leads to an increase of machine weight, increase of fuel consumption and decrease

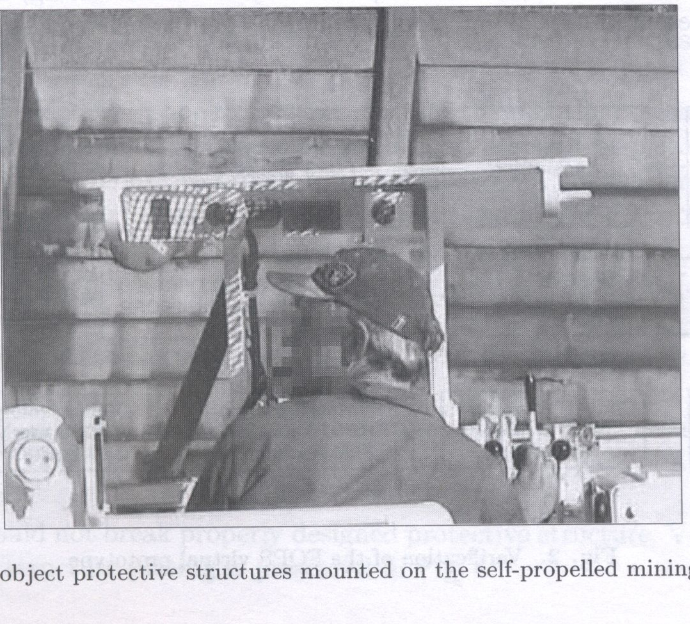


Fig. 1. Falling-object protective structures mounted on the self-propelled mining machine frame

of efficiency of braking system. To reduce the number of material prototypes to the indispensable minimum, the stand tests should be preceded with virtual prototyping of FOPS models. Then, the stand tests become also a form of verification of virtual prototypes. Verification of the FOPS prototype consists in a comparison of deformations found during experimental testing with deformations recorded during virtual prototyping. As the virtual prototyping is carried out in the Finite Elements Method (FEM) software, the geometric model of deformed protective structure is one of the forms of results presentation. Thus, the results of experimental testing should be also presented in a form of geometric model. Reverse Engineering method can be applied for that purpose. Reverse Engineering consist in creating a 3D virtual model of an existing physical part for use in 3D CAD, CAM, CAE and other software [9]. The reverse engineering process involves measuring an object and then reconstructing it as a 3D model. The measured data alone, usually represented as a point cloud, has no topological information and is therefore often processed and modeled into a more usable format such as a CAD. Reverse Engineering method uses the following special techniques for reconstruction of material objects, which are set in computer environment:

– digitaliztion realized by touching methods using measuring machines [2],

– scanning [2, 4],

– photogrametry [1].

Digitalization is realized on stationary measuring machines and it is limited to measurements of objects of sizes not greater than 0.8 m [2].

Stationary and portable scanners are used for spatial scanning of material objects. Stationary scanners have also limitation as regards dimensions of reconstructed objects. Both digitalization and scanning are carried out in special rooms, prepared for that purpose, of high cleanness standards. So, it means that portable scanners cannot be used in each room [10]. The FOPS testing are carried out either in separated parts of factory's rooms or on open air, where it is not possible to maintain the high cleanness standards.

Due to FOPS dimensions and conditions at the testing site, a reconstruction technique, which employs photos [7], was used in a discussed case. It makes neither any limitations in an access to the FOPS surfaces, which have to be reconstructed nor it is sensible for impurities at the testing place. The course of the verification of the virtual FOPS prototype is shown in Fig. 2. Two lines of activities can be seen. In one of them the virtual FOPS, created in CAD software environment, undergoes a virtual prototyping in FEM software environment. Prototyping results are saved in a format, which is used in CAD software environment.

In the second line of activities, the FOPS, after experimental testing, is reconstructed as the computer model represented as a point cloud, which is then transferred to the CAD software en-

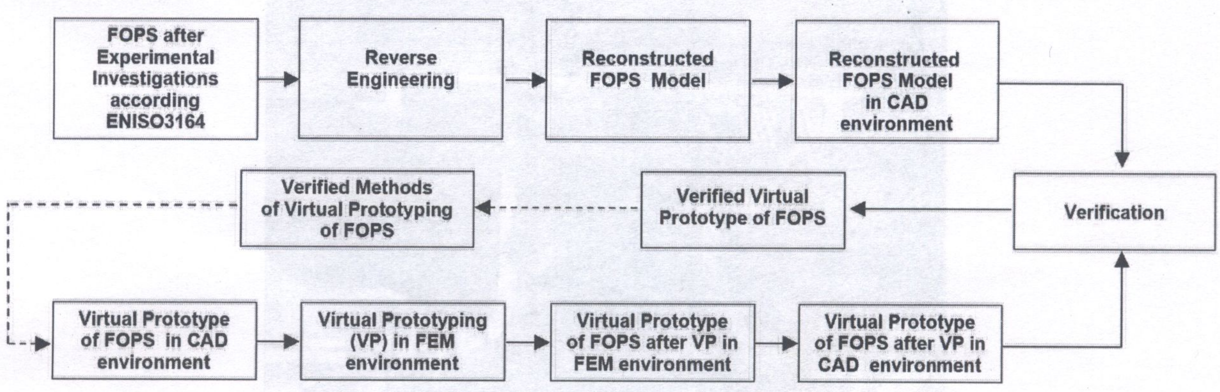


Fig. 2. Verification of the FOPS virtual prototype

vironment. Verification procedure consists in a comparison of both computer models in the same CAD software environment.

Positively verified virtual FOPS prototype confirms also a correctness of models accepted for creation of virtual prototypes and their testing. They make a reliable basis for virtual prototyping of other already designed FOPS. So it is possible to carry out only one experimental test, which is foreseen in the standard.

