Computational and experimental study of bird failure at different speeds of collision with a flexible plate

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Abstract. This article presents an experimental and computational study of bird collision with a flexible plate at different impact speeds. Tests were carried out with the aid of a pneumatic gun. The bird mass in the study was about 300 g, and the speed range was 49-75 m/s. The actual mechanical properties of the plate were determined with tensile tests of flat specimen-witness. A video recording and strain gauging were performed during the strike. Some frames of high speed video recording for the highest bird’s velocity c = 75 m/s are presented in the article to demonstrate the process of bird rupturing. Different models of the bird material were examined to compare computational and measured strains.

1. Introduction

Bird strikes on aircraft are a serious problem for civil aviation flight safety. The International Aviation Rules (AR, FAR, CS-E) regulate the studies of bird strikes on civil turbofan engines [1]-[3], and compliance is established on the basis of these tests, but the uniqueness and high costs of these tests prevent consideration of all possible cases. Therefore, computational methods become important, as these allow thorough study of the strike process and optimal design of the test program. The efficiency and reliability of computational analysis is essentially based on the use of material properties of the studied engine parts and the bird itself. These properties may be obtained by laboratory tests under relatively simple conditions. However, these conditions should reliably reproduce the features of the strike process of birds in collisions with engine parts in service.

Many authors use “soft” liquid columns as bird models, based on the previous work by Wilbeck [4]-[5]. The properties of this liquid column are accepted as being close to water properties. This assumption simplifies the bird model, but it may be incorrect in some cases, as shown, for example, by Liu et al. [6] who demonstrated that, at least, for a bird mass of about 1800 g at moderate strike velocities, the calculated results are acceptable when using an elastoplastic bird model.

The problem of bird strikes becomes more complicated because of significant variations in the collision conditions. For example, bird masses can range from 0.03 to 5 kg (and higher), and the absolute velocity of a bird strike changes from 30–50 m/s (for a side strike into a helicopter engine stator) to 400–500 m/s for the periphery of fan blades. Secondary strikes on other engine parts are also possible, apart from the initial strike. Pieces of the bird body may also block the engine inlet and cause surges. For these reasons, a reliable failure model of the bird body is also very important.
Clarification of the concepts of the process of a bird’s body failure should therefore be conducted under test conditions where the bird strikes a tight barrier and completely fractures while the barrier is deformed only elastically. The aim of the present work was to meet these conditions by conducting a detailed computational and experimental study of the failure process of a 300 g bird colliding at strike speeds up to 75 m/s with an elastically deformed titanium plate, while also taking into account the plate support flexibility. The second aim was a validity estimation of different material models for the bird.

The computational and experimental studies on strikes of real birds and their jelly imitators with a flat barrier have been reviewed by Hedayati and Sadighi in their book [7], which, in particular, contains a review of [4]-[7].

The present work carried out in Baranov Central Institute of Aviation Engines (CIAM) examines test results for a normal strike of a bird with a barrier at different speeds to provide data to clarify the nature of the bird body failure.

Brief information about the object and the test base are given in the first part of the article, which has mutual traits with [6], but with some differences, notably the barrier-plate material, plate flexibility, fixation method, and test preparation. The second part of the paper consists of the test results and data analysis, which showed, as suggested in earlier work [8], [9] that the bird model as a soft failure body produces reliable dynamic loads on a flexible wall.

2. The object and test base

2.1 The plate-target and experimental equipment

Plate target 3 (Fig. 1, a, b) was mounted to the base on two sides: through slewing base 4 – at the bottom, through slab 5, and up to mounting block 1 – at the top. The plate material is titanium alloy VT6, whereas the material of the test rig parts is steel. The structure of the test rig parts was chosen to sustain strikes of 350 g birds at velocities up to 250 m/s without residual deformations. The plate was fastened to the test rig by bolts in the central holes (see rectangular areas in Fig. 1a).

The plate thickness defines its bending stiffness and can significantly affect the computational results of plate normal modes and deformations during the strike process. Therefore, a geometry check using 3D scanning of several plates was performed before the tests. The thickness variation was 2.65–2.67 mm.

