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A numerical study of the dynamic response of sandwich plates initially damaged by low-velocity impact

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ABSTRACT

A finite element (FE) model has been developed for the analysis of the dynamic response of sandwich plates with impact-induced damage involving core crushing, face sheet damage and core-to-face sheet debonding. The effect of intermittent contact in fragments detached at the damaged interface due to the impact event is examined. Simulation of the strongly nonlinear transient and steady-state dynamic responses of impact-damaged sandwich plates are carried out with the FE code ABAQUS. The potential of the obtained numerical results for detecting and locating impact-induced damage is discussed.

1. Introduction

Many of modern aircraft and spacecraft designs typically include sandwich materials consisting of thin and rigid face sheets and a thick and soft core. While this type of the material structural concept possesses properties surpassing the traditional materials, it seems very susceptible to damage caused by out-of-plane loading such as low-velocity impact events. Therefore, those high performance structures must be designed so that to sustain in-service static and dynamic loads with barely visible impact damage (BVID) appeared. On the other hand, because BVID may lead to the significant strength reduction [1], this damage has to be detected within sandwich structures as early as possible. Vibration-based non-destructive monitoring techniques, using changes in vibration characteristics of a structure are suitable to identify BVID in highly heterogeneous sandwich materials [2]. Consequently, a good understanding of dynamics of sandwich structures, containing impact-induced damage is of primary importance toward a prediction of their reliability.

A huge number of papers in the literature are being devoted to a prediction the residual compression strength of impacted sandwich specimens, e.g. [3]. In comparison with this important issue, dynamics of impacted sandwich panels is less studied and, in essence, it is reduced to a study of dynamic behaviors of sandwich beams and plates with prescribed either a partially debonding interface or a locally damaged core. In the earliest papers related to dynamics of imperfect structures, e.g. [4,5], authors modeled a partially damaged beam by the split model that comprised of four Timoshenko beams connected at the detached edges. The 'free mode model', neglecting the overlapping between freely vibrating adjacent layers with and without the bending-extension coupling and 'constrain mode model' that implies for such debonded parts the same flexural deformations were developed for studying free vibrations of the beam. The recently reported beam models, improved by inserting virtual springs into the debonding interface allow for including the both models developed earlier as special cases [6]. By adopting a similar spring model the finite element method was used in [7] for a calculation of modal characteristics of sandwich plates with debonding. The influence of the size, location and form of debonding as well as various boundary conditions and core types on natural frequencies and mode shapes were examined. The extension of this FE model for analyzing sandwich plates with multiple debonding was considered in [8]. A high-order theory approach was applied in [9] to derive the equations of motion and to investigate free vibrations of sandwich beams with a locally damaged core.

In general, vibrations of structures with the imperfect interface in adjacent layers are accompanied by contact problems between the detached fragments. Therefore, to properly predict the dynamic response of such structures, intermittent contact–impact conditions for the debonded surfaces have to be included into a model. The free vibrations of a simply supported debonded sandwich beam taking into account interaction between the detached parts were analytically analyzed in [10]. The use of this approach for

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studying the transient dynamic response of such a sandwich beam was performed in [11]. The FE forced vibration analysis of beams with detached adjacent layers including the contact effect were presented in [12]. The nonlinear FE dynamic analysis involving contact–impact conditions for a detection of interfacial cracks in sandwich beams was carried out in [13].

The objective of this paper is to develop a FE analysis tool for examining the dynamic behavior of sandwich plates with a post-impact damage state. The contact problem in detached fragments at the impact-damaged site is paid special attention.

2. Impact-damaged sandwich plate

One configuration of a sandwich plate is used in this study. Consider a simply supported rectangular sandwich plate of 180 mm by 270 mm consisting of a 50 mm-thick WF51 foam core and 2.4 mm-thick GFRP face sheets. Mechanical properties of the constituent materials are the same as in [14] and are given in Table 1.