2. Design model of protective structure

Geometrical model of analyzed protective structure is presented in Fig. 3. The structure was designed at the KOMAG Centre, Gliwice, Poland, and it consists of upper and lower plating (Fig. 3a), between which there is a ribbing, which absorbs the energy of falling objects, (Fig. 3b) [5].

a) b)

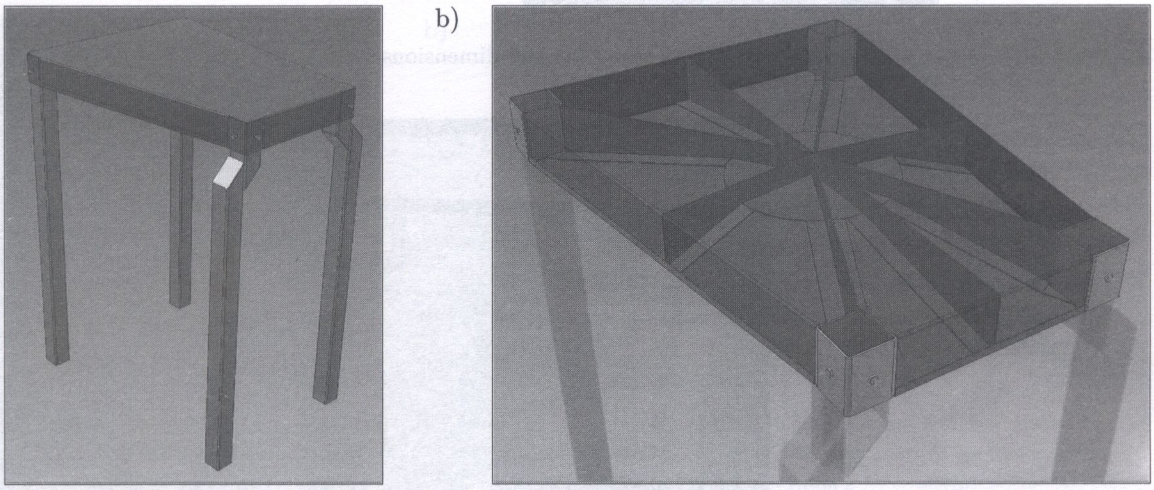


Fig. 3. Overall view of FOPS (a) and inside ribbing absorbing the impact energy (b)

3. Laboratory tests

Conditions for laboratory tests were determined in the [8] standard. The test stand is shown in Fig. 4a.

The test-piece is suspended on a hook of overhead crane. The outline of test-piece was marked with a line to improve the clarity of the photo. When dimensions of test-piece are as presented in Fig. 4b, its weight is equal to 520 kg. According to the standard, an impact energy of the test-piece has to be 11 600 J. It requires dropping the test-piece from the height $H = 2.3$ m. A mock-up of DLV (Deflection-Limiting Volume) space, of dimensions determined in the [3], which should not be disturb by components of deformed structure as well as by the test-piece itself, is placed under the lower plating, at the operator's seat, Fig. 5.

The DLV space corresponds to the space occupied by the tall, sitting operator in typical clothing in a helmet.

On the upper surface of FOPS structure there is a test-piece, which, after being drawn up to the height H, is dropped down to the place, which includes at least part of a projection of upper surface of DLV mock-up.

The falling object should not break properly designed protective structure. View of plastic strains on the surface of FOPS structure plating is presented in Fig. 6.

a) b)

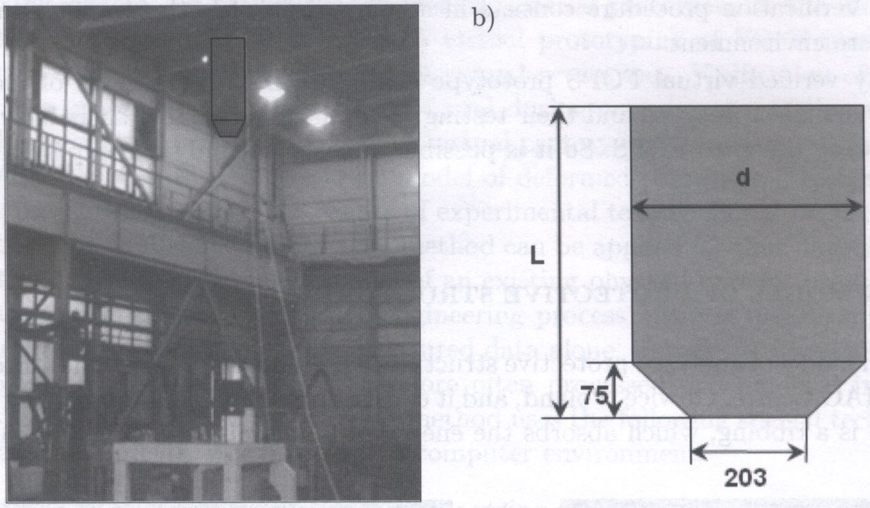


Fig. 4. View of test stand (a) and dimensions of test-piece (b)

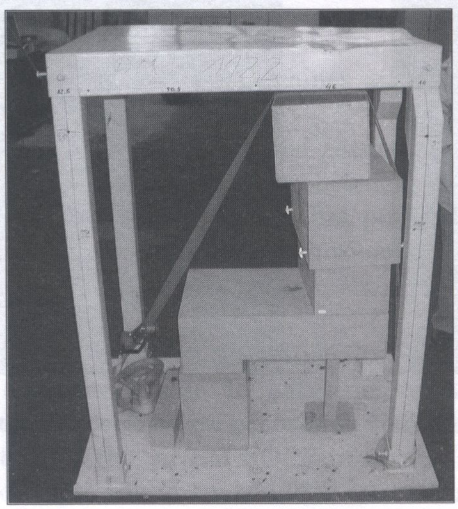


Fig. 5. Mock-up of DLV space

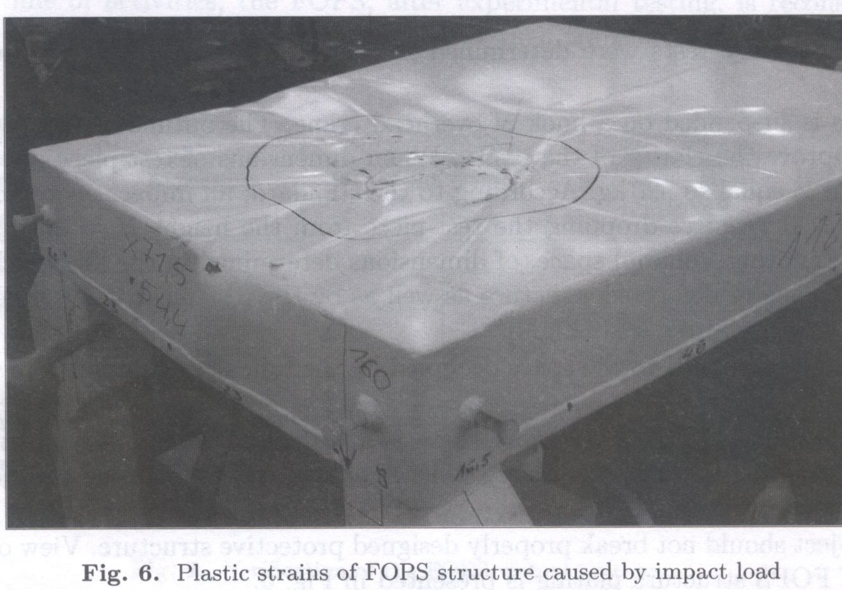
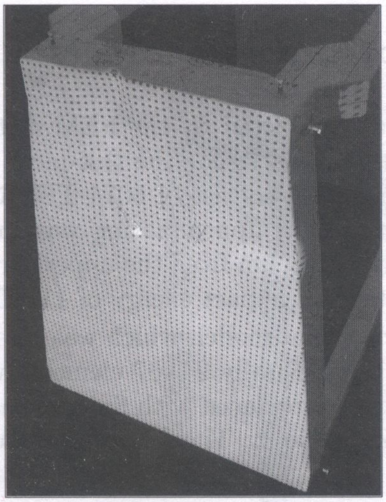


