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Sandwich shield subjected to bird impact: use of surrogate models for influencing parameters analysis and shield behaviour understanding

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Abstract

In this work, the behaviour of a sandwich shield subjected to a 1.82 kg bird impact at 175 m/s is studied using a finite element model. The most influential design parameters (6) are varied and their effects on the shield behaviour and on the target protection are assessed. First, we try to establish an engineer's visualization by varying parameters 2 by 2 using three 5-levels full-factorial designs of experiments (DOE). These three 2D DOE enable us to visualize precisely the different effects of each parameter. Then a full sensitivity analysis (6D) is performed using a Latin Hypercube sampling, to assess the possible interactions between parameters. Surrogate models are constructed using the Gaussian Process framework to follow the variation of the outputs in the 6D design space. These surrogate models are finally studied using two statistical methods: the Sobol' method and the Morris method. The methodology developed in this study enables to improve the understanding of the behaviour of a shield under a soft body impact, as a first step towards a shield design tool.

Highlights

- A finite element parametric study is conducted on a sandwich shield under bird impact
- It appears that six parameters have a great influence on the shield behaviour
- The influence of these six design parameters on the sandwich behaviour and the target protection is studied
- The three sandwich core parameters are the most influent

Keywords

Sandwich shield / Impact design / Bird strike / Parametric Study / Gaussian Process

34 1 Introduction

35 During its flight, one of the major threats an aircraft can encounter is the collision with a bird.
 36 Such collisions are known to occur frequently, and a 2008 study by the European Aviation
 37 Safety Agency [1] estimates the occurrence at 186 per million flying hours. The possible
 38 damages of such an impact can be very diverse, due to the wide range of possible impacting
 39 scenarios, from multiple small flock birds (weighting approximately 50 g) to heavy
 40 migratory birds (up to 4 kg). Moreover, the birds can impact all the forward facing structures,
 41 i.e. the nose, the windshield, the wings leading edge, the empennage, the engines, etc...

42 To ensure the protection of passengers and crew on a commercial aircraft, the aviation
 43 authorities [2][3] require that the plane should be able to continue its flight and land safely
 44 after a 1.82 kg (4 lb) impact at operational speed at sea level (typically around 175 m/s). In
 45 the case of an impact on the aircraft nose, the main danger is the failure of the pressurised
 46 bulkhead, electrical systems and equipment situated behind the radome instruments. Thus, to
 47 meet the certification requirements, a shield is placed in front of the bulkhead, behind the
 48 instruments (cf. Fig. 1).



49
 50 Fig. 1. Shield in the nose of an A320 aircraft

51 Due to their high specific stiffness and the good absorption properties of their core [4],
 52 sandwich structures are the ideal candidates for such shields, and are used for this application
 53 by most aircraft manufacturers. In this work, we focus on the study of the behaviour of such a
 54 sandwich shield under the certification impact (1.82 kg at 175 m/s).

55 The first studies about bird strike, in the late 1970s, were focused on understanding the
 56 behaviour of a bird impacting a plate at such speed. Using extensive testing, Barber, Taylor
 57 and Wilbeck [5][6][7] showed that the bird behave similarly to a fluid during impact: the
 58 force transmitted to the target starts with a peak and is followed by a long plateau
 59 corresponding to a steady flow. They also showed that, during experiments, the bird can be

60 substituted by an impactor made of gelatine with 10% porosity, with good improvements on
61 repeatability. Consequently, these substitutes are used in tests in most latter studies.

62 Due to the great number of possible impacting scenarios (size and speed of bird, impacted
63 structure, etc...) the literature on bird strike is quite large. In a 2011 review, Heimbs [8] lists
64 more than 190 numerical studies on bird strike, and identifies for each the impacted structure
65 (windshield, leading edge, etc...), the impact case (mass of bird, speed, geometry), and the
66 bird modelling strategy used. Three different numerical strategies are commonly used to
67 model a bird: Lagrangian, Arbitrary Lagrangian Eulerian (ALE) or Smoothed Particles
68 Hydrodynamics (SPH). These methods and their differences are presented in detail in [8].

69 Concerning the impactor shape and material laws, a study by Airoidi and Cacchione [9]
70 showed that the simulations were closer to test data when the material laws used represented
71 water with 10% porosity and when the impactor was modelled as a cylinder with hemi-
72 spherical caps and a length to diameter ratio of 1.6. More complex shapes and material laws
73 have also been studied in [10].

74 Only a few of these studies use a flat sandwich structure as target and focus on its behaviour.

75 We present here these 5 papers:

76 In 2006, Hanssen et al. studied a two layers sandwich panel [11]. Using simulation with the
77 ALE strategy, they were able to represent the observed experimental behaviour, including
78 failure at the clamping bolts. In a second part of their work, they used their model to minimize
79 the core thickness of a simple sandwich with 0.8 mm thick aluminium skins and a core made
80 of 150 kg/m^3 aluminium foam. The lighter sandwich able to stop the bird without front skin
81 tearing had a 150 mm thick core.

82 In 2012, Hohe et al. reproduced this load case [12] and showed that, using a graded core of
83 three layers with increasing density, the front skin strain was spread on a greater surface, with
84 the maximum strain being lower. They concluded that the use of a graded core could improve
85 the resistance of the sandwich shield.

86 In 2012 also, Liu et al. studied a sandwich with aluminium honeycomb core and a two layers
87 sandwich with the same core material and the same total height [13]. They created a finite
88 element model to simulate the load case and were able to represent correctly both impacts.

89 In 2015, Hedayati et al., in a numerical study, assessed the effect of the position of the middle
90 skin in a two layers sandwich, keeping the total height constant [14]. They showed that the
91 minimal backward deflection is obtained for the shield with balanced cores (i.e. middle plate

92 in the centre). In a second part, they showed that for cores with different densities, the best
93 result was obtained with the lighter core facing the impactor.

94 The same year, Liu et al. studied the influence of skins and core thickness at constant mass on
95 a simple sandwich with an aluminium foam core [15]. They showed that both the backward
96 deflection and the energy absorption of the panel increase when the core height increases and
97 the skins thickness decreases. Then, they studied the effect of the middle plate position on a
98 two layers sandwich with a constant total height. They showed that the minimal backward
99 deflection is obtained with a first layer height equal to zero, i.e. a simple sandwich with a
100 double front skin.

101 This latter conclusion seems to be in contradiction with the conclusion of [14]. This difference
102 can be explained by the fact that those two studies use slightly different boundary conditions
103 (respectively riveted or clamped) and by the fact that in [14], no bonding is modelled between
104 the skins and the cores.

105 All these results suggest that the behaviour of the shield is influenced not only by the core and
106 skins properties, but also by the structural coupling between the two. Thus, when designing a
107 new shield, it seems important not to study the skins and core properties separately, but to
108 study all the shield design properties together.

109 According to this conclusion, in this work the skins and core properties are all considered as
110 design parameters of the shield, along with the different heights and thicknesses. We then
111 study the influence of these parameters on the behaviour of the shield but also on the target
112 protection. This paper is organised as follows:

113 In Section 2, the case study is defined and the finite element model used is presented. Then,
114 the different outputs which will be followed throughout the study are presented and,
115 according to a previous study [16], the most influential parameters are determined.

116 In Section 3, these parameters are studied 2 by 2 using full factorial designs of experiments
117 (DOE). The effect of each parameter and its interactions with the other parameters are studied
118 and physical interpretations are proposed for the observed phenomenon.

119 In Section 4, these 2D studies are expanded in full 6D by adding 100 new simulation points.
120 Surrogate models are then created to follow the outputs variations in the 6D design space
121 using one of the main reference framework in the machine learning domain. Statistical
122 methods are then used to analyse the effects of each parameter and the interactions with the
123 others. The results obtained are confronted to the observations made on the 2D studies of the
124 previous section.

125 **2 Case study description**

126 The radome shields used today in the industry have a geometry which is strongly dependant
 127 on all the other surrounding systems, and thus they are different from one aircraft to the other,
 128 but these shields are usually flat sandwiches, with an area of about 1 square meter, directly
 129 supported by the protected bulkhead. These sandwiches are typically made of two aluminium
 130 skins and a core made of metallic foam or honeycomb. The skin thickness range from 1.5 to 5
 131 mm and the core height is usually about 100 mm.

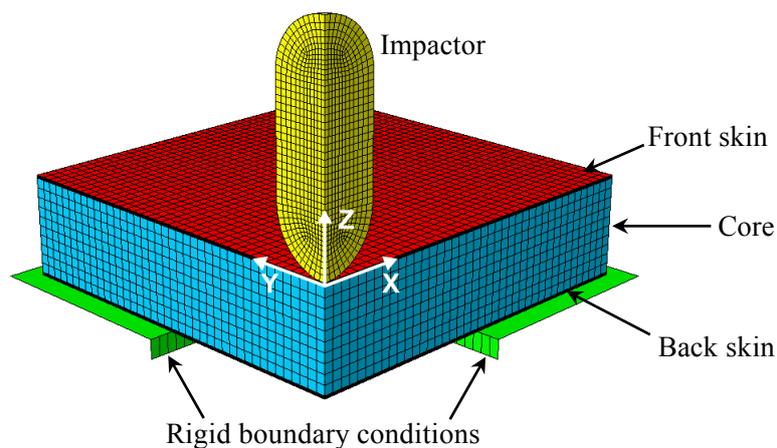
132 In this work we will study the shield under the impact of a 1.82 kg bird at 175 m/s,
 133 representing the certification case. This impact represents an initial kinetic energy of 27.9 kJ.