In according with the experimental findings [3], a model of the sandwich plate damaged by low-velocity impact has to capture a combination of failure modes among of which damage of the face sheet, core crushing and core-to-face sheet debonding are primary. It should be noted that in the case of BVID the face sheet remains almost undamaged and core crushing and debonding occur only. In this study, it was assumed that the foam-cored sandwich plate was struck by a spherical object at its center. Consequently, a circular region will further define the in-plane form of impact-induced damage of the sandwich plate as well as the impacted face sheet and the crushed core will get residual indentations corresponding to a part of the regular spherical surface. Fig. 1 shows the key parameters of the representative cross-section of the sandwich specimen, impacted in the above mentioned way, which include the peak depth of the residual face sheet indentation, δ_{dent}, the peak depth associated with core crushing, δ_{cr}, the cavity (debonding), δ_{cav}, developed between the face sheet and the core as a consequence of differences in their indentation depths and the radii of the planar dimension of the damaged face sheet, R_{dent}, and the crushed core, R_{cr}.

3. FE model development

In the paper a FE model is being developed to represent impact-damaged sandwich plates. The commercial FE code ABAQUS [15] is used to perform the FE dynamic analysis. The face sheets are discretized with 8-node reduced integrated continuum shell elements, `SC8R` and the core is modeled using 8-node linear solid elements with incompatible mode, `C3D8I`. The general mesh of the sandwich plate is subdivided into the fine meshed impacted region and the zone surrounding the impacted region with gradually decreased mesh density. Basing on results of the convergence analysis, performed before doing the base calculations, the mesh density was accepted with the maximum size of the characteristic element length about 4 mm that was considered as optimum between the computational cost and calculation accuracy. It is worth to notice that the smaller is the element size, the lesser is the integration time step in the explicit dynamic analysis. Both a typical FE

Table 1
Material properties of the foam-cored sandwich plate.

Components	Elastic constants
Foam core	E_c = 85 MPa, G_c = 30 MPa, ρ_c = 52 kg m^{-3}
Face sheet	$E_{xx} = E_{zz}$ = 19.3 GPa, E_{yy} = 3.48 GPa, $G_{xy} = G_{yz}$ = 1.65 GPa, G_{zx} = 7.7 GPa, ρ = 1650 kg m^{-3}

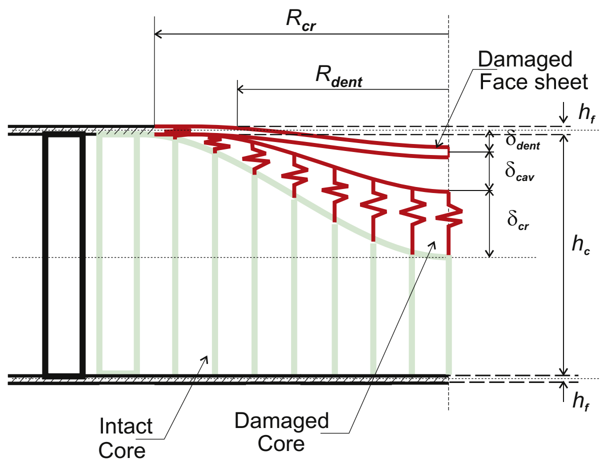

Fig. 1. Impact-damaged region.

mesh and details of the cross-section at the impacted site are represented in Fig. 2.

Damage imparted into the face sheet and the core as a result of the assumed impact event is simulated by reducing elastic properties of finite elements along the damaged regions. Appropriate reduction coefficients are used for this purpose. In Fig. 2 such regions are outlined in different ways. The residual indentations of the impacted face sheet and the crushed core as well as the cavity are modeled as they were presented in experiments taken from the literature [14] to simulate as close as possible physically real cases.

Using the FE code ABAQUS, free vibrations as well as transient and steady-state dynamic responses can be analyzed. The free vibration analysis has to be applied to a linear model of the sandwich plate only. The other two analyses can be run by utilizing both linear and nonlinear FE models. Thus, the linear FE model of the sandwich plate developed earlier in [7] will be used for its eigenvalue frequency analysis, and the nonlinear FE model, being developed herein will be used for studying general dynamics of the plate where during oscillations contact–impact conditions of detached surfaces at the impacted zone are taken into account.

4. Modal analysis

The influence of impact-induced damage on modal characteristics of the sandwich plate is firstly evaluated by comparing results between the plate containing impact damage and the same intact one. The dimensions of the impacted site were accepted as the following: $R_{dent} = R_{cr}$ = 39.3 mm, δ_{dent} = 0, δ_{cr} = 15 mm, δ_{cav} = 1 mm. The first 10 natural frequencies of the both plates, found with ABAQUS/Standard are presented in Table 2.