Fig. 6. Plastic strains of FOPS structure caused by impact load

4. Reverse engineering of damaged falling — object protective structures

The reconstruction of deformed *FOPS* upper plating was conducted by the Reverse Engineering method on the basis of FOPS photos, after stand tests. On the surface of FOPS upper plating the markers, which improve the depth of focus, were displayed by the overhead projector (Fig. 7a). The photographs were taken from different points to show all the characteristic details of FOPS with minimal number of photos, Fig. 7b.

The photos, saved in a digital form, were transferred to the special software and analyzed [7]. At first, the calibration of photos, by measuring the distance between two selected markers, was made (Fig. 8a). Indicating the same markers in different shots, Fig. 8b, identifies relationships between shots. The result of transformation of photos of deformed FOPS structure into the model presenting the "cloud of points" is shown in Fig. 9a. The same model, after being saved in DXF format and transferred to the CAD software, becomes a surface model (Fig. 9b).

a)

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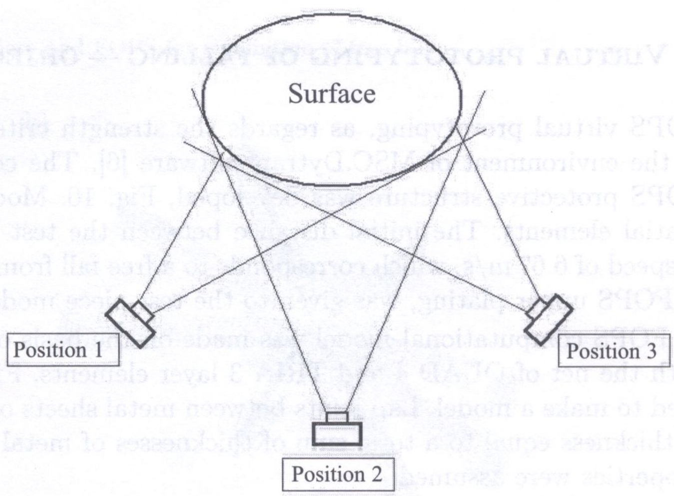
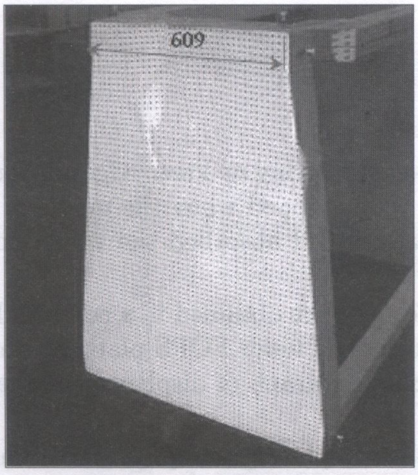


Fig. 7. View of deformed FOPS upper plating with markers (a) and arrangement of cameras relative to the FOPS (b)

a)


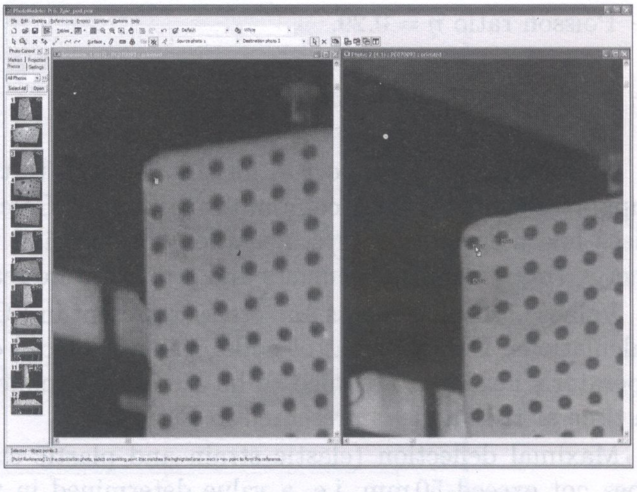
b)


Fig. 8. Calibration of pictures (a) and identification of relationships between the same markers in different shots (b)

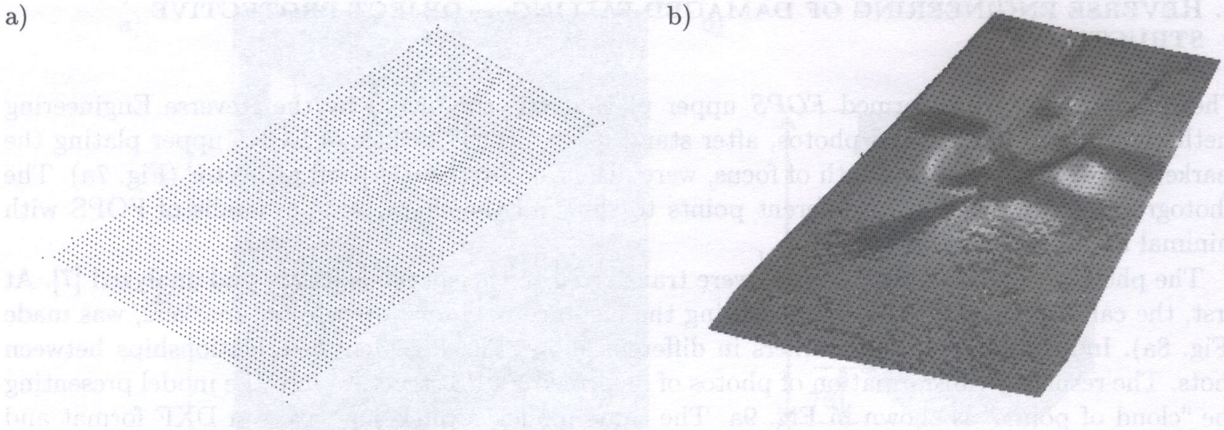


Fig. 9. FOPS reconstructed in a form of: "cloud of points" (a) and surface model (b)

5. Virtual prototyping of falling — object protective structures

FOPS virtual prototyping, as regards the strength criterion, was conducted by the FEM method in the environment of MSC.Dytran software [6]. The computational model for the test-piece and FOPS protective structure was developed, Fig. 10. Model of test-piece consist of 6074 TETRA 4 spatial elements. The initial distance between the test-piece and FOPS upper plating was 1 mm. A speed of 6.67 m/s, which corresponds to a free fall from the height of 2.3 m from the upper surface of FOPS upper plating, was given to the test-piece model to obtain an impact energy of 11 600 J.