134 **2.1 Finite element model**

135 In order to limit the number of geometrical and boundary conditions parameters, the limit
 136 conditions and the shield geometry have been simplified compared to a real engineering case.
 137 Moreover, to be able to simulate a great number of different shield designs at an acceptable
 138 cost, the finite element model is kept as simple as possible, and the material laws used are
 139 kept generic.

140 **2.1.1 Geometry**

141 The geometry chosen is an 800 mm square sandwich, supported by a rigid frame with a 400
 142 mm square aperture in its centre. The sandwich has two skins 3 mm thick and a core with a
 143 height of 100 mm. Due to symmetry conditions, only a fourth of the shield is modelled using
 144 ABAQUS/EXPLICIT (cf. Fig. 2).



145

146

Fig. 2. Finite element model of the sandwich shield

147 The support is modelled with rigid shell elements R3D4. The sandwich shield is modelled as
 148 one part, with no possible debonding between the skins and the core. Five layers of reduced
 149 integration brick elements (C3D8R) are used for the back skin, ten layers of fully integrated
 150 elements (C3D8) are used for the core and five layers of reduced integration elements
 151 (C3D8R) are used for the front skin. During the parametric study, the core and skins
 152 thicknesses will change but the number of elements used through thickness is kept constant.
 153 The in-plane element size is 10 mm by 10 mm, for a total number of elements for the
 154 sandwich of 32000. The impacting bird is modelled as a hemispherical ended cylinder with a
 155 radius of 55 mm and a length of 220 mm. 3490 Lagrangian reduced integration elements
 156 (C3D8R) are used, with enhanced hourglass control. The contact between the bird and the
 157 front skin, and between the back skin and the support, is modelled with ABAQUS general
 158 contact without friction. The total simulated time is 6 ms, enough to simulate the whole
 159 impact and the shield rebound.

160 **2.1.2 Material models**

161 In order to model the bird material behaviour, a tabulated equation of state representing the
 162 behaviour of water with porosity is used. The elements are deleted when their true strain
 163 become greater than 500%, in order to limit the decrease of the simulation time step due to
 164 highly distorted elements while allowing to represent the flow of the bird. The bird density is
 165 955 kg/m^3 , which gives a 1.82 kg bird.

166 The shield design parameters being varied during the parametric study, we give here the
 167 values for the central point of the design space. This reference case represents a shield with
 168 aluminium skins and an aluminium honeycomb core.

169 The skin material is represented using an isotropic material law. A Young modulus of 72 GPa
 170 and a Poisson coefficient of 0.33 are used, with a density of 2800 kg/m^3 . The plastic
 171 behaviour is modelled by ABAQUS Johnson-Cook isotropic hardening (equation (1)).

$$\sigma_p = A + B \cdot (\varepsilon_p)^n \quad (1)$$

172 where $A = 300 \text{ MPa}$, $B = 400 \text{ MPa}$ and $n = 0.27$. This model is used because it is able to
 173 represent the plastic behaviour of many different metals with only three parameters [17]. No
 174 skin failure is modelled, but the maximal skin in-plane strain will be studied to ensure that this
 175 hypothesis stay valid.

176 To simulate the core behaviour, a generic material law is implemented using a VUMAT user
 177 routine. An elasto-perfectly plastic law is used for all directions, followed by a densification

178 for the out-of-plane compression. Such a strain-stress curve have been shown to be typical for
 179 the cellular materials used as sandwich cores [4]. Uncoupled shearing and compressive
 180 behaviour is assumed. The material law parameters are adapted from [18]:

- 181 - In-plane modulus: $E_x = E_y = 1$ MPa.
- 182 - In-plane plateaus: $\sigma_{p_x} = \sigma_{p_y} = 0.9$ MPa.
- 183 - In-plane shear modulus: $G_{xy} = 5$ MPa.
- 184 - In-plane shear plateau: $\tau_{p_{xy}} = 1.2$ MPa.
- 185 - Out-of-plane shear modulus: $G_{xy} = G_{yz} = 200$ MPa.
- 186 - Out-of-plane shear plateaus: $\tau_{p_{xy}} = \tau_{p_{yz}} = 1.2$ MPa.
- 187 - Out-of-plane modulus: $E_{z_c} = 1000$ MPa.

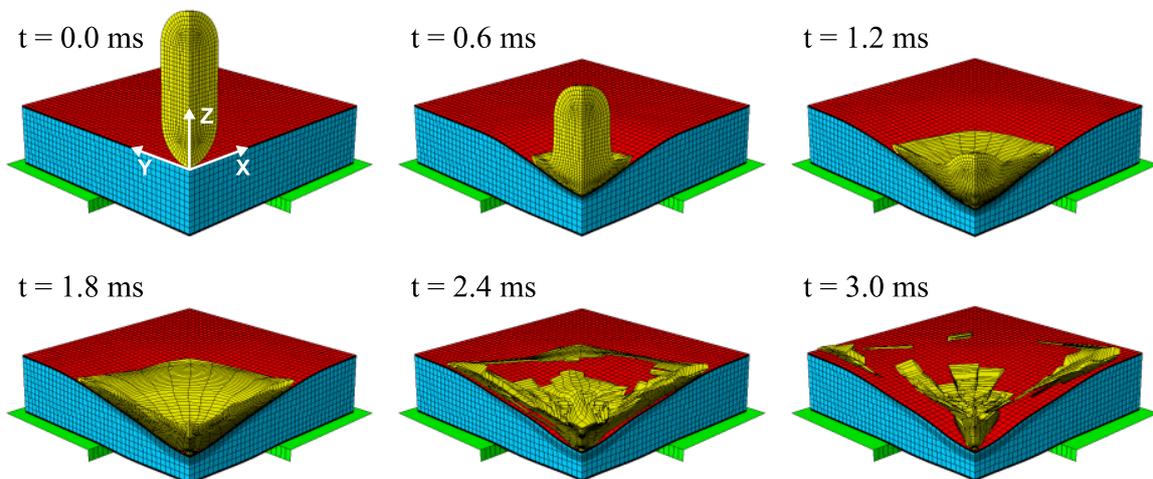
188 For out-of-plane compression, a plateau followed by densification behaviour has been
 189 modelled using equation (2).

$$\sigma_z = \sigma_{p_c} + C \cdot (e^{\varepsilon/\varepsilon_d} - 1) \quad (2)$$

190 with $\sigma_{p_c} = 0.9$ MPa the core crushing plateau, and $C = 0.01$ MPa and $\varepsilon_d = 0.37$ defining the
 191 densification phase. The core density is set to 50 kg/m^3 .

192 2.2 Outputs studied

193 With this generic finite element model, it is possible to simulate the impact of a bird on
 194 different shields, and to study the effect of the shield definition on the target protection. The
 195 simulation of one design case takes approximatively 2 hours on 4 CPU, using the CALMIP
 196 (Calculateur Midi-Pyrénées) supercomputer. This relatively small computing time allows
 197 simulating numerous design points during the parametric study. Fig. 3 presents the evolution
 198 of the reference shield shape during impact.



199 Fig. 3. Reference case: evolution of deformed shape during impact
 200

201 In such a parametric study, it is obviously impossible to analyse all the differences between
 202 all the finite element simulations, due to the important number of design case tested. It is then
 203 necessary to define simple outputs that can be followed during the parametric study and that
 204 define the shield behaviour.