Generally, the numerical results demonstrated that the presence of impact-induced damage in the sandwich plate results in significant shifting of the natural frequencies to decreasing their magnitudes with respect to the intact plate. The mode shapes of the impacted plate were also changed, they exhibited local deformation patterns in the impacted site along with the global deformed shape. Such influences of the impacted region were becoming more visible with increasing its size. However, as it follows from [16], the natural frequencies and mode shapes are almost insensitive to other parameters of the impacted zone, which were varied in the frequency analysis such as cavity and residual indentation depths as well as degraded properties of the impacted face sheet and the crushed core.

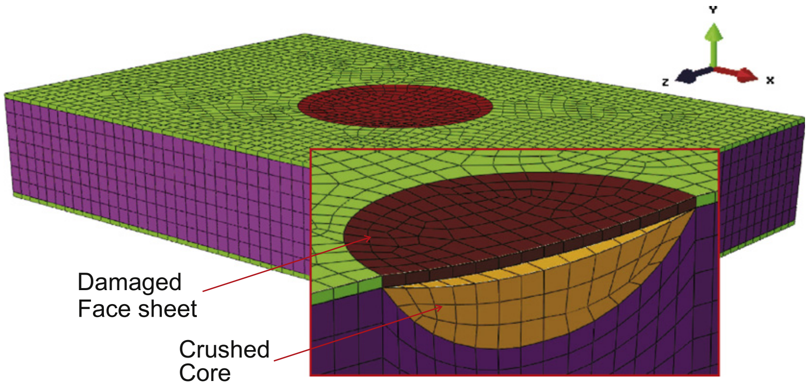

Fig. 2. Finite element model: a typical FE mesh and mesh details.

Table 2
Natural frequencies (Hz) of the intact and debonded foam-cored sandwich plates.

Mode	Intact	Damaged	Mode	Intact	Damaged
1	1066.2	937.19	6	2245.1	2011.6
2	1584.2	1246.6	7	2636.8	2086.8
3	1771.3	1440.2	8	2699.4	2098.9
4	1906.5	1640.9	9	2822.8	2396.0
5	2192.9	1697.6	10	2825.5	2430.4

5. General dynamic analysis

To provide a deeper insight into dynamics of the sandwich plate containing impact damage, its general dynamic response is examined with ABAQUS/Explicit, where contact–impact conditions for normal and tangential interactions of surfaces coming into contact during oscillations can be modeled and where the computationally efficient explicit integration rule is used [15].

The contactable parts of the face sheet and the core at the damaged interface of the vibrating sandwich plate are simulated by using their surface-to-surface discretization in terms of slave and master surfaces. This contact formulation enforces contact conditions in an average sense over regions nearby slave nodes rather than only at an individual slave node. Thereby, surface-to-surface contact will provide more accurate stress and pressure results, which are being used to form the right hand side of the equations of motion. Besides, such a formulation is less sensitive to master and slave surface designations than node-to-surface contact. The relative motion of the interacting surfaces in the contact simulation is described with finite sliding kinematics that is the most general case and allows any arbitrary motion of the surfaces involving their separation, sliding and rotation. The constitutive behavior of the surfaces coming into contact in the normal direction is assumed to be governed by the 'hard contact' model, whereas frictionless conditions are accepted between them in the tangential direction. It is worthwhile to notice that 'hard contact' implies that the interacting surfaces transmit no contact pressure unless the nodes of the slave surface contact the master surface and no penetration is allowed at each constraint location. Thus, the hard contact model will minimize a measure of overclosure of nodes of the slave surface into the master surface at the constraint locations in the best way. To resolve in the dynamic analysis the normal contact constraints imposed by physical pressure-overclosure relationships corresponding to the hard contact model applied, the penalty constraint enforcement algorithm is used. This method was chosen because it does not increase the cost of the analysis compared with the Lagrange multipliers algorithm.