FOPS computational model was made on the basis of constructional model, which was meshed with the net of QUAD 4 and TRIA 3 layer elements, Fig. 11a, b [6]. Totally 24 667 elements were used to make a model. Lap joints between metal sheets of plating were replaced with finite elements of thickness equal to a total sum of thicknesses of metal sheets in the joint. The following material properties were assumed:

- elastic-plastic type of material,
- Young's modulus $E = 2.068 \cdot 10^{11}$ Pa,
- Poisson ratio $\eta = 0.29$,
- yield point $R_{e\,\min} = 335$ MPa.

The same way of support as for the object at test stand, i.e. stiff fixing at lower edges of vertical supports, was used for a computational model. Calculations were stopped when the model of test-piece had a speed of 0 m/s, i.e. when construction which was verified absorbed the whole impact energy (maximal displacements and stresses were reached).

Values of displacements and stresses present in FOPS structure were obtained in a result of FEM calculations. Displacement of node, which is placed on the surface of lower FOPS plating, over the operator's head was assumed to be a criterion (node No. 11895). A graph of displacement changes in time at that node is presented in Fig. 12.

Maximal deflection (elastic strain and plastic strain) of lower plating is equal to 10 mm and does not exceed 50 mm, i.e. a value determined in the standard as the permissible [8]. A map of displacements and FOPS deformations is presented in Fig. 13a,b. Maximal deflection is equal to 41 mm and is present at the upper plating, at the place of test-piece hit, after 0.01152 s from the moment of hit.

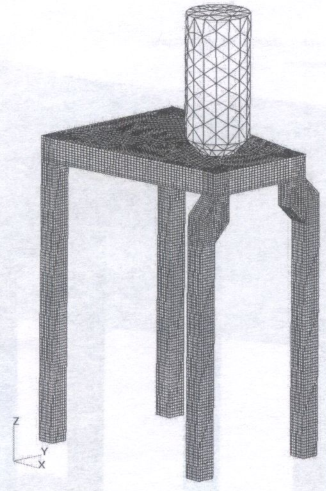


Fig. 10. Model of test-piece and FOPS for simulation of free fall

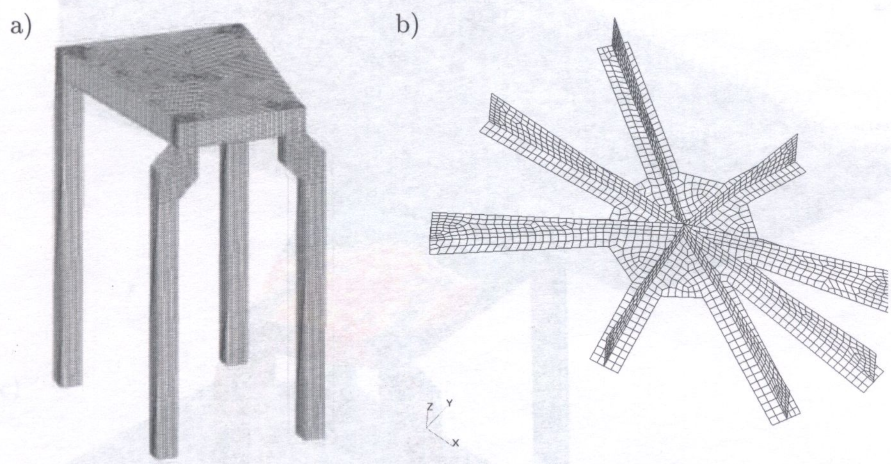


Fig. 11. *FOPS* computational model: view from outside (a) and model of frame between upper and lower plating (b)

