Numerical and experimental investigation of the shock and steady state pressures in the bird material during bird strike

Frederik Allaey, Geert Luyckx, Wim Van Paepegem and Joris Degrieck

Department of Material Science and Engineering, Ghent University

*Tech Lane Ghent Science Park - Campus A,
Technologiepark-Zwijnaarde 903, 9052 Zwijnaarde, Belgium*

Abstract

The impact of a bird on a structure can, in the first place, be characterized by the pressure exerted on that structure. In bird strike research, the first step towards bird strike modelling is therefore often the investigation of these impact pressures. During impact, two subsequent regimes can be distinguished: a shock and steady state regime. These regimes are characterized by an initially very high shock pressure and a much lower steady state pressure. How relevant the shock regime is during bird strike however can still be questioned. This paper will reveal some key parameters that influence the shock regime, based on the conclusions of several SPH simulations and an experimental test campaign. A zoom on the numerically obtained shock pressure pulse is made, which shows that the impact pressure and duration correspond very well with the theory. Slight tilting of the projectile however can increase the pressure up to 190% of the analytical value. The elastic energy as a measure for the presence of the shock regime is introduced. This shows that the shock regime is relatively negligible for hemispherical ends. The steady state pressures obtained from the simulations are investigated and finally, the analytical values and numerical results are compared to a series of experimental impact pressure measurements with real and (porous) gelatine birds.

Keywords: Numerical simulations, experiments, bird strike, shock regime, steady state regime

1. Introduction

The work covered in this paper is part of the European FP7 project called E-Break, where a task is devoted to the development of a numerical model that is able to validate the design rules of the booster vane in terms of bird strike robustness and investigate the possibilities of Variable Stator Vane (VSV) systems. Such numerical models are increasingly used in the design process prior to full scale testing and certification. To validate and verify the performance of a developed numerical model, some initial tests or benchmarks are required. As a first test or benchmark, impact pressure measurements are often performed and compared with the available analytical solutions introduced in the reference works from the 20th century [37–39]. This is generally done by modelling a rigid target plate and requesting contact pressure output over a certain small area, which gives a characteristic pressure profile with an initially very high shock pressure followed by a much lower steady state pressure. Especially for the shock regime, the pressure predicted by the theory is not always observed in literature, which can be the result of undersampled pressure peaks (aliasing).

In the numerical work found in literature, a shock peak pressure is obtained close to the analytical value in [1, 10, 11, 15, 17, 21, 23, 28, 30, 32, 34]. Underestimations of the peak pressure on the other hand can be observed in [1, 2, 13, 16–19, 26, 27, 29, 33, 35, 36]. From all these works, it can be observed that undersampling of the pressure peaks does not occur in [1, 2, 16, 17, 19, 28, 32, 34]. In [1, 5, 11, 12, 17, 29], a trend can be observed of decreasing peak pressure for smaller initial contact areas. Occasionally the recorded pressure signals are filtered first to remove numerical noise [1, 2, 32]. In [1], it is shown that the cut-off frequency has a big influence on the obtained shock pressure.

For the steady state regime, pressure distributions conform the analytical results of Wilbeck have been observed by [1] for a Lagrangian mesh. A similar

30 result has been observed by [22] for a SPH bird.

This paper focusses on the pressure peak by combining the use of dense meshes and forcing more output in time, to prove that the numerical model predicts the shock pressure quite well, independent of the contact area and
35 without filtering. Additionally the large influence on the shock pressure of tilting the bird is also revealed. However, pressure measurements are by definition very local and therefore not representative for the behaviour on a larger scale. A more global approach can therefore learn more about the influence of certain input parameters. The elastic energy inside the shock wave is proposed to be
40 such a global parameter, which can help to study convergence issues, the influence of the shape, numerical parameters, etc. A new analytical expression will be developed for cylindrical projectiles with flat ends and a comparison will be made numerically between cylinders with flat and hemispherical ends. Several experimental impact pressure measurements are also performed, using porous
45 and non-porous gelatine birds as well as pigeons, to validate the simulations and the analytical models.

In the next section, the available analytical solutions will be covered. Section 3 and 4 respectively will introduce the numerical model and the experimental
50 set-up. The results will be discussed in section 5, to end with a conclusion.