As noted in Section 2, the sandwich plate consists of the significantly dissimilar materials. Consequently, at the interactions of the face sheet and the core, the soft foam core will be deformed by the rigid face sheet. It is known that the WF51 foam used in the plate model exhibits the essential plastic compressibility [17]. Consequently, to ensure a proper contact–impact behavior between the detached face sheet and core at the impacted region in vibrations of the sandwich plate, the plastic response of the foam material is defined by the crushable foam model with a volumetric hardening effect. Moreover, to take into account plastic deformations induced in the foam core by the assumed impact event, prescribed initial conditions for the volumetric compacting plastic strain at the crushed core area were assigned. The input data, required by ABAQUS for the constitutive model of the foam core used were taken from the literature [18].

6. Numerical results

The impact-damaged sandwich plate, mentioned in the modal analysis was excited an impulse load at the center of the undamaged, bottom face sheet for modeling a hit of the plate with a hammer. For this, a concentrate force of 1000 N with the duration much shorter than the analysis time step was applied. Fig. 3 shows the deformed shapes of the impact-damaged sandwich plate, exciting under the impulse force. While the sandwich plate is oscillating as a whole entity, the intermittent contact–impact behavior of the detached fragments at the damaged core-to-face sheet interface can be clearly seen. Consequently, one can be suggested that such a local contact–impact phenomenon will change the global dynamic response of the impacted sandwich plate.

To evaluate the effect of intermittent contact–impact during the transient dynamic analysis, the same sandwich plate is analyzed with and without contact conditions imposed at the impacted region. Besides, the transient motion of the intact sandwich plate of the same size and constituent materials was also considered. Time history outputs corresponding to the transverse displacement, velocity and acceleration and the longitudinal logarithmic strain, calculated at the central point of the impacted face sheet are shown in Fig. 4. As one can see that the neglecting of contact leads to incorrect results, which mainly overestimate the amplitude of the dynamic response of all the presented outputs. Thereby, the contact model assigned for the damaged core-to-face sheet interface dampens the magnitudes of the displacement, velocity, acceleration and strain compared to the model without contact. This is because the contact model is of importance to prevent the interacting fragments from overlapping each other and, consequently, the modeling of the contact–impact behavior is necessary to properly represent the global dynamic response.

It also follows from Fig. 4 that the transient dynamic response for the intact and impact-damaged sandwich plates are quite dif-

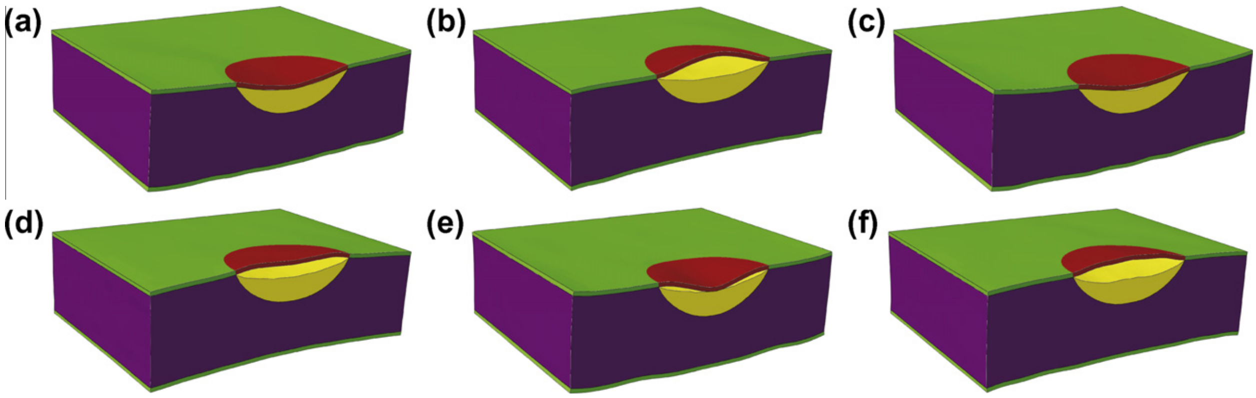

Fig. 3. Deformed shapes of the transient dynamic response of the impact-damaged sandwich plate at different time moments: (a) t = 1.0 ms; (b) t = 1.3 ms; (c) t = 1.9 ms; (d) t = 2.4 ms; (e) t = 2.8 ms; and (f) t = 3.4 ms.