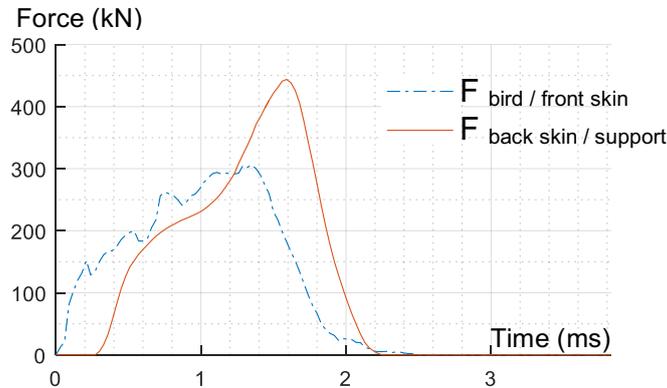
205 Here, we decided to follow four protection criterions, which could be used as design criterion
 206 in a real engineering case, and representing the protection capacity of the shield:

- 207 - The maximum total force applied to the support F_{Supp} . The total force is computed at each
 208 time step as the sum of all the contact forces between the back skin and the support. This
 209 force is then filtered using a moving mean with a window of 0.15 ms and F_{Supp} is defined
 210 as the maximum along time. For the reference shield, F_{Supp} is given in Fig. 4, with the
 211 total force applied by the bird on the front skin.
- 212 - The maximum pressure applied to the support P_{Supp} . This pressure is computed using the
 213 contact forces between the back skin of the shield and the support. The contact forces are
 214 filtered using a moving average with a window of 0.15 ms along time and a Gaussian filter
 215 on a 3*3 nodes window along space. P_{Supp} is then defined as the maximum along time and
 216 space of the pressure obtained. Cf. Fig. 5 for the evolution of P_{Supp} in the reference case.
- 217 - The maximum backward deflection of the back skin δ_{bs} . This criterion is often used in the
 218 industry since an important backward deflection can endanger critical systems situated
 219 behind the pressurised bulkhead.
- 220 - The maximum in-plan strain of the front skin ε_{fs} . Even if no skin rupture has been
 221 modelled in this work, this output allows to differentiate two shield designs by knowing
 222 how close they are of a potential front skin tearing.

223 Using these four criterions, it is possible to assess the capacity of a shield to protect the target,
 224 but these outputs give no information about the shield deformation. The goal of this
 225 parametric study being to understand the behaviour of the shield and its influence on the
 226 target protection, it is necessary to have outputs describing how the shield is deformed.

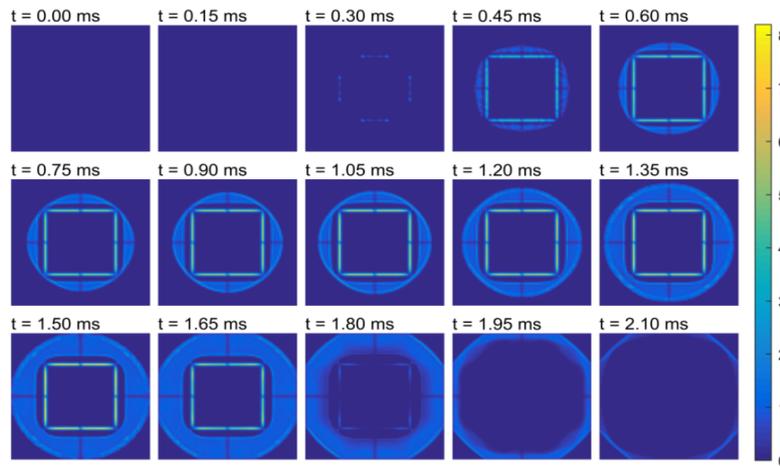
227 In a previous work [16], we described a behaviour analysis tool allowing to decompose the
 228 deformation of a shield into three modes: Indentation, Bending and Crushing. The main
 229 principle of this tool is to project at each time step the vector representing the shield
 230 deformation on a basis defined *a priori* and describing the three deformation modes. It has
 231 been shown that this decomposition describes efficiently the deformation of any shield with
 232 only a small residue (less than 10% in norm)[16].

233 Using this tool, it is then possible to extract the maximum norm of each deformation mode
 234 along time. These three behaviour criterions will give information about how the shield
 235 behaves and is deformed during impact without the need to analyse in detail each simulation.



236
 237
 238

Fig. 4. Reference case: contact forces (bird on front skin and back skin on support)



239
 240

Fig. 5. Reference case: contact pressure on back skin

241 2.3 Choice of parameters to study

242 The finite element model described here presents an important number of parameters. Thus, it
 243 is necessary to choose which parameters to take into account before conducting the parametric
 244 study. In [16], we conducted on this finite element model a screening analysis to identify the
 245 most influential parameters on the shield behaviour, using the deformation-based behaviour
 246 analysis tool presented above. This screening has been extended to identify influences on the
 247 shield behaviour (3 outputs) and the four protection criterions (4 additional outputs).

248 15 parameters or group of parameters have been studied independently. Along with its
 249 reference value, each parameter has been assigned a minimal and maximal value. 31 cases
 250 have then been simulated: the reference point and the minimal and maximal case for each
 251 parameter (One factor at a time DOE). For each of these simulations we measured the

252 difference of shield behaviour with respect to the reference case, in order to rank the 15
 253 parameters (mean rank on the 7 outputs). The main conclusions of this screening study are as
 254 follows:

- 255 - The most influential parameter is clearly the core crushing plateau σ_{pc} . Any change in the
 256 value of this parameter induces important change in the shield behaviour.
- 257 - The second most influential parameter is the core out-of-plane shearing plateau τ_{pc} .
- 258 - Then the parameters rank as follows: the core height H_c , the front skin yield strength A_{fs} ,
 259 the support aperture size L_{ap} , the front skin thickness t_{fs} , the elastic modulus of the front
 260 skin, the out-of-plane elastic modulus of the core, and then the other parameters.
- 261 - It appears that the in-plane properties of the core have very little influence on the shield
 262 behaviour, and that the back skin design has little influence compared to the front skin
 263 design.
- 264 - The effects of the parameters on the shield behaviour can be strongly non-linear, and
 265 sometimes even non-monotonic.

266 According to these conclusions, this parametric study will be focused on the 6 most influential
 267 parameters: The core out-of-plane crushing plateau σ_{pc} , the core out-of-plane shearing
 268 plateau τ_{pc} , the core height H_c , the support aperture size L_{ap} , the front skin thickness t_{fs} and
 269 the front skin yield strength A_{fs} . Moreover, it is necessary to choose a DOE allowing us to
 270 study the possible nonlinearities and interactions, as they were not studied in the screening
 271 study.

272 **3 2D parametric studies**

273 In order to be able to analyse precisely the effects of each parameter, and to be able to
 274 visualize the results more easily, the six identified parameters are first studied 2 by 2: the two
 275 core out-of-plane plastic plateaus σ_{pc} and τ_{pc} , the two front skin parameters A_{fs} and t_{fs} , and
 276 the geometric parameters H_c and L_{ap} . To be able to assess the nonlinearity and the possible
 277 interactions, 5 levels by parameters are chosen. When varying the inputs pairwise, remaining
 278 parameters are kept at the baseline values (presented in Section 2.1). The minimal and
 279 maximal parameters values used are presented in Table 1 and are the same as in [16],
 280 representing materials typically seen in the industry for such applications.

281

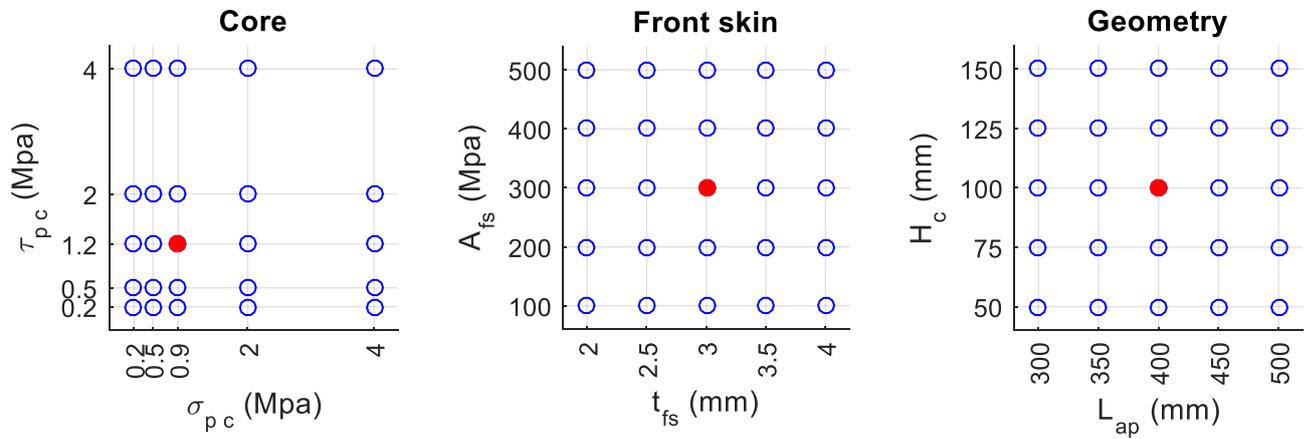
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283 Table 1: Minimal and maximal values of the six parameters studied

		Lower limit	Reference	Upper limit	Units
σ_{pc}	Core crushing plateau	0.2	0.9	4	MPa
τ_{pc}	Core shearing plateau	0.2	1.2	4	MPa
A_{fs}	Front skin yield stress	100	300	500	MPa
t_{fs}	Front skin thickness	2	3	4	mm
H_c	Core height	50	100	150	mm
L_{ap}	Support aperture size	300	400	500	mm

284

285 The designs of experiments used for these three 2D series are represented in Fig. 6. The
 286 reference case is indicated with a full red dot.