The use of a nominal plate thickness of h = 2.7 mm may lead to a 4% percent difference between the computational and test values of the deflection, and a 2% percent difference in frequency.

Figure 1. The plate-target and its fixation in the test rig: 1 – mounting block; 2, 6 – front and back locking plates; 3 – plate-target; 4 – slewing base; 5 – slab; 8–16 – bolts, nuts, and pins
2.2 Strain gauge scheme

Strain gauges with a 1 mm base were used for strain measurement during the strike. The strain gauges were glued onto the opposite side of the plates to the strike direction. The scheme is shown in Fig.2. A high-pass filter was switched on during signal recording to eliminate the signal zero frequency. The signal record had a 216 kHz sampling frequency that allows reproduction of the rate of strain change in the plate.

2.3 Ballistic test bench

A CIAM test bench was used for ballistic tests. The test bench consisted of the support frame, the pneumatic gun, the setting fixture of the gun, the measurement system of the projectile velocity, a data gathering system, a video recording system, the control board, and the air supply system.

The gun carriage and the frame with bird velocity sensors were located on the support frame, which provided necessary stiffness for the load-carrying parts [10]. The influence of the flexibility of the test rig itself was studied based on computations and test results.

2.4 Test preparation activities

For study of the strike process, shots were carried out by stepwise increases in the velocity in the range 50–75 m/s. Some domestic chickens were chosen as the projectiles; the mass of each chicken was about 300 g.

Each bird was slaughtered 15–20 minutes before the shot. The bird was weighed and packed in food film and a fabric bag (55% cotton, 45% polyester), and then put into a polyfoam case with the wad and placed in the pneumatic gun tube. The bird weight before and after packing into the food film showed that the film increased the bird mass by no more than 0.3%. The bag prevented the wings from opening during the flight, but the bag was slit along the length in four places to provide free deformation of the bird body. The polyfoam case provided free motion of the bird in the gun tube and then it was stopped by a special case trap located on the tube discharge. Analysis of the calibration shot results showed that the case trap could affect the trajectory of the bird. The accuracy of the hit was estimated semi automatically by video recording.

Figure 2. Strain gauge scheme
2.5 Estimation of the bird density

The main feature of the bird body defining the strike force was its averaged body density, which depended on not only the body mass, but also its size and non-uniformity. Plume saturation with air may have influenced the process of density measurement by way of water displacement and decreased the calculated density. This was especially evident for small birds with fluffy plumage. A comparison of the axial size of a bird with plumage and a plucked bird is shown in Fig.3.

![Figure 3. Comparison of the axial sizes of plucked and non-plucked birds](image)

The measured density of a packed bird by water displacement was 0.51 kg/m³ and was close to the density of a non-plucked bird of approximately the same mass [12]. The volume of the plucked birds was considerably less and the density was greater. The influence of plumage on the estimated density of the plucked bird was determined by water displacement. The bird mass was about 400 g (i.e., approximately the same as in the ballistic tests). The average density of a plucked bird was 950 kg/m³, which conformed approximately to the bird density of the same mass [12].

Note that the bird volume in computations should be defined by mass, and a 3D model of the bird should have the same volume regardless of its configuration.

2.6 Mechanical properties of the witness specimen

The actual mechanical properties of the plate were determined with tensile tests of flat specimen-witness. To study the influence of manufacturing technology, some of the specimens were cut out along the long side of the plate (see Fig.1), and some were cut along the short side. Three specimens were tested overall. The test results did not show any appreciable influence of the cut direction on the mechanical properties. Engineering stress-strain curves are shown in Fig.4. Specimens No. 2 and 3 were cut in orthogonal directions. The deformation curve for specimen No.1 was obtained at a load rate of 0.9 mm/s (hard loading) and the curves for specimens No. 2 and 3 were obtained at a load rate of 500 N/s (soft loading).

The curves were obtained using an extensometer (EP 3451) with a 12.5 mm base. An analysis of the test results showed that Young’s modulus is $E = 112$-117 Gpa, the proportional elastic limit is $\sigma_{pl} = 966$-980 Mpa, and the yield stress $\sigma_{02} = 1030$-1067 Mpa. The average tensile strength is $\sigma_B = 1080$-1118 Mpa. The residual elongation of the specimen is $\delta = 12.5\%$, the reduction of specimen area in the neck is $\psi = 23.5$-35%. The lower values correspond to specimen No.1. The mechanical properties for specimens No. 2 and 3 are practically the same. The obtained mechanical properties of the specimens slightly exceeded the usual VT6 properties referenced in literature.
3. Results of experimental and computational studies of the interaction between the plate and the bird.