2. Analytical solutions

The internal stresses of the bird material exceed the material strength to a large extent during bird strike. As a result, the bird shows fluid-like behaviour and several aspects from fluid dynamics can be applied to bird strike. In this
55 section, first some aspects of shock propagation in fluids relevant to bird strike will be covered. This will be mainly based on the work of Wilbeck [37–39].

In bird strike research, the shock regime is generally introduced with an

impact of a flat cylinder, which produces a very characteristic shocked state
 through time. Figure 1 shows four stages of the shock regime ?? . Point (a)
 shows the cylinder before impact, flying at the so-called particle speed v_p . The
 instantaneous stop of the material at the front of the bird results in a high
 pressure called the shock or Hugoniot pressure (b). This shocked region starts
 to expand through the material in the form of a shock wave, with a speed equal
 to v_s . Since the edges of the cylinder are not confined, the pressure is vented,
 which results in a pressure release wave travelling inwards (b up to d), with
 a speed of v_r which is higher than v_s . At (c), when the release wave reaches
 the centre axis of the projectile, the pressure at the surface of the target is not
 subjected to the shock pressure any more. The time between the start of the
 shock (b) and the end of the shock pressure at the target (c) is therefore also
 termed the shock duration. From point (d) onwards, the shock wave travels
 through the bird and the impact steadily changes to a steady state regime. The
 pressure in the projectile during the steady state regime is much lower (indicated
 by the transparent grey color).

Figure 1: The four stages showing the shock propagation in a flat cylinder ??.

A fundamental characteristic is the fact that for materials such as water and
 gelatine, a linear relationship exists between the shock velocity and the particle

velocity:

$$v_s = c_0 + s \cdot v_p \quad (1)$$

In this equation, c_0 represents the sound speed and s the slope of the linear relationship.

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To derive the shock pressure at impact, a 1-dimensional conservation of mass and momentum equilibrium can be written over the shock front. This results in the pressure rise also referred to as the shock or Hugoniot pressure P_H :

$$P_H = \rho_1 v_s v_p = \rho_1 (c_0 + s v_p) v_p \quad (2)$$

The release waves travel at the shocked speed of sound v_r , which is higher
85 than the speed of sound because of the non-linearity of the relationship between P and ρ (introduced later on):

$$v_r = \sqrt{\left. \frac{dp}{d\rho} \right|_{P_H}} \quad (3)$$

Wilbeck also considered the influence of a tilt angle on the shock wave. He stated that for a flat cylinder, beneath a critical angle ϕ_{crit} between the flat front face and the impact surface, the shock phenomenon would be exactly the
90 same as for the parallel case. And above this angle, no shock would exist at all. This critical angle is equal to $\arcsin(v_p/v_s)$. Only a short pressure peak would be created at the first point that touches the target (at the edge of the cylinder).

After several reflections, the shock wave will disappear as it dissipates energy
95 and converts to kinetic energy. A steady state flow regime forms. The pressure at the target, at the position of the central axis of the projectile is derived from Bernoulli's equation, assuming negligible shearing forces. For an incompressible flow the steady state pressure can be calculated as follows:

$$P_S = \frac{1}{2} \rho_0 v_p^2 \quad (4)$$

Two expressions have been developed that describe the radial pressure distribution on the target, starting from the stagnation pressure in the centre to zero somewhere outside the radius of the cylinder. The first one is represented by equation 5 [3] and the second one by equation 6 [24]:

$$P = \frac{1}{2}\rho_0 v_p^2 e^{-\zeta_1 (\frac{r}{a})^2} \quad (5)$$

$$P = \frac{1}{2}\rho_0 v_p^2 (1 - 3(\frac{r}{\zeta_2 a})^2 + (\frac{r}{\zeta_2 a})^3) \quad (6)$$

with r the radial distance from the centre, a the initial radius of the cylinder and $\zeta_1 = 0.5$ and $\zeta_2 = 2.58$ derived from the momentum equilibrium.

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A lot of research has been done in the 20th century to acquire pressure signals, including shock and steady state regime [4, 7–9, 37–39]. Performing a pressure measurement along the central axis of the bird gives a very characteristic signal. The typical shape of such a signal is shown in Figure 2. It includes a very short but high shock pressure followed by a much lower steady state pressure.

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Figure 2: A typical pressure signal for bird strike.

3. Numerical model

Explicit simulations are executed with Abaqus 6.14TM. In these simulations, the bird is modelled with smoothed particle hydrodynamics or SPH. SPH is increasingly used in bird strike simulations as it already proved to be quite capable

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of simulating high deforming matter with defragmentation [14]. A complete and clear explanation of SPH and its governing equations can be found in literature [25].