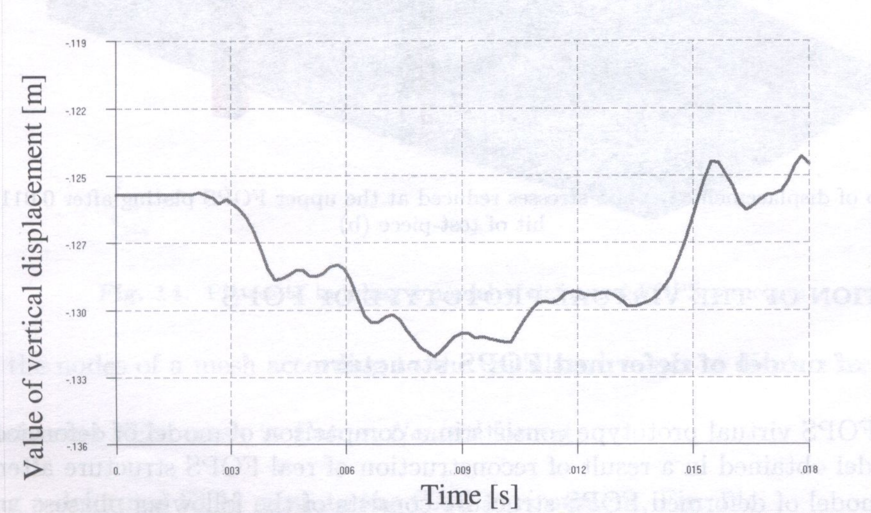


Fig. 12. A graph of changes in time the vertical displacement of node No. 11895

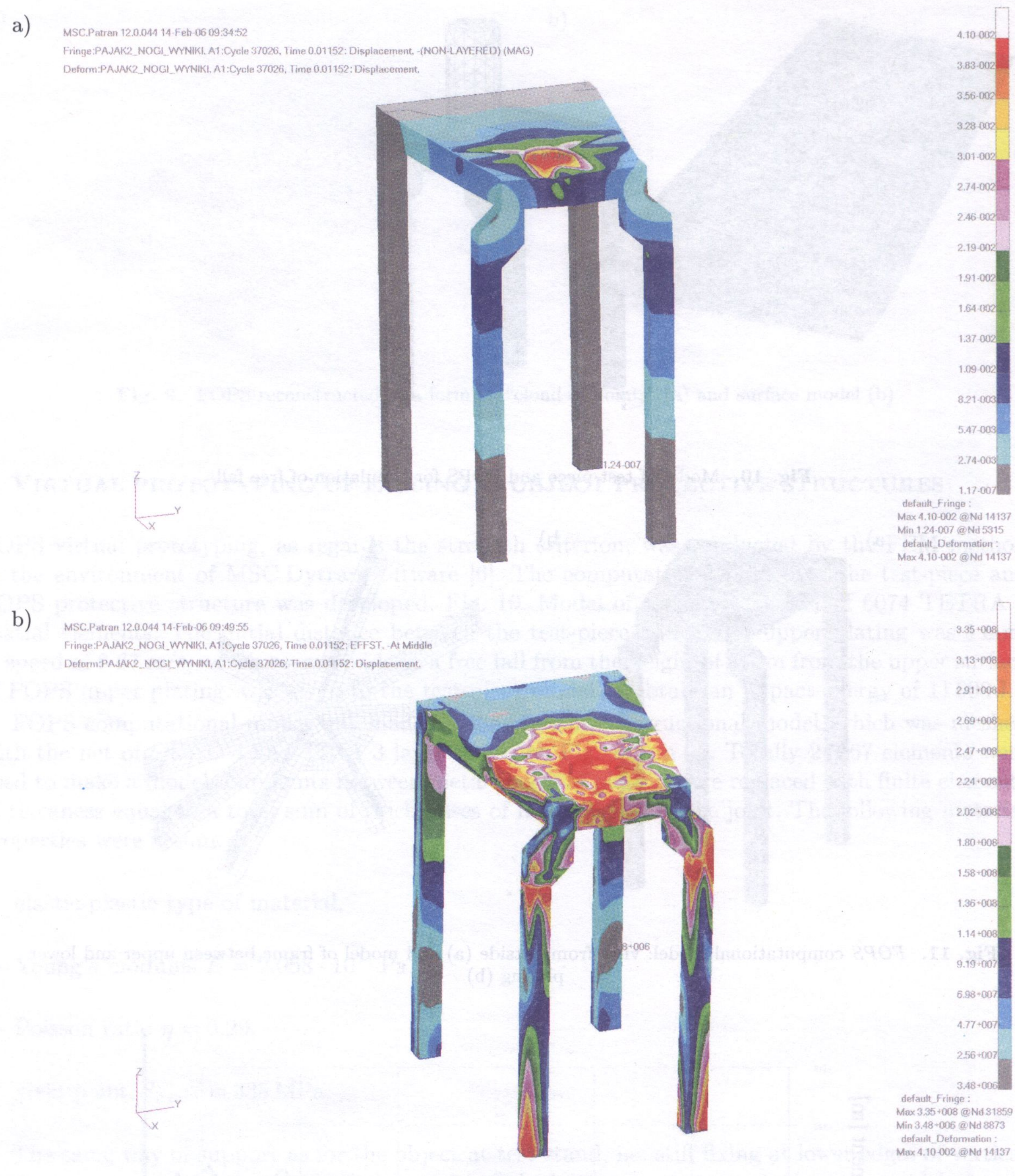


Fig. 13. Map of displacements (a) and stresses reduced at the upper FOPS plating after 0.01152 s from the hit of test-piece (b)

6. Verification of the virtual prototype of FOPS

6.1. Creation of model of deformed FOPS structure

Verification of FOPS virtual prototype consists in a comparison of model of deformed FOPS structure with a model obtained in a result of reconstruction of real FOPS structure after tests.

Building a model of deformed FOPS structure consists of the following phases:

- making a mesh of QUAD4 surface elements at the upper plating of FOPS structure, Fig. 14a,