3.1 Test Results
Five shots were carried out overall. The bird mass before and after packing, the actual velocities $c$, momentums $J$, and kinetic energies $T$ are given in Table 1. The video recording and strain gauging were performed during the strike.

Table 1. Actual test parameters

| Shot number | Bird mass before packing, g | Bird mass after packing, g | $c$, m/s | $J$, kg·m/s | $T$, N·m |
|-------------|-----------------------------|-----------------------------|----------|--------------|----------|
| 1           | 282                         | 315                         | 49       | 15.4         | 378      |
| 2           | 280                         | 294                         | 60       | 17.5         | 529      |
| 3           | 282                         | 295                         | 67       | 19.7         | 662      |
| 4           | 288                         | 301                         | 72.5     | 21.8         | 791      |
| 5           | 289                         | 315                         | 75       | 23.6         | 886      |
3.1.1 Bird body fragmentation

The test results showed whole failure of the bird body at \( c = 72–75 \text{ m/s} \). Some frames of high-speed video recording for \( c = 75 \text{ m/s} \) are shown in Fig.5, where plate deflection and slab (position 5 in Fig.1) movement are also evident. Time point \( t = 0 \) shows the beginning of visible contact between the bird and plate. As follows from Fig.5, the process of initial bird flattening had ended at time point \( t = 2 \text{ ms} \), then the bird body ruptured into flake-shaped fragments and spread along the plate surface (Fig.6). These video records were obtained for every bird velocity (see Table 1). The view of a completely ruptured bird is shown in Fig.7 at the time point when the plate had full straightening (\( t = 9 \text{ ms} \)). The bird body or its fragments were gathered after each shot for an estimation of residual damage. Photos of the bird body after the shot are shown in Fig.8. All photos are shown with the bag remnants except for the last shot at \( c = 75 \text{ m/s} \) when the bird completely ruptured and only one of the recovered flakes is shown.

![Figure 5. Frames of high-speed video recording, time range 0–2 ms, \( c = 75 \text{ m/s} \)](image-url)
\[ t = 4 \times 10^{-3} \text{ s} \]
\[ t = 4.5 \times 10^{-3} \text{ s} \]
\[ t = 5.7 \times 10^{-3} \text{ s} \]
\[ t = 7 \times 10^{-3} \text{ s} \]

**Figure 6.** Frames of high-speed video recording, time range 4-7 ms, \( c = 75 \text{ m/s} \)
3.1.2 Strain gauging results

The maximal measured strain amplitudes over the strain gauges are given in Table 2. Subscript figures correspond to the strain gauge number (see Fig.2).
Table 2. Maximal strain amplitudes

| $c$, m/c | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_3$ | $\varepsilon_4$ | $\varepsilon_5$ | $\varepsilon_6$ | $\varepsilon_7$ | $\varepsilon_8$ | $\varepsilon_9$ | $\varepsilon_{10}$ |
|----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 49       | 2.9             | 4.85            | 3.02            | 2.97            | 4.8             | 2.83            | 4.74            | 4.76            | 2.61            | 4.75            |
| 75       | 4.94            | 8.6             | 5.27            | 5.02            | 8.2             | 4.91            | 8.72            | 7.46            | 4.52            | 8.52            |
| 49/75=0.65 | 0.59            | 0.56            | 0.57            | 0.59            | 0.59            | 0.58            | 0.57            | 0.64            | 0.58            | 0.56            |

The strain gauge data for two cases of bird velocities $c = 49$ m/s and $c = 75$ m/s showed that the maximum strains are realized along the long side of the plate during the strike process (No. 2, 5, 7, 8, and 10), minimum strains are realized along the short side (No. 4, 6, and 9), and angular strain occurred in gauges No. 1 and 3. The strains of co-directional strain gauges were close to each other. Table 2 shows the close ratios of the velocities and strain amplitudes at different velocities, which attests to the objectivity of the measurements. As indicated in Table 2, the maximum strain amplitude occurred in strain gauge No. 2, so that record was used for further analysis. The maximum measured strain amplitudes were lower than the strain of the proportionality limit that allows using an elastic material model for the plate in further computations. The dependences of strain change for strain gauges No. 1, 2, and 9 are shown in Fig.9 for a bird velocity $c = 75$ m/s.