120 For the bird material model, a linear Mie-Gruneisen EOS is used, which relates the pressure to the density. Parameters for porcine gelatine can be found in literature ($c_0 = 1570$ m/s, $s = 1.77$ and $\Gamma_0=0$) [31], which is very similar to water. The default cubic kernel is used, with the default smoothing length calculation that aims for 30 to 50 particles in the initial support domain.
125 The smoothing length is kept constant trough the analysis. To reduce the high artificial dissipation, the linear and quadratic bulk viscosity factor are scaled down to 20%. A tensile failure criterion of 1 MPa is set as well. The Mie-Gruneisen EOS for $\Gamma_0=0$ is the following:

$$p = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2} \quad (7)$$

where η represents the nominal volumetric strain equal to $1 - \rho_0/\rho$ and ρ_0
130 and ρ respectively represent the density in initial and stressed condition.

Structured meshes are used for all the bird meshes (orthogonally aligned rows of particles, where the distance between each neighbouring particle is constant and referred to as the mesh size). The impact objects are scaled down,
135 which can be done because the shock wave pressure amplitude is independent of the size. Three geometries are considered to study the shock regime: a prismatic shape ($12 \times 12 \times 20$ mm), a cylinder with hemispherical ends ($d = 12$ mm, $l = 24$ mm) and a cylinder with flat ends ($d = 12$ mm, $l = 24$ mm). The target is modelled with cubic elements, after which a rigid constraint is applied,
140 fixing the position of all mesh elements with respect to a reference point. The dimensions of the target are $16 \times 16 \times 1$ mm.

The numerical model describing the deformation of a structure can differ

significantly from the one of a fluid. To model interaction between those two,
145 some sort of coupling is needed. For the contact of SPH in AbaqusTM, particles
behave as spheres with radii equal to half of the (structured) mesh size.
Two approaches can be distinguished: kinematic and penalty contact [20]. The
kinematic contact definition generates a contact force based on the predicted
penetration depth, the mass and the time increment. As a result, no penetration
150 occurs at the end of each time step. The kinematic contact definition consumes
kinetic energy in the form of external work [20]. Penalty contact allows small
penetrations in order to generate contact forces. A virtual spring creates a contact
force linear with the penetration depth. In the AbaqusTM general contact
definition which is adopted in this work, penalty contact is used by default.
155 The pressures in the particles of an impacting SPH mesh are therefore not used
directly to calculate the contact pressure, but the force increases with the depth
of penetration. So the question is rather, does the contact pressure represent
the exact pressure in the particles? When the SPH mesh is too coarse for ex-
ample, discrete contact pressures can be measured after which the pressure in
160 the particle starts to rise with a certain delay.

4. Experimental set-up

The experiments are performed on the Ghent University bird strike set-up
(Figure 3). The set-up is capable of shooting birds up to 42 kJ. Birds can be
launched with a weight of maximum 1.81 kg (4 lb) at speeds up to 250 m/s (the
165 maximum weight and speed does not imply both parameters can be used at the
same time, 4 lb at 250 m/s is not possible for example). At the beginning of
each experiment, a projectile called a sabot is filled with foam in accordance to
the desired shape, after which gelatine is moulded into the acquired foam shape.
The sabot is mounted in front of a pressure vessel and released at the required
170 pressure. After the release trigger, the sabot launches through a barrel and
separates from the bird in the stripper chamber using a cone shaped stripper,
after which the stripped bird flies into the test chamber and impacts on the

required target. Before each experiment, the test chamber is evacuated up to 0.2 bar absolute pressure to be able to perform precise velocity measurements.

Figure 3: Ghent university bird strike set-up.

175 To make an infinitely rigid experimental set-up to measure the impact pressures is impossible. A rigid set-up however can be approximated by making a very stiff structure. This can be done by creating a high confined inertia, which should have a minor effect on the pressure measurement. In this experimental study, the high confined inertia is achieved with a solid steel bar. Figure
180 4 shows the different parts of the set-up. The sensor (1) is mounted in an insert (2) which on its turn is screwed into the so-called sensor head (4). A 20 mm thick steel plate (3) enlarges the impact surface. Three bolts mount the steel plate (3) together with the sensor head (4) to the inertia in the shape of a solid steel bar (5). The entire assembly weighs approximately 100 kg and is
185 positioned at the correct height.