287

288

Fig. 6. Designs of experiments used for the three 2D studies

289 For the ‘core’ DOE, the choice was made to simulate more designs toward the lower bound of
 290 both σ_{pc} and τ_{pc} because the screening study showed that a decrease of those parameters has
 291 more effect on the shield behaviour than an increase.

292 3.1 Effect of the core design

293 For each of the 25 simulations of this DOE, the seven criterions (3 behaviour criterions and 4
 294 protection criterions) are measured. These results are given on Fig. 7 as a surface
 295 reconstructed from the simulation points (black) using linearly interpolated scheme. The red
 296 dot indicates the reference case and the value of the outputs at this point is shown by a red line
 297 on the colour scales.

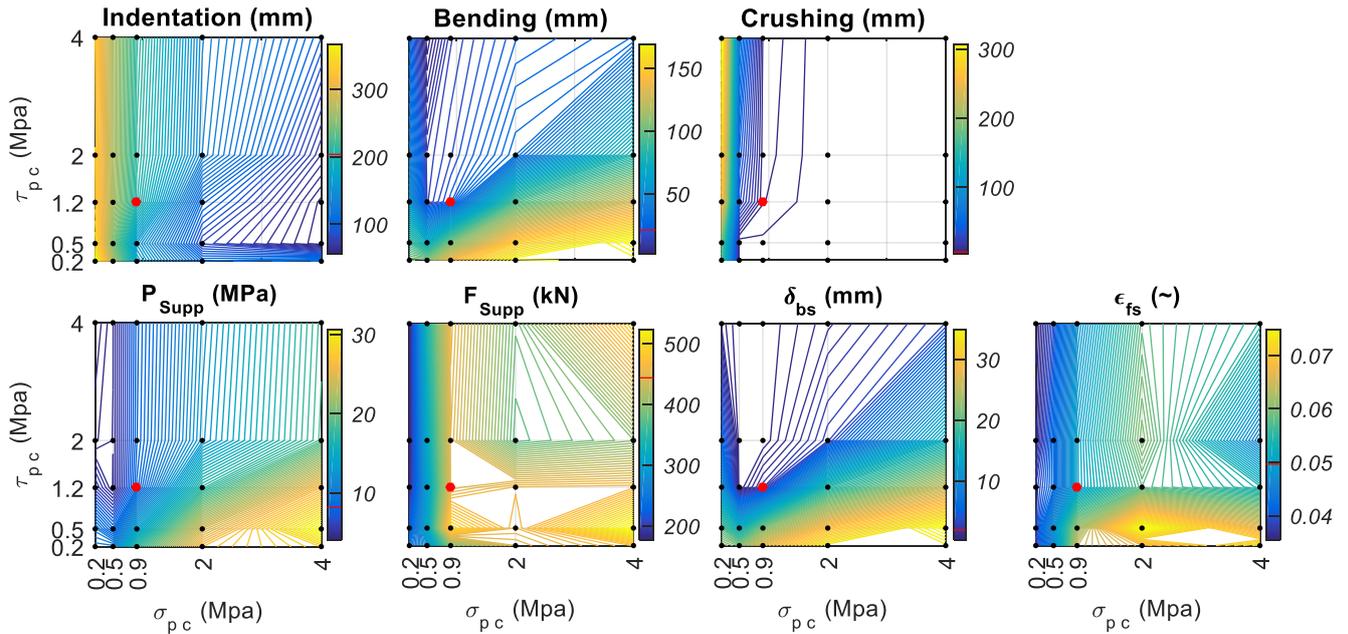


Fig. 7. Effects of the core design on the seven outputs

298
299

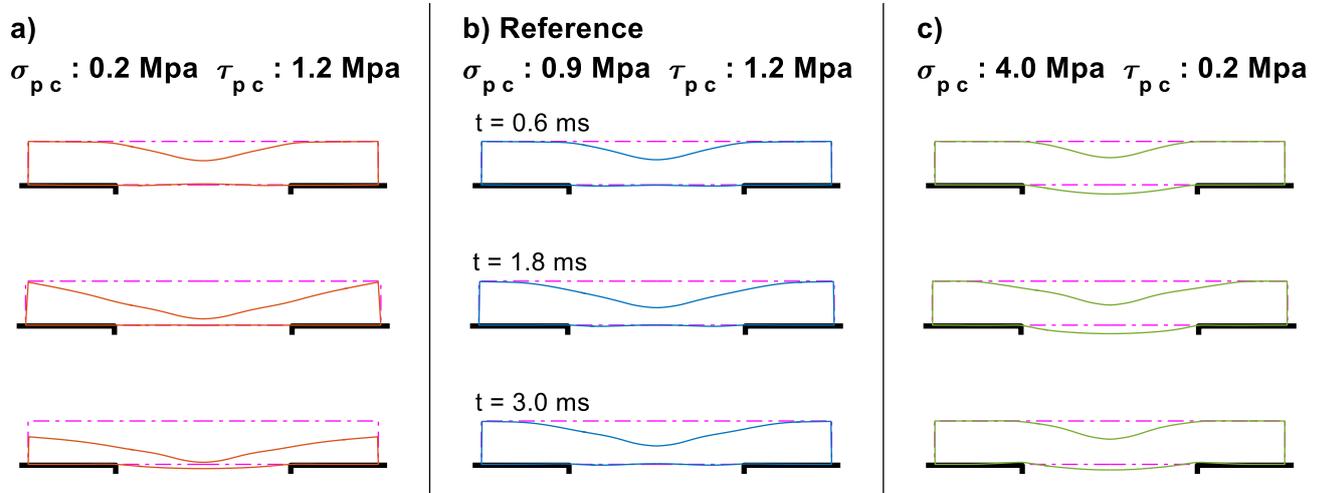
300 We can see on this figure that the effects of the core design are strongly non-linear and that an
301 interaction exists between the two design parameters. Two main effects can be observed.

302 First, there is a strong effect of σ_{pc} , which appears only when σ_{pc} is smaller than 0.8 MPa.
303 This effect can be observed on Fig. 7 for Indentation, Crushing, F_{Supp} and ϵ_{fs} . For a
304 decreasing value of σ_{pc} , the shield shows increasing values of Indentation and Crushing
305 modes, associated with reducing values of F_{Supp} and ϵ_{fs} . Thus, this strong crushing behaviour
306 is associated with a smaller force transmitted to the support and a smaller strain of the front
307 skin. This effect can be explained by the fact that the force transmitted to the support is linked
308 with the force transmitted between the two skins by the core. With a low crushing plateau of
309 the core, this force is necessarily smaller. Regarding ϵ_{fs} , its decrease may be explained by the
310 fact that a strong crushing behaviour induces an indentation which is less located at the centre
311 of the shield.

312 So, for a low core out-of-plane crushing plateau, the shield has a deformation dominated by
313 indentation and crushing, with comparatively small bending, whereas for a higher core out-of-
314 plane crushing plateau, the shield shows mainly indentation.

315 This change of behaviour can be seen clearly on Fig. 8: the shield in a) (with a low core
316 crushing plateau) shows a strong Crushing behaviour whereas the shield in b) (the reference
317 case) shows mainly Indentation. On this figure, only the outline of the core in the XZ plane is
318 represented (with the second half reconstructed by symmetry for easier visualization). The

319 undeformed profiles of the shields are represented by the dashed line and the rigid support is
 320 shown in black.



321
 322 Fig. 8. Behaviour of the shield during impact for three different core designs (core outline in xz plane)