Figure 9 shows that the signals of strain gauges No. 1 and 9 have evidently different amplitudes and characters when compared with the signal of strain gauge No. 2.
3.2 Strain computations. Imitation of a strike with different bird models

3.2.1 Normal modes
A 3D normal mode analysis was carried out before the tests. The plate thickness in the analysis was $h = 2.7$ mm, and the boundary conditions were accepted as a rigid fixation in cylindrical surfaces of the central bolt holes (see Fig.1). A finite element model for normal modes analysis was built in MSC.Patran. The model contains 122958 elements and 156086 nodes. It was accepted as three elements per plate thickness.

The dynamic Young’s modulus was accepted based on data [13] $E = 123$ Gpa, which was about 5% higher than the defined static modulus. The first eigenfrequency was $f_1 = 67$ Hz for accepted rigid supports. An analysis of the experimental record of damped oscillation showed that the first eigenfrequency of the plate in the test rig was $f_1 = 58-61$ Hz. The possible boundary condition influence was analyzed. Observation of the plate deformation during the strike by video recording showed that the slab (position 5 Fig.1) was involved in the oscillation process; this can also be seen in part in Fig.5 and 6. Slab shifting allows the plate to undergo additional bending.

For a simplified imitation of this phenomenon, springs of different stiffness were introduced into the nodes on the cylindrical surfaces of the bolt holes. The first eigenfrequency was $f_1 = 62$ Hz in case of free boundaries.

3.2.2 Strike duration
The duration of contact forces of the bird and plate interaction (the strike duration) is defined by forces decreasing during the increasing plate bending in the process of contact. The bend dependence on “equivalent” spring stiffness has a nonlinear character. Frames of the video recording (Fig.5 and 6) and strain records (Fig.8 and 9) show that the strike stops at a time point of about $t = (7-10)$ ms. Computations show that the experimental and test strains are close to each other when each spring stiffness is about $k = 7 \cdot 10^5$ N/m (the total number of springs in the model is 8), so this stiffness was adopted for comparisons between computations and tests.

3.2.3 Model of the “soft” ruptured body
Based on the momentum conservation law, a soft ruptured body (SRB) was offered as a model of the bird body [8]. A normal strike on a mobile rigid wall would have a momentum reduction of the mass $\Delta m$ moving with the velocity $v_b$ equal to the change of momentum at time $\Delta t$

$$\Delta F = \Delta m \cdot (v_b - v_0) = \Delta F \cdot \Delta t,$$

where $\Delta F = p \cdot \Delta S$ is strike force, $p$ is the dynamic pressure of the bird on the plate, $\Delta S$ is contact area, and $v_0$ is the wall velocity.

A cylindrical bird model with a height $\Delta l$ and a base area $\Delta S$ has a mass of

$$\Delta m = \rho \cdot \Delta l / \Delta S, \; \Delta t = \Delta l / (v_b - v_0),$$

and:

$$p = \rho (v_b - v_0)^2. \tag{2}$$

When the plate motion is caused only its elastic deformation and $v_0 \ll v_b$, the pressure is

$$p = \rho \overline{(v_b)^2}. \tag{3}$$

For this elementary problem statement, the dynamic pressure $p$ and contact force $F$ have constant values:

$$F = \rho \cdot \Delta S = \frac{m}{I} (v_b - v_0)^2. \tag{4}$$

Both the pressure and force act until the moment the last bird particle reaches the plate. When the contact pressure is known, a strain computation may be performed in any finite element analysis program. In the general case, it is necessary to use formula (2) and a stepwise approximation for the definition of $v_0$.