A 1:6 gelatine mixing ratio is used for the substitute birds. Porous versions are also made by adding phenolic microballoons, which decreases the non-porous density of 1040 kg/m^3 to roughly 960 kg/m^3 . The moulds for the substitute birds have a shape of a cylinder with hemispherical ends. After moulding how-
190 ever, all the gelatine birds were cut at the front to achieve a flat front (to increase the shock duration), the final weight being close to 300 gram. Pigeon carcasses are also fired head first, including feathers and paws. The pigeons weigh approximately 400 gram.

Figure 4: The impact pressure measurement set-up.

5. Results

195 In this section, the results will be covered. First the pressure pulse will be numerically investigated for orthogonal impact in section 5.1 and for tilted impact in section 5.2, using the prismatic geometry for the projectile. After that it will be shown that hemispherical ends give the same shock pressure amplitude. The elastic energy will be covered in section 5.4. The steady state regime will
 200 be discussed briefly in section 5.5 and finally the results of some experimental pressure measurements will be given.

5.1. The numerical shock pressure pulse

To record accurate numerical shock pressures, very fine meshes are used. Additionally, the simulation is deliberately forced to use very small time in-
 205 crements, to achieve a smooth solution in time. Apart from using dense SPH meshes which already leads to small increments, this is further reduced by enforcing field output with a much higher output frequency.

Simulations with an impact speed of 100 m/s (order of magnitude take off
 210 and landing speed) are executed for 10 μ s, enforcing 500 pressure field outputs.

The prismatic geometry with mesh sizes of 1 mm, 0.5 mm, 0.25 mm and 0.2 mm is considered (Figure 5).

Figure 5: Considered SPH meshes to study the shock regime.

Figure 6 shows the pressure in the centre particle at the front layer of SPH particles and Figure 7 the contact pressure measured at the centre node of the plate for the four considered meshes, together with the analytical solution ($P_H = 181.69$ MPa). A very stable shock pressure plateau can be observed for the particle pressure of the denser SPH meshes. The pressure matches the analytical result very well. The contact pressure curves do look worse (large oscillations superimposed on the pressure plateau). But apart from the oscillations, the pressure pulse is estimated quite good for 0.25 mm and 0.2 mm meshes. The smoothing inherent to the SPH algorithm is probably responsible for the smoother curves of the particle pressure.

A release wave speed of 1823.3 m/s can be calculated from Equation 3 and 7, which corresponds with a shock duration of $3.29 \mu s$ for the shortest edge (6 mm) up to $4.26 \mu s$ for the diagonal (8.49 mm), because of the cubic shape of the cross section. The figures indeed show that the pressure starts dropping approximately at $3.5 \mu s$ after impact. For the coarser meshes, it can be observed

Figure 6: Particle pressure for four SPH mesh sizes.

Figure 7: Contact pressure for four SPH mesh sizes.

that the shock pulse lasts slightly longer.

230 The 0.25 mm mesh can be used to check the influence of the impact velocity.
 Figure 8 shows the pressure pulse measured at the centre particle for 75, 100,
 150, 200 and 250 m/s.

Up to 200 m/s, the shock pressure is estimated very well, but the pressure
 pulse of 250 m/s is slightly overestimated. This might again be a mesh con-
 235 vergence issue. An overestimation of the pressure pulse was also seen for the
 coarser meshes in Figure 6. For higher pressures, the shock duration decreases

Figure 8: Particle pressure pulse for the 0.25 mm SPH mesh at 75, 100, 150, 200 and 250 m/s.

slightly because of an increase of the speed of sound at higher pressures (see also Equation 3).

5.2. Tilting a flat bird projectile

240 The behaviour described by Wilbeck is investigated using the 0.25 mm SPH mesh size. Because the particles do not impact at the same time, the contact pressure curves are worse. To maintain the same spatial resolution and to show the clear trend at increasing tilt angle, the signals are filtered with a cut-off frequency of 1 MHz. The results covered in this section are not necessarily
 245 converged. Figure 9 shows the contact pressure on the centre node of the plate after impact of the mesh at 100 m/s, with an angle of 0° , 2° , 3° , 4° , 6° , 8° and 15° with respect to the surface of the plate. According to Wilbeck, no shock wave should be observed any more at the centre of the plate above the critical angle of 3.28° . But this is not the case. At 2° , the amplitude starts to rise.
 250 At $3-4^\circ$, the shock pressure rises up to roughly 190 % of the theoretical value. Further increasing the tilt angle reduces the contact pressure again, ultimately creating a flow more similar to a steady state regime as for example for the 15° impact.