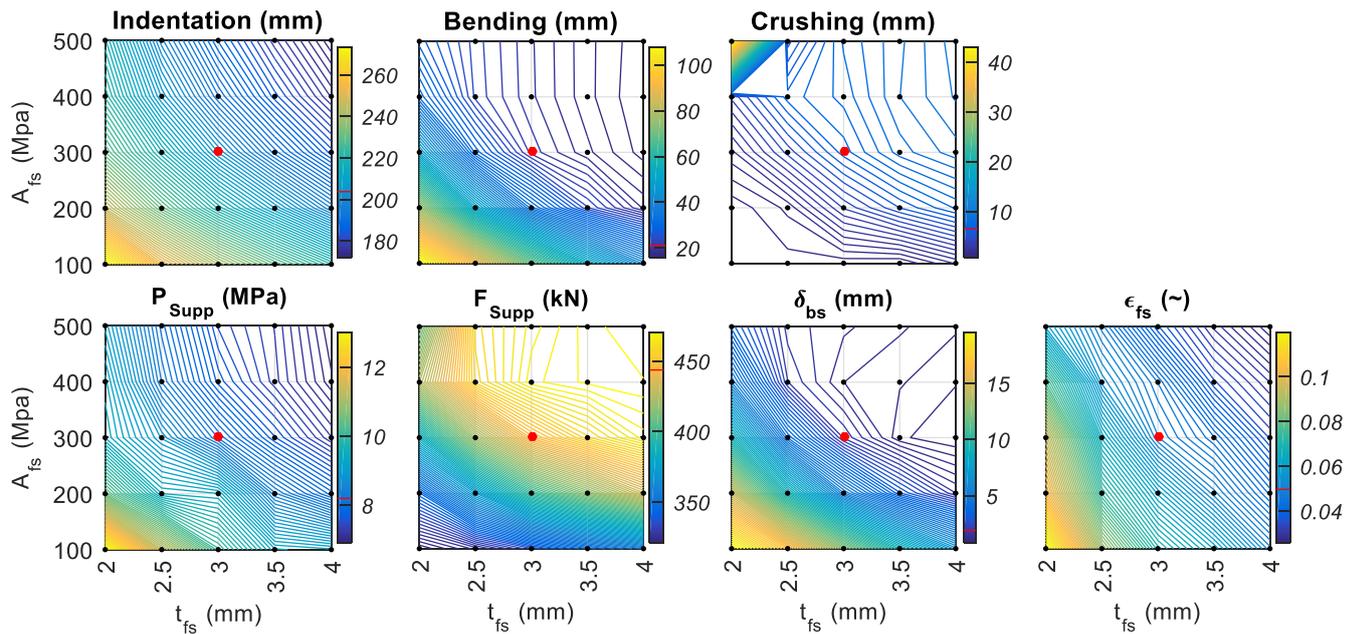
323 The second effect which can be observed on Fig. 7 is the increase of Bending, P_{Supp} , δ_{bs} and
 324 ϵ_{fs} for a low core out-of-plane shearing plateau associated with a strong core crushing
 325 plateau. The effect of τ_{pc} can be explained by the fact that the core out-of-plane shearing
 326 plateau have a direct influence on the sandwich bending resistance. Thus, a decrease of τ_{pc}
 327 will lead to an increase of bending, and this effect is enhanced for a high core crushing
 328 plateau, which increase the sandwich crushing resistance. This increase of bending leads to an
 329 increase of the back skin backward deflection δ_{bs} , which can be seen clearly on Fig. 8 where
 330 the shield c) (with low shearing plateau and a high crushing plateau) shows an important
 331 backward deflection. Similarly, the shield c) shows an indentation which is more located at
 332 the centre of the shield, which can explain the increase of the front skin maximum strain ϵ_{fs} .

333 Another consequence of the increase of bending is the increase of the maximum pressure
 334 transmitted to the support P_{Supp} . This consequence is explained by the fact that the bending of
 335 the shield localises the contact between the back skin and the support. Thus P_{Supp} increases
 336 without any increase of F_{Supp} .

337 In summary, the core design strongly influences the behaviour of the shield. A low core
 338 crushing plateau induces a behaviour dominated by the core crushing. On the contrary, a low
 339 core shearing plateau associated with a strong core crushing plateau leads to a shield
 340 behaviour with strong bending. For the reference case, the shield is deformed mainly by
 341 indentation.

342 **3.2 Effect of the front skin design**

343 The results for the 25 simulations studying the front skin design are presented on Fig. 9. First,
 344 we can see that nearly all the outputs vary less than on Fig. 8, which shows that, using these
 345 ranges of variation, the core design has more influence than the front skin design. This
 346 conclusion is coherent with the conclusions of [16], where the core plateau parameters were
 347 identified as the most influent parameters. Only the front skin maximum strain ϵ_{fs} is more
 348 influenced by the front skin design.



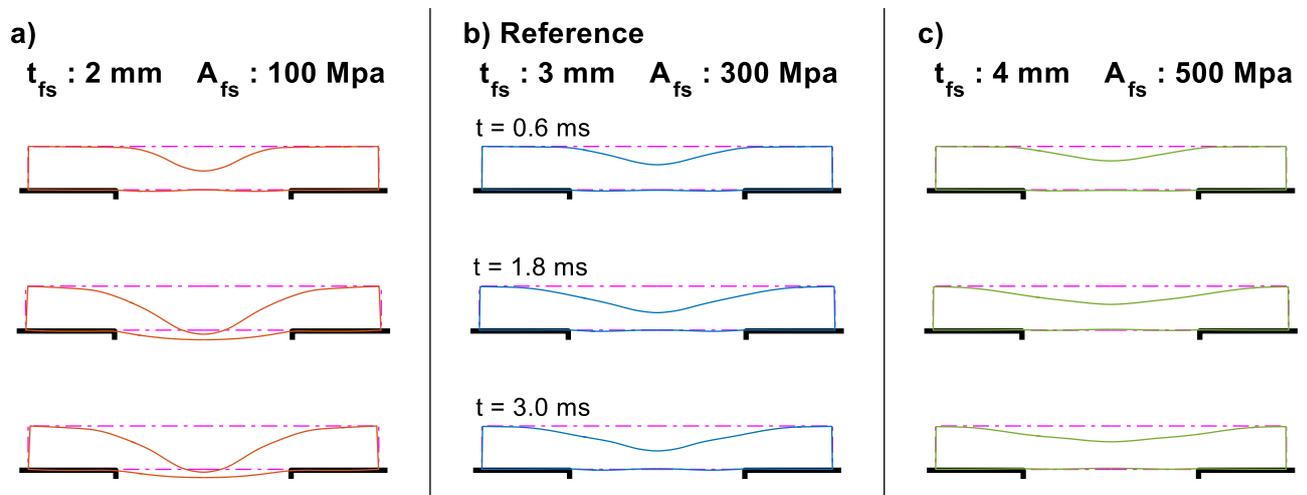
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Fig. 9. Effects of the front skin design on the seven outputs

351 It is clear from Fig. 9 that the front skin thickness t_{fs} and its yield strain A_{fs} play very similar
 352 roles. In fact, a shield with a thick skin and a low yield strain seems to behave similarly to a
 353 shield with a thin skin and a high yield strain. The only outlier design is the shield with $t_{fs} =$
 354 2 mm and $A_{fs} = 500\text{ MPa}$, especially for the Crushing output. When observing this finite
 355 element simulation in details, it appears that this is due to the buckling of the front skin, under
 356 the compression stresses due to the sandwich bending. This front skin buckling does not
 357 appear on any other case simulated in this study. It may come from a thin skin submitted to
 358 high stresses, due to a high yield strain.

359 All the other designs show that a weak front skin (thin and with a low yield strain) increases
 360 the indentation and bending of the shield, while a strong front skin reduces it, with nearly no
 361 effect on the crushing behaviour. In fact, the front skin strength has an influence on the

362 importance of the shield deformation, as can be seen on Fig. 10, where the three shields
 363 shown are the two extreme cases and the reference.



364 Fig. 10. Behaviour of the shield during impact for three different front skin designs (core outline in xz
 365 plane)
 366

367 On Fig. 9, it appears that the increase of the shield deformation due to a weaker front skin is
 368 associated with an increase of P_{Supp} (which is explained as in section 3.1 by an increase of
 369 bending localizing the contact between the back skin and the support), but also with a
 370 decrease of F_{Supp} . This effect may come from the fact that, due to the important deformation
 371 of the shield, the impacting bird is slowed down more progressively by a weak front skin than
 372 by a strong one. Indeed, the maximum force transmitted to the support occurs at $t = 1.86 \text{ ms}$
 373 for the shield a) in Fig. 10, at $t = 1.62 \text{ ms}$ for the shield b), and at $t = 1.56 \text{ ms}$ for the shield
 374 c).

375 The increase of the shield deformation is also associated with an increase of the back skin
 376 backward deflection (clearly seen on Fig. 10, shield a)), and an increase of the front skin
 377 maximum strain. This effect is due to the strong indentation of the sandwich, localizing the
 378 front skin strain at its centre. We can notice that the strong indentation also limits the capacity
 379 of the bird to flow radially. This phenomenon makes any front skin rupture dramatic since the
 380 loss of the front skin rigidity will induce a strong indentation, which will increase the front
 381 skin loading by limiting the bird radial flow.

382 3.3 Effect of the geometrical parameters

383 In the third 2D design of experiments, the influences of the core height H_c and the support
 384 aperture size L_{ap} are studied. The results of this DOE are given on Fig. 11.