A bird particle stopped under the strike is accepted as being completely ruptured, which allows excluding its mass in the computations. According to SRB, the single property of the bird is its body density, which defines the shock on the wall. The SRB model was successfully applied for bird strike
computations on several fan wheels [8], [9], [10] with the aid of an in-house subroutine of SRB interaction with the ANSYS transient option.

3.2.4 SPH model
The smooth particle hydrodynamics (SPH) method was developed in the 1970s for solving problems of star mechanics [14], and SPH procedures are included in some commercial software. Depending on the characteristics defining the particle properties, the method finds applications in different practical problems. The SPH method is also used for bird strike problems [15, 16, 17].

A. A liquid column as the bird model. Material model MAT_NULL was examined for a comparison with a widely used model in form of a liquid column [11], [18]. The material model is combined with the Gruneisen equation of state. The accepted properties of the model for computations and the Gruneisen constants are given in Table 3.

| MAT_NULL properties | Gruneisen parameters |
|---------------------|----------------------|
| \( \rho \), kg/m\(^3\) | PC, Pa | \( \mu \), Pa\(\cdot\)s | TE | TC | C, m/s | S1 | S2 | S3 |
| 950 | -63 | 0.0004 | 1.1 | 0.8 | 1483 | 2.56 | -1.98 | 0.27 |

The Gruneisen constants for water were accepted based on [19].

B. The bird model as a set of masses. To reveal the role of the terms that characterize the bird’s body as a liquid column, the model was considered when only the body density is taken into account, and all other parameters are accepted as equal to zero. We named this model “a set of masses”. In it, unlike in the SRB model, the contact problem is computed.

C. The elastoplastic material model of the bird body. The elastoplastic material model was examined for comparison with the other models. In a general case, taking into account the different properties for tension and compression is necessary, although some studies show that using plastic strain intensity is sufficient for failure estimation [6]. The accepted properties of the material model are given in Table 4. Values for the yield stress \( \sigma_{02} \), tangent modulus \( E_T \), and stress intensity \( \varepsilon_i \) were accepted based on the article by Liu et al. [6]. Values of Young’s modulus \( E \) and Poisson’s ratio \( \nu \) were obtained by way of \( G \) and \( K \) recalculations.

| Properties of the elastoplastic bird model |
|---------------------|---------------------|---------------------|---------------------|
| \( \rho \), kg/m\(^3\) | \( E \), GPa | \( \nu \) | \( \sigma_{02} \), MPa | \( E_T \), MPa | \( \varepsilon_i \) |
| 950 | 1.8 | 0.458 | 0.99 | 1.2 | 0.57 |

3.2.5 Bird strike upon the rigid plate
The pattern of the bird deformation process is shown in Fig. 10 to reveal influence of the model bird on the model properties. The bird body has a strictly cylindrical shape, and bird deformations refer to the same time point at bird velocity \( c = 75 \) m/s.

In the analytical solution for SRB, the shape of the bird body is not changed during the strike on the rigid plate. The computational strike force is constant at \( F = 14.74 \) kN for a bird mass \( m = 0.315 \) kg. Bird modeling using water properties shows it sloshing and spreading on the plate surface. Bird modeling using elastoplastic properties shows it only spreading on the rigid plate surface without sloshing. The results of the bird modeling as a set of masses are close to those for SRB modeling.
Analysis of the momentum transfer from the bird to the plate (Fig.12) shows that the time for full momentum transfer for the SRB model is close to the analytical solution, while for the elastoplastic
model and the liquid column, the momentum transfer ends later, at \( t \approx 2.5 \cdot 10^{-3} \) s. The value of momentum is somewhat higher than the theoretical value.

### 3.2.6 Bird strike upon the flexible plate with rigid supports

The plate mesh and material properties were accepted as the same as for normal mode computation. The rigid fixation of the cylindrical surfaces of the bolt holes was accepted as a boundary condition for the plate. This allowed analysis of just the influence of plate stiffness on the computational results.

The pattern of bird deformation for three types of material models is shown in Fig. 13 at the same time point that it was shown for the rigid plate.

As in the case of modeling the bird strike upon the rigid plate, bird modeling using the water properties shows its body sloshing and spreading on the plate surface. Bird modeling using the elastoplastic properties shows only the body spreading on the plate surface without sloshing. The results of the bird modeling as a mass set show no considerable spreading.