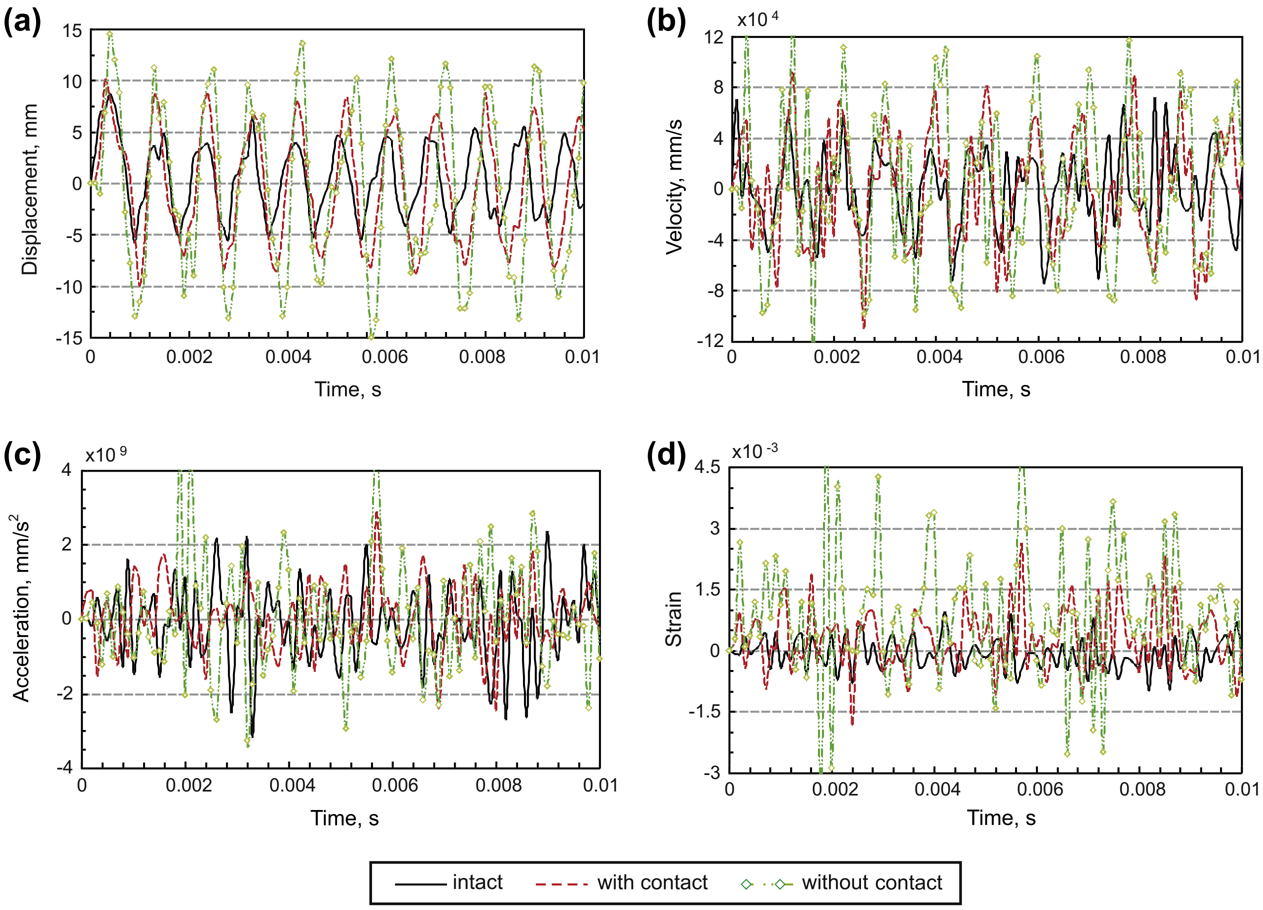

Fig. 4. Transient time history outputs of the central point of the impacted face sheet: (a) displacement; (b) velocity; (c) acceleration; and (d) longitudinal logarithmic strain.

ferent. Thereby, the nonlinear FE model of the sandwich plate, allowing for the local interaction between detached fragments of the core-to-face sheet interface can be useful to vibration-based non-destructive diagnosing for detecting and locating of impact-induced damage within the sandwich plate.