As seen in the contact pressure graph, the pressure can increase for certain
 255 impact angles. This is because of an additional material flow that originates

Figure 9: Contact pressure of a flat projectile tilted 0° , 2° , 3° , 4° , 6° , 8° and 15° .

and accumulates with the original impact speed, as shown in the speed vector plot of Figure 10, showing the speeds of a central vertical layer of particles at the moment where the additional flow reaches the centre of the target for the 3° tilted mesh.

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For angles beneath the critical angle, release waves still travel from the side that impacts first. The contact pressure is therefore a running pulse, as shown on the right in Figure 10. This running pulse can also be observed in the pressure field of the simulations. The spatially small pulse is also the cause of the shock

265 duration that is much smaller for tilted impacts. The angle would have to be much smaller than the critical angle for the release waves to have a negligible influence on the pressure distribution compared to a perpendicular impact.

These simulations indicate that there is no critical angle that determines whether a shock wave is created or not. There is a rather smooth transition

270 of pressure amplitude and duration when altering the tilt angle, resulting in a variety of pressure amplitudes (that can increase above the theoretical shock

Figure 10: Additional flow and a running pressure pulse

pressure because of the additional flow) and a variety of pressure pulse durations (because the release waves can vent the shock pressure from the side that impacts first). According to the authors' knowledge, this has not been observed before, but it is important to keep in mind when evaluating impact pressure measurements.

5.3. Hemispherical ends

Infinitesimally, the impact point of a hemispherical surface is also represented by a flat surface. Very locally, the creation of the shock wave is therefore similar to the impact of a flat cylinder or prism. The numerical representation of a hemisphere with a structured mesh inevitably consists of a flat surface at the front. This can be observed in Figure 11, which shows the hemisphere for three mesh sizes.

Figure 11: Discrete representation of a hemisphere by a structured particle mesh (side view).

285 In Figure 12, the pressure in a centre particle of the front layer of particles is shown. The peak pressure is slightly larger than the theoretical one (181 MPa), which might be because of the overshoot also seen in the simulations with the flat surfaces. From the 0.5 mm to the 0.2 mm mesh, the shock duration almost halved.

Figure 12: The pressure in a centre particle of the front layer of particles of the hemispherical 0.5 mm, 0.25 mm and 0.2 mm mesh.

290 The reduction of the shock duration will be partly the result of the decreased radius of the front layer of particles. But it will also partly be the result of convergence. It is computationally impossible however to obtain a much smaller radius of the front layer of particles.

5.4. Elastic energy

295 The elastic energy is proposed to be a more global measure for the shock regime, in contrast with pressure signals on element level. In this section, first a new analytical expression for the elastic energy in case of flat cylinders will be developed, after which it will be compared to the simulations. Finally, a comparison between a cylinder with flat and hemispherical ends will be made.

300 An expression is developed to compute the elastic energy inside the shocked region. This expression is based on the assumption of adiabatic compression (to-

gether with $dV = -V_0 d\eta$, which is deduced from the definition of η introduced in section 3):

$$\begin{aligned} E_{shock} &= - \int p dV = - \int -V_0 \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2} d\eta \\ &= - \left[\frac{\rho_0 c_0^2 V_0}{s^2} \left(\frac{1}{s\eta - 1} - \ln(|s\eta - 1|) \right) \right]_{\eta_0}^{\eta_1} \end{aligned} \quad (8)$$

Where $\eta_0 = 0$, η_1 can be calculated from the Mie-Grüneisen EOS and $V_0 =$
305 $V/(1 - \eta_1)$. This last substitution introduces the compressed volume in the equation, which can be determined based on the shock and release wave speed. Notice the minus sign to make the calculated elastic energy positive. In the derivation of the shocked volume, the following assumptions are made:

- The release and shock wave speed are equal to the ones derived from the
310 theory.
- The speed of the release and shock wave is constant. Just after impact this assumption is valid. But as the shock wave loses energy while it travels through the material, the speed of the material behind the shock wave is not zero any more.
- 315 • The pressure in the shocked region is constant.
- Both the release and shock wave are discrete surfaces travelling through the projectile.
- The release wave vents the shock pressure immediately when the two fronts collide.