Computational time dependences of the forces, momentums, plate bends, and strains for strain gauge No. 2 are given in Fig. 14, 15, 16, and 17 respectively. In the latter figure the strains are compared to experimental data.

![Figure 13. Cylindrical model of the bird body and the pattern of its rupture](image)

![Figure 14. Contact forces versus time: 1 – set of masses, 2 – elastoplastic model, 3 – liquid column](image)
Figure 15. Momentum versus time: 1 – set of masses, 2 – elastoplastic model, 3 – liquid column

Figure 16. Edge bends in the middle of the plate side versus time: 1 – set of masses, 2 – elastoplastic model, 3 – liquid column

Figure 17. Strains versus time for rigid supports: 1 – experimental data, 2 – set of masses, 3 – elastoplastic model, 4 – liquid column
3.2.7 Bird strike upon the flexible plate with elastic supports

The elastic supports of the plate were modeled using spring elements. The spring stiffness was chosen due to the condition of strike duration (for a comparison with plate straightening after a strike in the test, see Fig.9). The computational strain dependences for strain gauge No. 2 are given in Fig.18. As for the previous case of the flexible plate with rigid supports, three models of the bird and experimental data were examined with the same curves notation.

\[ \varepsilon(t) = \frac{F(t)}{A} \]

\[ F(t) = k \varepsilon(t) \]

\[ \varepsilon(t) = \frac{d^2 y}{dt^2} \]

\[ y(t) = \frac{F(t)}{k} + \frac{F_0}{k} \left(1 - e^{-\frac{t}{\tau}}\right) \]

3.3 Analysis of the experimental and computational results

3.3.1 General picture of bird rupture

Consideration of the video recording frames shows the next picture of the dynamical interaction of the tested birds with the plate. At the beginning of the strike, the bag bursts immediately in the places where it is notched. The interaction of the bird with the plate looks like the strike of a non-inflated ball on the elastic plate at low impact velocities. Feathers crawl out of the broken bag and the flattened body of the bird bounces due to the elasticity of the plate, without noticeable damage.

Impact velocities of more than 60 m/s are also attended by a “flattening” of the bird along the surface of the plate and bird rupturing. At a flight speed of \( c = 67 \) m/s, the cervical part of the bird body is torn off (Fig.8c); however, the bird’s body remains essentially unimpaired and the wings and legs do not detach from the bird's body.

The bird breaks into several parts at the impact velocity \( c = 72.5 \) m/s (Fig.7d). In the process of impact, the wings, legs, and cervical parts are torn off the bird's body. The bird strike on the plate at \( c = 75 \) m/s leads to the complete rupturing of the bird body (Fig.5, 6, and 8e). Fragments of the bird's body after impact take the form of flakes. The main destruction of the bird's body occurs after the first \( (3–4) \times 10^{-3} \) s and completely ends at \( (7–10) \times 10^{-3} \) s.

According to the authors’ observations, with a large increase in the impact velocity, the impact process is attended by the release of biological material: splashes of blood, fat, and fragments of internal organs.

The packaging of the bird body in a bag (see bright white areas in Figures 5-7), as can be seen from the video frames, does not prevent the deformation of the bird during an impact process, as the body freely slips out of the notched areas.

3.3.2 Analysis of strain gauge records

**Figure 18.** Strains versus time for elastic supports: 1 – experimental data, 2 – set of masses, 3 – elastoplastic model, 4 – liquid column
The time dependence of the strain gauges records shows two areas where the bird interacts with the elastic plate for the impact velocity of 75 m/s. The initial is the area of intense irregular oscillations during the first 30 ms, and the second is the area of shock-induced free vibrations.

In the second area of free vibrations, their slow damping is observed in terms of amplitudes and frequency. The fundamental period is $T = (17–18)$ ms.

Vibration decay at the impact speed of 75 m/s occurs somewhat faster than at a speed of 49 m/s. This may be conditional on more intense damping in the system, including friction in the bolted joints of the plate in the test rig (see Fig.1). The intense vibration damping is characterized by a certain increase in the period and a decrease in the oscillation frequency. The oscillation period for the curve at the impact speed of 49 m/s ($T_{49} = 16.6$ ms) is slightly less than for the curve for the impact speed of 75 m/s ($T_{75} = 18.2$ ms). When estimated as the inverse of the period, the vibration frequencies are 60.3 Hz and 55 Hz, respectively. This is also confirmed by the Fourier analysis of the strain gauge signals.