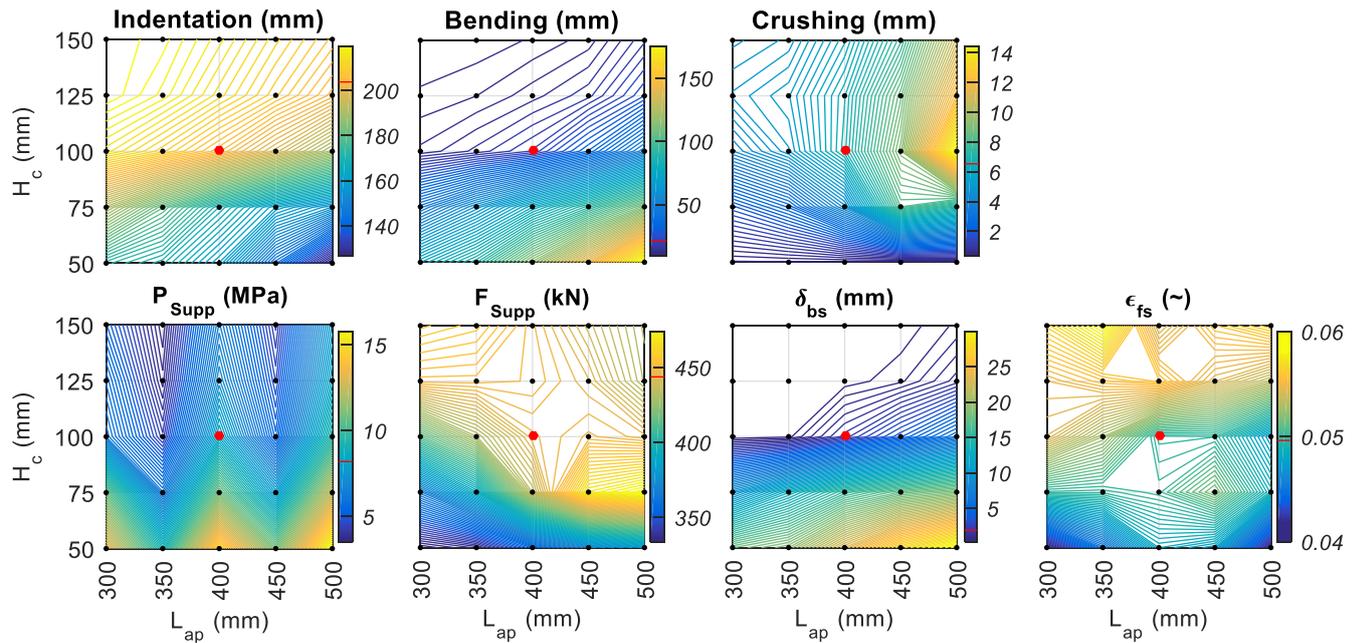


Fig. 11. Effects of the geometrical parameters on the seven outputs

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387 Here again, it appears that the variation ranges of the outputs are smaller than for the core
388 design study. Nevertheless a clear influence of the geometrical parameters on indentation and
389 bending can be seen on Fig. 11.

390 First, it appears that a decrease of H_c leads to a decrease of indentation and an increase of
391 bending. The increase of bending is explained simply by the bending rigidity of a sandwich,
392 which is directly influenced by its core height. This increase of bending is here associated
393 with an increase of the backward deflection and the maximum pressure transmitted to the
394 support, which is coherent with the phenomenon already identified.

395 Secondly, the increase of L_{ap} seems to have the same effect as a decrease of H_c on Bending
396 and δ_{bs} . This is explained by the fact that this parameter represents the size of the
397 unsupported area of the sandwich. The maximum pressure transmitted P_{Supp} seems to
398 oscillate with L_{ap} . This phenomenon doesn't have any physical justification and seems to be
399 caused by the relative position of the support and back skin elements in the simulation, which
400 change when the parameter L_{ap} change. Similarly, no physical explanation has been found to
401 justify the evolution of F_{Supp} .

402 Thus, it seems that the core height and the support aperture size have similar influences on the
403 shield behaviour, with a stronger effect for low values of H_c and high values of L_{ap} . To
404 illustrate this effect, the deformed shapes of three shields are represented in Fig. 12. The
405 shield a) has a high core and a small aperture, the shield b) is the reference, and the shield c)
406 has a thin core and a large aperture.

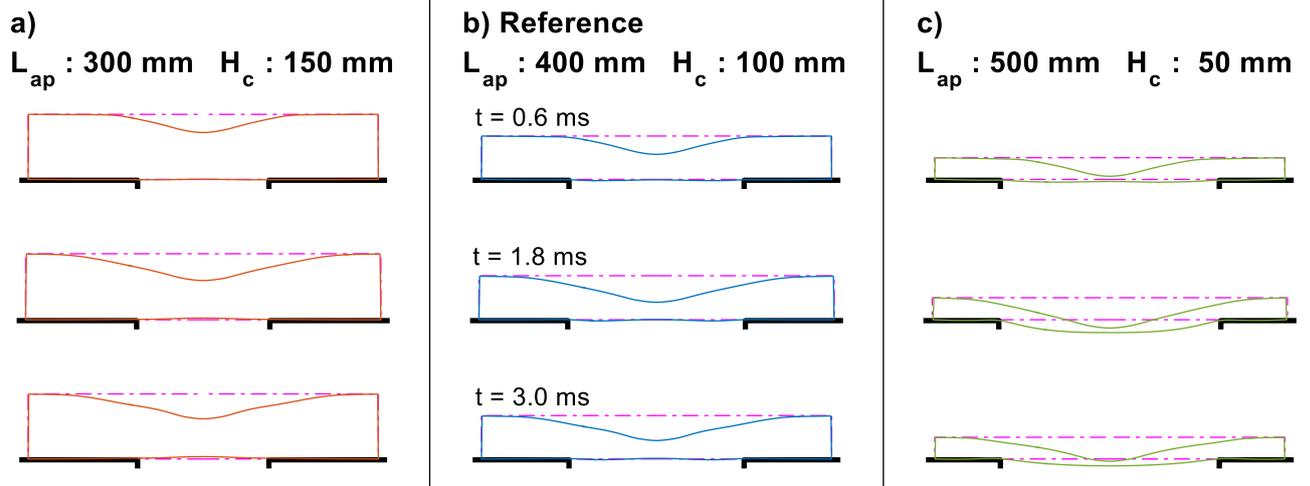


Fig. 12. Behaviour of the shield during impact for three different geometrical designs (core outline in xz plane)

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410 3.4 Conclusion on the 2D studies

411 With these three “two factors at a time” DOE, it was possible to explore in detail the influence
412 of each of the six parameters chosen. The use of 5 levels per parameters allowed us to observe
413 the nonlinearity of the different effects, and studying the parameters 2 by 2 showed that
414 important interactions can exist between the different parameters.

415 These 2D studies confirmed that the most globally influent parameters are the core crushing
416 and shearing plateaus, but they also showed that depending on the output studied, other
417 parameters can be more influent. Different shield behaviours have been identified for different
418 shield designs, and physical explanations for these different behaviours have been proposed.
419 The links between the behaviour criteria (Indentation, Bending and Crushing), and the
420 target protection criteria (P_{Supp} , F_{Supp} , δ_{bs} , ϵ_{fs}) have been identified and explained when
421 possible.

422 But all these conclusions have been obtained on a strongly reduced design space. In the full
423 6D space, only three 2D planes have been studied. Moreover, the results showed that
424 interactions can exist between the different parameters. To study these interactions, and to
425 assert the results obtained with these 2D studies, it is necessary to conduct a full 6D study, in
426 which all the parameters are varied together.

427 4 Expanding the parametric study in 6D

428 A 6D study is far more complex to conduct than a 2D study. First, it is impossible to use a
429 simple full factorial DOE, since the number of simulations needed increase exponentially (5
430 levels for six parameters lead to $5^6 = 15625$ simulations). Second, the visualisation of the

431 results is not possible is full 6D and can only be done using 2D slices. Third, it is complicated
432 to analyse the results since it is not possible to visualise them globally. It is then necessary to
433 use statistical methods to measure the influence of the different parameters.

434 To handle these issues, the usual approach is to construct and train a surrogate model. This
435 model is a mathematical function and its goal is to approximate the output studied everywhere
436 in the design space, and not only on the tested points. This approach is widely used in the
437 field of engineering design, and described in details in the revue [19] and the book [20]. The
438 main steps of this approach are as follows:

- 439 - First, the choice of the design points to simulate in order to train the surrogate model. The
440 model will interpolate the output between these known points, and thus the choice of this
441 design of experiment is crucial.
- 442 - Second, the construction, training and validation of the surrogate model. It is necessary to
443 choose the form of the mathematical functions which will be used to construct the
444 surrogate model, as it will constrain the precision of the model. The validation consists to
445 check if the model is able to approximate efficiently the output. If not, it is possible either
446 to change the form of the surrogate model or to return to the first step to add more known
447 points.
- 448 - Third, the analysis of the model obtained, in order to measure the effects of each parameter
449 and their interactions, and to conduct physical interpretations. Global methods of analysis
450 will be used to validate (or not) the observations made on the 2D studies in Section 3.

451 **4.1 Choice of the 6D design of experiments**

452 Usually, the choice of the DOE depends strongly on the form of the surrogate model to train,
453 which is chosen depending on the *a priori* available knowledge of the output. Here, the 2D
454 studies showed that the outputs behaviour can be strongly non-linear and with interactions. It
455 is then necessary to have a surrogate model able to adapt to a wide range of behaviour.
456 Moreover, in this work seven different outputs are studied and thus seven different surrogate
457 models will be constructed. As each simulation allows measuring the seven outputs, all seven
458 surrogate models will be trained on the same set of known points. For these reasons, the DOE
459 used needs to be as general as possible, to adapt to the different situations.