To confirm the last assumption, a numerical experiment was performed for evaluating a strain steady-state response. The longitudinal strain was calculated at two different points within the plate, the first one was the central point of the impacted site and another one was the point located outside this zone. The impacted sandwich plate was subjected to a concentrated transverse sinusoidal force with the amplitude of 1000 N at the central point of the bottom, undamaged face sheet. The frequency of the exciting force was 1000 Hz that is close to the fundamental frequency of the plate. Two different sizes of the impacted zone within the sandwich plate were considered. The radii $R_{dent} = R_{cr}$ were equal to 27.8 mm and 39.3 mm that corresponded to the interfacial damage parameter, D, defined as a fraction of the total area of the sandwich plate of 5% and 10%, respectively. Fig. 5 shows strain's steady-state response at the different measured points for both the impact-damaged sandwich plates and the same intact sandwich plate.

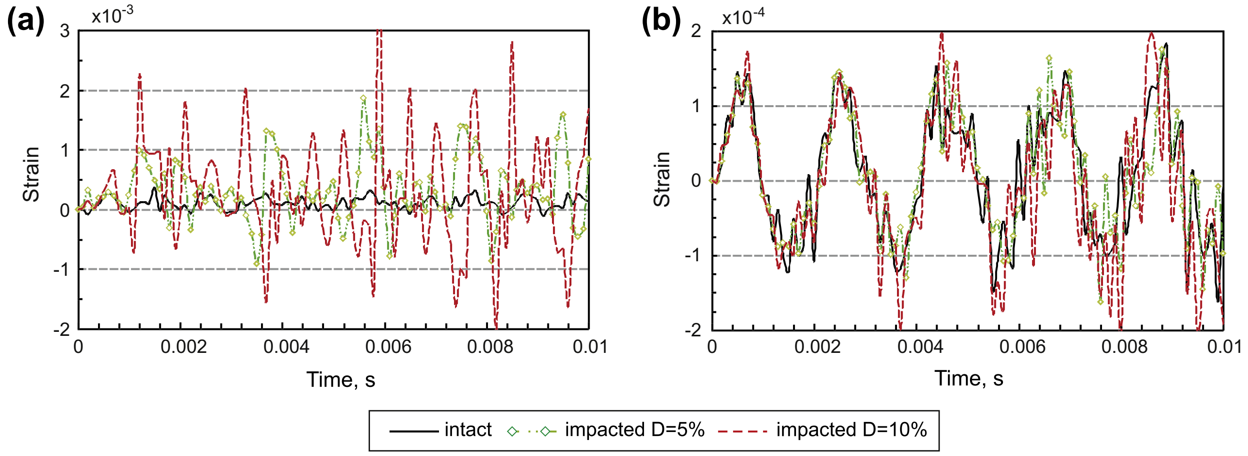

Fig. 5. Steady-state time history response of the longitudinal logarithmic strain in the impacted face sheet at the: (a) central point and (b) point belonging to the plate's quarter center.

As one can see, the magnitude of the strain measured outside the impacted zone is similar between the impacted and intact plates. Though, there are some differences in the variation of the strains with time, Fig. 5b. The differences increase with increasing the size of the impacted zone. Thereby, this strain response would detect the damage existence but would not locate it. Unlike this, impact-induced damage is easily detectable by observing the strain steady-state response at the point belonging to the damage region. Herewith, the larger is the damage size, the more clearly damage manifests itself. It can be seen that in this case the strains vary with the significantly bigger amplitudes than for the undamaged case, Fig. 5a. Therefore, the comparative analysis of strain steady-state responses of neighboring points, which belong and not belong to the damaged area can locate a post-impact defect.

7. Conclusions

The results obtained in the paper demonstrate that in order properly to simulate the dynamic response of sandwich plates with impact-induced damage, a local interaction of detached fragments at the impact-damaged site has to be taken into account. Thereby, the nonlinear dynamic analysis in conjunction with the definition of contact constraints at the certain zone of the FE model is required. It is follows from the results that the neglect of contact in dynamics of such impact-damaged sandwich plates will lead to the overestimation of their dynamic responses. The numerical experiments, performed with the nonlinear FE model, accounting for contact showed that even small impact-induced damage can be detected and its location can be defined by measuring the steady-state strain responses and the Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed by the European Regional Development Fund, Project "Modern material technologies in aerospace industry", Grant No. POIG.0101.02-00-015/08 (RT-15: Unconventional technologies of joining elements of aeronautical constructions).

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