Forced vibrations superimpose on the impact vibrations in the first area. The second strain peak seems connected with this ($t \approx 3.6$ ms). Rapidly decaying vibrations (which correspond to one of the high-frequency modes) are observed on the initial section of the strain records, along with vibrations with the fundamental period. Differences in the pattern of the strain records in the longitude and transverse directions indicate different modes, since differences should be expected only by strain magnitude for each mode.

The peak amplitudes of the fundamental mode of plate vibration are approximately proportional to the initial impact momentum, or (with the same mass) the bird's flight speed, as indicated in the last row of Table 3.

### 3.3.3 Comparison of the bird models

The matching of the maximum computed strain to its measured value is given in Table 5. The measured strain amplitude is given in the second column of Table 5, and the computed maximum strain amplitudes are given in columns 3–5. The curve numbers in Fig.18 and in Table 5 are the same. The density of the bird body was accepted $\rho = 950$ kg/m$^3$ for all three models.

Despite the differences in characteristics, except for the density, the proximity of the pattern for all three computed strain curves (at moderate differences of amplitudes) shows the prevailing role of the momentum conservation law for the estimation of the impact influence (and the estimation of the plate strength).

| $v_b$, m/s | $\varepsilon_2 \times 10^3$ | 2 (set of masses) | 3 (elastoplastic model) | 4 (liquid column) |
|------------|-----------------------------|-------------------|-------------------------|------------------|
| 75         | 8.6                         | -6%               | -15%                    | -32%             |

### 3.3.4 Contact force analysis and momentum duration

The calculation results for the contact force and momentum are presented in Fig.19 and Fig.20. The calculations were carried out for a 3D model of the plate accounting for springs.

As seen in Fig.19, the second strain peak is observed at time point $t \approx (3.5–3.6)$ and the bird transfers momentum $J = 23.6$ kg∙m/s. After that time point, the force falls and reaches zero at time point $t = (5-6)$ ms. The momentum change also stops.

The final value of the slowed-down momentum exceeds the initial momentum of the bird. The oscillating plate presses the remaining bird, which increases the transferred momentum.
4. Conclusions
A comparative analysis of the 300 g bird colliding at strike speeds up to 75 m/s on a flexible plate and the computational results for different bird models showed the following:

1. Visible damage to the bird's body was minimal at low impact speeds up to 67 m/s, and the bird's body completely bounced off the plate under the influence of the test device elasticity. The bird's body is torn into separate fragments at higher impact speeds of 67-75 m/s. The wings, legs, and cervical regions come off, with further rupture of the bird's body. Fragments of the body look like flakes of different sizes and do not reflect a rupture as supposed by the model of a liquid column. Complete rupture of the bird's body occurs at the impact speed of about 75 m/s.

2. Strain gauge glued onto the unstriked side of the flexible plate show a division in the area of the initial strike and the area of vibration decay with a fundamental period mainly of the first eigenfrequency. The strain level mainly depends on the strike force, which is defined by the parameters of the momentum conservation law (the bird's mass, its density, length, and velocity), and to a lesser degree, the strain level depends on the mechanical properties of the bird model. High-frequency vibrations generated by the strike superimpose on the strain curve in the area of the initial strike.
The average density of the plucked bird, as measured by water displacement, is 950 kg/m³, which is close to the published experimental results. This density is reliable for computations of a bird strike. The density of the bird with plumage is about 50% less than the indicated value for the plucked bird.

4. Computational 3D analysis in LS DYNA showed a prevailing role of the bird's body density in the estimation of the strike influence on the strain level.

5. Matching the test results and computations for the SRB model and accepting the bird model as a set of masses showed a satisfactory force transfer from the soft body of the bird to a stiffer plate.

6. The acceptable results obtained in the calculations using the SRB model for computations of large bird strikes [9], [10] shows that the approaches of item 5 are valid for these cases as well, although additional experimental proof is needed.

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