320 The last two assumptions for the release wave are likely the biggest error source in the obtained solution. The release waves indicate the start of the conversion of elastic energy to kinetic energy. This conversion however happens relatively slow.

325 The volume in function of time can be derived from a revolution about the axis of the bird projectile, of the area enclosed by the release wave, the shock

front and the axis of the projectile. As shown in Figure 13, the front of the initial release wave is always further propagated than any other point along the edge of the projectile because the release wave is faster than the shock wave.

Figure 13: Shocked region: the shock and release waves.

330 The radius of the release wave and the position of the shock front in function of time (Figure 14) can be written as follows:

$$r_r = v_r t; \quad x_s = v_s t \quad (9)$$

Figure 14: Derivation of the shocked volume in function of time.

The distance between the radial release wave and the x-axis can be integrated up to the location of the shock:

$$\begin{aligned} V &= \pi \int_{x_0}^{x_s} f(x)^2 dx = \pi \int_{x_0}^{x_s} (r - \sqrt{r_r^2 - x^2})^2 dx \\ &= \pi \left[r^2 x - 2r \left(\frac{x \sqrt{r_r^2 - x^2}}{2} + \frac{r_r^2}{2} \arcsin \left(\frac{x}{r_r} \right) \right) + r_r^2 x - \frac{x^3}{3} \right]_{x_0}^{x_s} \end{aligned} \quad (10)$$

with

$$x_0 = \begin{cases} 0 & \text{if } t \leq r/v_r \\ \sqrt{r_r^2 - r^2} & \text{if } r > r/v_r \end{cases} \quad (11)$$

335 and

$$x_s \leq \sqrt{\frac{r}{\frac{v_r^2}{v_s^2} - 1}} \quad (12)$$

Figure 15 compares the analytical result with the elastic energy in the simulation for the flat cylinder with a radius of 6 mm and a length of 24 mm. The analytical result is calculated for both the theoretical release wave speed of 1823 m/s and a 175 m/s slower release wave speed. The elastic energy is shown for a mesh size of 0.5 mm, 0.25 mm and 0.2 mm. The influence of 1 MPa tensile failure criterion is also shown for the 0.25 mm mesh. The theoretical end of the shock pressure on the target for the theoretical case is indicated with an asterisk.

Figure 15: Shock energy: analytically and numerically.

The analytical result underestimates the elastic energy quite a lot, which could be expected from the actual slow drop in pressure by the release waves. The influence of this slow pressure drop is shown by reducing the release wave

speed, which clearly makes the analytical result better correspond with the simulations. Nevertheless, the shape of the curve is very well represented. The deviation of the simulations without tensile failure from the shape of the analytical result at approximately $4 \mu s$ is because of a tensile wave that starts to form right after the pressure drops to zero. When tensile failure is set, this tensile wave cannot exist and therefore its energy cannot be observed.

Compared to the initial kinetic energy of 7.1 J, up to 10% approximately is temporarily converted to elastic energy at impact. According to the peak pressure in the centre, the 0.25 mm mesh is converged. This can be concluded from the elastic energy curve as well, both the 0.25 mm and 0.2 mm mesh give a very similar elastic energy curve over time.

The elastic energy can serve as an indicator for the presence of the shock regime. Comparing the shock energy between flat cylinders and cylinders with hemispherical ends for example clearly shows the negligible shock regime in case of the hemispherical ends. This is illustrated in Figure 16a, showing the elastic energy for the three hemispherical meshes considered in section 5.3 compared to the shock energy of the similar 0.25 mm flat cylinder plotted in Figure 15. This gives a much better impression of the shock regime for a cylinder with hemispherical ends compared to the shock pressure measurement at the centre, which exists only very locally at the impact point (Figure 12). When the speed is increased, the front surface impacts the plate quicker, but still, even for an impact at 250 m/s, the elastic energy reaches only half of the energy of the flat end at 100 m/s, while the impact kinetic energy is 6.25 times higher (Figure 16b).

Exactly the same conclusion can be made for a larger $r = 50$ mm and $l = 100$ mm projectile using a 0.8 mm mesh (25 J for a 250 m/s impact of the cylinder with hemispherical ends compared to the 60 J for a 100 m/s impact of the cylinder with flat ends).

(a) The much lower shock energy for a hemispherical end. (b) Influence of the speed on the shock energy.