460 A lot of different methods exists to create a design of experiments [19][21][22]. We choose
461 here to use a Latin Hypercube Sampling (LHS) strategy, because it allows to choose *a priori*
462 the number of design points. In a LHS design of experiments with N_s points, each parameter
463 has N_s levels and takes each level once and only once. This type of DOE is of particular

464 interest for computer experiments since no point is tested twice, and this property hold true if
465 any parameter appears irrelevant. Constructing a LHS is simple (by random permutation of
466 the rows of an identity matrix), but this approach can produce designs with very different
467 uniformity. In order to obtain a good LHS, the original one can be optimized to increase the
468 uniformity. For example, in [20] a strategy using the *maximin* [23] criterion is presented.
469 In this work, 73 sampling points have already been simulated during the 2D studies presented
470 in Section 3. In order to choose 100 new design points to be simulated, we adapted the
471 strategy presented in [20] to optimize the *maximin* criterion of the complete 173 points DOE.
472 The 100 new points chosen are then simulated and the seven outputs are measured for each
473 case. The 173 known points can then be used to create the surrogate models.

474 **4.2 Construction and validation of the surrogate models**

475 As seven models have to be constructed, it would be possible to choose different frameworks
476 for each, but for practical reasons we choose to create the seven surrogate models using the
477 same framework. A lot of different framework of surrogate models exist [19][20][22], and we
478 choose here to create our surrogate models using the Gaussian Process (GP) framework,
479 described in detail in the book [24]. All the computations for the creation and analysis of these
480 surrogate models are made on Matlab using the GPML toolbox available with the book.

481 GP are used because they can reproduce many different behaviours. Moreover, their statistical
482 framework allows us to estimate the approximation error at each point of the design space,
483 which can be very useful to estimate the precision of the surrogate models.

484 Thus, for each of the seven output, a surrogate model is constructed using a Matérn $\nu = 3/$
485 2 kernel with Automated Relevance Determination, and a constant mean [24]. The nine
486 hyper-parameters (the mean, the signal variance, the noise variance and the six length-scales)
487 are optimised using the log marginal likelihood maximisation function provided in the GPML
488 toolbox [24]. In order to ensure a good convergence of the hyper-parameters optimisation, the
489 data are first normalized using Matlab *zscore* function, to set their means to zero and their
490 variances to one in each direction.

491 The obtained surrogate models are then tested using the Leave-One-Out (LOO) method. This
492 method consists of training the surrogate model on all the data points minus one, and then of
493 testing it on the last data point. By repeating this process on each data point, a mean
494 prediction error can be computed. This mean error is presented for each output on Fig. 13, in
495 percentage of the variation range of the output.

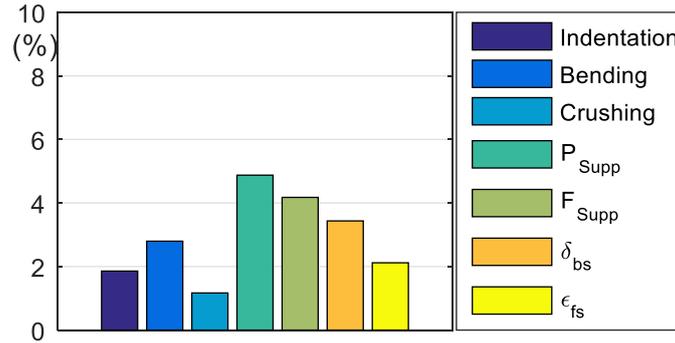


Fig. 13. Mean LOO error in % of the variation range for each output studied

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498 We can see on Fig. 13 that the mean LOO error is lower than 5% for all the outputs studied.
499 This shows that the surrogate models constructed are able to represent globally the evolution
500 of the seven outputs. Thus, these models will be used to analyse the influence of each
501 parameter.

502 4.3 Analysis of the full 6D design space

503 4.3.1 Methods used

504 In order to analyse a six dimensions space, we choose to use two complementary statistical
505 methods: the Morris method [25] and the Sobol' method [26].

506 - The Morris method consists in measuring the elementary effect of each parameter around
507 an initial point, using a one factor at a time design of experiments. By using multiple initial
508 points, evenly distributed in space, it is then possible to compute for each parameter k a
509 mean effect \bar{d}_k and its variance S_k . Then, the greater \bar{d}_k is, the more the parameter k is
510 influent, and the greater S_k is, the more this influence is non-linear or with interactions
511 with other parameters.

512 - The Sobol' method allows to compute the parameters sensitivity indices and their total
513 sensitivity indices. The sensitivity indice represents the fraction of the total variance of the
514 output contributed by the parameter individually, while the total sensitivity indice
515 represents the influence of the parameter and all its interaction with other parameters. To
516 estimate these indices, we use the Matlab toolbox GSAT [27].

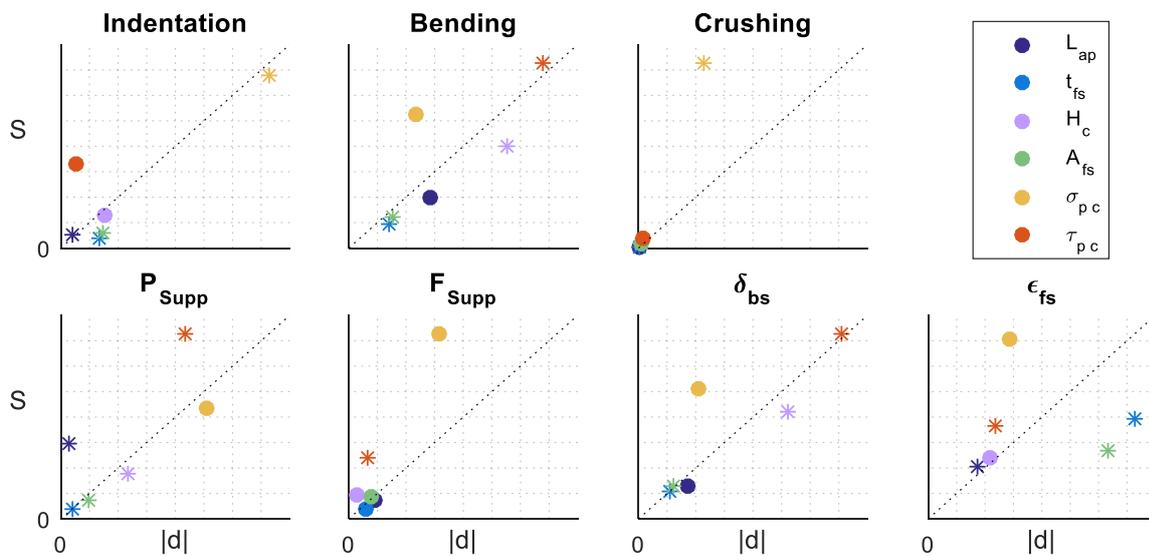
517 Thus, the Morris and Sobol' methods both estimate the influence of each parameter, but in
518 slightly different ways: the Morris method allows measuring the linear effect of a parameter
519 and the variance of this effect, without being able to distinguish between non-linearity and
520 interaction with other parameters, while the Sobol' method measure the total influence of a
521 parameter isolated and with interactions, without measuring the non-linearity of this

522 influence. In this work, we used both approach in order to obtain a maximum of knowledge
 523 about the output behaviour.

524 For both these approaches, it is necessary to use the unit hyper-cube as design space. Thus,
 525 the parameter space is normalized appropriately for all the surrogate models before any
 526 computation.

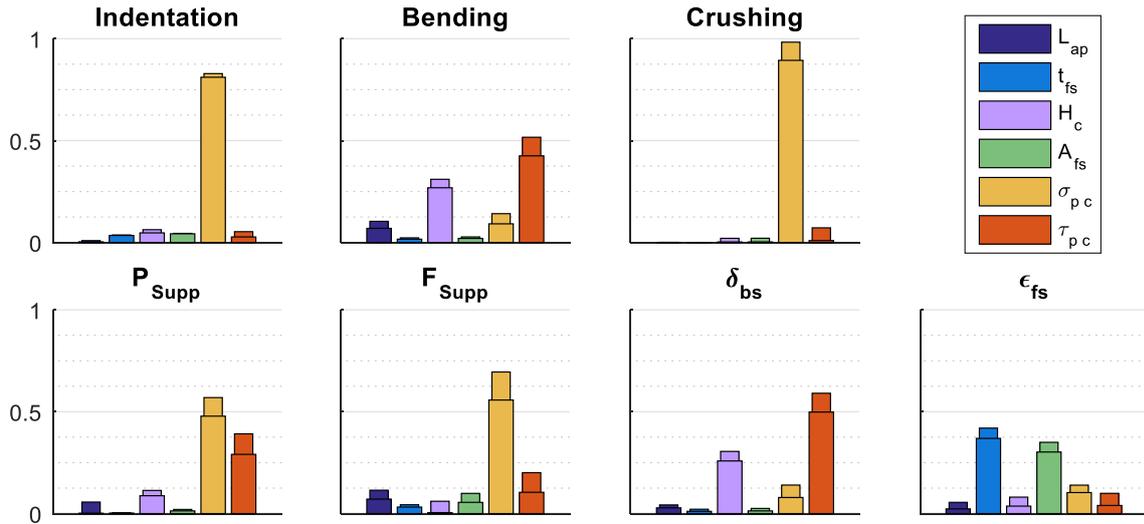
527 **4.3.2 Results and interpretations**

528 The results given by the Morris method are presented in Fig. 14. For each of the seven
 529 surrogate models, we used 100 000 initial points pseudo-randomly distributed to estimate the
 530 mean effects \bar{d}_k and their variance S_k . In order to compare the influence of each parameter,
 531 they are placed in the $(|\bar{d}|, S)$ space for each output in Fig. 14, where the dotted diagonal
 532 represents the line $|\bar{d}| = S$. To visualize the sign of the mean effects, the parameters are
 533 represented by a • when the mean effect is positive and by a * when it is negative. A
 534 positive/negative effect means that the output increases/decreases when the parameters
 535 increases.