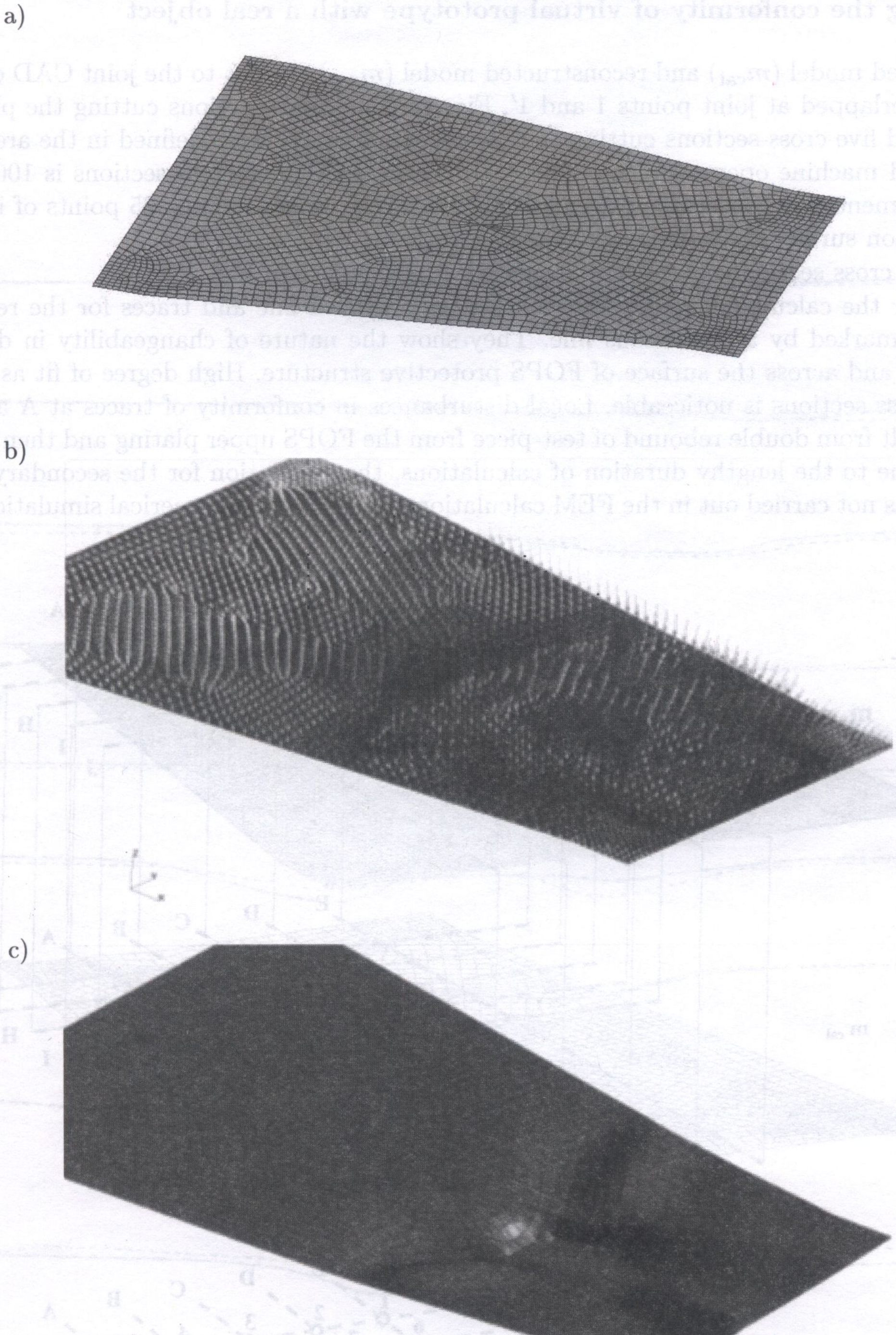


Fig. 14. Phases of building a model of deformed FOPS structure

- relocating the nodes of a mesh according to the calculated values of displacements, Fig. 14b,
- saving a deformed FEM mesh in *Patran Neutral* format,
- transferring a deformed FEM mesh to the CAD environment, Fig. 14c.

A model created in such way will be called a *calculated model*.

6.2. Testing the conformity of virtual prototype with a real object

The calculated model (m_{cal}) and reconstructed model (m_{rev}) are put to the joint CAD environment and then overlapped at joint points 1 and 1′, Fig. 15. Five cross-sections cutting the plating longitudinally and five cross-sections cutting the plating transversely were defined in the area above the self-propelled machine operator's head (F to J). Distance between cross-sections is 100 mm. Absolute displacements for both models are compared at those cross-sections. 25 points of intersections of cross-section surface tracks appeared.

Tracks of cross section surfaces are presented in a sequence of Fig. 16.

Traces for the calculated model were marked by a dotted line and traces for the reconstructed model were marked by a continuous line. They show the nature of changeability in displacement values along and across the surface of FOPS protective structure. High degree of fit as regards the tracks of cross sections is noticeable. Local disturbances in conformity of traces at A and H cross-sections result from double rebound of test-piece from the FOPS upper plating and then its overturn (Fig. 17). Due to the lengthy duration of calculations, the simulation for the secondary impacts of test-piece was not carried out in the FEM calculations. To conduct a numerical simulation of impact

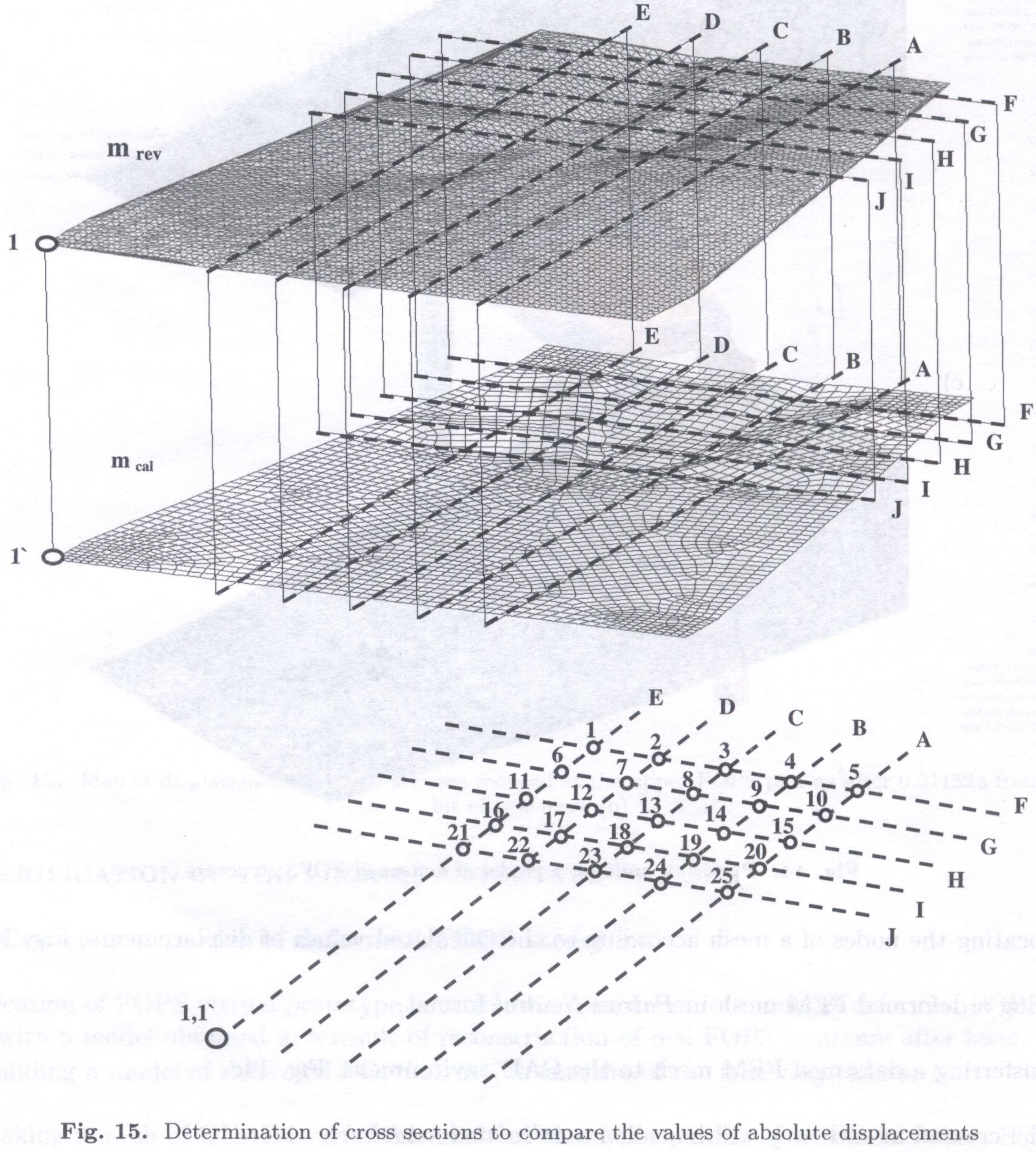


Fig. 15. Determination of cross sections to compare the values of absolute displacements