Figure 16: Shock energy for a hemispherical end.

5.5. The steady state regime

A hemispherical 0.8 mm mesh with a diameter of 50 mm and a length of 100 mm is used to investigate the steady state pressures. A larger plate with an element size of $8 \text{ mm} \times 8 \text{ mm}$ is used, to have 100 particles/element and assure a continuous pressure signal. From the centre to the edge of the plate, the single node surface forces are tracked and divided by 64 mm^2 to obtain an average pressure over the represented area. When a particle impacts an element, the force on element level is transferred to the surrounding nodes so the pressure distribution will only be an approximation. Averaging out can capture linear gradients. Especially in the centre, the pressure therefore can be slightly lower. Figure 17 shows a side view of the impact.

Figure 17: Particle distribution during steady state regime for a 100 m/s impact of a flat cylinder.

To determine the steady state pressure, including the shock pressure at the

start of impact or the decay near the end of impact would not be correct. In
 390 literature, it has been suggested to use the average of the pressure between $1/3T$
 and $2/3T$, where T stands for the impact duration [1, 32]. Figure 18a shows
 the numerical pressure signal at the centre node for a 100 m/s impact, includ-
 ing the two boundaries between which the pressure will be averaged out (0.33
 ms and 0.67 ms) and the theoretical steady state pressure. The steady state
 395 pressure corresponds very well with the theory. An average pressure of 5.1 MPa
 is obtained, compared to the theoretical pressure of 5.2 MPa (using Equation 4).

Figure 18b shows the pressure distribution along the radius for 100 m/s,
 150 m/s and 200 m/s, together with the two analytical expressions introduced
 400 in section 2, calculated for each impact speed (therefore six curves are shown).
 The shape is represented quite well. There is a only a slight overestimation at
 a radial position of 20 mm.

(a) Pressure signal at the centre node with the $1/3T$ and $2/3T$ interval and the theoretical steady state pressure. (b) Steady state pressure distribution along the radius for 100 m/s, 150 m/s and 200 m/s.

Figure 18: Steady state pressures.

5.6. Experimental results

In total, ten experiments are performed at speeds ranging from 110-140
 405 m/s: three experiments with gelatine birds with a 1:6 gelatine to water mixing

ration (MR), three with porous 1:6 MR gelatine birds and four experiments with pigeons. Not all the steady state pressures are trustworthy because some of the signals shift over the course of the impact, resulting in a non-zero pressure after impact. These are not included in the results discussed here. Three main
410 conclusions can be made from the performed experiments:

- The shock pressure is very dependent on the front surface of the bird.
- The steady state pressures correspond well with the theory.
- The steady state pressure signals for the pigeons are quite discontinuous.

The shock pressure

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The shock pressures for the three tests with non-porous gelatine are shown in Figure 19 (impact speeds are respectively 113.6 m/s, 121.3 m/s and 132.1 m/s). The solid and dashed black line respectively indicate the theoretical non-porous and porous shock pressure (derived from Wilbeck's theory [38]).

Figure 19: Shock pressure for the three tests with non-porous gelatine.

420 The shock pressure is twice much lower and once significantly higher than the theoretical pressure indicated by the black horizontal lines. If anything can be concluded, it is the fact that the front shape has a high influence on the obtained shock pressures and that most likely, dependent on the location where the pressure is measured, very different shock pressures can be obtained. Pos-
425 sibly a slightly non-parallel impact surface resulted in an increase of the shock

pressure up to almost double the theoretical value for the third test, as was also observed in section 5.2.

Theoretically, the shock duration should be around $32 \mu s$ for the three tests.
 430 For the third test, the shock duration is shorter (and the shock pressure higher), which is a trend that was also observed in section 5.2 (as a result of release waves that can vent the shock pressure sooner).

The average steady state pressures

435 The steady state pressures are obtained by averaging the pressure between $1/3T$ and $2/3T$. This interval however depends to a great extent on the assumed start and end of impact. For each experiment, the start of the signal is assumed to be the time at which the pressure starts to rise. The end of impact on the
 440 other hand, which defines T , is quite a subjective parameter (is it defined by the length of the bird or is there a better measure?). Here, the impact duration is obtained by (i) dividing the length of the bird by the impact speed or (ii) by estimating the time at which the pressure drops back to zero. The length of the bird however is not always the same as the one measured before launch. For the
 445 gelatine birds, the first method is used (the length can be estimated quite well), and for the real birds the second method is used (the neck of the bird does not always impact first and the length of the bird is also quite different).