536
 537 Fig. 14. Analysis of the seven surrogate models using the Morris method

538 The results of the Sobol' analysis are presented on Fig. 15. For each surrogate model and each
 539 parameter, the corresponding sensitivity indice and total sensitivity indice are presented as
 540 superposed bars of different width. Thus, the difference of height between the two bars of one
 541 parameter represents the sum of all the interactions with other parameters.

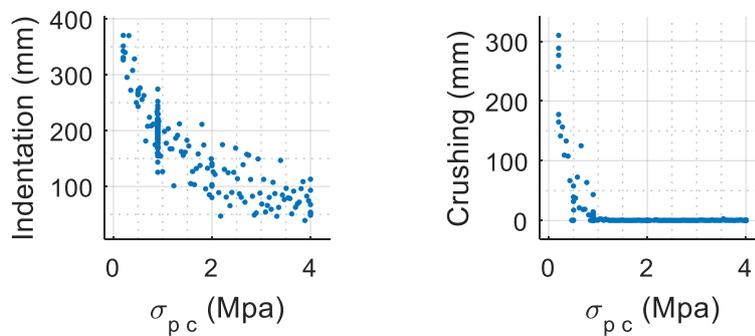


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Fig. 15. Analysis of the seven surrogate models using the Sobol' method

544 First, we can see on Fig. 14 that the parameters are mainly placed near or above the $|\bar{d}| = S$
 545 line, which shows important non-linearity or interactions. On the other hand, Fig. 15 shows
 546 that the interactions between parameters are not so important. Thus, we can conclude that the
 547 effects of the different parameters are strongly non-linear. This conclusion is coherent with
 548 the observations in Section 3.

549 By observing these two figures, it is clear that the more influential parameters are the core
 550 properties and then the core height. This confirms the parameter ranking obtained in [16] and
 551 the outputs ranges of variations observed in Section 3. This is particularly true for two
 552 behaviour outputs (Indentation and Crushing), where the core out-of-plane crushing plateau
 553 σ_{pc} seems to be the only influent parameter. This can be seen more clearly on Fig. 16, where
 554 the 173 simulations are represented in the (Indentation, σ_{pc}) and the (Crushing, σ_{pc}) planes.
 555 There is a clear correlation between the output value and the σ_{pc} parameter value.



556
557

Fig. 16. Effect of σ_{pc} on Indentation and Crushing

558 Fig. 16 also shows the strong non-linearity of the effect of σ_{pc} , already measured by the
 559 Morris method, as can be seen on Fig. 14 where the σ_{pc} point has a strong value of S . We can
 560 also see on Fig. 16 the strong threshold effect of σ_{pc} on the Crushing output, already
 561 identified in Section 3.1.

562 The Morris method also enables us to confirm the signs of the effects of the different
 563 parameters. For example, the effect of the core height H_c is negative on Bending and
 564 backward deflection δ_{bs} , while positive on front skin maximum strain ε_{fs} , which is coherent
 565 with the local observations of Section 3.3 (Fig. 12). These signs also show that the two core
 566 material parameters σ_{pc} and τ_{pc} have always opposed effects, which confirms that the two
 567 ‘extreme’ designs of core material are either a core with high crushing plateau and low
 568 shearing plateau or a core with low crushing plateau and high shearing plateau.

569 By observing Fig. 15 and Fig. 14, we can also see that the two front skin parameters (its
 570 thickness t_{fs} and yield stress A_{fs}) have effects which are quite similar, and with same sign, on
 571 all the outputs. Once again, it confirms the local observations of Section 3.2.

572 4.4 Conclusions on the full 6D study

573 In this section, the full 6D design space was studied using a set of 100 simulations spread
 574 evenly using a Latin Hyper-square DOE. Using these simulations and the 73 simulations
 575 already done in Section 3, one surrogate model was constructed for each output studied.

576 After validation, it was possible to use these models to analyse the design space using two
 577 different methods: the Morris method and the Sobol’ method. We saw that these two methods
 578 are complementary and that using the two in parallel allowed us to measure both the non-
 579 linearity of the parameters effects and the interactions between parameters.

580 Using the results obtained, we saw that, on the studied design space, the parameters have
 581 effects which are often strongly non-linear, but with only small interactions. Then, the results
 582 were compared to the local observations of Section 3. Both the ranking of parameters with
 583 respect of their influence, and the signs of the parameters effects were coherent with local
 584 observations.

585 Thus this 6D study allowed us to confirm globally the different behaviours observed in
 586 Section 3. But it is important to note that, due to the strong non-linearity of the parameters
 587 effects, these behaviours can be false locally.

588 5 General conclusion

589 To tackle the problem of bird impact on sandwich shield (numerous parameters, time-
590 dependant response...), DOE and machine learning methods were used in this study with
591 finite elements simulations. After an initial screening to reduce the number of parameters to
592 take into account, Gaussian Process were used to create surrogate models in a 6D domain,
593 using smart sampling. This method enables to analyse the effects of the six most influential
594 parameters and their interactions on the shield behaviour (deformed shape and protection
595 criterions) within a reasonable computation time.

596 The main conclusions of this study are the following:

- 597 - First, the two most influential design parameters are clearly the core out-of-plane crushing
598 plateau and the core shearing plateau. This means that during the design of a shield for soft
599 impact, great care should be taken in the choice of the core material. We also saw that
600 these two parameters have effects that are opposed. Thus, a shield with higher crushing
601 plateau and lower shearing plateau will transmit more stresses (and more localized) to the
602 back skin and the support, while reducing the area of core crushed and increasing
603 backward deflection. Yet, when changing the core material designers usually stay in the
604 same category of cellular material (ex. aluminium honeycombs), which mean changing
605 both plateaus parameters in the same direction (either increasing or decreasing).
- 606 - The two skin parameters (thickness and material yield stress) have very similar effects. A
607 stronger skin (i.e. higher thickness or higher yield stress) will tend to reduce the shield
608 indentation and flexion, thus spreading more evenly the core crushing and reducing
609 backward deflexion and front skin maximum strain. On the other hand, these two
610 parameters have very different effects on the shield mass. For a lightweight shield, it is
611 then more advantageous to increase the front skin yield strain while reducing its thickness.
612 This conclusion shows that a soft impact problem is very different from a hard impact
613 problem, where a softer front skin is usually beneficial [28]. This difference may come
614 from the fact that, for a soft impact case, the strain gradients are smaller. This implies that
615 the deformations inside the shield are more global and it appears that all the parts of the
616 shield are working together at the same time, and not one after the other (as can be the case
617 in hard impact). Thus the sandwich shield has to be studied as a whole and not as a
618 succession of different layers.
- 619 - The core height has a strong effect on the shield bending and backward deflection, which is
620 coherent with usual sandwich behaviour. Thus, a higher core is usually beneficial for target
621 protection.

622 For this work, we deliberately choose a quite simple finite element model in order to simulate
623 numerous possible designs, and the conclusions have to be taken with precautions. In
624 particular, the core material model used here is decoupled, which means that the real
625 interactions between the two core plateaus parameters are probably more important than
626 calculated. Another limitation of this study is the fact that we did not take into account the
627 possible front skin rupture. In the 173 configurations simulated, none showed front skin
628 strains greater than 15%, which shows *a posteriori* that this hypothesis was valid.
629 Nonetheless, we have to keep in mind that the front skin rupture would drastically change the
630 shield behaviour, as losing the front skin rigidity would mean losing the “sandwich”
631 behaviour.

632 At last, thanks to this new understanding, general rules have been proposed to orient the
633 design of better shields. Moreover, the surrogate models created here are a first step towards a
634 design tool to help engineers, as they can be used in an optimisation loop in order to find an
635 optimal shield with only a few more simulations.

636 Of course, such a numerical study requires validation, and an experimental campaign is
637 currently being conducted to validate the main conclusions.

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