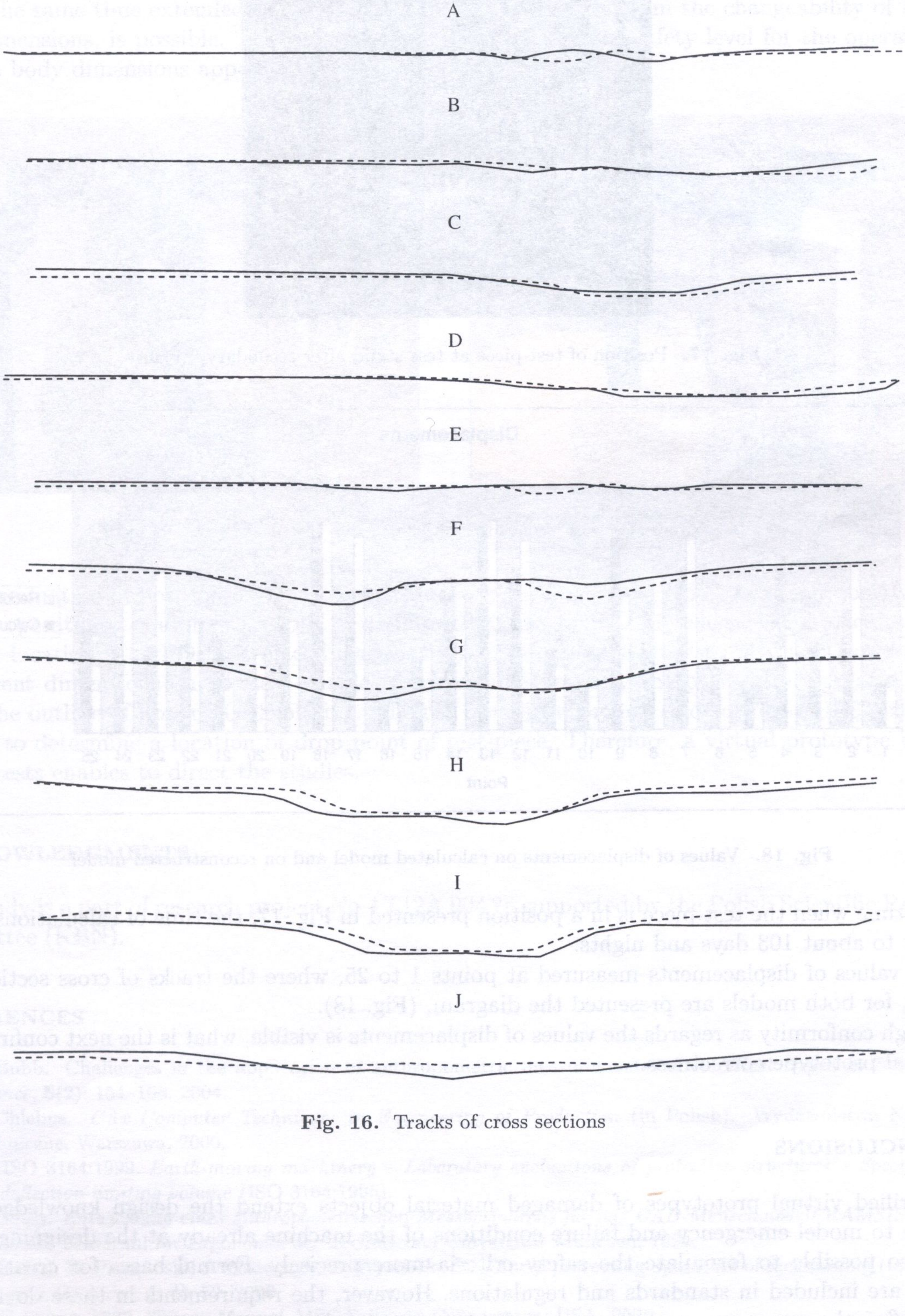


Fig. 16. Tracks of cross sections

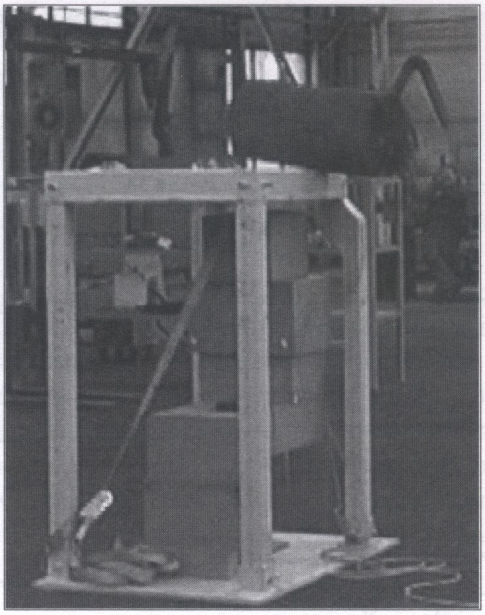


Fig. 17. Position of test-piece at test stand after secondary impact

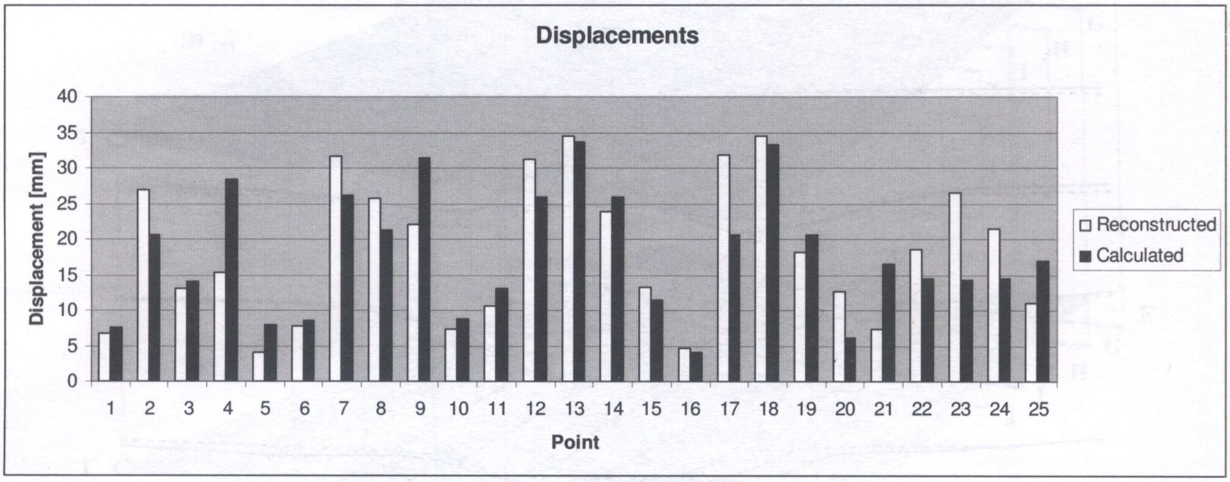


Fig. 18. Values of displacements on calculated model and on reconstructed model

till the time when the test-piece is in a position presented in Fig. 17, the time of calculations would amount to about 103 days and nights.

The values of displacements measured at points 1 to 25, where the tracks of cross sections are crossed, for both models are presented the diagram, (Fig. 18).

A high conformity as regards the values of displacements is visible, what is the next confirmation of virtual prototype correctness.

7. Conclusions

The verified virtual prototypes of damaged material objects extend the design knowledge. It is possible to model emergency and failure conditions of the machine already at the designing stage. It is also possible to formulate the safety criteria more precisely. Formal bases for creating the criteria are included in standards and regulations. However, the requirements in these documents often define the *necessary* conditions which have to be met, but they are not always the *sufficient* conditions. The necessary condition, as regards the FOPS structures, is to not disturb a DLV space by deformed plating. If this space is, to a some degree, a cubical representation of operator's body, then it is a static representation, which does not show the whole range of changeability of anthropometric features and factors, which change the body outline (clothing, equipment).

After transferring the model of deformed FOPS to the CAD environment and putting the Human Body Model inside it, the model of anthropotechnical system in emergency condition is created, Fig. 19. Verification of the project in the light of safety criterion, which is derived from standards and at the same time extended by additional conditions resulting from the changeability of human body dimensions, is possible. Thus a diversified assessment of the safety level for the operators of different body dimensions appears.

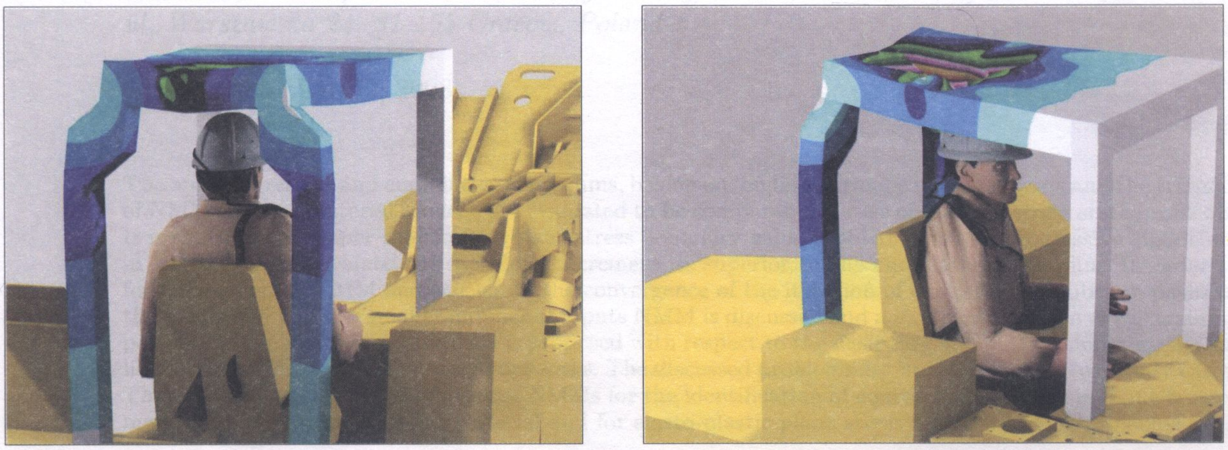