Figure 20 shows the steady state pressure together with some analytically
 450 determined steady state pressure curves.

In this figure, for the three types of bird, three analytical steady state pressures are included:

- **Gelatine birds:** The analytical curve assuming incompressibility is obtained directly from the gelatine density (Equation 4).
- 455 • **Porous birds:** Compressibility is taken into account (obtained by nu-

Figure 20: Overview experimentally measured steady state pressures.

merically integrating the Bernoulli equation together with the porosity EOS found in [38]). The porosity factor for the porous gelatine mixtures ($z = 0.077$) is obtained assuming a gelatine and mixture density of respectively 1040 kg/m^3 and 960 kg/m^3 .

- **Real birds:** Also here, compressibility is taken into account. The densities of the real birds are obtained from the logarithmic dependency with the mass found in [6] (approximately 1020 kg/m^3). For the porosity factor of 0.1 proposed in Wilbeck's work [37], a fluid density of 1133 kg/m^3 is assumed to obtain a mixture density of 1020 kg/m^3 .

The analytically calculated steady state pressure curves are quite similar. The one for the real birds is only slightly higher.

Despite the influence of the assumed impact duration T , the measured steady state pressures correspond quite well with the analytical results. In general, the steady state pressure seems to be slightly higher. For the scarce amount of tests, no clear distinction can be observed between the different bird types.

Pigeon steady state pressure signals

475 In Figure 21, the steady state pressures for the four experiments with pi-
geons are shown (108.5 m/s, 116.5 m/s, 128.0 m/s and 139.3 m/s). A relatively
large fluctuation of the pressures occurs in the steady state regime, which might
be an indication of the bird not being as homogeneous as expected at these
impact speeds. The red part of the pressure curve indicates the area over which
480 the steady state pressure is averaged (the horizontal grey line represents this
average) and the solid and dashed black horizontal line respectively indicate
the analytical steady state pressure with and without the assumption of incom-
pressibility.

485 Disregarding the heterogeneities, the steady state pressure corresponds well
with the analytical results.

Figure 21: Steady state pressures for the four experiments with pigeons.

No peaks can be observed in the first three plots. The birds are shot with
the head first. The high speed images revealed that for the first three tests, the
head impacts roughly 10 mm away from the sensor. Only for the fourth test,
490 the head impacted the sensor directly and a shock pressure is measured.

6. Conclusion

This paper discusses the results of an extensive numerical study on the shock and steady state regime during bird strike on a rigid plate. The analytical formulations developed in the reference works of the 20th century are introduced and
495 compared to numerical simulations and several experimental pressure measurements. Numerical models are created that allow to focus on the shock pressure pulse, which results in stable pressure plateaus that match very well with the analytical models (amplitude, shape and duration). A correct average steady state pressure distribution is observed as well. For hemispherical ends, the same
500 shock pressure amplitude is observed, which could be expected because of the infinitesimally identical situation at the centre.

The influence of a tilted impact surface is investigated. This reveals that there might not exist a critical angle as Wilbeck suggested, because for angles beneath the critical angle, release waves still can travel from the side that im-
505 pacts first. In contrast with the prediction of Wilbeck, simulations also show that slightly tilting the projectile can increase the shock pressure up to 190% of the analytical value. From these numerical results, it can be concluded that it might be very difficult to do experimental shock pressure measurements, since small differences in tilt angle or front shape can give very different results.

Investigating the shock regime using pressure signals can be tricky. It is very
510 important to understand what is happening at a discrete level. Even more, in more complex models, the behaviour at element level is often not representative for the global behaviour. In this work, the use of elastic energy to quantify the shock regime is introduced. An analytical model is developed for the elastic
515 energy in the shock region. The shape of this curve resembles well with the simulation, but the amplitude is underestimated due to a simplified representation of the release waves. The elastic energy shows to be a good measure for the presence of the shock regime. It shows for example that the shock regime for hemispherical ends is relatively negligible.

520 Finally, several experimental impact pressure measurements are performed

and investigated, showing a good correlation for the steady state pressure. Also in the experiments, peak pressures above the analytical value are detected as was also observed in simulations. It is also shown that at the considered range of impact speeds, the steady state pressure for pigeons is more discontinuous. This might be an indication of the bird not being as homogeneous as expected at these impact speeds.

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