Fig. 19. Verification of anthropotechnical system in emergency conditions

Determination of position of operator's seat on the machine body, which is already partly occupied by operational equipment, is one of design tasks. The operator's field of vision decides about the seat location. The FOPS is placed over this place. Locating the "sitting" Human Body models of different dimensions on the seat enables to determine precisely the position of operator's head inside the outline of upper FOPS plating. The use of verified models of deformed FOPS structures enables to determine a location of drop point of test-piece. Therefore, a virtual prototype verified during tests enables to direct the studies.

Acknowledgments

This study is a part of research project No 4 T12A 004 28 supported by the Polish Scientific Research Committee (KBN).

References

[1] H. Bubb. Challenges in the application of anthropometric measurements. *Theoretical Issues in Ergonomics Science*, **5**(2): 154–168, 2004.

[2] E. Chlebus. *CAx Computer Techniques in Engineering of Production* (in Polish). Wydawnictwa Naukowo-Techniczne, Warszawa, 2000.

[3] EN ISO 3164:1999. *Earth-moving machinery – Laboratory evaluations of protective structures – Specifications for deflection-limiting volume* (ISO 3164:1995).

[4] H. Geuss. *Entwicklung eines anthropometrischen Messverfahrens für das CAD-Menschmodell RAMSIS*. Dissertation am Lehrstuhl für Ergonomie der Technischen Universität München, 1994.

[5] M. Kalita, D. Prostański, J. Tokarczyk, E. Wyrobek. Structures protecting operators of face mining (in Polish). *Maszyny Górnicze*, **4**: 45–52, 2006.

[6] *MSC.Dytran 2002. Theory Manual.* MSC.Software Corporation, USA, 2001.

[7] *PhotoModeler Pro 5. User's Manual.* Eos Systems Inc., 2004.

[8] PN-EN 13627: 2002. *Earth-moving machinery. Falling-object protective structures. Laboratory tests and performance requirements* (in Polish).

[9] M. Rychlik. *Metoda Odtwarzania Złożonych Kształtów Przestrzennych dla Systemów CAD przy Zredukowanej Ilości Danych Pomiarowych.* PhD thesis (in Polish). Politechnika Poznańska, 2004.

[10] M. Wyleżoł. Reverse engineering improves product concept (in Polish). *Modelowanie Inżynierskie*, **1**(32): 485–490, 2006.